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RELATING THE RADAR BACKSCATTERING COEFFICIENT TO LEAD-AREA INDEX

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RELATING THE RADAR BACKSCATTERING COEFFICIENT TO LEAF-AREA INDEX

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ABSTRACT

This paper examines the relationship between the radar backscattering coefficient of a vegetation canopy, σ^o_{can}, and the canopy's leaf-area index (LAI). The relationship is established through the development of a model for corn and sorghum and another for wheat. Both models are extensions of the cloud model of Attema and Ulaby (1978). Analysis of experimental data measured at 8.6, 13.0, 17.0, and 35.6 GHz indicates that most of the temporal variations of σ^o_{can} can be accounted for through variations in green LAI alone, if the latter is greater than 0.5.

Mr. Eger is now with Shell Information Services, Houston, Texas

CROP YIELD

1.0 INTRODUCTION

Among the prime objectives of agricultural remote sensing is the early and accurate estimation of agricultural production in a manner superior to that of more conventional means. The first step in that direction is the identification of crop types, which usually is accomplished by means of multi-date observations of the particular test site or area of interest. Once the identities of the various field-covers in a given area have been determined, crop acreage can be estimated. In order to estimate crop production reliably, an estimate of yield-per-unit-area is needed for each of the crop types or fields concerned. In Section 2, traditional as well as remote-sensing approaches to crop yield estimation are discussed.

Several papers have been published over the past few years documenting the ability of radar to identify crop types correctly, i.e., with a classification accuracy of 90 percent or higher, based on two or three multi-date observations (Bush and Ulaby, 1978; Li et al., 1980; Hoogeboom et al., 1982; Brisco and Protz, 1981; and Shanmugan et al., 1983). The purpose of this paper is to examine the relationship between the radar backscattering coefficient of a vegetation canopy (σ^{o}_{can}) and the canopy's leaf-area-index (LAI), the latter being related to the solar radiation intercepted by the canopy, which in turn is a fundamental component of crop-yield models. The means of such an examination is based on an analysis of experimental data in terms of a modified form of the canopy "cloud" model of Attema and Ulaby (1978).

2.0 CROP YIELD AND LAI

The yield of a particular crop is a function of many variables, including the nutrients available to it and the weather conditions affecting it over the growing season. Successfully estimating a crop's yield requires knowledge of factors that include the health of the plants and their vigor at various points in time, the amount of fertilizer and water available to them, and hourly or daily weather-condition information (Daughtry et al., 1980). Meteorological information is available from organizations such as NOAA for the United States and related regions, and from the World Meteorological Organization (WMO) for worldwide weather monitoring.

Early attempts to predict yields were based upon such factors as previous years' yield, improvements in technology, and the effects of current weather conditions (MacDonald and Hall, 1980). By incorporating *a priori* knowledge such as soil type and water-table level, estimates of soil moisture information are added to the model, thus improving its predictive capacity. The amount of available solar radiation, which is the basic source of energy in the process of photosynthesis, is also a major determinant of overall yield.

As an energy source, solar radiation is available to the plant only when it interacts with the leaves. Thus, an estimate of the total area of exposed and active leaves, in conjunction with incident solar radiation, provides another measure of crop performance, and consequently of final yield. This was the reasoning used by Dale (1977) in the development of the energy-crop-growth (ECG) model. This model

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takes the form:

$$ECG = \sum_{i = t_1}^{t_2} (SR/600)_i \, (SRI)_i \, (WF)_i \, (FT)_i \qquad (1)$$

where SR is the daily solar radiation, WF is the ratio of daily evapotranspiration to potential evapotranspiration (Stuff et al., 1978), and FT is a daily temperature function that relates growth rate to temperature (Coelho and Dale, 1980). The term "solar radiation intercepted" (SRI) refers to the component that relates the available energy to that interacting with the leaves (Linvill et al., 1978).

For the maize (corn) canopy, Linvill et al., (1978) has related SRI to leaf area index (LAI) using the following equation:

$$SRI = 1 - \exp(-0.79 \cdot LAI) \qquad (2)$$

which has a range from zero to one and reaches 90 percent when LAI is about 2.9, as shown in Figure 1.

Investigators working in the optical region of the electromagnetic spectrum have related the ratio of an IR-band radiance and a red-band radiance to LAI to monitor plant performance for corn and wheat (Daughtry et al., 1980; Tucker et al., 1981). They have found that by integrating this ratio over a given period of time, accumulated dry matter, which is related to yield, may be estimated.

A correlation of 0.89 was reported between LAI and "greenness" for corn by Daughtry et al., (1982), and a correlation of 0.84 between the true yield of corn and its estimated yield, based upon meteorological data and spectral data, was also reported.

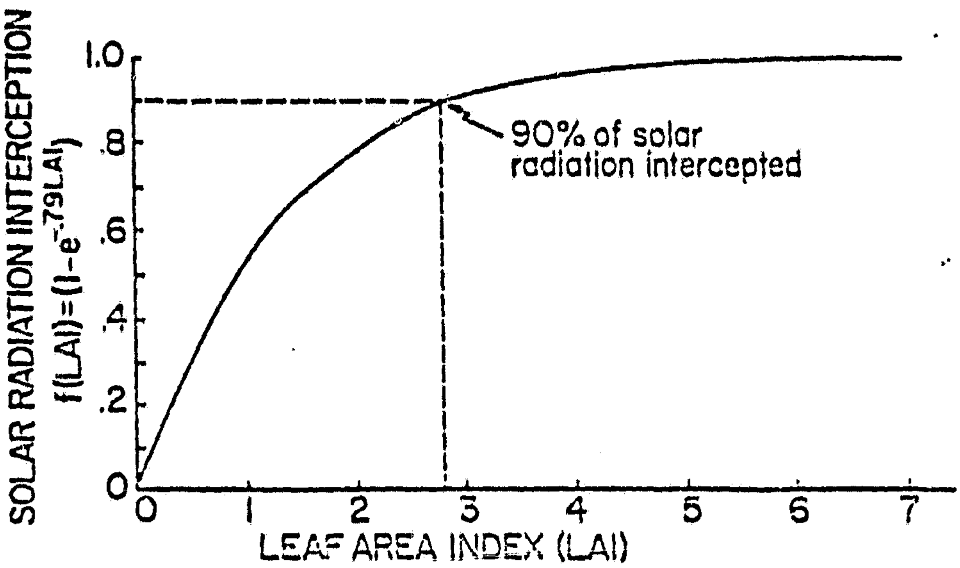
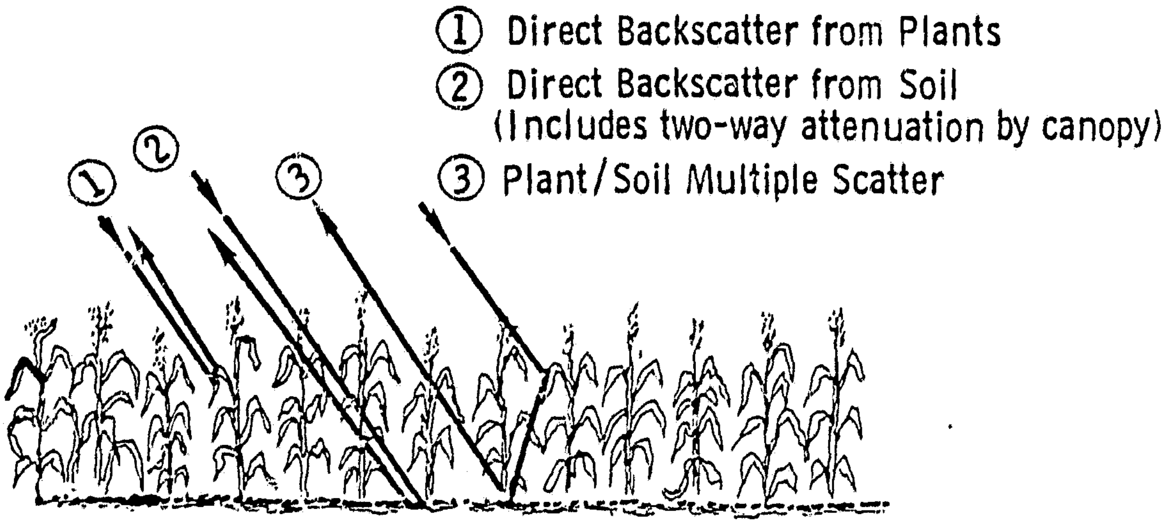


Figure 1. Solar radiation weighting factor for determining interception of solar energy by crop as a function of its leaf-area index (from Daughtry et al., 1982).

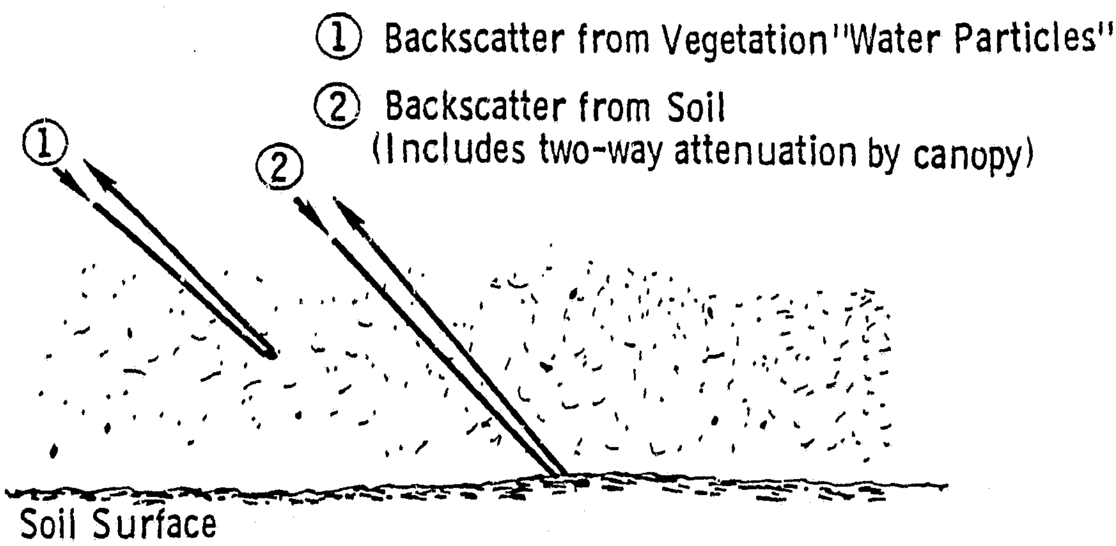
3.0 VEGETATION CANOPY MODEL

In the microwave region, a vegetation canopy may be modeled as a lossy volume of scattering elements, bounded by air above and by a scattering soil surface below (Figure 2a). The backscattering coefficient σ^o_{can} represents the sum of the contributions from the canopy itself, from direct backscattering by the soil (including two-way attenuation to account for propagation between the air-canopy boundary and the canopy-soil boundary and back), and from multiple scattering between the canopy scattering elements and the soil surface.

In general, the scattering behavior of the canopy volume is governed by the dielectric properties and geometric configurations of the scattering elements (leaves, stalks, and fruit), the latter being defined with respect to the wavelength, direction, and polarization of the incident wave. A first-order canopy backscattering model was developed by Attema and Ulaby (1978), who treated the canopy as a water cloud consisting of a collection of identical water particles (Fig. 2b) characterized by a uniform scattering phase function. The water-cloud assumption is a consequence of the domination of the dielectric constant of green vegetation (which is a mixture of vegetative matter and water) by the dielectric constant of water; while the relative dielectric constant of water is about 80 (below 10 GHz), the dielectric constant of dry vegetation is on the order of 2 to 3 (Carlson, 1967; Jedlicka et al., 1983). Ignoring contributions resulting from multiple scattering between the canopy particles and the soil surface, the backscattering coefficient of the canopy (including



(a) Scattering Sources



(b) Equivalent Cloud Model

Figure 2. Backscattering contributions from a vegetation canopy, (a) scattering sources, and (b) equivalent "cloud" representation in terms of water scatterers.

soil contributions) is given by:

$$\sigma^o_{can}(\theta) = \sigma^o_{veg}(\theta) + \sigma^o_{soil}(\theta) \qquad (3)$$

where σ^o_{veg} is the contribution of the vegetation volume, σ^o_{soil} is the backscattering contribution of the soil surface in the presence of vegetation cover, and θ is the angle of incidence relative to nadir. Assuming the scattering water particles to be uniformly distributed within the canopy volume, Attema and Ulaby (1978) derived an expression for $\sigma^o_{veg}(\theta)$ by integrating the backscattering contributions of thin strata between the air-vegetation boundary and the vegetation-soil boundary,

$$\sigma^o_{veg}(\theta) = \frac{\sigma_v \cos\theta}{2\,\kappa_e}\,[1 - T^2\,(\theta)],\ m^2\ m^{-2} \qquad (4)$$

where

$$T^2(\theta) = \exp(-2\kappa_e\ h\ \sec\theta) \qquad (5)$$

h = canopy height, m,

κ_e = canopy extinction coefficient, m^{-1},

σ_v = canopy volume backscattering coefficient, m^{-1}, and T^2 is the two-way transmission coefficient of the canopy, $m^2\ m^{-2}$.

The soil backscattering coefficient, $\sigma^o_{soil}(\theta)$, depends on the soil's surface roughness and its dielectric properties, the latter being governed strongly by the moisture content of the soil surface layer. When radar is used as a vegetation monitor, the angle of incidence θ usually is chosen to be greater than 40^o and the wavelength is chosen to be on the order of 3 cm or shorter. Both choices are made, in part, in order to make τ as small as possible, thereby decreasing the soil backscattering contribution (the second term in (3)) to a negligible level in comparison to the vegetation backscattering contribution. If the second term in (3) is indeed much smaller than the first, it may be neglected. In general, however, σ^o_{soil} may be described by the simple expression (Attema and Ulaby, 1978):

$$\sigma^o_{soil}(\theta) = [C(\theta)\ m_s]\ \tau^2(\theta) \tag{6}$$

where $C(\theta)$ is a constant for a given wavelength and polarization configuration, and m_s is the soil moisture content. In general, $C(\theta)$ is a function of the soil surface roughness, but if $\lambda \leq 3$ cm, $C(\theta)$ is approximately roughness-independent over the range of random roughness usually encountered in the case of agricultural crops.

4.0 Cloud Model in Terms of Canopy Water Content

Attema and Ulaby (1978) assumed that the "equivalent" scattering water particles of the vegetation volume are all spherical in shape, identical in size, and small relative to the wavelength λ, in which case,

$$\sigma_v = N\ \sigma_b \tag{7}$$

$$\kappa_e = N\ Q_e \tag{8}$$

where $N(m^{-3})$ is the number of scattering particles per unit volume and $\sigma_b(m^2)$ and $Q_e(m^2)$ are the backscattering cross-section and extinction cross-section for a single particle, respectively. For an atmospheric water cloud, κ_e is directly proportional to the cloud's volumetric water content m_v (kg m^{-3}). Hence, for the canopy "cloud," κ_e may be expressed as

$$\kappa_e = A_1 \, m_v \tag{9}$$

where A_1 is considered a constant at a given wavelength λ. In general, A_1 may also be a function of the physical temperature of the canopy (through the temperature dependence of the dielectric constant of water), the wave polarization, and the shapes and sizes of the real scattering elements (leaves, stalks, and fruit). Approaches that incorporate some of the geometrical characteristics of the canopy are discussed in the next section.

Similarly,

$$\sigma_v = A_2 \, m_v \tag{10}$$

where A_2 is a constant, and

$$\frac{\sigma_v}{2 \, \kappa_e} = \frac{A_1}{2 \, A_2} \overset{\Delta}{=} A_3. \tag{11}$$

Hence, the above ratio, which appears as the front part of the expression given by (4), is a constant. This is a consequence of the assumption that all the equivalent water particles are spherical in shape and identical in size. If the particles are spherical, but their sizes are distributed over a range of values, the relation given by (9) will continue to hold, but that given by (10) may not. For an atmospheric cloud, for example, σ_v is proportional to m_v^2 rather than to m_v. Hence, in general, the ratio on the right-hand side of (11) may be written in the form:

$$\frac{\sigma_v}{2\,\kappa_\theta} = A_4\, m_v^x \qquad (12)$$

where x is a constant exponent.

Upon inserting (4), (6), (9), and (12) into (3) and (5), the following expressions are obtained:

$$\sigma^o_{can}(\theta) = A_4\, m_v^x \quad \cos\theta\, [1 - \tau^2(\theta)] + \tau^2(\theta)\, C(\theta)\, m_s \qquad (13)$$

and

$$\tau^2(\theta) = \exp(-2\, A_1\, m_v\, h\, \sec\theta) \qquad (14)$$

where A_1, A_4, C, and x are constants for a given crop type and sensor configuration (wavelength, polarization, and incidence angle), m_v and h are physical parameters of the vegetation canopy, and m_s is the soil moisture content. As was mentioned earlier, Attema and Ulaby (1978) assumed that the particles are all identical in size, which corresponds to the case where $x = 0$. By regressing experimental data against a model of the form given in (13), they determined the values of A_1, A_4, and C for several crops at each of several frequencies. In a more recent study, Hoekman et al. (1982) also found the cloud model to provide a good description of the temporal behavior of the backscattering coefficient for several crop types. For cereal grains, however, the model failed to predict the large changes in σ^o_{can} that were observed in conjunction with the appearance of the heads. This led Hoekman et al. (1982) to subdivide the vegetation layer into two layers: a lower layer representing the stalks and leaves, and an upper layer representing the ears or heads. Using this two-layer form of the model, they obtained good agreement between measured and model-predicted values of σ^o_{can} over the full growth cycle for each of eight crops.

