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FINAL TECHNICAL REPORT

EXPERIMENTAL AND THEORETICAL TESTS OF A MODIFIED SUITS MODEL

by

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ABSTRACT

The project was carried out with support from NASA through grant NSG 9033, Supplement 2, from October 1, 1977, through September 30, 1978. This report has three main parts:

(1) A description and listing of experimental measurements on a grain sorghum cultivar of the field bidirectional reflectance (500-1350 nm), Suits model parameters, and dry plant biomass. Model calculations of the bidirectional reflectance of sorghum for the 1977-78 growing season using the Suits reflectance model are reported. Comparisons are made between the field bidirectional reflectance and the model values of bidirectional reflectance and reported as r^2 (coefficient of determination significant at the 95% level) values.

(2) An analysis of the seasonal study of bidirectional reflectance of two cultivars of wheat compared to the Suits model calculations.

(3) A report on a method of using the Suits bidirectional reflectance model along with a simple atmospheric model to predict the LANDSAT multispectral scanner (MSS) output for specific vegetative targets, such as wheat, cotton and sorghum. Limited results show surprisingly good agreement with actual MSS measurements. The method shows promise as a deterministic method for analyzing LANDSAT imagery.

Chapter 1

Grain Sorghum Field Data For the 1977-78 Growing Season

Introduction

The abundance of grain sorghum grown in the Great Plains is such that LANDSAT images will not assuredly contain significant amounts of the crop during its growing season. The ground based measurements of bidirectional reflectance reported here will furnish useful reference information about the seasonal changes one can expect in the canopy reflectance. Chapter 2 is a description of the seasonal reflectance of wheat. Combining these studies with the proposed LANDSAT calculation described in Chapter 3 offers the capability of performing a cause-effect simulation of LANDSAT data based on measured plant parameters, the Suits reflectance model, and a simple atmosphere model.

Data Collection Techniques and Procedures

Oro-Extrx sorghum [Sorghum vulgare (Pers.)] was used in this study. A plot at the USDA, SEA Research Farm at Weslaco, Texas, was seeded at 5.97 kg/hectare on April 10, 1978. Emergence of the sorghum was observed on April 15.

Determinations were made approximately weekly (16 during the growing season) of the following crop parameters: LAI, SPLAI, leaf biomass, plant biomass, hemispherical reflectance and transmittance of all canopy components (heads, stems, green leaves, and brown leaves when they occurred in the canopy), crop spectral reflectance, Suits Model parameters, and bare soil spectral reflectance.

LAI values were found by removing plants from measured segments (50 cm in length) along at least two adjacent rows judged by the authors to be characteristic of the growth within the field at that time, and calculating the ratio of the total leaf area (found by direct measurement on a Hayashi Denko optical planimeter) to the ground area of the plants. The sorghum LAI values reached a maximum of 7.65 with a minimum of 0.130 (Table 1). The LAI, SPLAI, and leaf biomass determination are found in Table 2 as a function of days after emergence.

It was found that there was a value of .75 for r^2 of the first 11 values of SPLAI versus the leaf dry mass (Table 2). This suggests that it might be possible to find the experimental SPLAI from dry leaf biomass (Fig. 1). A higher r^2 was expected, but the nature of sorghum leaf with large centeral vein may be responsible for the error in measuring SPLAI.

Hemispherical reflectance and transmittance of the vegetative components of the plants (green leaves, heads, stems, and brown leaves) were determined by removing representative plants from the field and transporting them in plastic bags over ice the six miles to the DK-2A spectrophotometer at the USDA laboratory in Weslaco, Texas. A sample that covered the instrument port was then constructed of each vegetative component, and the hemispherical reflectance and transmittance (not possible for heads and stems) was measured at 50 nm increments from 450 to 2500-nm. A large amount of data was generated by this portion of the experiment with a representative sample. A complete analysis of this data will be the subject of a subsequent publication.

Relative crop reflectance values were determined in the wheat field from a 6 meter tower using a hand-held radiometer. This data was used to verify the Suits model calculations. Data were collected in 50 nm increments from 450 nm to 1350 nm using a wedge-filter type radicmeter (ISCO Model SR) equipped with a 1.8 meter fiber optics probe. The radiometer field of view to half maximum was 13°; the spectral bandwidth was 15 nm in the visible and 30 nm in the ir. Reflectance was determined relative to a standard horizontal panel coated with barium sulfate-based paint (Eastman Kodak White Reflectance Coating #6080). A detailed discussion of how the Suits parameters are determined experimentally can be found in [1].

To complete each data set, a spectral scan was obtained of bare soil within the wheat field where the plants had been removed. Mild variation occurred in the bare soil reflectance for different dates due to changes in surface soil moisture and surface weathering, a finding consistent with Condit [2]. The soil spectral reflectance on 07/18/78 can be found in Figure 2 as discrete data points.

The Suits Model Plant Parameters for Oro-Extrx Sorghum

Table 3 summarizes the Suits Model parameters measured on 16 dates during the growing season. They can be used along with the reflectance and transmittance of the respective vegetative components (heads, leaves, stems, etc.) and the soil reflectance to implement the Suits Model calculations of the canopy reflectance. In the first two columns of the table, the date on which the data set was collected and the number of days from emergence are shown, respectively. Column three indicates the number of layers of different vegetation that was used to characterize the canopy on each date. Thus, early in the season a single layer of green leaves predominated in the sorghum canopy, but by the time the plants matured (06/14/78) three distinctive layers were apparent in the canopy: heads, green leaves, and a senescent layer of brown leaves. The vertical thickness of each layer is given in column five. One should always treat the number in this column as negative, due to the choice of the coordinate system used in solving the model. More than one type of vegetative component can exist within a given layer, for example, green leaves and stems in layer I (06/14/78). Column six names the components (plant parts) within each layer, while column seven lists the average number of components per unit volume in the layer. Columns eight and nine list the average horizontal (σ_H) and vertical (σ_V) surface area projections of the named plant parts within the appropriate layer.

