ABSTRACT

The two major objectives satisfied in this investigation include the development of an improved semi-empirical model for microwave backscatter from vegetation and the acquisition of a complete set of canopy attenuation measurements as a function of frequency, incidence angle and polarization. The semi-empirical model was tested on corn and sorghum data over the 8-35 GHz range. The model generally provided an excellent fit to the data as measured by the correlation and rms error between observed and predicted data. The model also predicted reasonable values of canopy attenuation. The attenuation data was acquired over the 1.6 - 10.2 GHz range for the linear polarizations at approximately 20° and 50° incidence angles for wheat and soybeans. An attenuation model was proposed which provided reasonable agreement with the measured data.

TABLE OF CONTENTS

Page

ACKNOWLEDGEMENT

This research is supported by NASA/GSFC Grant No. 923-677-24-01-16 92-2511, and is a continuation of work that was conducted at the University of Kansas under Grant NAG5-272.

LIST OF FIGURES

Page

LIST OF TABLES

NOMENCLATURE

SYMBOL	UNITS	DESCRIPTION
A	--	empirical constant
B	--	empirical constant
C	--	empirical constant
C1,C2,C3	--	designation for corn fields 1, 2, and 3, respectively
c	--	factor obtained from t-distribution for confidence-interval calculations
$C(f,\theta)$	--	empirical constant, which is a function of frequency and angle of incidence
D	--	empirical constant
dz	m	incremental path length through canopy
E	--	empirical constant
e	dB	rms error
e_1,e_2,e_3	dB	rms error for fields 1, 2, and 3, respectively
f	GHz	frequency
h	m	canopy height
HH	--	horizontal transmit, horizontal receive
HV	--	horizontal transmit, vertical receive
j	--	symbol used to designate imaginary part of a complex number
k	m^{-1}	wave number $(2\pi/\lambda)$
k_c	--	confidence-interval limit
L	m	correlation length
L_A	dB	loss from model A

$L_a^{st}(\theta,h)$	dB	stalk absorption loss as a function of incidence angle for horizontal polarization
$L_a^{st}(\theta,v)$	dB	stalk absorption loss as a function of incidence angle for vertical polarization
LAI	m^2/m^2	leaf area index
L_B	dB	loss from model B
L_C	dB	loss from model C
$L_C(f,\theta)$	dB	two-way canopy loss as a function of frequency and incidence angle
L_D	dB	loss from model D
L123	--	layers 1, 2, and 3 combined
MPHLEAF	kg/m^2	canopy leaf water content
MPHPLANT	kg/m^2	canopy whole-plant water content
MPHSTALK	kg/m^2	canopy stalk water content
MSVOL	gm/cm^3	volumetric soil moisture
m_v	--	plant or plant-part volume fraction of water
m_w	%	plant or plant-part moisture
N	--	number of leaves per plant
n	--	number of samples
n_e	--	complex index of refraction for extraordinary wave
n_e'	--	real part of n_e
n_e''	--	imaginary part of n_e
n_o	--	complex index of refraction for ordinary wave
n_o'	--	real part of n_o
n_o''	--	imaginary part of n_o

n''_v	--	imaginary part of complex index of refraction for vertically polarized wave
P	--	empirical constant
Q	--	empirical constant
R	--	empirical constant
r	--	correlation coefficient
R_{hh}	--	Fresnel reflection coefficient for horizontal polarization
r_1, r_2, r_3	--	correlation coefficient for fields 1, 2, and 3, respectively
S	--	empirical constant
s	--	sample standard deviation
S17VV50	--	radar backscattering coefficient (σ^o) at 17 GHz, VV polarization, 50°
S1,S2,S3	--	designation for sorghum or soybean fields 1, 2, and 3, respectively
t_ℓ	mm	leaf thickness
v_ℓ	--	volume fraction of leaves in canopy
VH	--	vertical transmit, horizontal receive
v_{st}	--	volume fraction of stalks in canopy
VV	--	vertical transmit, vertical receive
W1,W2	--	designation for wheat fields 1 and 2, respectively
$\hat{x}$	--	unit vector in x-direction
$\hat{y}$	--	unit vector in y-direction
$\hat{z}$	--	unit vector in z-direction
z_1, z_2	m	end points of path through canopy
ε	--	dielectric constant vector
ε'_c	--	real part of canopy dielectric constant

ε''_c	--	imaginary part of canopy dielectric constant
ε_e	--	extraordinary wave dielectric constant
ε_ℓ	--	leaf dielectric constant
ε'_ℓ	--	real part of ε_ℓ
ε''_ℓ	--	imaginary part of ε_ℓ
ε^L_ℓ	--	leaf dielectric constant at L-band
ε^C_ℓ	--	leaf dielectric constant at C-band
ε^X_ℓ	--	leaf dielectric constant at X-band
ε_o	--	ordinary-wave dielectric constant
ε^L_{pst}	--	primary-stem dielectric constant at L-band
ε^C_{pst}	--	primary-stem dielectric constant at C-band
ε^X_{pst}	--	primary-stem dielectric constant at X-band
$\varepsilon_{r\ell}$	--	random leaves' dielectric constant
$\varepsilon'_{r\ell}$	--	real part of $\varepsilon_{r\ell}$
$\varepsilon''_{r\ell}$	--	real part of $\varepsilon_{r\ell}$
ε_{rs}	--	random stalk dielectric constant
ε'_{rs}	--	real part of ε_{rs}
ε''_{rs}	--	imaginary part of ε_{rs}
ε^L_{sst}	--	secondary-stem dielectric constant at L-band
ε^C_{sst}	--	secondary-stem dielectric constant at C-band
ε^X_{sst}	--	secondary-stem dielectric constant at X-band
ε^L_{st}	--	stalk dielectric constant at L-band
ε^C_{st}	--	stalk dielectric constant at C-band

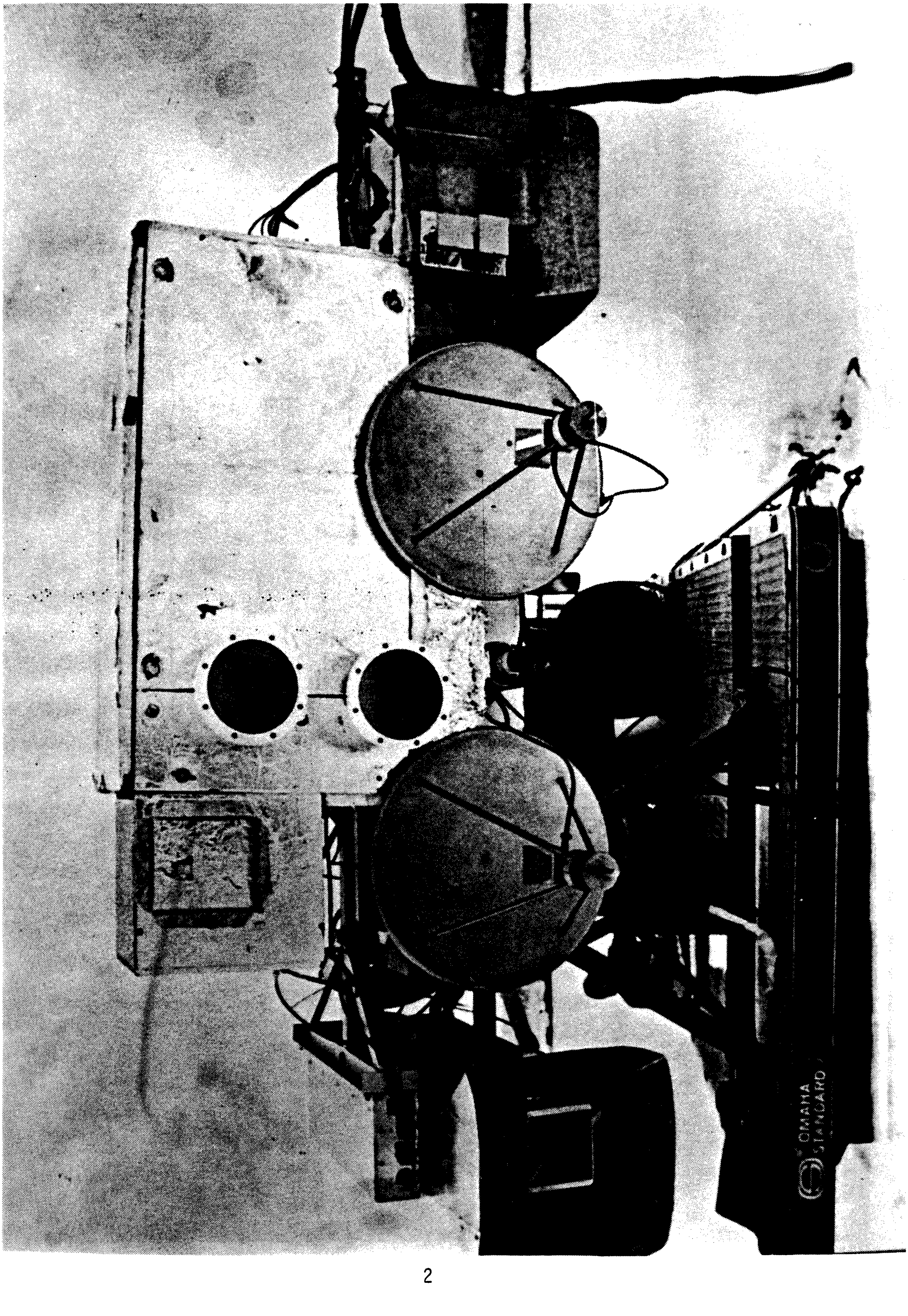
ε_{st}^{X}	--	stalk dielectric constant at X-band
ε_{st}	--	stalk dielectric constant
ε_{st}'	--	real part of ε_{st}
ε_{st}''	--	imaginary part of ε_{st}
ε_x	--	x-component of dielectric constant vector
ε_y	--	y-component of dielectric constant vector
ε_z	--	z-component of dielectric constant vector
κ_a	Nepers/m	absorption coefficient
κ_e	Nepers/m	extinction coefficient
κ_s	Nepers/m	scattering coefficient
κ_c	dB/m	canopy-attenuation coefficient
κ_ℓ	dB/m	leaf-attenuation coefficient
κ_{pst}	dB/m	primary-stem attenuation coefficient
κ_{sst}	dB/m	secondary-stem attenuation coefficient
κ_{st}	dB/m	stalk-attenuation coefficient
ω	--	albedo
λ	m	wavelength
λ_o	m	free-space wavelength
ρ_v	kg/m^3	vegetation density
σ	m	surface standard deviation
σ^o	dB or m^2/m^2	backscattering coefficient
σ_o^o	dB	observed backscattering coefficient
σ_p^o	dB	predicted backscattering coefficient
τ	Nepers	optical depth

$\tau_{\ell s}$	Nepers	optical-depth component due to leaf scattering
$\tau_{\ell a}$	Nepers	optical-depth component due to leaf absorption
τ_{sa}	Nepers	optical-depth component due to stalk absorption
θ	degrees	incidence angle from nadir

1.0 INTRODUCTION

A little over a century ago, mankind had to rely upon direct, on-the-ground observations to acquire the kinds of information useful in resource-management; as a result, such management was extremely limited in scope. Over the first eighty years of this century, aerial photography proved to be quite valuable to resource managers, and it is still a legitimate form of remote sensing today. But it was with the launching of satellites carrying onboard visible- and infrared-sensors in the 1970's that the science of remote sensing was revolutionized. Spaceborne sensors were able to provide high-resolution imagery of even the most remote parts of the Earth. Naturally, any satellite-based image contains a large quantity of information. Therefore, advances in digital-computer technology and digital image-processing techniques have been necessary and have led to the increased use of the resulting information by resource managers. Promising research is continuing in this vital aera.

Unfortunately, visible and infrared sensors--especially visible sensors--have some serious limitations. For example, cloud cover renders visible sensors useless and severely degrades the performance of infrared devices. In addition, visible sensors can be operated only during daylight hours and are affected by sun-angle. For this reason, much research is currently directed toward the development of microwave remote sensing systems, both active and passive, capable of supplementing


OMAHA
STANDARD

the data provided by visible and infrared sensors. Microwave systems may be operated either day or night, under clear-sky or cloudy conditions, and over a very wide range of frequencies. The present study is devoted to increasing the understanding of the responses of such systems--specifically active microwave or radar systems--to vegetation. An increased understanding of these responses will help to discover microwave remote sensing applications, not only in agriculture and food production, but also in water-resource management, energy utilization, conservation, and production.

1.1 Agricultural Applications

Agricultural resource management encompasses two major tasks: The first involves the discrimination and classification of crop species, which can ultimately provide an estimate of the acreage planted for each type of crop, and the second concerns monitoring crop growth and vigor, which in conjunction with acreage estimates, will allow forecasts of yield.

The problem of discrimination and classification has been studied extensively using radar alone (Bush, 1976a) and combining radar data with Landsat data (Eyton, 1979; Li, 1980). The results of these investigations indicate that radar and Landsat data are complementary in nature and that classification

TABLE 1. Sources of Dry Weight and Protein Intake on a Worldwide Basis (Adapted from Evans, 1975)

	Dry Matter (%)	Protein (%)
Wheat	18.2	17.5
Rice	17.7	12.3
Corn	15.5	13.1
Barley	7.6	6.2
Sorghum and Millet	5.5	3.9
Other Cereal Grains	5.1	0.6
Potatoes	4.4	3.2
Sweet Potatoes and Yams	2.6	1.5
Cassava	2.3	0.4
Sugar Cane	2.9	0.0
Sugar Beets	2.0	0.0
Soybeans	2.8	8.9
Peanuts	1.1	2.5
Peas	0.9	1.9
Beans	1.0	2.9
Vegetables	1.9	4.2
Fruit	1.7	0.7
Milk	3.5	7.7
Meat	1.9	6.7
Eggs	0.3	1.3
Fish	1.1	4.5
	100.0%	100.0%

accuracies of the order of 95% appear to be feasible when multi-date information is obtained.

The second task, i.e., the monitoring of crop growth and vigor and the estimation of yield, is not well understood. This limited understanding can be enhanced, however, by the development of improved mathematical models relating the microwave response to plant physiological changes. Models may range from simple linear regression analyses on microwave and ground-truth data to complex theoretical models based upon Maxwell's equations. A middle-of-the-road approach is the semi-empirical model, which is based upon electromagnetic theory but is generally simple, utilizing easily measured ground-truth parameters.

Electromagnetic models may be used in conjunction with evapotranspiration models developed by agronomists (Hodges, 1977; Kanemasu, 1977) to predict yield. In addition, microwave measurements and models may provide data on crop disease or stress and may provide valuable inputs to the hydrological models used in water-resource management.

1.2 Advantages of Microwave Sensors

The ability to penetrate cloud cover and to operate independently of solar radiation distinguishes microwave sensors from their visible and infrared counterparts. In addition to these advantages, microwave sensors can effectively control the "roughness" of the target under study by a change in wavelength; this property allows studies of target structure that are not possible in the visible and infrared regions. In addition, active microwave sensors have the ability to control the polarization of the illumination and to make cross-polarized measurements that often provide information not available in like-polarized data.

The Earth's atmosphere and ionosphere are not transparent to electromagnetic radiation at all wavelengths. An "optical window" extends from approximately 5 THz to 800 THz and a "radio window" extends from about 30 MHz to 300 GHz. The remainder of the spectrum is essentially useless for satellite-based remote sensing purposes. Even these "windows" are not totally clear, since the optical window contains many gaseous absorption lines, and the radio spectrum is obstructed by a few oxygen and water-vapor lines near the upper end.

Much of the interest in microwave sensors results from their ability to penetrate cloud cover. On the average, a very large portion of the Earth experiences 50% or greater coverage by clouds during the year. Since neither the visible nor the infrared sensors can penetrate this cloud cover, temporal data on crops is extremely difficult to obtain. This problem is critical, since plants may undergo some rather dramatic physiological changes within a period of a few days.

Although rainfall can degrade the performance of microwave sensors, it is actually the cloud cover associated with it that renders optical and infrared sensors useless. In fact, rainfall is not a major problem, since precipitation rates high enough to produce significant attenuation are in evidence only a small fraction of the time available for observation of vegetation.

In addition to the ability of microwave sensors to operate effectively day or night under most weather conditions, they have the unique ability to sense changes in target roughness and dielectric constant. It is this capability that provides the most promise in monitoring the growth and vigor of agricultural crops.

1.3 Prior Research

Some of the earliest scattering experiments on vegetation were conducted at Ohio State University in the late 1950's and 1960's (Cosgriff, 1960; Peake, 1971). Data were collected from a wide variety of agricultural and cultural targets by using a truck-mounted Doppler radar. The radar was capable of operating in the X (10 GHz), Ku (15.5 GHz), and Ka (35 GHz) bands and could measure backscattering from a 0° incidence angle (nadir) to an 80° incidence angle. The absolute calibration of this early Ohio State data is somewhat suspect when compared to more recent measurements (Bush, 1976b), but its precision is still estimated to be about ± 1 dB. Unfortunately, this series of experiments lacked adequate ground-truth support and was temporally incomplete for the purpose of monitoring crop development over an entire growing season. Despite these limitations, the Ohio State experiments are significant in that they launched the study of vegetation by means of microwaves and provided the basis for more detailed investigations.

In 1968, a program designed to investigate the radar backscattering from vegetation, crops, and soils was initiated in The Netherlands (deLoor, 1974). Initial measurements used a 75-

meter television tower as a platform for an X-band pulse-radar system. Because of the height of the tower and the locations of the agricultural fields of interest, data were limited to high incidence angles (≥ 80°). Despite these limitations, the experiments provided some insight into the statistics of radar backscattering from agricultural crops and, what is more important, provided evidence that crops may undergo significant changes in backscattering response over a growing season. In 1973, the group constructed a short-range FM-CW radar system that could be moved on rails along a series of test plots. This system was capable of taking data over an incidence-angle range from 20° to 75° with HH, HV, and VV polarization. This system has been used to acquire a considerable amount of data on crops (deLoor, 1982). The Dutch have also been active in vegetation dielectric constant investigations (de Loor, 1983) and modeling (Hoekman, 1982).

In 1974 and 1975, a group from the Soviet Union conducted experiments on vegetation using a K-band imaging radar (Basharinov, 1976). This series of experiments, although lacking adequate ground truth, noted significant changes in the backscattering coefficient over a growing season and specifically noted a large increase in the backscattering coefficient of winter wheat at approximately the "heading" stage of growth. The experimenters also reported an inverse relationship between the backscattering coefficient and the "productivity of green mass." The productivity of green mass apparently refers to the wet biomass of the vegetation, measured in kilograms per square meter. The Soviets have also reported backscattering data acquired over the 0.8-cm to 30-cm range of wavelengths, as well as laboratory measurements of microwave absorption and scattering of isolated vegetative elements (Shutko, 1981).

A study conducted by the Agricultural Engineering Department at Ohio State University (Story, 1968; Story, 1970), unrelated to the previously discussed backscattering measurement program, concluded that the attenuation by wheat heads is many times greater than the attenuation by stalks, and that transverse magnetic (VV) attenuation is more than twice as great as transverse electric (HH) attenuation. These results suggest that the wheat head should be considered individually as a scattering/absorption element in detailed modeling studies.

Measurements of the temporal response of rice have been completed in India at the Communications Area Space Applications Centre in Ahmedabad (Calla, 1979). The Indian group utilized a fixed X-band (9.4 GHz) CW radar system. This study is significant because rice is one of the world's most important crops, and because few, if any, data are available on its backscattering response. There is no information available on the precision of these data, which is of concern because spatial or frequency averaging was apparently not used; it is likely, however, that fading was reduced somewhat in this data set by time-averaging. In addition, some of the data are also questionable because the cross-polarized data are at times much greater in magnitude than the like-polarized data.

There has been considerable interest in the microwave remote sensing of vegetation in Canada in recent years. This activity has been concentrated at the University of Guelph and the Canada Centre for Remote Sensing in Ottawa (CCRS). A major interest has been the use of synthetic-aperture radar (SAR) imagery for crop discrimination purposes (Brisco, 1978; 1979; 1980). A joint experiment was conducted in Melfort, Saskatchewan by CCRS and the University of Kansas in 1983. A major objective of the experiment was to calibrate SAR imagery using ground-based backscattering measurements.

There is intense interest in the microwave remote sensing of vegetation in West Germany. The German Aerospace Research Establishment (DFVLR) has conducted vegetation studies using both ground-based systems (Sieber, 1979; Graf, 1978) and synthetic-aperture airborne systems (Sieber, 1983). The radar and ground-truth data acquired by this group are both extensive and of high quality. The West Germans were also deeply involved in the European Spacelab mission (Schlude, 1978), in which an X-band imaging radar system was carried aboard the STS-9 Space Shuttle flight. Although a malfunction prevented the acquisition of data during this flight, future flights are expected to provide valuable vegetation data. It should be noted that the West Germans and the University of Kansas worked jointly on a project to calibrate the X-band imagery with ground data and active calibrators; however, the Spacelab's radar malfunction prevented the successful completion of this effort.

There has also been significant activity in microwave remote sensing in France (Lopes, 1979; LeToan, 1982). The French have recently completed an in-depth study of the backscattering characteristics of wheat (Huet, 1983) and its attenuation properties (Lopes, 1983). The backscattering study covered the years 1980, 1981, and 1982 and included both winter wheat and spring wheat. The attenuation measurements presented are quite significant in that they are the first reliable data on the attenuation of wheat, and they illustrate the importance of polarization on attenuation. The measurements, however, were conducted in a laboratory setting, were limited to one frequency, and were conducted at an incidence angle of 90° only. The French work is of very high quality and includes extensive data on the seasonal variability of ground-truth parameters.

Undoubtedly, the most extensive measurement program on the radar backscattering response of vegetation was conducted in the United States at the University of Kansas (Ulaby, 1981). In the late 1960's, studies were directed toward demonstrating that panchromatic techniques were useful in the reduction of fading and that additional information could be obtained by measuring over an octave of bandwidth (Waite, 1970). The radar system used in this series of measurements was a pulse-type system with the carrier frequency continuously varied from pulse to pulse. The pulses were averaged after detection to reduce fading. This program stimulated interest in the development of a ground-based, mobile system with angular, frequency, and polarization agility. The first such system was constructed in 1971 (Mo, 1974) and was used to collect agricultural data near Eudora, Kansas, in the 4- to 8-GHz range. The system's calibration was suspect, unfortunately, and all data had to be reported with respect to a field of corn. In 1972, the system was redesigned and calibrated against a Luneberg lens rather than against a metallic sphere. The lens provided a much-improved calibration technique because of its large radar cross-section and its relative insensitivity to orientation. Using this improved system, data were again acquired in the Eudora region during the 1972 growing season.

Analysis of these data revealed that the moisture in the soil underlying the various crops had a significant influence on the backscattering response, especially at the lower frequencies and angles of incidence (Ulaby, 1975a). This result was the first indication that crop-monitoring studies should be conducted at higher frequencies and angles of incidence to eliminate the effects of soil-moisture variations. In 1973, the 4- to 8-GHz system was redesigned to allow 2 - 8-GHz operation and an 8- to 18-GHz FM-CW radar system was constructed. Some data were collected in 1973 (Ulaby, 1975b), but it was in the 1974 growing season that the first sets of temporally complete data were acquired on a wide variety of crops (corn, wheat, milo, soybeans, and alfalfa). Also in 1974, diurnal experiments were conducted in the 2- to 8-GHz range. One major conclusion reached from the 1974 experiments was that diurnal effects are minimized at frequencies above 8 GHz and that incidence angles of 40° or higher and frequencies of 8 GHz or greater minimize any response to soil moisture. The temporal data acquired (Bush, 1975c,d; Ulaby, 1975c) revealed that the two economically important crops, corn and wheat, exhibited substantial changes in the backscattering coefficient, σ^0, over a growing season and thus held promise for monitoring applications. Among the other crops studied, alfalfa displayed significant changes in σ^0 over the growing season, but milo (sorghum) and soybeans did not. A large number of technical reports and papers have resulted from analysis of these data (Bush, 1975a,b,c,d; Ulaby, 1975c; 1976). Agricultural data were again acquired in the 8- to 18-GHz range during the 1975 and 1976 growing seasons. Acquisition of these data greatly enlarged the available database on agricultural crops, which allowed enhanced statistical (Ulaby, 1979a), row-direction (Ulaby, 1979b), and classification (Eyton, 1979) studies to be performed. In 1977 and 1978, the emphasis in radar data acquisition shifted toward snow and soil-moisture applications, while analysis continued on the available agricultural database.

In 1979 and 1980, the University of Kansas conducted joint vegetation experiments with Kansas State University's Evapotranspiration Laboratory, which is associated with its Agronomy Department. The Kansas State group has been active in the development of evapotranspiration models for use in hydrological applications and crop-yield forecasting (Kanemasu, 1974; 1976; 1977; Brun, 1972; Hodges, 1977). Kansas State had used Landsat data as input to the evapotranspiration models but had experienced considerable difficulty in obtaining cloud-free data over a growing season. The group therefore was quite interested in the potential of microwave remote sensing, which led to the joint experiments. The data were acquired over the 8- to 35-GHz range on a number of test plots of corn and sorghum and on two commercial wheat fields (Eger, 1982; Wilson, 1984).

During the period from 1981 to 1983, the radar systems were re-designed to make them more mobile, so that an increased number of data sets could be acquired on a given day. The systems were limited to L- through X-bands to correspond to the operational systems planned for the late 1980's and early 1990's. In addition, a radiometer system was constructed to acquire passive microwave data. During this period, data were acquired on a number of crops near Lawrence, Kansas, and in 1983, the joint experiment with the Canadians was conducted. A number of special experiments including flooding, screening, defoliation, and attenuation were also conducted during this period. In 1984, L-, C-, and X-band data were acquired on a number of test plots producing small grains, and attenuation measurements were conducted on wheat and soybeans.

As this review indicates, interest in the microwave remote sensing of vegetation is global and has been increasing rapidly in recent years. The availability of the Space Shuttle to carry imaging radars will certainly vastly increase our knowledge in this area but will not eliminate the requirement for additional, detailed ground studies such as those described in this review.

1.4 Objectives of the Investigation

The investigation reported herein has two major objectives. The first is to develop an improved semi-empirical model (or models) to describe the observed backscattering response of vegetation in terms of easily measured ground-truth parameters. The second objective, closely related to the first, is to obtain data on the attenuation experienced by a microwave signal as it propagates through a vegetation canopy as a function of its frequency, polarization, and angle of incidence.

The semi-empirical model will be based upon high-quality data (corn and sorghum) acquired near Manhattan, Kansas. The data set is characterized by backscattering data with extensive spatial averaging to reduce fading, accurate calibration, and frequent observations over the growing season. The ground-truth information is also of high quality. In addition, the ground truth was carefully edited and "smoothed" using a polynomial curve-fitting routine. The objective was to postulate a model that would provide a good fit to the data as measured by the correlation coefficient between the observed and predicted data as well as a small root-mean-square (rms) error between the observed and predicted data points. Also, the model would provide a reasonable estimate of the attenuation through the vegetation canopy.

The objective of the attenuation measurements was to obtain an understanding of vegetation attenuation as a function of frequency, polarization, and incidence angle for its own scientific value as well as to provide data for testing semi-empirical and theoretical models. Although some limited attenuation measurements have been made in the past, this will be the first data set to demonstrate frequency, polarization, and angular dependence.

2.0 EXPERIMENT DESCRIPTION

The backscattering data analyzed and modeled in this investigation were acquired in 1979 and 1980 during a joint experiment conducted near Manhattan, Kansas by the University of Kansas and Kansas State University. The complete set of 1979 data is available in a technical memorandum (Wilson, 1984), and selected 1979 and 1980 data are available in a technical report (Eger, 1982; Ulaby, 1983).

The attenuation data to be analyzed and modeled in this investigation were acquired by the University of Kansas in 1984 at a site east of Lawrence, Kansas.

2.1 1979 Backscattering Measurements

The 1979 backscattering measurements were conducted at the Kansas State University agronomy research fields located approximately 14 km south of Manhattan near a small community called Ashland. University-owned research plots were used to study corn and sorghum; two privately owned fields adjacent to the research plots were used to study wheat.

The twelve test plots, each approximately 15 m x 60 m, or 900 m^2, were planted with varying densities of corn and sorghum (six each). The two wheat fields used were several acres in extent, although only a limited area of each was used for data collection.

The spring/summer growing season was unusually wet for Central Kansas, and all crops were generally healthy and vigorous.

Ground-truth data for this experiment were acquired by Kansas State University. Ground truth was taken simultaneously with radar data. Table 2 summarizes the ground-truth parameters measured.

The active microwave system used to acquire data for this study was the University of Kansas MAS 8 - 18/35-scatterometer system. The MAS 8-18/35 was a low-power microcomputer-based, FM-CW radar capable of operation over the 8- to 18-GHz range as well as at 35.6 GHz. This truck-mounted system was mobile and had its own source of electrical power. Acquired data were recorded on a standard data cartridge for subsequent transfer to larger computer systems. The system (Ulaby, 1979c) was modified prior to this study for single-antenna operation over the 8 - 18-GHz range (Wilson, 1980). The accuracy and precision of the MAS 8-18/35 have been investigated and reported previously (Stiles, 1979). Key system specifications are given in Table 3.

The choice of sensor combinations for this study was greatly influenced by prior work at the University of Kansas. To minimize the response to soil-moisture variations, angles of incidence greater than 30° and frequencies greater than 8 GHz were chosen. This choice of system parameters also minimized any response to crop row-direction effects. Data were taken using the three linear polarizations. Table 4 summarizes the sensor combinations used in the experiment.

Fifteen independent spatial samples were taken at 30° and 50°, whereas ten samples proved more than adequate at 70°.

TABLE 2. Ground-Truth Parameters

Leaf Area Index
Plant Wet Weight
Plant Dry Weight
Plant Density
Plant Height
Plant Growth Stage
Leaf Water Potential
Yield
Soil Moisture
Solar Radiation
Temperature
Precipitation
Wind Speed
Spectral Reflectance

TABLE 3. MAS 8-18/35 System Specifications

Radar Type	FM-CW
Modulating Waveform	Triangular
Frequency Range	8-18 and 35.6 GHz
FM Sweep	800 MHz
Transmitter Power	10 dBm
Intermediate Frequency	100 kHz
IF Bandwidth	10 kHz
Antennas	
Maximum Height Above Ground	20 m
8-18 GHz Feed	4-18 GHz Quad-ridged Horn
8-18 GHz Reflector	45.7 cm Diameter
35.6 GHz	Scalar Horn
Polarization	HH, HV, VV, RR, RL, LL
Incidence Angle Range	0° (Nadir) to 80°
Calibration	
Internal	Delay Line
External	Luneberg Lens

TABLE 4. Sensor Combinations

FREQUENCY	POLARIZATION	INCIDENCE ANGLE
8.6 GHz	HH	30°
13.0 GHz	HV	50°
17.0 GHz	VV	70°
35.6 GHz		

A "standard" data set consisted of the above number of independent spatial samples at each of the four frequencies for each polarization. Thus, 180 data points were obtained at 30° and 50°, with 120 data points at 70°, for a total of 480 data points per standard data set.

A "diurnal" data set consisted of fifteen independent spatial samples at 50° at the above frequency and polarization combinations, or 180 data points. A diurnal data set was repeated periodically throughout the day from before dawn to after dusk.

Table 5 summarizes the microwave data acquired in this experiment.

2.2 1980 Backscattering Measurements

The 1980 backscattering measurements were also conducted on the Kansas State University research fields. In 1980, however, data were acquired on corn and sorghum only.

The 1980 test plots were increased in size to approximately 30 m x 60 m or 1800 m^2. Three plots were planted in corn and three in sorghum. As in 1979, planting densities varied between plots.

The summer growing season in 1980 presented a sharp contrast to that of 1979 in that it was dry and was one of the hottest summers on record; irrigation was required to maintain the crops.

Ground-truth data were again acquired by Kansas State University. In 1980, sampling techniques were improved, and the data were expanded to include plant parameters both by layers and

TABLE 5. 1979 Microwave Data Acquired

WHEAT

24 Standard Data Sets
32 Diurnal Data Sets

CORN

40 Standard Data Sets
20 Diurnal Data Sets

SORGHUM

40 Standard Data Sets
20 Diurnal Data Sets

TOTAL DATA POINTS - 74,880

by parts. In addition, the ground-truth data were "smoothed" by a polynomial curve-fitting routine.

Increasing the number of data sets per field represented a significant improvement over the 1979 experiment. Because of the large number of fields, incidence angles, and frequencies in 1979, only about six data sets per field were acquired for corn and sorghum. In 1980, the number of fields was reduced and the angular data limited to 50°, so that approximately 25 data sets per field were obtained.

In 1980, improvements were also made in the microwave data-collection effort. The number of spatial samples in 1979 was set at 15 because of the limited test-plot width and because of time limitations. In 1980, since the size of the plots had been increased and since the only angle of incidence used was 50°, the number of spatial samples was increased to 25 to further reduce measurement uncertainty. Also in 1980, external calibration was performed on the system on all but five of the measurement days. These changes significantly improved the calibration and precision of the 1980 backscattering measurements as compared to 1979.

2.3 1984 Attenuation Measurements

The 1984 attenuation measurements were conducted by the University of Kansas on privately owned fields located approximately 6 km east of Lawrence, Kansas.

Two crops were studied: winter wheat and soybeans. The spring and early summer growing seasons were quite wet, which resulted in healthy and vigorous crops. Ground truth for this experiment was acquired both by layer and by part. The ground-truth measurements are tabulated in Appendix B.

The system used for data acquisition consisted of L-, C-, and X-band radars (1.55 GHz, 4.75 GHz, and 10.2 GHz) mounted on a boom truck (used only as a transmitter) and a receiver at ground level mounted on a "sled." The sled was designed to be pulled in synchronicity with the boom truck over fiberglass rails by means of a system of ropes and pulleys. Figure 1 illustrates the setup. The receiving antennas consisted of an L-band microstrip patch antenna and a 4- to 18-GHz quad-ridged horn for C- and X-bands. The C- and X-band antennas were followed by battery-powered amplifiers with approximately 25 dB of gain. The detector was a wide-dynamic-range power meter driving a chart recorder.

The rails, each approximately 6 meters long, were placed in the vegetation canopy at locations corresponding to approximately 24° and 56° incidence angle for wheat and 16° and 52° for soybeans. Vegetation was cleared at each end of the test strip so the free-space power could be measured and then used as a reference. A wheat decapitation experiment and a soybean defoliation experiment were conducted in addition to these "standard" experiments.

Attenuation measurements were made at the indicated angles, at L, C, and X-band, and for HH and VV polarization. Limited data were acquired for HV and VH polarization. The recordings were digitized, and a mean attenuation was calculated (relative to free space) along with its associated 99% confidence interval. Repeatability tests were conducted for all sensor combinations, and

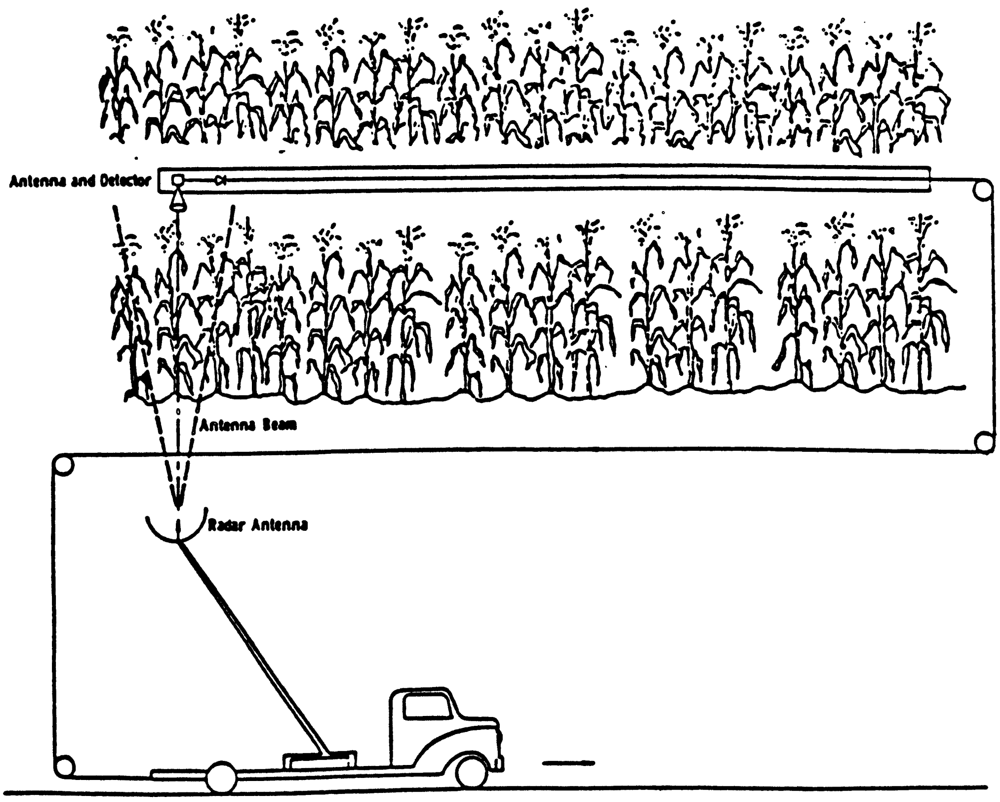


Figure 1. Configuration used to measure canopy attenuation.

it was found that the measurements were generally repeatable within 1 dB and, in most cases, within a fraction of a dB. The attenuation data are tabulated in Appendix B.

3.0 ANALYSIS OF BACKSCATTERING DATA

The 1979 backscattering experiment was significant in that it provided the first 35-GHz data on vegetation over a full growing season and served as the basis for an analysis of a number of overall vegetation backscattering characteristics. It was also valuable in that it was the first data set to include both active microwave data and leaf area index. The 1979 data set was, however, of limited value in modeling because of the small number of data sets taken per field.

The 1980 backscattering experiment was designed to correct the shortcomings of the 1979 experiment and to provide a very high quality data set for corn and sorghum, i.e., one suitable for modeling studies.

A preliminary analysis of the 1979 and 1980 data sets has already been completed (Eger, 1982) and includes temporal data for both years; thus, that information will not be repeated in this report. The emphasis here will be to present results that have not yet been published.

The statistical analysis was accomplished with the aid of the 1979 versions of the Biomedical Computer Programs, P-series (BMDP-79). These programs were developed at the Health Sciences Computing Facility at the University of California at Los Angeles

(Dixon, 1979). The Health Sciences Computing Facility was sponsored by NIH Special Resources Grant RR-3.

The BMDP routines used to examine the statistics of the microwave data were BMDP-2D, BMDP-5D, and BMDP-6D. BMDP-2D counts and lists distinct values for each variable in the analysis. It computes univariate statistics including the mean, median, standard deviation, skewness, and kurtosis. BMDP-2D also plots a histogram for each variable. BMDP-5D was utilized to provide histograms in a format much improved over that in BMDP-2D. BMDP-6D displays one variable against another in a scatter plot. It computes and prints the equations of the simple linear regression, relating each variable to the other, and indicates the places at which the regression lines intersect the frame of the plot. BMDP-AR, a nonlinear regression routine, was used in the modeling studies.

In addition to BMDP, a number of FORTRAN routines were used to calculate other statistics and provide special plots not available with BMDP.

3.1 Calibration, Accuracy, and Precision

The MAS 8-18/35 system used in these experiments utilized both internal and external calibration techniques. Internal calibration was achieved by periodically switching a coaxial delay line in place of the antenna(s). Power measurements in the delay-line mode were taken every few minutes during a measurement session and were used to remove short-term fluctuations in oscillator power and any other component variations.

External calibration was achieved by measuring the return from a Luneberg lens of known cross-section periodically throughout the measurement period (Ulaby, 1979c). In 1979, "lens sets" were taken approximately once per week; in 1980, lens sets were taken on the day of each data set--except for five dates.

After each lens set, a "sky-noise" measurement was taken to determine the system noise floor. Noise-floor data were used to ensure that all data points used in the analysis had an adequate signal-to-noise ratio.

Previous studies (Stiles, 1979) concluded that the accuracy of the MAS 8-18/35 was of the order of ± 2.6 dB.

Measurement precision is a function of the number of independent samples obtained (Stiles, 1979). In the MAS 8-18/35, independent samples are obtained by frequency averaging as well as by spatial averaging. The total number of independent samples is determined by the product of these two terms. The number of independent samples may also be calculated empirically from the data. It is estimated that the 90% confidence interval for the 1979 data is approximately ± 1.0 dB, whereas for the 1980 data it is ± 0.5 dB.

3.2 1979 Backscattering Data

The complete analysis of the 1979 data included consideration of each plot or field individually, various combinations of fields/plots of the same crop, and all crops combined. All of these cases were analyzed at all of the various frequency, polarization, and angular combinations. Since the 1979 data will not be used for modeling purposes in this investigation and because a preliminary analysis has been reported previously (Eger, 1982; Brakke, 1981), the emphasis here will be on overall vegetation characteristics.

Figure 2 is a histogram for all 1979 crops combined at 35.6 GHz, VV, 30°, expressed in dB. This distribution is approximately normal, as expected. Figure 3 is a histogram of the same data expressed in real units (m^2/m^2). This distribution is approximately log-normal, again as expected. These distributions are similar to those observed in the much larger agricultural data base maintained at the University of Kansas (Ulaby, 1979a).

Dynamic range is an important consideration in the design of an operational, active microwave remote-sensing system. If the microwave response to changes in plant parameters can be masked by system fluctuations and/or errors, there is little hope of acquiring meaningful data. Figure 4 illustrates that the dynamic range of all 1979 crops combined increases as the frequency is increased, especially for VV polarization.

It is possible that an operational microwave remote-sensing system could be designed to have a multi-frequency capability. This multi-frequency capability could be useful in monitoring vegetation, if additional information were gained by using additional frequencies. To investigate this consideration, frequency decorrelation plots were produced for each linear polarization. Figures 5, 6, and 7 illustrate that significant additional information may be obtained by operating at two or more

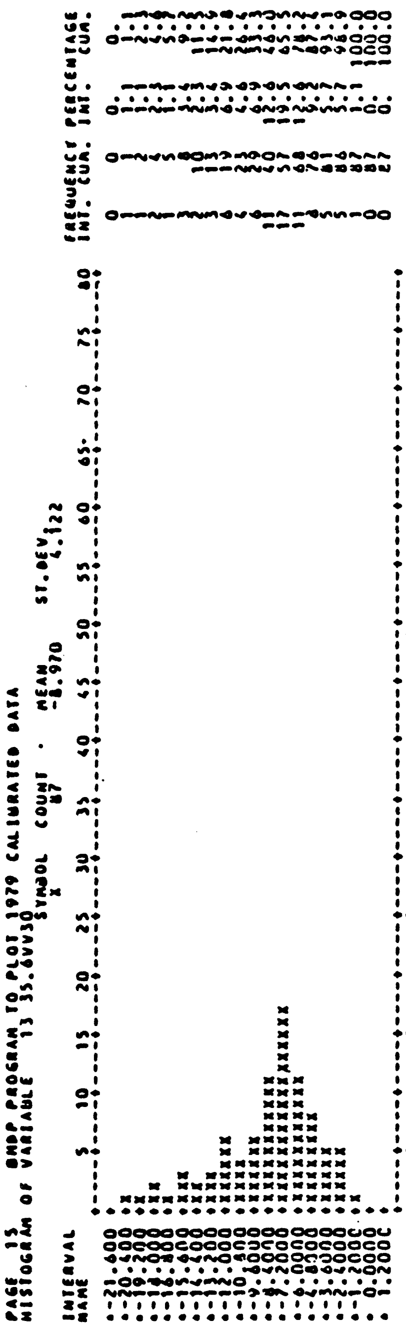


Figure 2. Histogram for all 1979 crops combined at 35.6 GHz VV 30° (dB).

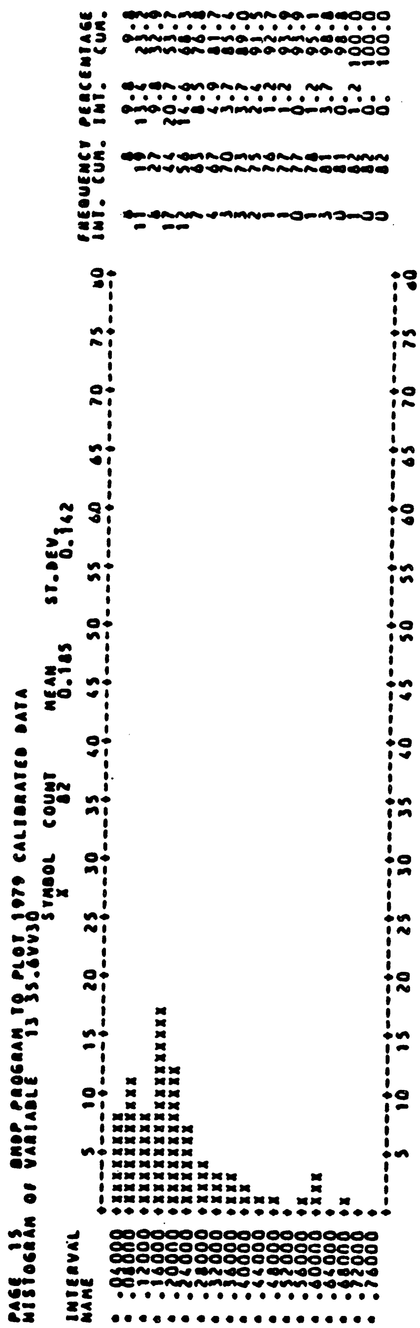


Figure 3. Histogram for all 1979 crops combined at 35.6 GHz VV 30° (real).