5.0 DESCRIPTION OF EXPERIMENT

In an effort to investigate further the connection between the physical parameters of the canopy (m_v, h, LAI, etc.) and the radar backscattering coefficient σ^o_{can}, field experiments were conducted at a test site near Manhattan, Kansas, during the growing seasons of 1979 and 1980. The experiments were conducted by the Remote Sensing Laboratory at the University of Kansas in cooperation with the Evapotranspiration Laboratory at Kansas State University, Manhattan.

A truck-mounted scatterometer was used to measure σ^o_{can} at 8.6, 13.0, 17.0, and 35.6 GHz (or equivalently, λ = 3.5 cm, 2.3 cm, 1.76 cm, and 8.4 mm). A total of 14 fields were observed in 1979, six each of corn and sorghum, and two of wheat (see Table 1). Each observation sequence consisted of measurements at angles of incidence θ of 30°, 50°, and 70° for each of three linear polarization configurations (HH, HV, VV). In 1980, the observations were limited to θ = 50°, and the number of fields was reduced to six, thereby increasing the number of temporal observations per field from an average of seven for 1979 to 23 for 1980.

In support of and contemporaneously with the radar observations, several plant- and soil-properties were measured, including plant height, the fresh weight W_w and dry weight W_d of individual plant parts (leaves, stalks, and fruit), plus the density of the whole plant, the

TABLE 1

Experiment Data Summary

1979 Experiment			
Crop	No. of Fields	Start/Stop Dates	No. of Observations Per Field
Wheat	2	4/26 - 7/2	10
Corn	6	6/5 - 9/11	6
Sorghum	6	6/5 - 9/11	6

1980 Experiment			
Crop	No. of Fields	Start/Stop Dates	No. of Observations Per Field
Corn	3	6/6 - 9/10	23
Sorghum	3	6/6 - 9/10	24

Radar Parameters

Angle of Incidence θ: 50° (also 30° and 70° in 1979)

Polarization: VV, VH, HH

Frequencies: 8.6, 13.0, 17.0, 35.6 GHz

LAI, soil moisture content m_s, planting density N_p (plants m^{-2}), and stage of growth. The volumetric water content of the canopy can be determined from:

$$m_v = (W_w - W_d)\ N_p/h \qquad (15)$$

where W_w and W_d are the average wet and dry weights of an entire plant.

Examples of the observed temporal patterns of σ^o_{can} are shown in Figures 3 to 5 for winter wheat, corn, and sorghum, all at 13.0 GHz, $\theta = 50^o$, and VV polarization configuration. Also shown in these figures are plots of the green-leaf area index, which show a fair degree of similarity to the plots of σ^o_{can}, except for the period preceding harvest. It was also observed from the field data that the leaf-area-index (LAI) was highly correlated to the dry and to the wet (leaf) vegetation biomasses. This proves to be an important link, as will become apparent in the next section.

6.0 Multi-Component Cloud Model

After completion of the processing and calibration of the data described in the previous section, the data were used to evaluate the applicability of the model given by (13). First, the model was evaluated by correlating the measured value of σ^o_{can} to the value calculated using (13) with the constants A_1, A_4, and C being assigned the values that were determined by Attema and Ulaby (1978). This

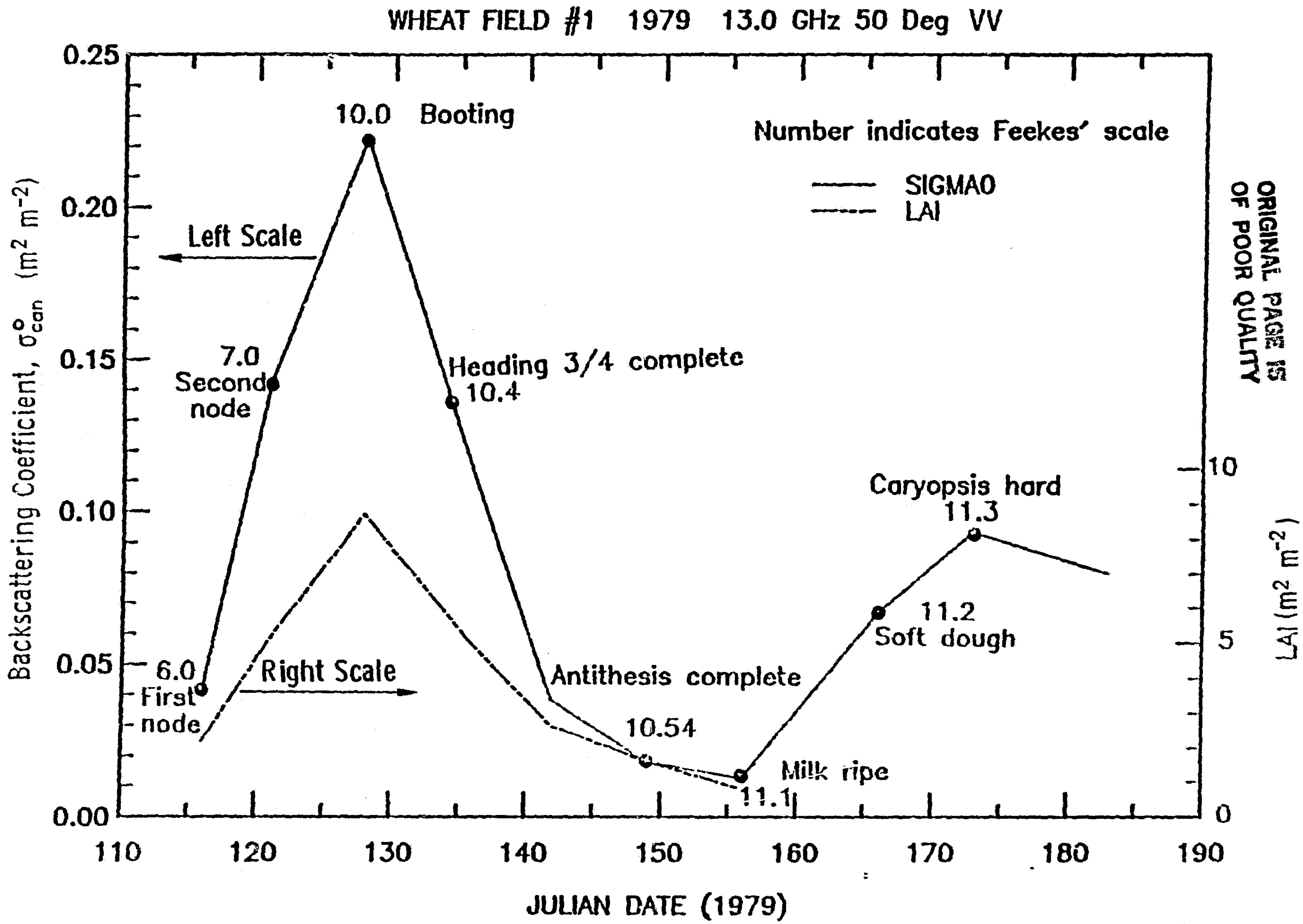


Figure 3. Measured temporal patterns of the backscattering coefficient and leaf-area index (LAI) of a wheat field. Stage of growth is indicated by the Feekes scale (Large, 1954).

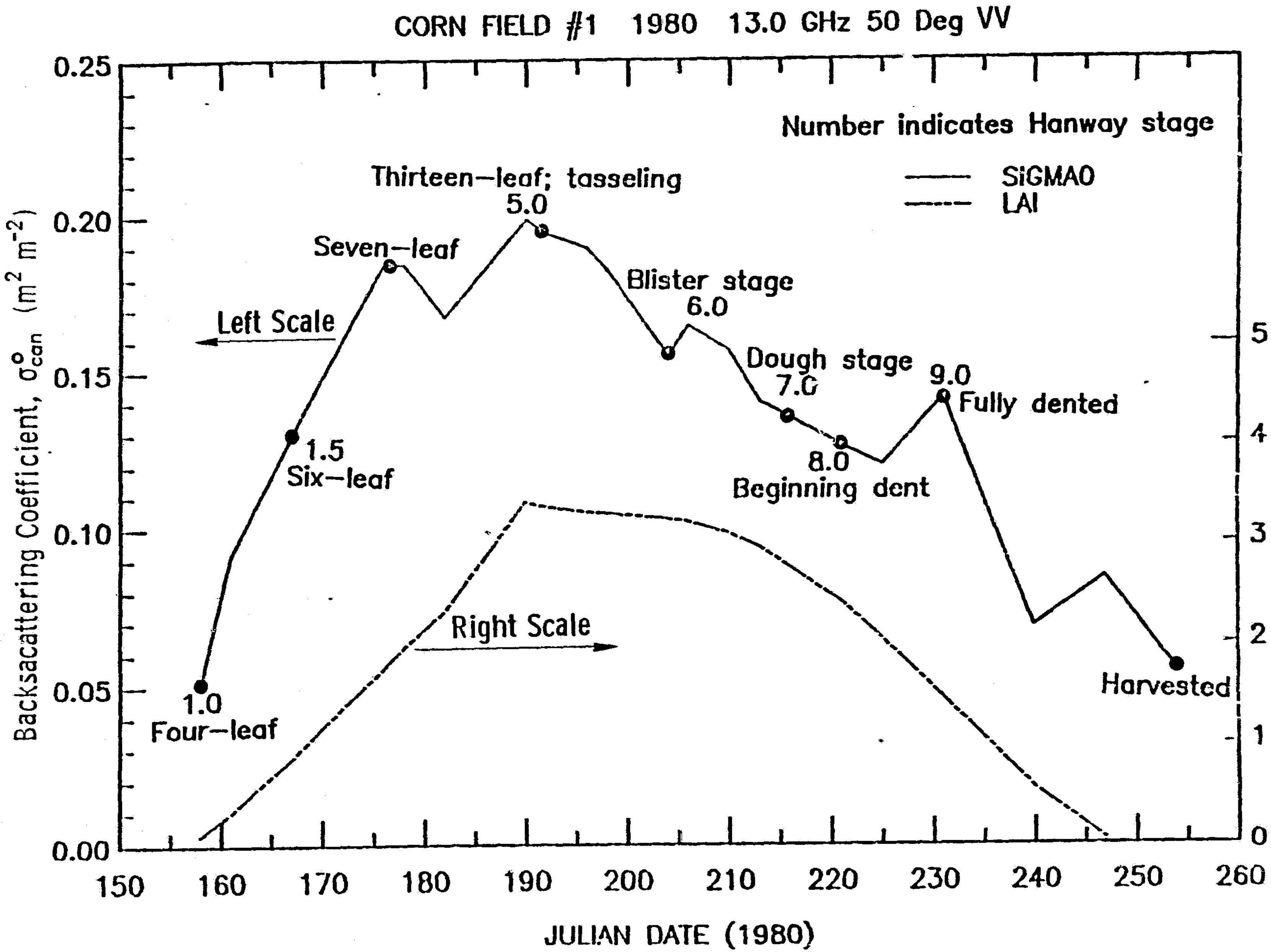


Figure 4. Measured temporal patterns of the backscattering coefficient and leaf-area index (LAI) of a corn field. Stage of growth is indicated by the Hanway stage (Hanway, 1971).

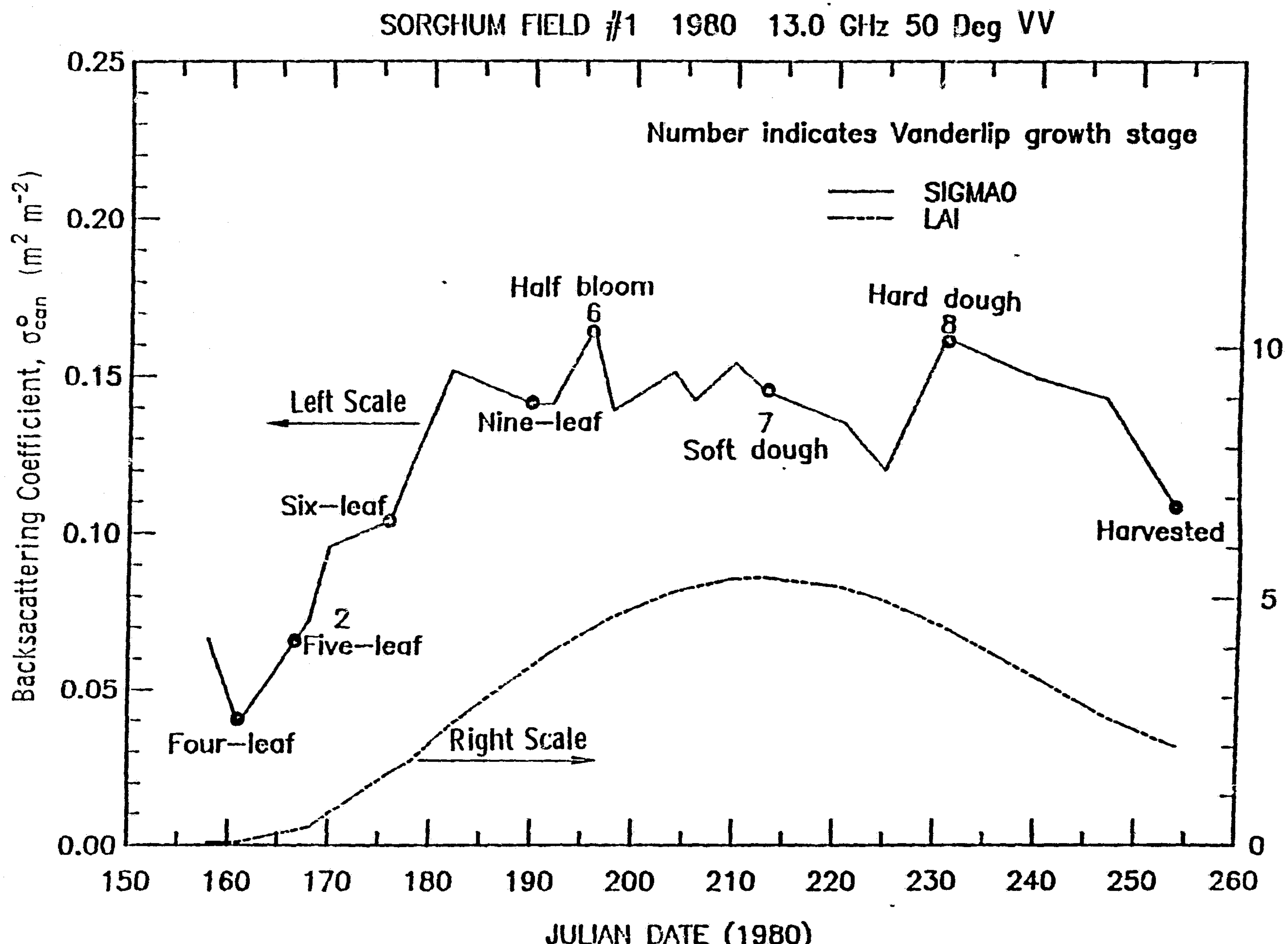


Figure 5. Measured temporal patterns of the backscattering coefficient and leaf-area index (LAI) of a sorghum field. Stage of growth is indicated by the Vanderlip growth stage (Vanderlip, 1972).

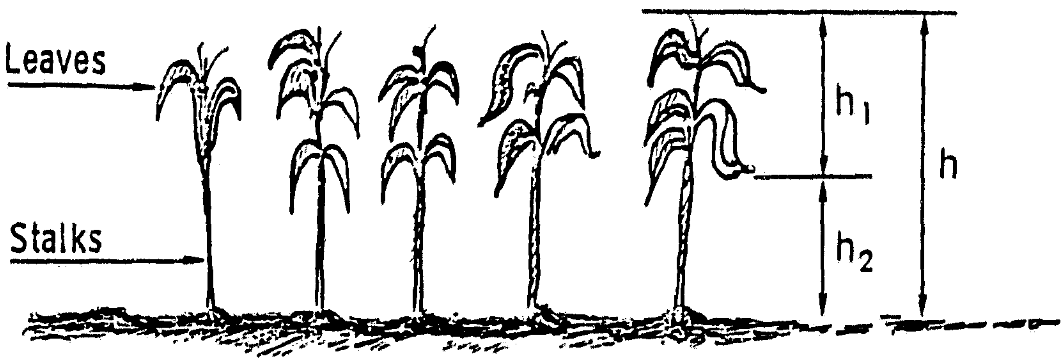
resulted in a linear correlation coefficient ρ between 0.6 and 0.8 (for the various combinations of crop type, microwave frequency, angle of incidence, and polarization). Next, another correlation analysis between measured and calculated values of σ^o_{can} was performed, except this time the constants were first determined empirically by regressing the data against the model. Some improvement in the magnitude of ρ was obtained, but ρ exceeded 0.8 only in a few cases.

