FINAL TECHNICAL REPORT

SEASONAL SOYBEAN CROP REFLECTANCE

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by

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Supplements 8, 9, and 10

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Chapter 1

Introduction

Collection of experimental data was completed during the summer of 1980. A six month extension of the grant allowed extra time for data analysis during the spring of 1981.

The original objectives were to (1) test the technique previously developed [4] for transforming reflectance at ground level to Landsat MSS digitial counts, (2) establish the existence of the "infinite green point" [4] for several crops using MSS infrared channels plotted against each other for several crops, and (3) take measurements of the radiation field inside a canopy and check the radiation equations developed and partially tested on cotton.[5]

In our conversations with Mr. Andy Scott of Rio Farms, Inc. of Monte Alto, Texas, we discovered that experimental plots of soybeans of Brazilian varieties released for the international markets in 1973 were being grown by Rio Farms. Dr. David Pitts of NASA, JSC expressed a desire (See Appendix) to collect sets of Suits model parameters on soybeans throughout the growing season. These data would be useful in simulating soybean reflectance from Brazilian sites for future NASA projects involving Brazilian agriculture. Suits model parameters from Brazilian soybean varieties used with soil reflectance data taken from Stoner's[1] report simulated soybean canopy reflectance with the Suits bidirectional reflectance model.

This report contains data from field measurements of 1980 including 5 acquisitions of hand-held radiometer reflectance measurements, 7 complete sets of parameters for implementing the Suits model, and other biophysical parameters to characterize the soybean canopy. Landsat calculations are presented on the simulated Brazilian soybean reflectance. Data are presented that were collected during the summer and fall of 1981 on soybean single leaf optical parameters for three irrigation treatments.

Chapter 2

Experimental Methods

Field measurements were carried out from a 6 meter tower located at the Rio Farms, Inc. Experimental Farm in Monte Alto, Texas. Crop reflectance measurements were taken with an ISCO field spectroradiometer in 50 nm increments from 50 nm to 1300 nm using the ISCO which has a spectral band pass of 15 nm in the visible and 30 nm in the infrared. A 3'x4' plywood panel spray painted with 3 layers of barium sulfate paint was used as a reflectance standard. A ratio of crop to panel readings was used to obtain crop reflectance.

On each day that crop reflectance measurements were recorded, a ratio of shadowed to sunlight panel readings was calculated. A shadow was cast on the panel sufficient only to fill the ISCO field of view, so that the smallest possible solid angle from the sky was intercepted. Readings from the shadowed panel are indicative of atmospheric scattering, giving an index of the type of atmosphere present during the measurement period. By trial and error, it was found that shadowed panel readings were needed only at one wavelength in the visible region and one wavelength in the infrared region.

Soybean crop reflectance was measured from atop the tower with a vertical view angle. The sun angles were near nadir, and measurements were always taken within 2 hours of solar noon. The radiometer (ISCO Model SRR) was equipped with a 1.8 meter fiber optics probe having a 15° field of view. The probe was extended horizontally 1.2 meters from the top of the scaffolding.

Successful measurements were taken 5 times during the growing season. During the summer of 1980, Hurricane Allen struck the Gulf Coast near our test site. High winds blew over our tower and prevented measurements for several weeks during the growing season because of excess water in the test site. Equipment failure was also rampant. Both of the portable electric power generators failed and time was consumed in their repair. The ISCO spectroradiometers failed and could not be repaired (they had been in service since 1965). The seasonal measurements were completed using a borrowed ISCO radiometer belonging to Dr. Ed Kanemasu, Kansas State University Evapotranspiration Lab., Manhattan, Kansas. The test area of the soybean field was inadvertently sprayed with a defoliant during the early stages of growth, necessitating a movement of the tower to a new test site. If all this were not enough, a tractor tilling the field hooked one of the tower guy wires and pulled the tower down, damaging the scaffold.

Table 1 gives a listing of the soybean field reflectance values for the dates shown as a function of wavelength. Leaf area index, sun zenith angle, diffuse fraction of the irradiance, percent ground cover, and soil reflectance are also included. Graphical presentations of these data are shown in Figs. 1-5. Included in these figures are the data for the bare soil reflectance. The measurements were made on sunlit soil between the rows in the test area. For full canopy coverage, enough of a row was removed so that sunlit bare soil was visible.

Table 2 is a presentation of the seasonal average single leaf reflectance and transmittance values made for 7 sampling dates and 2 samples on each date. The values shown are for 2 soybean cultivars grown during the summer of 1980. The light green variety was RA680 and the dark green was RA700. They were planted on 6 April 1981. The field we studied in 1981 was planted 15 July 1980. Table 2 shows the mean values of the reflectance and the transmittance for 6 dates and the standard deviation for all the leaves at that wavelength. Each date included two leaf measurements each from light green plants and dark green plants. Data are presented in Fig. 6 for all acquisition dates for 650 nm and 850 nm showing the reflectance and transmittance of the single leaves. The leaf optical properties remain fairly constant throughout the vegetative growth of the plants. Sinclair <u>et al</u> [2] also found that for soybeans, corn, sorghum, and sudangrass the reflectances of the single leaves were constant throughout the middle part of the growing season. Their results were not supported by a great amount of experimental data. They relied on the general finding that the main factors affecting reflectance are chlorophyll and the cartenoids in the visible (400-700 nm), the leaf cellular structure in the near i.r. (700-1300 nm), and the leaf water content in the intermediate infrared region (1300-2600 nm), and that these factors don't change significantly during the middle part of the growing season. Our previous results [3] on wheat for an entire growing season showed fairly constant optical properties for the leaves from a few weeks after emergence to the onset of senescence.

The data of Table 2 were obtained using the following procedures. Plants were removed from the soil, enclosed in a plastic bag, placed immediately over ice, and transported directly to the Remote Sensing Lab. The expired time was approximately 30-45 minutes between removal and measurement. A Beckman DK-2A automatic recording spectrophotometer with an integrating sphere attachment was used in the study. The instrument was provided by the USDA, SEA Research Center in Weslaco, Texas, whose continued cooperation makes this research possible.

There are some single leaf reflectance and transmittance data that seem to be in error. The transmittance values of the leaves show negative values in the visible part of the spectrum (450-650 nm). The problem was either a drifting of the calibration of the instrument because of inadequate warming-up or adjustment of the amplifier gain on the instrument.

It was later decided to rerun the single leaf transmittances and reflectances during the summer of 1981. Included in the Appendix are values measured to date. Since planting dates were different, the number of days since planting is included. A comparison between 650 nm and 850 nm reflectance values for single soybean leaves is shown in Fig. 6 for both the 1980 and 1981 growing seasons.

Table 3 is a synopsis of the plant data recorded for the dates indicated. Leaf slopes were measured with a protractor and plumb line along the central vein of the leaf. Horizontal and vertical projections of the leaf areas

(σ_n and σ_v) were found from the average area of a leaf, σ, multiplied by the cosine and sine of the average leaf slope, respectively. There was no apparent layering in the soybeans, so the canopy was treated as a homogeneous layer. Leaf area index (LAI) is shown along with projected leaf area index (PLAI) found using the actual width of the vegetation in the rows.

Our research assistant was directed in a project to measure the reflectances and transmittances on soybean leaves during the summer of 1981. The question being asked was, "How does soil moisture affect leaf reflectance and transmittance?" His findings are included in this report.

Results and Discussion

The results shown in Figs. 1-5 indicate the experimental reflectance, the Suits model reflectance calculations and also the soil reflectance from the observation site. Table 4 shows the coefficient of determination for field reflectance versus the Suits model for the dates where a significant amount of vegetation was present in the scene, i.e., L.A.I. ≥ 0.3. The values show that for September and October there is good agreement between the field data and model calculations. The poor agreement on 7 August 1980 (see Fig. 2) was most likely due to our radiometer chopper motor failure. The radiometer was discarded after this date.

The next calculation was a simulation of the reflectance to be expected from a Brazilian soybean canopy based on the Suits model. The soil reflectance was taken from Stoner's report [1] and is shown in Figs. 7a-7d at four geographical locations. Using Cascavel soil, Fig. 7a, and the Suits model parameters from Table 3, the Suits model bidirectional reflectance function was calculated and is shown in Figs. 8a-8g. These values were then used to calculate the Landsat multispectral scanner system digital counts in the 4 channels for a clear standard atmosphere [4] and a sun zenith angle of 30°. The results are shown in Table 5 and Fig. 9. The table shows that the visible channels, Ch 1 and Ch 2, show little change in digital counts with varying amounts of vegetation.

The Cascavel soil is quite dark and the reflectance of vegetation in the visible is 5-7%, so varying the amounts of vegetation that shows little contrast with the soil produces little change in scene reflectance in this spectral regime. One expects the reflectance to show the greatest sensitivity to vegetation in a spectral region where there is maximum contrast between soil and vegetation. For the i.r. channels this sensitivity is shown clearly in Fig. 9. Chance [4] has shown by using the Suits model and Landsat data that the leaf area index is exponentially related to the MSS digital counts.

References

1. Stoner, E. R., M. F. Baumgardner, L. L. Biehl, and B. F. Robinson, "Atlas of Soil Reflectance Properties," NASA Report No. NAS9-15466, 15 Nov. 1979.

2. Sinclair, T. R., R. M. Hoffer, and M. M. Schreiber, Agron. Jour. 63, 864-868 (1971).

3. Chance, J. E., and E. W. LeMaster, "Plant Canopy Light Absorption Model with Application to Wheat," Appl. Optics 17, 2629 (1978).

4. Chance, J. E., "Crop Identification and Leaf Area Index Calculations with Landsat Multitemporal Data," INT. J. Remote Sensing 2, 1 (1981).

TABLE 1

FIELD REFLECTANCE OF SOYBEANS

	Date: 08/07/80 θ_s = 29.3° f_D = 0.9 % cover = 33 LAI = 0.26	Date: 09/11/80 θ_s = 22.3 f_D = 0.29 % cover = 76.3 LAI = 2.40	Date: 09/16/80 θ_s = 30.1 f_D = 0.36 % cover = 84.3 LAI = 4.14	Date: 10/09/80 θ_s = 43.7° f_D = 0.20 % cover = 94.1 LAI = 2.99
λ	Reflectance	Reflectance	Reflectance	Reflectance
500	0.049	0.026	0.026	0.019
550	0.074	0.063	0.055	0.054
600	0.071	0.044	0.035	0.033
650	0.075	0.032	0.027	0.048
700	0.10	0.082	0.36	0.075
750	0.15	0.35	0.40	0.37
800	0.30	0.37	0.48	0.39
850	0.25	0.36	0.44	0.42
900	0.48	0.40	0.49	0.42
950	0.37	0.39	0.44	0.45
1000	0.28	0.38	0.44	0.47
1050	0.37	0.41	0.47	0.46
1100	0.46	0.42	0.44	0.46

TABLE 2

AVERAGE SINGLE LEAF OPTICAL PARAMETERS FOR TWO VARIETIES OF SOYBEANS

λ	Dark Green		Light Green	
	Reflectance	Transmittance	Reflectance	Transmittance
500	.035 ±.018	.011 ±.016	.037 ±.013	.006 ±.013
550	.078 ±.003	.045 ±.019	.100 ±.019	.045 ±.015
600	.060 ±.007	.027 ±.014	.076 ±.018	.023 ±.010
650	.057 ±.004	.018 ±.013	.065 ±.009	.010 ±.006
700	.21[illegible] ±.036	.163 ±.040	.247 ±.027	.164 ±.037
750	.419 ±.010	.361 ±.045	.436 ±.023	.327 ±.029
800	.422 ±.011	.360 ±.041	.444 ±.018	.340 ±.025
850	.429 ±.008	.304 ±.040	.447 ±.021	.347 ±.027
900	.429 ±.008	.368 ±.039	.448 ±.017	.350 ±.026
950	.423 ±.008	.366 ±.038	.442 ±.017	.350 ±.026
1000	.427 ±.009	.343 ±.082	.446 ±.016	.355 ±.027
1050	.420 ±.010	.376 ±.037	.446 ±.016	.360 ±.026
1100	.402 ±.010	.374 ±.037	.439 ±.016	.359 ±.027

TABLE 3. SUITS MODEL PARAMETERS FOR SOYBEANS

DATE	BIO-MASS (g)	TOTAL NUMBER OF PLANTS/ METER	AVERAGE LEAF SLOPE	TOTAL NUMBER OF LEAVES/ METER	AVERAGE PLANT HEIGHT (cm)	TOTAL LEAF AREA (cm^2)	LEAF NUMBER DENSITY (cm^{-3})	TOTAL LAI	PROJ. LAI	σ (cm^2)	σ_h (cm^2)	σ_v (cm^2)
8/07/80	5.39	21	15.4°	177	17	1,331.72	.0020	0.26	0.78	7.524	7.254	1.998
9/12/80	54.1	21	17.2°	612	57	12,230.5	.0021	2.40	4.91	19.98	19.08	5.90
9/18/80	83.2	22	26.5°	1174	66	21,115.4	.0035	4.14	6.21	17.99	16.099	8.037
9/30/80	91.3	24	25°	1294	71.3	27,377.4	.0036	5.37	6.52	21.16	19.127	8.942
10/09/80	85.8	25	31°	1065	71.3 Plants beginning to senesce	15,219.7	.0029	2.99	3.2	14.3	12.3	6.04
10/28/80	43.0	19	13.6°	798	71.3	12,229.1	.0022	2.40	2.4	15.3	14.9	3.60
11/07/80	22.9	27	7.28°	291	71.3	5,252.5	.0008	1.03	1.03	18.1	18.0	2.30

Table 4. Coefficient of determination for soybean field reflectance calculated from the Suits model versus the experimental reflectance from a hand-held radiometer.

Date	Coefficient of Determination
7 August 1980	0.58
11 September 1980	0.91
16 September 1980	0.95
9 October 1980	0.97

Table 5. Suits Model Simulation in Landsat 1 Digital Counts.

LAI	Ch 1	Ch 2	Ch 3	Ch 4
-0-	37	30	26	8
.26	37	29	33	11
2.4	38	28	53	20
4.14	38	27	53	21
5.37	37	27	54	21
2.99	37	27	53	20
2.40	38	28	54	21
1.03	38	28	47	17

Figure Captions

Fig. 1. The soybean field reflectance and bare soil reflectance early in the growing season. No Suits model calculation was made because the vegetation is only a small fraction of the scene and would appear as almost bare soil.

Fig. 2. Field reflectance for 7 Aug. 1980 Suits model calculation, and bare soil reflectance is shown for a 33% ground cover soybean crop with an LAI of 0.26. Table 1 gives numerical values of reflectances plotted here as well as parameters used in the Suits model. Single leaf reflectance values are shown in the Appendix. The explanation in the Appendix explains all values shown there. The coefficient of determination, r^2, is 0.58.

Fig. 3. Soybean field reflectance, Suits model, and bare soil reflectance values for 11 Sept. 1980 are shown. The ground cover is 76% and LAI is 2.40. The coefficient of determination is 0.91.

Fig. 4. Soybean data for 16 Sept. 1980 with 84% ground cover and LAI of 4.14. The coefficient of determination is 0.95.

Fig. 5. Soybean data for 9 Oct. 1980 with 94% ground cover and LAI of 2.99. The coefficient of determination is 0.97.

Fig. 6. Soybean single leaf reflectance for 650 nm and 850 nm for the 1980 and 1981 growing seasons.

Fig. 7. (a-d) The reflectance of Brazilian soil taken from the report of Stoner[1]. These soils are quite similar and are formed near the towns in Brazil named on the graph. a) Cascavel soil with 32.5% moisture by weight, b) Pato Branco, c) Guarapuava, d) Londrina soil with 33% moisture by weight.

Fig. 8. (a-g) Suits model reflectance values for soybeans using plant parameters from Table 3 for the dates shown. The leaf area index indicates the amount of vegetation; other details are found in Table 3. The soil was from Fig. 7a from Cascavel, Brazil (approx. 53°W Longitude and 25°S Latitude). The sun angle was 30° from zenith, observer angle was 0°, and the diffuse light was 20% of the total.

Fig. 9. The simulated Landsat 1 MSS digital counts in the two ir channels (Ch 3 band is .7-.8 and Ch 4 band is .8-1.0). Data is taken from Table 4. The reflectance is on a soybean field at different times in the growing season.

Fig. 1

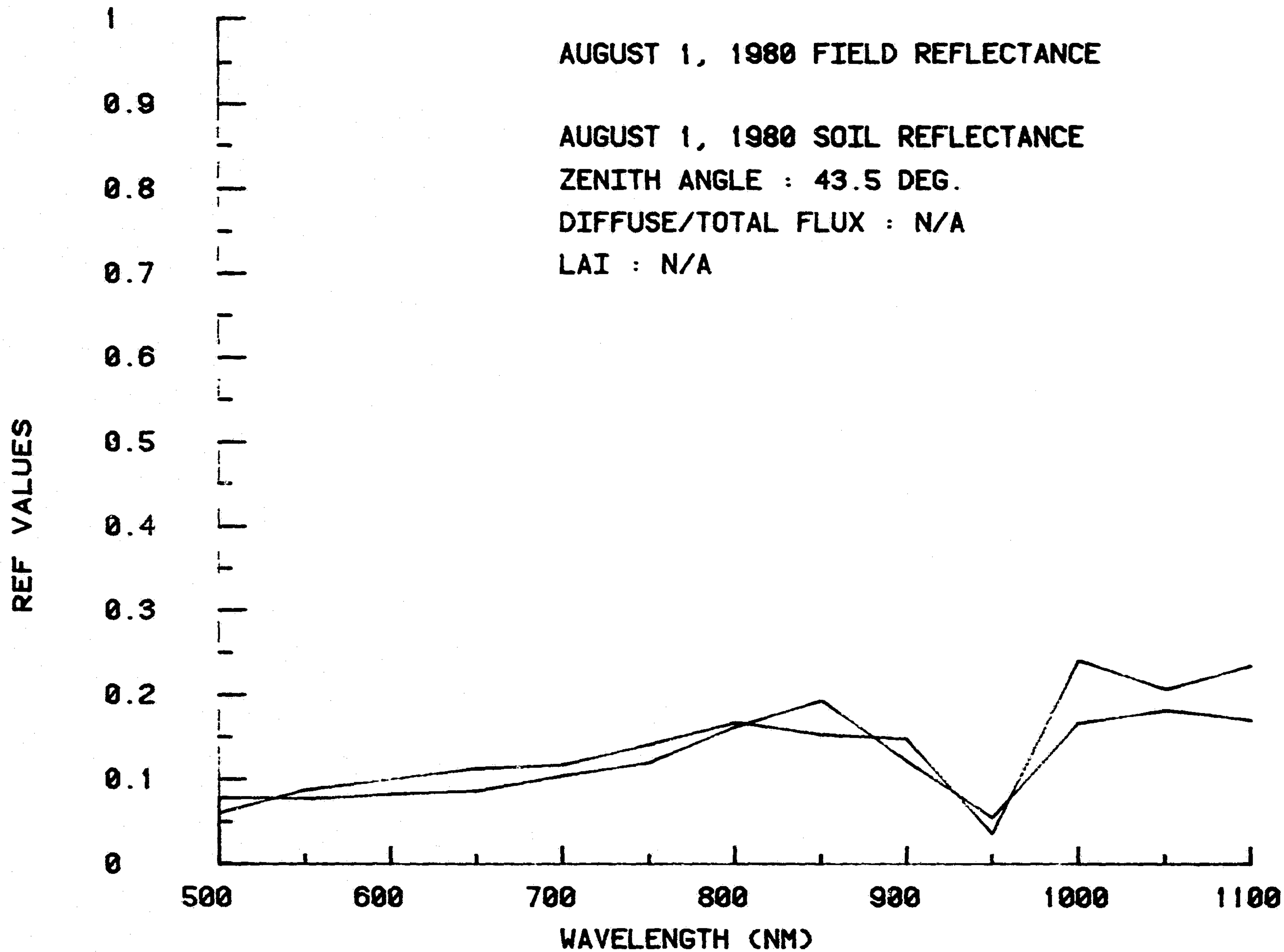
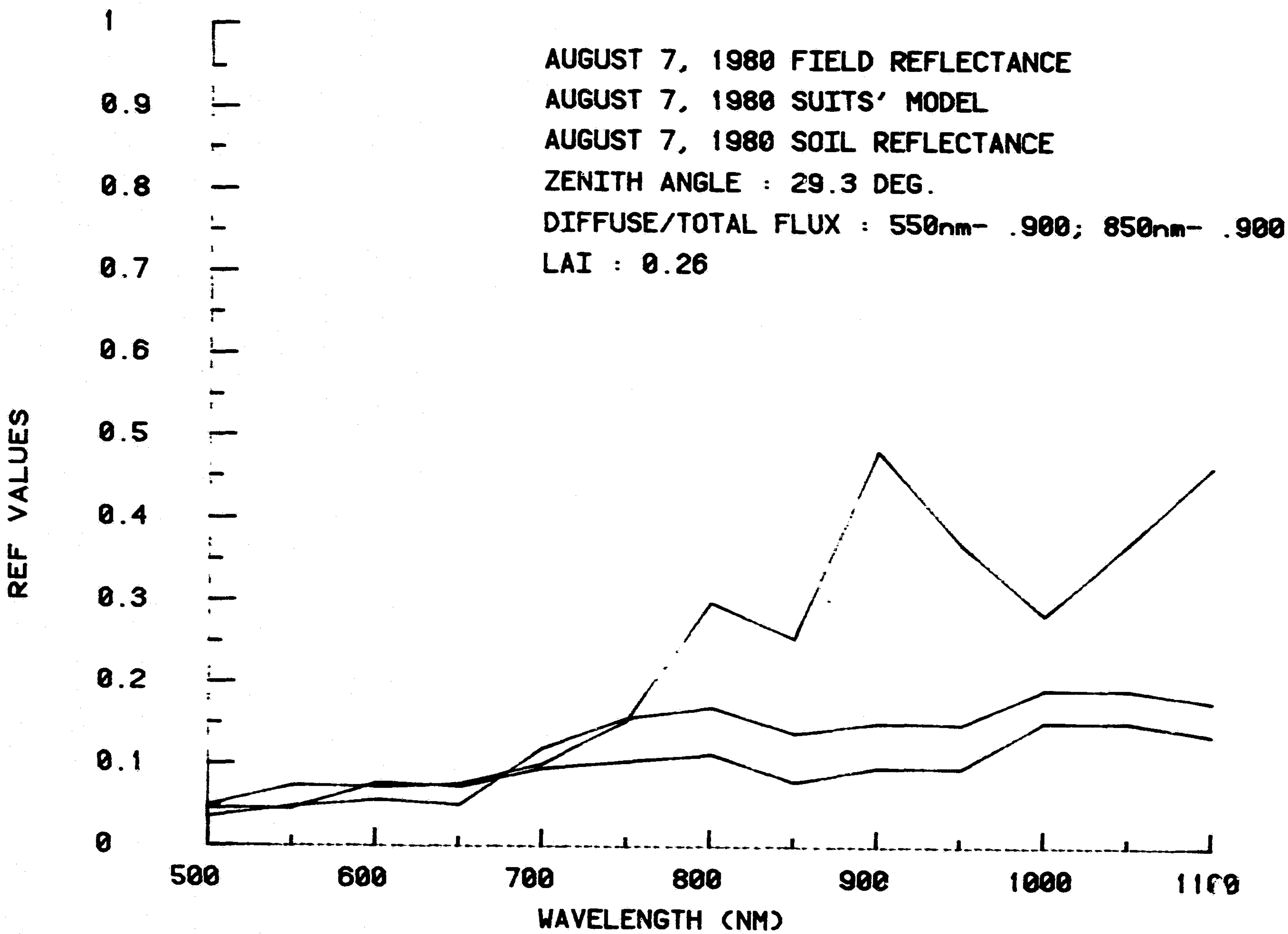