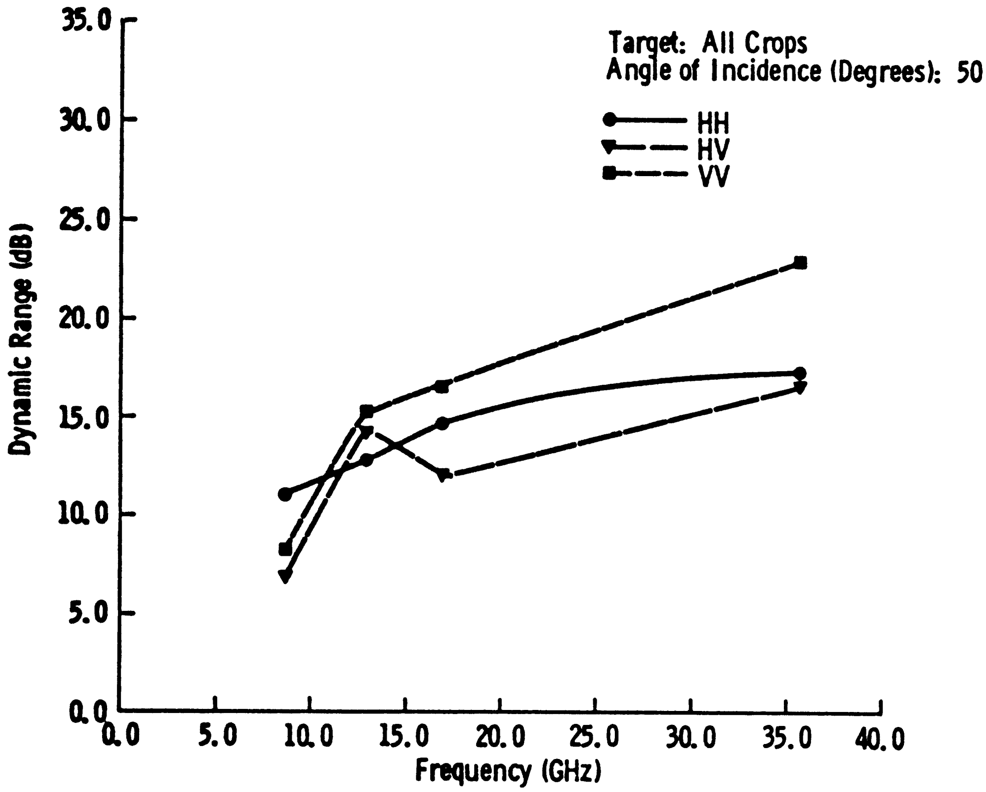


Figure 4. 1979 dynamic range versus frequency.

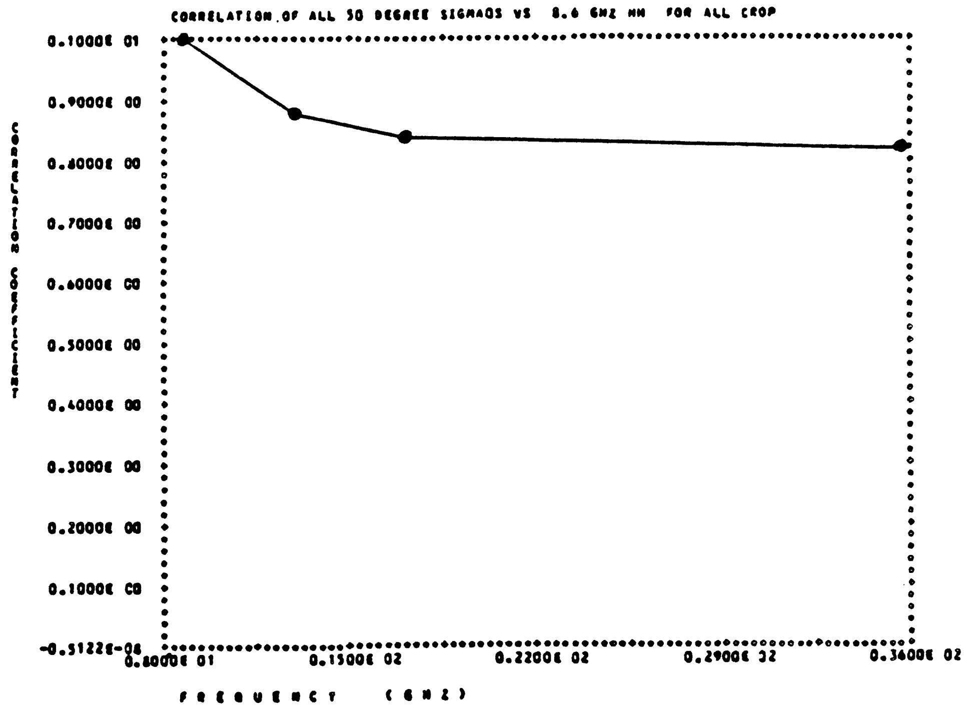


Figure 5. 1979 frequency decorrelation for HH polarization.

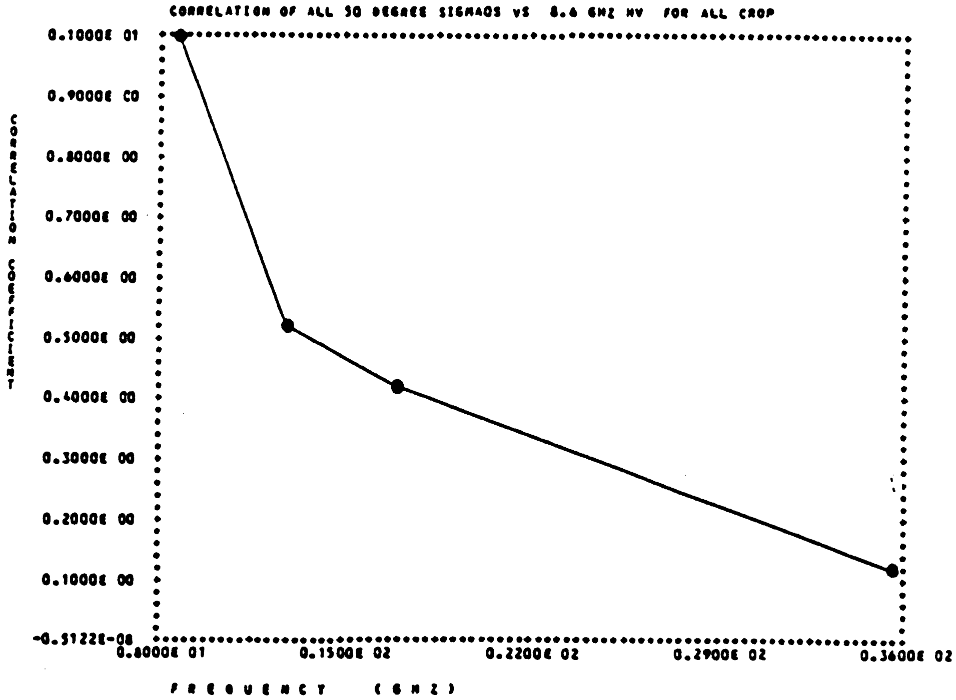


Figure 6. 1979 frequency decorrelation for HV polarization.

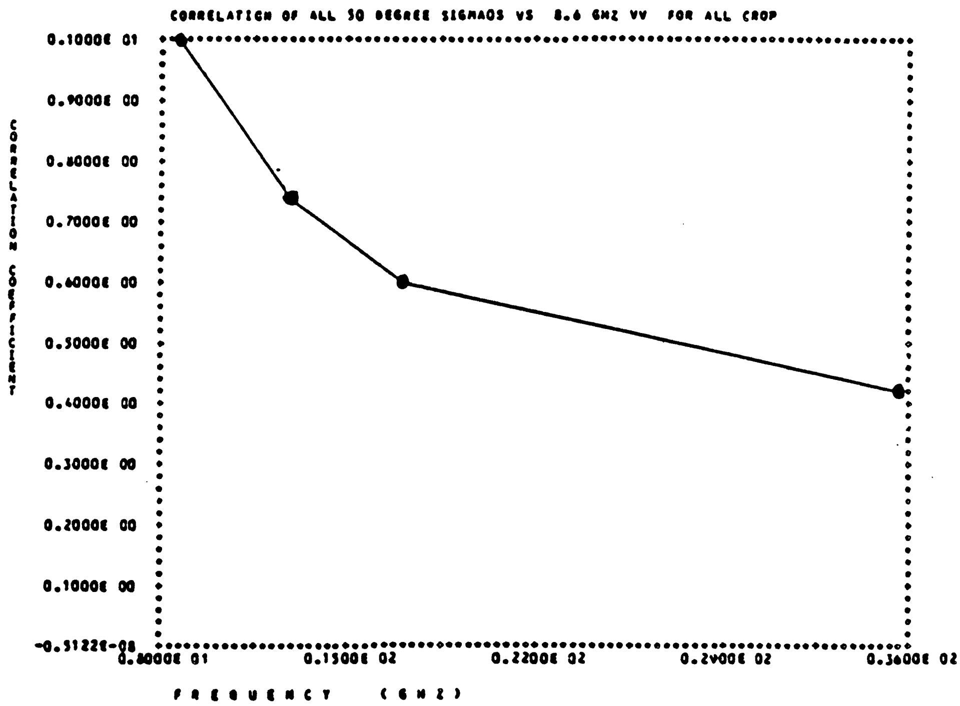


Figure 7. 1979 frequency decorrelation for VV polarization.

frequencies for HV and VV polarization but that there would be little advantage to such an arrangement for HH polarization.

Another possible design consideration for an operational system would be multi-angle capability. In spite of the possible advantages in remotely sensing soil moisture, Figures 8, 9, and 10 illustrate that little additional information on vegetation would be obtained from such an arrangement.

If a microwave system is to be used as a day/night sensor, then it is important to investigate any possible diurnal vegetation response that may corrupt acquired data or require correction. Figure 11 illustrates the results of a diurnal experiment on wheat. Figure 12 is a similar plot for corn, and Figure 13 is for sorghum. (The corn and sorghum experiments were conducted over a three-day period, as a result of system problems.) These plots indicate that the three crops studied exhibited minimal diurnal responses. These plots are typical of the complete data set.

3.3 1980 Backscattering Data

In the 1980 data analysis reported here, the emphasis will be on the relationships among the various ground-truth parameters and the relationship between ground truth and selected backscattering data. All data used in this analysis appear in Appendix A.

Figures 14 and 15 illustrate that the whole-plant water content expressed in kg/m^2 is highly correlated with the stalk water content, expressed in kg/m^2. The correlation coefficient for corn is 0.94 and for sorghum it is 0.97.

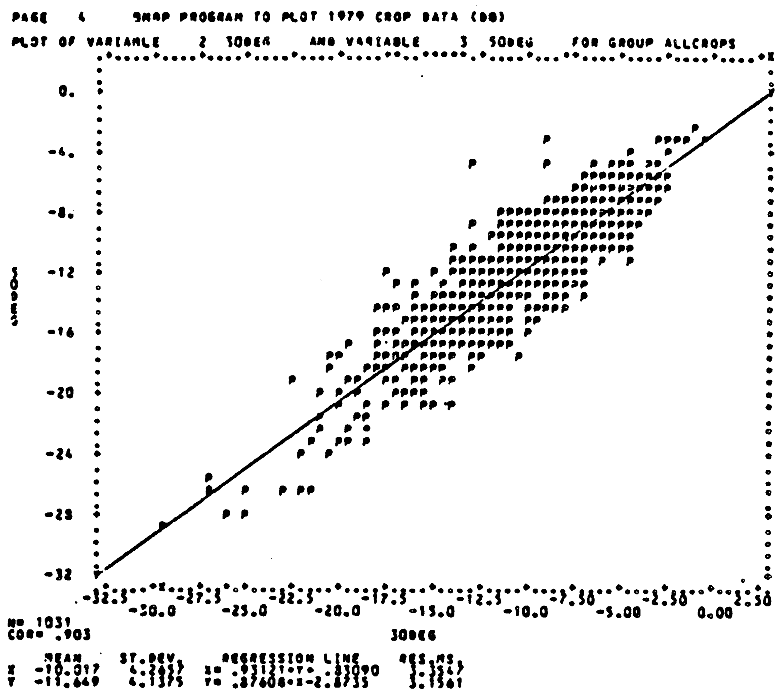


Figure 8. 1979 angular decorrelation of 30° versus 50°.

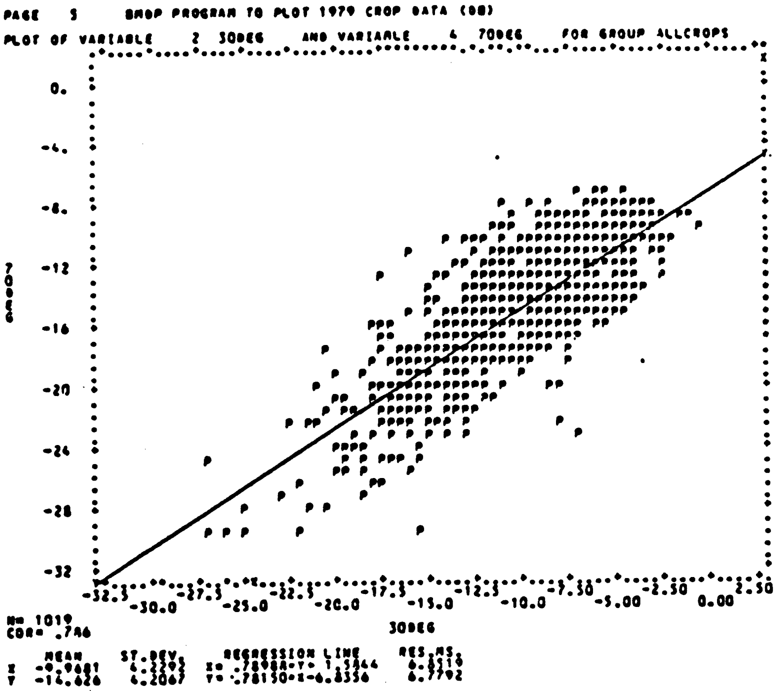


Figure 9. 1979 angular decorrelation of 30° versus 70°.

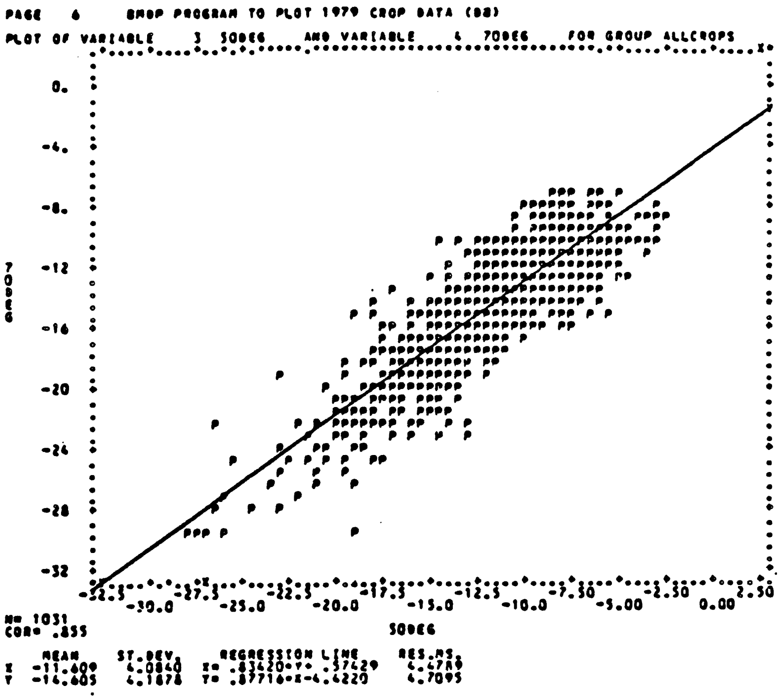


Figure 10. 1979 angular decorrelation of 50° versus 70°.

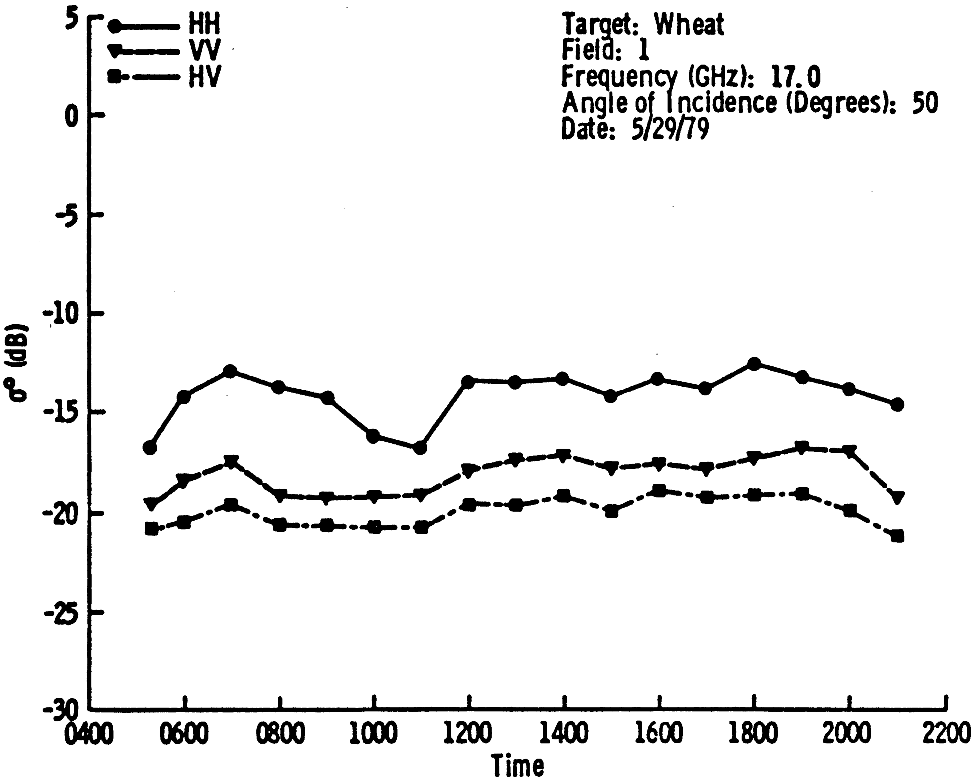


Figure 11. 1979 diurnal response of wheat at 17.0 GHz.

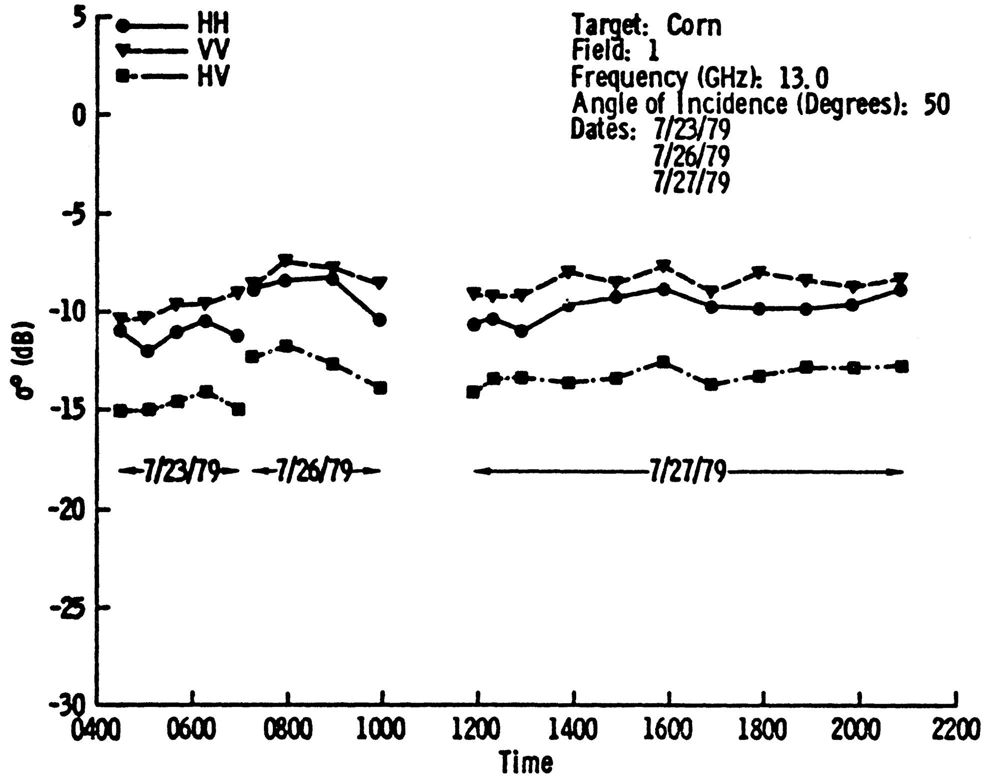


Figure 12. 1979 diurnal response of corn.

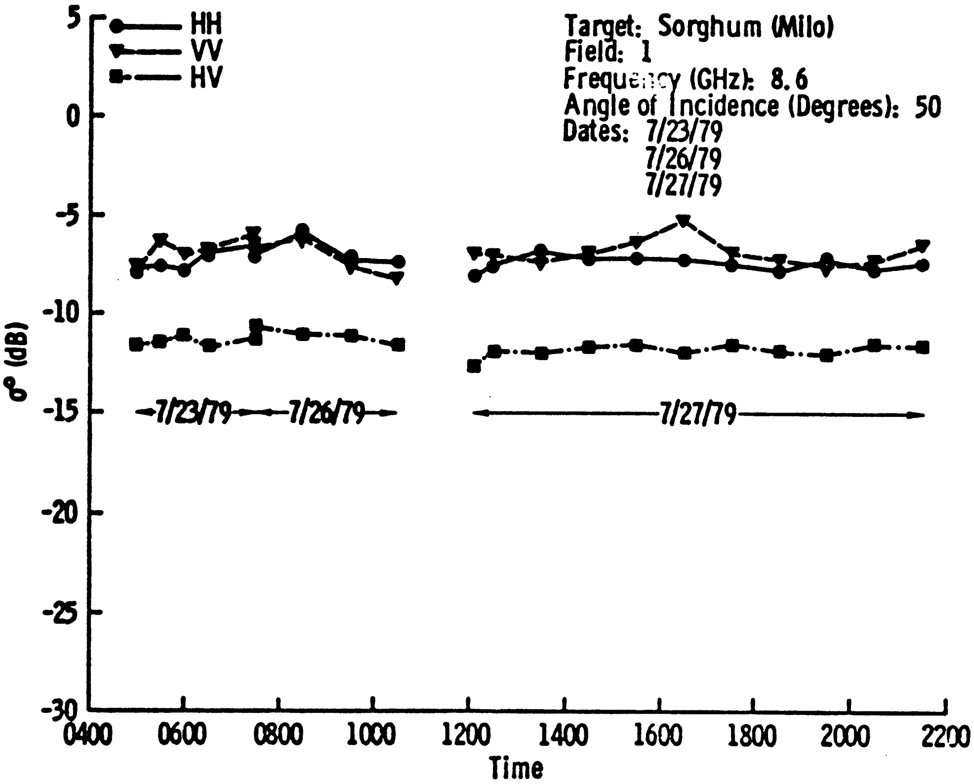


Figure 13. 1979 diurnal response of sorghum.

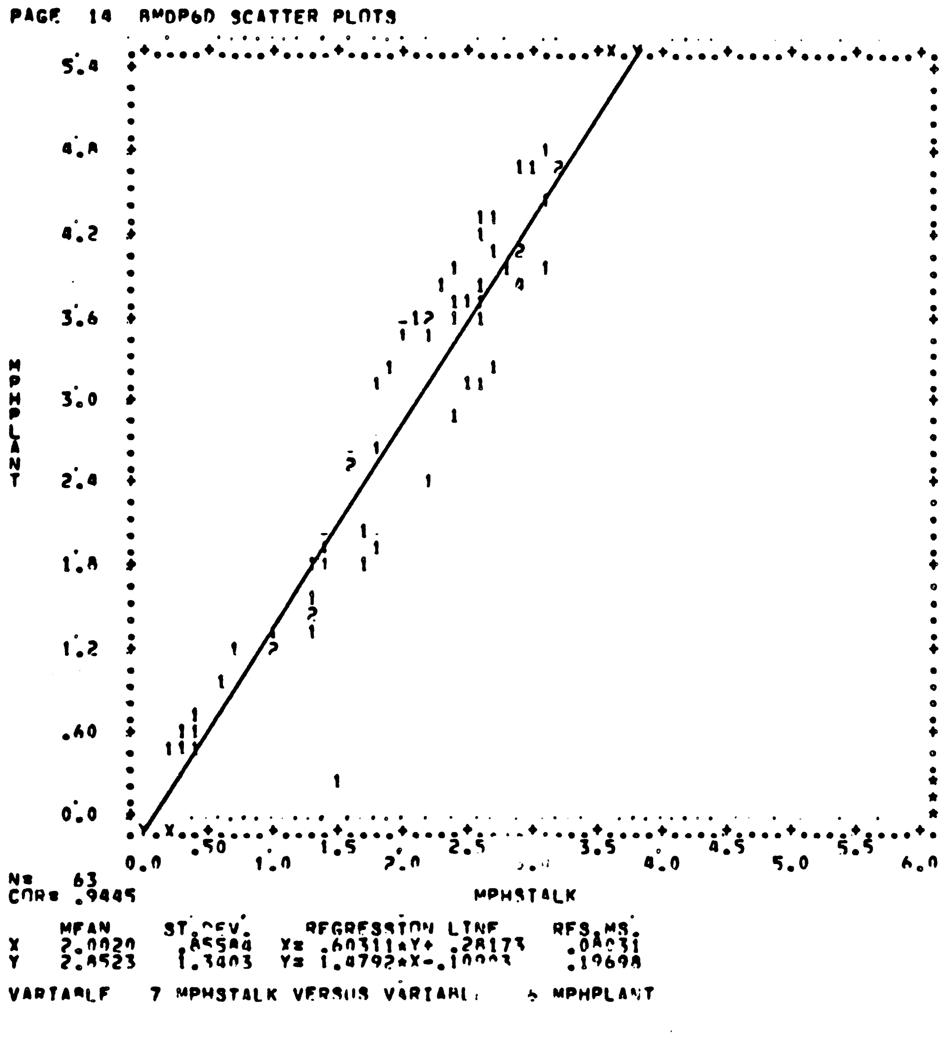


Figure 14. Whole-plant water (kg/m^2) versus stalk water (kg/m^2) for 1980 corn.

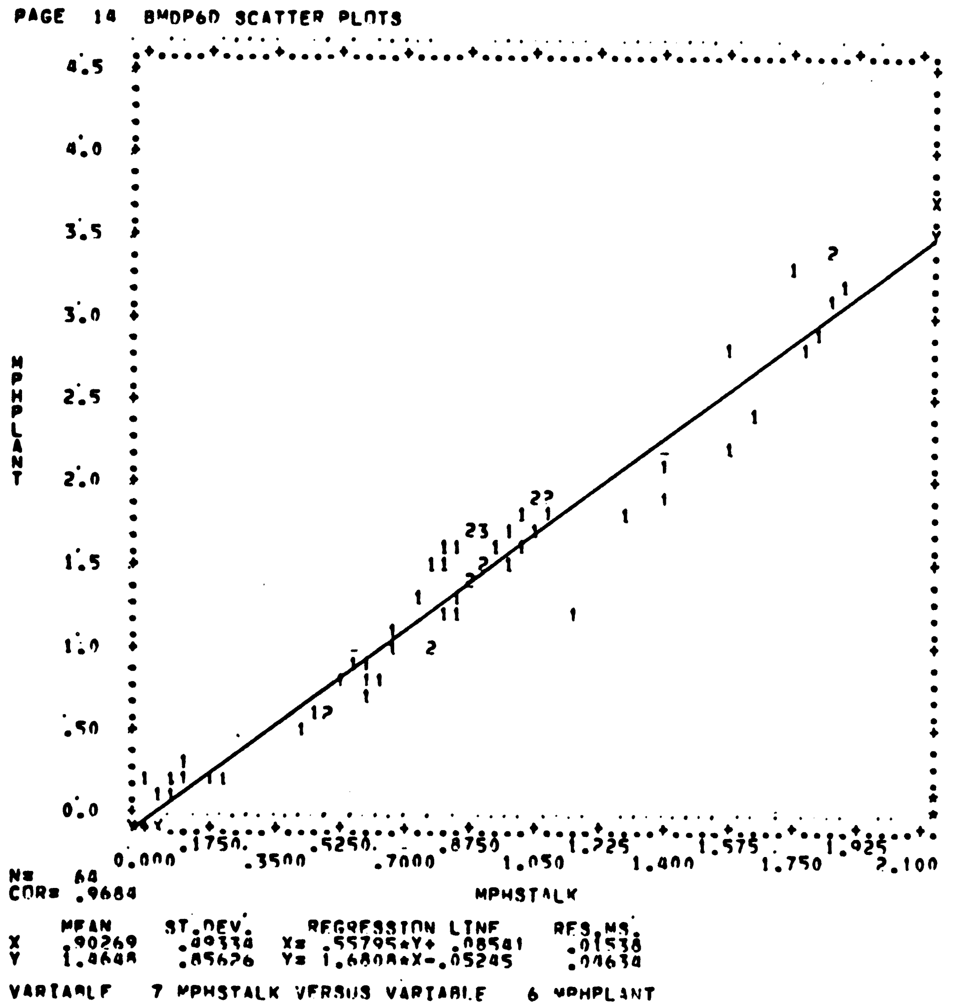


Figure 15. Whole-plant water (kg/m^2) versus stalk water (kg/m^2) for 1980 sorghum.

Figures 16 and 17 show reasonable correlation between leaf water content (kg/m^2) and stalk water content (kg/m^2), but note the "spread" at low values of water content for corn and at intermediate values for sorghum. The correlation coefficient for corn is 0.86; for sorghum it is 0.84.

Figures 18 and 19 demonstrate reasonable correlation between leaf area index (m^2/m^2) and stalk water (kg/m^2), but there is a significant "spread" at the lower end for corn and at intermediate values for sorghum. The correlation coefficients are 0.80 for corn and 0.94 for sorghum.

The plots in Figures 20 and 21 indicate that the correlation between leaf water (kg/m^2) and whole-plant water (kg/m^2) are 0.83 for corn and 0.89 for sorghum. Note, however, the two distinct clusters of data points for corn in the lower half of the plot; this effect is not evident n the sorghum plot.

Figures 22 and 23 illustrate leaf area index (m^2/m^2) versus whole-plant water content (kg/m^2). For corn the correlation is 0.79, and for sorghum it is 0.94. The two distinct clusters are again evident n the corn plot.

Leaf area index (m^2/m^2) and leaf water content (kg/m^2) correlate at a level of 0.93 for corn (Figure 24) and 0.90 for sorghum (Figure 25). The "spread" appears greater for corn than for sorghum; however, the scales on the plots differ, therefore it is similar for both crops.

Figures 26 and 27 plot radar backscattering in real units (m^2/m^2) at 17.0 GHz, VV polarization, and 50° incidence angle

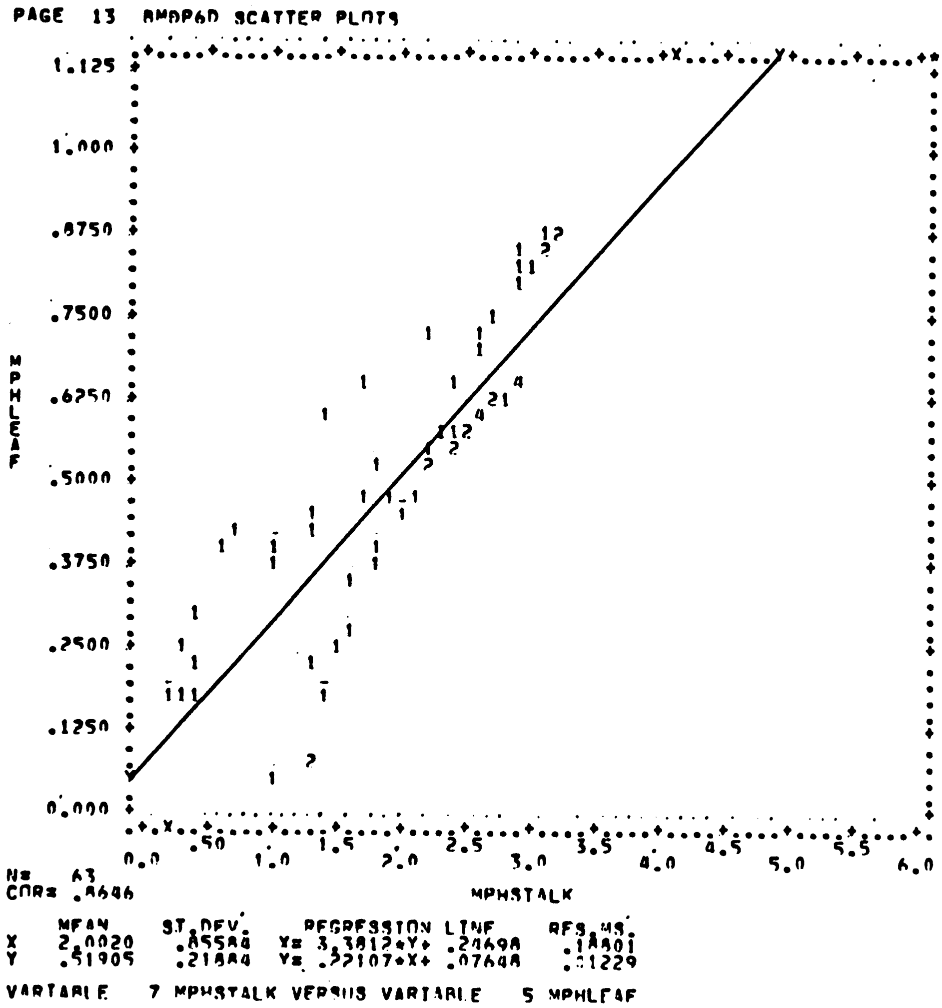


Figure 16. Leaf water content (kg/m^2) versus stalk water content (kg/m^2) for 1980 corn.

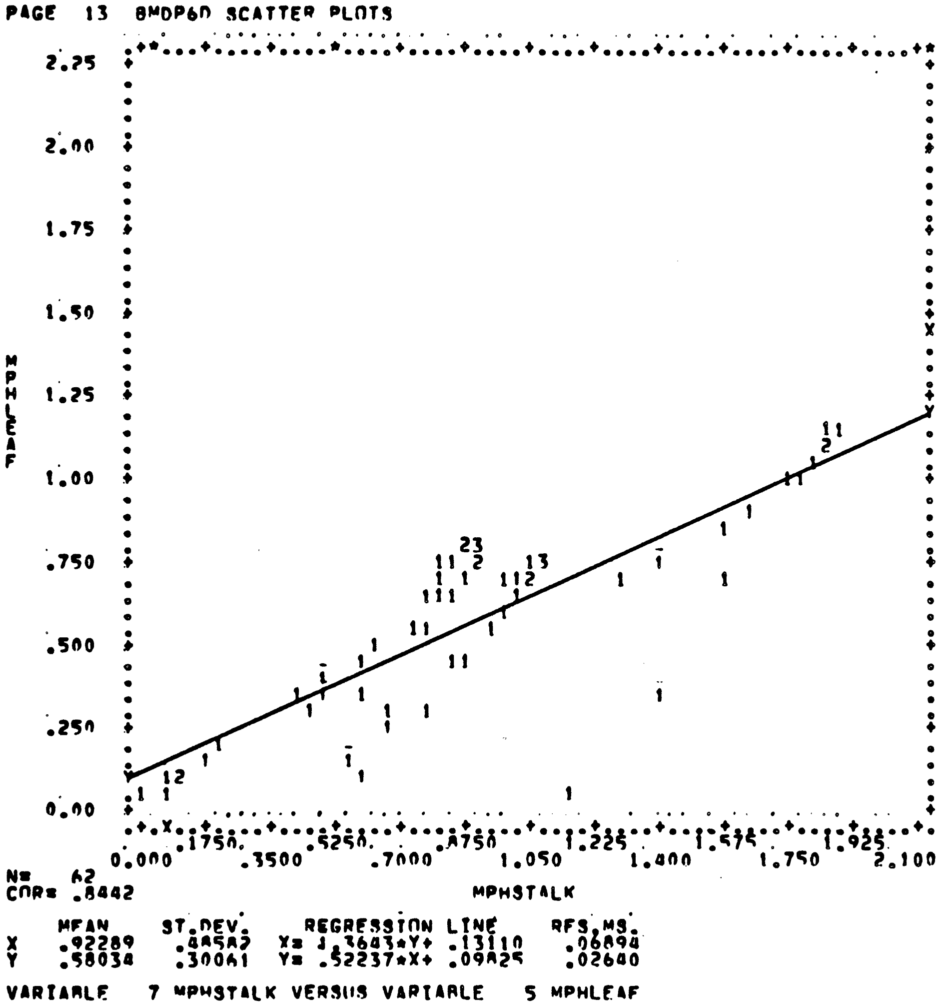


Figure 17. Leaf water content (kg/m^2) versus stalk water content (kg/m^2) for 1980 sorghum.

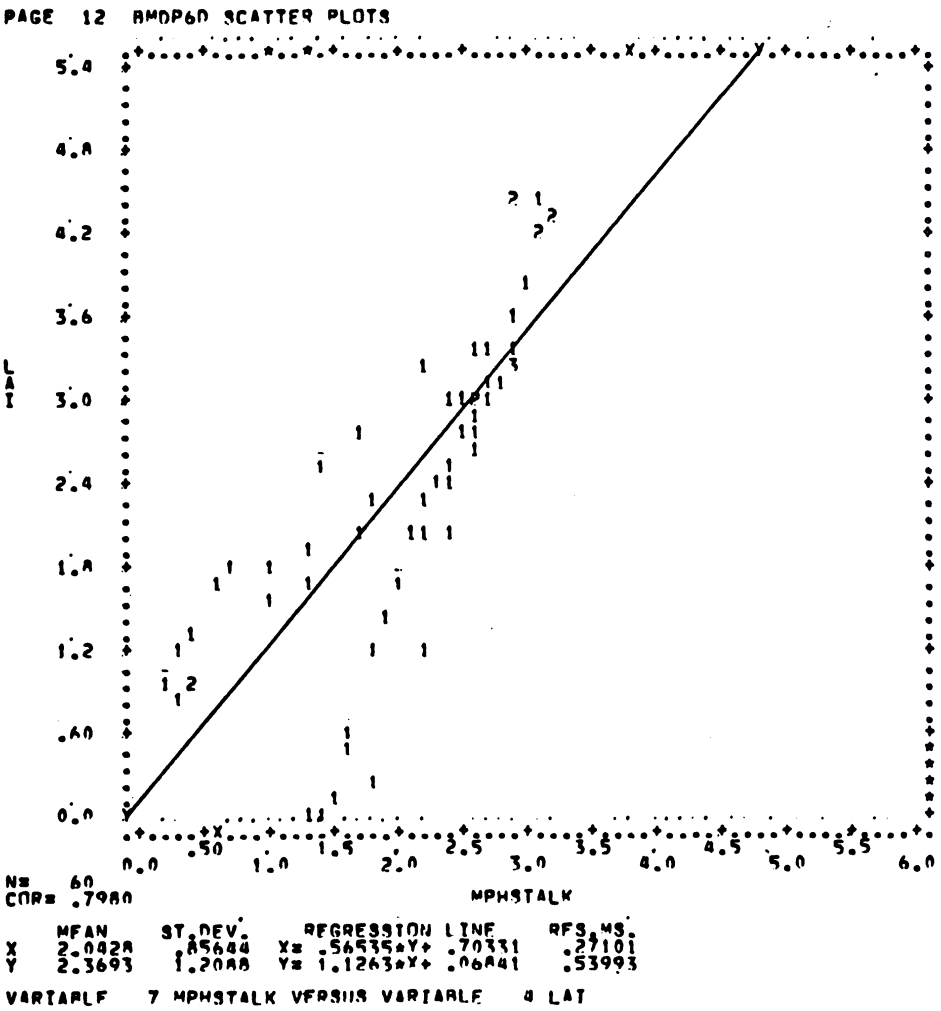


Figure 18. Leaf area index (m^2/m^2) versus stalk water (kg/m^2) for 1980 corn.

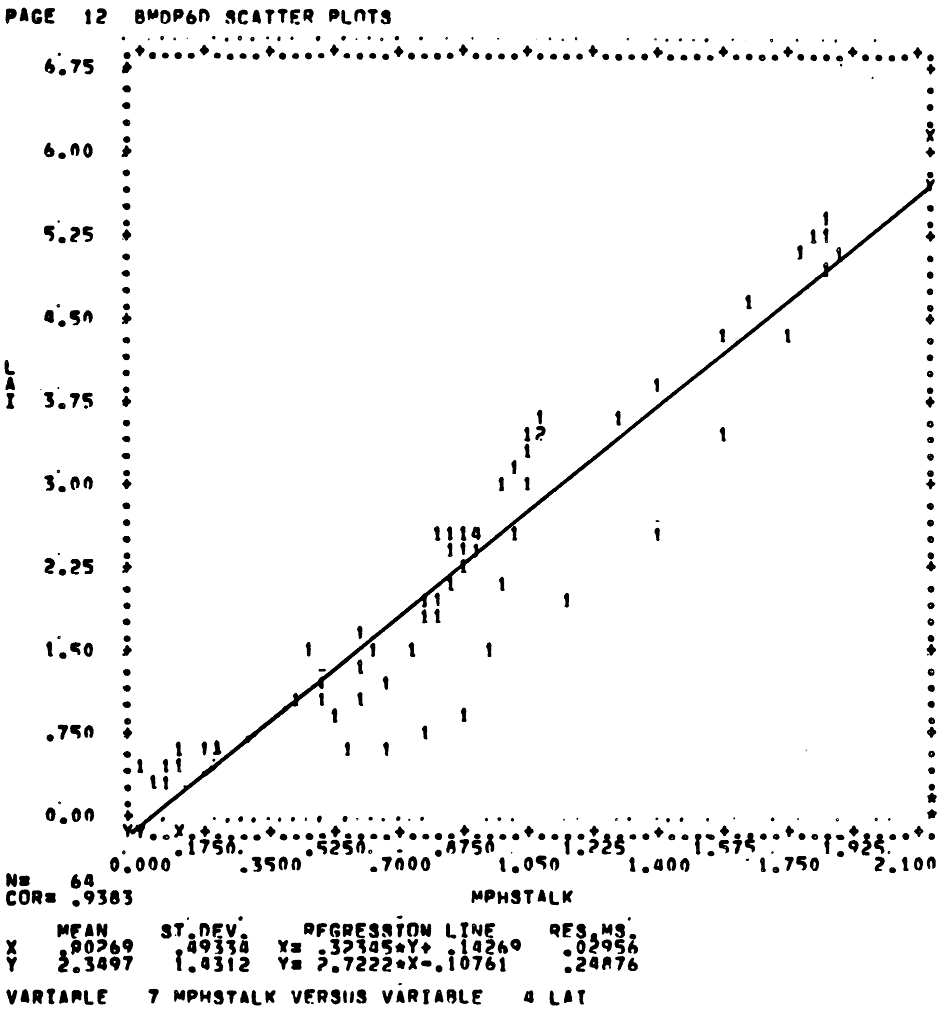


Figure 19. Leaf area index (m^2/m^2) versus stalk water (kg/m^2) for 1980 sorghum.

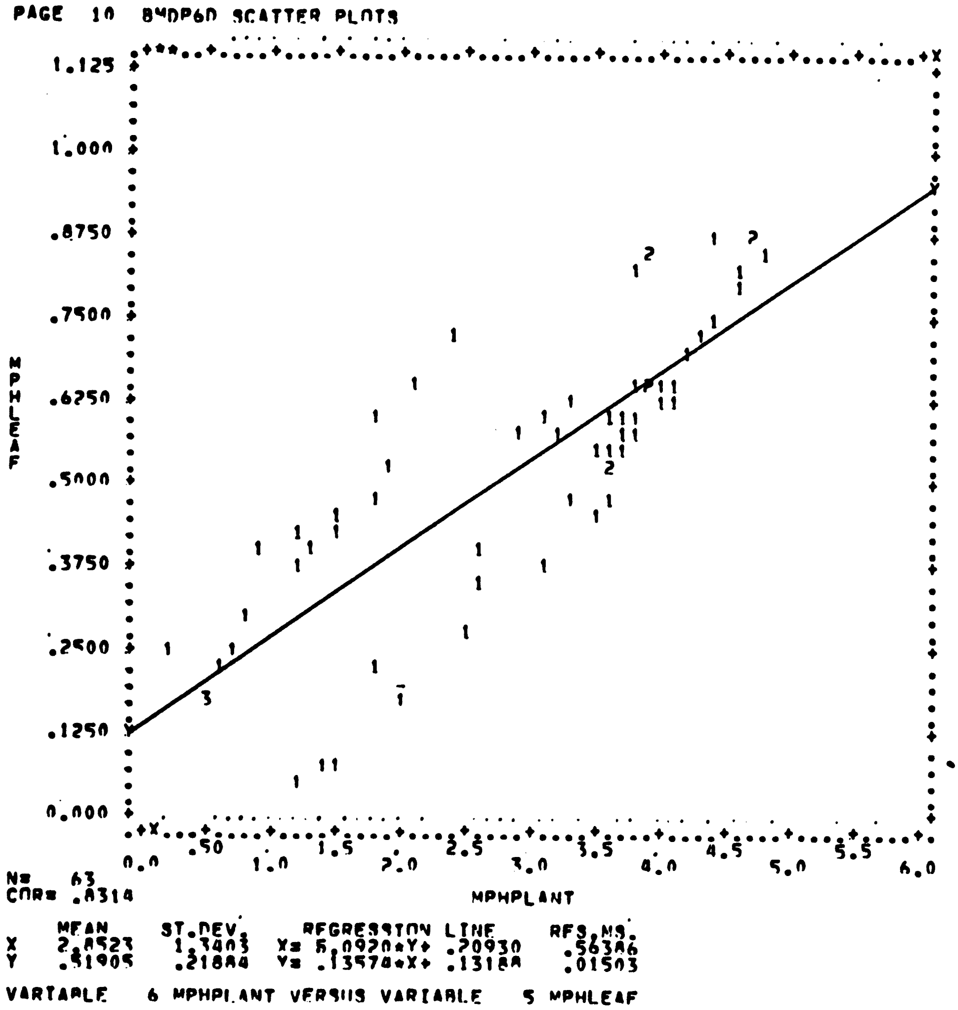


Figure 20. Leaf water (kg/m^2) versus whole-plant water (kg/m^2) for 1980 corn.