A Comparison of Experimental Canopy Reflectance Measurements with the Suits Model Calculations

Figure 2 compares model calculations, using the parameters determined on 07/18/78 for sorghum, and experimental crop reflectance measured on the same day. The crop had three distinct layers: heads, green leaves and stems, and brown leaves and stems. The observer angle was at zenith, while the sun zenith angle was 7.72°. A discrepancy between the experimental data and the model calculations also occurs as the curve rises to the ir shoulder at about 700 nm. The problem was first thought to have been due to a calibration error in the ISCO field spectroradiometer. But a calibration of this instrument with gas discharge lamps and a comparison with simultaneous data for crop reflectance taken with the U.S.D.A. field spectroradiometer indicated that the ISCO was correct to ±5 nm in the vicinity of 700 nm. The Beckman DK-2A (the instrument used to measure the reflectance and transmittance for plant components in the model) was then tested for accuracy in this wavelength region. A slide was made from green sorghum leaves and two reflectance and transmittance determinations were made, one with the photomultiplier system used in the range from 350-700 nm and the second using the solid state detector whose sensitivity ranges from 500-2500 nm. In the overlapping range from 500-700 nm, an average 25% disagreement in single leaf reflectance measurements was found and at 700 nm a disagreement of 65% existed. Our reported single leaf reflectance values were all determined with the 500-2500 nm solid state detector, and are considered to be in error at 700 nm. Thus, in the calculations that appear in this section, all 700 nm crop measurements and Suits model calculations are omitted.

In Table 4, coefficients of determination are tabulated for the regression of experimental data with Suits Model calculations. On each of the 16 dates shown, experimental data were collected from 500- to 1300-nm. Using the plant parameters determined on these dates and sun angles, the Suits Model calculations were made over the same wavelength interval at 50-nm increments. The field experimental reflectance data were then regressed against the Suits Model reflectance calculations at each of 16 wavelengths with the omission of 700 nm (the 700 nm data was omitted for reasons stated above). An average coefficient of determination for the entire season was found to be 86% for sorghum.

It should be noted that all canopy reflectance measurements were not made at the same time of day. The solar zenith angle corresponding to the time at which the experimental canopy reflectance was measured is also shown in Table 4 for each date.

1978 SORGHUM LEAF AREA INDEX

Date	SPLAI	LAI	$(\text{No. plants/cm})^{-1}$
April 27, 1978	.02	---	11.0/100 cm [21 measurements
May 2, 1978	0.120	0.130	12/100 cm
May 9, 1978	.1073	0.1067	12/100 cm
May 16, 1978	0.952	1.032	10/100 cm
May 23, 1978	2.92	2.11	8/100 cm
May 30, 1978	3.24	3.52	12/100 cm
June 7, 1978	3.18	2.87	10/100 cm
June 13, 1978	3.63	4.26	13/100 cm
June 20, 1978	3.02	3.01	11/100 cm
June 29, 1978	3.36	2.43	10/100 cm
July 5, 1978	3.10	2.53	9/100 cm
July 10, 1978	2.62	2.37	12/100 cm
July 18, 1978	2.62	2.61	11/100 cm
July 25, 1978	3.11	3.09	11/100 cm
August 2, 1978	7.69	7.65	11/100 cm
August 8, 1978	-	-	15/100 cm
			11.06 average of 36 measurements

TABLE 1. Listing of SPLAI, LAI, and number of plants per 100 Cm. for each date of observation.

SINGLE PLANT LEAF AREA INDEX VERSUS DRY LEAF BIOMASS

Date	SPLAI	Mass (grams)
5/9/78	.75	.74
5/16/78	1.01	3.35
5/23/78	2.92	10.74
5/30/78	3.14	13.83
6/7/78	3.16	14.9
6/13/68	3.69	17.53
6/20/78	3.15	15.10
6/27/78	3.34	15.74
7/5/78	3.10	18.14
7/10/78	2.27	17.18
7/18/78	2.62	16.57
7/25/78	3.11	18.30
8/2/78	7.69	20.58
8/8/78	----	16.95

TABLE 2. Listing of single plant leaf area index (SPLAI) and dry single plant leaf biomass for each date of observation. Single plant leaf area index is found by determining the average leaf area per plant divided by the average ground area per plant.