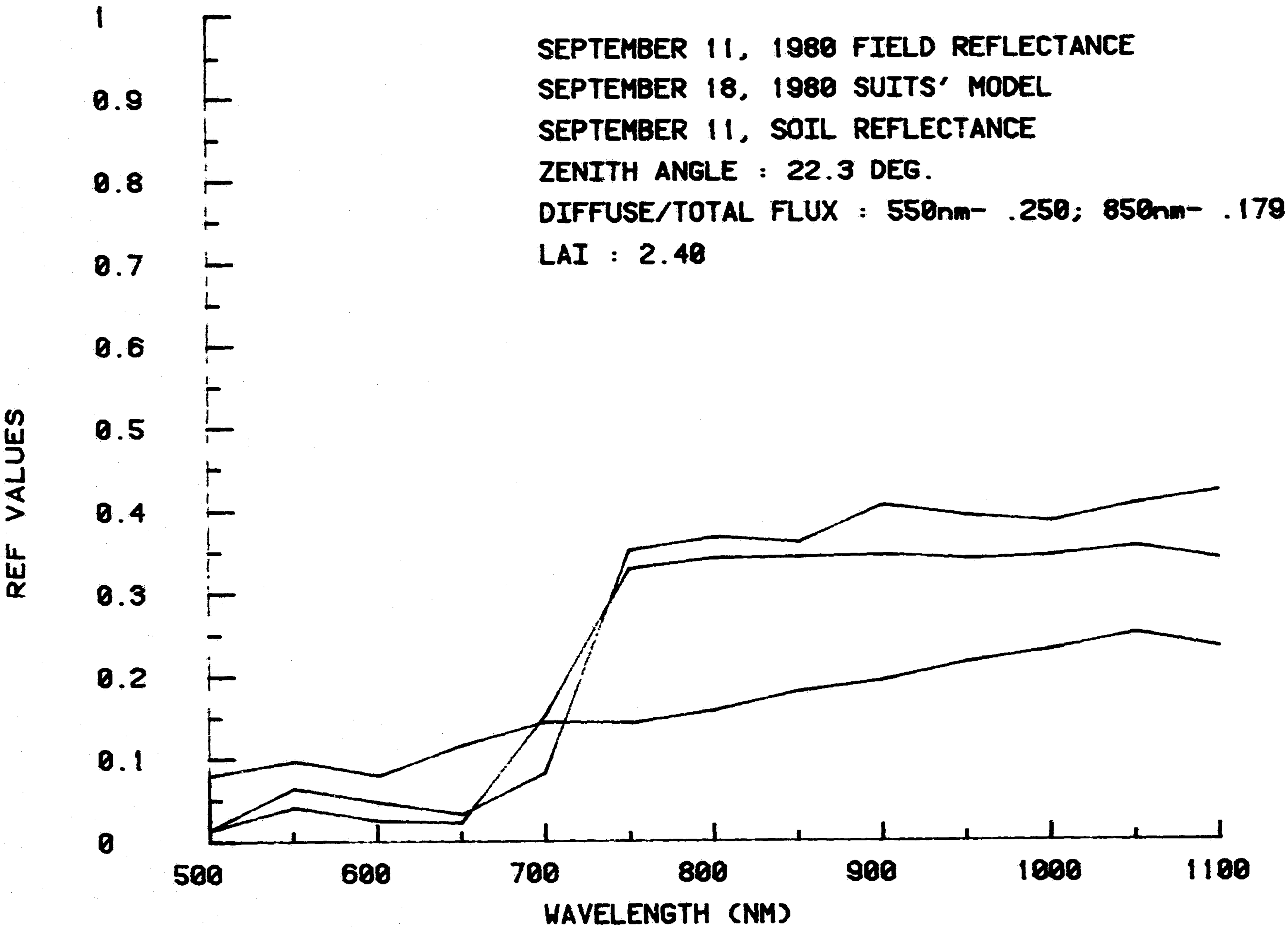
Figure 1

Fig. 2



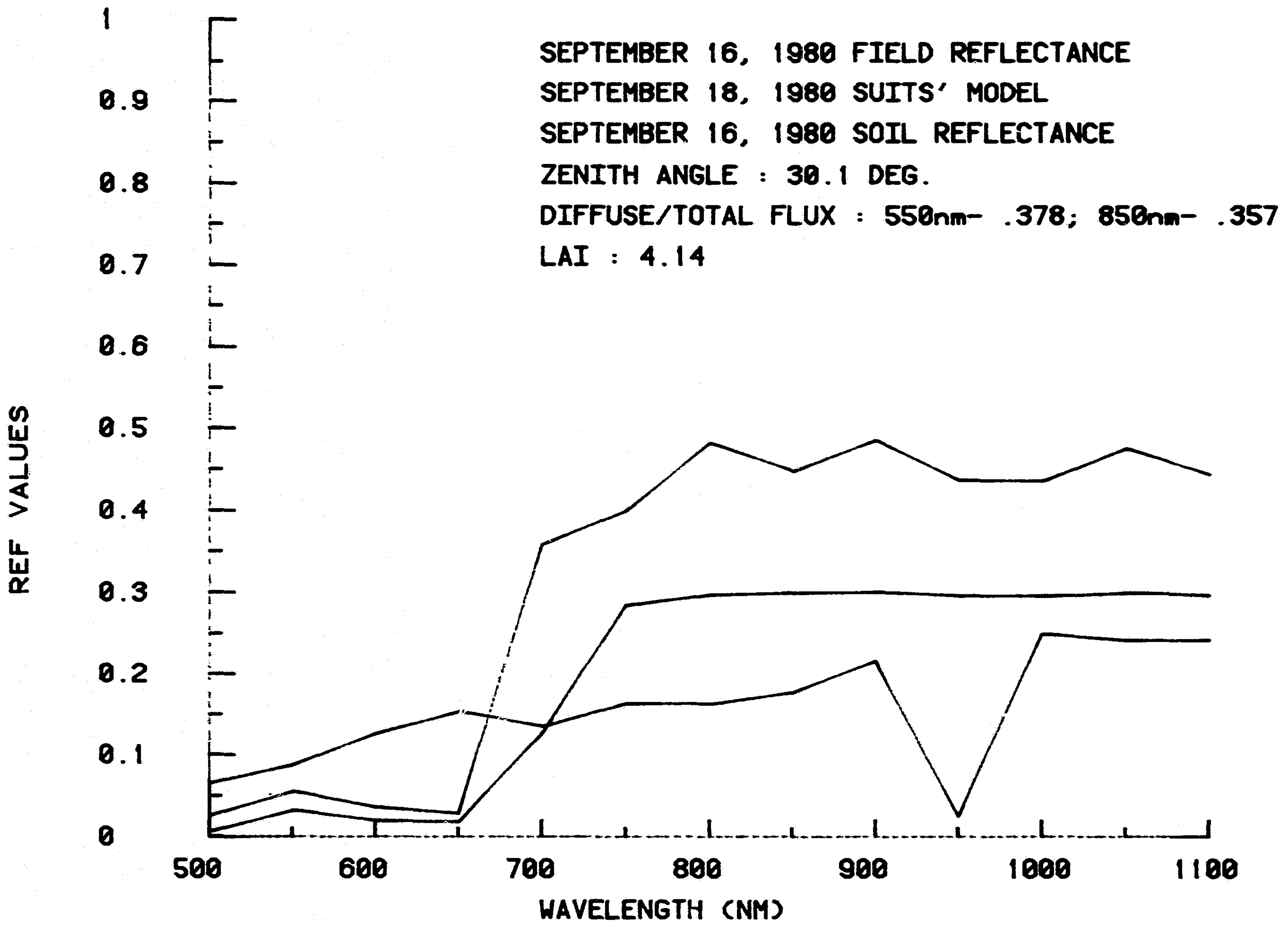
AUGUST 7, 1980 FIELD REFLECTANCE
AUGUST 7, 1980 SUITS' MODEL
AUGUST 7, 1980 SOIL REFLECTANCE
ZENITH ANGLE : 29.3 DEG.
DIFFUSE/TOTAL FLUX : 550nm- .900; 850nm- .900
LAI : 0.26
REF VALUES
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
500
600
700
800
900
1000
1100
WAVELENGTH (NM)

Fig. 3



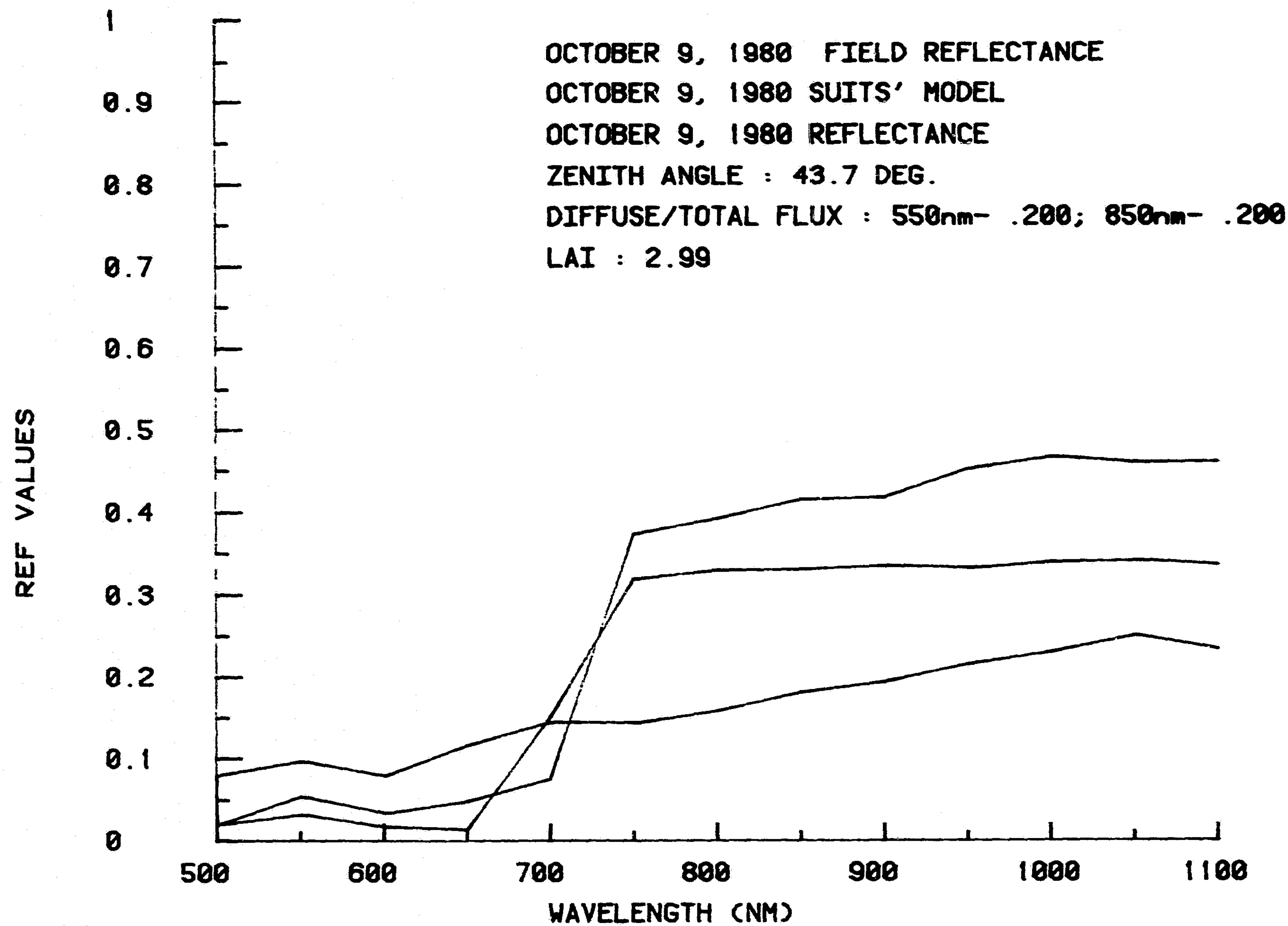
SEPTEMBER 11, 1980 FIELD REFLECTANCE
SEPTEMBER 18, 1980 SUITS' MODEL
SEPTEMBER 11, SOIL REFLECTANCE
ZENITH ANGLE : 22.3 DEG.
DIFFUSE/TOTAL FLUX : 550nm- .250; 850nm- .179
LAI : 2.40
REF VALUES
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
500
600
700
800
900
1000
1100
WAVELENGTH (NM)

FIG 4



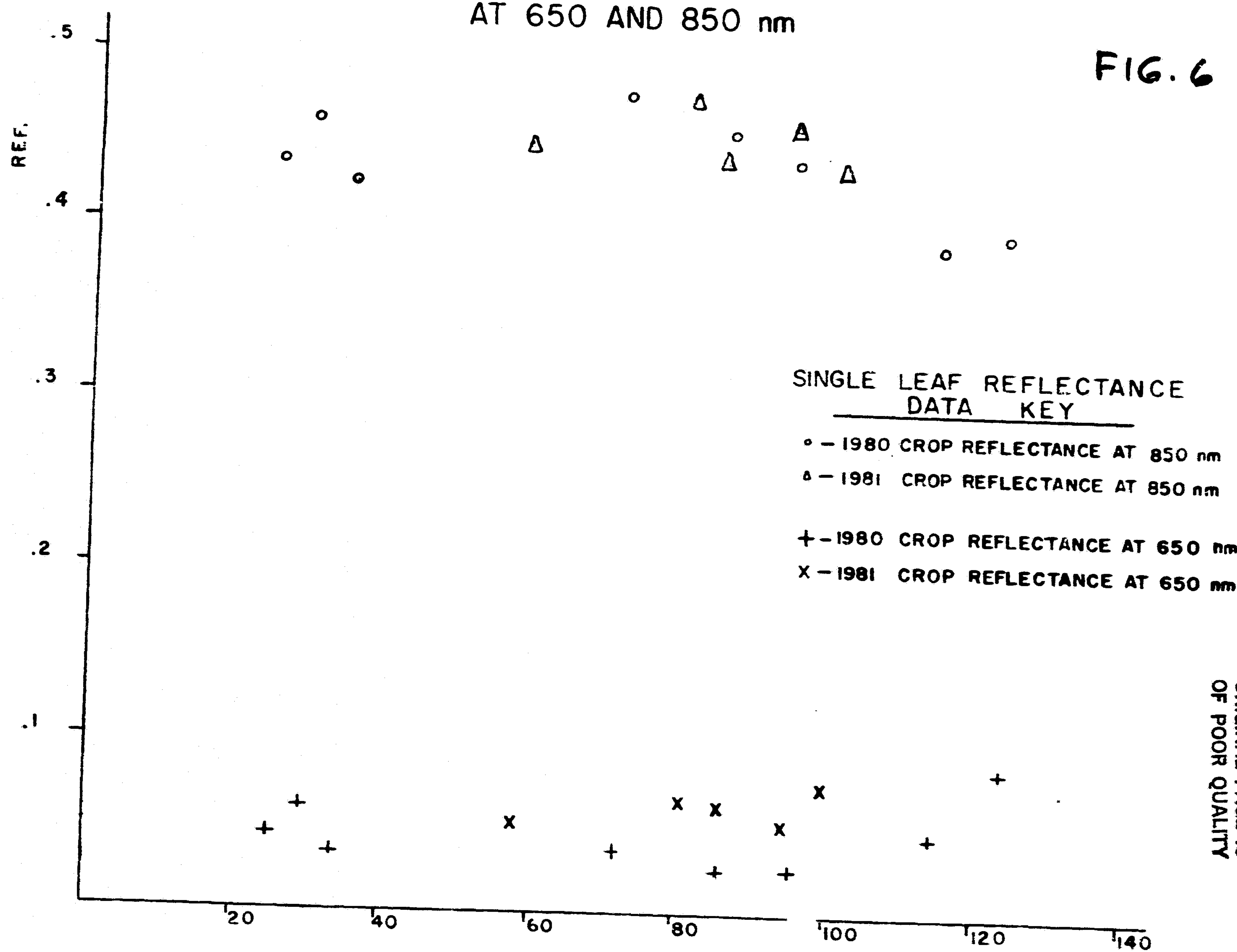
SEPTEMBER 16, 1980 FIELD REFLECTANCE
SEPTEMBER 18, 1980 SUITS' MODEL
SEPTEMBER 16, 1980 SOIL REFLECTANCE
ZENITH ANGLE : 30.1 DEG.
DIFFUSE/TOTAL FLUX : 550nm- .378; 850nm- .357
LAI : 4.14
REF VALUES
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
500
600
700
800
900
1000
1100
WAVELENGTH (NM)

FIG. 5


OCTOBER 9, 1980 FIELD REFLECTANCE
OCTOBER 9, 1980 SUITS' MODEL
OCTOBER 9, 1980 REFLECTANCE
ZENITH ANGLE : 43.7 DEG.
DIFFUSE/TOTAL FLUX : 550nm- .200; 850nm- .200
LAI : 2.99
REF VALUES
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
500
600
700
800
900
1000
1100
WAVELENGTH (NM)

DAYS INTO GROWING SEASON VS % REFLECTANCE
AT 650 AND 850 nm

FIG. 6



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OF POOR QUALITY

Fig. 7(a)