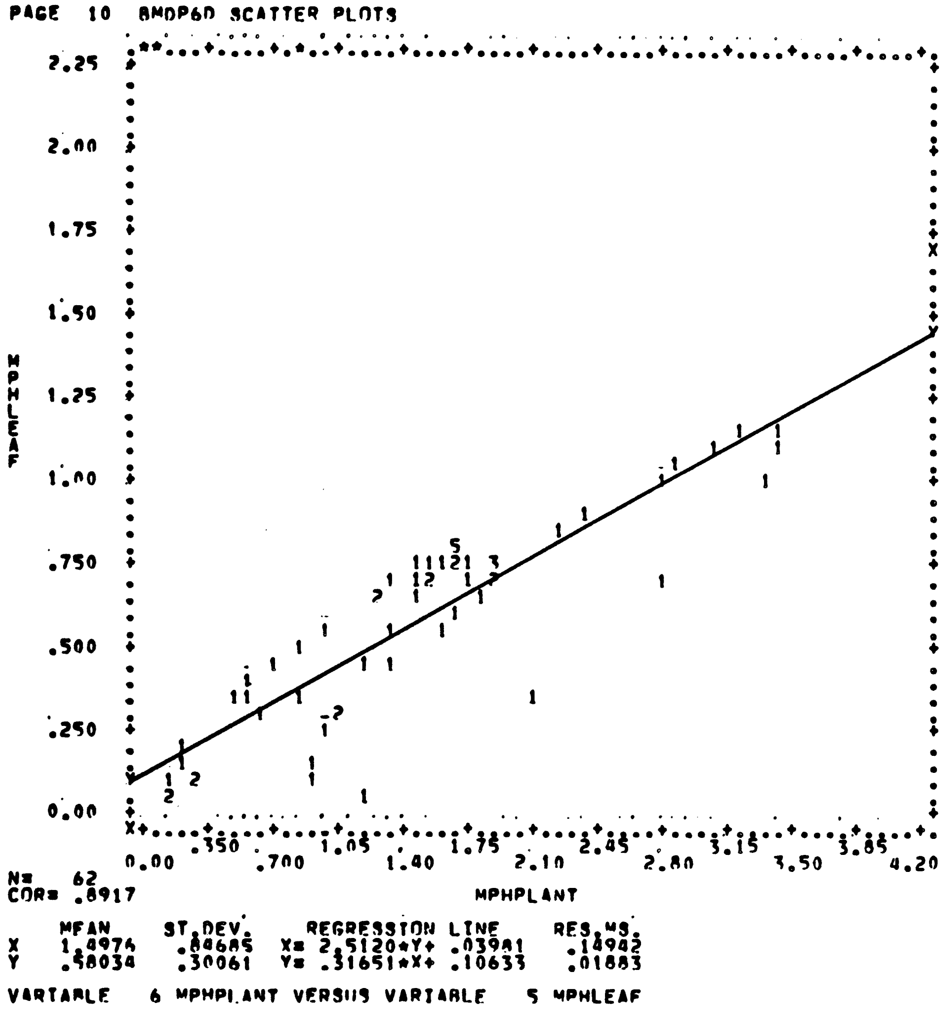


Figure 21. Leaf water (kg/m^2) versus whole-plant water (kg/m^2) for 1980 sorghum.

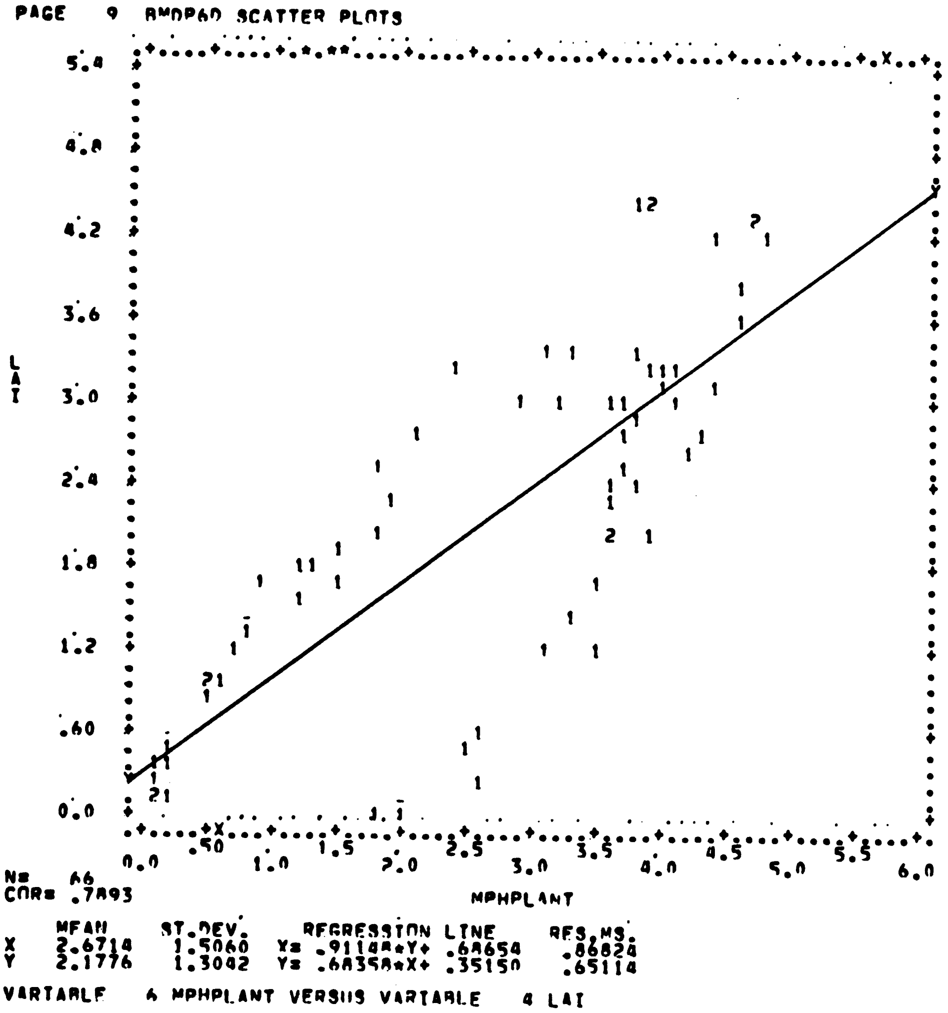


Figure 22. Leaf area index (m^2/m^2) versus whole-plant water (kg/m^2) for 1980 corn.

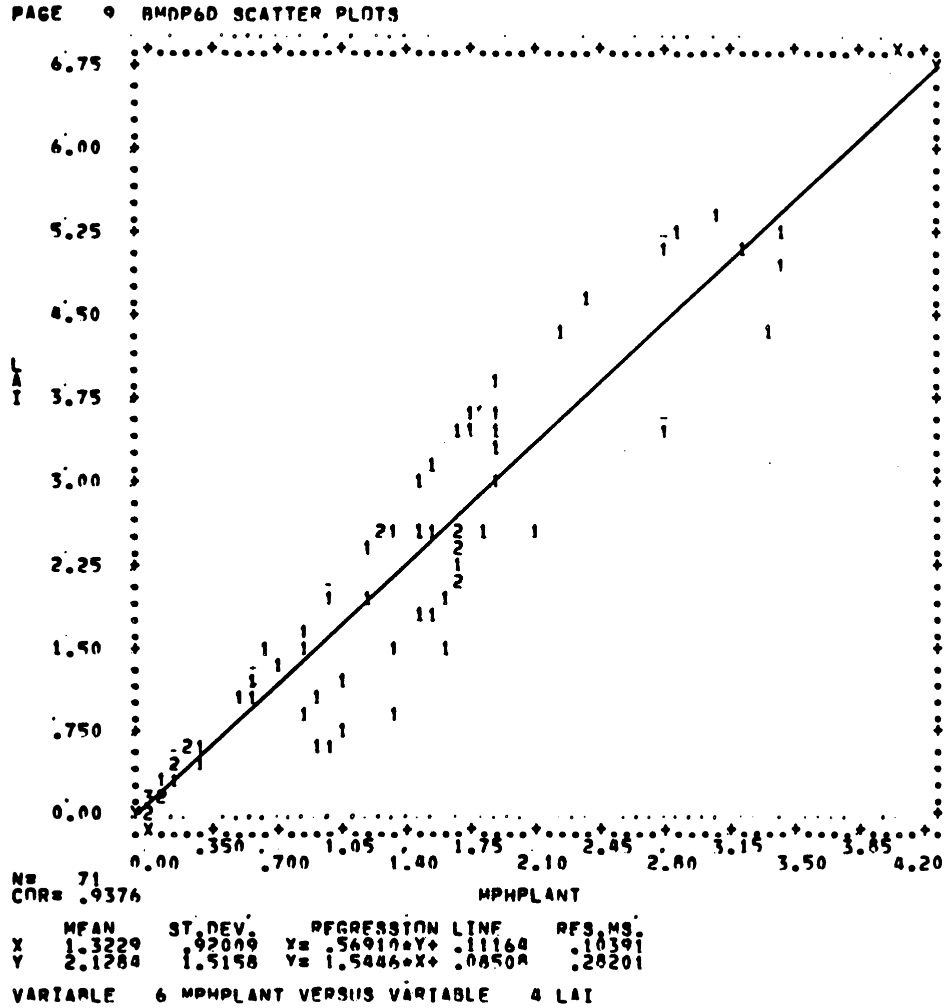
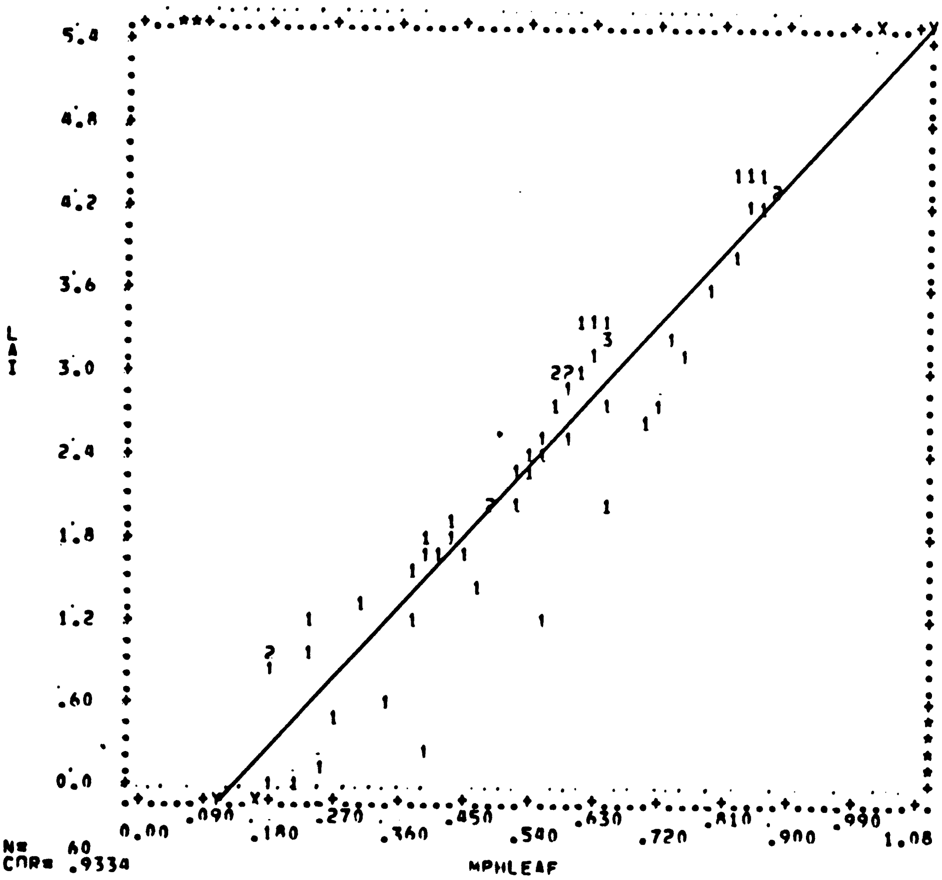


Figure 23. Leaf area index (m^2/m^2) versus whole-plant water (kg/m^2) for 1980 sorghum.

PAGE 7 BMDP6D SCATTER PLOTS



N= 60
COR= .9334

	MEAN	ST.DEV.	REGRESSION LINE	RES.MS.
X	.54157	.19873	X= .15345*Y+ .17809	.00517
Y	2.3693	1.2088	Y= 5.6781*X-.70578	.19131

VARIABLE 5 MPHLEAF VERSUS VARIABLE 4 LAI

Figure 24. Leaf area index (m^2/m^2) versus leaf water (kg/m^2) for 1980 corn.

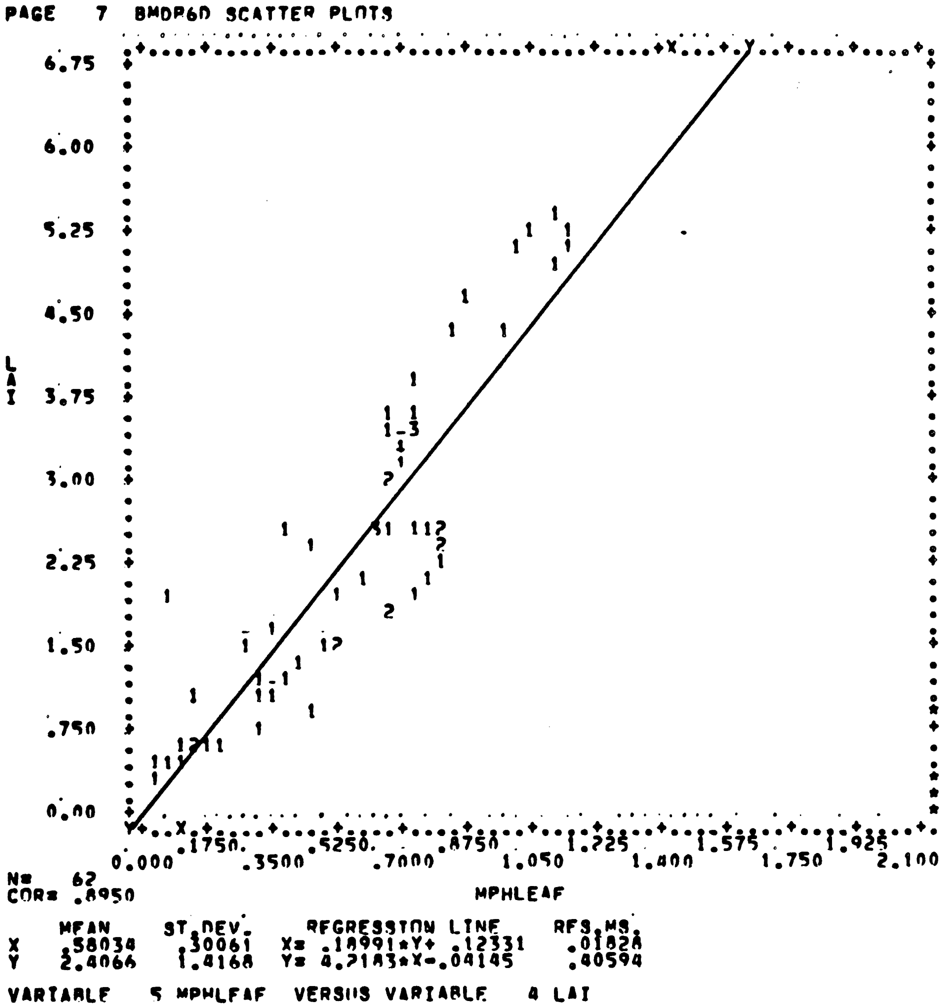


Figure 25. Leaf area index (m^2/m^2) versus leaf water (kg/m^2) for 1980 sorghum.

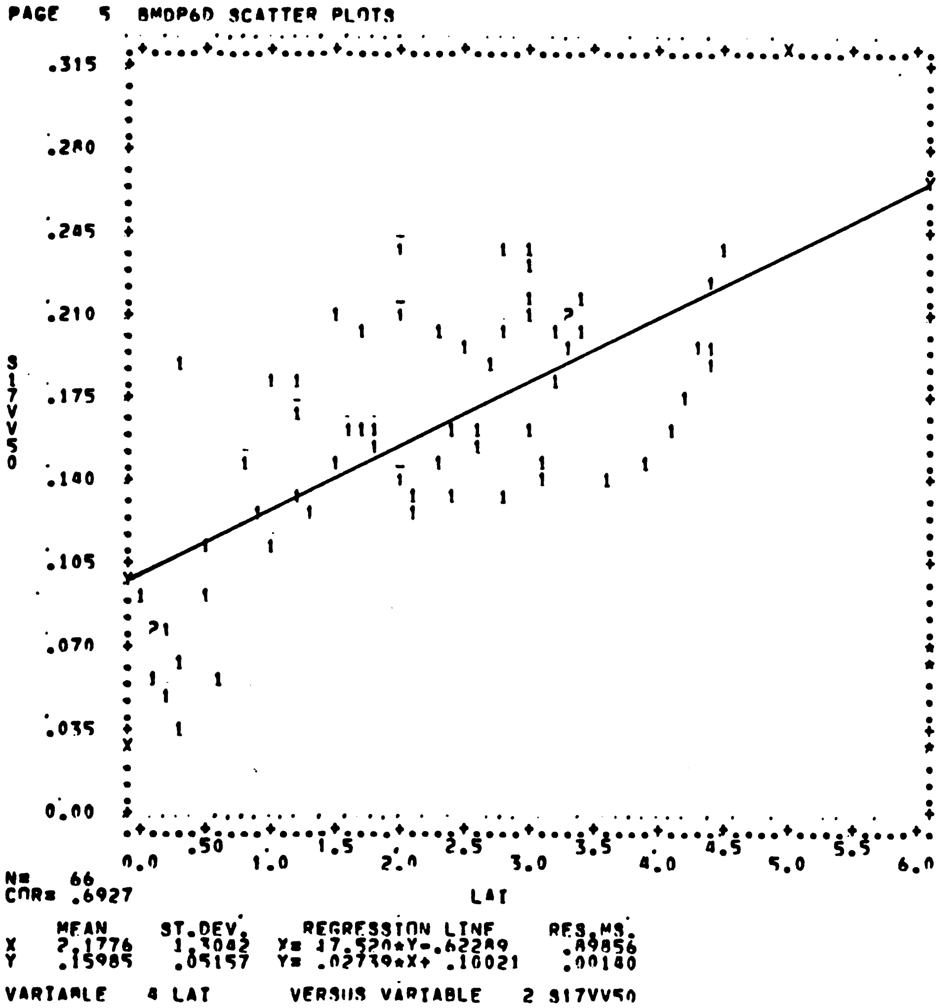


Figure 26. Backscatter (17 GHz, VV, 50°) versus leaf area index (m^2/m^2) for 1980 corn.

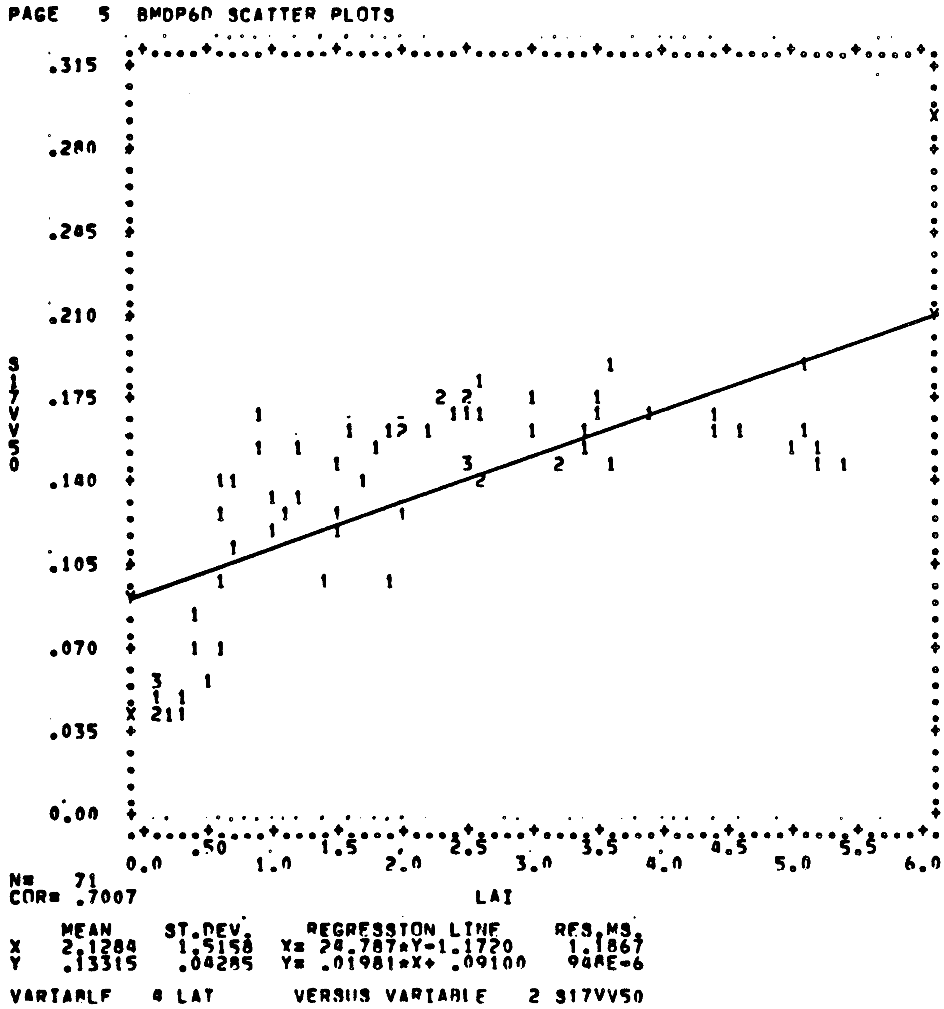


Figure 27. Backscatter (17 GHz, VV, 50°) versus leaf area index (m^2/m^2) for 1980 sorghum.

versus leaf area index (m^2/m^2). The correlation is 0.69 for corn and 0.70 for sorghum.

Leaf water (kg/m^2) versus radar backscattering (m^2/m^2) at 17.0 GHz, VV, 50° is illustrated in Figures 28 and 29. The correlation is a modest 0.58 for corn and 0.70 for sorghum.

Figures 30 and 31 provide plots of radar backscattering (m^2/m^2) at 17.0 GHz, VV, 50° versus whole-plant water (kg/m^2). The correlations are 0.41 for corn and 0.75 for sorghum.

The correlation of stalk water (kg/m^2) with radar backscattering (m^2/m^2) at 17.0 GHz, VV, 50° is given in Figures 32 and 33. Corn correlates at a level of 0.37, whereas sorghum correlates at 0.67.

Figures 34 and 35 illustrate the correlation between radar backscattering (m^2/m^2) at 17.0 GHz, VV, 50° and volumetric soil moisture (gm/cm^3). Corn shows little correlation at -0.06, and sorghum shows a slight negative correlation at -0.46.

Tables 6 and 7 summarize the results of this regression analysis.

To summarize, it is evident that all plant parameters are correlated to each other. This indicates that a simple model using any one of these parameters should provide reasonable results. The results of the regressions against backscattering data seem to indicate, however, that certain parameters perform better, depending upon crop type. The best overall single parameter for a model covering both crops is leaf area index.

Although the plant parameters are correlated with each other, it is reasonable to use more than one parameter in a more complex

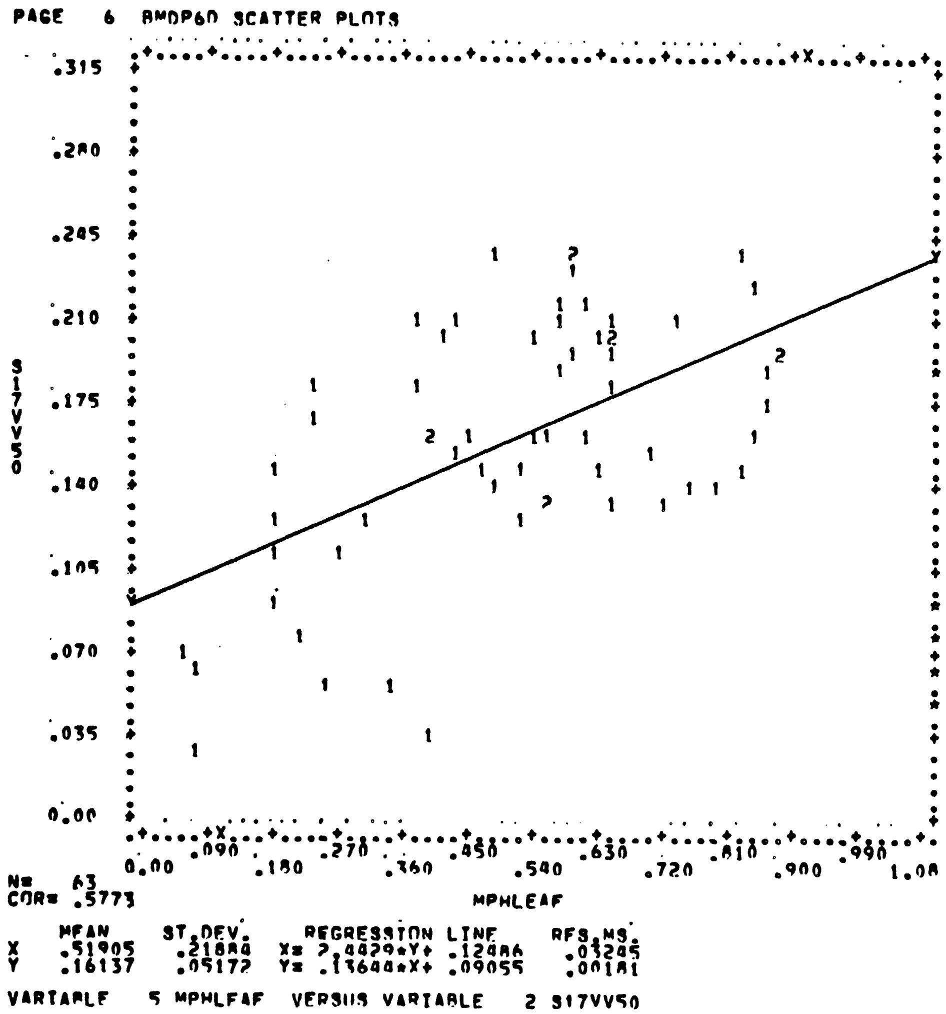


Figure 28. Backscatter (17 GHz, VV, 50°) versus leaf water (kg/m^2) for 1980 corn.

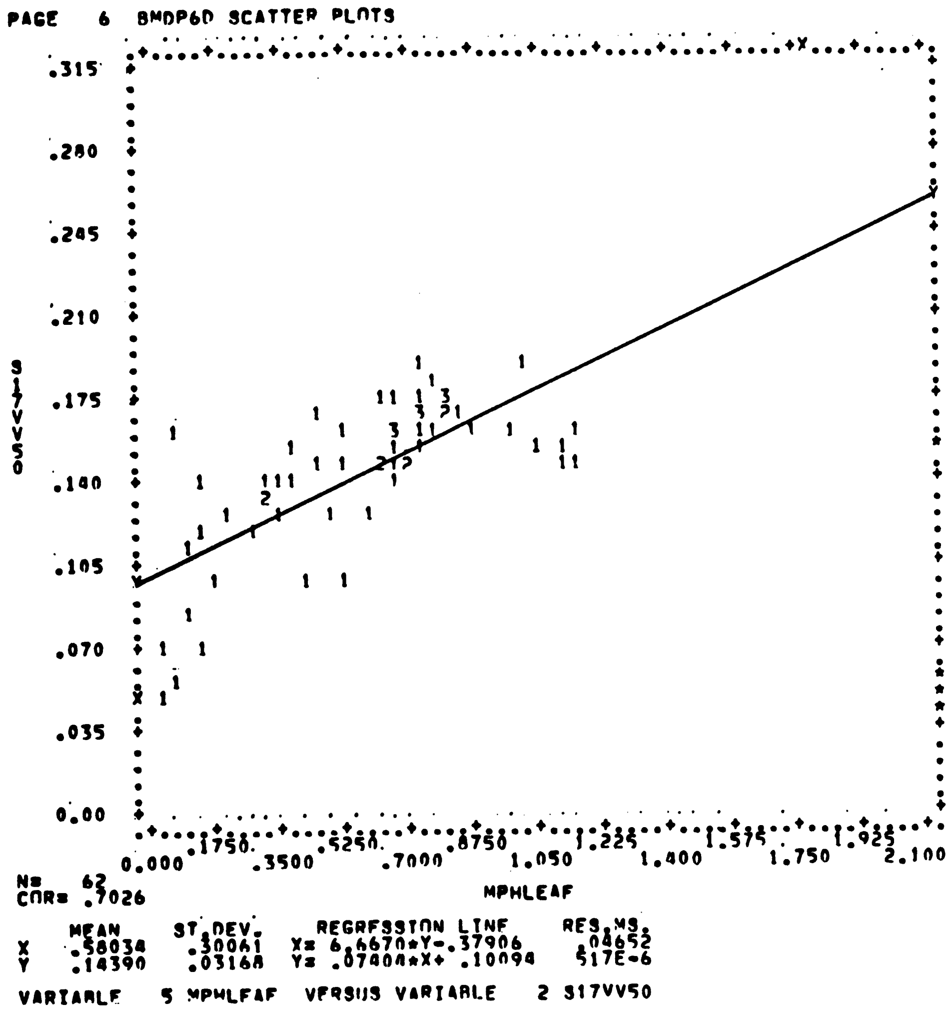
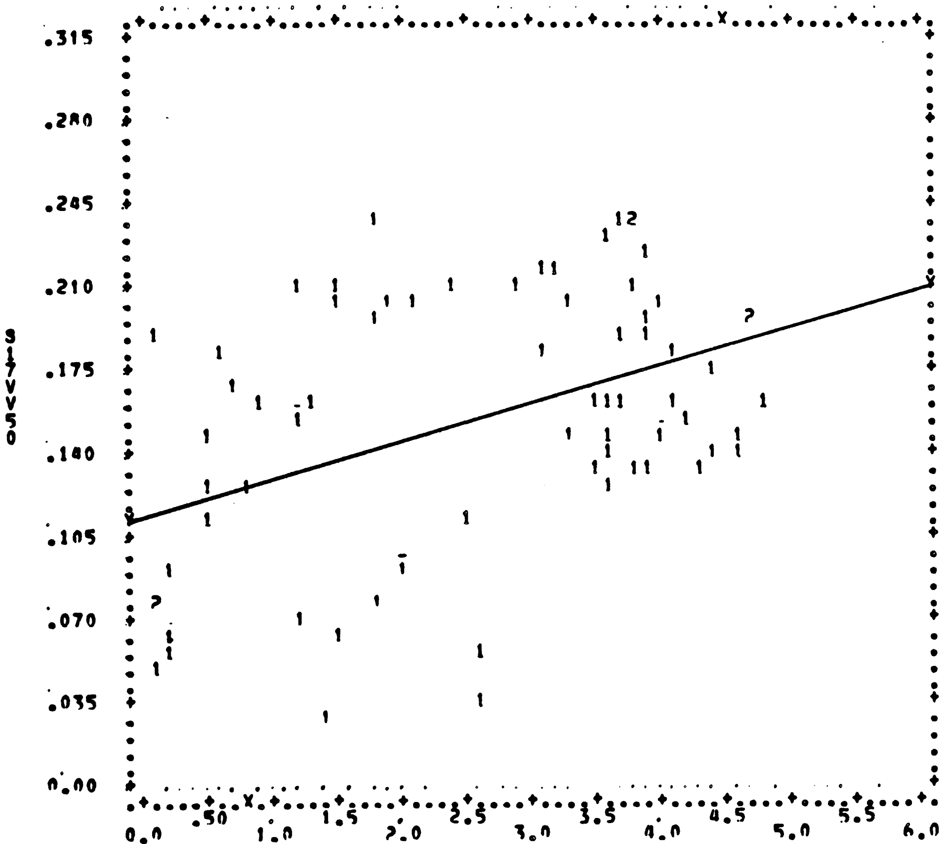


Figure 29. Backscatter (17 GHz, VV, 50°) versus leaf water (kg/m^2) for 1980 sorghum.

PAGE 8 BMDP6D SCATTER PLOTS



N= 69
COR= .4138

MPHPLANT

	MEAN	ST.DEV.	REGRESSION LINE	RES.MS.
X	2.6144	1.4970	X= 11.267*Y+ .86477	1.8856
Y	.15529	.05495	Y= .01518*X+ .11560	.00254

VARIABLE 6 MPHPLANT VERSUS VARIABLE 2 S17VV50

Figure 30. Backscatter (17 GHz, VV, 50°) versus whole-plant water (kg/m²) for 1980 corn.

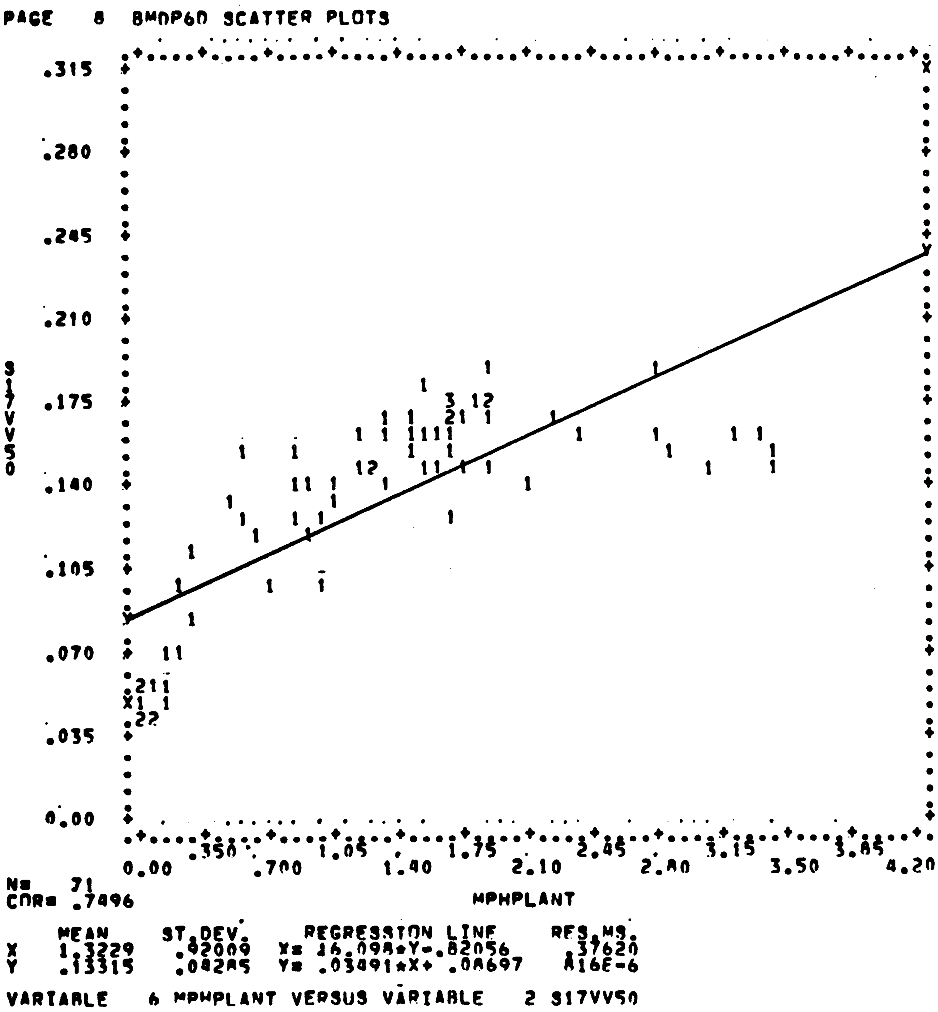


Figure 31. Backscatter (17 GHz, VV, 50°) versus whole-plant water (kg/m^2) for 1980 sorghum.

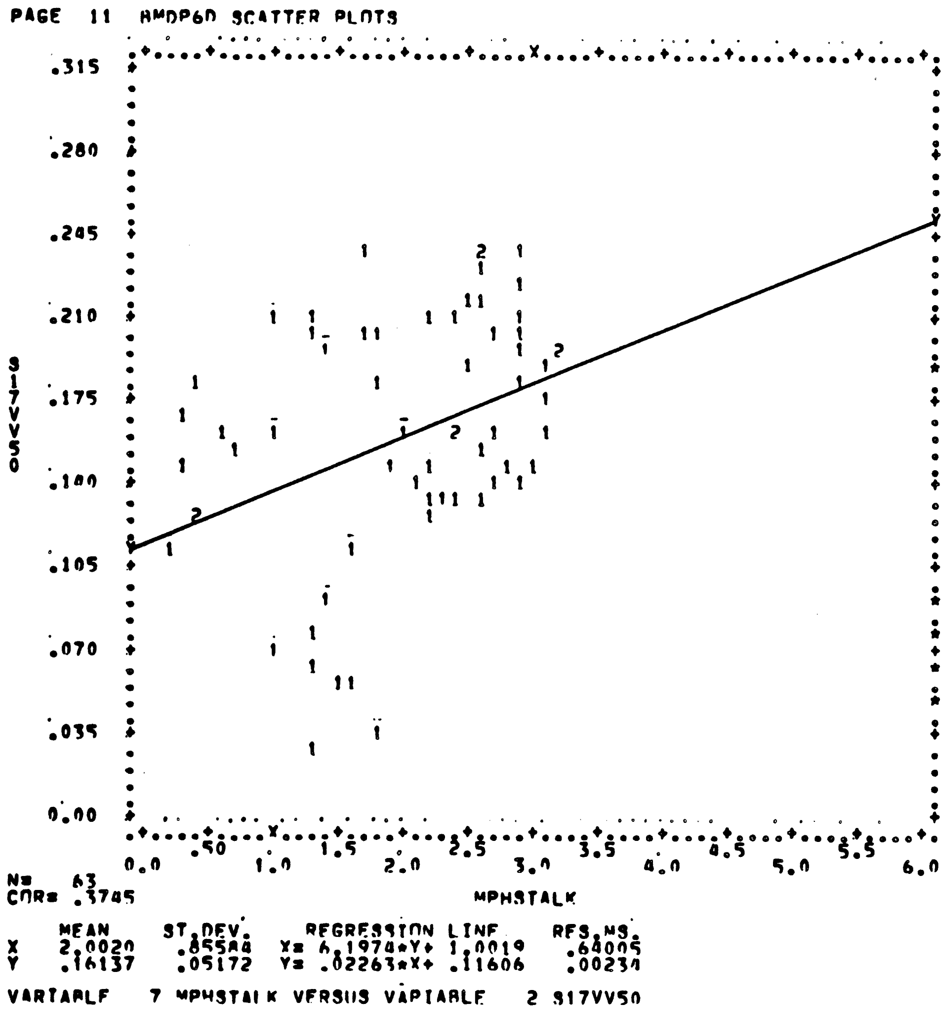


Figure 32. Backscatter (17 GHz, VV, 50°) versus stalk water (kg/m²) for 1980 corn.

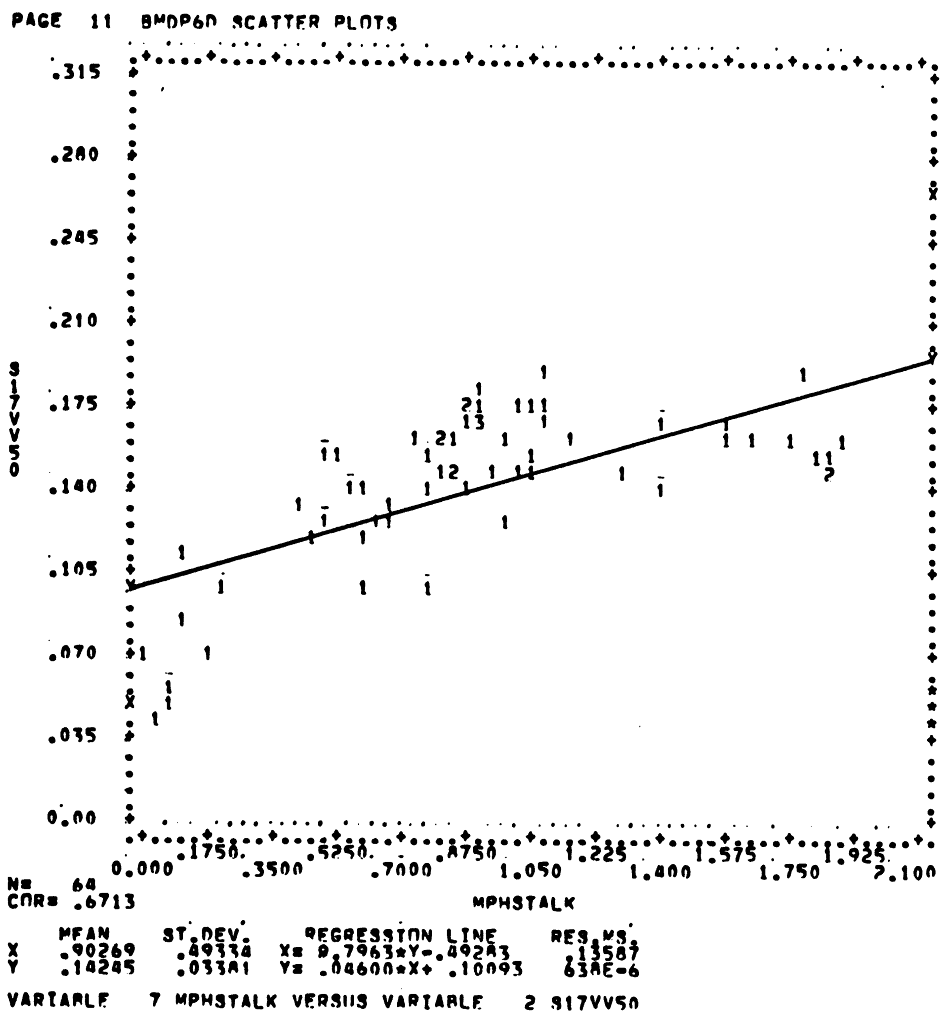
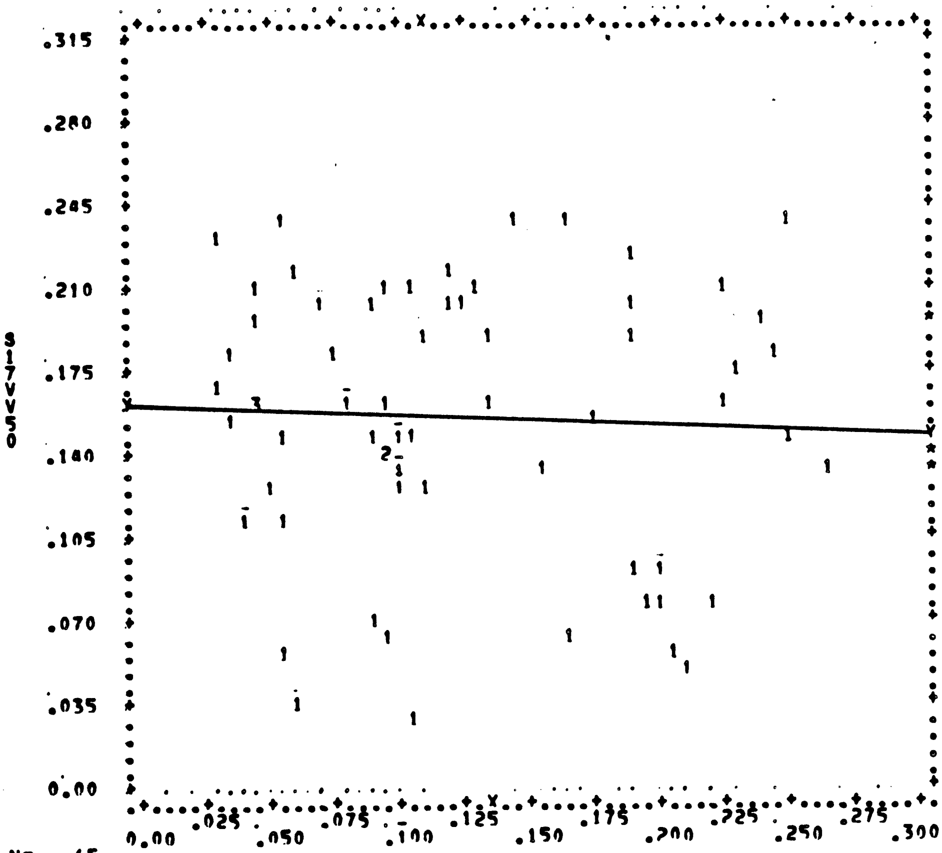


Figure 33. Backscatter (17 GHz, VV, 50°) versus stalk water (kg/m^2) for 1980 sorghum.

PAGE 4 BMDP6D SCATTER PLOTS



N= 65
COR=-.0647

	MEAN	ST.DEV.	REGRESSION LINE	RES.MS.
X	.12425	.06819	X=-.07863*Y+ .13641	.00470
Y	.15474	.05610	Y=-.05322*X+ .16135	.00318

VARIABLE 3 MSVOL VERSUS VARIABLE 2 S17VV50

Figure 34. Backscatter (17 GHz, VV, 50°) versus volumetric soil moisture (gm/cm^3) for 1980 corn.