To improve the applicability of the cloud model, two modifications were made, both of which resulted in better agreement between the measured temporal pattern of σ^o_{can} and that calculated by the model.

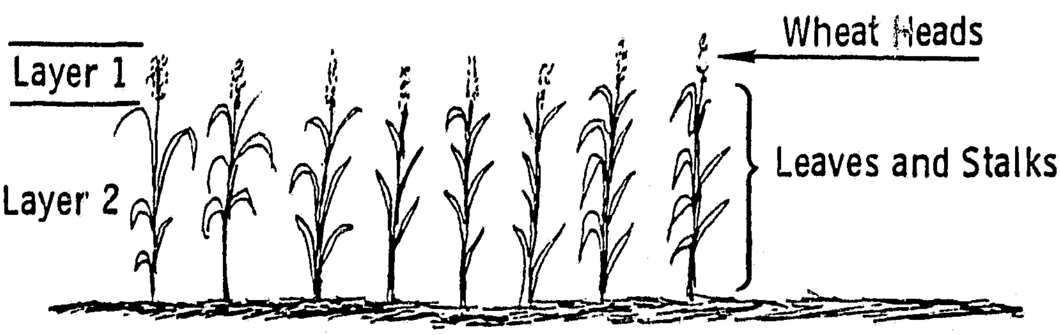
6.1 Corn and Sorghum

The first modification provides for separate accounting for the radar backscattering contributions of the leaves, the stalks, and the soil. For corn and sorghum, the canopy was assumed to consist of two layers: an upper layer of height h_1, dominated by leaves, and a lower layer of height h_2, dominated by stalks (Figure 6a). The backscatter contribution of the fruit was ignored, in part to simplify the model, and in part because of the results of a defoliation experiment for corn which showed that the backscattering contribution of the fruits is much smaller than that of the stalks or leaves (Ulaby, 1982). These assumptions lead to:

$$\sigma^o_{can}(\theta) = \sigma^o_{leaf}(\theta) + \sigma^o_{stalk}(\theta) + \sigma^o_{soil}(\theta) \qquad (16)$$



(a) Two-Layer Model for Corn and Sorghum



(b) Model for Wheat after Heading

Figure 6. Two-layer model for (a) corn and sorghum, and (b) for wheat after heading.

where $\sigma^o_{leaf}(\theta)$ has the same form as (4),

$$\sigma^o_{leaf}(\theta) = \frac{\sigma_{v\ell}\cos\theta}{2\,\kappa_{e\ell}}\left[1 - T^2_{leaf}(\theta)\right], \qquad (17)$$

and $T^2_{leaf}(\theta) = \exp(-2\,\kappa_{e\ell}\,h_1\sec\theta)$. (18)

In the above expressions, h_1 is the "effective" height of the top layer, assumed to consist of leaves exclusively, and $\sigma_{v\ell}$ and $\kappa_{e\ell}$ are the volume backscattering coefficient and extinction coefficient of that layer. The stalk's contribution was assumed to be given by:

$$\sigma^o_{stalk}(\theta) = T^2_{leaf}(\theta)\,\sigma^o_{stalk}(\theta;\ h_1 = 0) \qquad (19)$$

where σ^o_{stalk} $(h_1 = 0)$ is the stalk contribution in the absence of leaves. Finally, the soil component is given by a form similar to that of (6) except that the attenuation through the canopy is now due to two layers: a top layer with transmission coefficient T_{leaf} and a lower layer with transmission coefficient T_{stalk}.

$$\sigma^o_{soil}(\theta) = [C(\theta)\,m_s]\,T^2_{leaf}(\theta)\,T^2_{stalk}(\theta), \qquad (20)$$

where

$$T^2_{stalk}(\theta) = \exp(-2\,\kappa_{es}\,h_2\sec\theta) \qquad (21)$$

and κ_{es} is extinction coefficient of the stalk layer.

The second modification to the model involves the use of green LAI. In Section 4, σ^o_{can} was expressed in terms of three physical parameters: the soil moisture content m_s, the volumetric water content of the canopy m_v, and the canopy height h. Actually, the key quantity driving the model is the product $m_v h$, which represents the total amount of integrated water contained in a vertical column of unity horizontal cross-section. The model in this section divides the canopy into two layers, with the top layer assumed to contain essentially all the leaves and the bottom layer assumed to contain the entire length of the stalk. The quantity $m_v h_1$ for the top layer is related to the wet and dry biomasses of the leaves, which in turn, are related to the green LAI (Zrust et al., 1974; Ashley et al., 1965; Aase, 1978; Holben et al., 1980). Hence, instead of expressing τ_{leaf} in terms of $m_v h_1$ (as in (14)), it will be defined in terms of LAI:

$$\tau^2_{leaf}(\theta) = \exp(-2\, B_{leaf}\, \mathrm{LAI}\, \sec\theta). \qquad (22)$$

For the stalk layer, it will be assumed that the scattering by the stalks, as well as the attenuation by them, is proportional to $m_v h_2$ where m_v is the volumetric water content of the stalk layer, hence,

$$\sigma^o_{stalk}(\theta) = A_{stalk}\, m_v h_2\, \tau^2_{leaf}(\theta) \sin\theta \qquad (23)$$

and

$$\tau^2_{stalk}(\theta) = \exp(-2\, B_{stalk}\, m_v h_2 \sec\theta) \qquad (24)$$

where A_{stalk} and B_{stalk} are constants (for a given crop type, microwave frequency, and polarization). Finally, it will be assumed that the ratio $\sigma_{v\ell}/\kappa_{e\ell}$ obeys the assumptions that led earlier to (11). Grouping the above terms leads to:

$$\begin{aligned}\sigma^o_{can}(\theta) = {} & A_{leaf} \cos\theta[1 - \tau^2_{leaf}(\theta)] \\ & A_{stalk}\, m_v h_2\, \tau^2_{leaf}(\theta) \sin\theta \\ & + [C_{soil}(\theta)\, m_s]\, \tau^2_{leaf}(\theta) \tau^2_{stalk}(\theta)\end{aligned} \qquad (25)$$

The above expression contains five coefficients and three physical parameters: (a) green LAI, (b) $m_v h_2$, the total water content of the stalks per unit area, and (c) m_s, the volumetric soil moisture content. The coefficients were determined by using a non-linear regression program that minimizes the least-squares error between the predicted and observed values. Data from all three fields (of 1980 sorghum or 1980 corn) were used to generate the coefficients, and then the model was used to predict the temporal pattern of σ^o for each field individually. The values of the coeffcients obtained are given in Tables 2 and 3 for corn and sorghum, respectively. Also given is the linear correlation coefficient between the measured and predicted values of σ^o_{can} for each field at each of the four frequencies. Figures 7 and 8 show comparisons for corn and sorghum, respectively. Each figure contains a plot of the predicted σ^o_{can}, denoted σ^o_{pred}, as well as plots of its component contributions as defined by (16) or by the three individual terms in (25). It is observed that:

(a) Except for the period prior to Julian day 170 (for which the plant height was less than 0.8 m for corn and less than 0.6 m for sorghum) and for the pre-harvest period after Julian day 240, the leaves provide the overwhelming majority of the backscattered energy.

(b) The soil and stalk terms are important only if LAI < 0.5.

(c) The stalk attenuation coefficient, B_{stalk}, was found to be very small in magnitude, and when it was set equal to zero (i.e. setting $T_{stalk} = 1$), the model remained effectively the same.

(d) A better fit could be obtained for corn if the leaf attenuation coefficients, B_{leaf}, were to be assigned different values for the two periods before and after Julian day 190, which corresponds to the date

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TABLE 2

Coefficients for the Corn Model Given by Equation (25) Rewritten in the Following Abbreviated Form for $\theta = 50°$ and VV Polarization:

$$\begin{aligned}\sigma^o_{can} &= \sigma^o_{leaf} + \sigma^o_{stalk} + \sigma^o_{soil} \\ &= A'_{leaf}\,[1 - T^2_{leaf}] \\ &\quad + A'_{stalk} \cdot m_v \cdot h_2 \cdot T^2_{leaf} \\ &\quad + C_{soil} \cdot m_s \cdot T^2_{leaf} \cdot T^2_{stalk}\end{aligned}$$

$$\text{where } T^2_{leaf} = \exp(-B'_{leaf} \cdot LAI)$$

$$T^2_{stalk} = \exp(-B'_{stalk} \cdot m_v \cdot h_2)$$

and $h_2 = h$, the canopy height

The coefficients were determined through the use of a nonlinear regression program. The correlation coefficient ρ_i is the linear correlation between the observed values σ^o_{obs} and the predicted values σ^o_{pred} for Field i, and ρ_{all} is for all three fields combined.

Frequency (GHz)	A'_{leaf}	A'_{stalk}	B'_{leaf}	B'_{stalk} $m^2\ kg^{-1}$	C_{soil} $cm^3\ g^{-1}$	ρ_{all} (N = 69)	ρ_1 (N = 21)	ρ_2 (N = 22)	ρ_3 (N = 26)
8.6	0.1359	0.01662	1.046	0	0.2118	0.895	0.837	0.931	0.895
13.0	0.1697	0.01783	1.124	0	0.2094	0.885	0.900	0.899	0.928
17.0	0.1925	0.01254	0.895	0	0.271	0.852	0.845	0.860	0.938
35.6	0.2209	0.02487	0.8430	0	0.1451	0.914	0.894	0.938	0.926

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TABLE 3

Coefficients for the Sorghum Model Given by Equation (25) Rewritten in the Following Abbreviated Form for $\theta = 50°$ and VV Polarization:

$$\sigma^o_{can} = \sigma^o_{leaf} + \sigma^o_{stalk} + \sigma^o_{soil}$$
$$= A'_{leaf}\,[1 - T^2_{leaf}]$$
$$+ A'_{stalk} \cdot m_v \cdot h_2 \cdot T^2_{leaf}$$
$$+ C_{soil} \cdot m_s \cdot T^2_{leaf} \cdot T^2_{stalk}$$

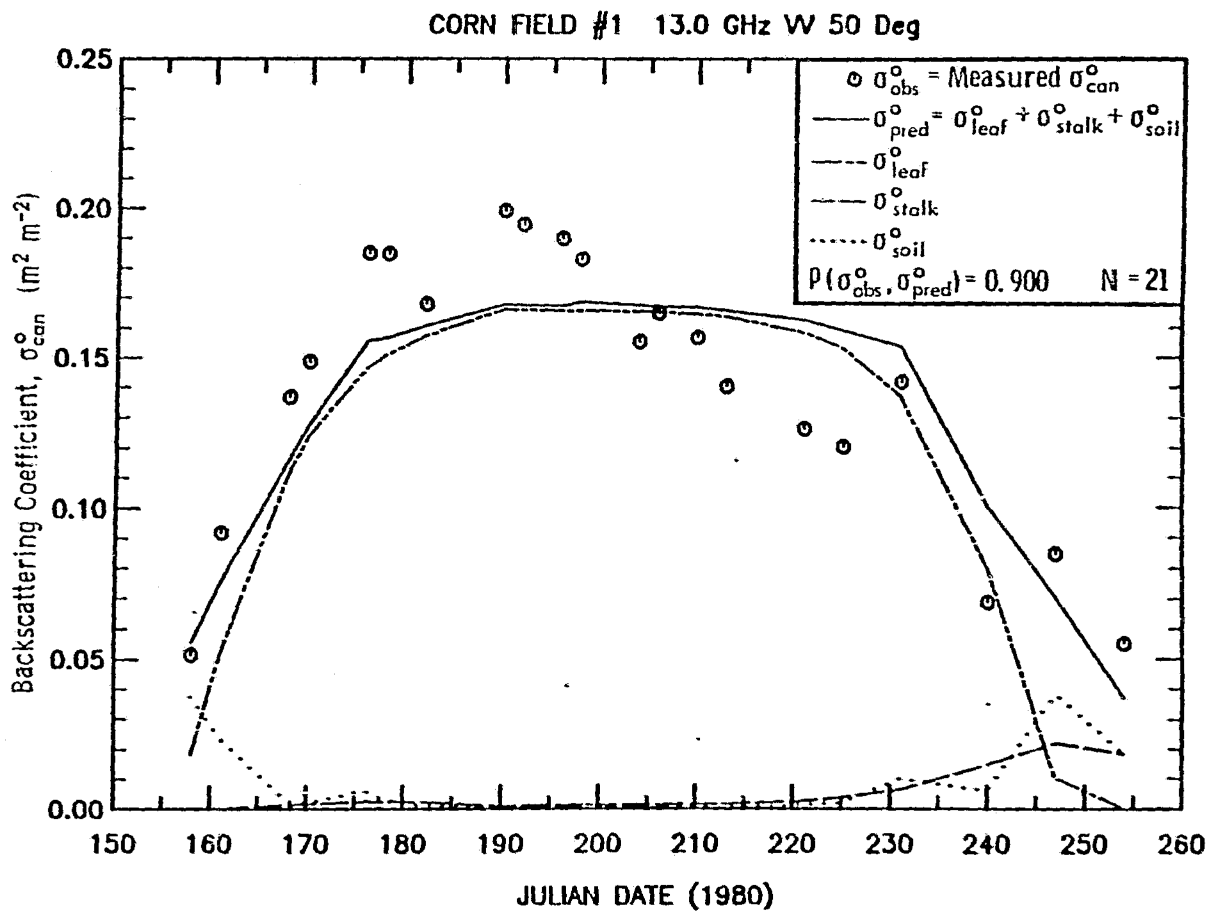
where $T^2_{leaf} = \exp(-B'_{leaf} \cdot LAI)$

$T^2_{stalk} = \exp(-B'_{stalk} \cdot m_v \cdot h_2)$

and $h_2 = h$, the canopy height

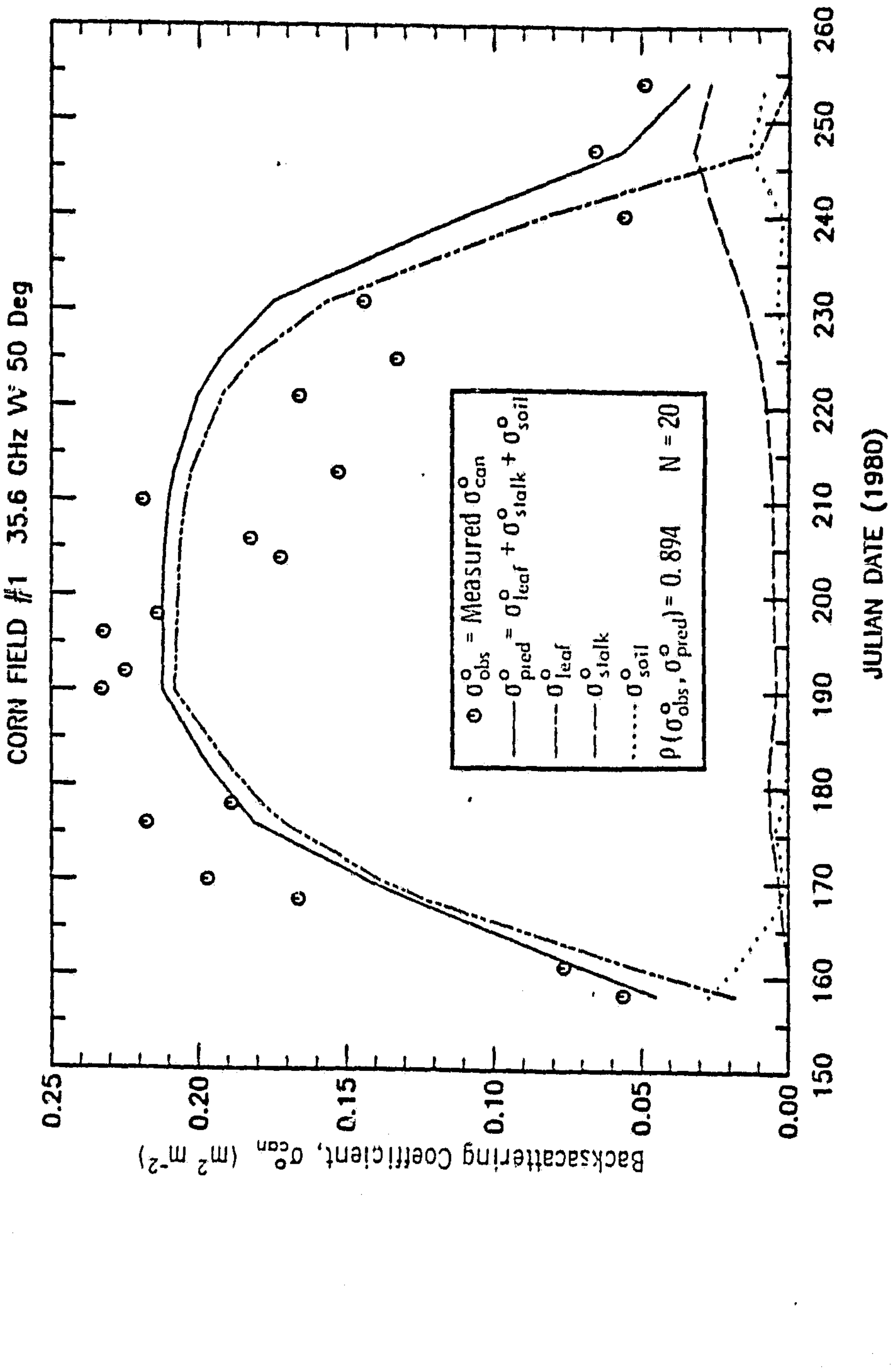
The coefficients were determined through the use of a nonlinear regression program. The correlation coefficient ρ_i is the linear correlation between the observed values σ^o_{obs} and the predicted values σ^o_{pred} for Field i, and ρ_{all} is for all three fields combined.