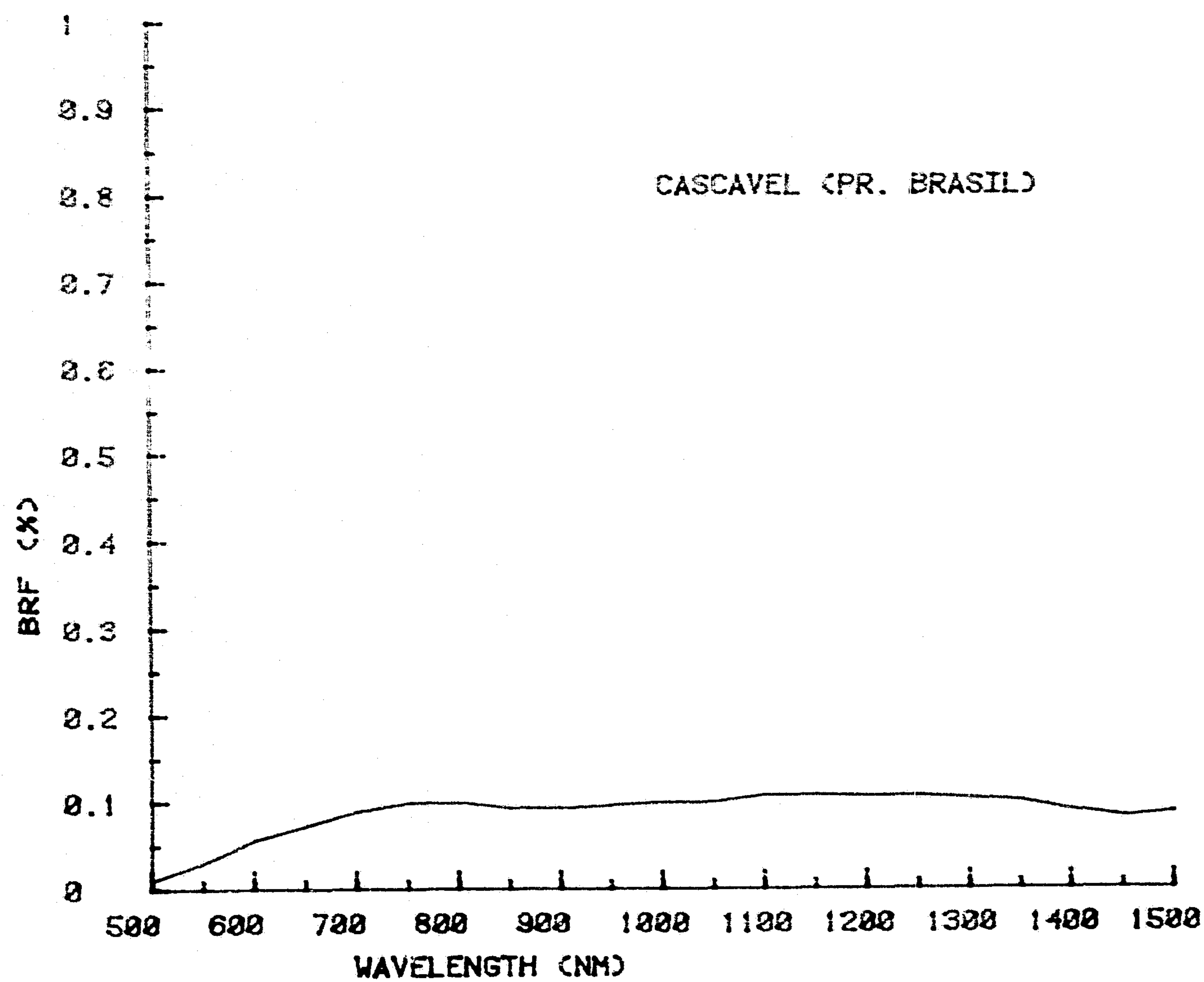

CASCAVEL (PR. BRASIL)
BRF (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
500
600
700
800
900
1000
1100
1200
1300
1400
1500
WAVELENGTH (NM)

Fig. 7(b)

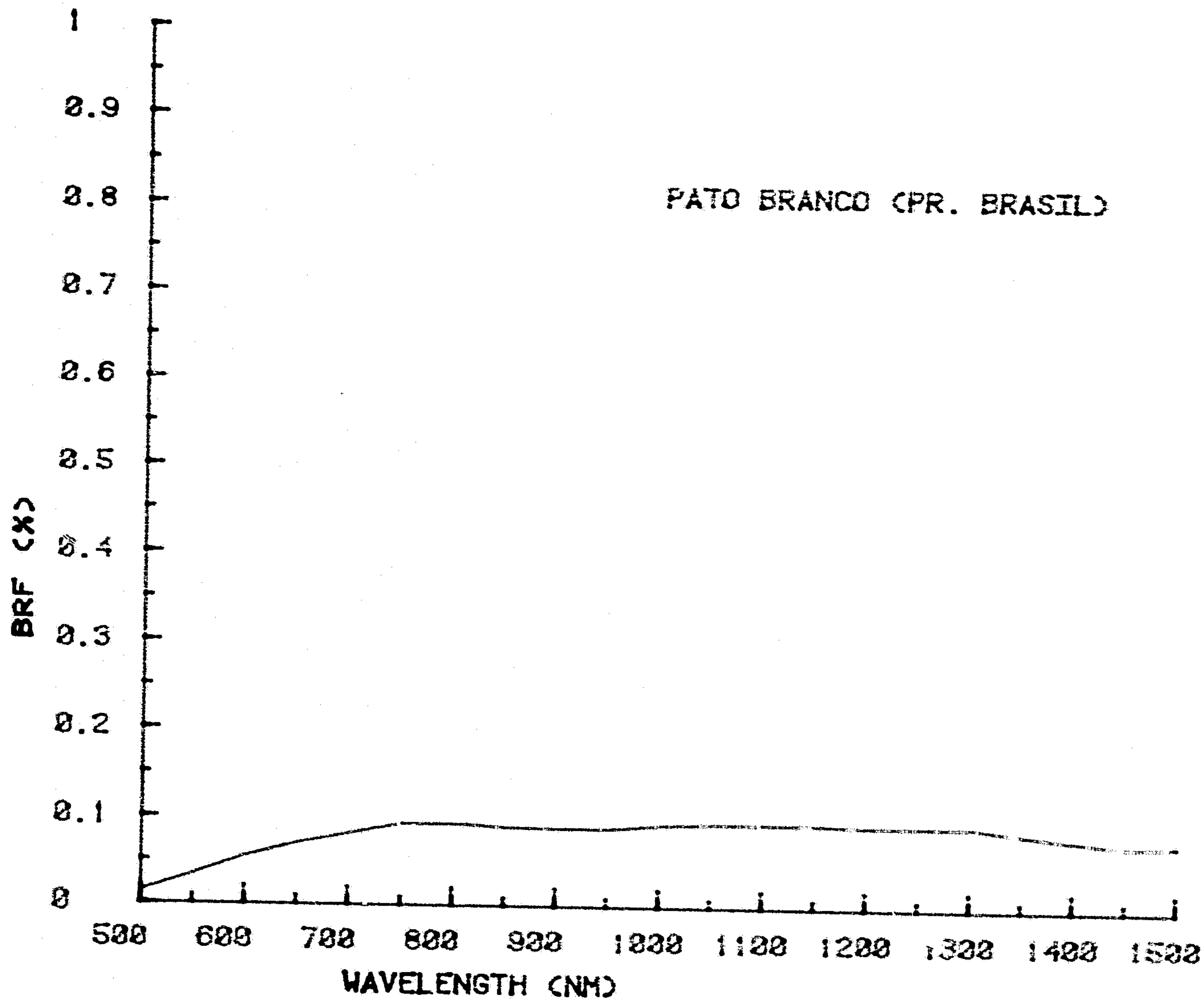
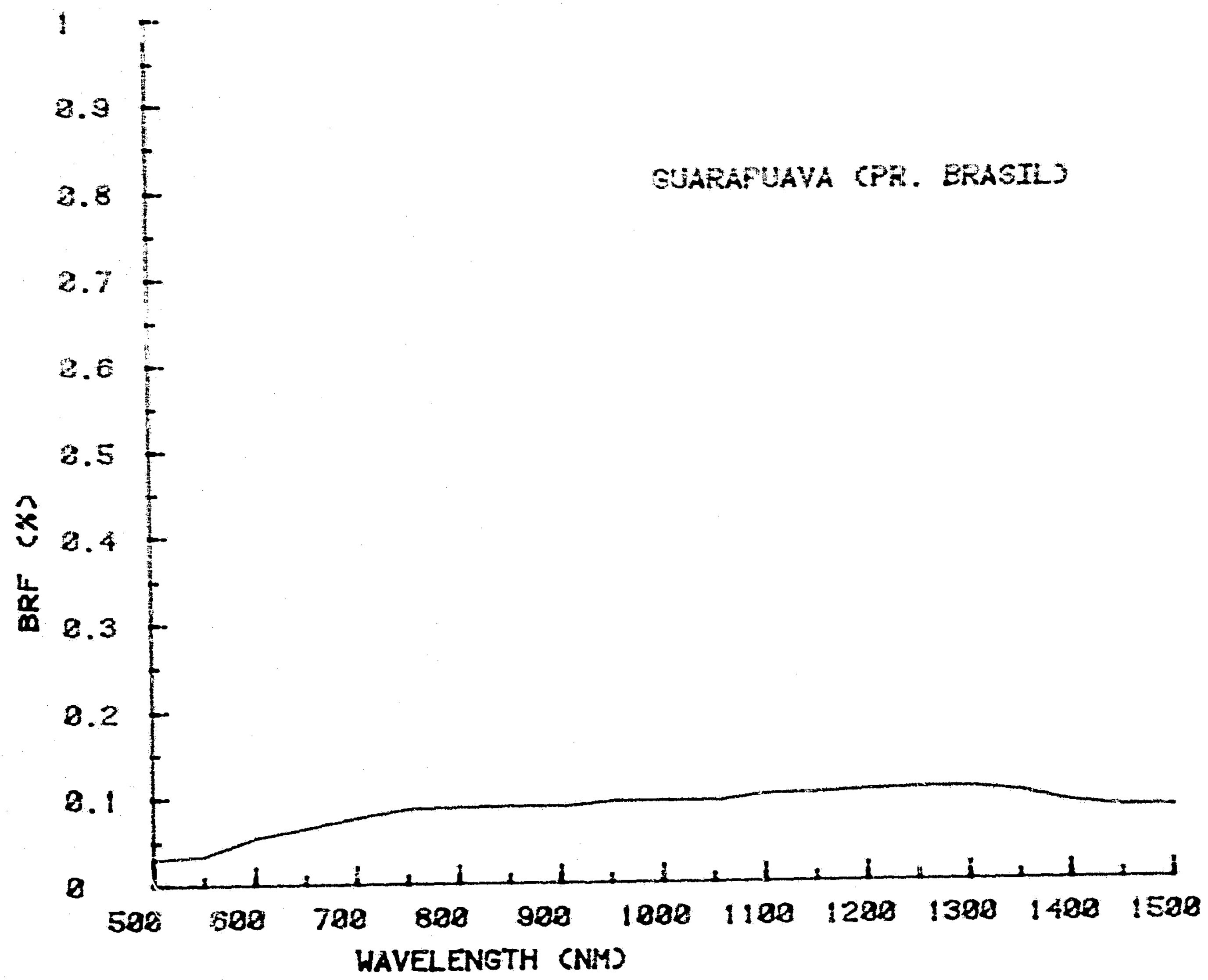
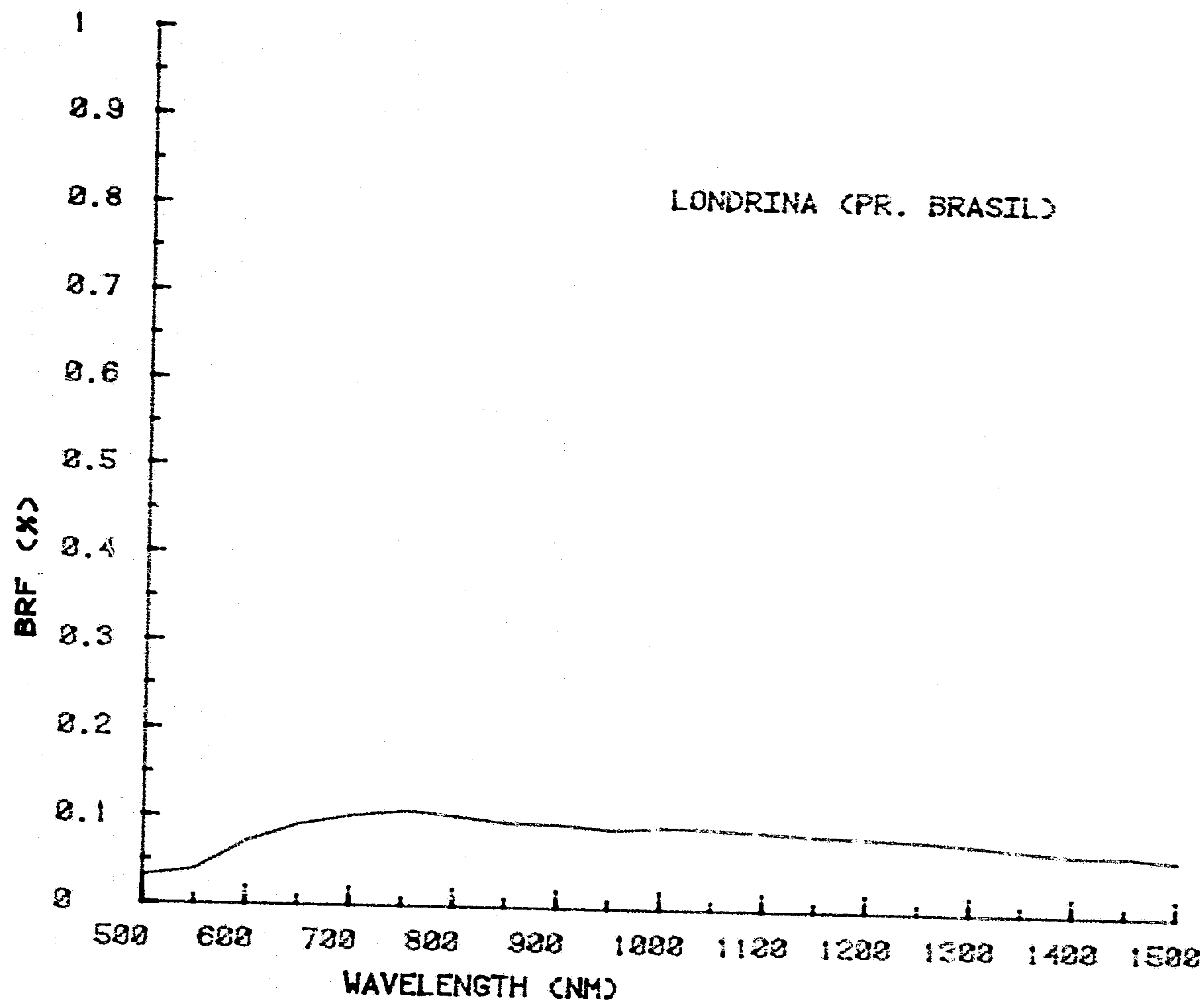

PATO BRANCO (PR. BRASIL)
BRF (%)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
500
600
700
800
900
1000
1100
1200
1300
1400
1500
WAVELENGTH (NM)

Fig. 7(c)



GUARAPUAVA (PR. BRASIL)
BRF (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
500
600
700
800
900
1000
1100
1200
1300
1400
1500
WAVELENGTH (NM)

Fig. 7(d)



LONDRINA (PR. BRASIL)
BRF (%)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
500 600 700 800 900 1000 1100 1200 1300 1400 1500
WAVELENGTH (NM)

Fig. 8(a)

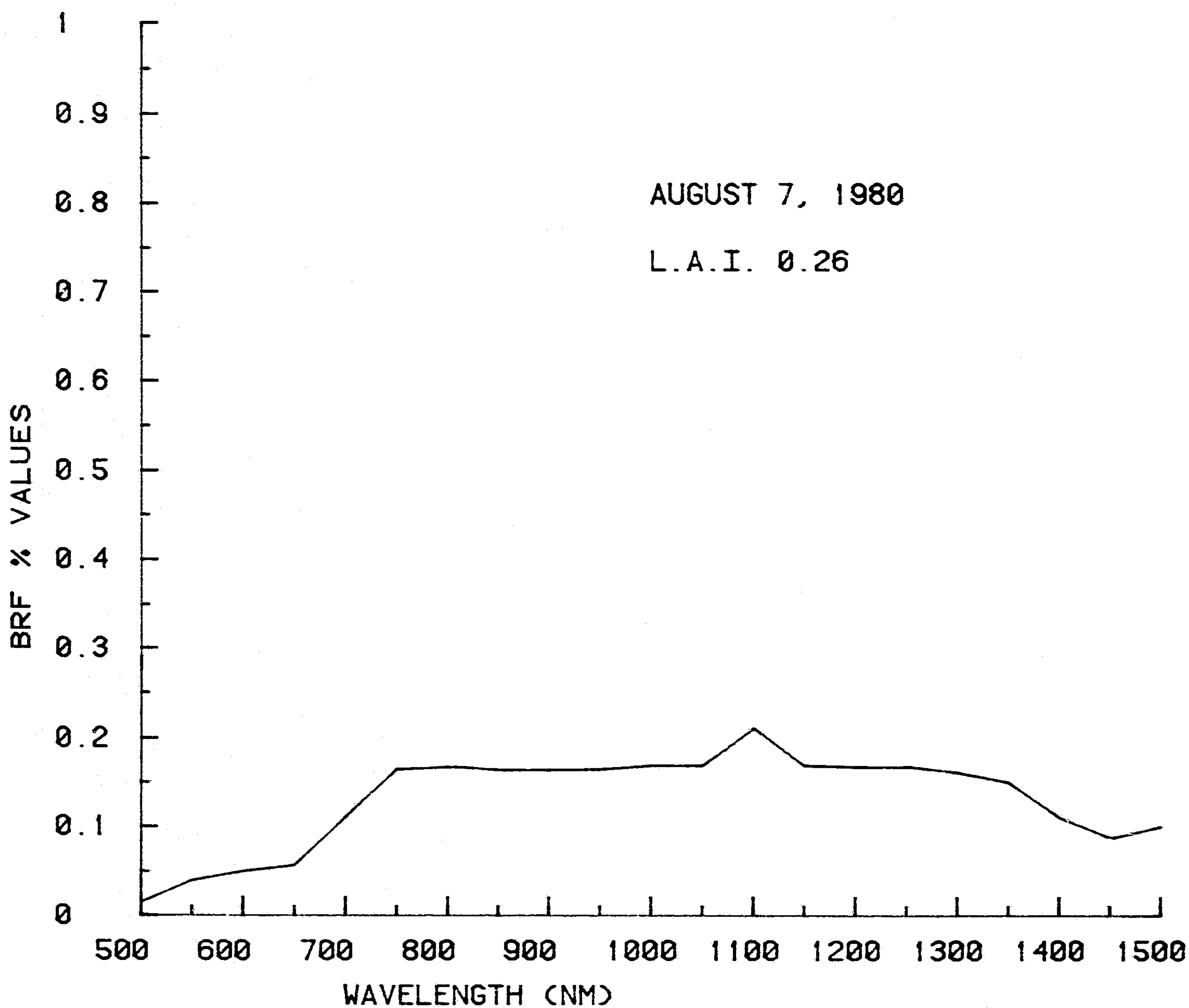
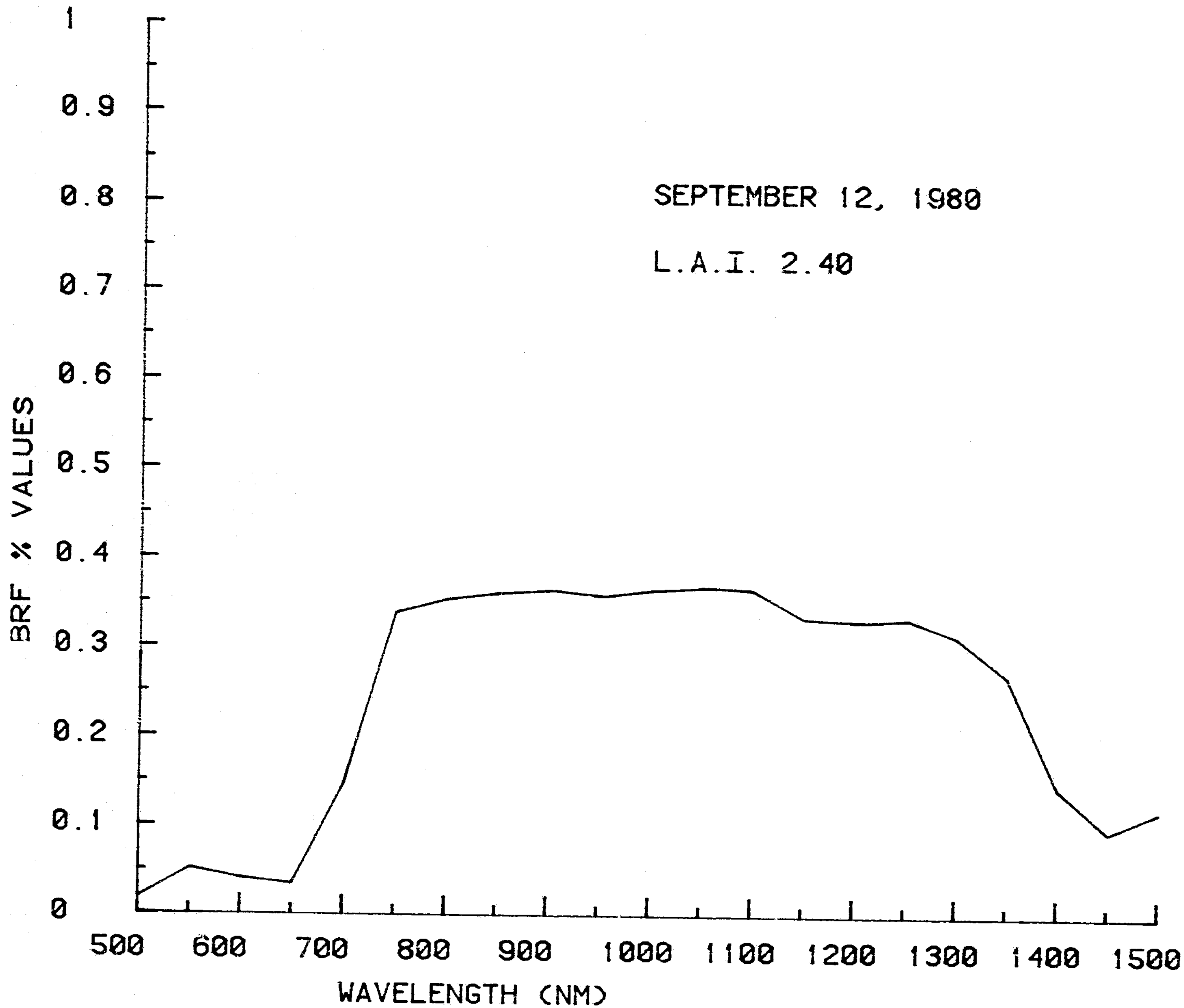