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FIG. 1

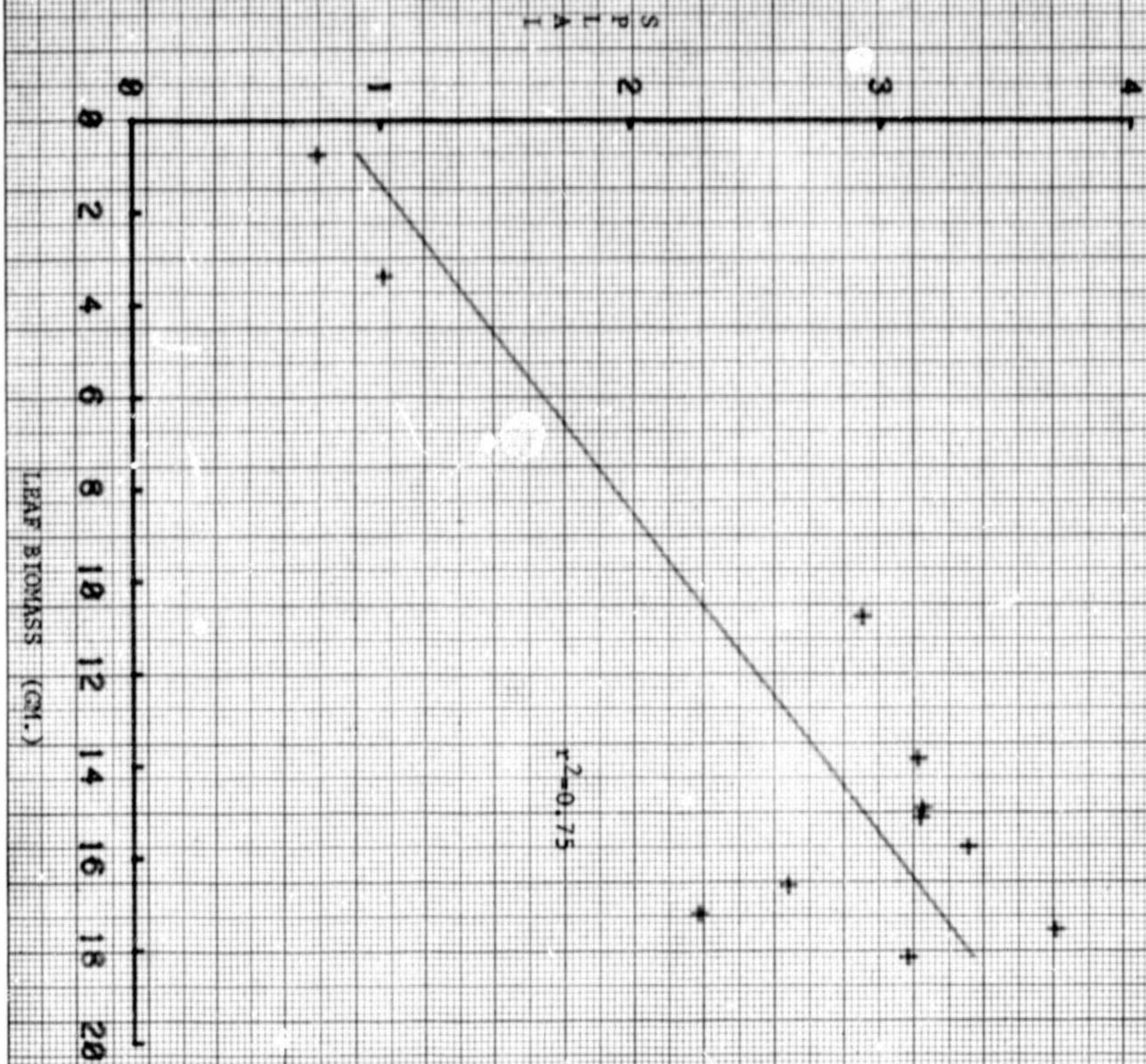

FIG.1. Dry weight in grams of a single plant's leaf blades from 50 Cm. row segments (Leaf Biomass) versus single plant leaf area index (SPLAI) for samples taken when SPLAI was increasing. + indicate a ctual observed points. Line indicates best fit for the observed values.