Frequency (GHz)	A'_{leaf}	A'_{stalk}	B'_{leaf}	B'_{stalk} $m^2\ kg^{-1}$	C_{soil} $cm^3\ g^{-1}$	ρ_{all} (N = 71)	ρ_1 (N = 21)	ρ_2 (N = 23)	ρ_3 (N = 27)
8.6	.1120	.1187	1.057	0	.1626	.890	.946	.917	.856
13.0	.1442	.1125	.9628	0	.1765	.925	.929	.929	.933
17.0	.1579	.1357	.8816	0	.1568	.943	.953	.938	.954
35.6	.1688	.03348	1.446	0	.07712	.936	.930	.963	.941

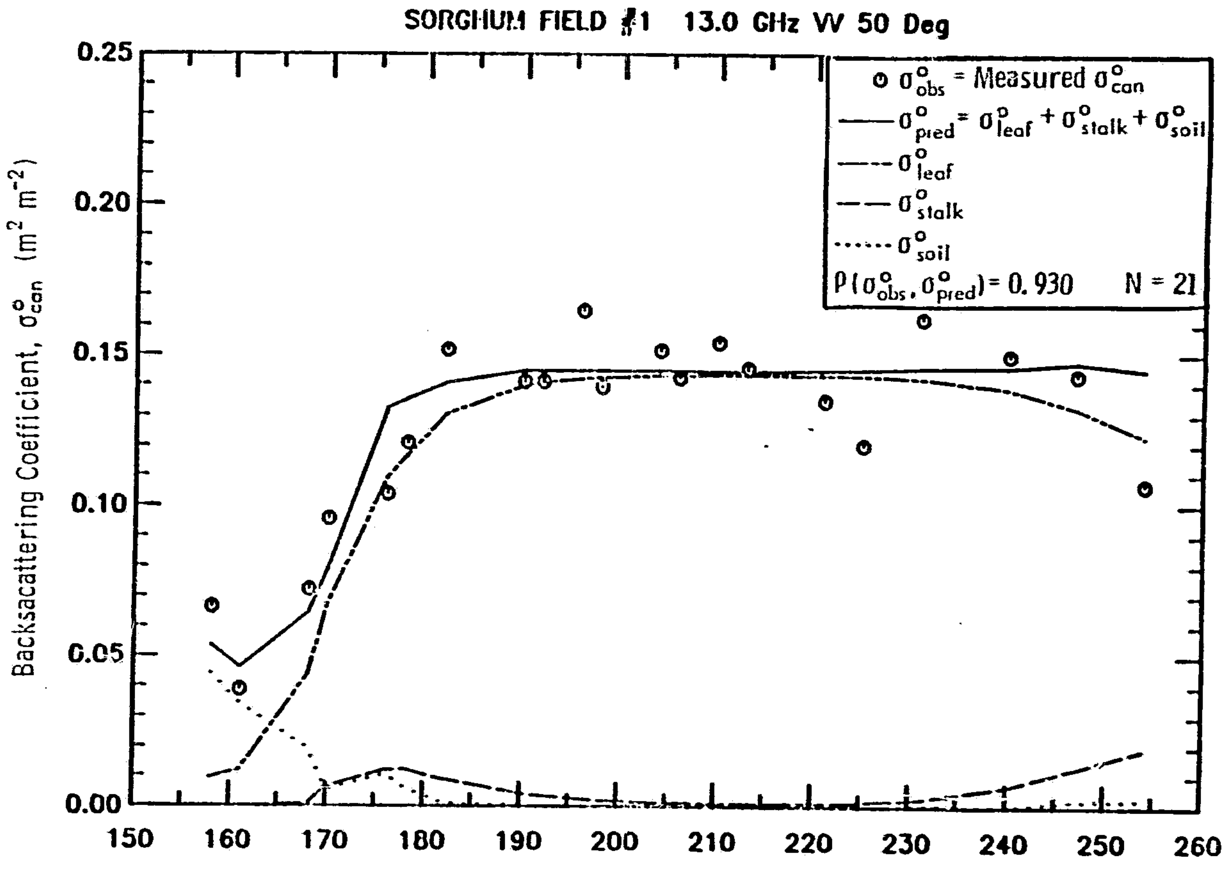


(a)

Figure 7. Comparison of measured backscattering coefficient of corn with that computed using Eq. (25) at (a) 13.0 GHz and (b) 35.6 GHz, 50° incidence angle, and VV polarization.

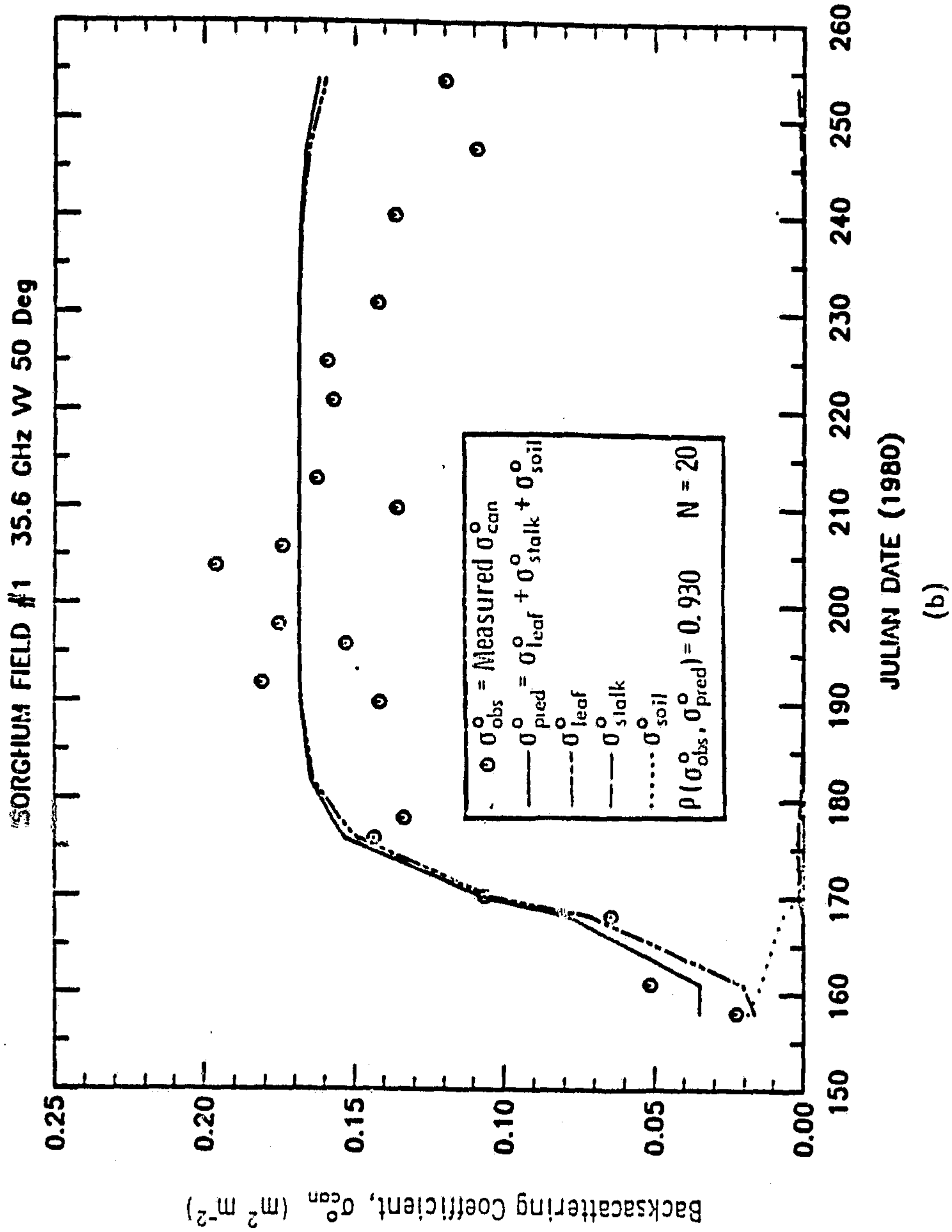

CORN FIELD #1 35.6 GHz VV 50 Deg
σ^o_{obs} = Measured σ^o_{can}
$\sigma^o_{pred} = \sigma^o_{leaf} + \sigma^o_{stalk} + \sigma^o_{soil}$
σ^o_{leaf}
σ^o_{stalk}
σ^o_{soil}
$\rho(\sigma^o_{obs}, \sigma^o_{pred}) = 0.894$ N = 20
Backscattering Coefficient, σ^o_{can} (m^2 m^{-2})
0.25
0.20
0.15
0.10
0.05
0.00
150
160
170
180
190
200
210
220
230
240
250
260
JULIAN DATE (1980)

(b)



(a)

Figure 8. Comparison of measured backscattering coefficient of sorghum with that computed using Eq. (25) at (a) 13.0 GHz and (b) 35.6 GHz, 50° incidence angle, and VV polarization.


SORGHUM FIELD #1 35.6 GHz VV 50 Deg
Backscattering Coefficient, σ^o_{can} ($m^2\ m^{-2}$)
JULIAN DATE (1980)
0.25
0.20
0.15
0.10
0.05
0.00
150
160
170
180
190
200
210
220
230
240
250
260
σ^o_{obs} = Measured σ^o_{can}
$\sigma^o_{pred} = \sigma^o_{leaf} + \sigma^o_{stalk} + \sigma^o_{soil}$
σ^o_{leaf}
σ^o_{stalk}
σ^o_{soil}
$\rho(\sigma^o_{obs}, \sigma^o_{pred}) = 0.930$ N = 20

(b)

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at which the LAI reaches its peak value. It has been suggested that the optical transmission properties of leaves change in magnitude as the plant enters the senescence phase. The same may be true for the microwave part of the spectrum, but no data exists at present to support such a hypothesis.

6.2 Wheat

Wheat has a significantly different geometry from that of corn or sorghum, thereby necessitating that certain modifications be introduced to the model of the previous section. First, the wheat stalks are much smaller and contain a smaller portion of the total plant water. Hence, the stalk's backscattering contribution will be neglected. Secondly, the size, location, and relative water content of the heads suggest that their backscattering contributions should be accounted for explicitly (rather than being ignored or lumped with the stalks, as was done in the previous section for corn and sorghum). Additionaly, since the heads of the wheat plants are above the leaves (Figure 6b), the leaves should not attenuate the backscattering from the head; rather, it should be the other way around. These modifications, plus some others discussed below, lead to the expression

$$
\begin{aligned}
\sigma^o_{can}(\theta) &= \sigma^o_{leaf}(\theta) + \sigma^o_{head}(\theta) + \sigma^o_{soil}(\theta) \\
&= A_{leaf} \cdot LAI[1 - T^2_{leaf}(\theta)]\ T^2_{head} \cos\theta \\
&+ A_{head}(\theta) \cdot M_{head} \\
&+ C_{soil}(\theta)\ m_s\ T^2_{leaf}(\theta)\ T^2_{head}(\theta)
\end{aligned}
$$

where $T^2_{leaf}(\theta)$ is given by (22), M_{head} is the head biomass in kg m^{-2}, and

$$T^2_{head}(\theta) = \exp(-2\ B_{head}\ M_{head}\ \sec\theta). \qquad (27)$$

The coefficient of the σ^o_{leaf} term is (A_{leaf} • LAI), which is somewhat equivalent to (12) with x = 1. This form is used, rather than simply A_{leaf}, because it resulted in significantly better agreement between the measured and predicted values of σ^o_{can} for wheat (as discussed in more detail in the next section).

The field measurements did not include direct measurements of the head's biomass, M_{head}; therefore, an estimate was needed. If the plant is assumed to be fully developed before heading takes place, then the dry weight due to the leaves and stalks should remain constant for the period during and after heading (assuming no leaves fall off the plant). Any change in dry weight after the onset of heading will therefore be directly related to the development of the head. This reasoning leads to:

$$M_{head}(t) = \begin{cases} 0, & \text{for } t < t_o;\ t_o = \text{heading date} \\ W_d(t) - W_d(t_o), & \text{for } t > t_o \end{cases} \qquad (28)$$

where W_d is the total plant dry biomass in Kg m^{-2}. For the fields observed in 1979, t_o = 136 (May 16, 1979).

Following a determination of the values of the five coefficients employed in the model (see Table 4), plots were generated to compare σ^o_{pred} to σ^o_{obs}. Examples are shown in Figures 9a and 9b for 13 GHz and 35.6 GHz, respectively. In both cases, the model provides a good fit to the measured data, and indicates that the backscatter is almost

TABLE 4

Coefficients for the Wheat Model Given by Eq. (26), Rewritten in the Following Abbreviated Form for $\theta = 50°$ and VV Polarization:

$$\sigma^o_{can} = \sigma^o_{leaf} + \sigma^o_{head} + \sigma^o_{soil}$$

$$= A'_{leaf} \cdot LAI\,(1 - T^2_{leaf})\,T^2_{head}$$

$$+ A_{head} \cdot M_{head}$$

$$+ C_{soil} \cdot m_s \cdot T^2_{leaf} \cdot T^2_{head}$$

where $T^2_{leaf} = \exp(-B'_{leaf} \cdot LAI)$

$$T^2_{head} = \exp(-B'_{head} \cdot M_{head})$$

Frequency (GHz)	A'_{leaf}	A_{head}	B'_{leaf}	B'_{head} $m^2\ kg^{-1}$	C_{soil} $cm^3\ g^{-1}$	ρ_1 (N = 10)	ρ_2 (N = 8)
8.6	0.0202	0.1062	1.1704	3.980	1.290	0.776	0.844
13.0	0.0267	0.0650	0.7480	2.778	0.8050	0.973	0.847
17.0	0.0297	0.0460	0.5530	2.223	0.5813	0.949	0.958
35.6	0.0348	0.0138	0.2228	1.284	0.2023	0.978	0.879

The coefficients were determined through the use of a nonlinear regression program. The correlation coefficient ρ_i defines the linear correlation between the observed values σ^o_{obs} and the predicted values σ^o_{pred} for Field i.