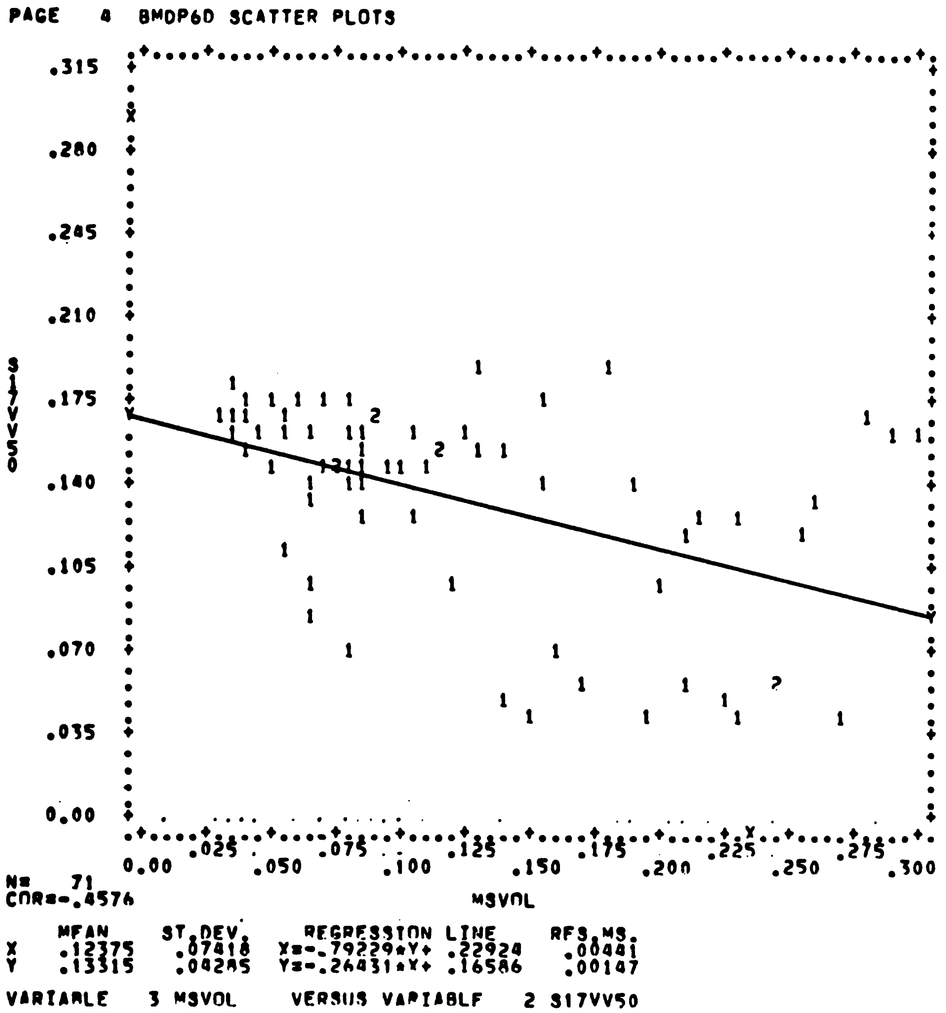


Figure 35. Backscatter (17 GHz, VV, 50°) versus volumetric soil moisture (gm/cm^3) for 1980 sorghum.

TABLE 6. Summary of Regression Analysis for 1980 Corn

	MPHPLANT	MPHLEAF	MPHSTALK	LAI	MSVOL	S17VV50
MPHPLANT	--	0.83	0.94	0.79	--	0.41
MPHLEAF	0.83	--	0.86	0.93	--	0.58
MPHSTALK	0.94	0.86	--	0.80	--	0.37
LAI	0.79	0.93	0.80	--	--	0.69
MSVOL	--	--	--	--	--	-0.06
S17VV50	0.41	0.58	0.37	0.69	-0.06	--

TABLE 7. Summary of Regression Analysis for 1980 Sorghum

	MPHPLANT	MPHLEAF	MPHSTALK	LAI	MSVOL	S17VV50
MPHPLANT	--	0.89	0.97	0.94	--	0.75
MPHLEAF	0.89	--	0.84	0.90	--	0.70
MPHSTALK	0.97	0.84	--	0.94	--	0.67
LAI	0.94	0.90	0.94	--	--	0.70
MSVOL	--	--	--	--	--	-0.46
S17VV50	0.75	0.70	0.67	0.70	-0.46	--

model, since each additional parameter adds additional information, which should result in an improved mathematical description of the process. In addition, although soil moisture showed little or even a slightly negative correlation with the radar data, it too should be included in the modeling effort. This analysis indicates that soil moisture is not important over most of the growing season, but other studies have shown that it can be quite significant either very early or very late in the season because of low canopy attenuation during these periods.

4.0 BACKSCATTERING RESPONSE MODELING

The microwave response to vegetation may be modeled using various levels of mathematical sophistication. The most elementary approach is via a simple linear regression; a slightly more complex method involves the use of multiple linear regressions. These methods are totally empirical and thus require no knowledge of the details of the target-sensor interaction. Empirical models are often developed by users of remote-sensing data. The advantage of empirical models is that they are simple and delineate a straightforward relationship between the observed microwave response and a given ground-truth parameter. The disadvantage of empirical models is that they provide little understanding of the nature of the target-sensor interaction; moreover, they often do not provide good fits to the observed data.

At the other end of the modeling spectrum, one may utilize electromagnetic scattering theory, based upon Maxwell's equations, to develop a rigorous solution to the target-sensor interaction problem (Ulaby, 1984a; Fung, 1977, Fung, 1979). The theoretical models for scattering from a vegetation volume are relatively complex mathematically and require ground-truth inputs that are difficult (and expensive) to obtain. Theoretical models contribute greatly to the understanding of the physical processes involved in vegetation scattering, but they are of limited value to users of remote-sensing data.

A middle-of-the-road approach to vegetation modeling is represented by the semi-empirical model. A semi-empirical model is based upon macroscopic physical principles and commonly measured ground-truth parameters. Such a model is developed with one or more constants whose value is determined by fitting the model expression to the observed microwave and ground-truth data using non-linear regression techniques. Semi-empirical models provide insight into the nature of the target-sensor interaction and are of value to users of microwave remote sensing data, since they are based upon easily measured ground-truth parameters. The semi-empirical approach to modeling is the basis for the material presented in this section.

4.1 Review of Previous Approaches

One of the first efforts to model the backscattering response of vegetation was conducted at Ohio State University (Peake, 1959), where wheat and grass were modeled as a collection of lossy dielectric cylinders.

In contrast, the initial approach made by the University of Kansas was to model the vegetation canopy as a homogeneous dielectric slab. The dielectric constant of the slab was calculated from a mixing formula for air and vegetation.

An improved semi-empirical model was subsequently developed at the University of Kansas by treating the vegetation as a water cloud (Attema, 1978). Portraying vegetation as a water cloud was justified by the fact that the dielectric constant of dry vegetation (Carlson, 1967) differs little from that of air (1.5 vs. 1.0), whereas the dielectric constant of free water is considerably higher. In this model, the vegetation canopy is modeled as a cloud characterized by its volumetric water content. The assumptions inherent in this model are that the cloud representing the vegetation consists of identical water particles uniformly distributed throughout the space according to a Poisson process, that only single scattering needs to be considered, and that the only significant variables are cloud height and cloud density. Cloud density is assumed to be proportional to the volumetric water content of the canopy. The cloud model has been tested on numerous data sets including the 1979 and 1980 data acquired near Manhattan, Kansas (Eger, 1982; Ulaby, 1983) and has yielded satisfactory although not spectacular results.

The Dutch have extended the basic cloud model to a multilayer approach (Hoekman, 1982) and have generated improved results. The Dutch model was tested on a wide variety of crops including beets, potatoes, peas, winter wheat, summer wheat, barley, and oats.

A recent approach to semi-empirical modeling, developed primarily for soil-moisture applications, uses the theoretical models for surface scattering and the cloud model for the vegetative cover (Mo, 1984).

Work has continued at the University of Kansas on semi-empirical modeling and alternate approaches have been developed that give reasonable fits to the observed data (Ulaby, 1984b; Allen, 1984).

The obvious questions that arise in this review are: Which model is best? By what criteria should such models be compared?

As illustrated in Section 3.3, plant parameters are highly correlated with each other, so it is possible to generate a number of different semi-empirical models using basically similar physical reasoning. It is common to judge such models by criteria such as the correlation between observed and predicted data and the rms error between observed and predicted values. These criteria are not sufficient, however. One essential criterion is that the canopy attenuation calculated from the model must be realistic. Since few independent canopy-attenuation measurements have been reported to date, a major objective of this investigation is to expand knowledge in this area. Attenuation data are presented in Section 5.

4.2 A Semi-Empirical Vegetation Model

This section presents an alternative approach to the semi-empirical modeling of a vegetation canopy designed to bridge the gap between the semi-empirical approach and the theoretical approach. The model is derived from recent work at the University of Kansas.

A theoretical model for scattering by a lossy volume over a surface via the radiative transfer approach is available in the literature (Ulaby, 1984a). In the case of a vegetation canopy the volume is treated as having no definable upper surface. The result is in the form of a matrix equation that is too complex for most users of remote-sensing data, including many individuals whose interest is in semi-empirical modeling.

Although the model is mathematically complex, it consists of only three basic components, as follows:

$$\sigma^0_{total} = \sigma^0_{surface} + \sigma^0_{volume} + \sigma^0_{interaction}.$$

In general, the surface term is a function of its dielectric constant and its surface roughness, characterized by the surface height standard deviation σ and the surface correlation length L. The three theoretical models used for surface scattering (depending upon surface roughness) are the Small-Perturbation Model, the Kirchhoff Scalar-Approximation Model, and the Kirchhoff Stationary-Phase-Approximation Model. Because the surface term is negligible over the majority of the growing season in most vegetation canopy situations, we may avoid the theoretical models and use a simple relationship for $\sigma^0_{surface}$:

$$\sigma^0_{surface} = C(f,\theta) \cdot L_C(f,\theta) \cdot MSVOL$$

where C is a constant that is a function of the frequency f and the incidence angle θ, and L_C is the two-way canopy loss that is also a function of frequency and incidence angle, and MSVOL is the volumetric soil moisture.

The volume term can be simplified greatly by assuming that losses due to scattering and absorption are polarization independent, that all scattering within the volume behaves in a Rayleigh phase manner, and that only single scattering is considered. Under these conditions, the model simplifies to:

$$\sigma^o_{VV} = \sigma^o_{HH} = 0.75\ \omega[1 - \exp(-2\tau\ \sec\theta)]\ \cos\theta$$

where ω is the single-scattering albedo and τ is the optical depth. This is exactly equivalent to the cloud model discussed previously.

A slightly more complex and accurate model may be obtained by assuming that the volume may be characterized by its albedo and optical depth, while including products and higher powers of ω and τ. The model is of the form:

$$\sigma^o_{VV} = \sigma^o_{HH} = P\ \omega(1 + Q\omega\tau + R(\omega\tau)^2)$$

$$\bullet(1 - \exp(-S\ \tau\ \sec\theta))\ \cos\theta$$

where P, Q, R, and S are constants. This model was fitted to the full theoretical model for the single-scattering case using non-linear regression to obtain the following result (Allen, 1984):

$$\sigma^o_{VV} = \sigma^o_{HH} = 0.742\ \omega(1 + 0.536\ \omega\tau - 0.237(\omega\tau)^2)$$

$$\bullet\ (1 - \exp(-2.119\ \tau\ \sec\theta))\ \cos\theta$$

the rms error associated with this fit was 0.174 dB, and the correlation coefficient was 0.999. The limits on this model are $8.4° < \theta < 84.5°$; $0.1 < \tau < 2.2$; $0.01 < \omega < 0.5$.

The interaction term turns out to be negligible for VV polarization with the above limits but of some significance for HH polarization. Using techniques similar to those used in developing the volume term, the interaction term becomes (Allen, 1984):

$$\sigma^o_{int_{VV}} = 0$$

$$\sigma^o_{int_{HH}} = 1.924\ \omega[1 + 0.924\ \omega\tau + 0.398(\omega\tau)^2]$$

$$\bullet\ [1 - \exp(-1.925\ \tau\ \sec\theta)]\ [\exp(-1.372\ \tau^{1.12}\ \sec\theta)]$$

$$\bullet\ \exp[-0.836(k\sigma)^2\ \cos\theta]\ |R_{hh}|^2\ \cos\theta$$

where $k = 2\pi/\lambda$, σ is the surface standard deviation and R_{hh} is the Fresnel Reflection Coefficient for horizontal polarization. The rms error associated with this fit was 0.233 dB and the correlation coefficient was 0.999. The limits of this model are $8.4° < 0 < 62.7°$; $0.1 < \tau < 2.2$; $0.01 < \omega < 0.5$; $0.1 < k\sigma < 0.9$.

Although these models are of theoretical interest, they still do not include ground-truth parameters that easily can be measured in the field. The semi-empirical models to be used in this investigation will be derived by postulating relationships between the albedo, ω and the optical depth, τ and ground-truth parameters.

Optical depth is defined as (Ulaby, 1982)

$$\tau = \int_{z_1}^{z_2} \kappa_e \, dz$$

where κ_e is the extinction coefficient and dz is an increment of path length through the vegetation canopy. Extinction in a volume is the result of scattering and absorption. Sources of extinction in a vegetation canopy include the leaves, fruit, and stalks. For the purposes of this model, it will be assumed that the only significant sources of extinction are scattering from leaves, absorption by leaves, and absorption by stalks. It will be further assumed that leaf scattering is proportional to leaf area index, leaf absorption is proportional to leaf water content, and stalk absorption is proportional to stalk water content. These assumptions lead to the following form for the optical depth, τ:

$$\tau = A \cdot LAI + B \cdot MPHLEAF + D \cdot MPHSTALK$$

where A, B, and D are constants, LAI is leaf area index (m^2/m^2), MPHLEAF is leaf water content (kg/m^2) and MPHSTALK is stalk water content (kg/m^2).

The albedo is defined as (Ulaby, 1982)

$$\omega = \frac{\kappa_s}{\kappa_e}$$

where κ_s. is the scattering coefficient. Based on the above assumptions for optical depth, the albedo is

$$\omega = \frac{A \cdot LAI}{\tau} \quad .$$

The albedo and optical depth are each a function of frequency. The two-way canopy loss required in the surface term as a function of optical depth is

$$L_C = \exp(-2 \; \tau \; \sec\theta) \; .$$

The surface term becomes

$$\sigma^o_{surface} = C \cdot MSVOL \cdot [\exp(- \; 2 \; \tau \; \sec\theta)].$$

The model, to be referred to as Model A, is summarized as follows for VV polarization:

$$\tau = A \cdot LAI + B \cdot MPHLEAF + D \cdot MPHSTALK$$

$$\omega = \frac{A \cdot LAI}{\tau}$$

$$\sigma^o_{VV} = 0.742 \; \omega(1 + 0.536 \; \omega\tau - 0.237(\omega\tau)^2)$$

$$\cdot \left(1 - \exp(-2.119 \; \tau \; \sec\theta)\right) \cos\theta + C$$

$$\cdot \ \mathrm{MSVOL} \cdot \exp(-2.0\ \tau\ \sec\theta).$$

For HH polarization, the following assumptions were made:

$$\tau = A \cdot \mathrm{LAI} + B \cdot \mathrm{MPHLEAF} \text{ (no stalk term)}$$

$$\omega = \frac{A \cdot \mathrm{LAI}}{\tau}$$

$$(k\sigma)^2 = C$$

$$|R_{hh}|^2 = D \cdot \mathrm{MSVOL}.$$

To keep the number of constants reasonable, the stalk-absorption term is not specifically included in this version; furthermore, it should be negligible for HH polarization. $(k\sigma)^2$ is assumed to be a constant because it depends upon surface roughness (which is essentially constant for the test data). $|R_{hh}|^2$ is assumed to be proportional to soil moisture, since it is a function of dielectric constant, and dielectric constant increases with increasing soil moisture.

Model A for HH polarization becomes:

$$\sigma^o_{HH} = 0.742\ \omega[1 + 0.536\ \omega\tau - 0.237(\omega\tau)^2]$$

$$\cdot \ [1 - \exp(-2.119\ \tau\ \sec\theta)]\ \cos\theta$$

$$+ 1.924\ \omega\ [1 + 0.924\ \omega\tau + 0.398(\omega\tau)^2]$$

$$\cdot \left[1 - \exp(-1.925\ \tau \cdot \sec\theta)\right]$$

$$\cdot \left[\exp(-1.372\ \tau^{1.12}\ \sec\theta)\right]$$

$$\cdot \left[\exp(-0.836 \cdot C \cdot \cos\theta)\right]$$

$$\cdot D \cdot MSVOL \cdot \cos\theta$$

$$+ E \cdot MSVOL \cdot \exp(-2\ \tau\ \sec\theta).$$

Model A was tested extensively using VV polarization on the 1980 data set described previously. The model was also tested using HH polarization at 17.0 GHz. The model was fitted to the backscattering and ground-truth data using the BMDP-AR non-linear regression routine (Dixon, 1979). The constants in the model were determined by combining all fields of either corn or sorghum. The model was then used to generate predicted σ^o values for each individual field. These σ^o values were compared to observed values by calculating the correlation coefficient (r) between predicted and observed data as well as the rms error (e). Additionally, plots of predicted and observed data were generated. All of the relevant data for this analysis are available in Appendix A.

Table 8 summarizes the Model A constants at 8.6 GHz, 13.0 GHz, 17.0 GHz, and 35.6 GHz for corn. In addition, constant

TABLE 8. Model A Constants for 1980 Corn

Crop	Frequency (GHz)	Polarization	A	B	C	D
Corn	8.6	VV	0.09	0.83	1.05	0.09
Corn	13.0	VV	0.14	1.35	1.32	0.03
Corn	17.0	VV	0.15	1.26	0.97	0.03
Corn	35.6	VV	0.14	0.50	0.88	0.14
Corn	10.2 (interpolated)	VV	0.11	1.02	1.15	0.07

values were obtained by interpolation for 10.2 GHz for use in a later section (4.5) on model attenuation.

The correlation between observed and model-predicted corn data is summarized in Table 9.

Table 10 presents the rms errors in dB for each corn field/frequency combination.

Figures 36, 37, 38, and 39 are plots of σ^0 predicted versus σ^0 observed for a selected corn field at each of the four frequencies utilized in the study.

Figure 40 illustrates the importance of the soil moisture term as compared to the vegetation term for a selected corn field at 8.6 GHz. This term is of some importance early in the growing season, of minor importance throughout most of the season, and quite important at the very end of the measurement period. It should be noted that 1980 was a very hot and dry year, and soil moisture values were generally quite low (Appendix A). A wetter growing season would have increased the contribution of the soil moisture term.

Table 11 summarizes the Model A constants obtained for 1980 sorghum. Table 12 illustrates the correlation coefficients, and the rms errors are tabulated in Table 13.

Figures 41, 42, 43, and 44 graphically illustrate the observed - versus - predicted backscattering response for 1980 sorghum. In general, the model provided a slightly inferior fit for sorghum as compared to corn.

Model A for HH polarization includes the soil-vegetation interaction term. This term is negligible for VV polarization,

TABLE 9. Model A Correlation Coefficients for 1980 Corn

Crop	Frequency (GHz)	Polarization	r_1	r_2	r_3
Corn	8.6	VV	0.87	0.87	0.86
Corn	13.0	VV	0.93	0.69	0.92
Corn	17.0	VV	0.93	0.78	0.94
Corn	35.6	VV	0.96	0.82	0.95

TABLE 10. Model A RMS Errors for 1980 Corn

Crop	Frequency (GHz)	Polarization	e_1(dB)	e_2(dB)	e_3(dB)
Corn	8.6	VV	0.66	0.78	0.93
Corn	13.0	VV	0.45	0.92	0.69
Corn	17.0	VV	0.66	0.96	0.69
Corn	35.6	VV	0.63	0.88	0.58

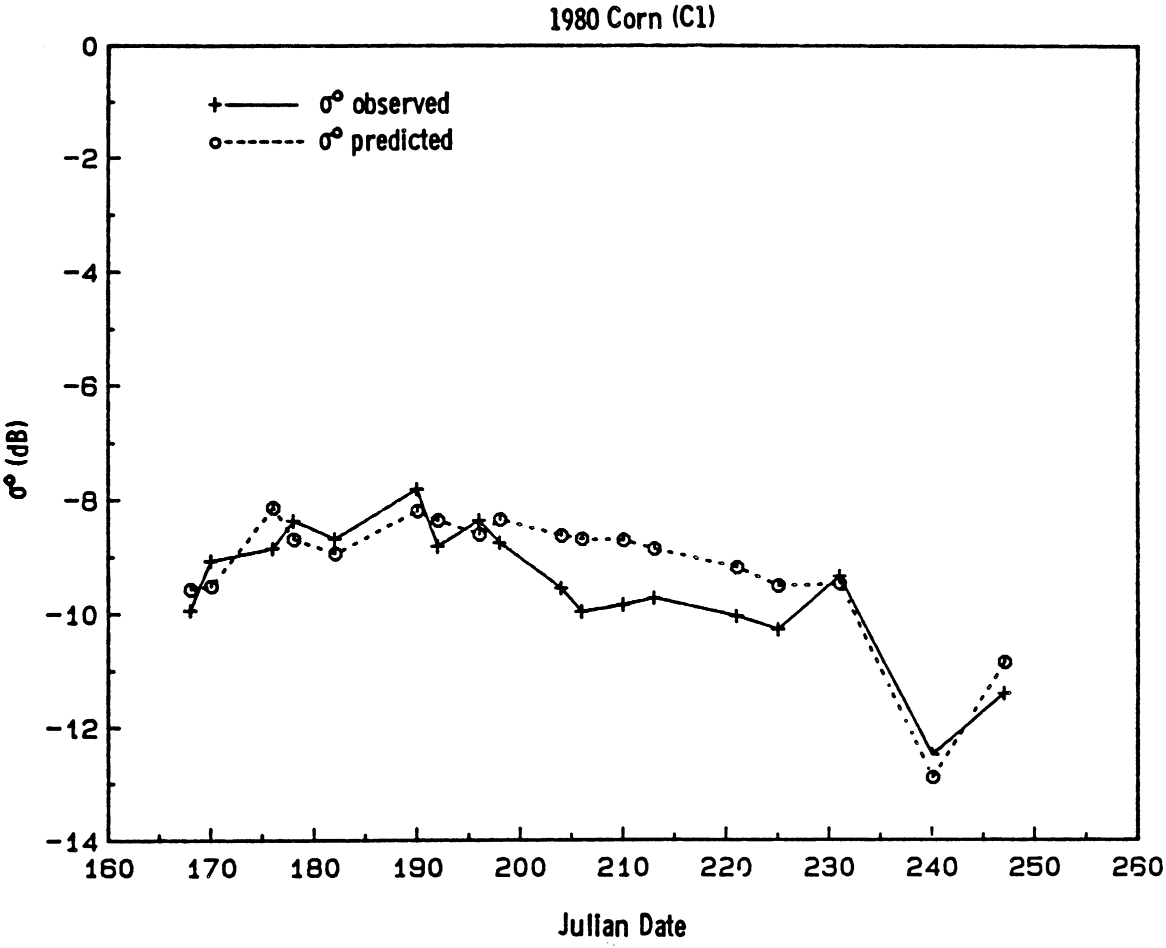


Figure 36. Observed versus predicted seasonal response for 1980 corn at 8.6 GHz, VV polarization, 50°; correlation is 0.87, and rms error is 0.66 dB.

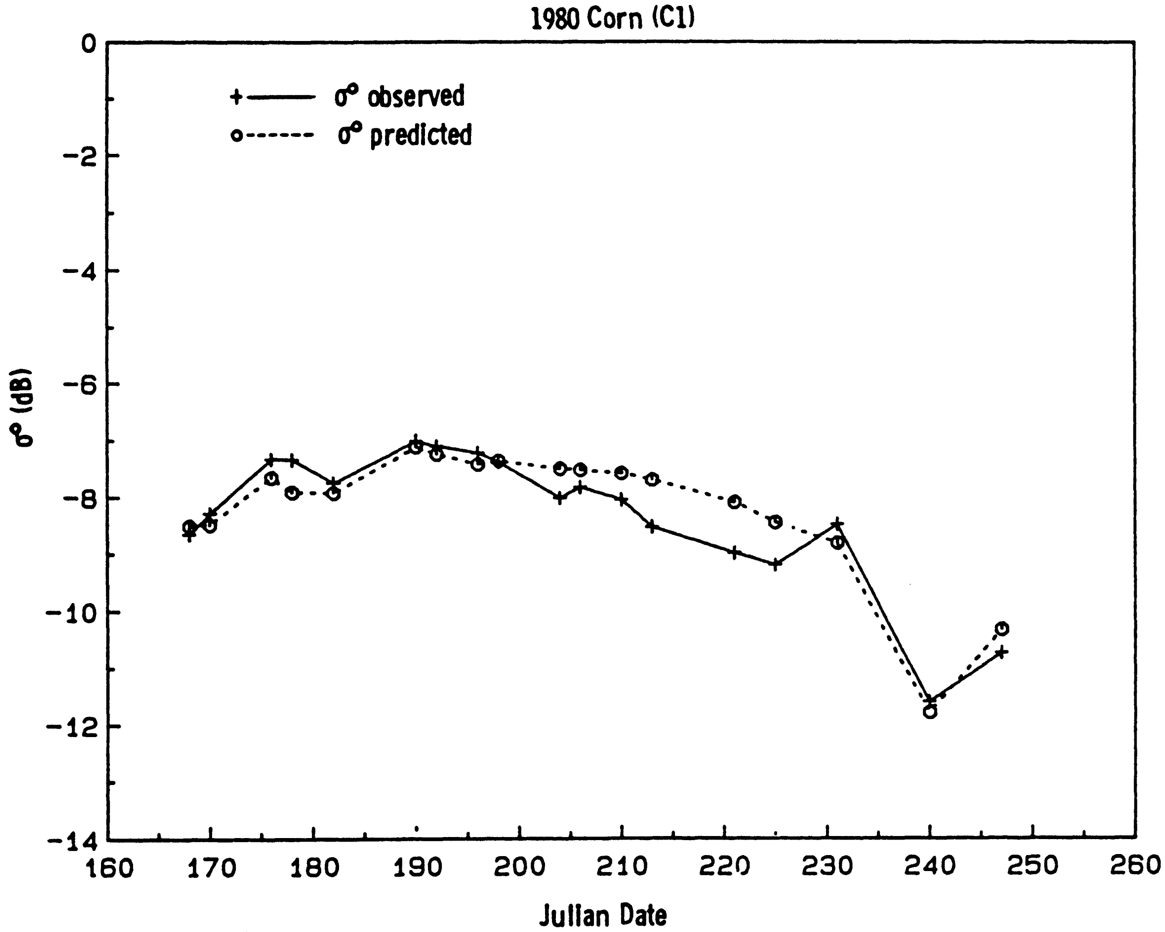


Figure 37. Observed versus predicted seasonal response for 1980 corn at 13.0 GHz, VV polarization, 50°; correlation is 0.93, and rms error is 0.45 dB.

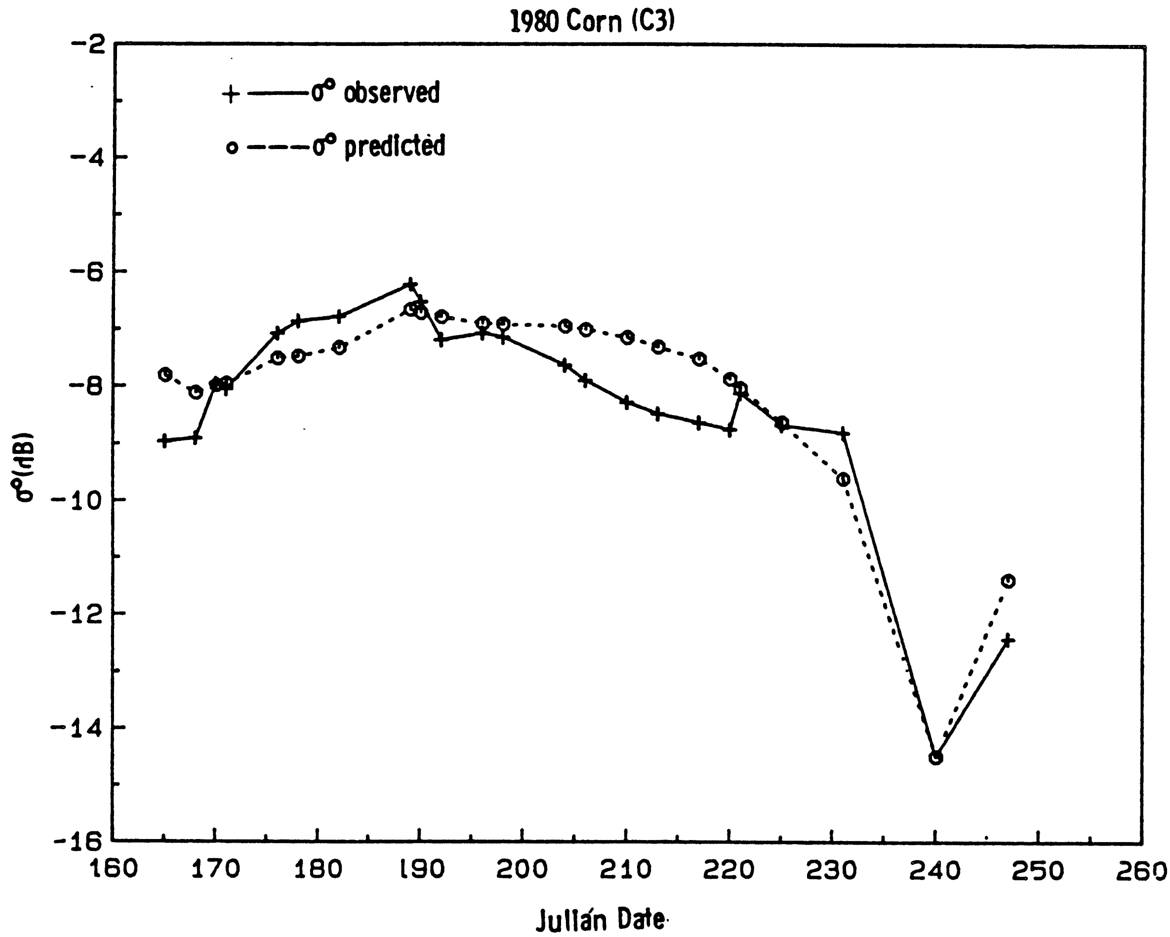


Figure 38. Observed versus predicted seasonal response for 1980 corn at 17.0 GHz, VV polarization, 50°; correlation is 0.94, and rms error is 0.69 dB.

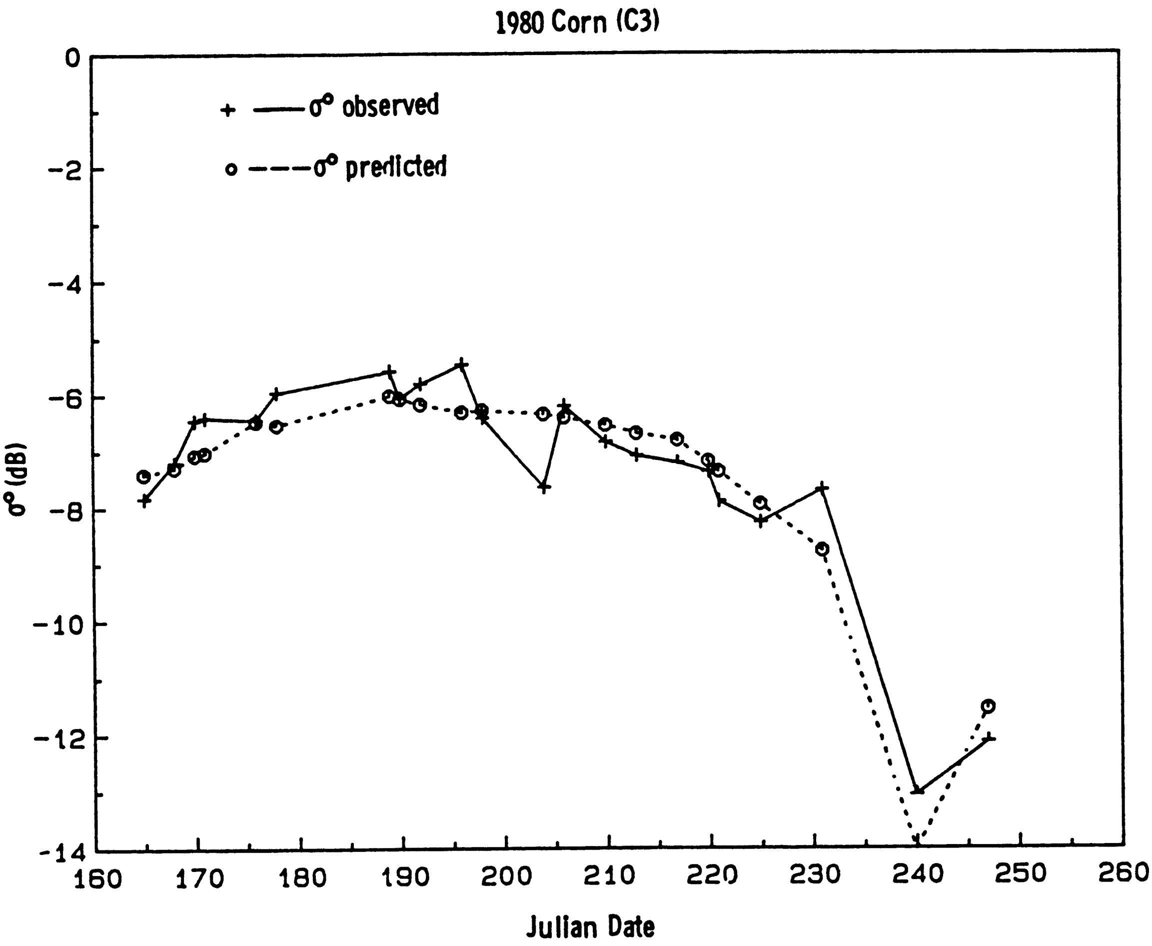


Figure 39. Observed versus predicted seasonal response for 1980 corn at 35.6 GHz, VV polarization, 50°; correlation is 0.95, and rms error is 0.58 dB.

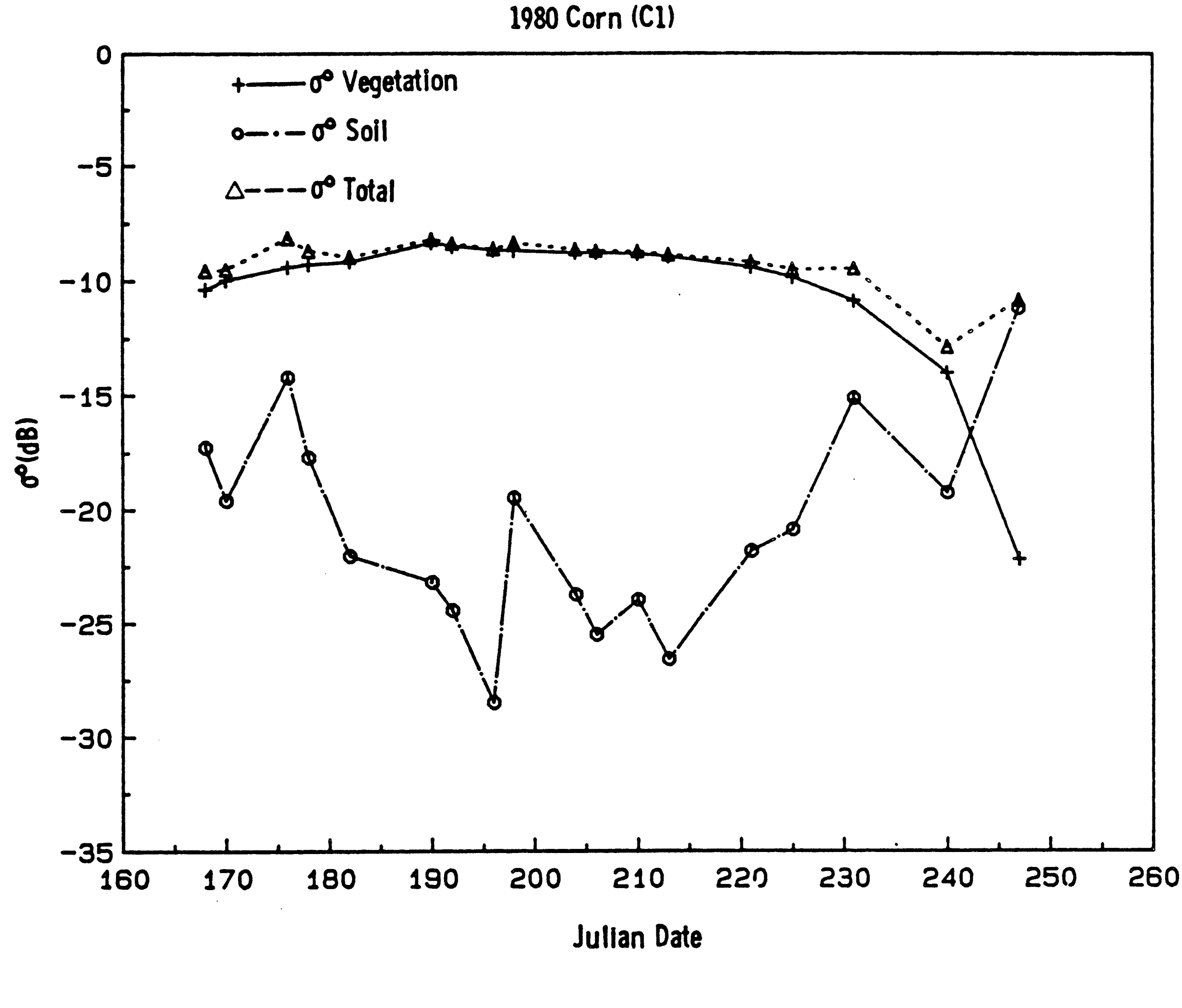


Figure 40. Comparison of model soil-moisture term to model vegetation term and total predicted σ^0 for 1980 corn (C1) at 8.6 GHz, VV polarization, 50°.

TABLE 11. Model A Constants for 1980 Sorghum

Crop	Frequency (GHz)	Polarization	A	B	C	D
Sorghum	8.6	VV	0.13	1.61	0.00	0.14
Sorghum	13.0	VV	0.15	1.45	0.00	0.15
Sorghum	17.0	VV	0.14	1.02	0.00	0.21
Sorghum	35.6	VV	0.11	0.33	0.32	0.40

TABLE 12. Model A Correlation Coefficients for 1980 Sorghum

Crop	Frequency (GHz)	Polarization	r_1	r_2	r_3
Sorghum	8.6	VV	0.95	0.47	0.54
Sorghum	13.0	VV	0.91	0.65	0.80
Sorghum	17.0	VV	0.95	0.61	0.78
Sorghum	35.6	VV	0.88	0.72	0.90

TABLE 13. Model A RMS Errors for 1980 Sorghum

Crop	Frequency (GHz)	Polarization	e_1(dB)	e_2(dB)	e_3(dB)
Sorghum	8.6	VV	1.10	1.36	1.08
Sorghum	13.0	VV	1.07	1.19	0.78
Sorghum	17.0	VV	0.95	1.40	0.90
Sorghum	35.6	VV	1.16	1.26	0.63

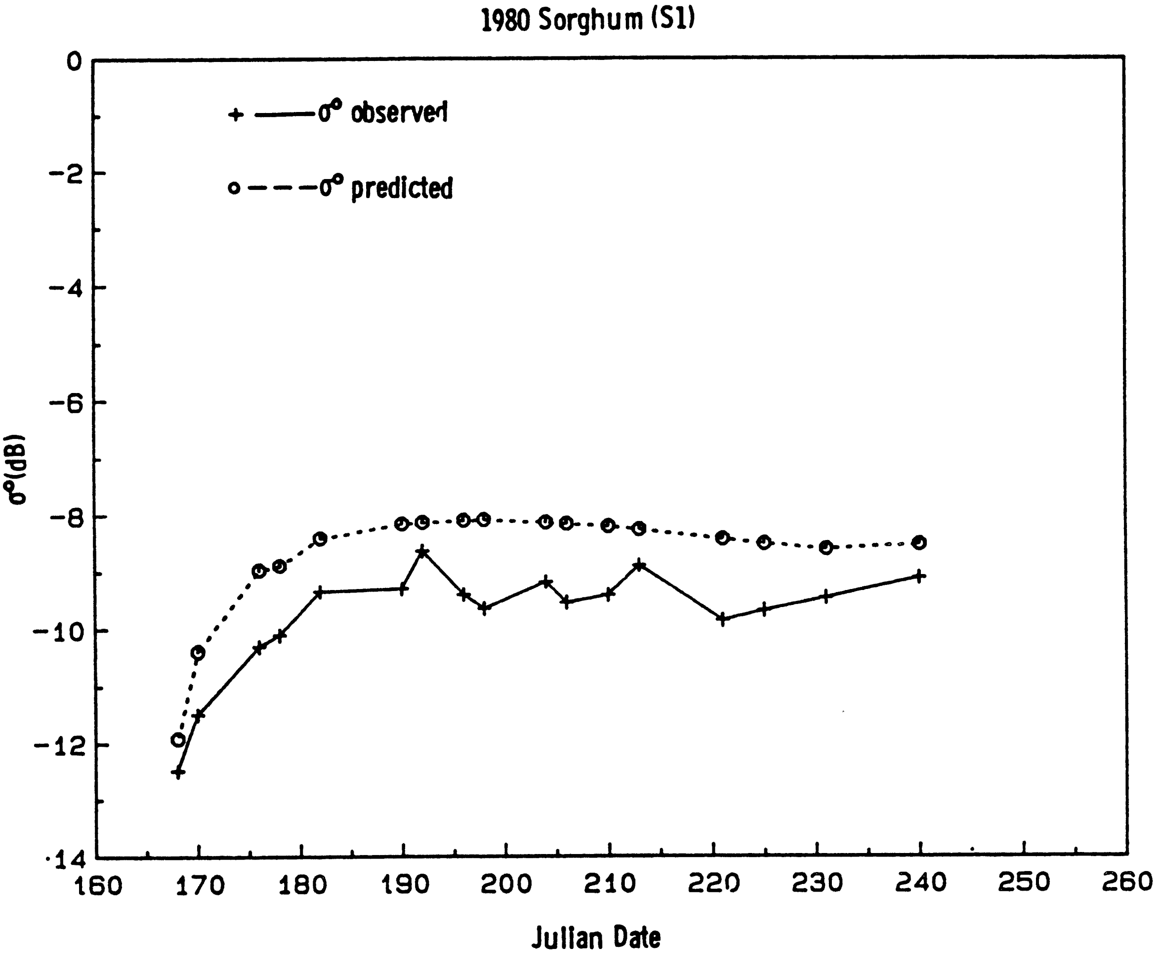


Figure 41. Observed-versus-predicted seasonal response for 1980 sorghum at 8.6 GHz, VV polarization, 50°; correlation is 0.95, and rms error is 1.10 dB.

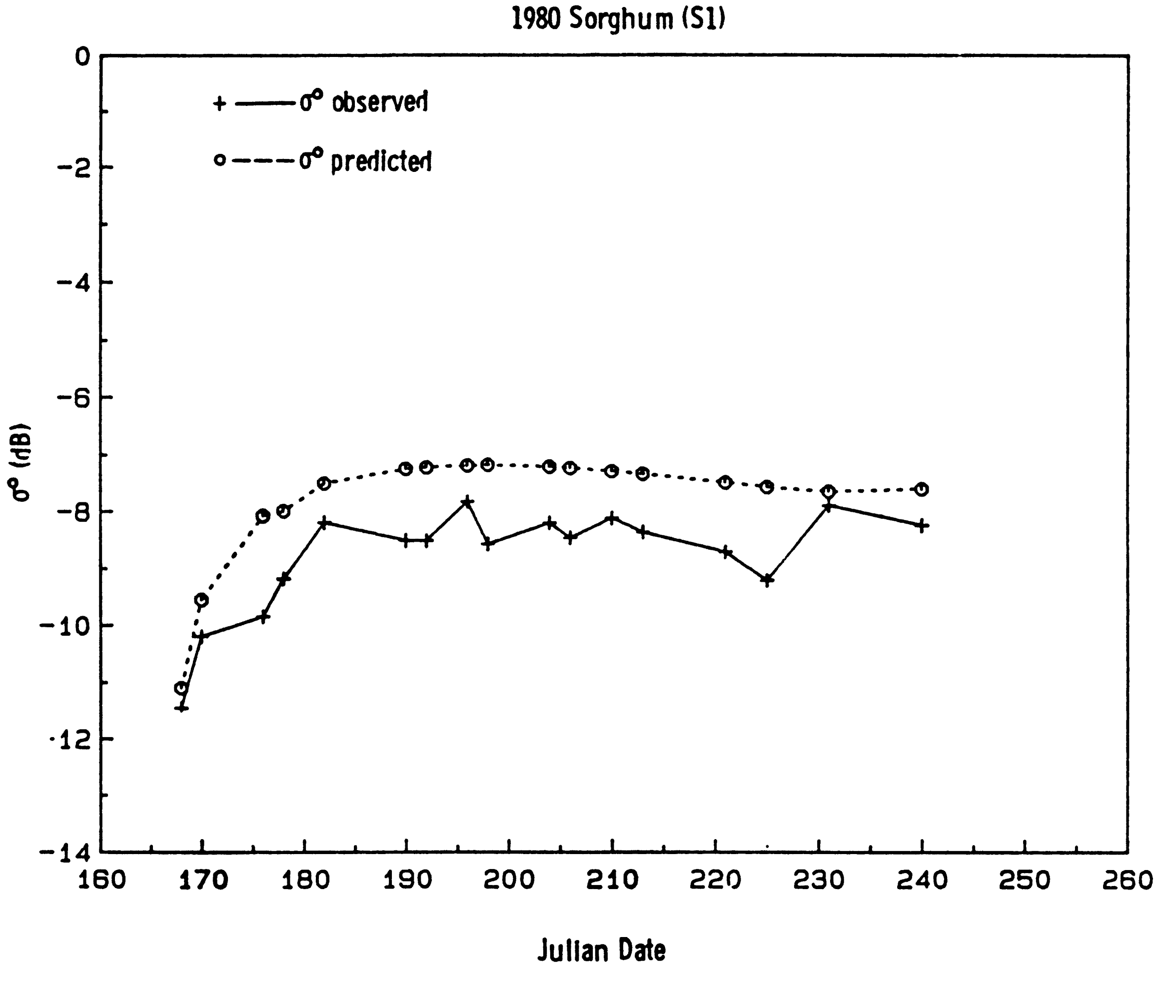


Figure 42. Observed-versus-predicted seasonal response for 1980 sorghum at 13.0 GHz, VV polarization, 50°; correlation is 0.91, and rms error is 1.14 dB.