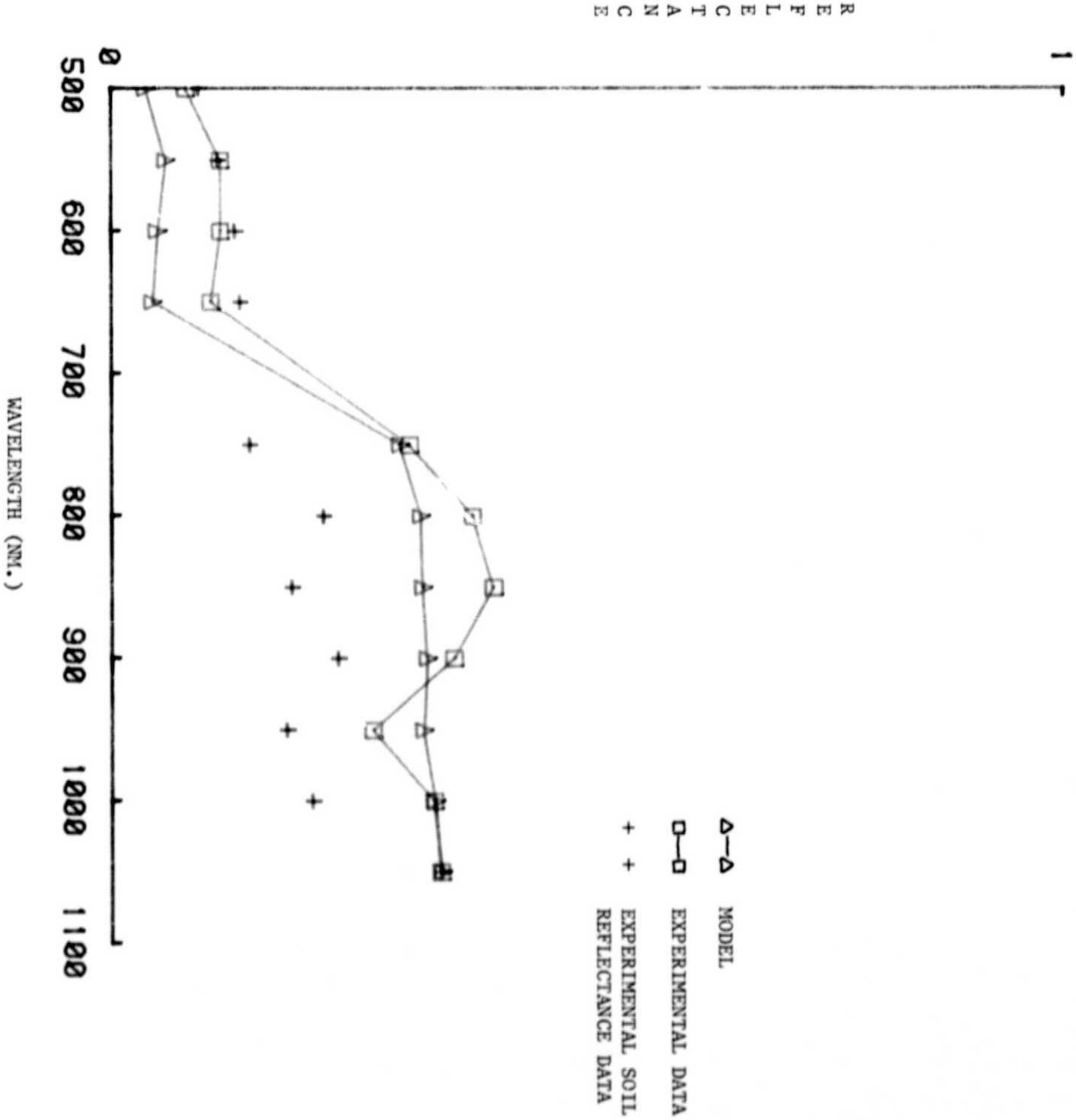

FIG. 2. Comparison of suits model, experimental crop refectance data, and experimental soil data measured on the same day (07/18/78). Sun zenith angle was 7.72 degrees at time of observation on 07/18/78.

TABLE 3

TABLE OF PARAMETERS

Sorghum

DATE	NO. OF DAYS	LAYERS	COMPO-NENTS	ΔX CM	TYPE OF VEGETATIONS	n LEAVES/CM^3	α_H CM^2/LEAF	α_V CM^2/LEAF
04/15/78	1	I	1st	--	Emergence	-	-	-
04/27/78	13	I	1st	11.33	Green leaves	3.8×10^{-4}	10.61	15.15
			2nd	11.33	Stem	9.5×10^{-5}	0	11.33
05/02/78	18	I	1st	30.0	Green leaves	2.16×10^{-4}	10.54	15.04
			2nd	30.0	Stem	3.60×10^{-5}	0	30.0
05/09/78	25	I	1st	37.0	Green leaves	1.51×10^{-4}	10.92	15.6
			2nd	37.0	Stem	2.92×10^{-5}	0	19.84
05/16/78	32	I	1st	32.62	Green leaves	2.69×10^{-4}	121.80	44.33
			2nd	32.62	Stem	3.32×10^{-5}	0	41.07
05/23/78	39	I	1st	46.75	Green leaves	1.62×10^{-4}	194.78	163.44
			2nd	46.75	Stem	2.31×10^{-5}	0	89.99
05/30/78	46	I	1st	49.26	Green leaves	2.46×10^{-4}	221.12	185.54
			2nd	49.26	Stem	2.16×10^{-5}	0	111.24
06/07/78	54	I	1st	67.3	Green leaves	1.82×10^{-3}	247.87	66.95
			2nd	67.3	Stem	1.61×10^{-5}	0	124.88
06/14/78	61	I	1st	86.92	Green leaves	1.28×10^{-4}	304.17	110.71
			2nd	86.92	Stem	1.24×10^{-5}	0	166.60
		[illegible]	1st	25.0	Head	4.33×10^{-5}	13.30	102.88
06/20/78	67	I	1st	90.8	Green leaves	1.09×10^{-4}	284.6	103.59
			2nd	90.8	Stem	$1.19.10^{-5}$	0	165.16
		II	1st	29.82	Head	3.63×10^{-5}	38.26	208.14
06/27/78	74	I	1st	85.81	Green leaves	1.21×10^{-4}	290.12	105.59
			2nd	85.81	Stem	1.26×10^{-5}	0	185.35
		II	1st	27.02	Head	4.00×10^{-5}	25.7	154.55
07/05/78	82	I	1st	87.09	Green leaves	1.16×10^{-4}	234.2	196.52
			2nd	87.09	Stem	1.24×10^{-5}	0	202.92
		II	1st	31.57	Head	3.43×10^{-5}	20.43	161.01
07/10/78	87	I	1st	88.22	Green leaves	9.50×10^{-5}	202.29	169.74
			2nd	88.22	Stem	1.23×10^{-5}	0	208.2
		II	1st	27.94	Head	3.87×10^{-5}	15.9	125.73
07/18/78	95	I	1st	88.47	Green leaves	6.00×10^{-5}	286.81	240.66
			2nd	88.47	Stem	1.22×10^{-5}	0	219.59
		II	1st	88.47	Brown leaves	3.89×10^{-5}	138.46	116.18
			2nd	88.47	Stem	1.22×10^{-5}	0	219.59
		III	1st	30.15	Head	3.59×10^{-5}	16.33	137.48
07/25/78	102	I	1st	87.1	Green leaves	7.00×10^{-5}	292.86	245.74
			2nd	87.1	Stem	1.24×10^{-5}	0	238.74
		II	1st	87.1	Brown leaves	5.08×10^{-5}	131.90	110.68
			2nd	87.1	Stem	1.24×10^{-5}	0	238.74
		III	1st	27.99	Head	3.86×10^{-5}	24.31	155.69
08/02/78	110	I	1st	86.97	Green leaves	7.92×10^{-5}	244.33	205.02
			2nd	86.97	Stem	1.24×10^{-5}	0	227.1
		II	1st	86.97	Brown leaves	3.84×10^{-5}	124.93	104.83
			2nd	86.97	Stem	1.24×10^{-5}	0	227.1
		III	1st	29.99	Head	3.61×10^{-5}	16.76	138.55
08/08/78	116	I	1st	89.28	Green leaves	6.51×10^{-5}	188.24	157.95
			2nd	89.28	Stem	1.21×10^{-5}	0	218.74
		II	1st	89.28	Brown leaves	3.63×10^{-5}	169.53	142.25
			2nd	89.28	Stem	1.21×10^{-5}	0	218.74
		III	1st	26.65	Head	4.06×10^{-5}	22.31	142.04