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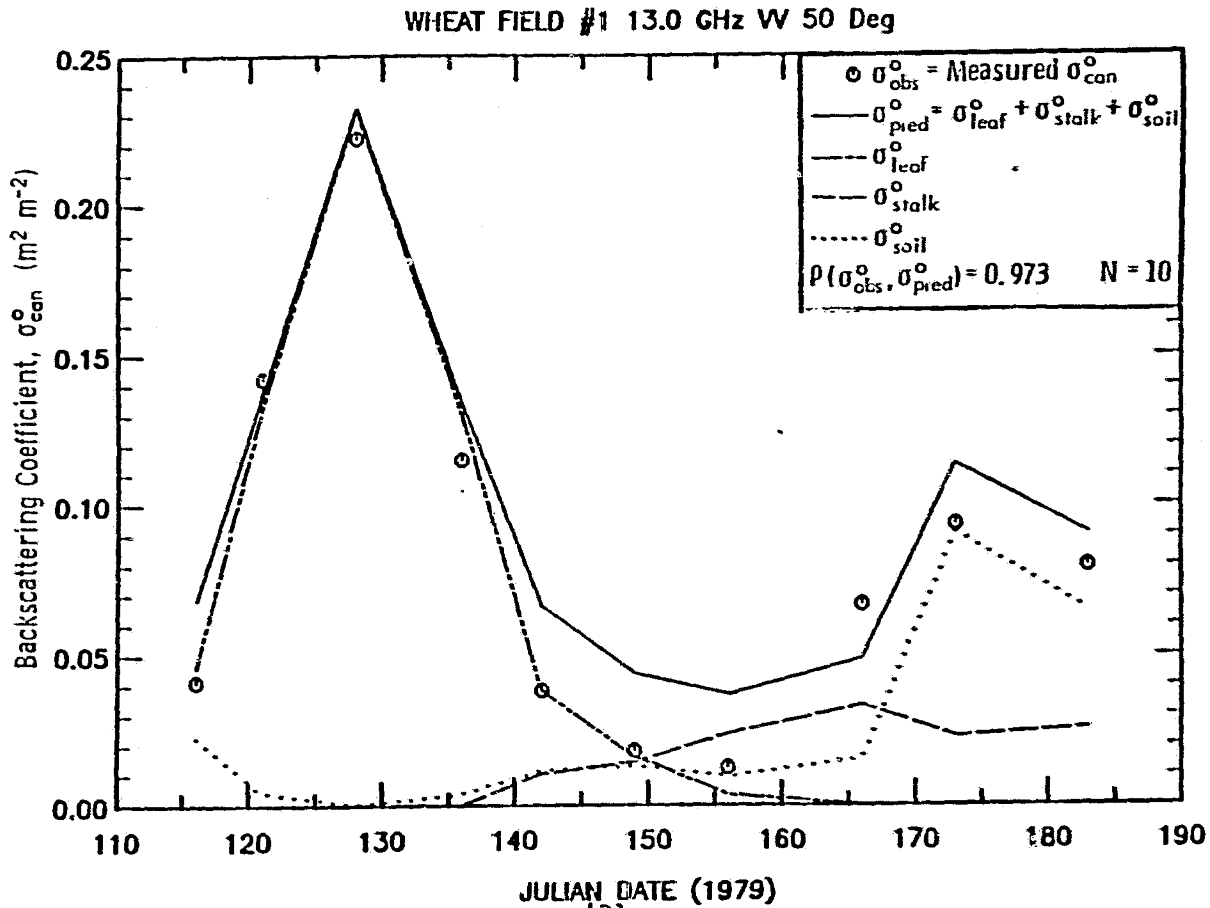
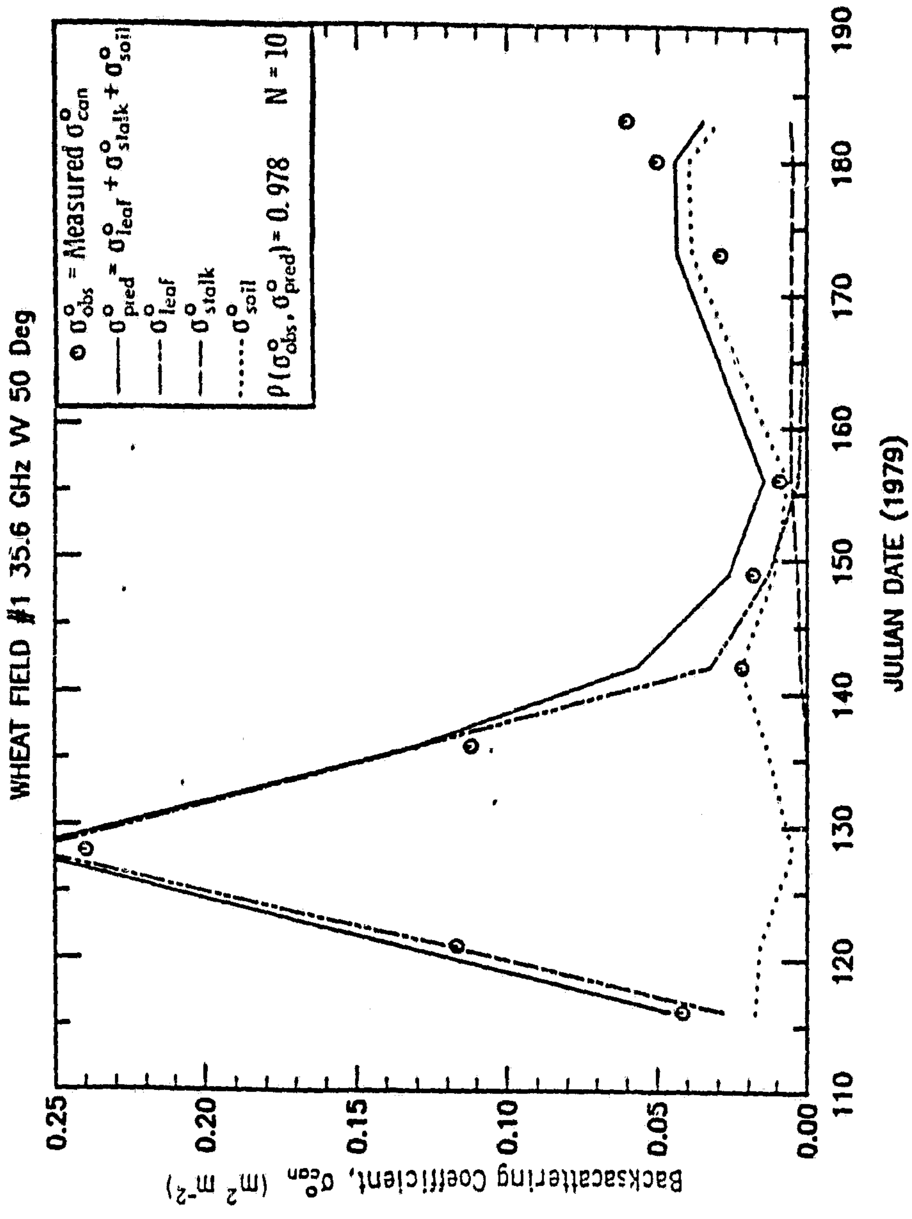


(a)

Figure 9. Comparison of measured backscattering coefficient of wheat with that computed using Eq. (26) at (a) 13.0 GHz and (b) 35.6 GHz, 50° incidence angle, and VV polarization.


WHEAT FIELD #1 35.6 GHz VV 50 Deg
σ^o_{obs} = Measured σ^o_{can}
$\sigma^o_{pred} = \sigma^o_{leaf} + \sigma^o_{stalk} + \sigma^o_{soil}$
σ^o_{leaf}
σ^o_{stalk}
σ^o_{soil}
$\rho(\sigma^o_{obs}, \sigma^o_{pred}) = 0.978$ N = 10
Backscattering Coefficient, σ^o_{can} ($m^2\ m^{-2}$)
0.25
0.20
0.15
0.10
0.05
0.00
110
120
130
140
150
160
170
180
190
JULIAN DATE (1979)

(b)

exclusively due to the leaves between Julian days 120 and 155. After Julian day 155, green LAI goes to zero, and the observed backscatter becomes due entirely to the heads and the soil surface.

7.0 APPROXIMATE FORM IN TERMS OF LAI

The models discussed in the previous section appear to agree well with experimental observations, which makes them useful tools for evaluating the sensitivity of the radar backscattering coefficient to the physical parameters of the plant canopy and soil surface. From an applications standpoint, however, radar would be far more useful if the backscattering coefficient it measures could be used to estimate a single, but important, physical parameter of the canopy, such as green LAI. The conclusions arrived at in the previous section relevant to the temporal "signature" of σ^o_{can} may be summarized as follows:

(a) During the early stage of growth (short plants and LAI < 0.5), the magnitude of σ^o_{can} may be affected, even dominated, by soil-moisture conditions.

(b) During the stage of growth characterized by LAI > 0.5, σ^o_{can} is dominated by the leaf contributions. Hence, $\sigma^o_{can} \approx \sigma^o_{leaf}$ for LAI $\geq$ 0.5.

(c) During the stage of growth prior to harvest and LAI < 0.5, σ^o_{can} is dominated by the soil and stalk contributions for corn and sorghum, and by the soil and head contributions for wheat.

Based on the above conclusions, the models may be simplified as presented in the next sections.

7.1 Corn and Sorghum

Ignoring the presence of the stalks in the canopy, (22) and (25) may be combined and simplified to:

$$\sigma^o_{can}(\theta) = A'_{leaf} + S(\theta)\, \exp(-\,B'_{leaf} \cdot LAI) \qquad (29)$$

where:

$$B'_{leaf} = 2\, B_{leaf} \sec\theta \qquad (30)$$

$$S(\theta) = \begin{cases} C_{soil}(\theta)\, m_s - A'_{leaf} & , \text{ for } LAI < 0.5 \qquad (31) \\ C'_{soil}(\theta) - A'_{leaf} & , \text{ for } LAI > 0.5 \qquad (32) \end{cases}$$

In (32), $C'_{soil} = C_{soil} \cdot \bar{m}_s$, where $\bar{m}_s$ is some representative value of the mean soil moisture content. It may be taken as $\bar{m}_s = 0.20$ g cm^3. For LAI > 0.5, the soil contribution may be assumed to be a constant (rather than ignored), thereby simplifying σ^o_{can} to the point where it becomes a function of only one variable: green LAI. The effect of soil moisture variations on σ^o_{can} is illustrated in Figure 10, which shows the range of values that σ^o_{can} may take in response to a change in soil moisture content from 0.05 g cm^{-3}, representing relatively dry conditions, to 0.25 g cm^{-3}, representing relatively wet conditions. Clearly, soil moisture variations are important only if LAI is small.

Figures 11 and 12 present experimental observations of σ^o_{can} for corn and sorghum, respectively, plotted as a function of LAI. In each case, the data includes all observations made over the season for all three fields of that crop type. Also shown are plots of the single-parameter (LAI) model (as defined by (29) and (32)) fitted to the

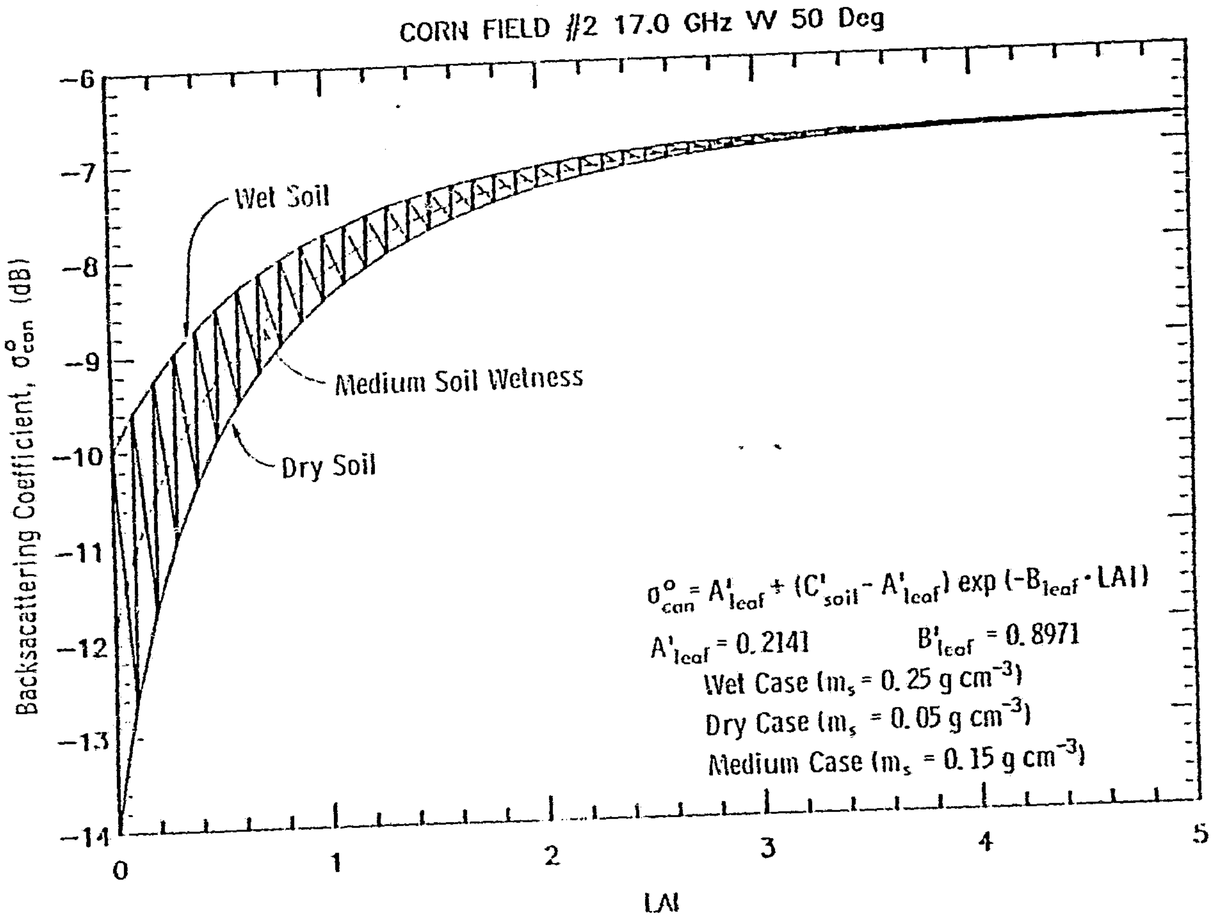


Figure 10. The effect of soil moisture variation is illustrated by the deviation of σ^o_{can} from the curve designated "medium soil wetness."

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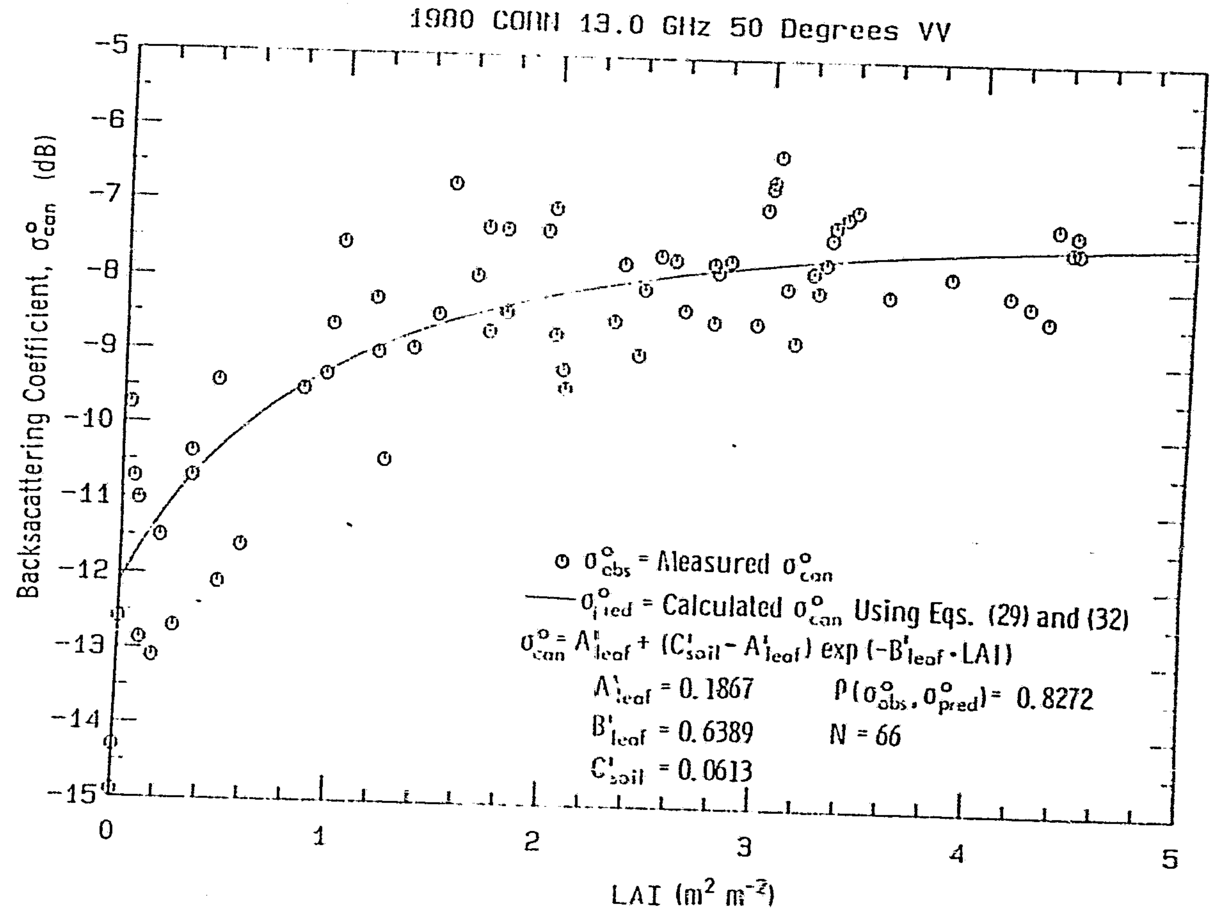

Figure 11. Comparison of measured backscattering coefficient of corn with that computed on the basis of the single-parameter (LAI) model.