AUGUST 7, 1980
L.A.I. 0.26
BRF % VALUES
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
500
600
700
800
900
1000
1100
1200
1300
1400
1500
WAVELENGTH (NM)

Fig. 8(b)


SEPTEMBER 12, 1980
L.A.I. 2.40
BRF % VALUES
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0.9
0.8
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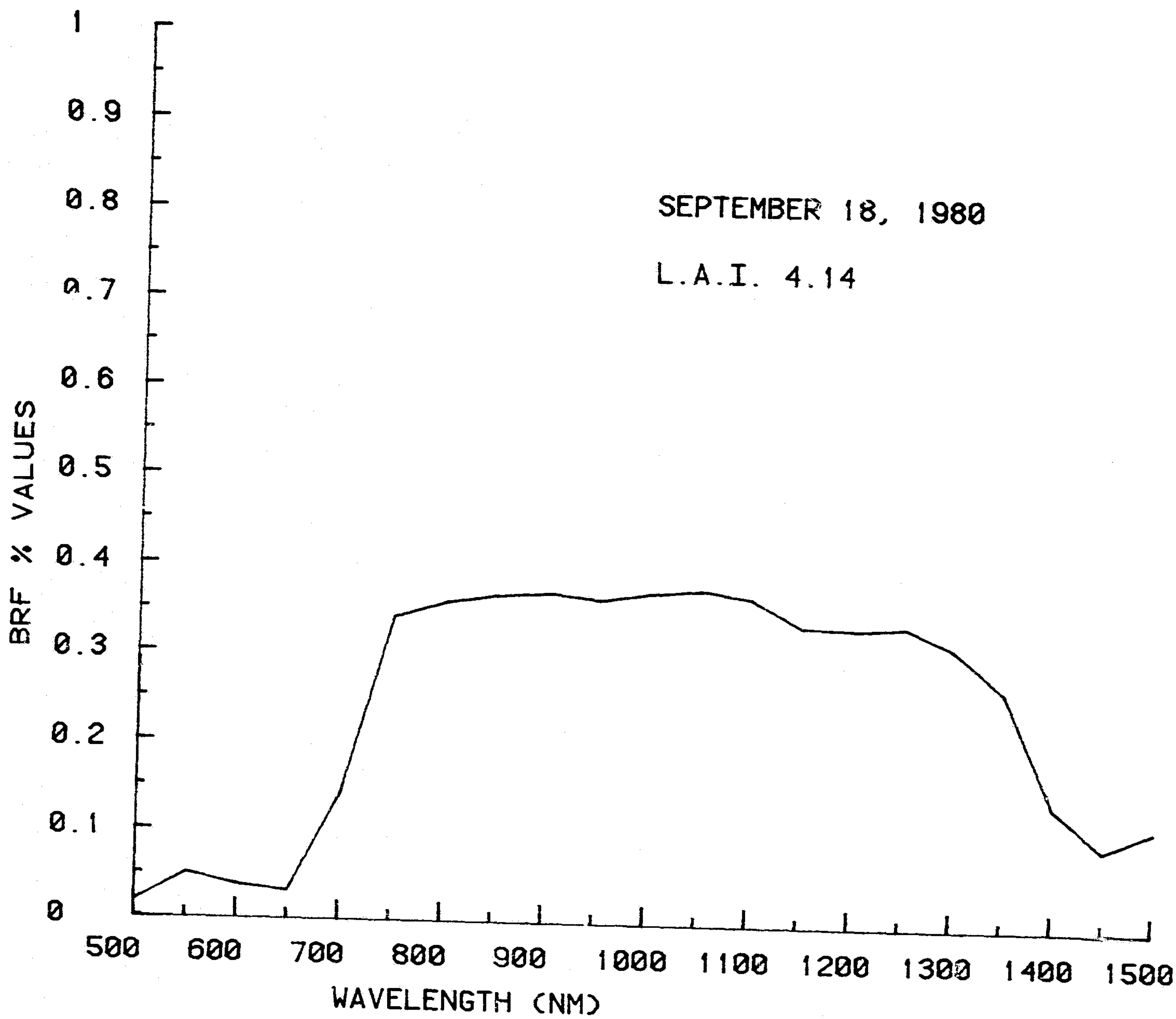
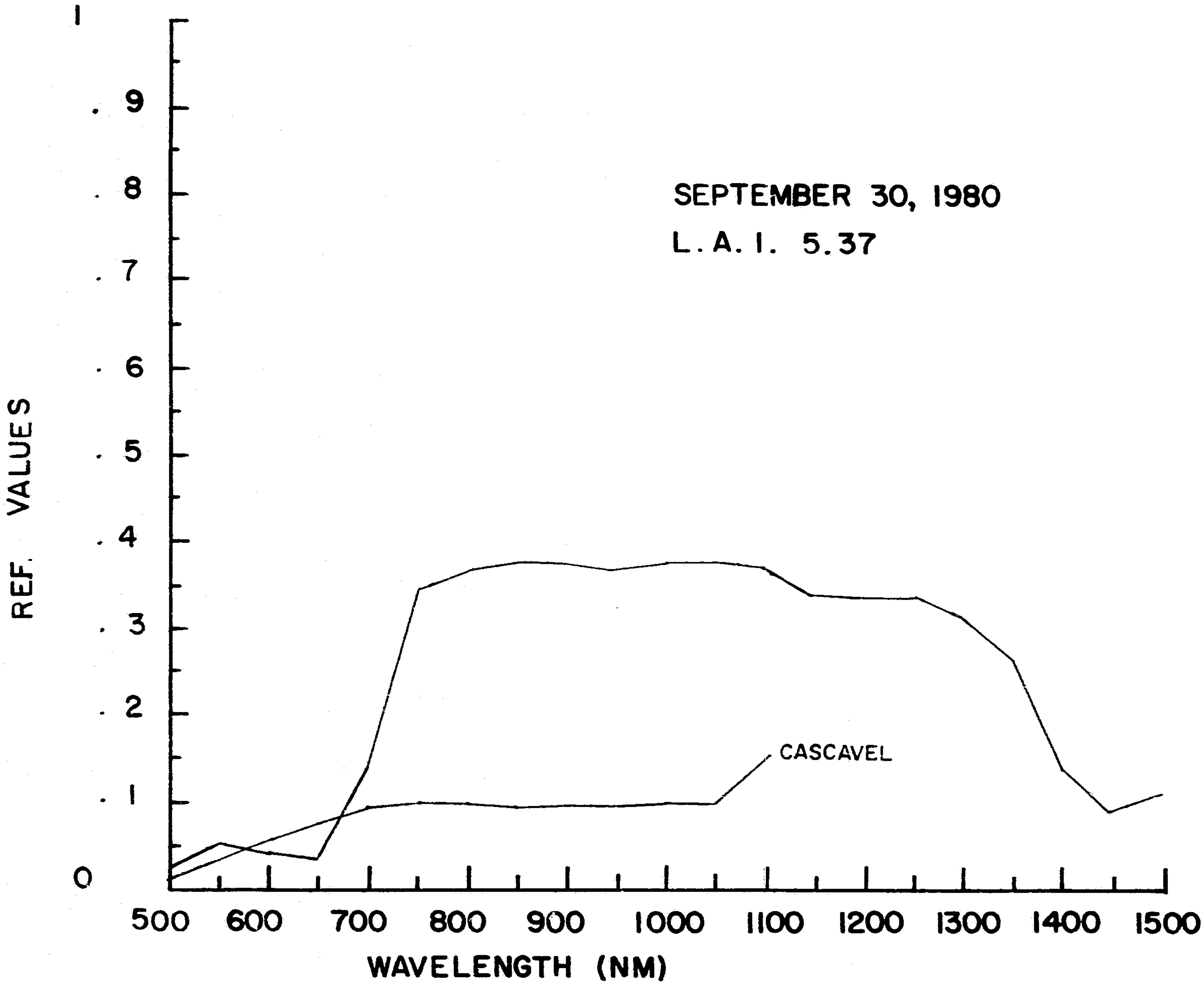
0.5
0.4
0.3
0.2
0.1
0
500
600
700
800
900
1000
1100
1200
1300
1400
1500
WAVELENGTH (NM)

FIG. 8(c)



SEPTEMBER 18, 1980
L.A.I. 4.14
BRF % VALUES
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
500
600
700
800
900
1000
1100
1200
1300
1400
1500
WAVELENGTH (NM)

Fig. 8(d)


SEPTEMBER 30, 1980
L.A.I. 5.37
CASCAVEL
REF. VALUES
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.9
.8
.7
.6
.5
.4
.3
.2
.1
0
500
600
700
800
900
1000
1100
1200
1300
1400
1500
WAVELENGTH (NM)

FIG. 8(e)

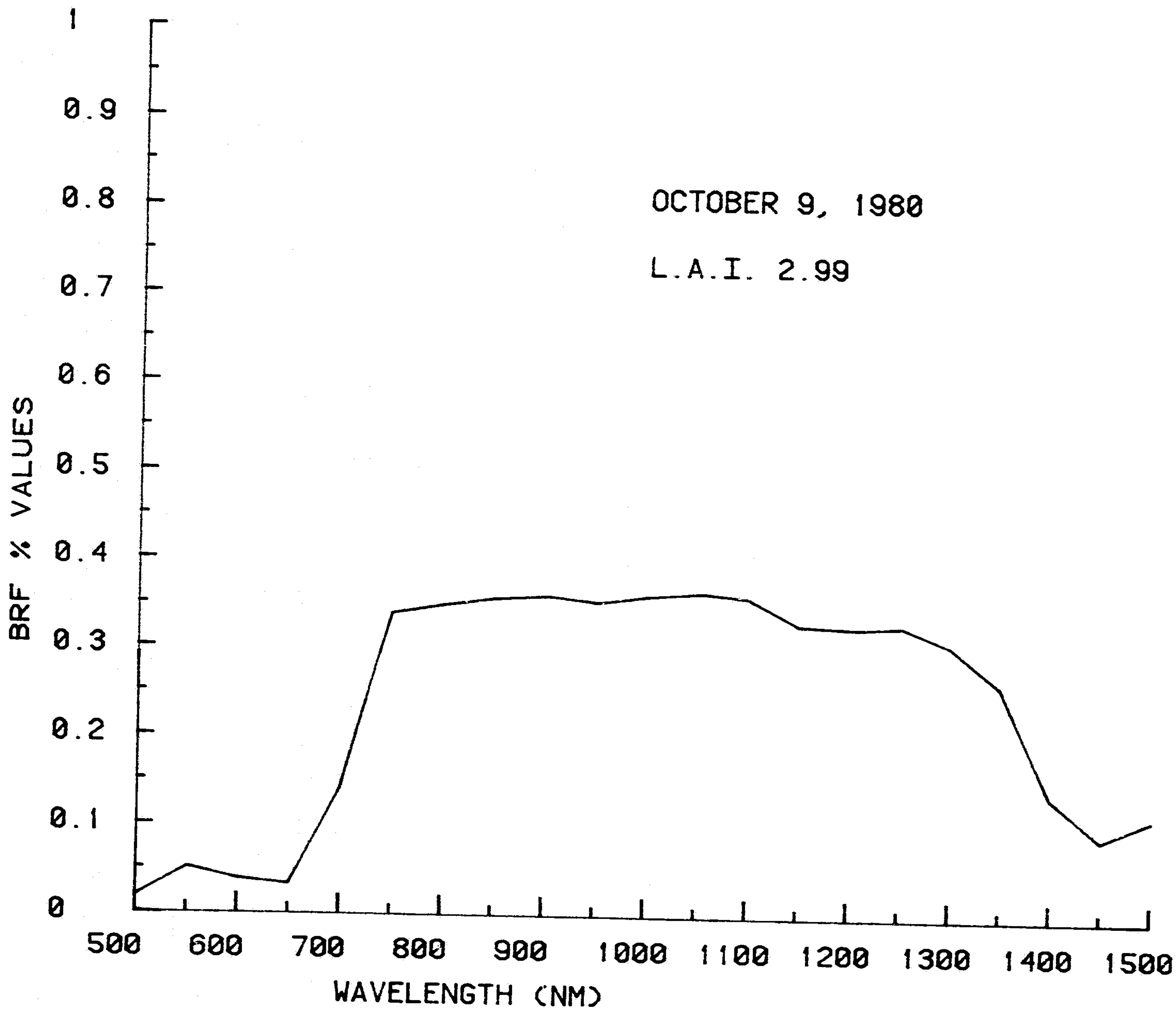

OCTOBER 9, 1980
L.A.I. 2.99
BRF % VALUES
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
500
600
700
800
900
1000
1100
1200
1300
1400
1500
WAVELENGTH (NM)

Fig. 8(f)

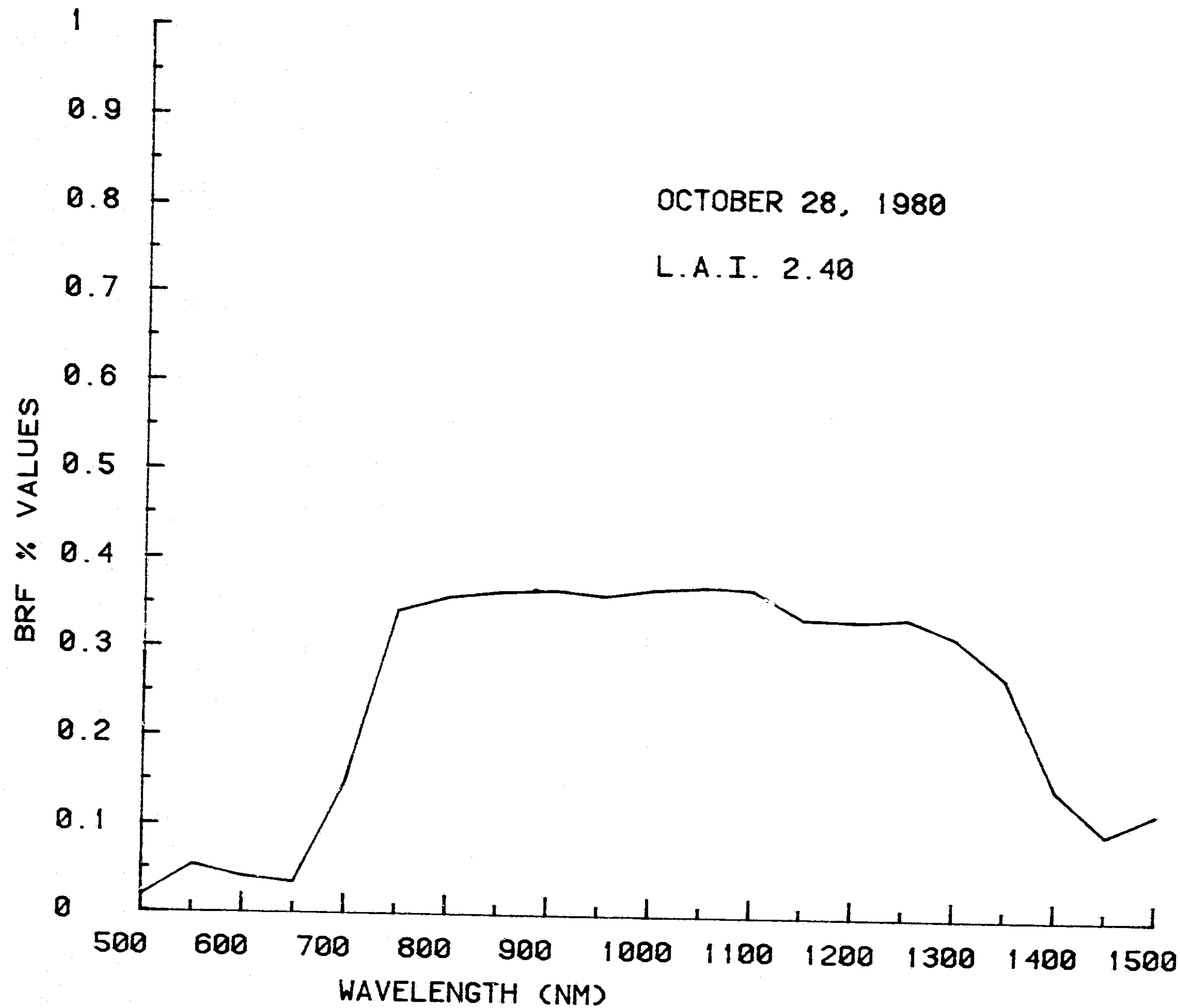

OCTOBER 28, 1980
L.A.I. 2.40
BRF % VALUES
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
500
600
700
800
900
1000
1100
1200
1300
1400
1500
WAVELENGTH (NM)

FIG. 8(g).