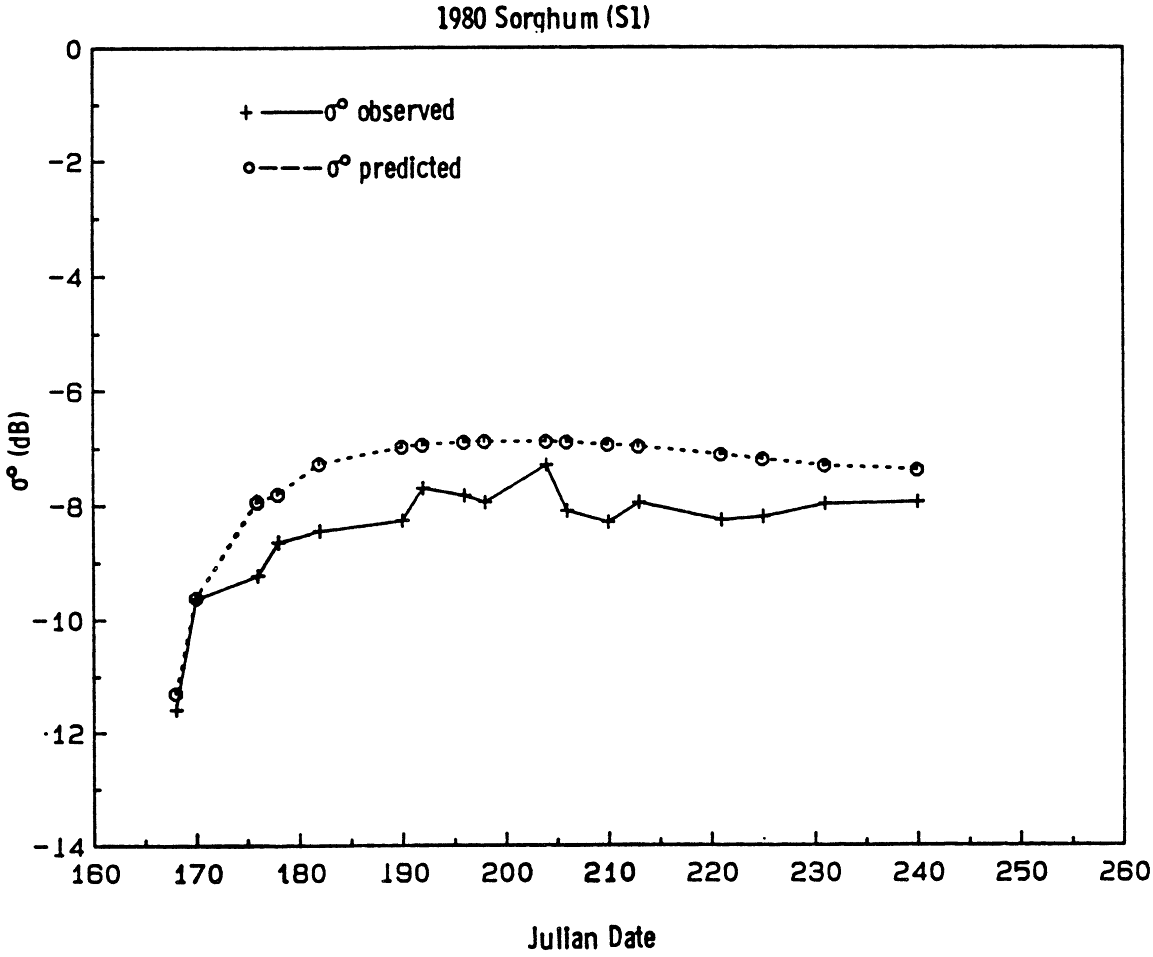


Figure 43. Observed-versus-predicted seasonal response for 1980 sorghum at 17.0 GHz, VV polarization, 50°; correlation is 0.95, and rms error is 0.95 dB.

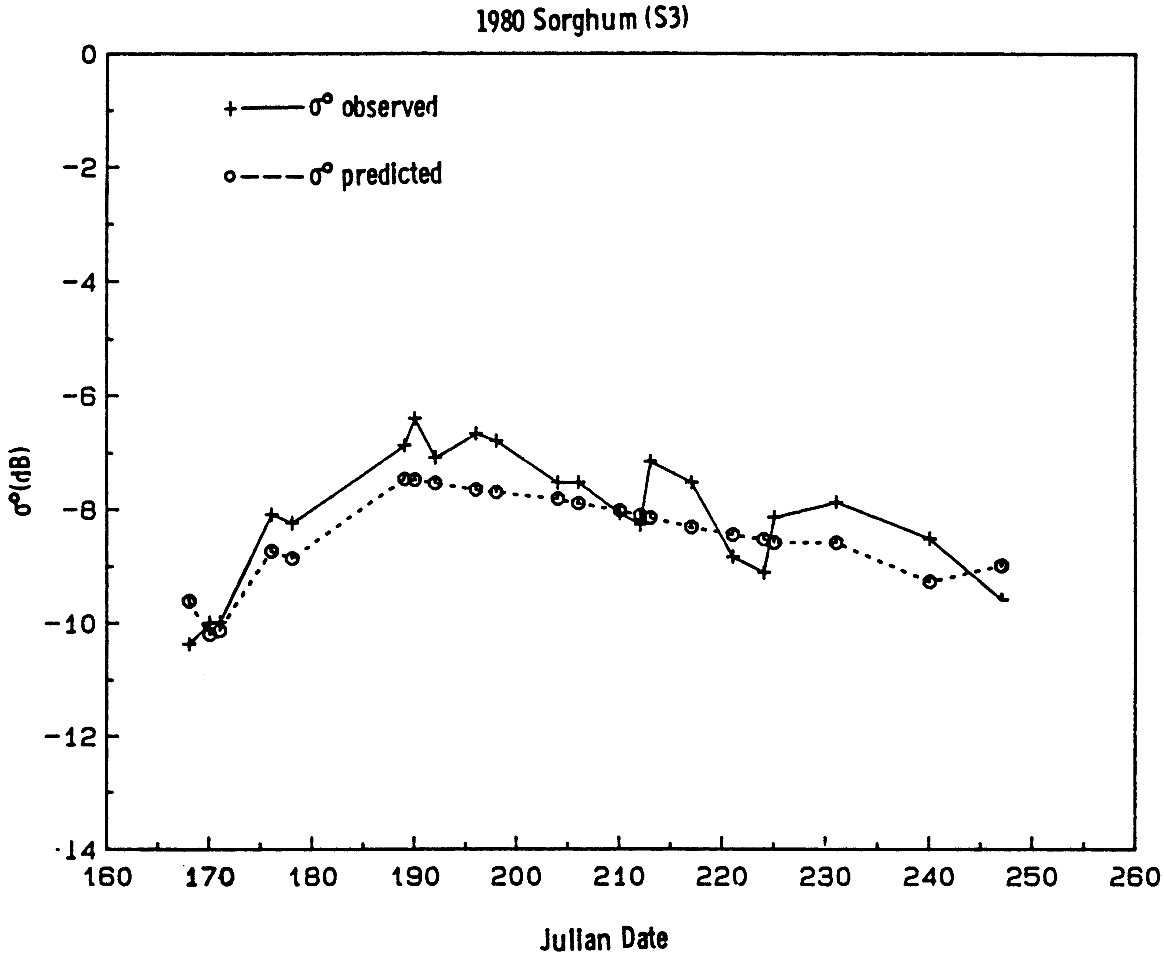


Figure 44. Observed-versus-predicted seasonal response for 1980 sorghum at 35.6 GHz, VV polarization, 50°; correlation is 0.90, and rms error is 0.63 dB.

but is normally of some significance for HH polarization; therefore, it was included in the model. The model also differs from the form for VV polarization in that a stalk-absorption term was not specifically included. This term was eliminated to reduce the number of constants in the model, which can be justified on the basis that a horizontally polarized wave should undergo little absorption by a vertically oriented stalk.

Table 14 summarizes Model A constants for HH polarization at 17.0 GHz, which was the only frequency studied. Table 15 tabulates the correlation coefficients, and Table 16 lists the rms errors. The only crop considered at HH polarization was corn.

Table 17 compares the magnitude of the volume, interaction, and soil (surface) terms for 17.0 GHz with HH polarization. It is notable that both the soil and the interaction terms are 15-20 dB below the level of the vegetation terms, which indicates that they are of minimal significance. It should be noted, however, that 1980 was a very hot and dry year and that these levels are depressed compared to more moist conditions. Further, the soil term is important very early in the growing season when there is minimal biomass and late in the season after vegetation has dried.

Figure 45 illustrates the seasonal response of observed versus predicted backscattering data at 17.0 GHz with HH polarization. The fit of these data is similar to that obtained for VV polarization.

Table 18 summarizes the individual contributions to the optical depth term by leaf scattering, leaf absorption and stalk absorption, as well as total optical depth and albedo for a

TABLE 14. Model A Constants for 1980 Corn at 17.0 GHz, HH Polarization

Crop	Frequency (GHz)	Polarization	A	B	C	D	E
Corn	17.0	HH	0.11	1.24	0.00	0.86	0.86

TABLE 15. Model A Correlation Coefficients for 1980 Corn at 17.0 GHz, HH Polarization

Crop	Frequency (GHz)	Polarization	r_1	r_2	r_3
Corn	17.0	HH	0.87	0.78	0.93

TABLE 16. Model A RMS Errors for 1980 Corn at 17.0 GHz, HH Polarization

Crop	Frequency (GHz)	Polarization	e_1(dB)	e_2(dB)	e_3(dB)
Corn	17.0	HH	0.76	0.93	0.64

TABLE 17. Comparison of the Volume, Interaction, and Soil (Surface) Terms at 17.0 GHz, VV Polarization

Date	Crop	Frequency (GHz)	Polarization	σ^o_{vol}(dB)	σ^o_{int}(dB)	σ^o_{soil}(dB)
170	Corn	17.0	HH	-8.9	-25.7	-23.6
204	Corn	17.0	HH	-7.5	-24.8	-27.7

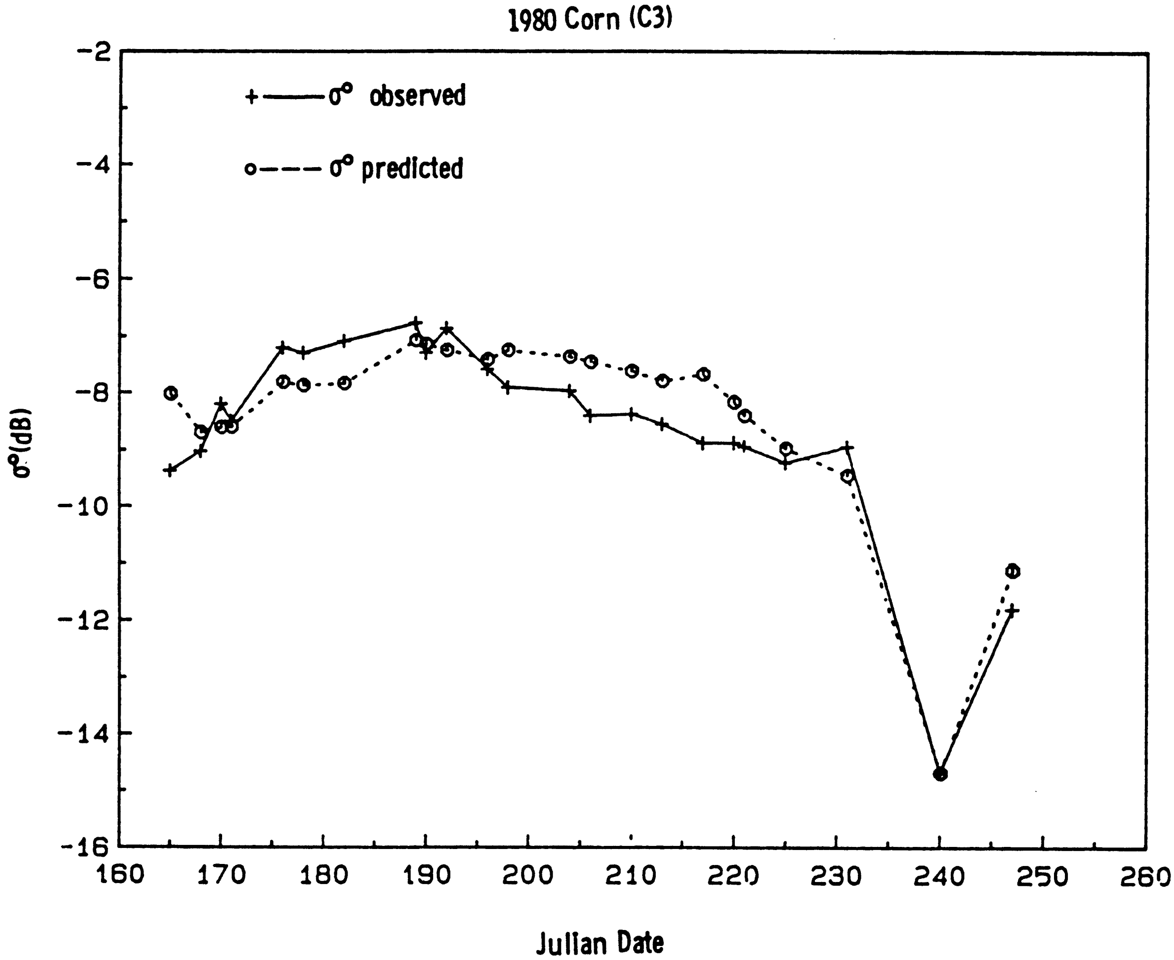


Figure 45. Observed-versus-predicted seasonal response for 1980 corn at 17.0 GHz, HH polarization, 50°; correlation is 0.93, and rms error is 0.64 dB.

TABLE 18. Contribution to Optical Depth by Leaf Scattering, Leaf Absorption, and Stalk Absorption; Total Optical Depth and Albedo for Corn Field C3 on Date 204, Using Model A

Crop	Frequency (GHz)	Polarization	$\tau_{\ell s}$	$\tau_{\ell a}$	τ_{sa}	τ	ω
Corn	8.6	VV	0.39	0.71	0.28	1.38	0.28
Corn	13.0	VV	0.59	1.17	0.09	1.85	0.32
Corn	17.0	VV	0.63	1.09	0.09	1.81	0.35
Corn	35.6	VV	0.60	0.42	0.44	1.46	0.41

selected field of 1980 corn at mid-season (Day of Year [also referred to as Day, Date, or Julian Date] 204). Figure 46 is a plot of the seasonal variation in optical depth and albedo for a different 1980 corn field. Note the "plateau" region of the optical depth and note that the albedo remains constant at approximately 0.3 until the end of the growing season. All data are for VV polarization.

Table 19 provides a tabulation identical to Table 18, except that it is for sorghum on the same mid-season date (204). These data are also for VV polarization.

4.3 Additional Semi-Empirical Models

Although Model A is attractive because it can be tied directly to a theoretical model based upon electromagnetic scattering theory, other semi-empirical approaches can yield good fits.

The following model, developed at the University of Kansas (Allen, 1984), will be referred to as Model B:

$$\sigma^0 = A[1 - \exp(-B \cdot LAI/h)]\,[1 - \exp(-2 \cdot E \cdot LAI \sec\theta)] \cos\theta + C$$

$$\cdot\ MSVOL[\exp(-2 \cdot E \cdot LAI \sec\theta)] + D$$

$$\cdot\ MPHSTALK[\exp(-2 \cdot E \cdot LAI \sec\theta)]$$

where h is the canopy height.

This model was tested on the 1980 corn data and produced a

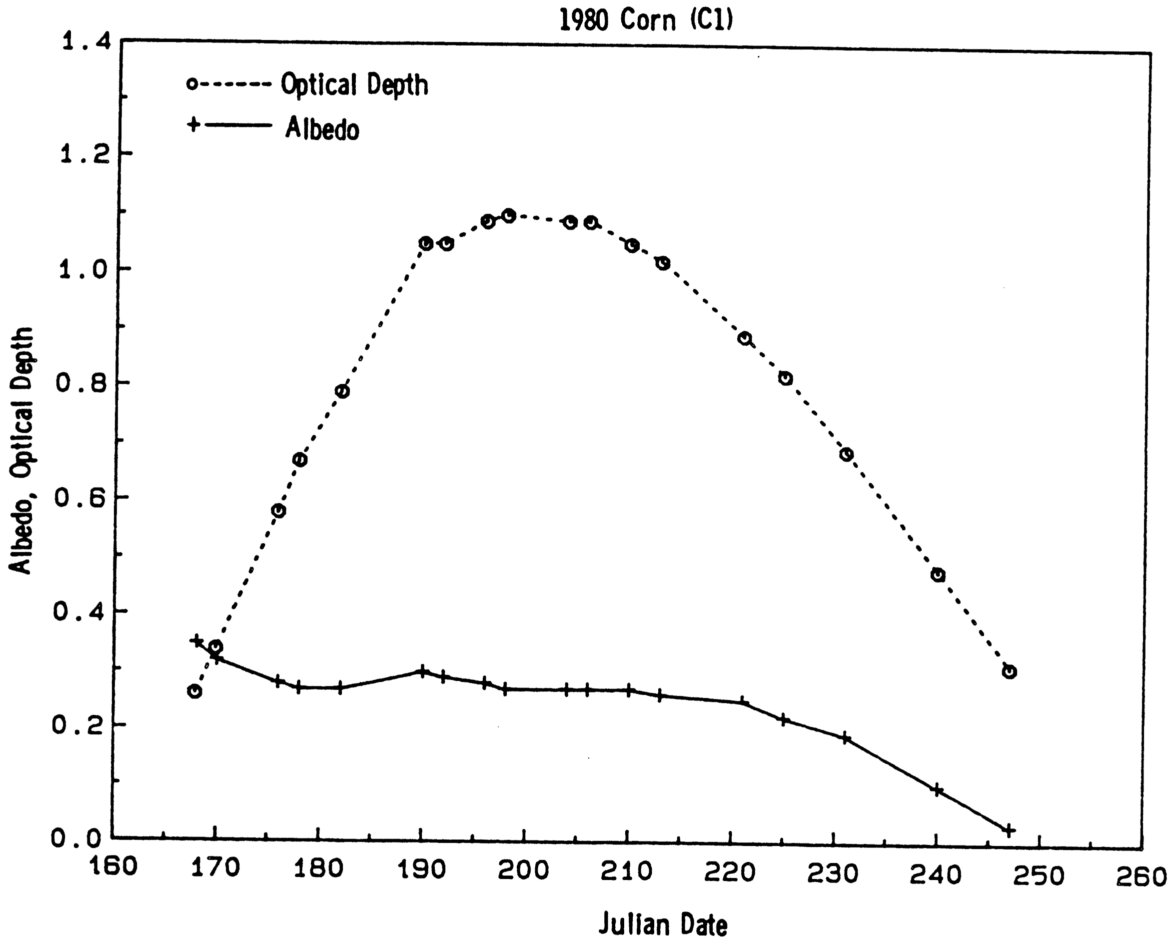


Figure 46. Seasonal variation of albedo and optical depth for 1980 corn (C1) at 8.6 GHz, VV polarization, 50°.

TABLE 19. Contribution to Optical Depth by Leaf Scattering, Leaf Absorption, and Stalk Absorption; Total Optical Depth and Albedo for Sorghum Field S1 on Date 204, Using Model A

Crop	Frequency (GHz)	Polarization	$\tau_{\ell s}$	$\tau_{\ell a}$	τ_{sa}	τ	ω
Sorghum	8.6	VV	0.67	1.64	0.25	2.56	0.26
Sorghum	13.0	VV	0.78	1.73	0.27	2.51	0.31
Sorghum	17.0	VV	0.72	1.41	0.37	2.13	0.34
Sorghum	35.6	VV	0.56	1.05	0.71	1.61	0.35

error. Table 20 summarizes the model constants, and Table 21 tabulates the correlation coefficients and rms errors for all fields combined. Note that this model is primarily driven by leaf area index, although a stalk term is included.

A model developed at NASA/JPL (Paris, 1984) was also tested using the 1980 corn data. This model introduces a new variable, N, i.e., the number of leaves per plant, into the model expressions. N is determined from the growth stage of the crop and is tabulated in Appendix A along with the other corn ground truth.

Model C is

$$\sigma^o = \frac{A \cdot LAI^B \cdot N}{2 \cdot MPHLEAF \cdot \sec\theta} \left[1 - \exp(-2 \cdot C \cdot MPHLEAF \cdot \sec\theta)\right]$$

$$+ \left[D + E \cdot MSVOL\right] \cdot \left[\exp(-2 \cdot C \cdot MPHLEAF \cdot \sec\theta)\right].$$

Table 22 summarizes the constants obtained by fitting the model to the 1980 corn data, and Table 23 gives the correlation coefficients and rms errors for all fields combined. Again, the model provides a good fit to the 1980 data.

In an effort to improve Model C, a stalk term was added to the expression, which will be referred to as Model D:

$$\sigma^o = \frac{A \cdot LAI^B \cdot N}{2 \cdot MPHLEAF \sec\theta} \left[1 - \exp(-2 \cdot C \cdot MPHLEAF \cdot \sec\theta)\right]$$

$$+ D \cdot MSVOL \cdot \left[\exp(-2 \cdot C \cdot MPHLEAF \cdot \sec\theta)\right]$$

$$+ E \cdot MPHSTALK \cdot \left[\exp(-2 \cdot C \cdot MPHLEAF \cdot \sec\theta)\right].$$

TABLE 20. Model B Constants for 1980 Corn

Crop	Frequency (GHz)	Polarization	A	B	C	D	E
Corn	8.6	VV	0.23	2.05	0.19	0.03	0.45
Corn	13.0	VV	0.28	2.09	0.18	0.04	0.47
Corn	17.0	VV	0.31	2.36	0.23	0.03	0.41
Corn	35.6	VV	0.40	1.35	0.10	0.04	0.43

TABLE 21. Model B Correlation Coefficients and RMS Error for all Fields Combined for 1980 Corn

Crop	Frequency (GHz)	Polarization	r_1	r_2	r_3	e(dB)
Corn	8.6	VV	0.85	0.94	0.89	0.71
Corn	13.0	VV	0.93	0.89	0.94	0.68
Corn	17.0	VV	0.91	0.88	0.91	0.73
Corn	35.6	VV	0.94	0.91	0.93	0.61

TABLE 22. Model C Constants for 1980 Corn

Crop	Frequency (GHz)	Polarization	A	B	C	D	E
Corn	8.6	VV	0.11	1.03	0.68	0.07	0.04
Corn	13.0	VV	0.11	0.94	1.10	0.07	0.00
Corn	17.0	VV	0.18	1.25	2.17	0.01	0.23
Corn	35.6	VV	0.17	1.08	1.17	0.07	0.00

TABLE 23. Model C Correlation Coefficients and RMS Error for all Fields Combined for 1980 Corn

Crop	Frequency (GHz)	Polarization	r_1	r_2	r_3	e(dB)
Corn	8.6	VV	0.81	0.86	0.83	0.81
Corn	13.0	VV	0.89	0.82	0.90	0.85
Corn	17.0	VV	0.93	0.86	0.94	0.89
Corn	35.6	VV	0.93	0.87	0.91	0.73

Note also that the soil-moisture term has been simplified in this model to reduce the number of constants.

Table 24 illustrates the constants derived by fitting this model to the 1980 corn data, and Table 25 gives the correlation coefficients and rms error for all fields combined. A comparison of Tables 21 and 23 indicates that the addition of the stalk term improves an already good fit to the data.

4.4 Model Comparisons

Table 26 provides a comparison of the average correlation for all fields and frequencies and the average rms error for all fields and frequencies for the four models studied. Although there are slight differences in performance, the results are nearly identical. As previously indicated, this is a result of the high correlation between the various ground-truth parameters used in these models.

The four models must be compared on the basis of the canopy attenuation they predict, however, before they can be considered valid. Canopy attenuation is the subject of the next section.

4.5 Canopy Attenuation from Models

The four models discussed in this section each have a two-way canopy attenuation of the form

$$L_C = \exp(-2 \tau \sec\theta)$$

TABLE 24. Model D Constants for 1980 Corn

Crop	Frequency (GHz)	Polarization	A	B	C	D	E
Corn	8.6	VV	0.10	1.05	1.49	0.26	0.06
Corn	13.0	VV	0.11	0.97	1.67	0.24	0.07
Corn	17.0	VV	0.12	1.00	1.59	0.31	0.07
Corn	35.6	VV	0.17	1.11	1.79	0.16	0.08

TABLE 25. Model D Correlation Coefficients and RMS Error for all Fields Combined for 1980 Corn

Crop	Frequency (GHz)	Polarization	r_1	r_2	r_3	e(dB)
Corn	8.6	VV	0.83	0.90	0.85	0.76
Corn	13.0	VV	0.91	0.85	0.85	0.91
Corn	17.0	VV	0.93	0.86	0.91	0.69
Corn	35.6	VV	0.94	0.92	0.92	0.67

TABLE 26. A Comparison of the Average Correlation and RMS Error for the Four Models Studied

	Model A	Model B	Model C	Model D
Correlation (r)	0.88	0.91	0.88	0.89
RMS Error (e)	0.74 dB	0.68 dB	0.82 dB	0.76 dB

or in dB,

$$L_C(\text{dB}) = 4.343\ (2\ \tau\ \sec\theta).$$

The models differ in their expressions for the optical depth, τ, however:

Model A: $\tau = A \cdot \text{LAI} + B \cdot \text{MPHLEAF} + D \cdot \text{MPHSTALK}$

Model B: $\tau = E \cdot \text{LAI}$

Model C: $\tau = C \cdot \text{MPHLEAF}$

Model D: $\tau = C \cdot \text{MPHLEAF}$.

The constants are derived from fitting the models to the data, and thus the values for "C" in Models C and D differ.

Table 27 provides a comparison of the two-way canopy attenuation calculated from the four models for a selected 1980 corn field on a mid-season date (204). Note that Models A, B, and D are in reasonable agreement with respect to the general level of attenuation over the frequency range considered but that Model C predicts a much lower attenuation, except at 17.0 GHz where it is similar to the others.

The only way the appropriateness of these models, each of which provides a good fit to the data, can be judged is through comparison to direct canopy attenuation data. Although canopy

TABLE 27. **Comparison of Two-Way Canopy Attenuation for Corn Field C3 on Date 204, Calculated from Models A, B, C, and D**

Crop	Frequency (GHz)	Polarization	L_A(dB)	L_B(dB)	L_C(dB)	L_D(dB)
Corn	8.6	VV	18.6	25.8	7.8	17.3
Corn	13.0	VV	25.0	26.9	12.8	19.5
Corn	17.0	VV	24.4	23.5	25.3	18.2
Corn	35.6	VV	19.7	24.6	13.6	20.8

attenuation data are extremely limited, data on corn at 10.2 GHz, VV polarization are available (Ulaby, 1984c).

The 10.2-GHz data were taken in 1982, which was a very wet year; therefore, the comparison to 1980, which was a very dry year, is not totally appropriate. In addition, data were not taken at 10.2 GHz in 1980, so model constants had to be interpolated. Another difference between 1980 and 1982 was canopy height; specifically, the 1982 corn was taller than the 1980 corn, due to more favorable moisture conditions.

Figure 47 provides a plot of the canopy attenuation calculated from Model A on a selected field of 1980 corn, over a growing season. The attenuation values have been normalized to dB/meter by dividing by the canopy height. The plot also includes the direct attenuation measurements from 1982, again normalized to dB/meter by dividing by the canopy height.

The agreement between these two curves is quite reasonable during the early part of the growing season, considering that they represent different fields during different years and were subject to different environmental conditions. The attenuation difference during the last part of the growing season, while not excessive, is most likely due to the fact that the 1982 corn remained green (and thus more moist), whereas the 1980 corn "browned-out" due to the hot, dry summer.

This comparison would seem to indicate that Models A, B, and D, which exhibit similar attenuation behavior, are reasonable, whereas Model C is not, because it predicts an unrealistically low canopy-attenuation value.

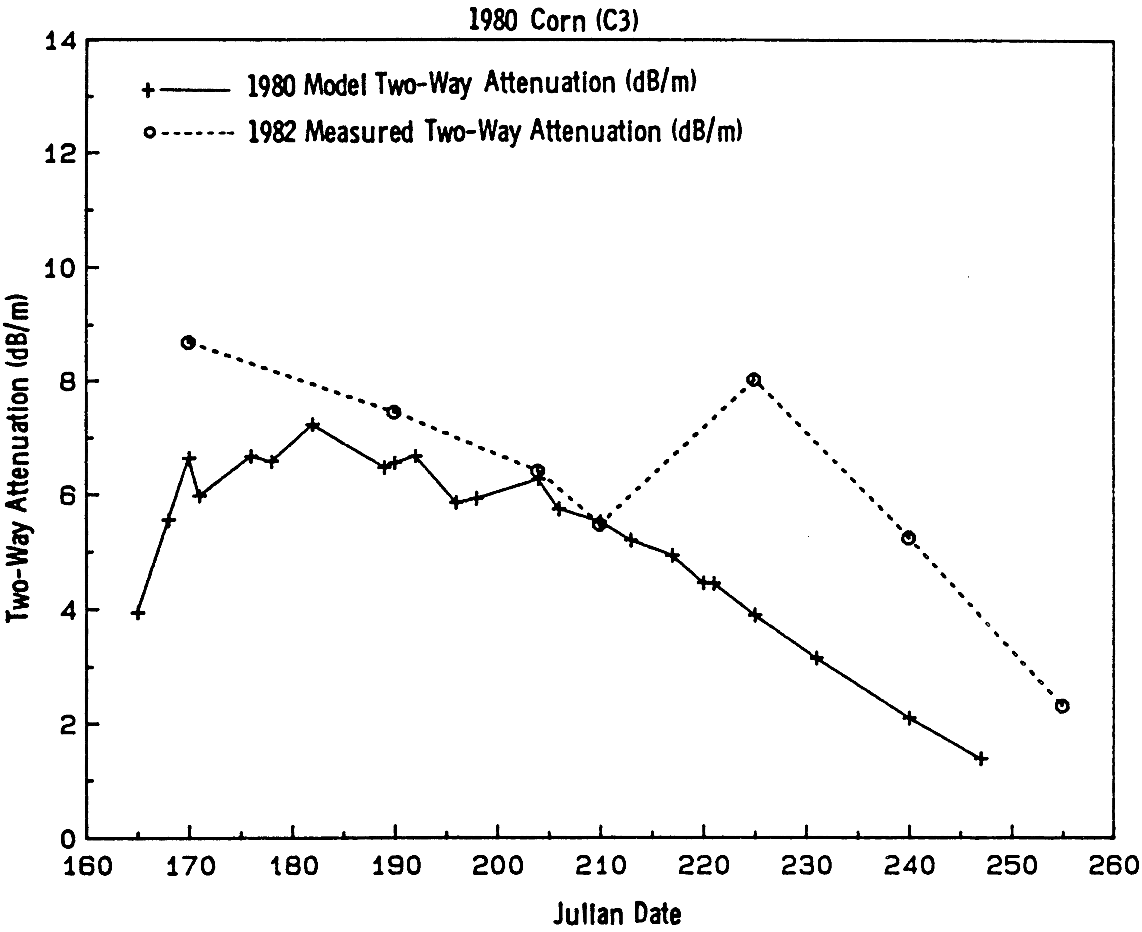


Figure 47. A comparison of corn-canopy attenuation calculated from Model A (1980 corn, C3) and canopy attenuation on corn measured directly at 10.2 GHz, VV polarization, 50°.

Comparing the four models, Model C is the only model without a stalk attenuation term, which may account for its relatively poor performance with respect to attenuation. Model D is essentially the same as Model C with the addition of a stalk term, and it performs well.

The ideal verification for this set of models would be direct attenuation data at the four frequencies of interest, with a leaf defoliation experiment to check the various components of attenuation suggested by Model A.

A complete set of canopy attenuation measurements as a function of frequency, polarization, and incidence angle for various crops and various growth stages (and moistures) would be an extremely valuable tool for individuals interested in the development of semi-empirical and theoretical vegetation models. Such a data set would also aid greatly in understanding the nature of microwave propagation and backscattering in vegetation. Although it may take several years to accumulate all of the desired data, the remainder of this report documents and attempts to model the first complete set of attenuation measurements as a function of frequency, angle, and polarization.

5.0 ATTENUATION DATA ANALYSIS

As previously discussed in this report, the only vegetation attenuation measurements to date have been very limited in scope. Data on vegetation attenuation are essential to validate semi-empirical and theoretical models and to provide increased understanding of microwave propagation and backscatter. The measurements reported here constitute the first complete set of attenuation measurements on vegetation as a function of frequency, polarization, and incidence angle. The crops chosen for the study were two economically important crops: wheat and soybeans. In addition to their economic importance, these two crops are of scientific interest because of their contrasting structures. Wheat is dominated by its vertical stalks, whereas soybean plants are dominated by their leafy structure. The frequency range chosen for the study was dictated by the microwave remote sensing systems planned for orbit in the late 1980's and early 1990's; thus L-, C-, and X-bands were chosen. The polarizations chosen for the study were the two linear polarizations, HH and VV, although some limited measurements were made at HV and VH. The angles of incidence chosen for the study included a low angle (16° or 24°), because of soil-moisture monitoring applications as well as for scientific interest, and a higher angle (52° or 56°) to correspond to likely vegetation-monitoring applications as well as for scientific interest. The angles of incidence chosen were also dictated to some extent by the physical conditions prevailing at the test sites.

The attenuation data presented here consist of a number of standard data sets, as well as special data sets including cross-polarized attenuation measurements, a wheat decapitation experiment, and a soybean defoliation experiment. The attenuation data will be modeled in Section 6.

5.1 Calibration, Accuracy, and Precision

As previously discussed, the attenuation data were acquired by pulling a receiver on a sled in synchronism with boom-truck-mounted transmitters. The data were captured on a chart recorder and later digitized and averaged. Figures 48, 49, 50, and 51 are tracings of actual recordings. These figures include data on both crops, wheat and soybeans, and provide samples of data at each of the frequencies, polarizations, and angles used. These recordings were selected as constituting a representative sample; the remaining ones were similar in nature. The figures indicate that even at maximum attenuation, the received signal was 10 dB to 20 dB above the noise floor. While this noise margin is typical, in a few cases it dropped to approximately 5 dB. None of the recordings indicated attenuation saturation due to receiver noise.

The attenuation measurements were calibrated by the simple procedure of referencing all attenuation to the power measured under free-space conditions. Free-space conditions were created by clearing the vegetation from each end of a canopy strip. Sources of error in this procedure include initial boresight error from transmitter to receiver, drift off boresight during horizontal travel, short-term transmitter power fluctuations, and

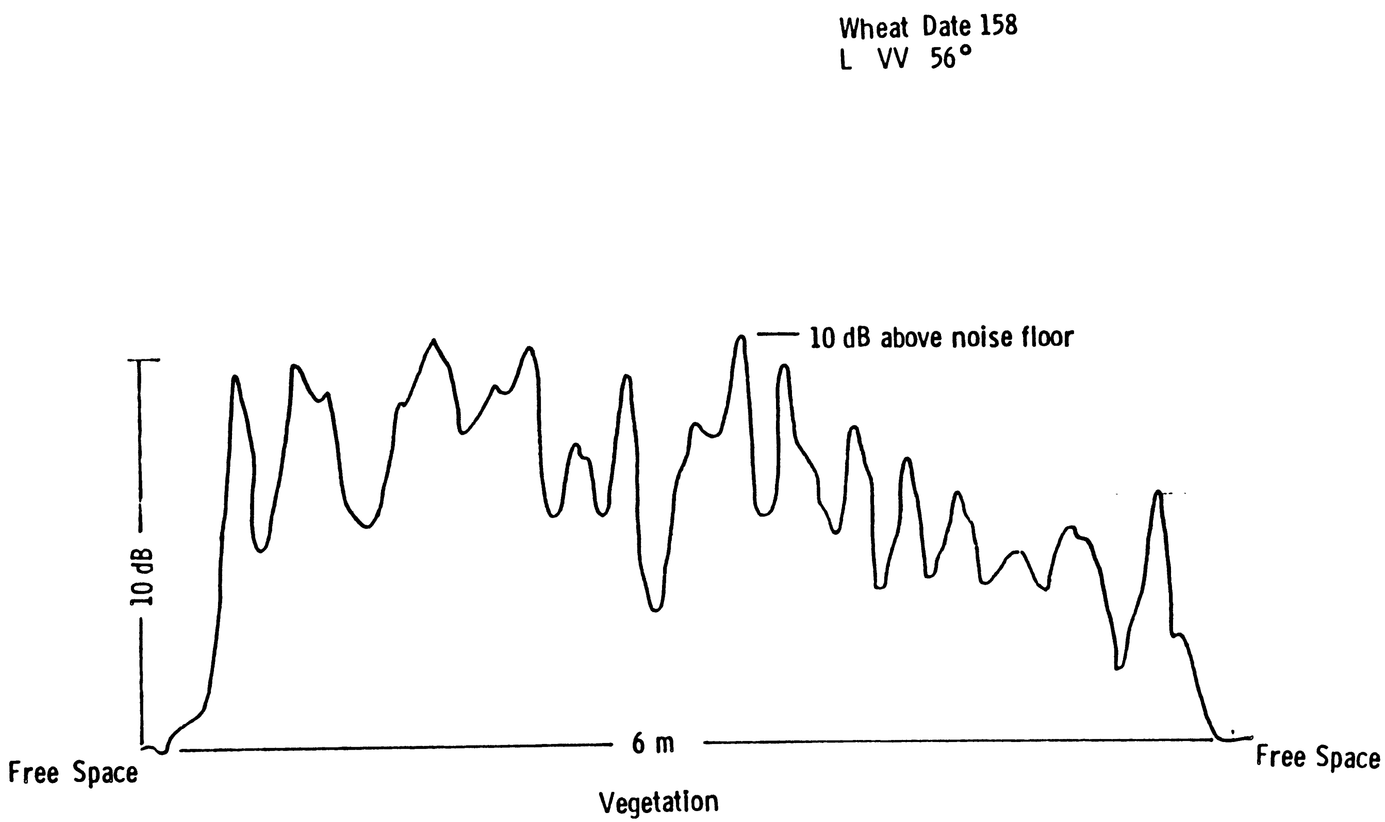


Figure 48. Attenuation recording of wheat at L-band, VV polarization and 56° incidence angle.

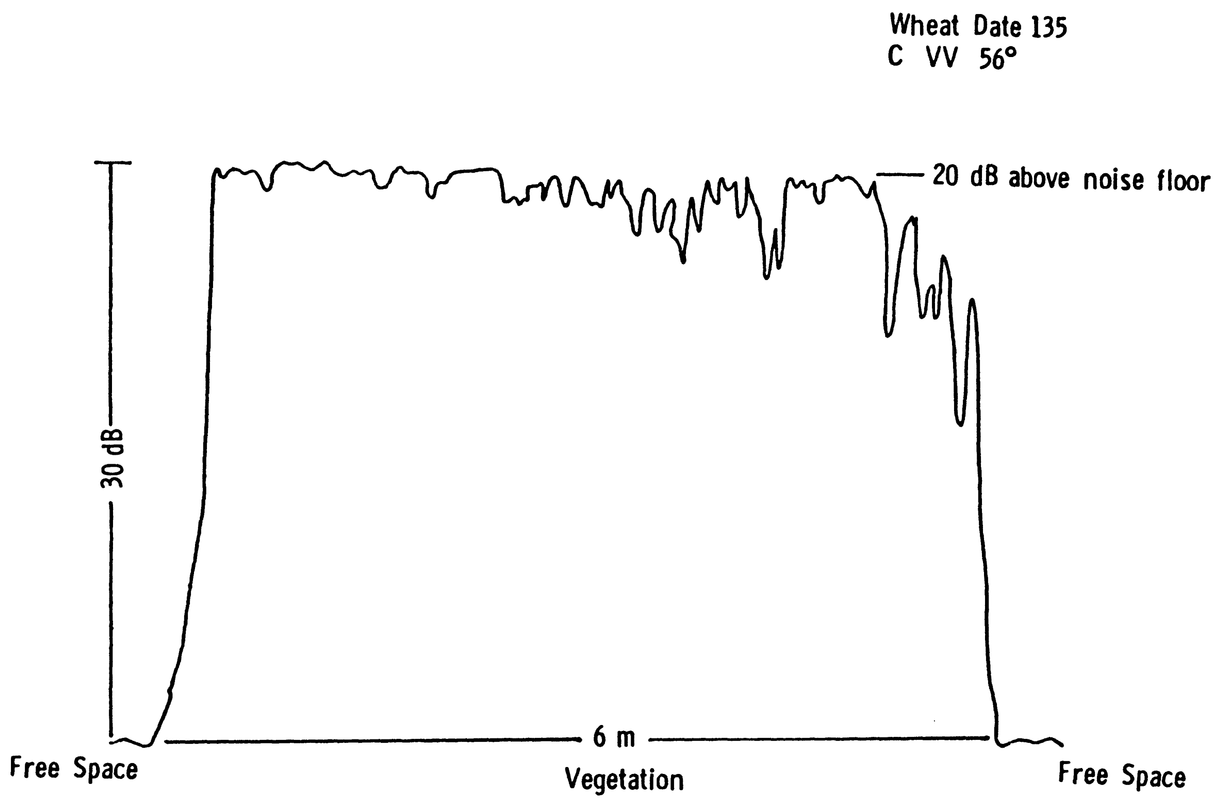


Figure 49. Attenuation recording of wheat at C-band, VV polarization, and 56° incidence angle.

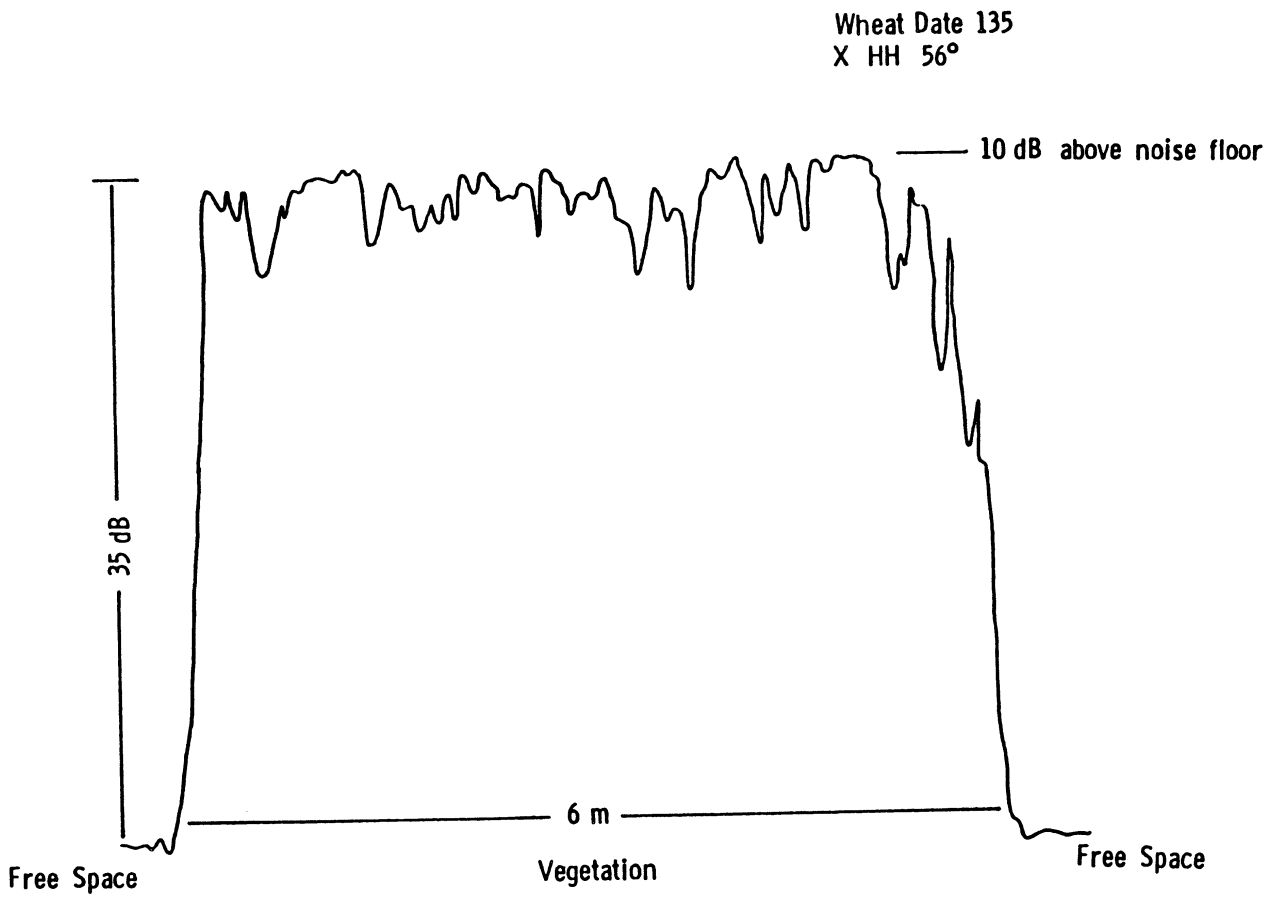


Figure 50. Attenuation recording of wheat at X-band, HH polarization and 56° incidence angle.