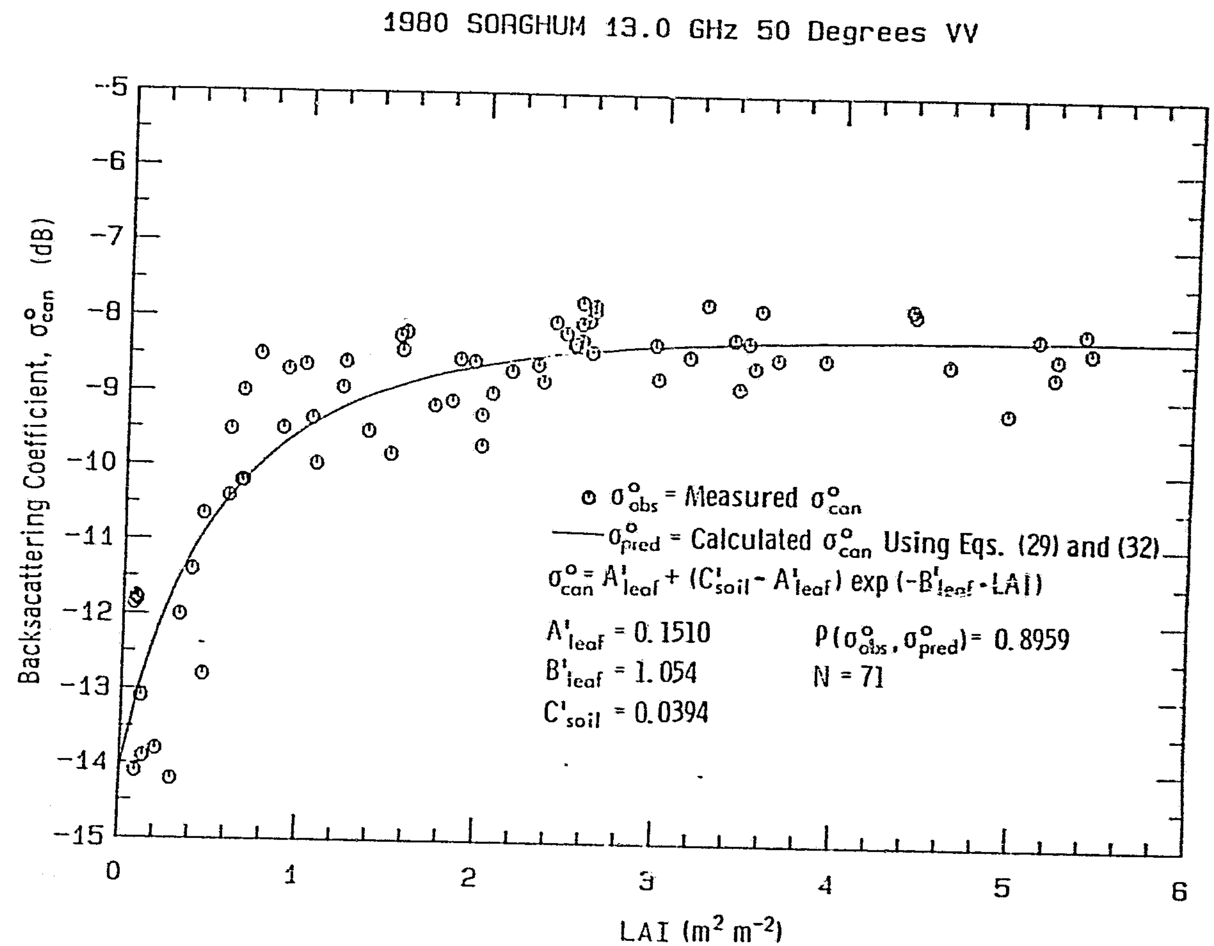

Figure 12. Comparison of measured backscattering coefficient of sorghum with that computed on the basis of the single-parameter (LAI) model.

data. The observed scattering is due to several sources, including: (a) sensor measurement precision, estimated to be about ±1 dB, (b) soil moisture variations, (c) errors associated with the measurement of LAI, and (d) within-field and between-field variations that are not accounted for by the model or the data.

7.2 Wheat

For wheat, a single-parameter model (in terms of LAI) may be written in the form:

$$\sigma^o_{can}(\theta) = A_{leaf}(LAI)^x \left[1 - \exp(-B'_{leaf} \cdot LAI)\right] + C_{soil}(\theta)\exp(-B'_{leaf} \cdot LAI), \quad \text{for } LAI > 0.5 \qquad (33)$$

which reduces to the combination of (29) and (31) if $x = 0$. Actually, this form was used in the non-linear regression program for all three crops, but the exponent, x, was assigned a value of zero or very close to zero by the program in each and every case for all the corn and sorghum data sets. For wheat, on the other hand, x was assigned a value between 0.7 and 1.4, depending on the frequency and polarization combination. The goodness of fit of (33) to the measured data is illustrated in Fig. 13.

8.0 CONCLUSIONS

By extending the canopy cloud model of Attema and Ulaby (1978) from its initial consideration of the canopy as a single layer with uniform volume scattering and attenuation properties to one consisting of more than one layer, it was possible to examine the relative backscattering

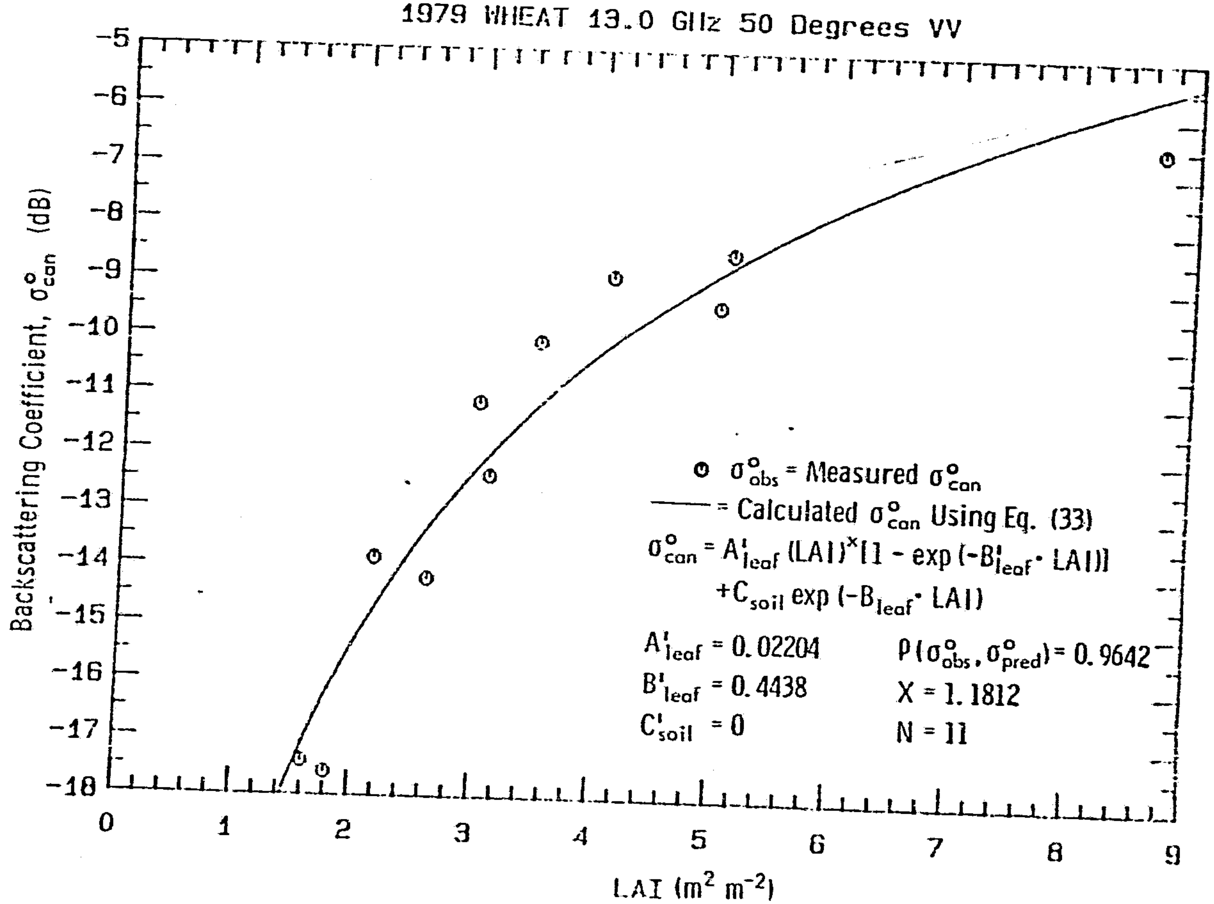

Figure 13. Comparison of measured backscattering coefficient of wheat with the computed on the basis of the single-parameter (LAI) model.

contributions of the leaves, stalks, and heads (of wheat). The analysis of radar backscattering data measured at an incidence angle of 50° and microwave frequencies of 8.6, 13.0, 17.0, and 35.6 GHz indicates that the backscattering coefficient of the canopy is dominated by the leaf contribution if green LAI is greater than approximately 0.5 for corn and sorghum and if, additionally, the heads have not yet appeared (for wheat). During the early stage of growth, a soil backscattering contribution may be very important, and for the end-period prior to harvest, the backscattering contributions of the soil and the stalks are important for sorghum and corn, and of the heads and soil for wheat. A simplified version of the model was developed in terms of a single parameter: green LAI.

ACKNOWLEDGMENT

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APPENDIX A

DATA DOCUMENTATION

Observed values of the backscattering coefficients and ground-truth values.

VARIABLE	UNITS	DESCRIPTION
SIGMA 0	dB	backscattering coefficient measured, pol = VV, $\theta = 50°$ (missing value represented by 0)
Plant Height	m	canopy height
Plant Water	kg m^{-3}	volumetric normalized plant water content
Soil Moisture	g cm^{-3}	volumetric soil moisture
Leaf Area Index	m^2 m^{-2}	green leaf area index
Plant Dry Mass	kg m^{-2}	total canopy dry biomass per square meter
Leaf Wet Mass	kg m^{-2}	fresh mass of leaves per square meter
Leaf Dry Mass	kg m^{-2}	dried mass of leaves per square meter
Stalk Wet Mass	kg m^{-2}	fresh mass of stalks per square meter
Stalk Dry Mass	kg m^{-2}	dried mass of stalks per square meter

MANHATTAN AGRICULTURAL EXPERIMENT 1979 CORN C-1

JULIAN DATE	SIGMAO 8.6GHZ	SIGMAO 13 GHZ	SIGMAO 17GHZ	SIGMAO 35.6GHZ	PLANT HEIGHT	PLANT WATER	SOIL MOIST.	LEAF AREA INDEX	PLANT DRY MASS
156.	-12.32	-12.40	-10.60	-12.30	0.2500	0.3000	0.1400	0.4000	0.0367
169.	-11.67	-11.15	-10.30	0.	0.5200	0.9600	0.2000	1.4000	0.1298
177.	-9.79	-10.70	-8.25	-9.20	0.8000	1.6300	0.3200	2.0000	0.2250
191.	-8.00	-8.55	-7.30	-6.80	1.8100	2.0700	0.3600	4.0100	0.6240
200.	-7.71	-8.74	-6.83	-7.35	2.5000	2.4400	0.3200	5.1000	0.8050
204.	-8.05	-8.32	-6.50	-6.80	2.6500	2.5400	0.3000	5.1000	0.8850
207.	-7.21	-8.55	-7.17	-7.20	2.7500	2.6400	0.3000	5.1000	0.9460
208.	-7.60	-8.39	-7.29	-7.13	2.7100	2.7500	0.3000	5.1000	0.9660
212.	-8.51	-8.70	-7.60	-8.01	2.6500	2.8000	0.2800	4.9000	1.0460
226.	0.	0.	0.	0.	2.5000	2.5600	0.2200	5.4696	1.3280
228.	0.	0.	0.	0.	2.5000	2.5200	0.2000	5.3522	1.8410
242.	-10.10	-9.50	-8.67	-9.71	2.5000	1.6400	0.1800	3.0000	2.5980

MANHATTAN AGRICULTURAL EXPERIMENT 1979 CORN C-2

JULIAN DATE	SIGMAO 8.6GHZ	SIGMAO 13 GHZ	SIGMAO 17GHZ	SIGMAO 35.6GHZ	PLANT HEIGHT	PLANT WATER	SOIL MOIST.	LEAF AREA INDEX	PLANT DRY MASS
156.	0.	0.	0.	0.	0.2500	0.0000	0.1400	0.3000	0.0240
169.	-12.56	-12.01	-10.70	0.	0.5200	0.5800	0.1800	0.5000	0.0400
177.	-11.80	-10.56	-9.72	-10.70	0.8000	1.5000	0.3200	1.3000	0.1220
191.	-8.80	-9.14	-7.47	-8.11	1.8100	2.5400	0.3200	3.1000	0.4150
200.	-8.89	-8.39	-8.14	-8.30	2.5000	2.4000	0.3000	3.5000	0.8140
212.	-9.80	-9.00	-8.01	-9.00	2.5600	3.0900	0.2800	3.7000	1.3460
228.	0.	0.	0.	0.	2.5000	2.4400	0.2000	4.2000	2.0000
242.	-10.10	-9.50	-8.87	-9.10	2.5000	1.8000	0.1800	2.5000	2.5830

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MANHATTAN AGRICULTURAL EXPERIMENT 1979 CORN C-3

JULIAN DATE	SIGMAO 8.6GHZ	SIGMAO 13 GHZ	SIGMAO 17GHZ	SIGMAO 35.6GHZ	PLANT HEIGHT	PLANT WATER	SOIL MOIST.	LEAF AREA INDEX	PLANT DRY MASS
156.	0.	0.	0.	0.	0.2500	0.0000	0.1400	0.1000	0.0090
169.	-12.23	-11.84	-10.90	0.	0.5200	0.3800	0.1600	0.3000	0.0270
177.	-11.90	-11.95	-10.10	-10.43	0.8000	1.6300	0.3200	1.3000	0.1280
191.	-9.00	-9.02	-8.02	-9.39	1.8100	1.8800	0.3000	2.0000	0.2660
200.	-8.90	-9.65	-8.19	-9.39	2.5000	1.9600	0.3000	2.1000	0.5390
212.	-9.12	-9.71	-8.19	-9.49	2.5600	2.2000	0.2400	2.6000	0.9020
228.	0.	0.	0.	0.	2.5000	2.0400	0.2000	2.7000	1.2340
247.	-10.39	-10.62	-8.89	-9.70	2.5000	1.2400	0.1200	1.5000	1.5800

MANHATTAN AGRICULTURAL EXPERIMENT 1979 CORN C-4

JULIAN DATE	SIGMAO 8.6GHZ	SIGMAO 13 GHZ	SIGMAO 17GHZ	SIGMAO 35.6GHZ	PLANT HEIGHT	PLANT WATER	SOIL MOIST.	LEAF AREA INDEX	PLANT DRY MASS
156.	0.	0.	0.	0.	0.2500	0.0000	0.1400	0.5000	0.0450
171.	-10.95	-11.50	-11.10	-10.00	0.6100	0.9800	0.1000	1.4000	0.0940
178.	-9.48	-10.94	-9.40	-8.71	0.8100	3.5800	0.2400	2.0500	0.1180
192.	-9.05	-8.81	-8.69	-8.22	1.9600	3.7800	0.2800	4.3000	0.9300
201.	-7.94	-8.90	-9.69	-7.50	2.4800	3.8700	0.3000	5.2000	1.4290
213.	-8.40	-9.10	-8.42	-8.64	2.5000	3.6500	0.2000	5.0000	1.5740
228.	0.	0.	0.	0.	2.5000	2.6000	0.2000	6.1000	1.6995
247.	-9.53	-11.13	-8.97	-10.20	2.5000	2.0800	0.1200	2.9000	1.8250

MANHATTAN AGRICULTURAL EXPERIMENT 1979 CORN C-5

JULIAN DATE	SIGMAO 8.6GHZ	SIGMAO 13 GHZ	SIGMAO 17GHZ	SIGMAO 35.6GHZ	PLANT HEIGHT	PLANT WATER	SOIL MOIST.	LEAF AREA INDEX	PLANT DRY MASS
156.	0.	0.	0.	0.	0.2500	0.0000	0.1400	0.3000	0.0207
171.	-10.42	-12.45	-11.00	-12.16	0.6100	0.6900	0.2400	1.0000	0.0520
178.	-10.05	-11.73	-10.20	-11.38	0.8100	1.9800	0.2400	1.7000	0.2150
192.	-9.26	-9.61	-9.24	-9.32	1.9600	2.1400	0.0600	2.8000	0.5930
201.	-8.32	-9.24	-9.29	-9.12	2.4800	1.9800	0.3200	3.1000	1.3220
213.	-8.80	-9.90	-9.50	-9.30	2.5900	2.1600	0.2000	3.4000	2.3700
228.	0.	0.	0.	0.	2.5000	1.8000	0.2000	3.1000	2.3990
254.	-9.81	-9.62	-10.76	-10.10	2.5000	1.1200	0.2400	1.7000	2.4490

MANHATTAN AGRICULTURAL EXPERIMENT 1979 CORN C-6

JULIAN DATE	SIGMAO 8.6GHZ	SIGMAO 13 GHZ	SIGMAO 17GHZ	SIGMAO 35.6GHZ	PLANT HEIGHT	PLANT WATER	SOIL MOIST.	LEAF AREA INDEX	PLANT DRY MASS
156.	0.	0.	0.	0.	0.2500	0.0000	0.1200	0.2000	0.0100
171.	-11.86	-12.06	-11.33	-12.15	0.6100	0.3300	0.2600	0.6500	0.0330
178.	-9.98	-11.29	-10.83	-10.83	0.8100	1.3600	0.2400	1.4000	0.1210
192.	-9.26	-10.40	-8.90	-9.30	1.9600	1.4800	0.2400	2.3000	0.4440
201.	-9.12	-9.67	-8.75	-9.20	2.4800	1.6100	0.2800	2.6000	0.6410
213.	-9.86	-9.90	-9.03	-9.40	2.5000	1.7600	0.2000	2.4000	0.9470
228.	0.	0.	0.	0.	2.5000	1.3300	0.2000	2.0000	1.4200
254.	-11.09	-10.19	-9.16	-10.00	2.5000	0.5000	0.2200	1.5000	2.0000