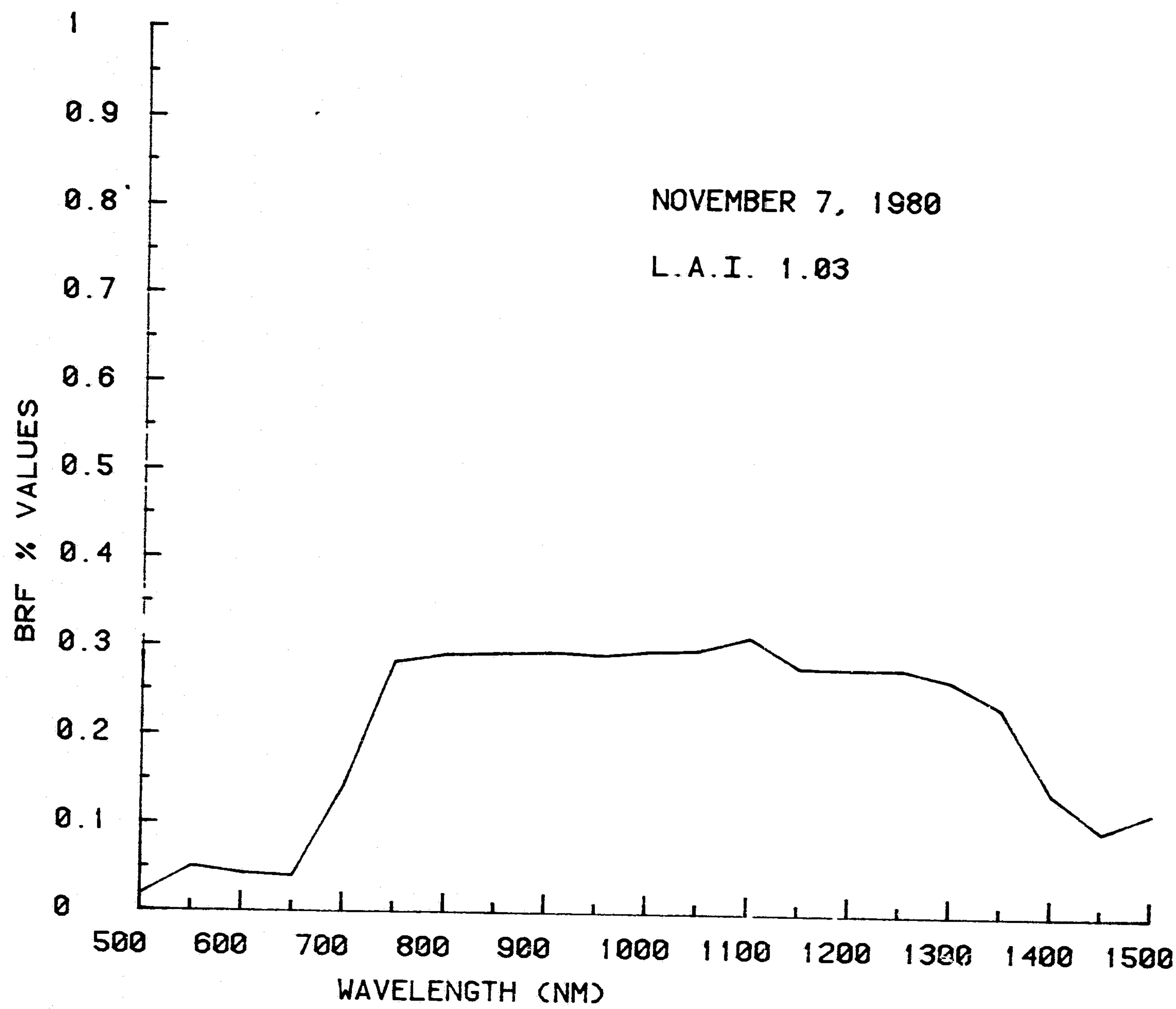
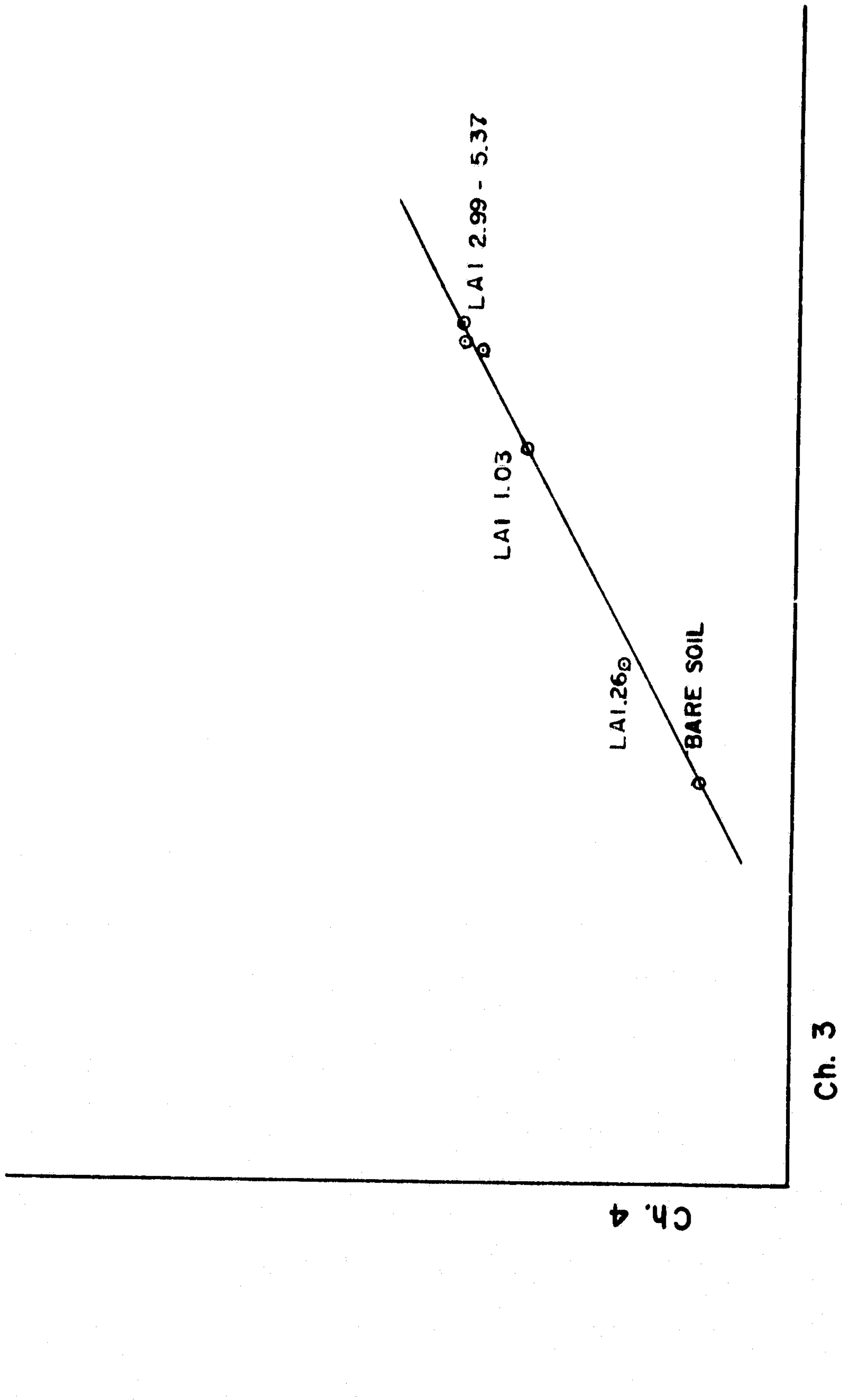

NOVEMBER 7, 1980
L.A.I. 1.03
BRF % VALUES
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
500
600
700
800
900
1000
1100
1200
1300
1400
1500
WAVELENGTH (NM)

FIG. 9



APPENDIX
Data Key

Throughout the 1980 growing season, eight (8) sets of soybean single leaf reflectance and transmittance data were gathered. As of 20 July 1981, five (5) sets of soybean single leaf reflectance and transmittance data were gathered for light green and dark green leaves.

The Data Table Appendix lists the 1980-81 single leaf data. Each data set is titled by 10 characters. The first character is always an S for soybeans. The next 5 characters designate the date on which the data were taken. The last 3 characters will designate either a single leaf data set by a "DAT" ending, or an average of light green data or average dark green data by an "AVL" or "AVD" respectively.

Each "DAT" data set will list a vitrolite record which served as our baseline for correction. This will always be found listed as REC #1 Data #1. For each data set within the 1980 growing season two leaves were sampled by the Beckman DK-2A laboratory spectrophotometer. In the "DAT" files following the vitrolite record, the next two (2) data records will list the reflectance values of the leaves. The transmittance values will be listed below the reflectance data records. For the 1981 data files the light green leaf data numbers will always be listed as #2-5, and the dark green leaf data numbers will always be listed as #6-9. So for each data set, the vitrolite data will be listed as Data #1. The reflectance values will be listed as DATA #2 and #3, and the transmittance values will be listed as DATA #4 and #5. For each 1981 data set Data #6 and #7 contain dark green reflectance and REC #8 and #9 contain dark green transmittance values.

The averaged data tables will show 2 data numbers for each data set. These correspond to the data numbers from which the data were averaged. So the first record number listed as REC #1 will contain averaged reflectance values. The next record number listed as REC #8 will contain averaged transmittance values.

Also within each set of averaged data, a standard deviation value for each wavelength will be listed. The wavelength will appear first followed by either a reflectance value or transmittance value. The standard deviation value is listed after the reflectance or transmittance value.

Brazilian soil reflectance values are listed on the last page.

```
 REC #    17 DATA #      4
  500 .001  550 .041  600 .016  650 .007  700 .165  750 .334  800 .347
  850 .356  900 .357  950 .356 1000 .195 1050 .369 1100 .365 1150 .350
 1200 .354 1250 .358 1300 .343 1350 .308 1400 .157 1450 .111 1500 .193
 REC #    21 DATA #      8
  500 .001  550 .029  600 .016  650 .005  700 .099  750 .308  800 .338
  850 .344  900 .352  950 .351 1000 [illegible] 1050 [illegible] 1100 [illegible] 1150 .351
 1200 .351 1250 .356 1300 .350 1350 [illegible] 1400 [illegible] 1450 [illegible] 1500 [illegible]


.EX BEKAVE.F4
LINK:   Loading
[LNKXCT BEKAVE Execution]
   ENTER THE FILE.EXT FROM WHICH DATA IS
   TO BE TAKEN: AVETRA.DG
   ENTER THE NUMBER OF RUNS TO BE AVERAGED: 6
   ENTER THE DATA NUMBER AND THE FIRST RECORD NUMBER
   FOR EACH RUN:
   DATA NUMBER( 1), RECORD( 1) = 8,1
   DATA NUMBER( 2), RECORD( 2) = [illegible]
   DATA NUMBER( 3), RECORD( 3) = 8,9
   DATA NUMBER( 4), RECORD( 4) = 4,13
   DATA NUMBER( 5), RECORD( 5) = 4,17
   DATA NUMBER( 6), RECORD( 6) = 8,21
   DO YOU WISH TO HAVE A LISTING OF THE AVE. VALUES? [illegible]


   THE DATA RUNS AVERAGED ARE:    8    [illegible]    8    [illegible]    [illegible]

  WL  VALUE STDEV       WL  VALUE STDEV       WL  VALUE STDEV

  500  .011  .016      850  .364  .040      1200  [illegible]
  550  .035  .019      900  .368  .039      1250  [illegible]
  600  .017  .017      950  .366  .038      1300  [illegible]
  650  .018  .016     1000  .343  .08[illegible]     1350  [illegible]
  700  .153  .040     1050  .376  .03[illegible]     1400  .268  [illegible]
  750  .361  .045     1100  .374  .037      1450  .151  [illegible]
  800  .360  .041     1150  .361  .03[illegible]     1500  .15[illegible]  [illegible]
   DO YOU WISH TO HAVE OUTPUT ON THE LPT? NO


   DO YOU WISH TO PUT THE AVE VALUES ON DISK? Y
   ENTER THE FILE.EXT WHERE DATA IS TO BE
   STORED: SUVTRA.AV9
   ENTER THE FIRST SEQUENTIAL NUMBER UNDER
   WHICH THE DATA WILL BE STORED IN THE FILE :
```

```
[illegible] .413  900 .419  950 .413 1000 [illegible] 1050 .416 1100 .411 1150 [illegible]
1200 .398 1250 .396 1300 .385 1350 [illegible] 1400 .255 1450 .206 1500 [illegible]
REC #     9 DATA #     6
 500 .038  550 .082  600 .066  650 .062  700 .236  750 .422  800 .426
 850 .431  900 .430  950 .424 1000 .428 1050 .426 1100 .420 1150 .414
1200 .400 1250 .398 1300 .384 1350 .356 1400 .229 1450 .160 1500 .199
REC #    13 DATA #     2
 500 .025  550 .078  600 .061  650 .050  700 .187  750 .427  800 .416
 850 .422  900 .422  950 .416 1000 .418 1050 .420 1100 .414 1150 .395
1200 .394 1250 .393 1300 .380 1350 .343 1400 .229 1450 .165 1500 .189
REC #    17 DATA #     2
 500 .026  550 .073  600 .054  650 .062  700 .218  750 .422  800 .407
 850 .429  900 .428  950 .422 1000 .427 1050 .426 1100 .417 1150 .395
1200 .397 1250 .396 1300 .376 1350 .334 1400 .221 1450 .172 1500 .213
REC #    21 DATA #     6
 500 .014  550 .082  600 .070  650 .061  700 .170  750 .404  800 .436
 850 .440  900 .442  950 .438 1000 .441 1050 .444 1100 .439 1150 .421
1200 .415 1250 .418 1300 .407 1350 [illegible] 1400 .257 1450 .163 1500 .188

[illegible]AVE.F4
[illegible]
[illegible]RAVE Execution]
ENTER THE FILE.EXT FROM WHICH [illegible]
TO BE TAKEN: AVEREF.DP
ENTER THE NUMBER OF RUNS TO [illegible] 6
ENTER THE DATA NUMBER AND THE [illegible] NUMBER
FOR EACH RUN:
DATA NUMBER( 1), RECORD( 1) = 6,[illegible]
DATA NUMBER( 2), RECORD( 2) = [illegible]
DATA NUMBER( 3), RECORD( 3) = 6,[illegible]
DATA NUMBER( 4), RECORD( 4) = 2,[illegible]
DATA NUMBER( 5), RECORD( 5) = 2,[illegible]
DATA NUMBER( 6), RECORD( 6) = 6,[illegible]
DO YOU WISH TO HAVE A LISTING OF THE AVE. VALUES [illegible]

THE DATA RUNS AVERAGED ARE:     6     6     6     2     2     6

 WL   VALUE STDEV        WL   VALUE STDEV        WL   VALUE STDEV

 500   .075  .013        850  .429  [illegible]  1200  .403  .006
 550   .078  .003        900  .429  [illegible]  1250  [illegible]  [illegible]
 600   .059  .007        950  .425  [illegible]  1300  [illegible]  [illegible]
 650   .057  .001       1000  .427  [illegible]  1350  [illegible]  .017
 700   .213  .035       1050  .427  [illegible]  1400  [illegible]  [illegible]
 750   .419  .016       1100  .420  [illegible]  1450  [illegible]  [illegible]
 800   .4[illegible] [illegible] 1150 [illegible] [illegible] 1500 [illegible] [illegible]
```

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```
DATA NUMBER( 3), RECORD( 3) = 4,9
DATA NUMBER( 4), RECORD( 4) = 4,13
DATA NUMBER( 5), RECORD( 5) = 5,17
DATA NUMBER( 6), RECORD( 6) = 4,21
DO YOU WISH TO HAVE A LISTING OF THE AVE. VALUES? YES

THE DATA RUNS AVERAGED ARE:     4     4     4     4     [illegible]     4
```

WL	VALUE	STDEV	WL	VALUE	STDEV	WL	VALUE	STDEV
500	.006	.013	850	.347	.027	1200	.349	.030
550	.045	.015	900	.350	.026	1250	.353	.028
600	.023	.010	950	.350	.026	1300	.343	.030
[illegible]	[illegible]	[illegible]	1000	.355	.027	1350	.316	[illegible]
[illegible]	.1[illegible]4	.037	1050	.360	[illegible]	1400	.195	.044
750	.32[illegible]	.029	1100	.359	.027	1450	.147	[illegible]
800	.340	.025	1150	.347	[illegible]	1500	.179	.046

```
DO YOU WISH TO HAVE OUTPUT ON THE LPT? NO

[illegible]
[illegible]R THE FILE.EXT WHERE DATA [illegible]
STORED: SOYTRA.AVL
ENTER THE FIRST SEQUENTIAL NUMBER UNDER
WHICH THE DATA WILL BE STORED IN THE FILE: 1

DATA STORED ON DISK UNDER FILE [illegible]
IN RECORDS    1 TO [illegible]

END OF EXECUTION
CPU TIME: 1.98  ELAPSED TIME: 1:48.8[illegible]
EXIT

[illegible] KI.F4
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[LNKXCT BUCK1 Execution]
ENTER THE FILE.EXT FROM WHICH DATA IS
TO BE TAKEN: S60381.DAT
ENTER THE NUMBER OF RUNS TO BE [illegible]
ENTER THE DATA NUMBER AND THE F[illegible]
FOR EACH RUN:
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DATA NUMBER( 2), RECORD( 2) = [illegible]
DO YOU WISH TO HAVE A LISTING [illegible]
DO YOU WISH TO HAVE OUTPUT ON [illegible]
```

```
ENTER [illegible] FILE.EXT FROM WHICH DATA IS
TO BE [illegible]AKEN: AVEREF.LG
ENTER THE NUMBER OF RUNS TO BE AVERAGED: 6
ENTER THE DATA NUMBER AND THE FIRST RECORD NUMBER,
FOR EACH RUN:
DATA NUMBER( 1), RECORD( 1) = 2,1
DATA NUMBER( 2), RECORD( 2) = 2,5
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DATA NUMBER( 4), RECORD( 4) = 2,13
DATA NUMBER( 5), RECORD( 5) = 3,17
DATA NUMBER( 6), RECORD( 6) = 2,21
DO YOU WISH TO HAVE A LISTING OF THE AVE. VALUES? YES

THE DATA RUNS AVERAGED ARE:    2    2    2    2    3    2
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WL	VALUE	STDEV	WL	VALUE	STDEV	WL	VALUE	STDEV
500	[illegible]	.013	850	.447	.021	1200	.416	.015
[illegible]	[illegible]	[illegible]	900	.448	.017	1250	[illegible]	[illegible]
[illegible]	[illegible]	.015	950	.442	.017	1300	.400	[illegible]
650	.065	.009	1000	.446	.016	1350	.364	[illegible]
700	.247	.027	1050	.446	.016	1400	.237	.030
750	.436	.023	1100	.439	.016	1450	.167	.023
800	.444	.018	1150	.419	.013	1500	[illegible]	[illegible]

```
DO YOU WISH TO HAVE OUTPUT ON THE [illegible]

DO YOU WISH TO PUT THE AVE VALUES ON DISK? Y
ENTER THE FILE.EXT WHERE DATA IS TO BE
STORED: SOYREF.AVL
[illegible] THE FIRST SEQUENTIAL NUMBER [illegible]
[illegible] THE DATA WILL BE STORED IN THE [illegible]

DATA STORED ON DISK UNDER FILE: SOYREF.AVL
IN RECORDS    1 TO    3

END OF EXECUTION
[illegible] ELAPSED TIME: 2:46.[illegible]
[illegible]
```

National Aeronautics and
Space Administration

Lyndon B. Johnson Space Center
Houston, Texas
77058

NASA

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Reply to Attn of: SF3/80-044

FEB 4 1980

Dr. Ed Lemaster
Pan American University
Edinburg, Texas 78539

Dear Ed,

As per our telecon on January 31, 1980, please determine the feasibility of performing the following tasks on the NASA Grant.

1. Develop requirements for field measurements (e.g. single leaf reflectances) to support the Suits model for corn and soybeans -needed by March 1, 1980.

2. Modify Suits models as appropriate to include soil background in a model of corn and soybean canopy reflectance-needed by June 1, 1980.

3. Conduct sensitivity test of canopy reflectance-specifically due to difference between soils in Southeastern U.S. (e.g./Williamsburg Co., Orangeburg Co., Marlboro Co., and Lee Co. South Carolina/ Laurens Co., Tift Co., Screven Co., Bullock Co., Sumter Co., Thomas Co., and Brooks Co. Georgia/ Sussex Co. Delaware/ Queen Annes Co., and Coraline Co. Maryland/ and Duplin Co., Halifax Co., Pitt Co., Waye Co., and Sampson Co. North Carolina/ and the following corn and soybean areas of Brazil; Rio Grande Do Sul, Santa Catering Parana, and Mines Gerais. The data from Eric Stoners report (enclosed) on spectral reflectance of soils should be of help in this task.

Initial results are needed on October 1, 1980 in order to support the Brazil Exploratory Investigation Technique development in FY81.

Final results would be needed on October 1, 1981 in order to support the Pilot Tests in FY83.

Let me know if this approach is feasible and how I can help facilitate these activities.

Sincerely,

Dave Pitts

Enclosure

```
. TY BPATOB.DAT
 REC #    1 DATA #    1
  500 .015  550 .034  600 .055  650 .070  700 .082  750 .093  800 .093
  850 .090  900 .089  950 .090 1000 .094 1050 .096 1100 .096 1150 .095
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  850 .090  900 .089  950 .094 1000 .094 1050 .093 1100 .101 1150 .102
 1200 .105 1250 .107 1300 .106 1350 .101 1400 .089 1450 .083 1500 .083
```

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CHANGES OF SOYBEAN SINGLE LEAF

SPECTRAL CHARACTERISTICS AS A FUNCTION OF MATURITY

UNDER VARIOUS CONDITIONS OF SOIL MOISTURE[1]

Mark Stephen Rogers[2]
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Pan American University
Edinburg, TX 78539

Current Address:

NASA JSC/SG3
Houston, TX 77058

ABSTRACT

A temporal study was conducted during the Fall 1981 growing season which monitored soybean single leaf spectral characteristics and canopy growth for soybeans grown under normal, water saturated, and drought simulated field conditions. During the experiment, single leaf data were acquired at least weekly from the respective field conditions and spectrophotometrically analysed to test the hypothesis that single leaves selected from canopies grown under normal, water saturated, and drought simulated field conditions would not produce differences in the reflectance, transmittance, and absorptance of the soybean single leaves within the visible and infrared wavelengths for any same acquisition date. Based on experimental evidence and statistical analysis, the experiment failed to reject the hypothesis. Temporal changes in the spectral characteristics of the single leaves were seen to occur as a function of maturity which demonstrated that the absorptance of a soybean single leaf is more a function of the transmittance characteristic than the seasonally consistent single leaf reflectance.

BACKGROUND

Canopy reflectance models which include single leaf spectral parameters have been developed to predict crop canopy reflectances as seen from remote multispectral scanning satellites (Chance and Cantu, 1975; Chance and LeMaster, 1977; Beeth, 1977; Smith and Oliver, 1973; Suits, 1972.) While the Suits model is based on canopy layers made up of single leaf area elements, the single leaf reflectance, transmittance, and absorptance characteristics are integrated with a soil background to predict canopy reflectance. The model assumes that the leaves are perfectly Lambertian and that the plants are azimuthally symmetric. In addition, the Beeth model, a modified Suits model and the Smith model which employs a Monte Carlo distribution model to predict canopy reflectance, also utilize single leaf spectral data for canopy reflectance predictions.

While field testing the Suits model during the Fall 1980 and Spring 1981 growing seasons, LeMaster and Chance (1981) observed temporal changes in the spectral characteristics of soybean (UVF-1) single leaves at the 650, 850, 1100, and 1450 nanometer (nm) wavelengths. The single leaf reflectance was observed to vary as much as 9% between any two successive acquition dates. These changes corresponded to periods of rainfall and irrigation in the field.

Carlson et al (1971) found relationships between relative leaf water content and spectral responses of the single leaves for corn, soybeans, and sorghum. A question then developed concerning the degree of influence that soil moisture and water within the single leaf have on the spectral characteristics of soybean single leaves.