COEFFICIENTS OF DETERMINATION AND SUN ZENITH ANGLES

DATE	r^2	θ_s
April 27, 1978	0.90	28.22°
May 2, 1978	0.77	27.42°
May 9, 1978	0.91	27.14°
May 16, 1978	0.75	8.04°
May 23, 1978	0.98	8.84°
June 7, 1978	0.98	22.99°
June 14, 1978	0.86	31.10°
June 20, 1978	0.89	6.95°
June 27, 1978	0.88	23.27°
July 5, 1978	0.90	30.08°
July 10, 1978	0.79	7.72°
July 18, 1978	0.94	7.72°
July 25, 1978	0.82	7.64°
August 2, 1978	0.68	15.29°
August 8, 1978	0.91	29.03°

TABLE 4. Listing of coefficients of determination (r^2) for the regression of the experimental data with Suits Model calculations. Sun zenith angles (θ_s) are expressed in degrees.

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1. Chance, J. E., and E. W. LeMaster, "Suits reflectance models for wheat and cotton: theoretical and experimental tests," Appl. Opt. 16, 407 (1977).

2. Condit, H. R., "The spectral reflectance of American soils," Photogrammetric Engr. Vol. 36, September 1970.

Chapter 2

Introduction

Application of LANDSAT multi-spectral scanner data to agricultural problems, such as crop identification, crop yeild, and the identification of crop disease, has prompted studies on the interaction of solar radiation with crop canopies. To this end, several experimental studies are now in progress. The most extensive program of this type is the Large Area Crop Inventory Experiment (LACIE), as described by Hammond (1975), which has concentrated on discriminating wheat from other vegetation, estimating hectarage, and forecasting yields in the Great Plains. Coupled with this experimental effort, mathematical models have been developed which predict spectral reflectance from plant canopies as a function of solar, plant, and soil parameters. Notable among these mathematical models are the stochastic model developed by Oliver and Smith (1973) and the deterministic model of Suits (1972). This paper discusses results obtained by the authors with the Suits Model.

Chapter 3

Introduction

LeMaster and Chance [1] have shown that the Suits model for vegetative canopy reflectance predicts a simplified functional relationship for canopy reflectance as a function of

λ - wavelength (nms)

n - leaf area index (LAI

m_1 - sun air mass

m_2 - observer air mass.

This relationship is

$$R(\lambda,n,m_1,m_2) = R(\lambda,0,m_1,m_2)e^{-k(\lambda)n} + R(\lambda,\infty,m_1,m_2)\left[1-e^{-k(\lambda)n}\right] \quad (1)$$

where

$K(\lambda)$ is the canopy extinction coefficient and $R(\lambda,n,m_1,m_2)$ is the crop target reflectance which varies from bare soil reflectance $R(\lambda,0,m_1,m_2)$ (LAI-0) to infinite crop reflectance $R(\lambda,\infty,m_1,m_2)$ (LAI large). An explanation is necessary to clarify the concept of infinite reflectance. Suppose one imagines a leafy vegetative canopy. This canopy exhibits infinite reflectance whenever the addition of more leaves and vegetative components to the canopy by growth fails to change the canopy reflectance. The phenomena of infinite canopy reflectance has been observed experimentally for single leaves by Allen and Richardson [2] and appears in data published by LACIE [3] for wheat crops. Chance and LeMaster [4] have used the Suits spectral model for vegetative canopy reflectance to predict that canopy reflectance is within 5% of infinite canopy reflectance for LAI in excess of 2.1 in the 500-700 nm region and canopy reflectance within 5% of infinite canopy reflectance for LAI in excess of 6.1 in the 700-1100 nm region. These results suggest that the canopy extinction coefficient remains constant within each of these two wavelength intervals, as has been substantiated with experimental data taken by LeMaster and Chance and has been shown qualitatively for cotton leaves by Allen and Richardson [2], Figure 2.

With these theoretical results, one can calculate

$$K(\lambda) = .63, \quad 500 \leq \lambda(\mathrm{nm}) \leq 700$$
$$= .49, \quad 700 < \lambda(\mathrm{nm}) \leq 100.$$

The purposes of this paper are to use equation (1) to explain LANDSAT data taken at different times during the growing season of commercial cultivars. Equations are given to convert ground based crop reflectance measurements into LANDSAT digital counts, and finally methods are developed for the use of LANDSAT data for crop identification and to determine crop LAI.