MANHATTAN AGRICULTURAL EXPERIMENT 1979 SORGHUM S-1

JULIAN DATE	SIGMAO 8.6GHZ	SIGMAO 13 GHZ	SIGMAO 17GHZ	SIGMAO 35.6GHZ	PLANT HEIGHT	PLANT WATER	SOIL MOIST.	LEAF AREA INDEX	PLANT DRY MASS
156.	-11.13	-10.12	-9.59	-13.42	0.1500	0.3273	0.0700	0.6000	0.0700
169.	-9.88	-8.83	-8.21	0.	0.4300	1.6300	0.1400	1.2000	0.0960
177.	-7.65	-9.45	-7.80	-9.00	0.5100	2.5000	0.2800	3.6000	0.3610
191.	-7.80	-7.54	-6.11	-6.19	0.8000	3.7300	0.3200	5.4000	0.5574
200.	-7.16	-7.59	-5.83	-5.82	0.9500	3.5800	0.3200	6.5000	0.6680
204.	-6.08	-6.69	-5.75	-6.59	1.0800	3.7000	0.2800	6.4500	0.8230
207.	-6.51	-7.12	-5.92	-6.19	1.1800	3.7300	0.2800	6.6000	0.9390
208.	-6.80	-6.65	-6.40	-6.20	1.1900	3.8700	0.2800	6.7000	0.9780
212.	-7.30	-6.90	-6.43	-5.70	1.2600	4.1300	0.2200	6.0000	1.1330
242.	-7.80	-7.40	-8.10	-6.99	1.2700	2.5000	0.2000	4.0000	1.8500

MANHATTAN AGRICULTURAL EXPERIMENT 1979 SORGHUM S-2

JULIAN DATE	SIGMAO 8.6GHZ	SIGMAO 13 GHZ	SIGMAO 17GHZ	SIGMAO 35.6GHZ	PLANT HEIGHT	PLANT WATER	SOIL MOIST.	LEAF AREA INDEX	PLANT DRY MASS
169.	-9.21	-9.76	-9.71	0.	0.4300	1.4000	0.1400	1.3000	0.0960
177.	-8.22	-9.07	-7.90	-7.19	0.5100	2.1200	0.2600	2.8000	0.2140
191.	-7.80	-7.44	-6.80	-6.11	0.8000	2.8800	0.2800	4.7000	0.4000
200.	-6.90	-7.19	-6.18	-5.88	0.9500	4.0000	0.3000	5.6000	0.7850
212.	-7.72	-7.00	-6.55	-5.95	1.2600	4.6000	0.2400	6.8000	1.2980
242.	-7.30	-7.19	-7.90	-7.59	1.2700	2.0500	0.1600	3.3000	2.1550

MANHATTAN AGRICULTURAL EXPERIMENT 1979 SORGHUM S-3

JULIAN DATE	SIGMAO 8.6GHZ	SIGMAO 13 GHZ	SIGMAO 17GHZ	SIGMAO 35.6GHZ	PLANT HEIGHT	PLANT WATER	SOIL MOIST.	LEAF AREA INDEX	PLANT DRY MASS
169.	-9.39	-9.18	-9.71	0.	0.4300	1.4000	0.1000	0.5000	0.0850
177.	-8.47	-8.60	-8.23	-10.10	0.5100	3.3693	0.2200	1.3000	0.2510
191.	-7.74	-7.80	-6.38	-7.19	0.8000	5.0000	0.3000	5.6000	0.6360
200.	-7.26	-8.01	-5.96	-6.42	0.9500	3.9288	0.2800	5.6000	0.8170
212.	-7.69	-7.28	-6.50	-6.90	1.2600	3.4653	0.2200	5.6000	1.0580
247.	-6.70	-7.40	-8.60	-9.00	1.2700	1.5700	0.1000	3.5000	1.7620

MANHATTAN AGRICULTURAL EXPERIMENT 1979 SORGHUM S-4

JULIAN DATE	SIGMAO 8.6GHZ	SIGMAO 13 GHZ	SIGMAO 17GHZ	SIGMAO 35.6GHZ	PLANT HEIGHT	PLANT WATER	SOIL MOIST.	LEAF AREA INDEX	PLANT DRY MASS
171.	-9.59	-9.39	-7.96	-9.00	0.5000	1.4000	0.1000	1.4000	0.1060
178.	-7.27	-8.43	-6.88	-8.78	0.6000	3.0000	0.3000	2.9000	0.3860
192.	-7.10	-7.19	-6.29	-7.97	0.8200	3.5000	0.3200	4.8894	0.7580
201.	-6.75	-7.55	-6.27	-6.36	1.0000	3.9000	0.3000	5.3000	1.1350
213.	-7.40	-7.56	-6.80	-6.55	1.2700	4.0200	0.2000	6.8000	1.5120
247.	-7.40	-7.40	-7.59	-9.28	1.2700	1.5000	0.1000	3.3000	1.8320

MANHATTAN AGRICULTURAL EXPERIMENT 1979 SORGHUM S-5

JULIAN DATE	SIGMAO 8.6GHZ	SIGMAO 13 GHZ	SIGMAO 17GHZ	SIGMAO 35.6GHZ	PLANT HEIGHT	PLANT WATER	SOIL MOIST.	LEAF AREA INDEX	PLANT DRY MASS
171.	-9.47	-9.78	-9.21	-9.61	0.5000	1.0000	0.1200	1.0000	0.0790
178.	-8.39	-8.32	-6.99	-8.13	0.6000	1.8300	0.2200	3.2000	0.3250
192.	-7.19	-7.30	-6.76	-7.87	0.8200	2.8000	0.3000	5.0000	0.4760
201.	-7.30	-6.95	-5.86	-6.68	1.0000	3.6000	0.3200	6.5000	1.0740
213.	-7.59	-7.30	-7.13	-6.40	1.2700	4.1700	0.2000	6.8000	1.8710
254.	-6.90	-6.70	-7.30	-8.70	1.2700	1.3400	0.2400	2.7000	2.4000

MANHATTAN AGRICULTURAL EXPERIMENT 1979 SORGHUM S-6

JULIAN DATE	SIGMAO 8.6GHZ	SIGMAO 13 GHZ	SIGMAO 17GHZ	SIGMAO 35.6GHZ	PLANT HEIGHT	PLANT WATER	SOIL MOIST.	LEAF AREA INDEX	PLANT DRY MASS
171.	-9.92	-9.85	-8.79	-9.73	0.5000	0.8000	0.1200	0.4000	0.0660
178.	-9.00	-8.90	-7.31	-8.63	0.6000	3.1700	0.3000	1.3000	0.2490
192.	-7.80	-8.21	-6.76	-7.76	0.8200	4.7000	0.3000	4.8000	0.5870
201.	-7.00	-7.45	-6.00	-7.14	1.0000	4.8000	0.3400	6.0000	1.3520
213.	-7.50	-7.59	-7.37	-6.63	1.2700	4.2500	0.2000	6.0000	1.5619
254.	-6.51	-6.56	-7.40	-8.30	1.2700	2.1300	0.2400	3.7000	2.4690

MANHATTAN AGRICULTURAL EXPERIMENT 1979 WHEAT W-1

JULIAN DATE	SIGMAO 8.6GHZ	SIGMAO 13 GHZ	SIGMAO 17GHZ	SIGMAO 35.6GHZ	PLANT HEIGHT	PLANT WATER	SOIL MOIST.	LEAF AREA INDEX	PLANT DRY MASS
116.	-14.77	-13.86	-13.31	-13.80	0.4100	4.3900	0.1400	2.1500	0.2510
121.	-12.20	-8.47	-6.72	-9.32	0.4600	3.9100	0.2400	5.1000	0.5240
128.	-7.07	-6.53	-5.21	-6.20	0.6000	6.1700	0.1600	8.7000	0.6000
136.	-11.30	-9.39	-8.41	-9.51	0.7100	3.8000	0.2000	5.0000	0.8910
142.	-14.74	-14.20	-12.80	-16.59	1.0200	3.2400	0.2400	2.6000	1.0520
149.	-14.22	-17.40	-17.09	-17.46	1.0800	2.8700	0.1000	1.6000	1.1130
156.	-11.58	-19.00	-17.80	-20.40	1.0800	2.3100	0.0600	0.8000	1.2590
166.	-8.51	-11.75	-12.80	0.	1.0300	1.7500	0.0800	0.	1.4050
173.	-8.79	-10.30	-8.01	-15.41	1.0300	0.3900	0.3000	0.	1.2440
180.	0.	0.	0.	-13.00	0.8900	0.4500	0.3000	0.	1.2230
183.	-7.80	-11.00	-9.39	-12.20	0.8900	0.4500	0.2400	0.	1.2840

MANHATTAN AGRICULTURAL EXPERIMENT 1979 WHEAT W-2

JULIAN DATE	SIGMAO 8.6GHZ	SIGMAO 13 GHZ	SIGMAO 17GHZ	SIGMAO 35.6GHZ	PLANT HEIGHT	PLANT WATER	SOIL MOIST.	LEAF AREA INDEX	PLANT DRY MASS
116.	-11.01	-11.13	-8.93	-10.38	0.3400	5.5900	0.2000	3.0000	0.3600
121.	-11.86	-10.07	-8.80	-10.47	0.4300	4.1900	0.2800	3.5000	0.3810
128.	-8.45	0.	0.	-7.75	0.5700	3.3300	0.2200	6.1000	0.6000
136.	-10.80	-8.89	-8.53	-11.00	0.7000	3.1400	0.2400	4.1000	0.6130
142.	-14.56	-12.40	-10.80	-15.91	0.9400	2.8700	0.2600	3.1000	0.9240
149.	-15.45	-17.59	-14.94	-16.44	1.1000	2.7300	0.1000	1.8000	0.9800
156.	-13.68	-16.70	-15.90	-18.60	1.0600	2.0800	0.0600	0.6000	1.0100
166.	-11.70	0.	-15.20	0.	1.0900	1.2800	0.0800	0.	1.0390
173.	-12.30	-15.00	-11.80	-18.70	1.0200	0.7800	0.3400	0.	1.2230
180.	0.	0.	0.	-12.00	0.8700	0.5700	0.3000	0.	1.3380
183.	-9.51	-10.90	-10.20	-11.50	0.8700	0.1100	0.2800	0.	1.1840

MANHATTAN AGRICULTURAL EXPERIMENT 1980 CORN C-1

JULIAN DATE	SIGMAO 8.6GHZ	SIGMAO 13 GHZ	SIGMAO 17GHZ	SIGMAO 35.6GHZ	PLANT HEIGHT	PLANT WATER	SOIL MOIST.	LEAF AREA INDEX	LEAF WET MASS	LEAF DRY MASS	STALK WET MASS	STALK DRY MASS
158.	-12.17	-12.87	-11.20	-12.51	0.2160	0.3289	0.2007	0.1016	0.	0.	0.	0.
161.	-11.40	-10.37	-12.00	-11.18	0.3736	0.4399	0.1627	0.3235	0.	0.	0.	0.
168.	-9.94	-8.64	-9.54	-7.79	0.7484	0.7176	0.0396	0.9651	0.2152	0.0354	0.2715	0.0326
170.	-9.07	-8.28	-7.76	-7.05	0.8154	0.7986	0.0314	1.1656	0.2873	0.0472	0.3739	0.0425
176.	-8.84	-7.33	-7.90	-6.62	1.2272	1.0365	0.2243	1.7695	0.4757	0.0804	1.1429	0.1146
178.	-8.37	-7.34	-6.83	-7.24	1.3420	1.1122	0.1308	1.9633	0.5295	0.0912	1.4234	0.1391
182.	-8.68	-7.75	-6.91	0.	1.5426	1.2552	0.0695	2.3263	0.6238	0.1125	1.9778	0.1883
190.	-7.82	-7.01	-6.65	-6.33	2.0540	1.4958	0.1217	3.4117	0.7625	0.1538	2.8670	0.2858
192.	-8.81	-7.11	-6.87	-6.48	2.1360	1.5445	0.0922	3.3679	0.7872	0.1634	3.0180	0.3096
196.	-8.37	-7.22	-6.71	-6.34	2.3450	1.6260	0.0426	3.3145	0.8253	0.1811	3.2289	0.3560
198.	-8.75	-7.38	-7.10	-6.70	2.3463	1.6585	0.3319	3.2982	0.8388	0.1889	3.2923	0.3785
204.	-9.55	-8.09	-6.98	-7.64	2.3500	1.7208	0.1226	3.2440	0.8581	0.2068	3.3470	0.4423
206.	-9.96	-7.83	-7.37	-7.39	2.3710	1.7295	0.0753	3.2137	0.8577	0.2106	3.3299	0.4622
210.	-9.85	-8.05	-8.25	-6.60	2.3120	1.7289	0.0999	3.0946	0.8474	0.2143	3.2588	0.4992
213.	-9.73	-8.53	-7.96	-8.16	2.3860	1.7125	0.0458	2.9551	0.8314	0.2134	3.1817	0.5245
221.	-10.04	-8.98	-8.68	-7.80	2.3920	1.6052	0.0996	2.4060	0.7570	0.1943	2.9185	0.5795
225.	-10.28	-9.19	-9.09	-8.77	2.3870	1.5195	0.1020	2.0507	0.7036	0.1760	2.7701	0.5993
231.	-9.34	-8.48	-8.39	-8.41	2.4190	1.3567	0.2505	1.4584	0.6050	0.1392	2.5385	0.6176
240.	-12.50	-11.61	-12.65	-12.53	2.4190	1.0558	0.0539	0.5634	0.4200	0.0726	2.1808	0.6163
247.	-11.41	-10.73	-11.27	-11.84	2.2860	0.7996	0.1946	0.0563	0.2495	0.0253	1.8940	0.5878
254.	-12.76	-12.59	-11.62	-13.11	2.1833	0.5526	0.0894	0.	0.0595	0.0001	1.6009	0.5748

MANHATTAN AGRICULTURAL EXPERIMENT 1980 CORN C-2

JULIAN DATE	SIGMAO 8.6GHZ	SIGMAO 13 GHZ	SIGMAO 17GHZ	SIGMAO 35.6GHZ	PLANT HEIGHT	PLANT WATER	SOIL MOIST.	LEAF AREA INDEX	LEAF WET MASS	LEAF DRY MASS	STALK WET MASS	STALK DRY MASS
158.	-12.87	-13.10	-12.99	-14.60	0.1942	0.2997	0.2116	0.1674	0.	0.	0.	0.
161.	-12.47	-10.70	-9.24	-11.80	0.3535	0.4112	0.1875	0.3273	0.	0.	0.	0.
168.	-10.36	-9.51	-8.39	-9.24	0.7346	0.6828	0.0531	0.8368	0.2070	0.0343	0.3324	0.0399
170.	-8.82	-7.54	-7.41	-8.35	0.8182	0.7605	0.0341	1.0029	0.2782	0.0464	0.4053	0.0461
176.	-7.88	-6.74	-6.82	-6.65	1.2520	0.9857	0.2266	1.5138	0.4601	0.0797	1.1603	0.1185
178.	-8.01	-7.31	-6.89	0.	1.4188	1.0566	0.1212	1.6800	0.5106	0.0901	1.4177	0.1417
182.	-8.12	-7.04	-6.25	0.	1.5500	1.1892	0.0567	1.9932	0.5972	0.1103	1.9048	0.1868
190.	-7.53	-6.28	-6.84	-6.57	2.0370	1.4090	0.0970	3.0457	0.7166	0.1467	2.6317	0.2710
192.	-8.27	-6.63	-6.62	-6.24	2.1860	1.4527	0.0623	3.0177	0.7361	0.1547	2.7477	0.2907
196.	-7.61	-6.71	-6.37	-6.34	2.3530	1.5254	0.0301	3.0128	0.7634	0.1687	2.9028	0.3285
198.	-7.69	-7.00	-6.23	-6.70	2.3560	1.5540	0.1632	2.9909	0.7716	0.1747	2.9460	0.3465
204.	-8.20	-7.69	-6.26	-7.12	2.3680	1.6075	0.1443	2.8254	0.7758	0.1872	2.9695	0.3970
206.	-9.06	-7.73	-7.26	-7.00	2.2870	1.6145	0.1099	2.7487	0.7709	0.1893	2.9505	0.4126
210.	-8.63	-7.69	-8.01	-7.41	2.3180	1.6124	0.0949	2.5620	0.7524	0.1904	2.8860	0.4419
213.	-8.15	-8.09	-7.87	-7.40	2.2800	1.5968	0.0450	2.4248	0.7315	0.1881	2.8214	0.4622
217.	-8.63	-8.53	-8.26	-7.60	2.3220	1.5585	0.1071	2.2871	0.6950	0.1810	2.7227	0.4867
221.	-9.34	-8.73	-8.44	-6.72	2.4240	1.5013	0.0941	2.0126	0.6498	0.1694	2.6166	0.5085
225.	-9.67	-8.70	-8.01	-7.13	2.4270	1.4271	0.0800	1.6978	0.5969	0.1535	2.5085	0.5274
231	-9.15	-9.00	-7.34	-7.76	2.3980	1.2897	0.2442	1.1825	0.5056	0.1235	2.3496	0.5500
240.	-11.90	-9.42	-9.48	-8.78	2.3980	1.0465	0.0555	0.4373	0.3490	0.0711	2.1284	0.5704
247.	-11.10	-9.75	-10.40	-11.12	2.2880	0.8526	0.2000	0.0294	0.2178	0.0330	1.9734	0.5745
254.	-13.30	-14.30	-11.80	-11.69	2.2183	0.6840	0.0957	0.	0.0848	0.0066	1.8326	0.5676