In an attempt to better understand the relationship between plant physiology, spectral characteristics of the single leaf, and the contribution these components make toward canopy reflectance, the hypothesis was tested during the Fall 1981 growing season that single leaves selected from soybean canopies grown under normal, water saturated, and drought simulated field conditions would not produce differences in the reflectance, transmittance, and absorptance of the soybean single leaves within the visible and infrared wavelengths for any same aquisition date.

EXPERIMENTAL METHODS AND MATERIALS

A portion of an agricultural field on Rio Farms Inc. of Monte Alto, TX (Lat. 26.4 N, Long. 98.6 W) was chosen as the experimental site. The planting date of the determinate type soybean crop (UVF-1) was 2 August, 1981. Crop emergence occured on 4 August and is considered to be day 1 of the growing season. Within this agricultural field, an area (83 m^2) was isolated from normal field irrigation by flood dikes. Within this isolated area (16.5 m X 5 m) a 3 m row of soybean plants was impounded and saturated with 20 l of water every Tuesday and Thursday throughout the growing season. The Hidalgo Sandy Loam (Typic Haplustroll) (U.S.D.A.,1981) absorbed the 20 l of water within 30 minutes of application. The Versitile Soil Moisture Budget model (VSMB) (Baier and Robertson, 1966) was used to analyse and quantify the three field conditions based on the available water content within the soil.

From each of the three conditions tested in the field, five leaves were selected from each field condition for spectrophotometric analysis by the double-beam, ratio recording Beckman DK-2A Spectrophotometer equiped with a reflectance attachment[3] (Beckman Instruments, Fullerton, CA) located at the United States Department of Agriculture Remote Sensing Laboratory in Weslaco, Texas. The spectral measurements were completed within 2 hours of harvesting and the data were normalized for decay of the $BaSO_4$ standard to give absolute radiometric data between the 500 nm and 2500 nm wavelengths (Allen and Richardson, 1971). Spectral data samples were gathered at least weekly, averaged, and a standard deviation was calculated from the mean values from each field condition (Steel and Torrie, 1960).

Single leaf selections were based on several factors: same chronological age into the growing season between each field condition, same position within the top layer of leaves in the canopy, and same physical characteristics and conditions. Once the canopy had developed sufficiently, the leaves selected during any acquisition were older than leaves selected on prior acquisition dates. As the single leaves were selected, a portion of each leaf was individually prepared for micrographic cross-sectioning by being immersed in the chemical fixative Formalin. Each leaf was then placed in a separate Ziploc storage bag, tagged, and placed within a cooler of ice until spectral measurements could be completed by the Beckman DK-2A spectrophotometer.

To determine the temporal changes occuring in the single leaves, plots were drawn of the mean reflectance (R), transmittance (T), and absorptance (A) of the single leaves from each of the three field conditions at the 650 nm, 850 nm, 1650 nm, and 2200 nm wavelengths as a function of time into the growing season (Figs. 1-3). Single leaf absorptance values (A_λ) were calculated from the single leaf reflectance values (R_λ) and the single leaf transmittance values (T_λ) as:

$$\{A_\lambda = 1 - (R_\lambda + T_\lambda)\} \tag{1}$$

where $\emptyset < R_\lambda < 1$, $\emptyset < T_\lambda < 1$, and $\emptyset < (R_\lambda + T_\lambda) < 1$.

The 650 nm wavelength was chosen for study because of the chlorophyl absorption of the red wavelength (Gausman, 1974). The 850 nm wavelength was chosen for study of the changes in the intercellular structure of the single leaf that may be caused by water content (Gausman, 1974). The 1650 nm and 2200 nm wavelengths were chosen for study because of the the water absorption bands of the mid infrared waveband (Escobar and Gausman, 1974).

Canopy growth was monitored for height and width throughout the growing season for the three field conditions. Normal field condition samples were first harvested on day 8 of the growing season. The water saturated field condition treatment commenced on day 8 and harvesting began on day 10 of the growing season. The drought simulated area, being isolated from normal irrigation, went without water during the entire growing season other than at times when natural rainfall occured, as shown in Table 1. The first irrigation occured on day 45 of the growing season and harvesting of the drought simulated leaves commenced on that day. Five data sets were gathered for leaf moisture content from an average of 20 leaves per field condition. The results of the leaf moisture analysis are shown in Table 2. The U.S.D.A. weather recording station supplied on-site records of the enviornmental conditions throughout the growing season which were used in the VSMB model.

The Statistical Analysis System (SAS) "TTEST" (SAS Institute Inc., 1979) along with a correlation analysis was used to detect significant differences between the spectral characteristics of each field condition for any same acquisition date.

RESULTS AND DISCUSSION

Data from the Hidalgo Co., TX Soil Survey (U.S.D.A.,1981) shows that soil in the experimental plots had a potential water capacity of 22.0 cm of water through a 1.83 m depth. The mean water level for the three field conditions throughout the growing season with respect to enviornmental conditions as calculated by the VSMB model are as follows:

Normal:	14.2 cm $\pm$ 1.8 cm
Water Saturated:	20.0 cm $\pm$ 2.6 cm
Drought Simulated:	10.8 cm $\pm$ 1.9 cm

Canopy growth was monitored throughout the growing season for the three field conditions. The mean dimensions of the 25 plants sampled for size within each field condition were:

	Height (cm)	Width (cm)	Area (cm^2)
Normal:	85	105	8225
Water Saturated:	105	120	12600
Drought Simulated:	77	105	8085

Fig. 1. shows the soybean single leaf reflectance at the 650 nm, 850 nm, 1650 nm, and 2200 nm wavelengths as a function of time into the growing season. Slightly higher reflectances were found to exist at the begining and end of the growing season for all wavelengths tested due to the decreased concentrations of chlorophyl. Overall, the graphs tended to be horizontally straight lines exhibiting little change throughout the growing season. This information implies that seasonal estimates of soybean single leaf reflectance values should be reliable, and could be used in canopy prediction models on a seasonal basis.

Fig. 2. shows single leaf transmittance for the 650 nm, 850 nm, 1650 nm, and 2200 nm wavelengths. the graphs show dramatic changes occuring in the soybean single leaf transmittance characteristic and demonstrates the greatest variability with time of the spectral characteristics examined, thereby making seasonal estimates of the single leaf transmittance values very unreliable. Fig. 3. shows the single leaf absorptance values as derived from equation 1. It is evident from equation 1. that temporal variability of the single leaf absorptance is more a function of the single leaf transmittance characteristic due to the seasonally consistent single leaf reflectance. In addition, although Gausman (1974) showed the 850 nm wavelength to be sensitive to cell development within the single leaf, these data show that the mid infrared wavelengths are sensitive as well, based on the similarity of the curves between the wavelengths tested in Figs. 1-3, and the correlation data shown in Table 3. Analysis of the spectral characteristic values for the 650 nm, 850 nm, 1650 nm, and 2200 nm wavelengths by the SAS "TTEST" showed no significant differences between the normal, water saturated, and drought simulated field conditions for any same acquisition date ($P = 0.05$).

Data shown in Table 3. agree with the Thematic Mapper (TM) correlation matrix of Badhwar and Henderson (1981) except for the low correlation of TM band 4 (TM 4) to TM 5 which correspond to the 850 nm to 1650 nm wavelengths. Since the 850 nm wavelength has been shown to be sensitive to leaf biomass (Gausman et al, 1969), it is postulated that the configurations of the single leaves within the plant canopy would interfere with the good correlations that the single leaf reflectance at the 850 nm wavelength has to the 1650 nm and 2200 nm wavelengths.

A problem was encountered in sampling leaves for moisture content. An evapotranspiration rate of 0.005 grams per second was observed as the leaves were collectively weighed prior to oven drying. Even though the leaves were selected and placed in seperate Ziploc storage bags and then placed in a light-tight ice cooler, the time lapse during the weighing process could have allowed enough moisture to vaporize out of the leaves to allow a margin of error to exist in the percent water content values. Sinclair et al (1971) showed soybean single leaf reflectances for three periods during a growing season along with two micrographic cross-sections which showed percent water content values. The data shown in Table 2. lies within $\pm$ 4.3% of the Sinclair data for a normal leaf at 75% water content which also indicates that the error in Table 2. may be small. Fig. 1. shows reflectance in the infrared (850 nm, 1650 nm, 2200 nm) wavelengths increasing slightly after day 65 due to senescence, which also agrees with Sinclair et al (1971).

Micrographic cross-sections of soybean single leaves were processed from each field condition on day 65 and day 70 of the growing season. Figs. 4 and 5 show the normal (A), water saturated (B), and drought simulated (C) single leaf micrographs for days 65 and 70. Corresponding spectral characteristics for each single leaf are shown at the bottom of the figures. The normal leaf on day 70 (Fig. 5A) shows higher reflectance and transmittance than the normal leaf of day 65 (Fig. 4A). The absorptance for the normal leaf on day 70 is lower for all wavelengths shown which indicates that the leaf is in an early stage of senescence. The water saturated leaf for day 70 (Fig. 5B) showed higher reflectance and absorptance for the wavelengths tested than did the water saturated leaf for day 65 (Fig. 4B). The drought simulated leaf on day 70 (Fig.. 5C) showed higher transmittance than did the drought simulated leaf for day 65 (Fig. 4C), however, the drought simulated leaf for day 65 showed higher absorptance for the wavelengths tested. Evidence of drought stress can be seen in Figs. 4C and 5C, but Fig. 4C shows the highest absorptance for the 650 nm and 850 nm wavelengths and the lowest absorptance for the 1650 nm and 2200 nm wavelengths. However, it is important to note that the single leaf reflectance, transmittance, and absorptance values for day 65 for the three field conditions show less variability for the same wavelengths than the values for day 70, even though the water saturated leaf in Fig. 4B is 1.5 times as thick as the drought stressed leaf in Fig. 4C. The variability in the values for day 70 may be an example of single leaves in different stages of senescence. Only one trend is clear based on single leaf thickness for the three field conditions. The water saturated leaf for day 70 was found to have the lowest transmittance consistent at all wavelengths shown for any field condition for both days. This suggests that the probability of a photon passing through a single leaf decreases as a function of leaf thickness when the leaf thickness is a function of water content.

LeMaster and Chance (1974) showed that 95% of the visible light is reflected off of a canopy by the top two layers of single leaves. For the infrared wavelengths, a maximum of eight single leaves was sufficient.[4] A question then arises as to what degree of influence the temporally changing transmittance and absorptance of the single leaf characteristics have on the total reflectance of the soybean canopy. Implications also arise as to the effect of background soil radiation transmitting up through a canopy to affect overall canopy reflectance, particularly around day 30 when canopy width is narrow, canopy height is short, and Leaf Area Index (LAI)[5] is small. Since single leaf transmittance is at a maximum and single leaf absorptance is at a minimum on day 30, background soil radiation should have a greater influence on canopy reflectance measurements than has previously been considered for this particular stage of the growing cycle.

CONCLUSION

Based on the results of the VSMB model and the canopy measurements, the field conditions were well simulated. Analysis of the single leaf spectral characteristics by the SAS "TTEST" found no significant differences to exist between any field condition for the same data acquisition date. Spectral characteristic data shown in Figs. 1-3 show that single leaf maturity occured approximately 3/4 into the growing season and that the single leaves began to senesce approximately 7 days after peak maturity.

While trends for the single leaf spectral characteristics are quite clear as a function of time into the growing season, the single leaf spectral trends are not so easily seen nor explained as a function of leaf thickness. It is important to note that although single leaf reflectances maintain a $\pm$ 2.5% stability for the wavelengths tested throughout the growing season, the single leaf transmittance seems to be the key factor in determining the values of the single leaf absorptance based on the changing multi-temporal trends. The implications of the trends suggest that research efforts conducted to investigate crop reflectances in the field should place a greater emphasis on the transmittance characteristics of the single leaf as a function of time into the growing season.

FOOTNOTES

1. This research effort was carried out under the supervision of Drs. Edwin W. LeMaster and Joseph E. Chance of the Physics Department and Mathematics Department respectively of Pan American University, Edinburg, Texas, and Dr. Harold W. Gausman of the United States Department of Agriculture Research Center in Weslaco, Texas, and was partially funded by NASA Grant #NSG 9033.
2. Mark S. Rogers is currently an undergraduate of Pan American University, Edinburg, Texas, majoring in physics. While Mr. Rogers was conducting this research, he was registered as a Junior and was also responsible for 17 semester hours of classes. At the time of this writing, he is working in the Earth Resources Division of the Johnson Space Center for the National Aeronautics and Space Administration under the Cooperative Education Program.
3. Trade names and company names are included for the benefit of the reader and do not imply an endorsement or preferential treatment of the product by Pan American University, the United States Department of Agriculture, the National Aeronautics and Space Administration, or the author.
4. The 650 nm wavelength was chosen to represent the visible band; LAI = 2.13. The 850 nm wavelength was chosen to represent the infrared band; LAI = 6.11.
5. Leaf Area Index (LAI) is a dimensionless number which represents the probability of finding a single leaf anywhere within a cubic volume (cm^3) of the plant canopy. The function of an LAI and its various formulae for derivation will not be discussed in this paper.

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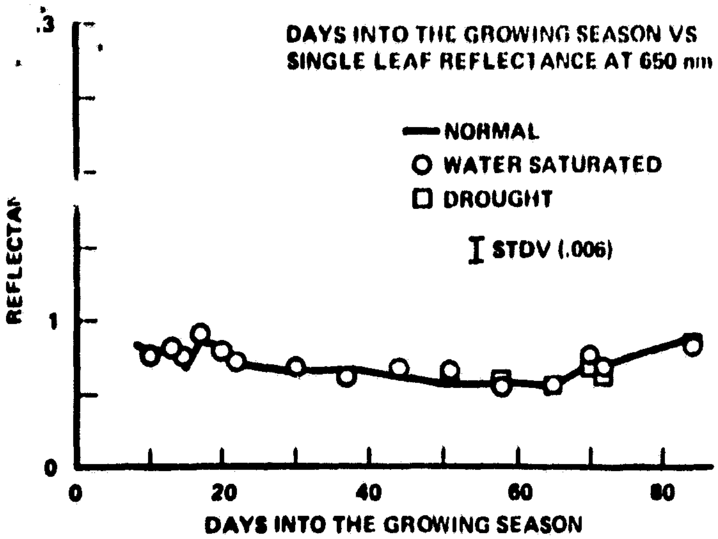
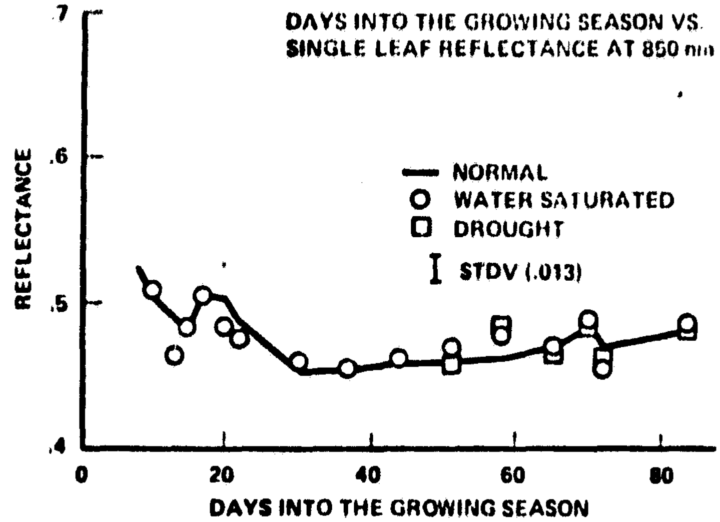
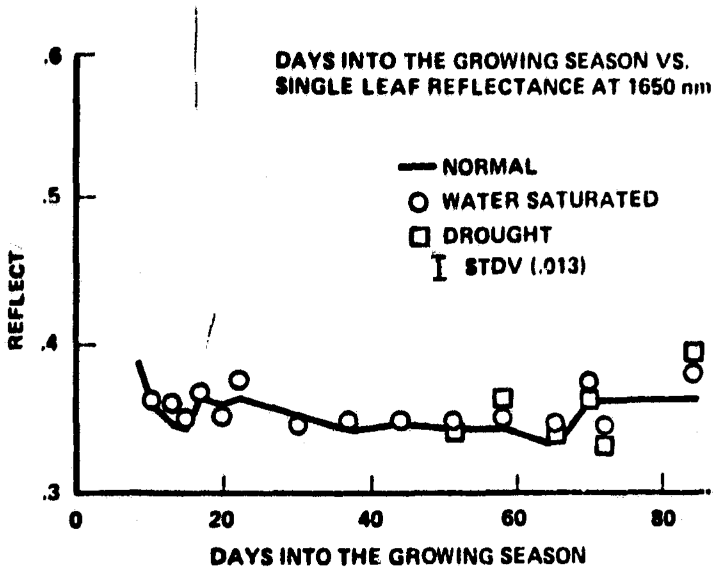
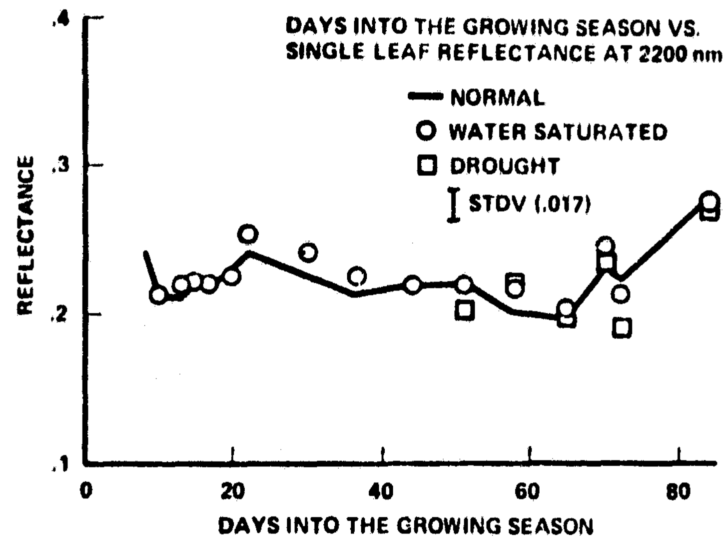
FIGURE CAPTIONS

Figure 1	Soybean single leaf reflectances as a function of time into the growing season for the 650 nm, 850 nm, 1650 nm, and 2200 nm wavelengths.
Figure 2	Soybean single leaf transmittances as a function of time into the growing season for the 650 nm, 850 nm, 1650 nm, and 2200 nm wavelengths.
Figure 3	Soybean single leaf absorptances as a function of time into the growing season for the 650 nm, 850 nm, 1650 nm, and 2200 nm wavelengths.
Figure 4	Micrographic cross-sections of soybean leaves on day 65 of the growing season for normal (A), water saturated (B), and drought simulated (C) field conditions and corresponding spectral characteristics.
Figure 5	Micrographic cross-sections of soybean leaves on day 70 of the growing season for normal (A), water saturated (B), and drought simulated (C) field conditions and corresponding spectral characteristics.
Table 1	Rainfall During the Growing Season
Table 2	Leaf Moisture Data
Table 3	Spectral Characteristic Correlation and Regression Factors