Formulas for the Conversion of Ground Based Crop Reflectance Measurements to LANDSAT Digital Counts

It is not the author's purpose to develop a detailed atmospheric transfer model in this paper. Much work in this area has been done with models developed that consider a wide variety of input parameters. A notable example of such a model is the Turner Atmospheric Model developed by ERIM [5].

A model can be derived by considering sequentially the modifications of a light ray entering the atmosphere and traveling downward to a vegetative canopy, being reflected from the canopy, traveling upward in the atmosphere to LANDSAT, and finally being converted by the LANDSAT system to digital counts. The number of digital counts in channel i, Ch(i) for i=1,2,3,4, is

$$Ch(i) = \frac{1}{\pi A(i)} \int_{\alpha_{i-1}}^{\alpha_i} E(\lambda,m_1)R(\lambda,n,m_1m_2)D(\lambda,m_2)K(\lambda,i)d\lambda - \frac{B(i)}{A(i)} \quad (2)$$

where

(i) $E(\lambda,m_1)$ is the solar spectral radiant flux for air mass m_1 (Watts $cm^{-2}nm^{-1}$). The data used came from Gates [6] for an atmosphere with 10 millimeters of precipitable water, 200 particles per cubic centimeter of aerosol, and .35 centimeter of ozone.

(ii) $D(\lambda,m_2)$ is the transmittance of the atmosphere for air mass m_2. No suitable data could be found for the evaluation of equation (2), so atmospheric transmittance was set to 1 in the resulting derivations.

(iii) $K(\lambda,i)$ is the relative response of channel i in LANDSAT at wavelength λ. These response functions were found in ERIM report [7] for LANDSAT-1.

(iv) A(i), B(i) are LANDSAT calibration constants for channel i, published by NASA [8]. The subsequent equations that appear in this section of the paper were derived for LANDSAT-1, but a transformation is given that will convert these results to other LANDSAT readings.

(v) α_{i-1}, α_i are the lower and upper limits of wavelengths in nms for radiant energy detected in channel i of LANDSAT, found in [7].

Equation (2) was used to develop the formulas needed to convert ground based reflectance measurements into LANDSAT-1 digital counts. Using the data found in [6], [7], and [8], (2) was evaluated using the trapezoidal rule for numerical integration at 50 nm step sizes over the respective channels. These step sizes were chosen to conform to previously measured ground based reflectance measurements taken by LeMaster and Chance [9] for wheat, grain sorghum, and cotton. The set of formulas given below were derived for solar and observer air masses of 1, but have been found to give agreement for solar air mass of 1.30 (40° solar zenith angle). On the other hand, these equations give poor agreement for large solar air mass. Equations useful for large solar air mass can be derived in a similar manner from Equation (2) by further use of Gates' data. The equations, valid for LANDSAT-1, are ($R(\lambda)$ is the crop reflectance at wavelength λ nm.):

$$\begin{aligned}
Ch(1) &= 55.5\ R(500) + 118.8\ R(550) + 55.0\ R(600) \\
Ch(2) &= 82.6\ R(600) + 139.0\ R(650) + 63.0\ R(700) \\
Ch(3) &= 84.4\ R(700) + 61.7\ R(750) + 38.8\ R(800) \\
Ch(4) &= 10.2\ R(800) + 22.2\ R(850) + 14.1\ R(900) \\
&\quad + 6.6\ R(950) + 7.0\ R(1000) + 3.2\ R(1050).
\end{aligned} \tag{3}$$

Equations (3) have been used with the data given by Condit [10] on the reflectance of American soils to reproduce the Kauth Soil Line in LANDSAT space [11]. Figure 1 is a plot of channel 3 vs. channel 4 LANDSAT-1 digital count for grain sorghum spectral reflectance data collected by LeMaster and Chance. The dots represent data points simulated by Equations (3) with spectral reflectance data taken during the growing season from plots grown at the USDA - SEA Research farm north of Weslaco, Texas. The sun zenith angles were never larger than 25° for each spectral reflectance data set. It is of interest to observe that the multitemporal data from equations (3) initiates at the soil point and progresses upward along a near straight line with increasing LAI. The grain sorghum crop from which the spectral reflectance measurements were taken reached a maximum LAI of 3. This data compares favorably with data collected by Richardson [12] from LANDSAT-1 for grain sorghum fields in the Lower Rio Grande Valley of Texas. This data appears as crosses in Figure 1 and was collected for a sun zenith angle of 28°. Again, the data rises along what appears to be the same line as the simulated LANDSAT-1 data with increasing LAI and joins that line with good agreement at LAI=3. Figure 1 suggests that an appropriate scaling of the line along which the data points increase would give a knowledge of crop LAI. This will be shown to be the case in a later section of this paper. Figure 2 is a plot of channel 3 versus channel 4 digital counts simulating LANDSAT-1 data for Milam wheat grown in a plot north of Weslaco, Texas, at the USDA - SEA Research Farm.

Seasonal spectral reflectance data and LAI were collected by LeMaster and Chance [9] and used with equations (3) to calculate the data points seen in Figure 2. The data points correspond to the entire growing season and rise along a near straight line to maximum LAI=9 at the flowering stage. As the crop progresses past the flowering stage to the grain filling stage, the leaves lose their green color and LAI decreases, the data points in Figure 2 fall back toward the Kauth soil line along the same straight line, suggesting that channels 3 and 4 are not affected by crop chlorophyll and water content but measure crop dry biomass content. If Figures 1 and 2 are superimposed, it can be seen that both data sets originate at the same soil point and rise along lines that diverge with increasing LAI indicating that these lines have different slopes. This suggests that different cultivars might be identified from multitemporal LANDSAT data plots, such as figures 1 and 2, by examination of the slopes of these lines. This hypothesis is examined in a later section of the paper.