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MANHATTAN AGRICULTURAL EXPERIMENT 1980 CORN C-3

JULIAN DATE	SIGMAO 8.6GHZ	SIGMAO 13 GHZ	SIGMAO 17GHZ	SIGMAO 35.6GHZ	PLANT HEIGHT	PLANT WATER	SOIL MOIST.	LEAF AREA INDEX	LEAF WET MASS	LEAF DRY MASS	STALK WET MASS	STALK DRY MASS
158.	-12.80	-11.50	-11.20	-11.70	0.2367	0.3154	0.2183	0.1811	0.	0.	0.	0.
161.	-12.90	-12.10	-10.40	-11.50	0.3922	0.4749	0.1877	0.4631	0.	0.	0.	0.
165.	-10.30	-9.31	-8.97	-7.83	0.6784	0.7382	0.1096	0.9411	0.2109	0.0338	0.4741	0.0568
168.	-9.68	-8.94	-8.91	-7.19	0.7802	0.9736	0.0483	1.3491	0.3674	0.0586	0.5056	0.0607
170.	-8.64	-7.95	-7.96	-6.44	0.8078	1.1486	0.0442	1.6339	0.4625	0.0741	0.6984	0.0686
171.	-9.05	-8.44	-8.05	-6.39	1.0010	1.1661	0.0362	1.7773	0.5074	0.0815	0.8243	0.0791
176.	-8.36	-7.63	-7.07	-6.43	1.2630	1.3938	0.2394	2.4942	0.7054	0.1171	1.5317	0.1356
178.	-8.36	-7.84	-6.86	-5.95	1.4073	1.4778	0.1877	2.7680	0.7728	0.1307	1.8314	0.1599
182.	-7.98	-7.71	-6.78	0.	1.4962	1.6312	0.1073	3.2730	0.8883	0.1570	2.4071	0.2104
189.	-7.65	-7.50	-6.22	-5.58	2.0630	1.8462	0.2484	4.4571	1.0317	0.1992	3.1831	0.3032
190.	-7.64	-7.28	-6.53	-6.06	2.0600	1.8708	0.1887	4.4459	1.0465	0.2047	3.2620	0.3167
192.	-8.67	-7.49	-7.19	-5.80	2.0540	1.9151	0.1359	4.4235	1.0719	0.2151	3.3953	0.343
196.	-8.12	-7.20	-7.08	-5.46	2.3470	1.9836	0.0432	4.3563	1.1070	0.2333	3.5716	0.3975
198.	-8.62	-8.43	-7.15	-6.40	2.3430	2.0077	0.4330	4.3267	1.1169	0.2408	3.6202	0.4240
204.	-8.34	-8.23	-7.63	-7.64	2.1700	2.0380	0.2277	4.2351	1.1188	0.2561	3.6473	0.5007
206.	-9.74	-8.10	-7.90	-6.20	2.3390	2.0342	0.1330	4.1399	1.1106	0.2584	3.6265	0.5249
210.	-9.49	-7.86	-8.29	-6.84	2.3050	2.0061	0.0877	3.8625	1.0821	0.2582	3.5546	0.5707
213.	-9.61	-8.13	-8.49	-7.08	2.3510	1.9677	0.0965	3.5742	1.0506	0.2538	3.4811	0.6023
217.	-10.09	-8.77	-8.64	-7.21	2.3000	1.8945	0.4914	3.1365	0.9965	0.2423	3.3655	0.6399
220.	-9.74	-8.52	-8.75	-7.37	2.3520	1.8241	0.2669	2.7538	0.9475	0.2294	3.2695	0.6643
221.	-10.00	-8.37	-8.12	-7.90	2.3450	1.7979	0.1726	2.6163	0.9297	0.2244	3.2361	0.6717
225.	-10.24	-9.45	-8.68	-8.27	2.3500	1.6807	0.1568	2.0644	0.8515	0.2007	3.0972	0.6966
231.	-9.70	-10.44	-8.81	-7.70	2.3590	1.4728	0.3347	1.2274	0.7160	0.1567	2.8757	0.7192
240.	-13.50	-12.70	-14.50	-13.00	2.3590	1.1156	0.0606	0.2603	0.4806	0.0823	2.5160	0.7137
247.	-10.92	-11.02	-12.42	-12.12	2.3560	0.8316	0.2071	0.0765	0.2796	0.0313	2.2064	0.6710
254.	-14.60	-14.90	-15.30	-13.60	2.3560	0.5767	0.1043	0.	0.0711	0.0022	1.8553	0.5893

MANHATTAN AGRICULTURAL EXPERIMENT 1980 SORGHUM S-1

JULIAN DATE	SIGMAO 8.6GHZ	SIGMAO 13 GHZ	SIGMAO 17GHZ	SIGMAO 35.6GHZ	PLANT HEIGHT	PLANT WATER	SOIL MOIST.	LEAF AREA INDEX	LEAF WET MASS	LEAF DRY MASS	STALK WET MASS	STALK DRY MASS
158.	-12.00	-11.78	-14.00	-16.45	0.1016	0.0046	0.2680	0.0700	0.	0.	0.	0.
161.	-14.10	-14.10	-12.50	-12.90	0.1982	0.0788	0.2118	0.0900	0.	0.	0.	0.
168.	-12.50	-11.40	-11 60	-11.90	0.4856	0.3494	0.1596	0.3817	0.0603	0.0112	0.0105	0.0012
170.	-11.50	-10.19	-9.62	-9.74	0.5738	0.4480	0.0574	0.6591	0.1329	0.0261	0.1162	0.0128
176.	-10.30	-9.83	-9.22	-8.44	0.8210	0.7875	0.2566	1.4854	0.3609	0.0803	0.5095	0.0572
178.	-10.10	-9.17	-8.63	-8.74	0.8903	0.9125	0.1905	1.7246	0.4390	0.1003	0.6557	0.0748
182.	-9.34	-8.19	-8.43	0.	0.9959	1.1751	0.0737	2.4556	0.5961	0.1415	0.9526	0.1134
190.	-9.30	-8.50	-8.26	-8.49	1.0265	1.7268	0.0824	3.6494	0.9028	0.2218	1.5017	0.2006
192.	-8.63	-8.50	-7.70	-7.42	1.0313	1.8654	0.0544	3.9201	0.9756	0.2403	1.6209	0.2237
196.	-9.40	-7.83	-7.83	-8.16	1.0394	2.1372	0.0414	4.4090	1.1140	0.2747	1.8328	0.2707
198.	-9.65	-8.56	-7.94	-7.56	1.0428	2.2689	0.0326	4.6229	1.1787	0.2906	1.9250	0.2943
204.	-9.18	-8.20	-7.29	-7.08	1.0501	2.6363	0.1785	5.1215	1.3504	0.3328	2.1476	0.3639
206.	-9.54	-8.46	-8.10	-7.59	1.0516	2.7468	0.1149	5 2258	1.3989	0.3453	2.2046	0.3863
210.	-9.42	-8.12	-8.30	-8.67	1.0532	2.9447	0.0768	5.3816	1.4803	0.3684	2.2947	0.4292
213.	-8.89	-8.37	-7.96	-7.89	1.0531	3.0697	0.0538	5.4174	1.5263	0.3845	2.3428	0.4591
221.	-9.86	-8.70	-8.26	-8.04	1.0478	3.2810	0.1112	5.2111	1.5750	0.4243	2.3973	0.5261
225.	-9.68	-9.20	-8.20	-7.98	1.0423	3.3075	0.0825	4.9566	1.5531	0.4423	2.3881	0.5506
231.	-9.46	-7.90	-7.98	-8.47	1.0305	3.2290	0.2983	4.4208	1.4538	0.4631	2.3319	0.5734
240.	-9.11	-8.25	-7.94	-8.65	1.0049	2.8002	0.0628	3.4021	1.1345	0.4525	2.1530	0.5693
247.	-9.42	-8.44	-8.50	-9.63	0.9784	2.1650	0.1567	2.6016	0.7247	0.3561	1.9279	0.5277
254.	-9.97	-9.71	-7.96	-9.23	0.9461	1.2259	0.1031	1.9948	0.1555	0.0957	1.6104	0.4466

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MANHATTAN AGRICULTURAL EXPERIMENT 1980 SORGHUM S-2

JULIAN DATE	SIGMAO 8.6GHZ	SIGMAO 13 GHZ	SIGMAO 17GHZ	SIGMAO 35.6GHZ	PLANT HEIGHT	PLANT WATER	SOIL MOIST.	LEAF AREA INDEX	LEAF WET MASS	LEAF DRY MASS	STALK WET MASS	STALK DRY MASS
158.	-12.95	-11.86	-13.98	-15.48	0.1538	0.1132	0.2279	0.0600	0.	0.	0.	0.
161.	-13.80	-13.10	-12.70	-12.40	0.2445	0.1413	0.2435	0.1100	0.	0.	0.	0.
165.	-13.70	-13.80	-14.00	-13.06	0.3827	0.2388	0.1950	0.2000	0.	0.	0.	0.
168.	-12.80	-12.00	-13.00	-10.54	0.4931	0.3467	0.1408	0.3200	0.0320	0.0057	0.0609	0.0073
170.	-11.30	-10.65	-10.90	-11.10	0.5674	0.4361	0.0628	0.4400	0.1481	0.0267	0.1168	0.0118
176.	-10.42	-9.96	-9.09	-7.88	0.7784	0.7227	0.2294	1.0683	0.4452	0.0843	0.5585	0.0612
178.	-10.40	-9.53	-10.20	0.	0.8402	0.8257	0.1977	1.3571	0.5281	0.1018	0.6793	0.0768
182.	-10.29	-8.57	-9.99	0.	0.9428	1.0354	0.1203	1.9426	0.6709	0.1347	0.8821	0.1068
190.	-9.50	-8.32	-7.87	-7.77	1.0460	1.4179	0.0802	2.9601	0.8725	0.1918	1.1513	0.1610
192.	-10.20	-8.48	-8.35	-7.34	1.0460	1.4999	0.0520	3.1521	0.9068	0.2042	1.1950	0.1733
196.	-9.50	-8.90	-8.15	-7.91	1.0397	1.6414	0.0381	3.4355	0.9578	0.2266	1.2599	0.1960
198.	-9.36	-8.62	-7.75	-6.81	1.0366	1.6997	0.0317	3.5224	0.9751	0.2366	1.2826	0.2066
204.	-8.87	-7.86	-7.30	-7.43	1.0272	1.8191	0.1287	3.5514	0.9968	0.2609	1.3194	0.2344
206.	-9.82	-8.29	-7.64	-7.29	1.0240	1.8395	0.0618	3.4843	0.9949	0.2672	1.3230	0.2423
210.	-8.87	-7.79	-8.24	-7.87	1.0177	1.8511	0.0686	3.2434	0.9788	0.2765	1.3198	0.2562
213.	-9.29	-8.78	-7.54	-7.64	1.0130	1.8347	0.0519	2.9799	0.9570	0.2807	1.3098	0.2648
217.	-9.69	-7.79	-7.55	-7.35	1.0067	1.7813	0.0395	2.5424	0.9165	0.2825	1.2878	0.2735
221.	-10.20	-9.00	-8.99	-8.07	1.0005	1.6957	0.1063	2.0442	0.8649	0.2799	1.2576	0.2792
225.	-9.60	-8.44	-8.23	-7.33	0.9942	1.5837	0.0870	1.5364	0.8041	0.2729	1.2204	0.2817
231.	-9.16	-8.70	-7.78	-8.12	0.9848	1.3835	0.2783	0.8966	0.7003	0.2547	1.1527	0.2790
240.	-8.83	-8.50	-8.53	-7.85	0.9706	1.0792	0.0872	0.7442	0.5292	0.2121	1.0257	0.2596
247.	-10.53	-8.99	-8.90	-10.50	0.9596	1.0052	0.2143	0.6500	0.3965	0.1705	0.9029	0.2309
254.	-9.69	-9.52	-8.54	-9.48	0.9486	0.9352	0.0794	0.5800	0.2757	0.1265	0.7517	0.1896

MANHATTAN AGRICULTURAL EXPERIMENT 1980 SORGHUM S-3

JULIAN DATE	SIGMAO 8.6GHZ	SIGMAO 13 GHZ	SIGMAO 17GHZ	SIGMAO 35.6GHZ	PLANT HEIGHT	PLANT WATER	SOIL MOIST.	LEAF AREA INDEX	LEAF WET MASS	LEAF DRY MASS	STALK WET MASS	STALK DRY MASS
158.	-11.92	-11.80	-12.37	-15.00	0.1541	0.0800	0.2435	0.0800	0.	0.	0.	0.
161.	-14.40	-13.90	-13.10	-12.60	0.2409	0.0370	0.2251	0.1286	0.	0.	0.	0.
165.	-15.00	-14.20	-14.00	-12.78	0.3732	0.1501	0.1506	0.2919	0.	0.	0.0284	0.0031
168.	-14.20	-12.80	-12.50	-10.36	0.4796	0.2592	0.1692	0.4531	0.0976	0.0185	0.0783	0.0082
170.	-10.37	-10.40	-11.68	-9.99	0.5516	0.3405	0.0789	0.5785	0.1850	0.0367	0.1774	0.0183
171.	-10.12	-10.19	-10.22	-9.98	0.5875	0.3832	0.0651	0.6466	0.2272	0.0459	0.2276	0.0235
176.	-10.40	-9.36	-8.84	-8.08	0.7597	0.6095	0.2579	1.0391	0.4222	0.0910	0.4738	0.0495
178.	-9.57	-8.59	-8.04	-8.24	0.8222	0.7031	0.1423	1.2200	0.4929	0.1080	0.5654	0.0600
182.	-10.00	-8.24	-9.07	0.	0.9300	0.8890	0.0847	1.5261	0.6216	0.1386	0.7286	0.0812
189.	-9.26	-8.33	-8.40	-6.86	1.0371	1.1893	0.1024	2.5118	0.8062	0.1801	0.9382	0.1177
190.	-8.80	-8.29	-8.43	-6.39	1.0484	1.2279	0.0937	2.5472	0.8283	0.1848	0.9602	0.1228
192.	-9.27	-8.02	-8.46	-7.08	1.0401	1.3010	0.0628	2.5827	0.8694	0.1932	0.9988	0.1330
196.	-9.28	-7.89	-7.70	-6.66	1.0392	1.4286	0.0344	2.6144	0.9387	0.2068	1.0562	0.1527
198.	-8.97	-7.82	-7.37	-6.79	1.0385	1.4822	0.0371	2.6123	0.9669	0.2122	1.0762	0.1623
204.	-9.08	-8.06	-7.53	-7.53	1.0358	1.5974	0.1563	2.5431	1.0260	0.2250	1.1089	0.1893
206.	-10.22	-8.34	-7.70	-7.53	1.0346	1.6268	0.0915	2.5017	1.0371	0.2285	1.1124	0.1977
210.	-10.30	-8.05	-7.72	-8.07	1.0318	1.6425	0.0891	2.3957	1.0464	0.2354	1.1111	0.2133
212.	-9.41	-8.83	-7.63	-8.27	1.0302	1.6486	0.0784	2.3327	1.0446	0.2390	1.1070	0.2205
213.	-9.60	-8.61	-7.64	-7.15	1.0294	1.6382	0.0676	2.2990	1.0421	0.2409	1.1041	0.2240
217.	-9.85	-8.70	-7.91	-7.53	1.0257	1.6064	0.0441	2.1522	1.0211	0.2489	1.0887	0.2365
221.	-9.44	-9.30	-7.95	-8.83	1.0214	1.5474	0.0838	1.9903	0.9827	0.2577	1.0677	0.2470
224.	-8.98	-8.55	-7.85	-9.11	1.0179	1.4878	0.1259	1.8627	0.9425	0.2645	1.0490	0.2534
225.	-9.01	-9.11	-8.11	-8.14	1.0167	1.4654	0.1127	1.8195	0.9269	0.2667	1.0423	0.2553
231.	-8.26	-8.20	-7.91	-7.88	1.0085	1.3114	0.2879	1.5600	0.8105	0.2766	0.9975	0.2628
240.	-8.75	-8.94	-8.72	-8.52	0.9940	1.0606	0.0666	1.2039	0.5616	0.2598	0.9171	0.2619
247.	-10.02	-8.64	-9.18	-9.59	0.9809	0.9102	0.2082	0.9934	0.3062	0.1830	0.8427	0.2497
254.	-10.17	-9.50	-8.09	-9.17	0.9662	0.8682	0.1307	0.8770	0.	0.	0.7543	0.2260