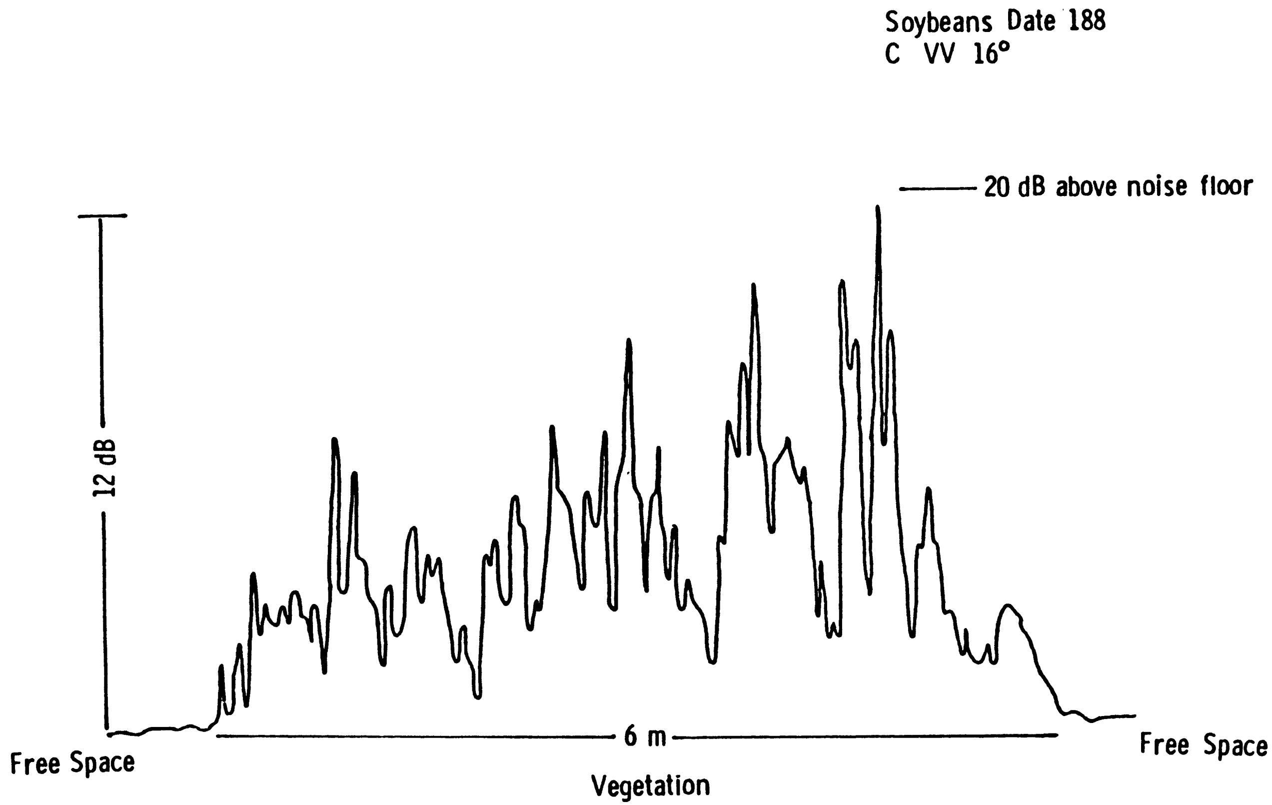


Figure 51. Attenuation recording of soybeans at C-band, VV polarization and 16° incidence angle.

variations in connector loss due to vibration. In addition, error is associated with digitization and determination of the free-space reference line. It is estimated that the accuracy of these measurements is approximately 10%.

The attenuation recordings were digitized at intervals corresponding to approximately 14 cm in length. This interval resulted in approximately 45 samples for the 6-meter canopy-strip length. In many instances, 90 or more samples were obtained by repeating the measurement. The sampling interval was in excess of the Nyquist rate necessary to accurately reproduce the somewhat periodic waveforms. The attenuation data in Appendix B include a mean attenuation value and the limits for the 99% confidence interval about that mean. The confidence interval limits were calculated from

$$k_c = \frac{s\ c}{\sqrt{n}}$$

where $\pm\ k_c$ are the confidence-interval limits, s is the sample standard deviation, and n is the number of samples. c is a constant obtained from the t-distribution, depending upon the confidence level chosen. This procedure is valid for distributions that are normal with unknown variance or for other distributions with unknown variance with a sufficiently large number of samples. In this case the distributions are approximately normal, and even if they were not, the number of samples is large enough to ensure the validity of the procedure.

The 99% confidence-interval limits ranged from ± 0.1 dB, usually at L-band, to ± 2.4 dB for some X-band measurements.

In summary, the experimental procedure used to acquire these attenuation data produced an accuracy and precision comparable to the accuracy and precision found in published backscattering data.

5.2 Angular, Polarization, and Frequency Response of Wheat Data

The wheat measurements were conducted at two widely separated sites on the same privately owned wheat field. Site W1 was used for the frequency, angular, and polarization studies, whereas Site W2 was used for the special decapitation experiment reported in Section 5.4. All wheat attenuation data and associated ground truth are available in Appendix B.

Table 28 provides a summary of wheat attenuation measurements at Site W1 on Dates 135 and 158. The attenuation values are expressed in dB per meter to allow valid comparisons between the two sets of angular data, as well as comparisons between data on dates characterized by different canopy heights. The path length used in these computations is simply the slant-length through the canopy and is tabulated in Appendix B.

Figure 52 is a plot of the attenuation data in dB per meter as measured on Date 135. The values of attenuation at 56° versus those at 24° are noteworthy. The difference is not due to a difference in path length, since the data have been normalized to dB per meter.

TABLE 28. **Summary of Wheat Attenuation Measurements at Site W1**

Frequency (GHz)	Polarization	Angle (°)	One-Way Canopy Loss (dB/m) Date 135	One-Way Canopy Loss (dB/m) Date 158
1.55	VV	24	2.0	1.1
1.55	HH	24	2.5	1.1
4.75	VV	24	2.3	4.7
4.75	HH	24	3.3	3.2
10.20	VV	24	9.4	9.4
10.20	HH	24	7.0	8.1
1.55	VV	56	6.6	3.7
1.55	HH	56	2.1	1.4
4.75	VV	56	24.3	9.4
4.75	HH	56	8.3	3.2
10.20	VV	56	31.9	19.0
10.20	HH	56	28.8	14.1

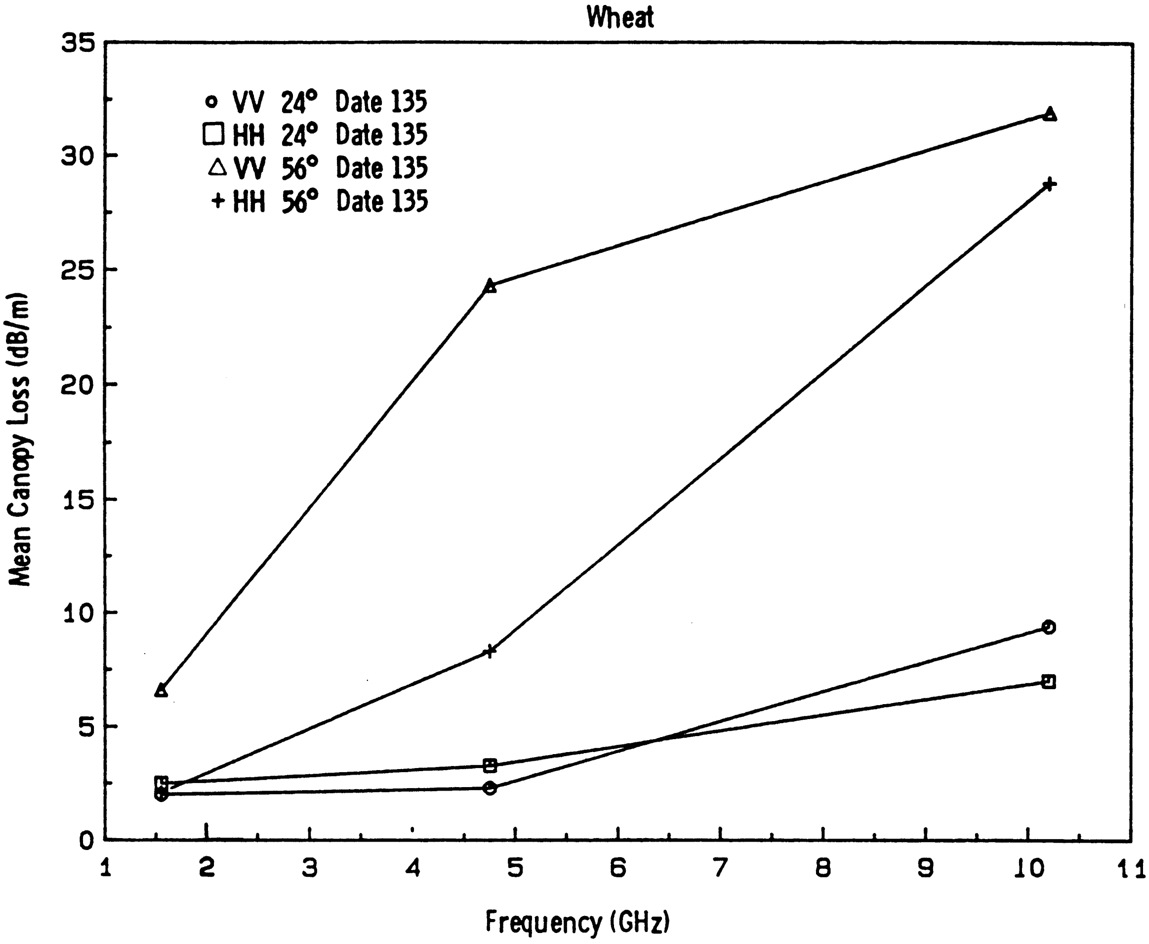


Figure 52. Wheat attenuation measurements on Date 135.

Also noteworthy is the large difference between HH and VV polarization at 56°. The difference is roughly three times at L- and C-band but is almost equal at X-band. Note also that the attenuation remains relatively flat at 24°, especially from L-band to C-band. Figure 53 illustrates identical measurements on Date 158. By Date 158, the wheat plants had dried as compared to Date 135, and the leaf area index was less than one-half of its value on Date 135. The 24° attenuation values were roughly comparable on both dates, but the 56° values on Date 158 were depressed considerably from those on Date 135. Figure 54 compares the 56° data on these two dates.

5.3 Angular, Polarization, and Frequency Response of Soybean Data

The soybean measurements were conducted at a single site on a privately owned field. Site S1 was used for frequency, angular, and polarization studies and was also used for the special defoliation experiment reported in Section 5.4. All soybean attenuation data and associated ground truth are available in Appendix B.

Table 29 provides a summary of soybean attenuation measurements at Site S1 on Date 181 and Date 188. As with wheat, the attenuation values are expressed in dB per meter. The path length used in the computations is available in Appendix B.

Figure 55 is a plot of the soybean attenuation data on Date 181, while Figure 56 plots identical measurements on Date 188. Both plots present attenuation data in dB per meter. The data taken on Date 181 illustrate increasing attenuation with

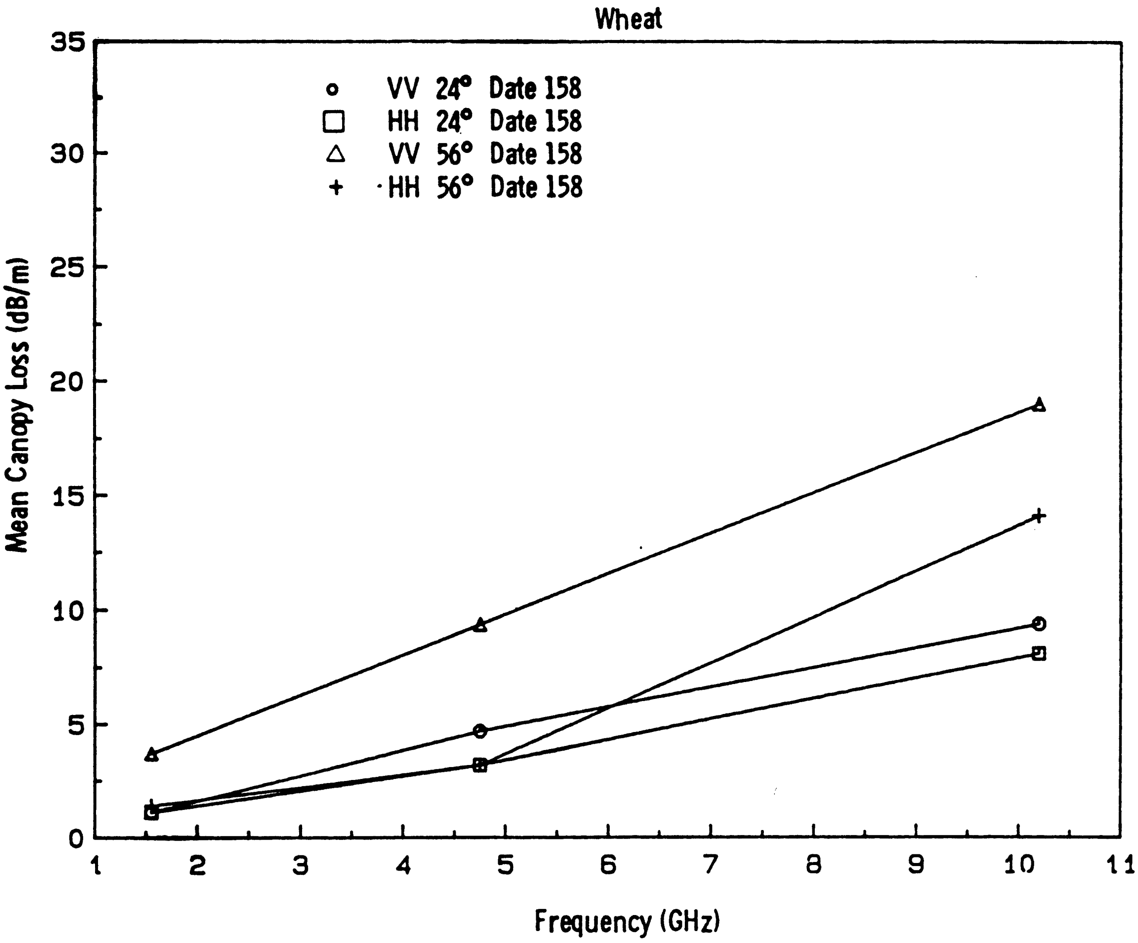


Figure 53. Wheat attenuation measurements on Date 158.

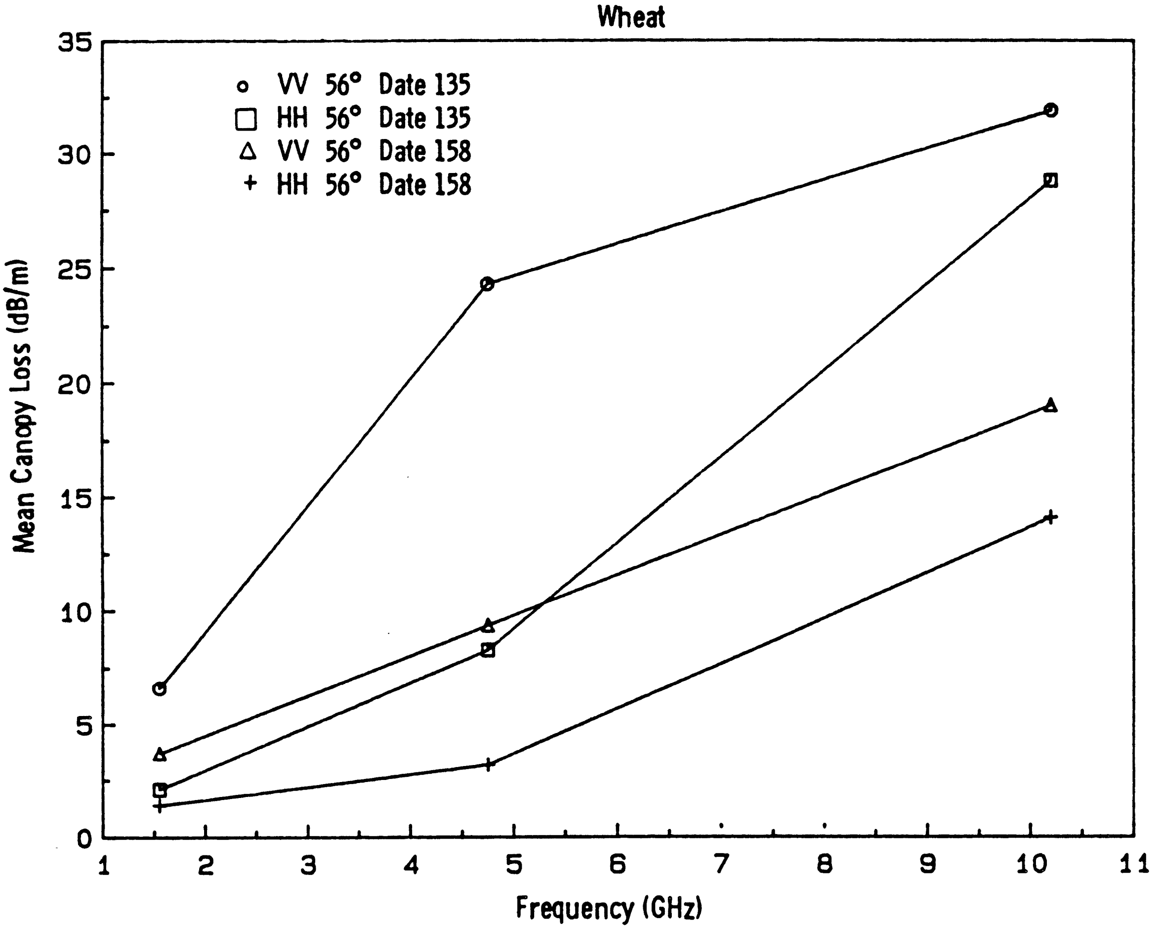


Figure 54. A comparison of wheat attenuation on Dates 135 and 158 at 56° incidence angle.

TABLE 29. Summary of Soybean Attenuation Measurements at Site S1

Frequency (GHz)	Polarization	Angle (°)	One-Way Canopy Loss (dB/m)	
			Date 181	Date 188
1.55	VV	16	3.3	4.8
1.55	HH	16	1.1	1.5
4.75	VV	16	5.8	7.0
4.75	HH	16	4.4	6.7
10.20	VV	16	9.6	14.4
10.20	HH	16	10.2	20.2
1.55	VV	52	2.7	3.3
1.55	HH	52	0.7	0.9
4.75	VV	52	14.3	12.7
4.75	HH	52	5.7	4.0
10.20	VV	52	19.7	16.0
10.20	HH	52	13.3	15.5

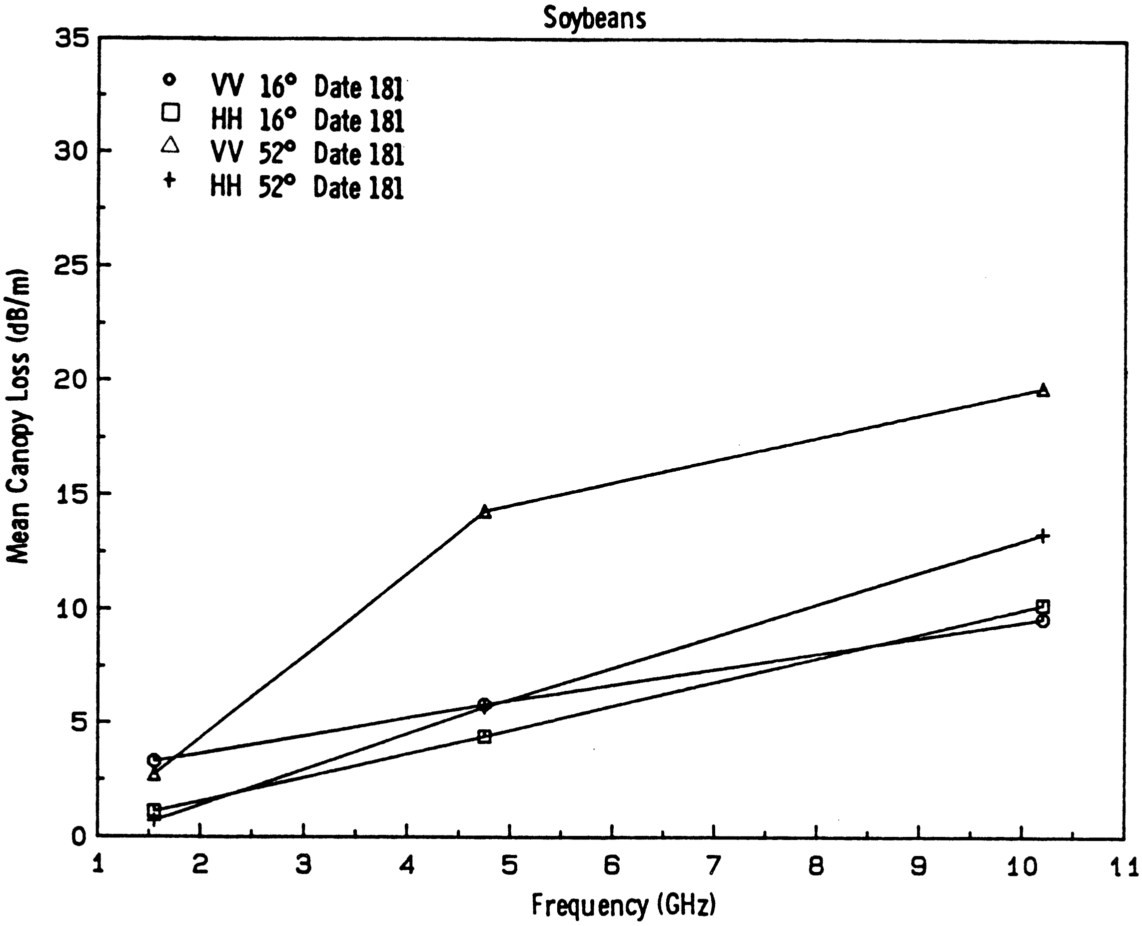


Figure 55. Soybean attenuation measurements on Date 181.

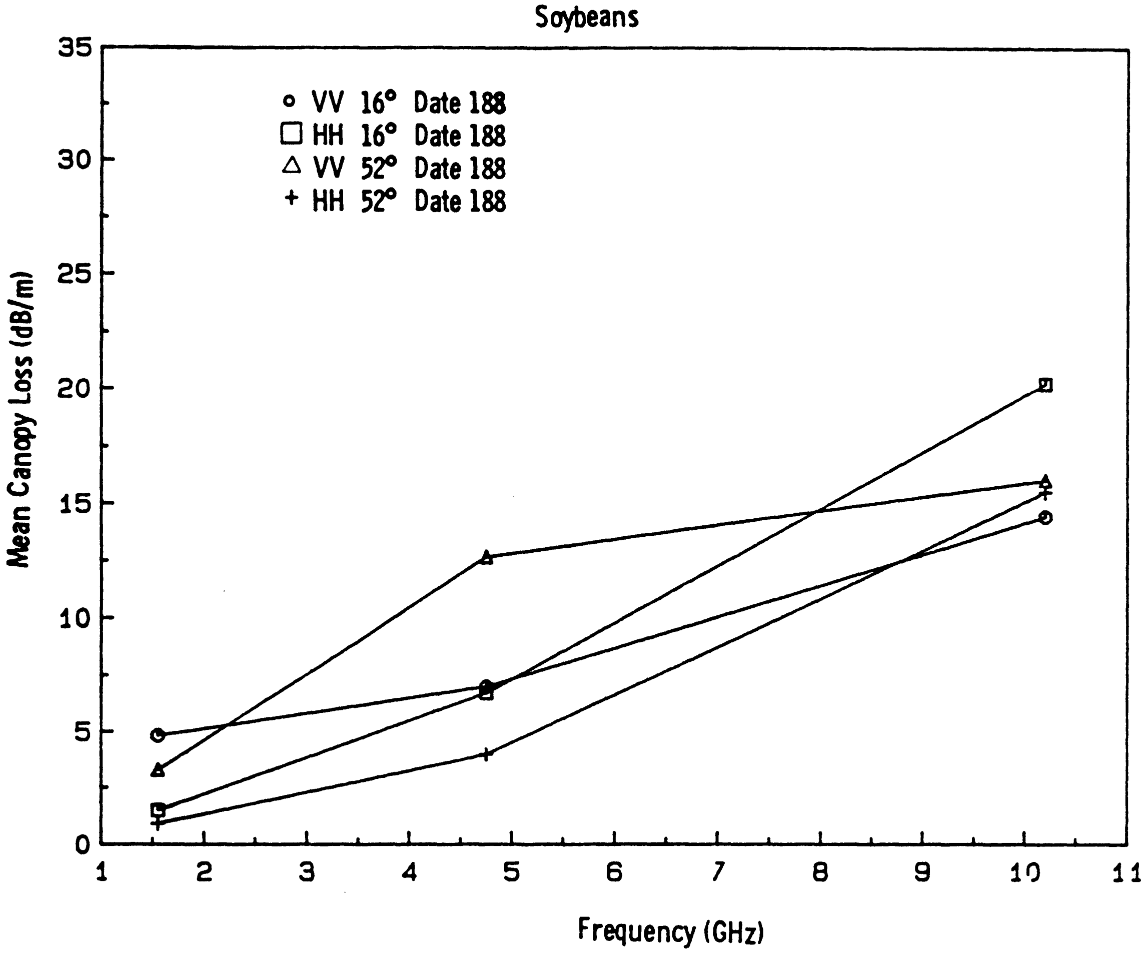


Figure 56. Soybean attenuation measurements on Date 188.

frequency and minimal angular difference between 16° and 52°, except for VV data at C-band and X-band. Note again that the difference in path length is not reflected in these plots, since they are in dB per meter. The data illustrated in Figure 56 are generally similar to those in Figure 55, except for X-band, HH, 16°, which is nearly twice the value measured approximately one week earlier. This data point should be considered questionable, although no errors were apparent in either the measurement process or the digitization. The ground truth as tabulated in Appendix B is similar for both dates.

5.4 Special Attenuation Experiments

In addition to the primary objective of obtaining data on the frequency, polarization, and angular attenuation characteristics of vegetation, a number of special experiments were conducted at the two test sites. These experiments included cross-polarized attenuation measurements, a wheat decapitation experiment, and a soybean defoliation experiment.

Cross-polarized data were taken on wheat on three dates. On Date 135, VH data were taken at C-band, 56°, at site W1; on Date 150, VH and HV data were taken at C-band, 56°, at site W2; and on Date 158, X-band HV data were taken at 56°, at site W1. In referring to cross-polarized measurements, the first letter refers to the **transmit** polarization, whereas the second refers to **receive** polarization. HV polarization therefore means that a horizontally polarized EM wave was transmitted and was subsequently received with a vertically polarized antenna. The cross-polarized measurements are tabulated in Table 30. The data in Table 30 are presented in dB per meter. The data show the interesting characteristic that cross-polarized attenuation is lower than the attenuation measured for like polarization in all cases. This characteristic is most likely the result of depolarization by the canopy, which partially compensates for the attenuation by the canopy. Although these data are of theoretical interest, it is not apparent that they are of any practical value.

A special wheat-head decapitation experiment was conducted at Site W2. This experiment, conducted at a 56° angle of incidence, consisted of attenuation measurements at each frequency and polarization for a normal strip of wheat and for the same strip with the heads sheared off (to obtain a uniform height, some stalk below the head was also removed). The data for this experiment are tabulated in Table 31. The data indicate that decapitation reduced attenuation in all but the case of L-band, VV (which showed a slight increase). However, the decapitation process reduced the average canopy height from 1.11 m to 0.70 m and the path length from 1.59 m to 0.86 m. Table 31 also gives attenuation expressed in dB per meter. When the attenuation is expressed in this fashion, an increase is observed following decapitation. Although this result may seem puzzling at first, an examination of the wheat canopy reveals that the upper portion (containing the head) is less dense than the lower portion (containing leaves) at this growth stage. The removal of the less dense head portion of the canopy leaves only the lower section, which provides greater attenuation when expressed on a per-

TABLE 30. Summary of Cross-Polarized Measurements of Wheat and Corresponding Like-Polarized Measurements

Frequency (GHz)	Polarization	Angle (°)	One-Way Canopy Loss (dB/m) Date 135	Date 150	Date 158
4.75	VV	56	24.3	11.3	--
4.75	HH	56	8.3	1.9	--
4.75	HV	56	--	0.3	--
4.75	VH	56	4.5	0.8	--
10.20	VV	56	--	--	19.0
10.20	HH	56	--	--	14.1
10.20	HV	56	--	--	10.4

TABLE 31. Wheat Decapitation Experiment Data

FREQUENCY (GHz)	POLARIZATION	NON-DECAPITATED CANOPY LOSS (dB)	DECAPITATED CANOPY LOSS (dB)	NON-DECAPITATED CANOPY LOSS (dB/m)	DECAPITATED CANOPY LOSS (dB/m)
1.55	VV	3.2	3.9	2.0	4.5
1.55	HH	1.3	0.9	0.8	1.1
4.75	VV	17.9	13.1	11.3	15.2
4.75	HH	3.0	2.9	1.9	3.4
10.20	VV	31.2	21.4	19.6	24.9
10.20	HH	14.1	8.4	8.9	9.8

meter basis. It should be noted that this experiment was conducted at a growth stage during which the head was still quite moist (82.2% H_2O) and that different results might have been obtained after the head had dried and hardened.

A special soybean defoliation experiment was conducted at Site S1. This experiment, conducted at a 52° angle of incidence, consisted of a "standard" set of attenuation measurements for the non-defoliated canopy strip and a second set of measurements with all leaves removed from approximately one-half of the length of the canopy strip. Figure 57 is a recording of the partially defoliated strip at X-band, HH polarization. Note the dramatic decrease in attenuation for the defoliated section. Table 32 is a tabulation of the soybean defoliation data. Note that for VV polarization, the removal of the leaves made almost no difference in the attenuation value measured, thus indicating that they are of minor importance. At X-band, VV, however, the leaves do contribute to the attenuation, as the data illustrate. For HH polarization, the leaves appear to be very significant contributors to attenuation at all frequencies but especially at X-band. The results of this experiment can be explained by the predominantly horizontal orientation of the soybean leaves and the predominantly vertical orientation of the primary stem; the secondary stems tend to be oriented approximately randomly. The results of this experiment are significant in that they demonstrate that leaf and stem characteristics may be separated by means of microwave measurements.

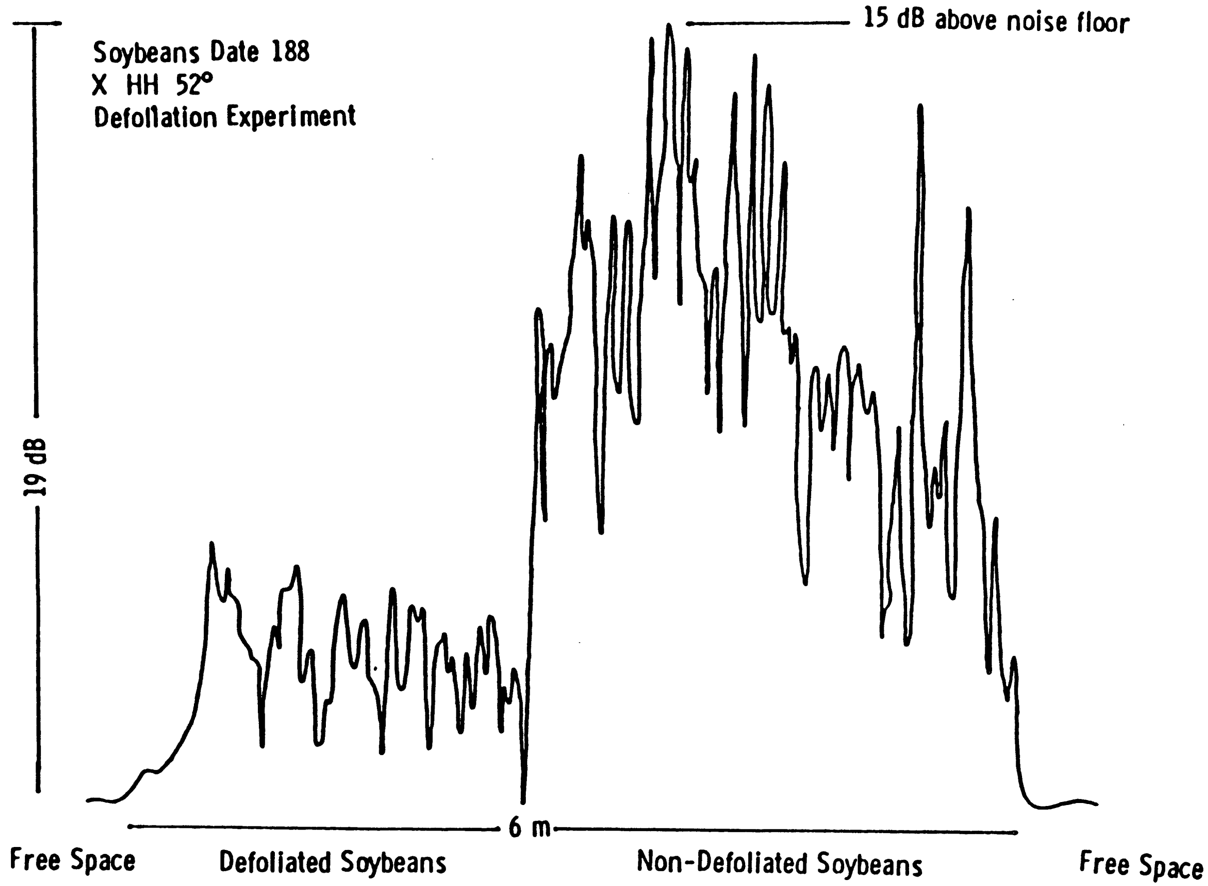


Figure 57. Recording of soybean defoliation experiment at X-band, HH polarization and 52° incidence angle.

TABLE 32. Soybean Defoliation Experiment Data

FREQUENCY (GHz)	POLARIZATION	NON-DEFOLIATED CANOPY LOSS (dB)	DEFOLIATED CANOPY LOSS (dB)	NON-DEFOLIATED CANOPY LOSS (dB/m)	DEFOLIATED CANOPY LOSS (dB/m)
1.55	VV	2.6	2.4	3.3	3.6
1.55	HH	0.7	0.4	0.9	0.6
4.75	VV	9.9	8.8	12.7	13.1
4.75	HH	3.1	1.7	4.0	2.5
10.20	VV	12.5	8.3	16.0	12.4
10.20	HH	12.1	3.7	15.5	5.5

6.0 ATTENUATION MODELING

The attenuation measurements presented in the previous section help to fill a void in experimental data. These measurements will assist those involved in modeling the backscattering response in order to develop and validate both semi-empirical and theoretical models. These measurements can also contribute to the understanding of the nature of microwave propagation through a vegetation canopy. The most effective means of gaining this understanding is to postulate mathematical models and to check their output against measured attenuation data. Reasonable agreement between observed and predicted data is a good indication that a model describes the physical process adequately.

The results presented in this section will be rough approximations only, not simply because of experimental error, or because of the possible inapplicability of the models but because there is a lack of dielectric data on the two crops studied. Dielectric data on other vegetation have, however, been greatly expanded recently (Ulaby, 1984c) and useful estimates of the dielectric properties of wheat and soybeans may be derived from these measurements.

6.1 Dielectric Properties of Vegetation

A vegetation canopy is a dielectric mixture consisting of discrete dielectric inclusions such as leaves, stalks, fruit, etc., distributed in a host material such as air. Since the dielectric inclusions are often comparable to a wavelength in the microwave portion of the spectrum, the canopy is an inhomogeneous anisotropic medium. Propagation through such a medium is subject to absorption and scattering loss.

Absorption, often described by the volume absorption coefficient κ_a, and scattering, usually described by the volume scattering coefficient κ_s, are functions of polarization, incidence angle, dielectric constant, volume fraction, and canopy geometry.

The dielectric constant of a vegetation canopy cannot be measured directly; therefore, the usual approach to the estimation of its dielectric properties involves dielectric mixing models (Ulaby, 1984a). All of the dielectric mixing models assume dielectric inclusions much smaller than a wavelength in a host medium. Since this condition is often violated at microwave frequencies, the result is only an approximation. Many dielectric mixing models assume a geometry (needles, disks, etc.) that may not accurately describe the vegetative inclusions. In addition, mixing models require the volume fraction of the inclusion, which is difficult to estimate accurately. Despite all of these limitations, it is possible to compute a reasonable value for the canopy dielectric constant and to estimate the volume absorption coefficient, κ_a from:

$$\kappa_a \simeq \frac{2 \pi \varepsilon''_c}{\lambda_o \sqrt{\varepsilon'_c}} \simeq \frac{2 \pi \varepsilon''_c}{\lambda_o} .$$

Simple models for calculating the volume scattering coefficient of a vegetation canopy have not been developed, but this is not a serious drawback in this analysis, since at the frequencies of interest loss will primarily be due to absorption.

The dielectric properties of a canopy element such as a leaf or a stalk are governed by the dielectric properties of the dry vegetative material and the properties of the vegetative fluid. The dielectric constant of dry vegetative material differs little from that of air, so the dielectric constant of any vegetative material is dominated by the properties of its fluid. Vegetative fluid has properties similar to water with an equivalent NaCl salinity of approximately 10 $^0/_{00}$ to 15 $^0/_{00}$. The dielectric constant of this fluid, and therefore the dielectric constant of the vegetative part, will be a function of its fluid salinity (especially at the lower frequencies), its temperature, the fraction of "bound" water, and the volume fraction of water in the plant part. The volume fraction of water in a plant (m_v) is related to its gravimetric moisture content (m_w) by the vegetation density ρ_v:

$$m_v = m_w \rho_v .$$

Empirical formulas that may be used to estimate ρ_v have been recently reported (Ulaby, 1984c) as follows:

Corn Stalks:	$\rho_v = 0.75\ m_w + 0.25$
Corn Leaves:	$\rho_v = 0.64\ m_w + 0.17$
Wheat Stalks:	$\rho_v = 0.76\ m_w + 0.20$
Wheat Leaves:	$\rho_v = 0.76\ m_w + 0.20$

The recently available data on the vegetative dielectric constant (Ulaby, 1984c) are presented as plots of the real and imaginary parts of the dielectric constant as a function of the volume fraction of water, m_v. Data are available on wheat heads, leaves, and stalks from 7.6 GHz to 8.4 GHz and on corn leaves and stalks over the following frequency ranges: 1.1 GHz to 1.9 GHz, 3.5 GHz to 6.5 GHz, and 7.6 GHz to 8.4 GHz. All reported measurements were made with a sweep-oscillator waveguide network-analyzer system.

For purposes of this report, the dielectric properties of wheat at the frequencies of interest will be extrapolated from the reported measurements of wheat for X-band and will be estimated from reported measurements of corn for L-band and C-band. For soybeans, dielectric data will be estimated from corn data for all frequencies.

6.2 Vertical Stalk Absorption Loss Model

The model to be used to estimate the absorption loss of vertical stalks of vegetation is the **uniaxial crystal model** developed at the University of Kansas (Ulaby, 1984a). The model applies to a canopy of thin vertical stalks whose diameters are much smaller than the wavelength λ, where $\lambda = \lambda_0/\sqrt{\varepsilon'_v}$ is the wavelength in the stalk material with relative permittivity ε'_{st}. The applicability of this model therefore depends upon stalk diameter, stalk water content, and the signal wavelength λ_0. Although the model will not be strictly applicable at the higher frequencies used in this study, it will be used to provide an estimate of stalk absorption loss.

The uniaxial crystal model assumes a dielectric slab containing thin parallel cylinders oriented along the z-axis. The slab is therefore an anisotropic dielectric medium with

$$\vec{\varepsilon} = \hat{x}\,\varepsilon_x + \hat{y}\,\varepsilon_y + \hat{z}\,\varepsilon_z .$$

Because of azimuthal symmetry, $\varepsilon_x = \varepsilon_y$. The dielectric components ε_x and ε_z can be related to the dielectric constants of the inclusions by dielectric mixing formulas. In addition, since ε_x and ε_y are associated with the propagation of a so-called "ordinary wave," and ε_z is associated with the propagation of an "extraordinary wave" in the dielectric slab, it is convenient to use the notation $\varepsilon_x = \varepsilon_y = \varepsilon_o$, and $\varepsilon_z = \varepsilon_e$. The Polder-Van Santen/de Loor dielectric mixing formula (Ulaby, 1984a) for needles (stalks) oriented along the z-axis in air is an appropriate mixing formula, as follows:

$$\varepsilon^x = \varepsilon^y = \varepsilon_o = 1 + \frac{2\,v_{st}\,(\varepsilon_{st} - 1)}{(\varepsilon_{st} + 1)}$$

$$\varepsilon^z = \varepsilon_e = 1 + v_{st}(\varepsilon_{st} - 1) .$$

The real and imaginary parts of these expressions are

$$\varepsilon_o' = 1 + 2\,v_{st}\left[\frac{(\varepsilon_{st}' - 1)\,(\varepsilon_{st}' + 1) + (\varepsilon_{st}'')^2}{(\varepsilon_{st}' + 1)^2 + (\varepsilon_{st}'')^2}\right]$$

$$\varepsilon''_o = \frac{4\, v_{st}\, \varepsilon''_{st}}{(\varepsilon'_{st} + 1)^2 + (\varepsilon''_{st})^2}$$

$$\varepsilon'_e = 1 + v_{st}(\varepsilon'_{st} - 1)$$

$$\varepsilon''_e = v_{st}\, \varepsilon''_{st} .$$

In these expressions the stalk dielectric constant is $\varepsilon_{st} = \varepsilon'_{st} - j\varepsilon''_{st}$, and v_{st} is the volume fraction of stalks in the canopy. The uniaxial crystal model is normally developed in terms of the complex indices of refraction:

$$n_o = n'_o - j\, n''_o$$

$$n_e = n'_e - j\, n''_e .$$

The model requires:

$$n''_o = |\mathrm{Im}\{\sqrt{\varepsilon_o}\}|$$

$$n''_e = |\mathrm{Im}\{\sqrt{\varepsilon_e}\}| .$$

For a vertically polarized wave propagating in a uniaxial crystal, the index of refraction is

$$n''_v = n''_o \cos^2\theta + n''_e \sin^2\theta.$$

The stalk absorption loss for this vertically polarized wave is

$$L_a^{st}(\theta,v) = \exp(\frac{4\ \pi\ n_v''\ h\ \sec\theta}{\lambda_o})$$

where h is the canopy height and θ is the angle of incidence. For horizontal polarization the stalk absorption loss is

$$L_a^{st}(\theta,h) = \exp(\frac{4\ \pi\ n_o''\ h\ \sec\theta}{\lambda_o}) \ .$$

Expressed in dB, the model becomes

$$L_a^{st}(\theta,v) = \frac{4.343\ (4\pi)\ n_v''\ h\ \sec\theta}{\lambda_o}$$

$$L_a^{st}(\theta,h) = \frac{4.343\ (4\pi)\ n_o''\ h\ \sec\theta}{\lambda_o} \ .$$

6.3 Random-Leaf Absorption Loss Model

A reasonable approximation to use in deriving a leaf absorption loss model is to assume that the leaves are randomly distributed within the canopy and that interactions between leaves can be ignored. Under these conditions, the Polder-Van Santen/deLoor dielectric mixing formula for thin circular disks (leaves) in air may be used to obtain a complex dielectric constant ($\varepsilon_{r\ell}$) of the equivalent isotropic medium

$$\varepsilon_{r\ell} = 1 + \frac{v_\ell}{3}\ (\varepsilon_\ell - 1)\ (2 + \frac{1}{\varepsilon_\ell}) \approx 1 + \frac{2\ v_\ell\ \varepsilon_\ell}{3}$$

$$= 1 + \frac{2\ v_\ell}{3}\ (\varepsilon_\ell' - j\ \varepsilon_\ell'') = \varepsilon_{r\ell}' - j\ \varepsilon_{r\ell}'' \ .$$

The leaf absorption coefficient κ_a is

$$\kappa_a \approx \frac{2\pi\, \varepsilon''_{r\ell}}{\lambda_o} = \frac{2\pi}{\lambda_o}\left(\frac{2\, v_\ell\, \varepsilon''_\ell}{3}\right) = \frac{4\pi\, v_\ell\, \varepsilon''_\ell}{3\, \lambda_o} .$$

The leaf absorption loss is

$$L_a^\ell(\theta) \approx \exp(\kappa_a\, h \sec\theta) = \exp\left(\frac{4\pi\, v_\ell\, \varepsilon''_\ell\, h \sec\theta}{3\, \lambda_o}\right).$$

In terms of leaf area index the expression becomes:

$$L_a^\ell(\theta) \approx \exp\left(\frac{4\pi\, \varepsilon''_\ell\, t_\ell \sec\theta\, LAI}{3\, \lambda_o}\right)$$

where t_ℓ is the mean leaf thickness and LAI is the leaf area index. In dB the expression is

$$L_a^\ell(\theta) = \frac{4.343\, (4\pi)\, \varepsilon''_\ell\, t_\ell \sec\theta\, LAI}{3\, \lambda_o} .$$

6.4 Random Stalk Absorption Loss Model

Some vegetation canopies include primary or secondary stalks that are approximately randomly oriented. The absorption coefficient and absorption loss for such a canopy may be derived in a fashion similar to that for random leaves. The Polder-Van Santen/deLoor mixing formula for random needles (stalks) in air gives the following complex dielectric constant ($\varepsilon_{r\ell}$) of the equivalent isotropic medium

$$\varepsilon_{rs} = 1 + \frac{v_{st}(\varepsilon_{st} - 1)\,(5 + \varepsilon_{st})}{3\,(1 + \varepsilon_{st})} = \varepsilon'_{rs} - j\, \varepsilon''_{rs} .$$

The random stalk absorption coefficient κ_a is

$$\kappa_a \approx \frac{2\pi\ \varepsilon''_{rs}}{\lambda_o} .$$

The random stalk absorption loss is

$$L_a^{rs}(\theta) \approx \exp(\kappa_a\ h\ \sec\theta) = \exp\left(\frac{2\pi\ \varepsilon''_{rs}\ h\ \sec\theta}{\lambda_o}\right).$$

This expression is equivalent to the expression for the absorption loss of random leaves except that in this case a simple expression for ε''_{rs} in terms of ε''_{st} is possible but not as accurate. The expression in dB is

$$L_a^{rs}(\theta) = \frac{4.343\ (2\pi)\ \varepsilon''_{rs}\ h\ \sec\theta}{\lambda_o} .$$

6.5 Wheat Attenuation Model

Wheat will be modeled as vertical stalks having random leaves. It will be assumed that there is no interaction between the stalks and the leaves, so that the attenuation for each may be calculated separately and then summed to obtain the total canopy attenuation. Based upon the wheat-head decapitation experiment reported in Section 5.4, the head will be considered part of the stalk, and the total canopy height will be used in all computations. This approximation is valid for this set of measurements (in which the head is quite moist) but may not be valid for situations in which the head has dried, and loss due to scattering increases. Accurate modeling of the dry wheat head may require the development of a scattering-loss model.

Table 33 summarizes stalk and leaf gravimetric water content (m_w), density (ρ_v), and the volume fraction of water (m_v) for the three dates on which data were available for wheat. A complete set of ground-truth data is available in Appendix B. As discussed in Section 6.1, dielectric data are available as a function of the volume fraction of water m_v and frequency for corn and wheat (Ulaby, 1984c). Table 34 provides a summary of the estimated dielectric constants of wheat stalks and leaves as derived from the published data. The subscripts on the ε's in the table indicate either stalks (st) or leaves (ℓ), and the superscripts indicate microwave band (L, C, or X).