Equations (3) apply only to LANDSAT-1, but can be corrected to model LANDSAT-2 data by adjustment of the calibration constants that are discussed in (iv) of this section. If Ch2(i) is the digital count in channel i of LANDSAT-2, then one can use equations (3) to find Ch(i) and

$$Ch2(i) = Ch(i) \cdot C(i) - D(i).$$

The C(i) and D(i) are constants listed in Table 1, both for data from 1-22-75 to 7-15-75 and from 7-16-75 to at least 1977. For use on later LANDSAT-2 data, it should be determined whether or not subsequent changes in the calibration constants have been made.

whether or not subsequent changes in the calibration constants have been made.

Multitemporal Behavior of LANDSAT Data

To model the multitemporal behavior of LANDSAT data, substitute equation (1) into (2). After some simplification

$$Ch(i) = S(i)e^{-.63n} + I(i)\left[1-e^{-.63n}\right] - \frac{B(i)}{A(i)} \qquad (4)$$

for $i = 1,2$

$$Ch(i) = S(i)e^{-.49n} + I(i)\left[1-e^{-.49n}\right] - \frac{B(i)}{A(i)} \qquad (5)$$

for $i = 3,4$

where

$$S(i) = \frac{1}{\pi A(i)} \int_{\alpha_{i-1}}^{\alpha_i} E(\lambda,m_1)D(\lambda,m_2)R(\lambda,0,m_1,m_2)K(\lambda,i)d\lambda$$

$$I(i) = \frac{1}{\pi A(i)} \int_{\alpha_{i-1}}^{\alpha_i} E(\lambda,m_1)D(\lambda,m_2)R(\lambda,\infty,m_1,m_2)K(\lambda,i)d\lambda.$$

S(i) is a term that measures the effects of bare soil reflectance on LANDSAT data, and I(i) is a term that measures the effect of infinite crop reflectance. In what follows it will be assumed that S(i) and I(i) remain constant for every data acquisition data of LANDSAT. Such will never be the case for any real situation, however, since soil reflectance changes with change in soil moisture, the quality of the atmosphere varies from day to day, and the solar air mass varies slightly from one acquisition date to another due to solar declination.

Using the above assumption, solving equations (4) for $e^{-.63n}$ and equating like terms yields

$$\frac{Ch(1) - I(1) + \frac{B(1)}{A(1)}}{S(1) - I(1)} = \frac{Ch(2) - I(2) + \frac{B(2)}{A(2)}}{S(2) - I(2)}. \qquad (6)$$

Performing the same operations on equations (5) yields

$$\frac{Ch(3) - I(3) + \frac{B(3)}{A(3)}}{S(3) - I(3)} \qquad \frac{Ch(4) - I(4) + \frac{B(4)}{A(4)}}{S(4) - I(4)}. \qquad (7)$$

Equation (6) predicts a linear relationship between channels 1 and 2 and equation (7) predicts the same for channels 3 and 4. These results have been verified experimentally many times with LANDSAT data by other authors. It is of interest to observe that the spread of data in Figures 1 and 2 about this line is probably due to variation in S(i) and I(i) from one acquisition date to another, out appears to have only a moderate effect on the linearity of the data.

If one solves equations (4) and (5) for e^{-n}, then the relationship between channel i in the visible (i=1,2) and channel j in the infrared (j=3,4) is

$$\left[\frac{Ch(i) - I(i) + \frac{B(i)}{A(i)}}{S(i) - I(i)}\right]^{1.59} = \left[\frac{Ch(j) - I(j) + \frac{B(j)}{A(j)}}{S(j) - I(j)}\right]^{2.04} \qquad (8)$$

Equation (8) is a nonlinear relationship which has been observed experimentally in graphs of channel i versus channel j. This nonlinearity is due physically to the differences in light attenuation through vegetative canopies that occur between the visible and infrared wavelengths. For example, multitemporal plots of LANDSAT channel 2 versus channel 3 originate at the bare soil point with channel 2 readings decreasing with increasing LAI and channel 3 readings increasing. Channel 2 readings do not decrease appreciably for LAI greater than 2 while channel 3 readings tend to increase up to an LAI of 6, causing a vertical asymptote in the graph. In contrast, as has been seen from Figures 1 and 2 channel 3 versus channel 4 plots increase in a linear manner with detectable changes observed for LAI greater than 2. Observations from LANDSAT data further indicates that in the visible channels there is a relatively small change in digital counts from soil reflectance to infinite reflectance which tends to compress the data on a small scale. In addition, the visible channels tend to be more affected by changes in the quality of the atmosphere and soil moisture than the infrared channels. It is for these reasons that the author has chosen equation (7) for further analysis, so that the remaining portion of the paper is spent in discussing its uses.