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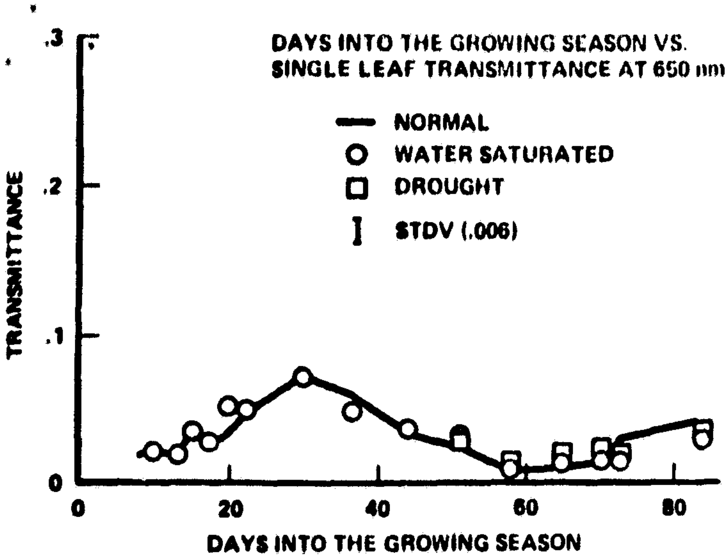
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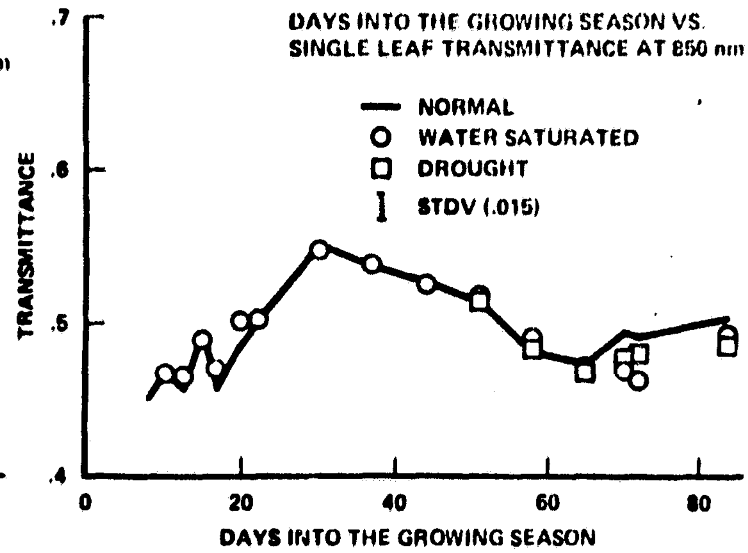
NORMAL
WATER SATURATED
DROUGHT
STDV (.006)
TRANSMITTANCE
.3
.2
.1
0
0
20
40
60
80
DAYS INTO THE GROWING SEASON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WATER SATURATED
DROUGHT
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TRANSMITTANCE
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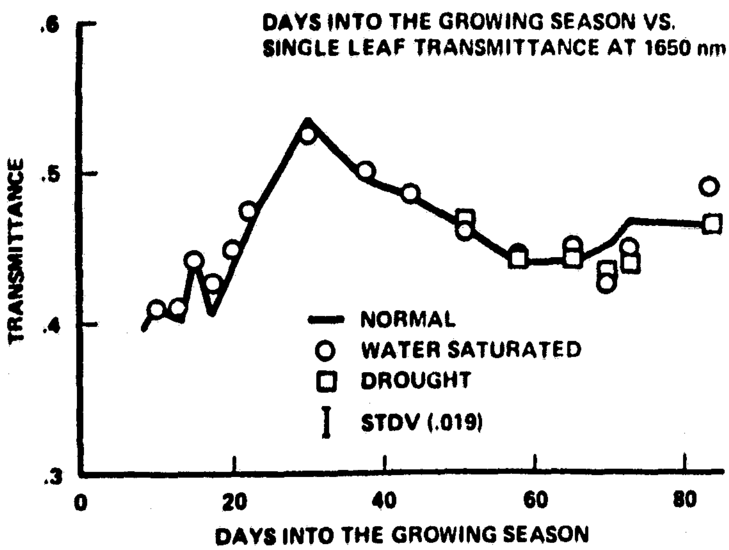
.6
.5
.4
0
20
40
60
80
DAYS INTO THE GROWING SEASON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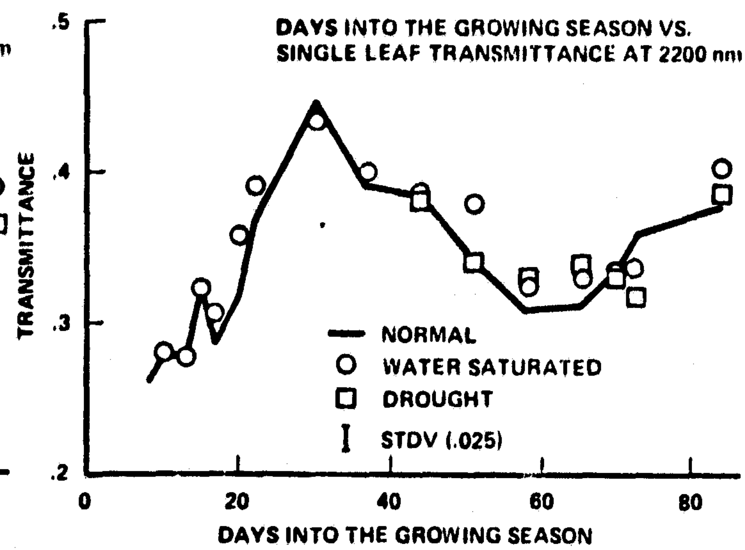
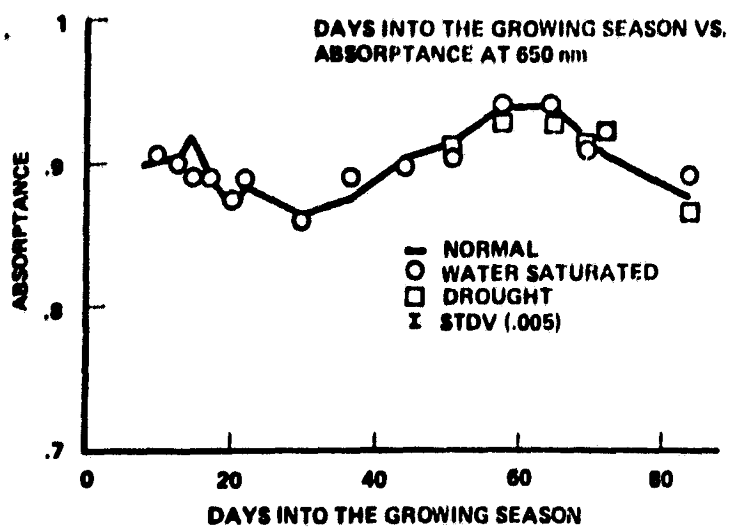
NORMAL
WATER SATURATED
DROUGHT
STDV (.019)
TRANSMITTANCE
.6
.5
.4
.3
0
20
40
60
80
DAYS INTO THE GROWING SEASON


DAYS INTO THE GROWING SEASON VS. SINGLE LEAF TRANSMITTANCE AT 2200 nm
NORMAL
WATER SATURATED
DROUGHT
STDV (.025)
TRANSMITTANCE
.5
.4
.3
.2
0
20
40
60
80
DAYS INTO THE GROWING SEASON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WATER SATURATED
DROUGHT
STDV (.005)
ABSORPTANCE
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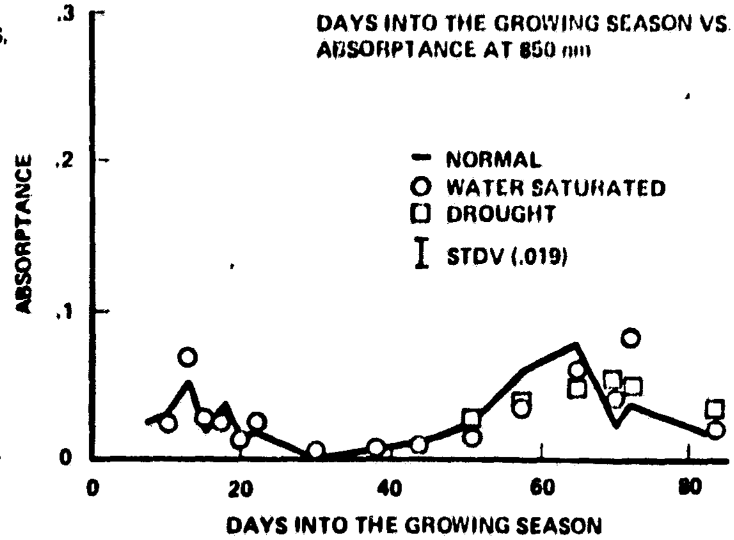
.8
.7
0
20
40
60
80
DAYS INTO THE GROWING SEASON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40
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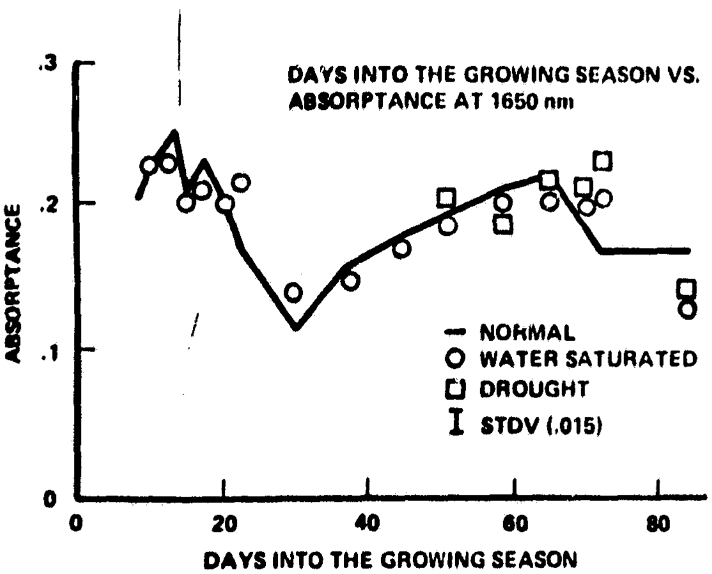
80
DAYS INTO THE GROWING SEASON


DAYS INTO THE GROWING SEASON VS. ABSORPTANCE AT 1650 nm
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WATER SATURATED
DROUGHT
STDV (.015)
ABSORPTANCE
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0
0
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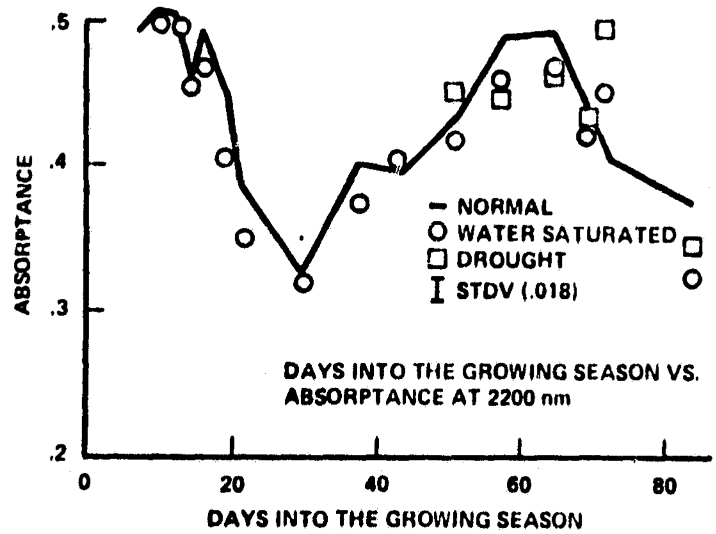
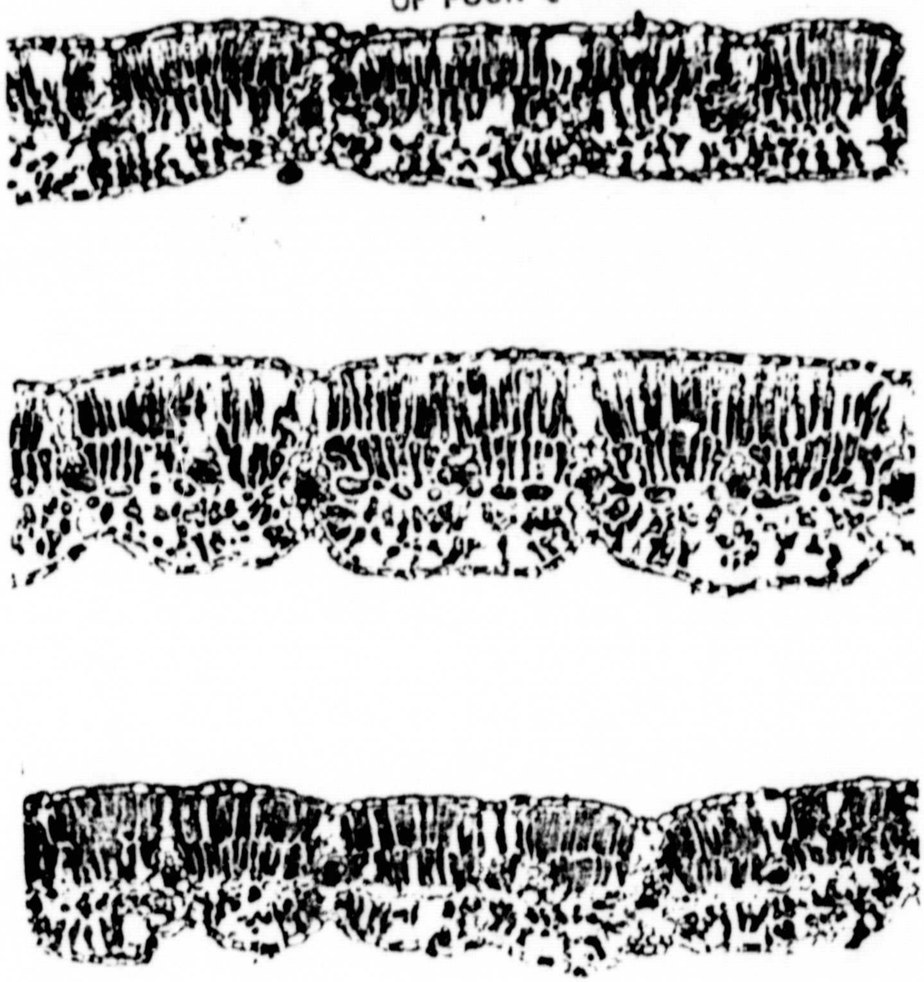
40
60
80
DAYS INTO THE GROWING SEASON


NORMAL
WATER SATURATED
DROUGHT
STDV (.018)
DAYS INTO THE GROWING SEASON VS. ABSORPTANCE AT 2200 nm
ABSORPTANCE
.5
.4
.3
.2
0
20
40
60
80
DAYS INTO THE GROWING SEASON



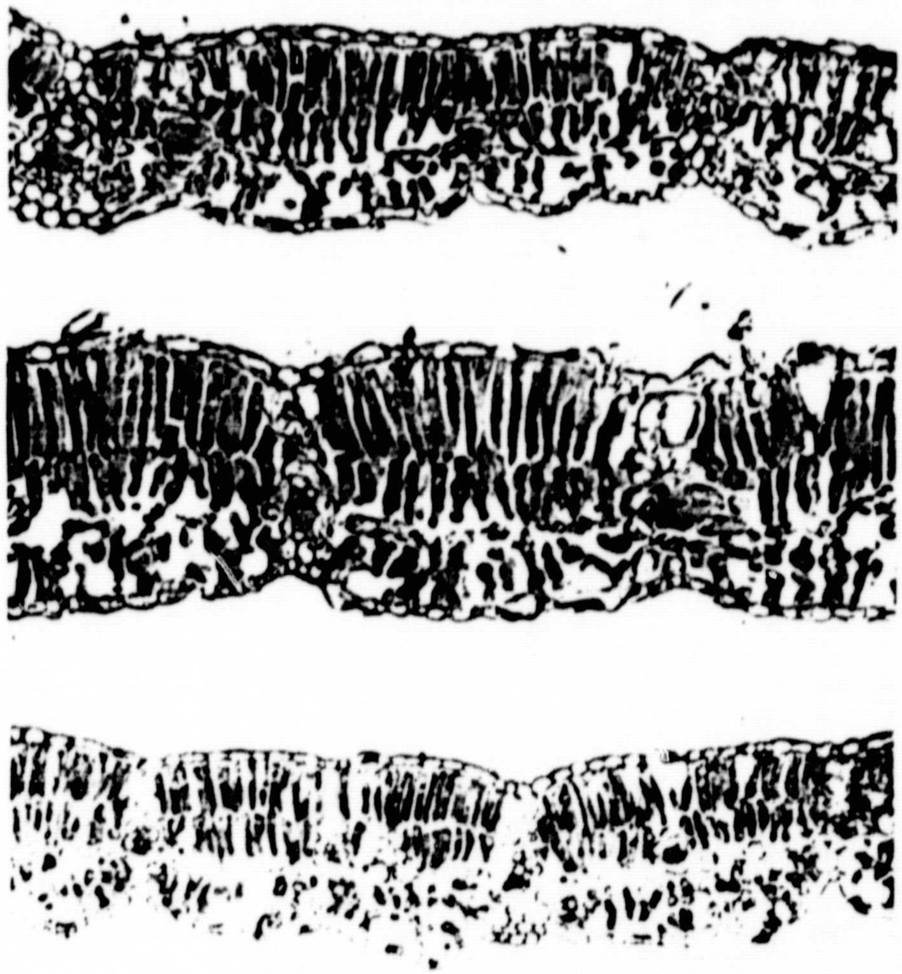
(A)

(B)

(C)

FIELD CONDITION	λ (n.m.)	REFLECTANCE	TRANSMITTANCE	ABSORPTANCE
(A) NORMAL	650	.075	.020	.905
	850	.467	.475	.058
	1650	.368	.434	.198
	2200	.232	.315	.453
(B) WATER SATURATED	650	.063	.021	.916
	850	.473	.463	.064
	1650	.378	.427	.195
	2200	.241	.319	.440
(C) DROUGHT SIMULATED	650	.060	.019	.921
	850	.465	.458	.077
	1650	.389	.430	.181
	2200	.249	.322	.429

Figure 4.- Micrographic cross-sections of soybean single leaves and related spectral characteristics for day 65.



FIELD CONDITION	λ (n.m.)	REFLECTANCE	TRANSMITTANCE	ABSORPTANCE
(A) NORMAL	650	.083	.017	.900
	850	.472	.494	.034
	1650	.371	.504	.125
	2200	.232	.329	.439
(B) WATER SATURATED	650	.065	.016	.919
	850	.518	.438	.044
	1650	.406	.385	.209
	2200	.241	.269	.490
(C) DROUGHT SIMULATED	650	.074	.023	.903
	850	.473	.472	.055
	1650	.402	.453	.145
	2200	.269	.360	.371

Figure 5.- Micrographic cross-sections of soybean single leaves and related spectral characteristics for day 70.

Table 1 Rainfall Data

Precipitation in inches			
Day	Amt	Day	Amt
17	0.26	43	0.03
18	0.10	55	0.28
20	0.30	56	1.79
22	1.23	57	0.02
23	0.02	65	0.14
24	0.13	75	0.07
25	1.04	76	0.27
26	0.93	79	0.04
32	0.31	80	3.07
33	0.03	81	0.26

Table 2 : Leaf Moisture Data

Date	Day After Emergence	Moisture Content		
		Normal	Water Saturated	Drought Simulated
19 Aug 81	15	75.2 %	78.1 %	-
21 Aug 81	17	79.8 %	79.6 %	-
24 Aug 81	20	77.5 %	81.7 %	-
15 Oct 81	72	70.9 %	71.3 %	69.6 %
27 Oct 81	84	69.4 %	70.1 %	69.5 %

Table 3 SPECTRAL CHARACTERISTIC CORRELATION AND REGRESSION FACTORS

SINGLE LEAF REFLECTANCE									
Wavelength (nm)	850(x_i), 1650(y_i)			850(x_i), 2200(y_i)			1650(x_i), 2200(y_i)		
Field Condition	N.	W.S.	D.	N.	W.S.	D.	N.	W.S.	D.
Correlation	.744[1]	.615[3]	.799[4]	.824[1]	.057	.773[4]	.692[2]	.626[3]	.947[2]
$\hat{\sigma}_{y_i}$	.013	.014	.021	.015	.018	.027	.014	.027	.027
$\hat{\sigma}_{Regression}$	.009	.011	.013	.012	.018	.011	.010	.021	.006
Equations: N.	$\hat{y}_i = .471\ x_i + .128$			$\hat{y}_i = .207\ x_i + .720$			$\hat{y}_i = .759\ x_i - .048$		
W.S.	$\hat{y}_i = .540\ x_i + .101$			$\hat{y}_i = .063\ x_i + .196$			$\hat{y}_i = .790\ x_i - .056$		
D.	$\hat{y}_i = 1.678\ x_i - .439$			$\hat{y}_i = 2.088\ x_i - .786$			$\hat{y}_i = 1.252\ x_i - .244$		

SINGLE LEAF TRANSMITTANCE									
Wavelength (nm)	850(x_i), 1650(y_i)			850(x_i), 2200(y_i)			1650(x_i), 2200(y_i)		
Field Condition	N.	W.S.	D.	N.	W.S.	D.	N.	W.S.	D.
Correlation	.967[1]	.880[1]	.651	.950[1]	.622[3]	.115	.981[1]	.958[1]	.764[4]
$\hat{\sigma}_{y_i}$	.036	.033	.014	.048	.044	.022	.049	.044	.022
$\hat{\sigma}_{Regression}$	.009	.016	.101	.015	.035	.022	.009	.002	.014
Equations: N.	$\hat{y}_i = 1.197\ x_i - .139$			$\hat{y}_i = 1.550\ x_i - .429$			$\hat{y}_i = 1.295\ x_i - .250$		
W.S.	$\hat{y}_i = 1.021\ x_i - .047$			$\hat{y}_i = 1.745\ x_i - .527$			$\hat{y}_i = 1.295\ x_i - .243$		
D.	$\hat{y}_i = .582\ x_i + .169$			$\hat{y}_i = .169\ x_i + .261$			$\hat{y}_i = 1.250\ x_i - .222$		

SINGLE LEAF ABSORPTANCE									
Wavelength (nm)	850(x_i), 1650(y_i)			850(x_i), 2200(y_i)			1650(x_i), 2200(y_i)		
Field Condition	N.	W.S.	D.	N.	W.S.	D.	N.	W.S.	D.
Correlation	-.005	.633[3]	-.061	.006	.581[3]	-.403	.963[1]	.836[1]	.950[2]
$\hat{\sigma}_{y_i}$	.030	.030	.029	.052	.057	.047	.052	.050	.047
$\hat{\sigma}_{Regression}$	.030	.023	.029	.052	.047	.043	.017	.031	.015
Equations: N.	$\hat{y}_i = .009\ x_i + .192$			$\hat{y}_i = .018\ x_i + .441$			$\hat{y}_i = 1.535\ x_i + .147$		
W.S.	$\hat{y}_i = .840\ x_i + .168$			$\hat{y}_i = 1.472\ x_i + .384$			$\hat{y}_i = 1.593\ x_i + .120$		
D.	$\hat{y}_i = .252\ x_i + .203$			$\hat{y}_i = -2.439 x_i + .526$			$\hat{y}_i = 1.545\ x_i + .139$		

[1]Significant at the .1% probability level.
[2]Significant at the 1% probability level
[3]Significant at the 5% probability level
[4]Significant at the 10% probability level

ACKNOWLEDGMENT

The author especially thanks Drs. Edwin W. LeMaster and Joseph E. Chance of Pan American University in Edinburg, Texas, and Dr. Harold W. Gausman of the United States Department of Agriculture Research Center in Weslaco, Texas, for their invaluable assistance, contributions, and numerous consultations which helped make this paper possible. The author gratefully acknowledges the kind generosity of Mr. Andy Scott of Rio Farms Inc. of Monte Alto, Texas, for the donation of the experimental site. In addition, many thanks are given to Research Leader Dr. Harold W. Gausman and Laboratory Technicians Mr. David E. Escobar, Mr. Romeo Rogriquez, and Mrs. Maricela V. Garza for their valuable assistance in the processing of the data for this paper within the Remote Sensing Laboratory at the U. S. D. A. Research Center in Weslaco, Texas. Also, the author would like to thank Dr. Forrest G. Hall, Dr. David E. Pitts, and Dr. Gautam D. Badhwar of the National Aeronautics and Space Administration, Earth Resources Division, at the Johnson Space Center in Houston, Texas for their valuable comments concerning the manuscript. As well, the author would like to express his appreciation to Dr. Jack F. Paris of the Earth Resources Division, NASA/JSC and Dr. William W. Hildreth of Lockheed Engineering and Management Services Co. Inc. for their assistance with the Versitile Soil Moisture Budget Model. Finally, I would like to thank my Mother and Father, Mrs. Helen K. Rogers of Gap, PA, and Mr. C. M. Rogers III of Naperville, IL, other members of my family, and my lady friends for their kind support in my continuing education.