Other ground-truth information necessary to the stalk model includes plant density and stalk diameter. The leaf model requires leaf thickness and leaf area index. Both models require wavelength, angle of incidence, and canopy height. All pertinent data are available in Appendix B.

In Tables 35 to 37, the output of the models is compared to measured data. Attenuation data are presented in dB per meter for both calculated and measured values. The subscripts on the κ's refer to stalks (st), leaves (ℓ), or canopy (c).

The uncertainty (±) associated with each model-calculated attenuation value was determined by assuming that in the worst case, stalk diameter and leaf thickness could only be determined within ± 20% and that density, dielectric constant, and leaf area index could be determined within ± 10%.

TABLE 33. Summary of Wheat Stalk and Leaf Moisture Data

DATE	STALK m_w	STALK ρ_v	STALK m_v	LEAF m_w	LEAF ρ_v	LEAF m_v
135	0.85	0.84	0.71	0.80	0.81	0.65
150	0.67	0.71	0.47	0.55	0.62	0.34
158	0.76	0.78	0.59	0.64	0.69	0.44

TABLE 34. Summary of Estimated Wheat Leaf and Stalk Dielectric Constants

Date	ε_{st}^{L}	ε_{st}^{C}	ε_{st}^{X}	ε_{ℓ}^{L}	ε_{ℓ}^{C}	ε_{ℓ}^{X}
135	34-j4	40-j15	30-j15	42-j15	30-j10	23-j13
150	16-j2	21-j5	18-j9	20-j7	12-j3	9-j4
158	27-j3	30-j10	24-j11	27-j10	17-j5	14-j7

TABLE 35. Predicted Versus Observed Attenuation Data for Wheat on Date 135

FREQUENCY (GHz)	POLARIZATION	ANGLE (°)	MODEL κ_{st}(dB/m)	MODEL κ_{ℓ}(dB/m)	MODEL κ_c(dB/m)	MEASURED κ_c(dB/m)
1.55	VV	24	0.5 ± 0.3	2.7 ± 1.2	3.2 ± 1.5	2.0 ± 0.5
1.55	HH	24	0.0 ± 0.0	2.7 ± 1.2	2.7 ± 1.2	2.5 ± 0.5
4.75	VV	24	5.2 ± 3.4	5.5 ± 2.5	10.7 ± 5.9	2.3 ± 0.7*
4.75	HH	24	0.1 ± 0.1	5.5 ± 2.5	5.6 ± 2.6	3.3 ± 0.5
10.20	VV	24	11.6 ± 7.7	15.3 ± 6.9	26.9 ± 14.6	9.4 ± 2.3*
10.20	HH	24	0.3 ± 0.2	15.3 ± 6.9	15.6 ± 7.1	7.0 ± 2.0
1.55	VV	56	1.9 ± 1.3	2.7 ± 1.2	4.6 ± 2.5	6.6 ± 1.0
1.55	HH	56	0.0 ± 0.0	2.7 ± 1.2	2.7 ± 1.2	2.1 ± 0.5
4.75	VV	56	21.6 ± 14.3	5.5 ± 2.5	27.1 ± 16.8	24.3 ± 2.9
4.75	HH	56	0.1 ± 0.1	5.5 ± 2.5	5.6 ± 2.6	8.3 ± 1.8
10.20	VV	56	47.4 ± 31.3	15.3 ± 6.9	62.7 ± 38.2	31.9 ± 3.8
10.20	HH	56	0.3 ± 0.2	15.3 ± 6.9	15.6 ± 7.1	28.8 ± 3.3*

* Model and measured bands non-overlapping.

TABLE 36. Predicted Versus Observed Attenuation Data for Wheat on Date 150

FREQUENCY (GHz)	POLARIZATION	ANGLE (°)	MODEL κ_{st}(dB/m)	MODEL κ_{ℓ}(dB/m)	MODEL κ_c(dB/m)	MEASURED κ_c(dB/m)
1.55	VV	56	0.6 ± 0.4	0.4 ± 0.2	1.0 ± 0.6	2.0 ± 0.8
1.55	HH	56	0.0 ± 0.0	0.4 ± 0.2	0.4 ± 0.2	0.8 ± 0.4
4.75	VV	56	4.7 ± 3.1	0.5 ± 0.2	5.2 ± 3.3	11.3 ± 1.8*
4.75	HH	56	0.1 ± 0.1	0.5 ± 0.2	0.6 ± 0.3	1.9 ± 0.7*
10.20	VV	56	18.1 ± 12.0	1.5 ± 0.7	19.6 ± 12.7	19.6 ± 3.9
10.20	HH	56	0.2 ± 0.2	1.5 ± 0.7	1.7 ± 0.9	8.9 ± 3.1*

* Model and measured bands non-overlapping.

TABLE 37. Predicted Versus Observed Attenuation Data for Wheat on Date 158

FREQUENCY (GHz)	POLARIZATION	ANGLE (°)	MODEL κ_{st}(dB/m)	MODEL κ_{ℓ}(dB/m)	MODEL κ_c(dB/m)	MEASURED κ_c(dB/m)
1.55	VV	24	0.4 ± 0.3	0.5 ± 0.2	0.9 ± 0.5	1.1 ± 0.2
1.55	HH	24	0.0 ± 0.0	0.5 ± 0.2	0.5 ± 0.2	1.1 ± 0.3*
4.75	VV	24	3.6 ± 2.4	0.8 ± 0.4	4.4 ± 2.8	4.7 ± 1.1
4.75	HH	24	0.1 ± 0.1	0.8 ± 0.4	0.9 ± 0.5	3.2 ± 0.7*
10.20	VV	24	8.7 ± 5.7	2.5 ± 1.1	11.2 ± 6.8	9.4 ± 2.6
10.20	HH	24	0.3 ± 0.2	2.5 ± 1.1	2.8 ± 1.3	8.1 ± 1.9*
1.55	VV	56	1.5 ± 1.0	0.5 ± 0.2	2.0 ± 1.2	3.7 ± 1.0
1.55	HH	56	0.0 ± 0.0	0.5 ± 0.2	0.5 ± 0.2	1.4 ± 0.7
4.75	VV	56	14.7 ± 9.7	0.8 ± 0.4	15.5 ± 10.1	9.4 ± 1.2
4.75	HH	56	0.1 ± 0.1	0.8 ± 0.4	0.9 ± 0.5	3.2 ± 0.9
10.20	VV	56	35.4 ± 23.4	2.5 ± 1.1	37.9 ± 24.5	19.0 ± 2.9
10.20	HH	56	0.3 ± 0.2	2.5 ± 1.1	2.8 ± 1.3	14.1 ± 2.7*

*Model and measured bands non-overlapping.

The worst-case uncertainty associated with the measured value includes the ± 10% estimated accuracy error plus the precision estimate.

An examination of the data reveals overlapping between the observed and predicted values, in most instances. For the cases in which values do not overlap, sources of error not included in the uncertainty calculations may be responsible. These potential errors include the canopy-height measurement and the condition that the inclusions in the mixing models must be small compared to a wavelength (which was violated).

6.6 Soybean Attenuation Model

The soybean canopy will be modeled as vertical stalks representing the primary stems, random stalks representing the secondary stems, and random leaves. As with wheat, it will be assumed that there is no interaction between parts, so that attenuation values first may be calculated separately and then summed to obtain the total canopy attenuation.

Table 38 summarizes the primary-stem gravimetric water content (m_w), density (ρ_v), and volume fraction of water (m_v). Tables 39 and 40 provide identical information for the secondary stems and leaves. The density values were computed from the empirical relationship developed for corn given in Section 6.1, since an equivalent relationship for soybeans is not available. A complete set of ground-truth data is available in

TABLE 38. Summary of Soybean Primary-Stem Moisture Data

Date	Primary-Stem m_w	Primary-Stem ρ_v	Primary-Stem m_v
181	0.88	0.91	0.80
188	0.79	0.84	0.66

TABLE 39. Summary of Soybean Secondary-Stem Moisture Data

Date	Secondary-Stem m_w	Secondary-Stem ρ_v	Secondary-Stem m_v
181	0.91	0.93	0.85
188	0.82	0.87	0.71

TABLE 40. Summary of Soybean Leaf-Moisture Data

Date	Leaf m_w	Leaf ρ_v	Leaf m_v
181	0.78	0.67	0.52
188	0.72	0.63	0.45

Appendix B. The estimated dielectric constants tabulated in Tables 41, 42, and 43 were derived from the published data for corn. The subscripts on the ε's in the table headings indicate primary stem (pst), secondary stem (sst) or leaves (ℓ); the superscript indicates the microwave band (L, C, X).

Additional ground truth necessary for the primary stem model includes plant density, stem length and stem diameter. The secondary stem model requires plant density, stem diameter, mean number of stems per plant, and mean stem length. The leaf model requires leaf thickness and leaf area index. All models require wavelength, canopy height and angle of incidence. All necessary data is available in Appendix B.

The output of the models is compared to measured data in Tables 44 and 45. Attenuation data is presented in dB per meter for both calculated and measured values. The subscripts on the κ's refer to primary stems (pst), secondary stems (sst), leaves (ℓ) and canopy (c).

The uncertainty ($\pm$) associated with each model calculated attenuation value was determined by assuming that in the worst case the primary and secondary stem diameters and the leaf thickness could only be determined within $\pm$ 20% and that the density, dielectric constant, secondary stem length, and leaf area index could be determined within $\pm$ 10%. As with wheat, the worst-case uncertainty associated with the measured value includes both the $\pm$ 10% estimated accuracy error plus the precision estimate.

TABLE 41. Summary of Estimated Soybean Primary-Stem Dielectric Constants

Date	ε_{pst}^{L}	ε_{pst}^{C}	ε_{pst}^{X}
181	42-j6	48-j21	46-j23
188	31-j3	38-j14	30-j15

TABLE 42. Summary of Estimated Soybean Secondary-Stem Dielectric Constants

Date	ε_{sst}^{L}	ε_{sst}^{C}	ε_{sst}^{X}
181	45-j7	51-j24	50-j25
188	35-j4	40-j15	35-j18

TABLE 43. Summary of Estimated Soybean-Leaf Dielectric Constants

Date	ε_{ℓ}^{L}	ε_{ℓ}^{C}	ε_{ℓ}^{X}
181	32-j12	22-j7	20-j9

TABLE 44. Predicted Versus Observed Attenuation Data for Soybeans on Date 181

FREQUENCY (GHz)	POLARIZATION	ANGLE (°)	MODEL κ_{pst}(dB/m)	MODEL κ_{sst}(dB/m)	MODEL κ_{ℓ}(dB/m)	MODEL κ_c(dB/m)	MEASURED κ_c(dB/m)
1.55	VV	16	0.1 ± 0.1	0.2 ± 0.2	3.2 ± 1.4	3.5 ± 1.7	3.3 ± 0.4
1.55	HH	16	0.0 ± 0.0	0.2 ± 0.2	3.2 ± 1.4	3.4 ± 1.6	1.1 ± 0.2*
4.75	VV	16	1.0 ± 0.7	2.1 ± 1.9	5.6 ± 2.5	8.7 ± 5.1	5.8 ± 1.0
4.75	HH	16	0.0 ± 0.0	2.1 ± 1.9	5.6 ± 2.5	7.7 ± 4.4	4.4 ± 0.7
10.20	VV	16	2.4 ± 1.8	4.7 ± 4.3	15.5 ± 7.0	22.6 ±13.1	9.6 ± 1.6
10.20	HH	16	0.0 ± 0.0	4.7 ± 4.3	15.5 ± 7.0	20.2 ±11.3	10.2 ± 1.6
1.55	VV	52	0.8 ± 0.6	0.2 ± 0.2	3.7 ± 1.7	4.7 ± 2.5	2.7 ± 0.5
1.55	HH	52	0.0 ± 0.0	0.2 ± 0.2	3.7 ± 1.7	3.9 ± 1.9	0.7 ± 0.2*
4.75	VV	52	8.0 ± 5.8	2.3 ± 2.1	6.6 ± 3.0	16.9 ±10.9	14.3 ± 2.2
4.75	HH	52	0.0 ± 0.0	2.3 ± 2.1	6.6 ± 3.0	8.9 ± 5.1	5.7 ± 1.1
10.20	VV	52	19.0 ±13.9	5.2 ± 4.8	18.1 ± 8.2	42.3 ±26.9	19.7 ± 3.6
10.20	HH	52	0.0 ± 0.0	5.2 ± 4.8	18.1 ± 8.2	23.3 ±13.0	13.3 ± 2.2

*Model and measured bands non-overlapping.

TABLE 45. Predicted Versus Observed Attenuation Data for Soybeans on Date 188

FREQUENCY (GHz)	POLARIZATION	ANGLE (°)	MODEL κ_{pst}(dB/m)	MODEL κ_{sst}(dB/m)	MODEL κ_{ℓ}(dB/m)	MODEL κ_c(dB/m)	MEASURED κ_c(dB/m)
1.55	VV	16	0.0 ± 0.0	0.1 ± 0.1	2.0 ± 0.9	2.1 ± 1.0	4.8 ± 0.7*
1.55	HH	16	0.0 ± 0.0	0.1 ± 0.1	2.0 ± 0.9	2.1 ± 1.0	1.5 ± 0.4
4.75	VV	16	0.6 ± 0.4	1.2 ± 1.1	3.7 ± 1.7	5.5 ± 3.2	7.0 ± 1.5
4.75	HH	16	0.0 ± 0.0	1.2 ± 1.1	3.7 ± 1.7	4.9 ± 2.8	6.7 ± 1.1
10.20	VV	16	1.4 ± 1.0	3.1 ± 2.9	9.2 ± 4.1	13.7 ± 8.0	14.4 ± 2.8
10.20	HH	16	0.1 ± 0.1	3.1 ± 2.9	9.2 ± 4.1	12.4 ± 7.1	20.2 ± 3.4
1.55	VV	52	0.3 ± 0.2	0.1 ± 0.1	2.2 ± 1.0	2.6 ± 1.3	3.3 ± 0.6
1.55	HH	52	0.0 ± 0.0	0.1 ± 0.1	2.2 ± 1.0	2.3 ± 1.1	0.9 ± 0.3
4.75	VV	52	4.7 ± 3.4	1.3 ± 1.2	4.0 ± 1.8	10.0 ± 6.4	12.7 ± 2.2
4.75	HH	52	0.0 ± 0.0	1.3 ± 1.2	4.0 ± 1.8	5.3 ± 3.0	4.0 ± 0.7
10.20	VV	52	10.8 ± 7.9	3.3 ± 3.0	9.9 ± 4.5	24.0 ±15.4	16.0 ± 3.2
10.20	HH	52	0.1 ± 0.0	3.3 ± 3.0	9.9 ± 4.5	13.3 ± 7.5	15.5 ± 2.7

*Model and measured bands non-overlapping.

Examination of the data reveals overlapping between the observed and predicted values in all but three instances. The sources of potential error that are not accounted for are the same as those indicated for wheat.

The model output is also relatively consistent with the defoliation experiment, which demonstrated that the primary and secondary stems were much more important in VV polarization than in HH polarization.

7.0 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The two major objectives of this investigation were to develop an improved semi-empirical model for the backscattering from vegetation and to obtain data on the frequency, angular, and polarization responses of attenuation resulting from vegetation canopies. Both of these objectives were accomplished, as were a number of supporting objectives. Although the results may contribute to the body of knowledge in the field of microwave remote sensing and microvave propagation, they also point to the need for additional work in these areas. This section will provide a brief summary of the conclusions that may be drawn from this work and will suggest directions for additional research efforts.

7.1 Conclusions

The 1979 backscattering measurements were significant in that they were the first to include leaf area index as a ground-truth parameter and were the first backscattering measurements made at 35 GHz over an entire growing season. The data acquired, however, were not suitable for detailed modeling efforts. In spite of this drawback, several key conclusions can be drawn from the data. The data demonstrated that dynamic range increases with frequency over the 8 - 35-GHz range, and that dynamic range is greatest for VV polarization. Another conclusion that may be drawn from these data is that VV and HV polarization decorrelate with frequency much faster than HH polarization over the 8 - 35-GHz range. The data also showed that angular decorrelation is minimal from 30° to 70° over the 8 - 18-GHz range. Diurnal experiments on the 1979 data showed that such variations are not important for corn, sorghum, or wheat over the 8 - 35-GHz range. The most important contribution of the 1979 experiment, however, was to provide the experience necessary to design an improved experiment in 1980, which would produce high-quality data suitable for modeling studies.

Analysis of the 1980 data revealed relationships between key plant parameters over a growing season. Especially important was the fact that many of these parameters are highly correlated with each other. The study also demonstrated that leaf area index was the best single parameter to use in modeling studies (at 17 GHz).

The semi-empirical model developed in this study provides a direct link to more complex theoretical models, but it is relatively simple mathematically and utilizes commonly measured ground-truth parameters. The model also provides an estimate of the loss due to leaf and stalk absorption and leaf scattering.

Because of the high correlation between plant parameters, it was shown that alternate models could also provide good fits to the data. It was demonstrated, however, that a good fit is not the only criterion to be met in judging the performance of a model; equally important is the prediction of a realistic value for canopy attenuation.

Data on canopy attenuation as a function of frequency, incidence angle, and polarization have been the missing link in modeling studies. The 1984 attenuation experiment was a first step toward forging that link. The data acquired on wheat and soybean attenuation will not only provide those who have an interest in modeling with a check on the validity of their models, they will also contribute greatly to the understanding of microwave propagation through a vegetation canopy. The attenuation models proposed in this study provided outputs that were in reasonable agreement with measured values, which is an indication that a basic understanding of the processes involved is achievable.

7.2 Recommendations for Future Work

As indicated previously, there is a continuing need for additional ground-based studies to complement the data acquired by satellite systems.

In the area of the modeling of backscattering, the proposed model, as well as alternative models, need to be tested on a wide variety of crops, and the data acquired must be of a quality comparable to the 1980 data utilized in this study. Work should also continue on improving the performance of semi-empirical models. One possible means of improvement would be to utilize ground-truth data taken both by layer and by part in both the proposed model and the alternate models.

Simultaneously with the acquisition of backscattering data for the modeling studies, attenuation data should be acquired on the same fields as a function of frequency, angle, and polarization. These data would provide direct validation for the backscattering models developed and would enlarge the available attenuation data base, which would lead in turn to increased understanding. Also, to aid in our understanding of the propagation of microwaves through vegetation, additional data are needed on the dielectric properties of vegetative parts. Dielectric mixing models that are fully applicable to vegetative parts at microwave frequencies would also be useful. Work should also continue on the development of improved attenuation models, since the ones utilized in this investigation are only marginally applicable at the frequencies of interest.

In summary, much work remains to be done. Satellite-based sensors will provide additional data, which will in turn suggest more detailed ground studies.

REFERENCES

Allen, C. T. (1984), "Modeling the Temporal Behavior of the Microwave Backscattering Coefficient of Agricultural Crops," Ph.D. Dissertation, University of Kansas, Lawrence, Kansas, May.

Attema, E. P. W., and F. T. Ulaby (1978), "Vegetation Modeled as a Water Cloud," Radio Science, Vol. 13, pp. 357-364.

Bashavinov, A. E., E. N. Zotova, and M. I. Naumov (1976), "Microwave Experimental Investigation of the Vegetation Cover Scattering Properties," presented at XXVII Congress, International Astronautical Federation, Anaheim, CA, October.

Brakke, T. W., E. T. Kanemasu, J. L. Steiner, F. T. Ulaby, and E. Wilson (1981), "Microwave Radar Response to Canopy Moisture, Leaf Area Index, and Dry Weight of Wheat, Corn and Sorghum," Remote Sensing of Environment, Vol. 11, pp. 207-220.

Brisco, B. and R. Protz (1978), "Evaluation of High Resolution Side-Looking Airborne Radar on the University of Guelph Test Strip," presented to the 5th Canadian Symposium on Remote Sensing, Victoria, British Columbia, August.

Brisco, B., and R. Protz (1979), "Analysis of the Characteristics of Soil-Plant Systems which Affect the Backscattering Coefficient of Synthetic Aperture Radar Systems," Technical Memo 79-02, Department of Land Resource Science, University of Guelph, Ontario, April.

Brisco, B., and R. Protz (1980), "Corn Field Identification Accuracy Using Airborne Radar Imagery," Can. J. Rem. Sens., Vol. 6, pp. 14-25.

Brun, L. J., E. T. Kanemasu, and W. L. Powers (1972), "Evapotranspiration from Soybean and Sorghum Fields," Agronomy Journal, Vol. 64.

Bush, T. F., and F. T. Ulaby (1975a), "Radar Return from a Continuous Vegetation Canopy," Remote Sensing Laboratory Technical Report 177-56, University of Kansas Center for Research, Inc., Lawrence, Kansas, August.

Bush, T. F., and F. T. Ulaby (1975b), "On the Feasibility of Monitoring Croplands with Radar," Proceedings of the Tenth International Symposium on Remote Sensing of the Environment, Ann Arbor, Michigan, October.

Bush, T. F., and F. T. Ulaby (1975c), "Remotely Sensing Wheat Maturation with Radar," Remote Sensing Laboratory Technical Report 177-55, University of Kansas Center for Research, Inc., Lawrence, Kansas, May.

Bush, T. F., F. T. Ulaby, and T. Metzler (1975d), "Radar Backscatter Properties of Milo and Soybeans," Remote Sensing Laboratory Technical Report 177-59, University of Kansas Center for Research, Inc., Lawrence, Kansas, October.

Bush, T. F., and F. T. Ulaby (1976a), "Cropland Inventories Using an Orbital Imaging Radar," Remote Sensing Laboratory Technical Report 330-4, University of Kansas Center for Research, Inc., Lawrence, Kansas, June.

Bush, T. F., and F. T. Ulaby (1976b), "Variability in the Measurement of Radar Backscatter," IEEE Transactions on Antennas and Propagation, Letters, Vol. AP-24, No. 6, pp. 896-899, November.

Calla, O. P. N., N. S Pillai, O. P. Kaushik, and S. Sivaprasad (1979), "Temporal Study on Paddy (rice) Using X-Band Scatterometer, Proceedings of the Sixteenth International Symposium on Remote Sensing of the Environment, Ann Arbor, Michigan, April.

Carlson, N. L. (1967), "Dielectric Constant of Vegetation at 8.5 GHz," TR 1903-5, Electroscience Laboratory, Ohio State University, Columbus, Ohio.

Cosgriff, R. L., W. H. Peake, and R. C. Taylor (1960), "Terrain Scattering Properties for Sensor System Design" (Terrain Handbook II), Volume XXIX, No. 3, Engineering Experiment Station, Ohio State University, Columbus, Ohio, May.

de Loor, G. P., A. A. Jorriëns, and H. Gravesteijn (1974), "The Radar Backscatter from Selected Agricultural Crops," IEEE Transactions on Geoscience Electronics, April.

de Loor, G. P., P. Hoogeboom, and E. P. W. Attema (1982), "The Dutch ROVE Program," IEEE Transactions on Geoscience and Remote Sensing, January.

de Loor, G. P. (1983), "The Dielectric Properties of Wet Materials," IEEE Transactions on Geoscience and Remote Sensing, July.

Dixon, W. J., and M. B. Brown (1979), BMDP-79: Biomedical Computer Programs, P-Series, University of California Press, Berkeley, California.

Eger, G. W. III, F. T. Ulaby, and E. T. Kanemasu (1982), "A Three-Part Geometric Model to Predict the Radar Backscatter from Wheat, Corn, and Sorghum," Remote Sensing Laboratory Technical Report 360-18, University of Kansas Center for Research, Inc., Lawrence, Kansas, April.

Evans, L. T. (1975), Crop Physiology, Cambridge University Press.

Eyton, R. J., R. Li, and F. T. Ulaby (1979), "Combined Radar and Landsat Multitemporal Crop Classification," Remote Sensing Laboratory Technical Report 360-10, University of Kansas Center for Research, Inc., Lawrence, Kansas, February.

Fung, A. K., and H. S. Fung (1977), "Application of First-Order Renormalization Method to Scattering from a Vegetation-Like Half-Space," IEEE Transactions on Geoscience Electronics, GE-15, pp. 189-195, October.

Fung, A. K. (1979), "Scattering from a Vegetation Layer," IEEE Transactions on Geoscience Electronics, January.

Graf, G. (1978), "High Resolution Imaging of Radar Targets with Microwaves," Proceedings of the Military Microwave Conference, London, England, October.

Hodges, T. and E. T. Kanemasu (1977), "Modeling Daily Dry Matter Production of Winter Wheat," Agronomy Journal, Vol. 69.

Hoekman, D. H., L. Krul, and E. P. W. Attema (1982), "A Multilayer Model for Radar Backscattering from Vegetation Canopies," Digest of the 2nd IEEE Intl. Geoscience and Remote Sensing Symp., Munich, West Germany, 1-4 June.

Huet, M. (1983), "Evolution des parametres de structure et de biomass d'un couvert de ble. Utilisation des techniques de teledetection micro-ondes," Ph.D. dissertation, Universite Paul Sabatier de Toulouse, France, October.

Kanemasu, E. T. (1974), "Seasonal Canopy Reflectance Patterns of Wheat, Sorghum, and Soybeans," Remote Sensing of Environment, Vol. 3.

Kanemasu, E. T., L. R. Stone, and W. L. Powers (1976), "Evapotranspiration Model Tested for Soybeans and Sorghum," Agronomy Journal, Vol. 68.

Kanemasu, E. T. (1977), "An Evaluation of an Evapotranspiration Model for Corn," Agronomy Journal, Vol. 69.

LeToan, T. (1982), "Active Microwave Signature of Soil and Crops," Digest, 2nd Annual International Geoscience and Remote Sensing Symposium, Munich, West Germany, June.

Li, R. Y., F. T. Ulaby, and J. R. Eyton (1980), "Crop Classification with a Landsat/Radar Sensor Combination," presented at the Sixth Purdue Symposium on Machine Processing of Remotely Sensed Data, Purdue University, West Layfayette, Indiana, June.

Lopes, A. (1983), "Etude experimentale et theorique de l'attentuation et de la retrodiffusion des micro-ondes par un couvert de ble. Application a la teledetection," Ph.D. Dissertation, Universite Paul Sabatier de Toulouse, France, October.

Lopez, J. M. (1979), "RAMES: A Ground-Based Radar for Microwave Remote Sensing Experiment," Proceedings of the EARSeL, Workshop Report: Microwave Remote Sensing on Bare Soil, Paris, France, April.

Mo, T., T. J. Schmugge, and T. J. Jackson (1984), "Calculations of Radar Backscattering Coefficient of Vegetation-Covered Soils," Remote Sensing of Environment, Vol. 15, pp. 119-133.

Moe, R. D. (1974), "Spectral Characteristics of Cultivated Crops at Microwave Frequencies," Ph.D. Dissertation, University of Kansas, Lawrence, Kansas, April.

Paris, J. (1984), "Effects of Vegetation Canopy Structure on Microwave Scattering," NASA Technical Memorandum 86078, NASA Goddard Space Flight Center, Greenbelt, Maryland, March.

Peake, W. H. (1959), "Interaction of Electromagnetic Waves with Some Natural Surfaces," IRE Transactions on Antennas and Propagation, Vol. AP-7.

Peake, W. H., and T. L. Oliver (1971), "The Response of Terrestrial Surfaces at Microwave Frequencies," OSURF Report Number 2440-7, Electroscience Laboratory, Ohio State University, Columbus, Ohio, May.

Schlude, F. (1978), "Analysis of Remote Sensing Payload for the Spacelab D3 Mission," European Space Agency TT-482.

Shutko, A. M., and A. A. Chukhlantsev (1981), "Microwave Radiation Peculiarities of Vegetative Covers," presented at URSI Meeting, University of Kansas, Lawrence, Kansas, January.

Sieber, A. J. (1979), "Signatures of Vegetation and Bare Soil in a High-Resolution Radar Measurement Mode (8-18 GHz)," Proceedings of the Symposium of Measurement Physics, DFVLR, Oberpfaffenhoffen, West Germany, December.

Sieber, A. J., and J. W. Trevett (1983), "Comparison of Multifrequency Band Radars for Crop Classification," IEEE Transactions on Geoscience and Remote Sensing, GE-21, pp. 285-294, July.

Stiles, W. H., D. Brunfeldt, and F. T. Ulaby (1979), "Performance Analysis of the MAS (Microwave Active Spectrometer) Systems: Calibration, Precision and Accuracy," Remote Sensing Laboratory Technical Report 360-4, University of Kansas Center for Research, Inc., Lawrence, Kansas, April.

Story, A. G. (1968), "Scattering of Centimeter-Wavelength

Electromagnetic Energy by Standing Grain," Ph.D. Dissertation, Ohio State University, Columbus, Ohio.

Story, A. G., W. H. Johnson, and R. E. Stewart (1970), "Remote Measurement of Concentration and Height of Heads of Standing Grain with Microwave Energy," Transactions of the ASAE, Vol. 13, No. 1, pp. 28-32.

Ulaby, F. T., (1975a), "Radar Response to Vegetation," IEEE Transactions on Antennas and Propagation, Vol. AP-23, No. 1, pp. 36-45, January.

Ulaby, F. T., T. F. Bush, and P. P. Batlivala (1975b), "Radar Response to Vegetation II: 8-18 GHz Band," IEEE Transactions on Antennas and Propagation, Vol. AP-23, No. 5, pp. 608-618, September.

Ulaby, F. T., and T. F. Bush (1975c), "Corn Growth as Monitored by Radar," Remote Sensing Laboratory Technical Report 177-57, University of Kansas Center for Research, Inc., November.

Ulaby, F. T., and T. F. Bush (1976), "Monitoring Wheat Growth with Radar," Photogrammetric Engineering and Remote Sensing, Vol. 42, No. 4, pp. 557-568, April.

Ulaby, F. T., and G. Burns (1979a), "Statistical Properties of the Radar Scattering Coefficient of Agricultural Crops," Remote Sensing Laboratory Technical Report 360-2, University of Kansas Center for Research, Inc., Lawrence, Kansas, July.

Ulaby, F. T., and J. E. Bare (1979b), "Look-Direction Modulation Function of the Radar Backscattering Coefficient of Agricultural Fields," Photogrammetric Engineering and Remote Sensing, Vol. 45, pp. 1495-1506, November.

Ulaby, F. T., W. H. Stiles, D. R. Brunfeldt, and M. E. Lubben (1979c), "MAS 8-18/35 Scatterometer," Remote Sensing Laboratory Technical Report 360-5, University of Kansas Center for Research, Inc., Lawrence, Kansas, February.

Ulaby, F. T., R. K. Moore, and A. K. Fung (1981), Microwave Remote Sensing Active and Passive, Volume I, Addison-Wesley Publishing Company, Reading, Massachusetts.

Ulaby, F. T., R. K. Moore, and A. K. Fung (1982), Microwave Remote Sensing Active and Passive, Volume II, Addison-Wesley Publishing Company, Reading, Massachusetts.

Ulaby, F. T., C. T. Allen, G. W. Eger, and E. T. Kanemasu (1983), "Relating the Radar Backscattering Coefficient to Leaf-Area Index," Remote Sensing Laboratory Technical Report 360-20, University of Kansas Center for Research, Inc., Lawrence, Kansas, April.

Ulaby, F. T., R. K. Moore, and A. K. Fung (1984a) Microwave Remote Sensing Active and Passive, Volume III, Benjamin-Cummings Publishing Company, Menlo Park, California (forthcoming).

Ulaby, F. T., C. T. Allen, and G. Eger III (1984b), "Relating the Microwave Backscattering Coefficient to Leaf Area Index," Remote Sensing of Environment, Vol. 14, pp. 113-133.

Ulaby, F. T., and R. P. Jedlicka (1984c), "Microwave Dielectric Properties of Plant Materials," IEEE Transactions on Geoscience and Remote Sensing, GE-22, pp. 406-414, July.

Waite, W. P. (1970), "Broad-Spectrum Electromagentic Backscatter," CRES Technical Report 133-17, University of Kansas, Lawrence, Kansas, August.

Wilson, E. A., D. R. Brunfeldt, F. T. Ulaby, and J. C. Holtzman (1980), "Circularly Polarized Measurements of Radar Backscatter from Terrain," U. S. Army Engineer Topographic Laboratories Report ETL-0201, February.

Wilson, E. A. (1984), "1979 Agricultural Experiment Data Documentation," Remote Sensing Laboratory Technical Memorandum 360-2, University of Kansas Center for Research, Inc., Lawrence, Kansas, June.

APPENDIX A

Model A Predicted and Observed Backscatter Data and Associated Ground Truth

1980 CORN 8.6 GHz VV C1
Model A

r = 0.87 rms error = 0.66 dB A = 0.09 B = 0.83 C = 1.05 D = 0.09

DATE	σ_o^o(dB)	σ_p^o(dB)	LAI	MPHLEAF	MSVOL	MPHSTALK	N
168	- 9.94	- 9.58	0.97	0.18	0.04	0.24	6
170	- 9.07	- 9.52	1.17	0.24	0.03	0.33	6
176	- 8.84	- 8.14	1.77	0.40	0.22	1.03	7
178	- 8.37	- 8.69	1.96	0.44	0.13	1.28	8
182	- 8.68	- 8.94	2.33	0.51	0.07	1.79	11
190	- 7.82	- 8.20	3.41	0.61	0.12	2.58	13
192	- 8.81	- 8.37	3.37	0.62	0.09	2.71	14
196	- 8.37	- 8.61	3.31	0.64	0.04	2.87	15
198	- 8.75	- 8.35	3.30	0.65	0.33	2.91	16
204	- 9.55	- 8.63	3.24	0.65	0.12	2.90	16
206	- 9.96	- 8.69	3.21	0.65	0.08	2.87	16
210	- 9.85	- 8.71	3.09	0.63	0.10	2.76	16
213	- 9.73	- 8.87	2.96	0.62	0.05	2.66	16
221	-10.04	- 9.19	2.41	0.56	0.10	2.34	16
225	-10.28	- 9.52	2.05	0.53	0.10	2.17	16
231	- 9.34	- 9.49	1.46	0.47	0.25	1.92	16
240	-12.50	-12.90	0.56	0.35	0.05	1.56	16
247	-11.41	-10.86	0.06	0.22	0.19	1.31	16

1980 CORN 8.6 GHz VV C2
Model A

r = 0.87 rms error = 0.78 dB A = 0.09 B = 0.83 C = 1.05 D = 0.09

DATE	σ_o^o(dB)	σ_p^o(dB)	LAI	MPHLEAF	MSVOL	MPHSTALK	N
168	-10.36	- 9.73	0.84	0.17	0.05	0.29	6
170	- 8.82	- 9.95	1.00	0.23	0.03	0.36	6
176	- 7.88	- 8.40	1.51	0.38	0.23	1.04	7
178	- 8.01	- 9.12	1.68	0.42	0.12	1.28	8
182	- 8.12	- 9.40	1.99	0.49	0.06	1.72	11
190	- 7.53	- 8.40	3.05	0.57	0.10	2.36	13
192	- 8.27	- 8.57	3.02	0.58	0.06	2.46	14
196	- 7.61	- 8.72	3.01	0.59	0.03	2.57	15
198	- 7.69	- 8.56	2.99	0.60	0.16	2.60	16
204	- 8.20	- 8.74	2.83	0.59	0.14	2.57	16
206	- 9.06	- 8.85	2.75	0.58	0.11	2.54	16
210	- 8.63	- 9.02	2.56	0.56	0.09	2.44	16
213	- 8.15	- 9.23	2.42	0.54	0.05	2.36	16
217	- 8.63	- 9.11	2.29	0.51	0.11	2.24	16
221	- 9.34	- 9.38	2.01	0.48	0.09	2.11	16
225	- 9.67	- 9.80	1.70	0.44	0.08	1.98	16
231	- 9.15	- 9.39	1.18	0.38	0.24	1.80	16
240	-11.90	-13.13	0.44	0.28	0.06	1.56	16
247	-11.10	-10.52	0.03	0.18	0.20	1.40	16

1980 CORN 8.6 GHz VV C3
Model A

r = 0.86 rms error = 0.93 dB A = 0.09 B = 0.83 C = 1.05 D = 0.09

DATE	σ_o^o(dB)	σ_p^o(dB)	LAI	MPHLEAF	MSVOL	MPHSTALK	N
165	-10.30	- 8.61	0.94	0.18	0.11	0.42	5
168	- 9.68	- 9.27	1.35	0.31	0.05	0.44	6
170	- 8.64	- 9.17	1.63	0.39	0.04	0.63	6
171	- 9.05	- 9.17	1.78	0.43	0.04	0.74	6
176	- 8.36	- 8.40	2.49	0.59	0.24	1.40	7
178	- 8.36	- 8.55	2.77	0.64	0.19	1.67	8
182	- 7.98	- 8.62	3.27	0.73	0.11	2.20	11
189	- 7.65	- 7.96	4.46	0.83	0.25	2.88	11
190	- 7.64	- 8.04	4.45	0.84	0.19	2.95	13
192	- 8.67	- 8.16	4.42	0.86	0.14	3.05	14
196	- 8.12	- 8.33	4.36	0.87	0.04	3.17	15
198	- 8.62	- 8.21	4.33	0.88	0.43	3.20	16
204	- 8.34	- 8.32	4.24	0.86	0.23	3.15	16
206	- 9.74	- 8.40	4.14	0.85	0.13	3.10	16
210	- 9.49	- 8.57	3.86	0.82	0.09	2.98	16
213	- 9.61	- 8.74	3.57	0.80	0.10	2.88	16
217	-10.09	- 8.65	3.14	0.75	0.49	2.73	16
220	- 9.74	- 9.13	2.75	0.72	0.27	2.61	16
221	-10.00	- 9.37	2.62	0.71	0.17	2.56	16
225	-10.24	- 9.95	2.06	0.65	0.16	2.40	16
231	- 9.70	-10.24	1.23	0.56	0.33	2.16	16
240	-13.50	-15.32	0.26	0.40	0.06	1.80	16
247	-10.92	-11.08	0.08	0.25	0.21	1.54	16

1980 CORN 13.0 GHz VV C1
Model A

r = 0.93 rms error = 0.45 dB A = 0.14 B = 1.35 C = 1.32 D = 0.03

DATE	σ^o_o(dB)	σ^o_p(dB)	LAI	MPHLEAF	MSVOL	MPHSTALK	N
168	- 8.64	- 8.50	0.97	0.18	0.04	0.24	6
170	- 8.28	- 8.48	1.17	0.24	0.03	0.33	6
176	- 7.33	- 7.65	1.77	0.40	0.22	1.03	7
178	- 7.34	- 7.91	1.96	0.44	0.13	1.28	8
182	- 7.75	- 7.92	2.33	0.51	0.07	1.79	11
190	- 7.01	- 7.12	3.41	0.61	0.12	2.58	13
192	- 7.11	- 7.25	3.37	0.62	0.09	2.71	14
196	- 7.22	- 7.42	3.31	0.64	0.04	2.87	15
198	- 7.38	- 7.36	3.30	0.65	0.33	2.91	16
204	- 8.01	- 7.50	3.24	0.65	0.12	2.90	16
206	- 7.83	- 7.53	3.21	0.65	0.08	2.87	16
210	- 8.05	- 7.58	3.09	0.63	0.10	2.76	16
213	- 8.53	- 7.70	2.96	0.62	0.05	2.66	16
221	- 8.98	- 8.10	2.41	0.56	0.10	2.34	16
225	- 9.19	- 8.45	2.05	0.53	0.10	2.17	16
231	- 8.48	- 8.81	1.46	0.47	0.25	1.92	16
240	-11.61	-11.80	0.56	0.35	0.05	1.56	16
247	-10.73	-10.32	0.06	0.22	0.19	1.31	16

1980 CORN 13.0 GHz VV C2
Model A

r = 0.69 rms error = 0.92 dB A = 0.14 B = 1.35 C = 1.32 D = 0.03

DATE	σ_o^o(dB)	σ_p^o(dB)	LAI	MPHLEAF	MSVOL	MPHSTALK	N
168	- 9.51	- 8.71	0.84	0.17	0.05	0.29	6
170	- 7.54	- 8.90	1.00	0.23	0.03	0.36	6
176	- 6.74	- 7.95	1.51	0.38	0.23	1.04	7
178	- 7.31	- 8.32	1.68	0.42	0.12	1.28	8
182	- 7.04	- 8.35	1.99	0.49	0.06	1.72	11
190	- 6.28	- 7.32	3.05	0.57	0.10	2.36	13
192	- 6.63	- 7.44	3.02	0.58	0.06	2.46	14
196	- 6.71	- 7.53	3.01	0.59	0.03	2.57	15
198	- 7.00	- 7.49	2.99	0.60	0.16	2.60	16
204	- 7.69	- 7.66	2.83	0.59	0.14	2.57	16
206	- 7.73	- 7.74	2.75	0.58	0.11	2.54	16
210	- 7.69	- 7.89	2.56	0.56	0.09	2.44	16
213	- 8.09	- 8.03	2.42	0.54	0.05	2.36	16
217	- 8.53	- 8.00	2.29	0.51	0.11	2.24	16
221	- 8.73	- 8.26	2.01	0.48	0.09	2.11	16
225	- 8.70	- 8.64	1.70	0.44	0.08	1.98	16
231	- 9.00	- 8.67	1.18	0.38	0.24	1.80	16
240	- 9.42	-11.91	0.44	0.28	0.06	1.56	16
247	- 9.75	- 9.65	0.03	0.18	0.20	1.40	16

1980 CORN 13.0 GHz VV C3
Model A

r = 0.92 rms error = 0.69 dB A = 0.14 B = 1.35 C = 1.32 D = 0.03

DATE	σ_o^o(dB)	σ_p^o(dB)	LAI	MPHLEAF	MSVOL	MPHSTALK	N
165	- 9.31	- 7.79	0.94	0.18	0.11	0.42	5
168	- 8.94	- 8.40	1.35	0.31	0.05	0.44	6
170	- 7.95	- 8.34	1.63	0.39	0.04	0.63	6
171	- 8.44	- 8.32	1.78	0.43	0.04	0.74	6
176	- 7.63	- 7.86	2.49	0.59	0.24	1.40	7
178	- 7.84	- 7.85	2.77	0.64	0.19	1.67	8
182	- 7.71	- 7.73	3.27	0.73	0.11	2.20	11
189	- 7.50	- 7.05	4.46	0.83	0.25	2.88	11
190	- 7.28	- 7.10	4.45	0.84	0.19	2.95	13
192	- 7.49	- 7.17	4.42	0.86	0.14	3.05	14
196	- 7.20	- 7.30	4.36	0.87	0.04	3.17	15
198	- 8.43	- 7.30	4.33	0.88	0.43	3.20	16
204	- 8.23	- 7.34	4.24	0.86	0.23	3.15	16
206	- 8.10	- 7.39	4.14	0.85	0.13	3.10	16
210	- 7.86	- 7.54	3.86	0.82	0.09	2.98	16
213	- 8.13	- 7.72	3.57	0.80	0.10	2.88	16
217	- 8.77	- 7.90	3.14	0.75	0.49	2.73	16
220	- 8.52	- 8.26	2.75	0.72	0.27	2.61	16
221	- 8.37	- 8.43	2.62	0.71	0.17	2.56	16
225	- 9.45	- 9.03	2.06	0.65	0.16	2.40	16
231	-10.44	- 9.83	1.23	0.56	0.33	2.16	16
240	-12.70	-14.54	0.26	0.40	0.06	1.80	16
247	-11.02	-10.50	0.08	0.25	0.21	1.54	16

1980 CORN 17.0 GHz VV C1
Model A

r = 0.93 rms error = 0.66 dB A = 0.15 B = 1.26 C = 0.97 D = 0.03

DATE	σ_o^o(dB)	σ_p^o(dB)	LAI	MPHLEAF	MSVOL	MPHSTALK	N
168	- 9.54	- 8.30	0.97	0.18	0.04	0.24	6
170	- 7.76	- 8.20	1.17	0.24	0.03	0.33	6
176	- 7.90	- 7.44	1.77	0.40	0.22	1.03	7
178	- 6.83	- 7.59	1.96	0.44	0.13	1.28	8
182	- 6.91	- 7.55	2.33	0.51	0.07	1.79	11
190	- 6.65	- 6.75	3.41	0.61	0.12	2.58	13
192	- 6.87	- 6.88	3.37	0.62	0.09	2.71	14
196	- 6.71	- 7.04	3.31	0.64	0.04	2.87	15
198	- 7.10	- 7.00	3.30	0.65	0.33	2.91	16
204	- 6.98	- 7.12	3.24	0.65	0.12	2.90	16
206	- 7.37	- 7.15	3.21	0.65	0.08	2.87	16
210	- 8.25	- 7.20	3.09	0.63	0.10	2.76	16
213	- 7.96	- 7.31	2.96	0.62	0.05	2.66	16
221	- 8.68	- 7.72	2.41	0.56	0.10	2.34	16
225	- 9.09	- 8.09	2.05	0.53	0.10	2.17	16
231	- 8.39	- 8.59	1.46	0.47	0.25	1.92	16
240	-12.65	-11.59	0.56	0.35	0.05	1.56	16
247	-11.27	-11.27	0.06	0.22	0.19	1.31	16