<u>Use of Multitemporal LANDSAT Data to Determine LAI</u>

Solving equations (5) for n gives

$$n = -2.04 \ \ell n \left(\frac{Ch(i) - I(i) + \frac{B(i)}{A(i)}}{S(i) - I(i)} \right)$$

which can be used in either channel 3 or channel 4. For LANDSAT-1 $B(i) = 0$ so that

$$n = -2.04 \ \ell n \left(\frac{Ch(i) - I(i)}{S(i) - I(i)} \right) \qquad i=3,4 \tag{9}$$

To use equation (9) a data base must be collected from previous LANDSAT readings. For example, to determine the LAI of grain sorghum grown in Eastern Hidalgo County, Texas, the LANDSAT digital counts for bare soil in this location must be known as well as the LANDSAT digital counts for a grain sorghum crop exhibiting infinite reflectance. Once these parameters are known equation (9) can be used. In Table 2 a comparison is made between LAI calculated by equation (9) using channel 3 of LANDSAT-1 and experimentally measured LAI, as published by Richardson [12]. The sun zenith angle was 28° and all data was taken from one frame of LANDSAT data. One should be cautious to use values for I(i) and S(i) having the same or very nearly the same solar zenith angle as that for which the crop data was acquired.

Use of LANDSAT Data for Crop Identification

As a crop grows to maturity and its LAI increases, the corresponding LANDSAT observati ns for channels 3 and 4 when plotted as ordered pairs progress about a straight line. This straight initiates about a point (S(3), S(4)) on the Kauth Soil Line [11] corresponding to the soil reflectance for soils in the same geographical area as the crop and terminates at the infinite reflectance point (I(3), I(4)) for the crop. This infinite reflectance point can be determined in practice from LANDSAT data taken for the crop in question during previous years. The solar zenith angles for the infinite reflectance data should correspond to the solar zenith angles expected during LANDSAT acquisition dates for the crop.

Table 3 is a listing of infinite reflectance readings for LANDSAT-1 for several commercial cultivars, and from this data it appears that a difference exists between the infinite reflectance points. In channels 3 and 4, sugar cane and cotton are closely grouped, corn and grain sorghum are closely grouped, and wheat appears separate from the other two groups. These results are displayed geometrically in Figure 3. These differences are also mirrored in the ground based spectral reflectance data. Figure 4 is a plot of the spectral reflectances of cotton and wheat from data collected by LeMaster and Chance in which both cultivars had LAI in excess of 8. Only insignificant differences occur in reflectance values in the visible region, but marked changes in reflectance occur in the near ir. Such differences in crop reflectance would not be expected to be seen for low LAI crops, as the soil reflectance would tend to "mask" the weaker vegetative reflectances. Also, such a result can not be attributed to the reflectance differences in single leaves of cotton and wheat, as examination of monograph, The Leaf Mesophylls of Twenty Crops, Their Light Spectra, and Optical and Geometrical Parameters by Gausman, Allen, Wiegand, Escobar, Rodriguez, and Richardson [13], indicates. The cause of such a reflectance difference in the near ir could be caused by differences in plant physiology or plant geometry between cotton and wheat.

Conclusions

1. A simplified atmospheric transfer model that converts ground based crop spectral reflectance measurements into LANDSAT-1 digital counts has been shown to give results that are in agreement with actual LANDSAT-1 digital counts.
2. An equation is given for calculating crop LAI in terms of LANDSAT digital counts in either channels 3 or 4. This equation is shown to predict LAI in agreement with experimentally determined LAI.
3. Multitemporal LANDSAT data plots of channel 3 versus channel 4 are shown to yield both information on crop LAI and crop discrimination.
4. Further experimental work and research into past LANDSAT data records should be continued to determine if LANDSAT digital counts for crops exhibiting infinite reflectance uniquely determine the crop.

Channel	C(i)	D(i)	
1	.124	.637	1/22/75 to 7/15/75
2	1.342	5.983	
3	1.314	6.666	
4	1.146	2.197	
1	.970	3.980	7/16/75 to present
2	1.172	4.478	
3	1.200	5.217	
4	1.211	1.824	

Table 1.

Calibration Constants Required to Convert Equations (3) from LANDSAT-1 to LANDSAT-2.

Channel 3 LANDSAT-1 reading Ch(3)	Experimentally Determined LAI	LAI from Equation (9)
46	3.0	2.0
58	3.9	4.1
56	4.1	3.6
58	4.2	4.1
53	4.2	3.0
56	4.9	3.6
60	5.1	4.8
65	6.9	undef. (6.1 or greater)
67	7.3	undef. (6.1 or greater)
65	8.5	undef. (6.1 or greater)

$$I(3) = 65, \ S(3) = 13$$

$$LAI = -2.04 \ \ln \left(\frac{65 - Ch(3)}{52} \right)$$

Table 2

A Comparison of LAI Calculated from Equation (9) with Experimentally Determined LAI Using LANDSAT-1 Data Published by Richardson [12].

Cultivar	Ch(1)	Ch(2)	Ch(3)	Ch(4)	Type of Data
Cotton	15	15	71	39	LANDSAT-1 simulation using equation (3) with small solar zenith angle.
Wheat	8	5	42	30	LANDSAT-1 simulation using equation (3) with small solar zenith angle.
Grain sorghum	36	28	65	38	LANDSAT-1 data from Richardson [12] with small solar zenith angle.
Corn	29	22	67	33	LANDSAT-1 converted from LANDSAT-2 data by Table 1 with small solar zenith angle. LANDSAT-2 data supplied by Jerry Richardson, USDA-SEA, Weslaco, Texas.
Sugar-cane	19	25	74	41	LANDSAT-1 simulation using equation (3) from crop reflectance data supplied by Ross Leamer, USDA-SEA, Weslaco, Texas.

Table 3.

LANDSAT-1 Digital Counts for Several Cultivars with LAI in Excess of 8 and Small Solar Zenith Angle.

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