1980 CORN 17.0 GHz VV C2
Model A

r = 0.78 rms error = 0.96 dB A = 0.15 B = 1.26 C = 0.97 D = 0.03

DATE	σ_o^o(dB)	σ_p^o(dB)	LAI	MPHLEAF	MSVOL	MPHSTALK	N
168	- 8.39	- 8.59	0.84	0.17	0.05	0.29	6
170	- 7.41	- 8.65	1.00	0.23	0.03	0.36	6
176	- 6.82	- 7.78	1.51	0.38	0.23	1.04	7
178	- 6.89	- 8.02	1.68	0.42	0.12	1.28	8
182	- 6.25	- 7.98	1.99	0.49	0.06	1.72	11
190	- 6.84	- 6.95	3.05	0.57	0.10	2.36	13
192	- 6.62	- 7.06	3.02	0.58	0.06	2.46	14
196	- 6.37	- 7.15	3.01	0.59	0.03	2.57	15
198	- 6.23	- 7.13	2.99	0.60	0.16	2.60	16
204	- 6.26	- 7.29	2.83	0.59	0.14	2.57	16
206	- 7.26	- 7.37	2.75	0.58	0.11	2.54	16
210	- 8.01	- 7.52	2.56	0.56	0.09	2.44	16
213	- 7.87	- 7.65	2.42	0.54	0.05	2.36	16
217	- 8.26	- 7.65	2.29	0.51	0.11	2.24	16
221	- 8.44	- 7.91	2.01	0.48	0.09	2.11	16
225	- 8.01	- 8.31	1.70	0.44	0.08	1.98	16
231	- 7.34	- 8.58	1.18	0.38	0.24	1.80	16
240	- 9.48	-11.84	0.44	0.28	0.06	1.56	16
247	-10.40	-10.72	0.03	0.18	0.20	1.40	16

1980 CORN 17.0 GHz VV C3
Model A

r = 0.94 rms error = 0.69 dB A = 0.15 B = 1.26 C = 0.97 D = 0.03

DATE	σ_o^o(dB)	σ_p^o(dB)	LAI	MPHLEAF	MSVOL	MPHSTALK	N
165	- 8.97	- 7.81	0.94	0.18	0.11	0.42	5
168	- 8.91	- 8.11	1.35	0.31	0.05	0.44	6
170	- 7.96	- 7.99	1.63	0.39	0.04	0.63	6
171	- 8.05	- 7.95	1.78	0.43	0.04	0.74	6
176	- 7.07	- 7.51	2.49	0.59	0.24	1.40	7
178	- 6.86	- 7.47	2.77	0.64	0.19	1.67	8
182	- 6.78	- 7.32	3.27	0.73	0.11	2.20	11
189	- 6.22	- 6.66	4.46	0.83	0.25	2.88	11
190	- 6.53	- 6.71	4.45	0.84	0.19	2.95	13
192	- 7.19	- 6.78	4.42	0.86	0.14	3.05	14
196	- 7.08	- 6.90	4.36	0.87	0.04	3.17	15
198	- 7.15	- 6.91	4.33	0.88	0.43	3.20	16
204	- 7.63	- 6.95	4.24	0.86	0.23	3.15	16
206	- 7.90	- 7.00	4.14	0.85	0.13	3.10	16
210	- 8.29	- 7.14	3.86	0.82	0.09	2.98	16
213	- 8.49	- 7.31	3.57	0.80	0.10	2.88	16
217	- 8.64	- 7.52	3.14	0.75	0.49	2.73	16
220	- 8.75	- 7.87	2.75	0.72	0.27	2.61	16
221	- 8.12	- 8.03	2.62	0.71	0.17	2.56	16
225	- 8.68	- 8.63	2.06	0.65	0.16	2.40	16
231	- 8.81	- 9.61	1.23	0.56	0.33	2.16	16
240	-14.50	-14.48	0.26	0.40	0.06	1.80	16
247	-12.42	-11.38	0.08	0.25	0.21	1.54	16

1980 CORN 35.6 GHz VV C1
Model A

r = 0.96 rms error = 0.63 dB A = 0.14 B = 0.50 C = 0.88 D = 0.14

DATE	σ_o^o(dB)	σ_p^o(dB)	LAI	MPHLEAF	MSVOL	MPHSTALK	N
168	- 7.79	- 7.82	0.97	0.18	0.04	0.24	6
170	- 7.05	- 7.56	1.17	0.24	0.03	0.33	6
176	- 6.62	- 6.59	1.77	0.40	0.22	1.03	7
178	- 7.24	- 6.88	1.96	0.44	0.13	1.28	8
190	- 6.33	- 6.36	3.41	0.61	0.12	2.58	13
192	- 6.48	- 6.51	3.37	0.62	0.09	2.71	14
196	- 6.34	- 6.70	3.31	0.64	0.04	2.87	15
198	- 6.70	- 6.62	3.30	0.65	0.33	2.91	16
204	- 7.64	- 6.76	3.24	0.65	0.12	2.90	16
206	- 7.39	- 6.79	3.21	0.65	0.08	2.87	16
210	- 6.60	- 6.82	3.09	0.63	0.10	2.76	16
213	- 8.16	- 6.92	2.96	0.62	0.05	2.66	16
221	- 7.80	- 7.28	2.41	0.56	0.10	2.34	16
225	- 8.77	- 7.63	2.05	0.53	0.10	2.17	16
231	- 8.41	- 8.03	1.46	0.47	0.25	1.92	16
240	-12.53	-11.28	0.56	0.35	0.05	1.56	16
247	-11.84	-11.34	0.06	0.22	0.19	1.31	16

1980 CORN 35.6 GHz VV C2
Model A

r = 0.82 rms error = 0.88 dB A = 0.14 B = 0.50 C = 0.88 D = 0.14

DATE	σ_o^o(dB)	σ_p^o(dB)	LAI	MPHLEAF	MSVOL	MPHSTALK	N
168	- 9.24	- 8.16	0.84	0.17	0.05	0.29	6
170	- 8.35	- 8.04	1.00	0.23	0.03	0.36	6
176	- 6.65	- 6.94	1.51	0.38	0.23	1.04	7
190	- 6.57	- 6.54	3.05	0.57	0.10	2.36	13
192	- 6.24	- 6.67	3.02	0.58	0.06	2.46	14
196	- 6.34	- 6.78	3.01	0.59	0.03	2.57	15
198	- 6.70	- 6.74	2.99	0.60	0.16	2.60	16
204	- 7.12	- 6.90	2.83	0.59	0.14	2.57	16
206	- 7.00	- 6.99	2.75	0.58	0.11	2.54	16
210	- 7.41	- 7.14	2.56	0.56	0.09	2.44	16
213	- 7.40	- 7.29	2.42	0.54	0.05	2.36	16
217	- 7.60	- 7.27	2.29	0.51	0.11	2.24	16
221	- 6.72	- 7.56	2.01	0.48	0.09	2.11	16
225	- 7.13	- 7.98	1.70	0.44	0.08	1.98	16
231	- 7.76	- 8.23	1.18	0.38	0.24	1.80	16
240	- 8.78	-11.84	0.44	0.28	0.06	1.56	16
247	-11.12	-11.32	0.03	0.18	0.20	1.40	16

1980 CORN 35.6 GHz VV C3
Model A

r = 0.95 rms error = 0.58 dB A = 0.14 B = 0.50 C = 0.88 D = 0.14

DATE	σ_o^o(dB)	σ_p^o(dB)	LAI	MPHLEAF	MSVOL	MPHSTALK	N
165	- 7.83	- 7.40	0.94	0.18	0.11	0.42	5
168	- 7.19	- 7.28	1.35	0.31	0.05	0.44	6
170	- 6.44	- 7.06	1.63	0.39	0.04	0.63	6
171	- 6.39	- 7.01	1.78	0.43	0.04	0.74	6
176	- 6.43	- 6.46	2.49	0.59	0.24	1.40	7
178	- 5.95	- 6.52	2.77	0.64	0.19	1.67	8
189	- 5.58	- 6.01	4.46	0.83	0.25	2.88	11
190	- 6.06	- 6.07	4.45	0.84	0.19	2.95	13
192	- 5.80	- 6.16	4.42	0.86	0.14	3.05	14
196	- 5.46	- 6.30	4.36	0.87	0.04	3.17	15
198	- 6.40	- 6.27	4.33	0.88	0.43	3.20	16
204	- 7.64	- 6.33	4.24	0.86	0.23	3.15	16
206	- 6.20	- 6.39	4.14	0.85	0.13	3.10	16
210	- 6.84	- 6.53	3.86	0.82	0.09	2.98	16
213	- 7.08	- 6.69	3.57	0.80	0.10	2.88	16
217	- 7.21	- 6.80	3.14	0.75	0.49	2.73	16
220	- 7.37	- 7.18	2.75	0.72	0.27	2.61	16
221	- 7.90	- 7.36	2.62	0.71	0.17	2.56	16
225	- 8.27	- 7.95	2.06	0.65	0.16	2.40	16
231	- 7.70	- 8.76	1.23	0.56	0.33	2.16	16
240	-13.00	-14.02	0.26	0.40	0.06	1.80	16
247	-12.12	-11.54	0.08	0.25	0.21	1.54	16

1980 SORGHUM 8.6 GHz VV S1
Model A

r = 0.95 rms error = 1.10 dB A = 0.13 B = 1.61 C = 0.00 D = 0.14

DATE	σ_o^o(dB)	σ_p^o(dB)	LAI	MPHLEAF	MSVOL	MPHSTALK
168	-12.50	-11.93	0.38	0.05	0.16	0.01
170	-11.50	-10.39	0.66	0.11	0.06	0.10
176	-10.30	- 8.97	1.49	0.28	0.26	0.45
178	-10.10	- 8.89	1.72	0.34	0.19	0.58
182	- 9.34	- 8.41	2.46	0.45	0.07	0.84
190	- 9.30	- 8.17	3.65	0.68	0.08	1.30
192	- 8.63	- 8.14	3.92	0.74	0.06	1.40
196	- 9.40	- 8.11	4.41	0.84	0.04	1.56
198	- 9.65	- 8.10	4.62	0.89	0.03	1.63
204	- 9.18	- 8.14	5.12	1.02	0.18	1.78
206	- 9.54	- 8.17	5.23	1.05	0.11	1.82
210	- 9.42	- 8.21	5.38	1.11	0.08	1.87
213	- 8.89	- 8.27	5.42	1.14	0.05	1.88
221	- 9.86	- 8.44	5.21	1.15	0.11	1.87
225	- 9.68	- 8.52	4.96	1.11	0.08	1.84
231	- 9.46	- 8.61	4.42	0.99	0.30	1.76
240	- 9.11	- 8.53	3.40	0.68	0.06	1.58

1980 SORGHUM 8.6 GHz VV S2
Model A

r = 0.47 rms error = 1.36 dB A = 0.13 B = 1.61 C = 0.00 D = 0.14

DATE	σ_o^o(dB)	σ_p^o(dB)	LAI	MPHLEAF	MSVOL	MPHSTALK
168	-12.80	-12.45	0.32	0.03	0.14	0.05
170	-11.30	-12.17	0.44	0.12	0.06	0.11
176	-10.42	-10.87	1.07	0.36	0.23	0.50
178	-10.40	-10.41	1.36	0.43	0.20	0.60
182	-10.29	- 9.72	1.94	0.54	0.12	0.76
190	- 9.50	- 8.85	2.96	0.68	0.08	0.99
192	-10.20	- 8.71	3.15	0.70	0.05	1.02
196	- 9.50	- 8.51	3.44	0.73	0.04	1.06
198	- 9.36	- 8.45	3.52	0.74	0.03	1.08
204	- 8.87	- 8.41	3.55	0.74	0.13	1.09
206	- 9.82	- 8.45	3.48	0.73	0.06	1.08
210	- 8.87	- 8.62	3.24	0.70	0.07	1.06
213	- 9.29	- 8.83	2.98	0.68	0.05	1.05
217	- 9.69	- 9.24	2.54	0.63	0.04	1.01
221	-10.20	- 9.85	2.04	0.59	0.11	0.98
225	- 9.60	-10.70	1.54	0.53	0.09	0.94
231	- 9.16	-12.36	0.90	0.45	0.28	0.87
240	- 8.83	-12.18	0.74	0.32	0.09	0.77
247	-10.53	-11.96	0.65	0.23	0.21	0.67
254	- 9.69	-11.68	0.58	0.15	0.08	0.56

1980 SORGHUM 8.6 GHz VV S3
Model A

r = 0.54 rms error = 1.08 dB A = 0.13 B = 1.61 C = 0.00 D = 0.14

DATE	σ_o^o(dB)	σ_p^o(dB)	LAI	MPHLEAF	MSVOL	MPHSTALK
168	-14.20	-11.59	0.45	0.08	0.17	0.07
170	-10.37	-11.36	0.58	0.15	0.08	0.16
171	-10.12	-11.25	0.65	0.18	0.07	0.20
176	-10.40	-10.72	1.04	0.33	0.26	0.42
178	- 9.57	-10.51	1.22	0.38	0.14	0.51
182	-10.00	-10.31	1.53	0.48	0.08	0.65
189	- 9.26	- 9.18	2.51	0.63	0.10	0.82
190	- 8.80	- 9.21	2.55	0.64	0.09	0.84
192	- 9.27	- 9.31	2.58	0.68	0.06	0.87
196	- 9.28	- 9.52	2.61	0.73	0.03	0.90
198	- 8.97	- 9.62	2.61	0.75	0.03	0.91
204	- 9.08	- 9.91	2.54	0.80	0.16	0.92
206	-10.22	-10.01	2.50	0.81	0.09	0.91
210	-10.30	-10.19	2.40	0.81	0.09	0.90
212	- 9.41	-10.27	2.33	0.81	0.08	0.89
213	- 9.60	-10.31	2.30	0.80	0.07	0.88
217	- 9.85	-10.45	2.15	0.77	0.04	0.85
221	- 9.44	-10.55	1.99	0.73	0.08	0.82
224	- 8.98	-10.60	1.86	0.68	0.13	0.80
225	- 9.01	-10.61	1.82	0.66	0.11	0.79
231	- 8.26	-10.56	1.56	0.53	0.29	0.73
240	- 8.75	-10.07	1.20	0.30	0.07	0.66
247	-10.02	- 9.32	0.99	0.12	0.21	0.59

1980 SORGHUM 13.0 GHz VV S1
Model A

r = 0.91 rms error = 1.07 dB A = 0.15 B = 1.45 C = 0.00 D = 0.15

DATE	σ_o^o(dB)	σ_p^o(dB)	LAI	MPHLEAF	MSVOL	MPHSTALK
168	-11.40	-11.11	0.38	0.05	0.16	0.01
170	-10.19	- 9.55	0.66	0.11	0.06	0.10
176	- 9.83	- 8.09	1.49	0.28	0.26	0.45
178	- 9.17	- 8.00	1.72	0.34	0.19	0.58
182	- 8.19	- 7.51	2.46	0.45	0.07	0.84
190	- 8.50	- 7.26	3.65	0.68	0.08	1.30
192	- 8.50	- 7.23	3.92	0.74	0.06	1.40
196	- 7.83	- 7.20	4.41	0.84	0.04	1.56
198	- 8.56	- 7.19	4.62	0.89	0.03	1.63
204	- 8.20	- 7.22	5.12	1.02	0.18	1.78
206	- 8.46	- 7.25	5.23	1.05	0.11	1.82
210	- 8.12	- 7.30	5.38	1.11	0.08	1.87
213	- 8.37	- 7.35	5.42	1.14	0.05	1.88
221	- 8.70	- 7.50	5.21	1.15	0.11	1.87
225	- 9.20	- 7.58	4.96	1.11	0.08	1.84
231	- 7.90	- 7.67	4.42	0.99	0.30	1.76
240	- 8.25	- 7.62	3.40	0.68	0.06	1.58

1980 SORGHUM 13.0 GHz VV S2
Model A

r = 0.65 rms error = 1.19 dB A = 0.15 B = 1.45 C = 0.00 D = 0.15

DATE	σ_o^o(dB)	σ_p^o(dB)	LAI	MPHLEAF	MSVOL	MPHSTALK
168	-12.00	-11.66	0.32	0.03	0.14	0.05
170	-10.65	-11.30	0.44	0.12	0.06	0.11
176	- 9.96	- 9.90	1.07	0.36	0.23	0.50
178	- 9.53	- 9.43	1.36	0.43	0.20	0.60
182	- 8.57	- 8.74	1.94	0.54	0.12	0.76
190	- 8.32	- 7.89	2.96	0.68	0.08	0.99
192	- 8.48	- 7.76	3.15	0.70	0.05	1.02
196	- 8.90	- 7.57	3.44	0.73	0.04	1.06
198	- 8.62	- 7.51	3.52	0.74	0.03	1.08
204	- 7.86	- 7.47	3.55	0.74	0.13	1.09
206	- 8.29	- 7.51	3.48	0.73	0.06	1.08
210	- 7.79	- 7.67	3.24	0.70	0.07	1.06
213	- 8.78	- 7.87	2.98	0.68	0.05	1.05
217	- 7.79	- 8.28	2.54	0.63	0.04	1.01
221	- 9.00	- 8.88	2.04	0.59	0.11	0.98
225	- 8.44	- 9.70	1.54	0.53	0.09	0.94
231	- 8.70	-11.35	0.90	0.45	0.28	0.87
240	- 8.50	-11.23	0.74	0.32	0.09	0.77
247	- 8.99	-11.06	0.65	0.23	0.21	0.67
254	- 9.52	-10.82	0.58	0.15	0.08	0.56

1980 SORGHUM 13.0 GHz VV S3
Model A

r = 0.80 rms error = 0.78 dB A = 0.15 B = 1.45 C = 0.00 D = 0.15

DATE	σ_o^o(dB)	σ_p^o(dB)	LAI	MPHLEAF	MSVOL	MPHSTALK
168	-12.80	-10.76	0.45	0.08	0.17	0.07
170	-10.40	-10.48	0.58	0.15	0.08	0.16
171	-10.19	-10.35	0.65	0.18	0.07	0.20
176	- 9.36	- 9.76	1.04	0.33	0.26	0.42
178	- 8.59	- 9.54	1.22	0.38	0.14	0.51
182	- 8.24	- 9.32	1.53	0.48	0.08	0.65
189	- 8.33	- 8.21	2.51	0.63	0.10	0.82
190	- 8.29	- 8.24	2.55	0.64	0.09	0.84
192	- 8.02	- 8.33	2.58	0.68	0.06	0.87
196	- 7.89	- 8.52	2.61	0.73	0.03	0.90
198	- 7.82	- 8.61	2.61	0.75	0.03	0.91
204	- 8.06	- 8.89	2.54	0.80	0.16	0.92
206	- 8.34	- 8.98	2.50	0.81	0.09	0.91
210	- 8.05	- 9.15	2.40	0.81	0.09	0.90
212	- 8.83	- 9.23	2.33	0.81	0.08	0.89
213	- 8.61	- 9.27	2.30	0.80	0.07	0.88
217	- 8.70	- 9.40	2.15	0.77	0.04	0.85
221	- 9.30	- 9.51	1.99	0.73	0.08	0.82
224	- 8.55	- 9.56	1.86	0.68	0.13	0.80
225	- 9.11	- 9.57	1.82	0.66	0.11	0.79
231	- 8.20	- 9.55	1.56	0.53	0.29	0.73
240	- 8.94	- 9.16	1.20	0.30	0.07	0.66
247	- 8.64	- 8.53	0.99	0.12	0.21	0.59

1980 SORGHUM 17.0 GHz VV S1
Model A

r = 0.95 rms error = 0.95 dB A = 0.14 B = 1.02 C = 0.00 D = 0.21

DATE	σ_o^o(dB)	σ_p^o(dB)	LAI	MPHLEAF	MSVOL	MPHSTALK
168	-11.60	-11.30	0.38	0.05	0.16	0.01
170	- 9.62	- 9.61	0.66	0.11	0.06	0.10
176	- 9.22	- 7.93	1.49	0.28	0.26	0.45
178	- 8.63	- 7.80	1.72	0.34	0.19	0.58
182	- 8.43	- 7.27	2.46	0.45	0.07	0.84
190	- 8.26	- 6.98	3.65	0.68	0.08	1.30
192	- 7.70	- 6.94	3.92	0.74	0.06	1.40
196	- 7.83	- 6.89	4.41	0.84	0.04	1.56
198	- 7.94	- 6.88	4.62	0.89	0.03	1.63
204	- 7.29	- 6.88	5.12	1.02	0.18	1.78
206	- 8.10	- 6.90	5.23	1.05	0.11	1.82
210	- 8.30	- 6.94	5.38	1.11	0.08	1.87
213	- 7.96	- 6.98	5.42	1.14	0.05	1.88
221	- 8.26	- 7.12	5.21	1.15	0.11	1.87
225	- 8.20	- 7.20	4.96	1.11	0.08	1.84
231	- 7.98	- 7.32	4.42	0.99	0.30	1.76
240	- 7.94	- 7.39	3.40	0.68	0.06	1.58

1980 SORGHUM 17.0 GHz VV S2
Model A

r = 0.61 rms error = 1.40 dB A = 0.14 B = 1.02 C = 0.00 D = 0.21

DATE	σ_o^o(dB)	σ_p^o(dB)	LAI	MPHLEAF	MSVOL	MPHSTALK
168	-13.00	-11.93	0.32	0.03	0.14	0.05
170	-10.90	-11.33	0.44	0.12	0.06	0.11
176	- 9.09	- 9.62	1.07	0.36	0.23	0.50
178	-10.20	- 9.12	1.36	0.43	0.20	0.60
182	- 9.99	- 8.38	1.94	0.54	0.12	0.76
190	- 7.87	- 7.51	2.96	0.68	0.08	0.99
192	- 8.35	- 7.38	3.15	0.70	0.05	1.02
196	- 8.15	- 7.19	3.44	0.73	0.04	1.06
198	- 7.75	- 7.13	3.52	0.74	0.03	1.08
204	- 7.30	- 7.10	3.55	0.74	0.13	1.09
206	- 7.64	- 7.14	3.48	0.73	0.06	1.08
210	- 8.24	- 7.30	3.24	0.70	0.07	1.06
213	- 7.54	- 7.51	2.98	0.68	0.05	1.05
217	- 7.55	- 7.92	2.54	0.63	0.04	1.01
221	- 8.99	- 8.53	2.04	0.59	0.11	0.98
225	- 8.23	- 9.38	1.54	0.53	0.09	0.94
231	- 7.78	-11.09	0.90	0.45	0.28	0.87
240	- 8.53	-11.12	0.74	0.32	0.09	0.77
247	- 8.90	-11.08	0.65	0.23	0.21	0.67
254	- 8.54	-10.97	0.58	0.15	0.08	0.56

1980 SORGHUM 17.0 GHz VV S3
Model A

r = 0.78 rms error = 0.90 dB A = 0.14 B = 1.02 C = 0.00 D = 0.21

DATE	σ_o^o(dB)	σ_p^o(dB)	LAI	MPHLEAF	MSVOL	MPHSTALK
168	-12.50	-10.89	0.45	0.08	0.17	0.07
170	-11.68	-10.47	0.58	0.15	0.08	0.16
171	-10.22	-10.28	0.65	0.18	0.07	0.20
176	- 8.84	- 9.51	1.04	0.33	0.26	0.42
178	- 8.04	- 9.24	1.22	0.38	0.14	0.51
182	- 9.07	- 8.96	1.53	0.48	0.08	0.65
189	- 8.40	- 7.80	2.51	0.63	0.10	0.82
190	- 8.43	- 7.82	2.55	0.64	0.09	0.84
192	- 8.46	- 7.90	2.58	0.68	0.06	0.87
196	- 7.70	- 8.06	2.61	0.73	0.03	0.90
198	- 7.37	- 8.15	2.61	0.75	0.03	0.91
204	- 7.53	- 8.39	2.54	0.80	0.16	0.92
206	- 7.70	- 8.47	2.50	0.81	0.09	0.91
210	- 7.72	- 8.63	2.40	0.81	0.09	0.90
212	- 7.63	- 8.71	2.33	0.81	0.08	0.89
213	- 7.64	- 8.74	2.30	0.80	0.07	0.88
217	- 7.91	- 8.89	2.15	0.77	0.04	0.85
221	- 7.95	- 9.01	1.99	0.73	0.08	0.82
224	- 7.85	- 9.08	1.86	0.68	0.13	0.80
225	- 8.11	- 9.10	1.82	0.66	0.11	0.79
231	- 7.91	- 9.16	1.56	0.53	0.29	0.73
240	- 8.72	- 9.04	1.20	0.30	0.07	0.66
247	- 9.18	- 8.74	0.99	0.12	0.21	0.59

1980 SORGHUM 35.6 GHz VV S1
Model A

r = 0.88 rms error = 1.16 dB A = 0.11 B = 0.33 C = 0.32 D = 0.40

DATE	σ_o^o(dB)	σ_p^o(dB)	LAI	MPHLEAF	MSVOL	MPHSTALK
168	-11.90	- 9.77	0.38	0.05	0.16	0.01
170	- 9.74	- 9.64	0.66	0.11	0.06	0.10
176	- 8.44	- 7.61	1.49	0.28	0.26	0.45
178	- 8.74	- 7.68	1.72	0.34	0.19	0.58
190	- 8.49	- 7.00	3.65	0.68	0.08	1.30
192	- 7.42	- 6.95	3.92	0.74	0.06	1.40
196	- 8.16	- 6.86	4.41	0.84	0.04	1.56
198	- 7.56	- 6.83	4.62	0.89	0.03	1.63
204	- 7.08	- 6.76	5.12	1.02	0.18	1.78
206	- 7.59	- 6.76	5.23	1.05	0.11	1.82
210	- 8.67	- 6.76	5.38	1.11	0.08	1.87
213	- 7.89	- 6.78	5.42	1.14	0.05	1.88
221	- 8.04	- 6.90	5.21	1.15	0.11	1.87
225	- 7.98	- 7.01	4.96	1.11	0.08	1.84
231	- 8.47	- 7.20	4.42	0.99	0.30	1.76
240	- 8.65	- 7.62	3.40	0.68	0.06	1.58

1980 SORGHUM 35.6 GHz VV S2
Model A

r = 0.72 rms error = 1.26 dB A = 0.11 B = 0.33 C = 0.32 D = 0.40

DATE	σ_o^o(dB)	σ_p^o(dB)	LAI	MPHLEAF	MSVOL	MPHSTALK
168	-10.54	-10.49	0.32	0.03	0.14	0.05
170	-11.10	-11.01	0.44	0.12	0.06	0.11
176	- 7.88	- 8.97	1.07	0.36	0.23	0.50
190	- 7.77	- 7.26	2.96	0.68	0.08	0.99
192	- 7.34	- 7.13	3.15	0.70	0.05	1.02
196	- 7.91	- 6.96	3.44	0.73	0.04	1.06
198	- 6.81	- 6.88	3.52	0.74	0.03	1.08
204	- 7.43	- 6.84	3.55	0.74	0.13	1.09
206	- 7.29	- 6.90	3.48	0.73	0.06	1.08
210	- 7.87	- 7.09	3.24	0.70	0.07	1.06
213	- 7.64	- 7.32	2.98	0.68	0.05	1.05
217	- 7.35	- 7.78	2.54	0.63	0.04	1.01
221	- 8.07	- 8.40	2.04	0.59	0.11	0.98
225	- 7.33	- 9.30	1.54	0.53	0.09	0.94
231	- 8.12	-10.54	0.90	0.45	0.28	0.87
240	- 7.85	-11.24	0.74	0.32	0.09	0.77
247	-10.50	-10.70	0.65	0.23	0.21	0.67
254	- 9.48	-11.30	0.58	0.15	0.08	0.56

1980 SORGHUM 35.6 GHz VV S3
Model A

r = 0.90 rms error = 0.63 dB A = 0.11 B = 0.33 C = 0.32 D = 0.40

DATE	σ_o^o(dB)	σ_p^o(dB)	LAI	MPHLEAF	MSVOL	MPHSTALK
168	-10.36	- 9.60	0.45	0.08	0.17	0.07
170	- 9.99	-10.18	0.58	0.15	0.08	0.16
171	- 9.98	-10.12	0.65	0.18	0.07	0.20
176	- 8.08	- 8.71	1.04	0.33	0.26	0.42
178	- 8.24	- 8.84	1.22	0.38	0.14	0.51
189	- 6.86	- 7.46	2.51	0.63	0.10	0.82
190	- 6.39	- 7.47	2.55	0.64	0.09	0.84
192	- 7.08	- 7.53	2.58	0.68	0.06	0.87
196	- 6.66	- 7.64	2.61	0.73	0.03	0.90
198	- 6.79	- 7.69	2.61	0.75	0.03	0.91
204	- 7.53	- 7.80	2.54	0.80	0.16	0.92
206	- 7.53	- 7.89	2.50	0.81	0.09	0.91
210	- 8.07	- 8.02	2.40	0.81	0.09	0.90
212	- 8.27	- 8.10	2.33	0.81	0.08	0.89
213	- 7.15	- 8.14	2.30	0.80	0.07	0.88
217	- 7.53	- 8.31	2.15	0.77	0.04	0.85
221	- 8.83	- 8.44	1.99	0.73	0.08	0.82
224	- 9.11	- 8.52	1.86	0.68	0.13	0.80
225	- 8.14	- 8.58	1.82	0.66	0.11	0.79
231	- 7.88	- 8.58	1.56	0.53	0.29	0.73
240	- 8.52	- 9.26	1.20	0.30	0.07	0.66
247	- 9.59	- 8.98	0.99	0.12	0.21	0.59

1980 CORN 17.0 GHz HH C1
Model A

r = 0.87 rms error = 0.76 dB A = 0.11 B = 1.24 C = 0.00 D = 0.86
E = 0.86

DATE	σ_o^o(dB)	σ_p^o(dB)	LAI	MPHLEAF	MSVOL	MPHSTALK	N
168	-10.09	- 8.92	0.97	0.18	0.04	0.24	6
170	- 8.42	- 8.87	1.17	0.24	0.03	0.33	6
176	- 8.27	- 7.51	1.77	0.40	0.22	1.03	7
178	- 7.26	- 7.92	1.96	0.44	0.13	1.28	8
182	- 6.95	- 8.02	2.33	0.51	0.07	1.79	11
190	- 6.97	- 7.12	3.41	0.61	0.12	2.58	13
192	- 7.26	- 7.28	3.37	0.62	0.09	2.71	14
196	- 6.93	- 7.50	3.31	0.64	0.04	2.87	15
198	- 6.84	- 7.15	3.30	0.65	0.33	2.91	16
204	- 7.42	- 7.49	3.24	0.65	0.12	2.90	16
206	- 7.96	- 7.57	3.21	0.65	0.08	2.87	16
210	- 8.30	- 7.60	3.09	0.63	0.10	2.76	16
213	- 8.60	- 7.78	2.96	0.62	0.05	2.66	16
221	- 9.71	- 8.11	2.41	0.56	0.10	2.34	16
225	- 9.75	- 8.45	2.05	0.53	0.10	2.17	16
231	- 9.07	- 8.53	1.46	0.47	0.25	1.92	16
240	-12.08	-11.95	0.56	0.35	0.05	1.56	16
247	-10.61	-11.11	0.06	0.22	0.19	1.31	16

1980 CORN 17.0 GHz HH C2
Model A

r = 0.78 rms error = 0.93 dB A = 0.11 B = 1.24 C = 0.00 D = 0.86
E = 0.86

DATE	σ_o^o(dB)	σ_p^o(dB)	LAI	MPHLEAF	MSVOL	MPHSTALK	N
168	- 9.79	- 9.12	0.84	0.17	0.05	0.29	6
170	- 8.45	- 9.30	1.00	0.23	0.03	0.36	6
176	- 6.60	- 7.79	1.51	0.38	0.23	1.04	7
178	- 7.24	- 8.34	1.68	0.42	0.12	1.28	8
182	- 6.50	- 8.47	1.99	0.49	0.06	1.72	11
190	- 7.26	- 7.35	3.05	0.57	0.10	2.36	13
192	- 6.78	- 7.50	3.02	0.58	0.06	2.46	14
196	- 6.99	- 7.63	3.01	0.59	0.03	2.57	15
198	- 6.25	- 7.43	2.99	0.60	0.16	2.60	16
204	- 6.48	- 7.61	2.83	0.59	0.14	2.57	16
206	- 7.75	- 7.73	2.75	0.58	0.11	2.54	16
210	- 8.30	- 7.90	2.56	0.56	0.09	2.44	16
213	- 7.75	- 8.11	2.42	0.54	0.05	2.36	16
217	- 8.86	- 7.98	2.29	0.51	0.11	2.24	16
221	- 8.51	- 8.25	2.01	0.48	0.09	2.11	16
225	- 8.57	- 8.65	1.70	0.44	0.08	1.98	16
231	- 7.96	- 8.37	1.18	0.38	0.24	1.80	16
240	- 9.96	-11.85	0.44	0.28	0.06	1.56	16
247	-10.81	-10.55	0.03	0.18	0.20	1.40	16

1980 CORN 17.0 GHz HH C3
Model A

r = 0.93 rms error = 0.64 dB A = 0.11 B = 1.24 C = 0.00 D = 0.86 E = 0.86

DATE	σ_o^o(dB)	σ_p^o(dB)	LAI	MPHLEAF	MSVOL	MPHSTALK	N
165	- 9.39	- 8.03	0.94	0.18	0.11	0.42	5
168	- 9.03	- 8.71	1.35	0.31	0.05	0.44	6
170	- 8.21	- 8.62	1.63	0.39	0.04	0.63	6
171	- 8.51	- 8.60	1.78	0.43	0.04	0.74	6
176	- 7.21	- 7.82	2.49	0.59	0.24	1.40	7
178	- 7.31	- 7.88	2.77	0.64	0.19	1.67	8
182	- 7.10	- 7.84	3.27	0.73	0.11	2.20	11
189	- 6.78	- 7.09	4.46	0.83	0.25	2.88	11
190	- 7.31	- 7.16	4.45	0.84	0.19	2.95	13
192	- 6.88	- 7.26	4.42	0.86	0.14	3.05	14
196	- 7.60	- 7.42	4.36	0.87	0.04	3.17	15
198	- 7.93	- 7.26	4.33	0.88	0.43	3.20	16
204	- 7.99	- 7.38	4.24	0.86	0.23	3.15	16
206	- 8.42	- 7.47	4.14	0.85	0.13	3.10	16
210	- 8.39	- 7.64	3.86	0.82	0.09	2.98	16
213	- 8.57	- 7.81	3.57	0.80	0.10	2.88	16
217	- 8.89	- 7.69	3.14	0.75	0.49	2.73	16
220	- 8.89	- 8.18	2.75	0.72	0.27	2.61	16
221	- 8.96	- 8.42	2.62	0.71	0.17	2.56	16
225	- 9.25	- 8.99	2.06	0.65	0.16	2.40	16
231	- 8.96	- 9.47	1.23	0.56	0.33	2.16	16
240	-14.69	-14.69	0.26	0.40	0.06	1.80	16
247	-11.81	-11.12	0.08	0.25	0.21	1.54	16

APPENDIX B

Crop Attenuation Data and Associated Ground Truth

Crop	Wheat
Site	W1
Julian Date	135
Low Angle (24°) Path Length (m)	0.69
High Angle (56°) Path Length (m)	1.13

FREQUENCY (GHz)	POLARIZATION	ANGLE (°)	MEAN ONE-WAY CANOPY LOSS (dB)	99% CONFIDENCE-INTERVAL LIMITS (dB)*
1.55	VV	24	1.4	± 0.3
1.55	HH	24	1.7	± 0.2
4.75	VV	24	1.6	± 0.5
4.75	HH	24	2.3	± 0.2
10.20	VV	24	6.5	± 1.4
10.20	HH	24	4.8	± 1.3
1.55	VV	56	7.4	± 0.3
1.55	HH	56	2.4	± 0.3
4.75	VV	56	27.4	± 0.5
4.75	HH	56	9.4	± 1.0
4.75	VH	56	5.1	± 0.2
10.20	VV	56	36.0	± 0.8
10.20	HH	56	32.5	± 0.4

*Does not include estimated ± 10% accuracy error.

Crop	Wheat
Site	W2
Julian Date	150
Low Angle (24°) Path Length (m)	--
High Angle (56°) Path Length (m)	1.59

FREQUENCY (GHz)	POLARIZATION	ANGLE (°)	MEAN ONE-WAY CANOPY LOSS (dB)	99% CONFIDENCE INTERVAL LIMITS (dB)*
1.55	VV	56	3.2	± 0.6
1.55	HH	56	1.3	± 0.3
4.75	VV	56	17.9	± 0.7
4.75	HH	56	3.0	± 0.5
4.75	VH	56	0.4	± 0.1
4.75	HV	56	1.2	± 0.5
10.20	VV	56	31.2	± 1.9
10.20	HH	56	14.1	± 2.2

* Does not include estimated ± 10% accuracy error.

Crop	Wheat
Site	W2
Julian Date	150
Low Angle (24°) Path Length (m)	--
High Angle (56°) Path Length (m)	0.86 (decapitated)

FREQUENCY (GHz)	POLARIZATION	ANGLE (°)	MEAN ONE-WAY CANOPY LOSS (dB)	99% CONFIDENCE INTERVAL LIMITS (dB)*
1.55	VV	56	3.9	± 0.5
1.55	HH	56	0.9	± 0.3
4.75	VV	56	13.1	± 0.9
4.75	HH	56	2.9	± 0.7
10.20	VV	56	21.4	± 2.4
10.20	HH	56	8.4	± 1.5

* Does not include estimated ± 10% accuracy error.

Crop	Wheat
Site	W1
Julian Date	158
Low Angle (24°) Path Length (m)	1.16
High Angle (56°) Path Length (m)	1.90

FREQUENCY (GHz)	POLARIZATION	ANGLE (°)	MEAN ONE-WAY CANOPY LOSS (dB)	99% CONFIDENCE INTERVAL LIMITS (dB)*
1.55	VV	24	1.3	± 0.1
1.55	HH	24	1.3	± 0.2
4.75	VV	24	5.4	± 0.6
4.75	HH	24	3.7	± 0.4
10.20	VV	24	10.9	± 1.7
10.20	HH	24	9.4	± 1.1
1.55	VV	56	7.1	± 0.6
1.55	HH	56	2.6	± 0.6
4.75	VV	56	17.8	± 0.3
4.75	HH	56	6.0	± 0.6
10.20	VV	56	36.1	± 1.0
10.20	HH	56	26.7	± 1.3
10.20	HV	56	19.8	± 0.8

* Does not include estimated ± 10% accuracy error.

Crop	Soybeans
Site	S1
Julian Date	181
Low Angle (16°) Path Length (m)	0.45
High Angle (52°) Path Length (m)	0.60

FREQUENCY (GHz)	POLARIZATION	ANGLE (°)	MEAN ONE-WAY CANOPY LOSS (dB)	99% CONFIDENCE INTERVAL LIMITS (dB)*
1.55	VV	16	1.5	± 0.1
1.55	HH	16	0.5	± 0.1
4.75	VV	16	2.6	± 0.4
4.75	HH	16	2.0	± 0.3
10.20	VV	16	4.3	± 0.6
10.20	HH	16	4.6	± 0.6
1.55	VV	52	1.6	± 0.2
1.55	HH	52	0.4	± 0.1
4.75	VV	52	8.6	± 0.8
4.75	HH	52	3.4	± 0.5
10.20	VV	52	11.8	± 1.6
10.20	HH	52	8.0	± 0.9

* Does not include estimated ± 10% accuracy error.

Crop	Soybeans
Site	S1
Julian Date	188
Low Angle (16°) Path Length (m)	0.54
High Angle (52°) Path Length (m)	0.78

FREQUENCY (GHz)	POLARIZATION	ANGLE (°)	MEAN ONE-WAY CANOPY LOSS (dB)	99% CONFIDENCE INTERVAL LIMITS (dB)*
1.55	VV	16	2.6	± 0.2
1.55	HH	16	0.8	± 0.2
4.75	VV	16	3.8	± 0.8
4.75	HH	16	3.6	± 0.4
10.20	VV	16	7.8	± 1.4
10.20	HH	16	10.9	± 1.4
1.55	VV	52	2.6	± 0.3
1.55	HH	52	0.7	± 0.2
4.75	VV	52	9.9	± 0.9
4.75	HH	52	3.1	± 0.3
10.20	VV	52	12.5	± 1.6
10.20	HH	52	12.1	± 1.1

* Does not include estimated ± 10% accuracy error.

Crop	Soybeans (Defoliated)
Site	S1
Julian Date	188
Low Angle (16°) Path Length (m)	--
High Angle (52°) Path Length (m)	0.67 (Defoliated)

FREQUENCY (GHz)	POLARIZATION	ANGLE (°)	MEAN ONE-WAY CANOPY LOSS (dB)	99% CONFIDENCE INTERVAL LIMITS (dB)*
1.55	VV	52	2.4	± 0.5
1.55	HH	52	0.4	± 0.4
4.75	VV	52	8.8	± 1.9
4.75	HH	52	1.7	± 0.9
10.20	VV	52	8.3	± 2.3
10.20	HH	52	3.7	± 1.1

* Does not include estimated ± 10% accuracy error.

Crop	Wheat
Site	W1
Julian Date	135
Mean Canopy Height (m)	0.73
Head Length (m)	--
Row Spacing (m)	0.15
Density (stems/m^2)	1694
Top-1/3 Leaf H_2O	80.0% (1.46 kg/m^2)
Mid-1/3 Leaf H_2O	80.2% (0.71 kg/m^2)
Low-1/3 Leaf H_2O	81.1% (0.11 kg/m^2)
Top-1/3 Stalk H_2O	86.1% (1.19 kg/m^2)
Mid-1/3 Stalk H_2O	84.1% (1.56 kg/m^2)
Low-1/3 Stalk H_2O	83.8% (1.46 kg/m^2)
Head H_2O	--
L123 Leaf H_2O	80.1% (2.28 kg/m^2)
L123 Stalk H_2O	84.6% (4.21 kg/m^2)
Whole Plant H_2O	82.9% (6.49 kg/m^2)
Leaf Area Index	8.0
Growth Stage*	23 (Flag Leaf Visible)
Leaf Thickness (mm)	0.15
Stem Diameter (mm)	2.00
Look Direction	Perpendicular to Rows
Receiver Height (m)	0.10

* LACIE Crop Inventory System

Crop	Wheat
Site	W2
Julian Date	150
Mean Canopy Height (m)	1.11 (0.70 Decapitated)
Head Length (m)	0.08
Row Spacing (m)	0.15
Density (stems/m^2)	1027
Top-1/3 Leaf H_2O	68.9% (0.18 kg/m^2)
Mid-1/3 Leaf H_2O	52.1% (0.15 kg/m^2)
Low-1/3 Leaf H_2O	8.3% (0.00 kg/m^2)
Top-1/3 Stalk H_2O	65.8% (0.41 kg/m^2)
Mid-1/3 Stalk H_2O	69.0% (0.75 kg/m^2)
Low-1/3 Stalk H_2O	63.4% (0.43 kg/m^2)
Head H_2O	82.2% (1.11 kg/m^2)
L123 Leaf H_2O	55.2% (0.33 kg/m^2)
L123 Stalk H_2O	66.6% (1.59 kg/m^2)
Whole Plant H_2O	69.9% (3.03 kg/m^2)
Leaf Area Index	3.6
Growth Stage*	34 (Kernels Formed)
Leaf Thickness (mm)	0.15
Stem Diameter (mm)	2.00
Look Direction	Perpendicular to Rows
Receiver Height (m)	0.22

* LACIE Crop Inventory System

Crop	Wheat
Site	W1
Julian Date	158
Mean Canopy Height (m)	1.16
Head Length (m)	0.08
Row Spacing (m)	0.15
Density (stems/m^2)	1694
Top-1/3 Leaf H_2O	72.6% (0.46 kg/m^2)
Mid-1/3 Leaf H_2O	53.7% (0.15 kg/m^2)
Low-1/3 Leaf H_2O	47.8% (0.07 kg/m^2)
Top-1/3 Stalk H_2O	75.7% (0.87 kg/m^2)
Mid-1/3 Stalk H_2O	78.2% (1.49 kg/m^2)
Low-1/3 Stalk H_2O	72.9% (1.00 kg/m^2)
Head H_2O	72.5% (1.13 kg/m^2)
L123 Leaf H_2O	64.0% (0.69 kg/m^2)
L123 Stalk H_2O	75.9% (3.36 kg/m^2)
Whole Plant H_2O	73.3% (5.18 kg/m^2)
Leaf Area Index	4.0
Growth Stage*	42 (Soft Dough)
Leaf Thickness (mm)	0.15
Stem Diameter (mm)	2.00
Look Direction	Perpendicular to Rows
Receiver Height (m)	0.10

* LACIE Crop Inventory System

Crop	Soybeans
Site	S1
Julian Date	181
Mean Canopy Height (m) Low Angle (16°)	0.56
Mean Canopy Height (m) High Angle (52°)	0.50
Row Spacing (m)	0.77
Row Width (m)	0.54
Density (plants/m^2)	42.0 (59.9)*
Leaf H_2O	78.3%* (0.75 kg/m^2)*
Main Stem H_2O	87.7%* (0.60 kg/m^2)*
Secondary Stem H_2O	90.9%* (0.66 kg/m^2)
Whole Plant H_2O	84.8%* (2.00 kg/m^2)*
Leaf Area Index (m^2/m^2)	4.2 (6.0)*
Mean Main Stem Length (m)	0.34
Mean Secondary Stem Length (m)	0.18
Mean Secondary Stems per Plant	11.1
Growth Stage**	31 (One Open Flower)
Leaf Thickness (mm)	0.2
Main Stem Diameter (mm)	5.6
Secondary-Stem Diameter (mm)	1.9
Look Direction	Perpendicular to Rows
Receiver Height (m)	0.13

* Vegetated portion of field only (percent cover ≈70%)

** LACIE Crop Inventory System

Crop	Soybeans
Site	S1
Julian Date	188
Mean Canopy Height (m) - Low Angle (16°)	0.65
Mean Canopy Height (m) - High Angle (52°)	0.61 (0.54 Defoliated)
Row Spacing (m)	0.77
Row Width (m)	0.64
Density (plants/m^2)	42.0 (51.6)*
Leaf H_2O	72.1%* (0.62 kg/m^2)*
Main Stem H_2O	78.5%* (0.58 kg/m^2)*
Secondary Stem H_2O	81.7%* (0.60 kg/m^2)*
Whole Plant H_2O	77.2%* (1.80 kg/m^2)*
Leaf Area Index (m^2/m^2)	4.6 (5.5)*
Mean Main Stem Length (m)	0.44
Mean Secondary Stem Length (m)	0.22
Mean Secondary Stems per plant	11.1
Growth Stage**	32 (Full Bloom)
Leaf Thickness (mm)	0.2
Main Stem Diameter (mm)	5.6
Secondary-Stem Diameter (mm)	1.9
Look Direction	Perpendicular to Rows
Receiver Height (m)	0.13

* Vegetated portion of field only (percent cover ≈83%)

** LACIE Crop Inventory System