A TEST OF THE SUITS VEGETATIVE CANOPY REFLECTANCE MODEL WITH LARS SOYBEAN CANOPY REFLECTANCE DATA

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Abstract

The Suits vegetative canopy reflectance model is tested with an extensive set of field reflectance measurements made by the Laboratory for Applied Remote Sensing for soybean canopies. The model is tested for the full hemisphere of observer directions as well as the nadir direction. The results show moderate agreement for the visible channels of the Landsat MSS and poor agreement in the near infrared channel of Landsat MSS. An analysis of errors is given.

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Introduction

The motivation for this paper came as a result of a two week conference sponsored by the National Aeronautical and Space Administration (NASA) held at Colorado State University during the summer of 1982[1].

Two important recommendations made by the conferees at this meeting were:

A. Identification of existing vegetative canopy reflectance models, the stage of development of such models, and their data requirements

B. The testing of those models identified in A with a common data set of vegetative canopy reflectance measurements.

The location of a data set satisfying the diversity of parameter needs required for each of the canopy models was not an easy task. However, a common data set was finally decided upon which appeared to meet all requirements.

The exquisitely detailed and complete data set developed by Laboratory for Applications of Remote Sensing (LARS) from Purdue University for soybean canopy reflectance[2] was chosen by the NASA conferees as the common data source. This document represents, in the opinion of the authors, one of the most complete sets of canopy measurements on a vegetative canopy to yet appear in the literature.

Thus the stage was set for what some observers at NASA would refer to as the "model bake-off." The purpose of this paper is to report on a comparison of the Suits vegetative canopy reflectance model with the LARS measurements and to discuss some of the possible error sources. Since the derivation of the Suits model by G. Suits[3] in 1972, various researchers, such as Suits[4], Bunn[illegible], and Chance and LeMaster[6], have conducted model verification experiments. Such results as have been published naturally emphasize the nadir observer direction since this type of field data is most convenient to collect and applies directly to current satellite systems. Thus, no systematic field measurements were made in the full observer hemisphere, and the Suits model was yet to be tested in these parameters. The important question of how good a job the Suits model did in characterizing the total reflected radiation field needed to be answered, not only for satellite applications, but for photosynthetic studies as well. This LARS data set, using equipment and techniques developed by LARS personnel, contains the full hemisphere of off-nadir reflectance measurements, so that for the first time, off-nadir comparisons of actual field data with the Suits model can be established.

The Suits Model and Its Parameter Requirements

It is not within the scope of this paper to present a detailed derivation of the Suits model. Many papers abound on the subject; for example, Suits[3], Slater[4], Bunnik[5], and Chance and Cantu[6]. Further, a complete discussion of the LARS data set is not within the scope of this paper, but can be found in [2]. We only present a summary of the data necessary for model calculations. Canopy reflectance data was collected by LARS for a soybean canopy having green leaf area index (LAI) of 2.87±.44, yellow leaf area index of .06±.04, canopy cover of 98.9%±1%, and in maturity stage V20R6. It was decided that a one-layer Suits model having only one component, green leaves, would be used for calculations.

The horizontal vertical projections of the average leaf were, respectively 21.8 cm^2 and 27.5 cm^2. The number of leaves per unit volume used in the calculations was 8.03×10^{-4}. These parameters were calculated from canopy measurements included in the LARS data set.

Disagreement existed about the single leaf reflectance and transmittance measurements reported by LARS, and these data were subsequently corrected. The calculations shown in this paper use the single leaf optical data reported in a November 2, 1982, communication from LARS and shown graphically in Fig. 1.

LARS made shadowed panel reflectance readings on a barium sulfate standard throughout the canopy measurement period so that diffuse target irradiance could be calculated and used as parameter inputs to the Suits model. Nadir and off-nadir canopy reflectance measurements made by LARS were with an Exotech 100 radiometer having spectral bands almost exactly the same as those in Landsat channels 1, 2, 3, and 4. The field of view of the instrument was limited to 10° by field stops. The radiometer placed 10 meters above the ground in a truck-mounted boom, was designed to allow azimuthal scans at a fixed target.

Soil reflectance in 50 nm increments was not included in the LARS data set; only the Exotech 100 readings on the bare soil were reported for the 4 broad band channels. Soil reflectance was chosen at each 50 nm interval such that it closely approximated the reflectance of soil Stoner[7] collected from the Purdue farm site and the broad-band calculation algorithm (see below) would yield values reported in the LARS data set as measured by their Exotech 100.

Finally, it was felt by the authors that measurements made by a broad band radiometer should not be compared directly to a single wavelength calculation such as that obtained from the Suits model without making adjustments for variations in solar irradiance and instrument spectral response. As solar irradiance energy varies as a function of wavelength and that this energy is also selectively absorbed by the atmosphere, some correction should be applied. However, as the atmosphere varies over the test site continuously, the necessary corrections needed are impossible to know. Therefore, it was decided to assume the clear standard atmosphere of Eltermann[8] and to introduce corrections for atmosphere, solar zenith angle, and Landsat relative responsivity in a manner similar to Chance[9]. The results are as follows, with $R(\cdot)$ the Suits model calculations; θ, the solar zenith angle; and Ch(1), Ch(2), Ch(3), Ch(4), the four Exotech 100 readings:

$$
\begin{aligned}
Ch(1) &= 70.4\exp(-.370\mathrm{Sec}\theta)R(500) + 139.2\exp(-.331)\mathrm{Sec}\theta)R(550) \\
&\quad + 73.8\exp(-.305\mathrm{Sec}\theta)R(600) \\
Ch(2) &= 91.7\exp(-.305\mathrm{Sec}\theta)R(600) + 164.2\exp(-.252\mathrm{Sec}\theta)R(650) \\
&\quad + 63.5\exp(-.217\mathrm{Sec}\theta)R(700) \\
Ch(3) &= 83.0\exp(.217\mathrm{Sec}\theta)R(700) + 106.9\exp(-.200\mathrm{Sec}\theta)R(750) \\
&\quad + 47.5\exp(-.187\mathrm{Sec}\theta)R(800) \\
Ch(4) &= 12.3\exp(-.187\mathrm{Sec}\theta)R(800) + 21.8\exp(-.177\mathrm{Sec}\theta)R(850) \\
&\quad + 15.6\exp(-.166\ \mathrm{Sec}\theta)R(900) + 10.6\exp(-.159\mathrm{Sec}\theta)R(950) \\
&\quad + 6.3\exp(-.151\mathrm{Sec}\theta)R(1000) + 3.0\exp(-.148\mathrm{Sec}\theta)R(1050).
\end{aligned}
\tag{1}
$$

Reflectance panel readings in the Exotech channels are obtained by setting $R(\cdot)=1$ in (1); and the broad-band reflectances are then obtained by a ratio of calculated crop readings to calculated panel readings.

Results and Conclusions

Denoting θ and A as the zenith angle and the azimuth angle (from north), respectively, and the subscripts s and v for the sun and viewer, respectively, the results are seen in Tables 1, 2, and 3. The columns denoted as E% represent the percent error, calculated as

$$E\% = \frac{R_{LARS} - R_{Suits}}{R_{LARS}} \times 100.$$

Tables 1, 2, and 3 represent azimuthal scans for solar zenith angles, respectively, of about 30°, 45°, and 60°. The LARS data set contains a much larger variety of solar zenith angle measurements of the canopy reflectance. However, the results shown in these tables are representative of the larger data set [10], so the authors felt justified in selecting only small, moderate, and large zenith angles for comparison. Data omitted from the tables is a result of the boom casting a shadow over the target for that combination of solar and observer angles. The E% will become negative when the Suits model values are greater than the values measured in the field.

Table 4 is a comparison of LARS data to the Suits model using a nadir viewer angle and solar zenith angles that vary from 30° to 60° in approximate increments of 5°.

From Tables 1, 2, and 3 two pronounced patterns in the errors appear evident.

(i) In all channels, the errors are largest when the observer either faces the sun or has his back to the sun.

This observation suggests that the azimuthal corrections made for the Suits model[11] are inadequate to explain the inherent non-Lambertian nature of the specular reflectance of leaf surfaces. The non-Lambertian nature of soybean leaves in the reflectance of specular light has been demonstrated by Breece and Holmes[12]. The derivation of the Suits model, however, considers each leaf to be a Lambertian reflector of light. Such an assumption is probably valid (see [12]) for diffuse incident radiation; but specular incident radiation on exposed leaf surfaces appear to be the greater contributor to non-Lambertian canopy reflectance. Such a hypothesis could be verified with field measurements taken on overcast days where most light incident to the canopy is diffuse.

(ii) At all combinations of viewer and observer angles, channel 4 shows a significant negative error, indicating a possible bias. To explain such behavior, several hypotheses are offered. Figures 1 and 2 offer a comparison between the optical properties of a single soybean leaf as reported by LARS[2] and a single wheat leaf as reported by Gausman et al [13]. A qualitative comparison of the two figures indicate a comparable absorption in the range from 500-800 nm, but from 800-1100 nm, the absorption of the soybean leaf becomes much smaller (about 5% for wheat versus about 1% for soybeans). The cause for this low absorption in channel 4 can be explained by examining a table of leaf thicknesses presented by Gausman and Allan[14]. This table includes leaf thicknesses for 29 plant species that include onion, lettuce, cantaloupe, sorghum, bean tomato, orange, cotton, pepper, corn, and okra. The thickest leaf was onion at .978 mm, while sorghum had the thinnest leaf of all 29 plant species tabulated at .140 mm.

Thus, it appears that in the infrared regime the thin soybean leaf is readily penetrated by radiation; the leaf acting only as a scatterer and not a good absorber. The Suits model has given better results on other cultivars such as wheat in the infrared region[15], possibly due to the larger absorption of the thicker wheat leaves. Single leaf absorption of a plant species may be a limiting factor on the use of the Suits model in the ir region of the spectrum. Furthermore, Chance and Cantu[6] have noted that the solution of the Suits model changes whenever the single leaf absorption is zero, e.g., the eigenvalues of the system of differential equations become repeated. The authors are now investigating the sensitivity of the Suits model to slight changes in the absorption whenever the absorption is assumed to be zero.

It should also be noted that the authors have assumed in this paper that the optical properties of both the upper and lower surfaces of the soybean leaves are identical. Such is certainly not the case, but very little data now exists that indicates the optical properties of both surfaces. Gausman and Cardenas[16] report significant differences between the reflectance and transmittance of upper and lower surfaces for soybean leaves. The Suits model can be revised include such differences and the effect of such an incorporation will reduce the error in channel 4, but the magnitude of the error reduction is difficult to estimate. The authors are now considering such a revision of the Suits model.

Table 4 is a comparison of the LARS data with Suits model calculations for a nadir look angle. It is of interest to observe the trends in the errors caused by shadowing of the canopy. The errors appear to increase in channels 1, 2, and 3 with increasing solar zenith angle whereas channel 4 shows no such effect. As the Suits model does not consider the effects of mutual shading between canopy vegetative elements, those channels in which vegetative light absorption is highest show the most pronounced effect. However, in channel 4 where very little absorption of light occurs within individual leaves, the effect of mutual shading is minimized.

This comparison of the Suits model with LARS field measurements has pointed out several new areas of improvement that need to be incorporated into vegetative canopy models. Such careful field measurements as have been made by LARS need to be continued and should include the consideration of "open canopies" such as corn and row crops with incomplete ground cover. Without such a data base the testing of realistic vegetative canopy models is very difficult. The art of modeling often requires assumptions as to which physical phenomena should be included in the model and which physical phenomena can be ignored. The modeler is never fully justified in such assumptions until a large base of experimental data is taken that concurswith his judgements.

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Table Captions

Table 1. A comparison of the Suits model with LARS reflectance data for a viewer zenith angle of about 30°.

Table 2. A comparison of the Suits model with LARS reflectance data for a viewer zenith angle of about 45°.

Table 3. A comparison of the Suits model with LARS reflectance data for a viewer zenith angle of about 60°.

Table 4. A comparison of the Suits model with LARS reflectance data for a nadir view angle.

SUITS MODEL %

θ_s	A_s	θ_v	A_v	Ch 1	E%	Ch 2	E%	Ch 3	E%	CH 4	E%
32	162	30	0	4.07	-24	3.35	-20	27.95	-05	58.33	-47
31	165	30	45	3.95	-27	3.27	-24	27.39	-01	57.43	-42
31	165	30	90	3.91	-14	3.28	-13	27.20	06	57.09	-34
31	165	30	135	4.04	02	3.40	04	27.62	13	57.68	-24
31	165	30	180	----		----		-----		-----	
32	162	30	225	3.93	-08	3.30	-06	27.29	10	57.23	-29
32	162	30	270	3.92	-18	3.25	-14	27.28	09	57.28	-28
32	162	30	315	4.05	-22	3.34	-18	27.85	00	58.17	-41
32	162	45	0	4.22	-25	3.41	-20	28.98	-08	60.23	-51
31	165	45	45	4.01	-18	3.27	-14	28.07	05	58.79	-34
31	165	45	90	3.96	-13	3.27	-11	27.78	07	58.26	-32
31	165	45	135	4.15	04	3.47	05	28.44	17	59.18	-19
31	165	45	180	4.21	09	3.52	11	28.66	19	59.50	-15
32	162	45	225	4.00	02	3.32	05	27.96	16	58.52	-20
32	162	45	270	3.97	-12	3.25	-09	27.95	10	58.60	-27
32	162	45	315	4.18	-18	3.38	-13	28.83	01	59.99	-42
32	162	60	0	4.42	-16	3.49	-10	30.06	01	61.91	-38
31	166	60	45	4.10	-14	3.28	-10	28.71	05	59.80	-33
31	166	60	90	4.01	-05	3.28	-03	28.25	13	58.97	-23
31	166	60	135	4.29	03	3.56	04	29.21	18	60.30	-16
31	166	60	180	4.39	13	3.65	16	29.57	18	60.83	-16
32	162	60	225	4.09	10	3.36	12	28.55	17	59.40	-18
32	162	60	270	4.05	06	3.26	10	28.53	12	59.51	-25
32	162	60	315	4.36	-12	3.45	-06	29.83	00	61.56	-41

Table 1

SUITS MODEL %

θ_s	A_s	θ_v	A_v	Ch 1	E%	Ch 2	E%	Ch 3	E%	Ch 4	E%
44	236	30	0	3.93	-06	3.22	-04	27.71	06	58.08	-33
45	238	30	45	4.11	-21	3.34	-17	28.50	01	59.33	-39
45	238	30	90	4.04	-16	3.29	-13	28.20	02	58.87	-38
45	238	30	135	3.85	-08	3.18	-06	27.42	07	57.62	-33
45	238	30	180	3.91	09	3.27	08	27.55	22	57.73	-11
44	238	30	225	----		----		-----		-----	
44	236	30	270	4.02	11	3.38	12	27.92	23	58.25	-09
44	236	30	315	3.85	05	3.21	06	27.34	14	57.45	-23
44	237	45	0	4.14	-07	3.34	-03	29.05	02	60.47	-39
45	238	45	45	4.46	-13	3.55	-08	30.38	03	62.55	-34
45	238	45	90	4.34	-18	3.47	-13	29.91	02	61.82	-37
45	238	45	135	4.05	-02	3.30	00	28.67	11	59.86	-27
45	238	45	180	4.14	05	3.44	05	28.87	18	60.03	-16
45	238	45	225	----		----		-----		-----	
45	237	45	270	4.32	13	3.62	14	29.52	25	60.95	-07
44	237	45	315	4.04	07	3.33	10	28.51	14	59.54	-23
44	237	60	0	4.44	-03	3.52	02	30.57	07	62.86	-30
45	239	60	45	4.97	-08	3.87	-02	32.76	04	66.28	-32
45	239	60	90	4.76	-02	3.73	04	31.93	06	65.00	-28
45	239	60	135	4.33	03	3.46	06	30.07	13	62.05	-22
45	238	60	180	4.45	10	3.68	11	30.35	18	62.26	-16
45	237	60	225	4.87	18	4.07	19	31.81	25	64.34	-06
44	237	60	270	4.69	19	3.91	19	31.50	24	63.38	-05
44	237	60	315	4.29	09	3.50	11	29.77	14	61.47	-22

Table 2

SUITS MODEL %

θ_s	A_s	θ_v	A_v	Ch 1	E%	Ch 2	E%	Ch 3	E%	Ch 4	E%
61	257	30	0	3.81	10	3.11	14	27.53	14	57.61	-24
62	259	30	45	4.02	01	3.24	07	28.58	08	59.24	-31
62	259	30	90	4.13	00	3.32	08	29.08	03	60.01	-37
62	259	30	135	3.89	06	3.15	12	27.96	09	58.27	-31
62	259	30	180	3.80	20	3.14	23	27.43	25	57.36	-09
62	259	30	225	----		----		-----		-----	
62	257	30	270	4.11	19	3.46	20	28.66	28	59.12	-03
61	257	30	315	3.88	17	3.23	19	27.71	22	57.76	-13
61	258	45	0	4.25	03	3.43	09	29.80	07	61.41	-33
61	259	45	45	4.61	05	3.66	15	31.56	04	64.17	-35
62	259	45	90	4.78	-02	3.79	08	32.36	-02	65.41	-42
62	259	45	135	4.40	09	3.52	17	30.57	10	62.63	-29
62	259	45	180	4.26	14	3.48	18	29.72	20	61.18	-15
61	258	45	225	----		----		-----		-----	
61	258	45	270	4.74	17	3.99	19	31.63	27	63.87	-03
61	258	45	315	4.37	15	3.63	17	30.13	19	61.72	-23
62	259	60	0	4.87	02	3.88	09	32.61	07	65.80	-30
62	259	60	45	5.43	05	4.24	15	35.37	07	70.14	-29
62	259	60	90	5.69	09	4.43	22	36.60	05	72.03	-31
62	259	60	135	5.12	09	4.02	25	33.87	08	67.79	-29
62	259	60	180	4.89	13	3.97	18	32.58	17	65.58	-18
61	258	60	225	5.37	17	4.50	18	34.44	24	68.15	-06
61	258	60	270	----		----		-----		-----	
61	258	60	315	5.05	14	4.17	17	33.11	19	66.28	-13

Table 3

NADIR LOOK ANGLE

θ_s	A_s	θ_v	Ch 1	E%	Ch 2	E%	Ch 3	E%	Ch 4	E%
31°	164	0	3.53	-08	3.29	-18	25.61	13	53.55	-22
37°	138	0	3.71	-05	3.17	-04	25.24	17	53.05	-18
40°	132	0	3.64	00	3.09	00	25.04	21	52.77	-12
45°	237	0	3.51	01	2.98	-01	24.68	18	52.24	-17
49°	244	0	3.40	01	2.88	02	24.36	16	51.74	-20
56°	253	0	3.19	14	2.70	15	23.70	22	50.66	-14
60°	257	0	3.06	27	2.59	28	23.25	30	49.88	-04

Table 4

Figure Captions

Figure 1. Mean Reflectance and Transmittance (T) for Single Leaves of Soybeans. (LARS 1982)

Figure 2. Errors in channel 1 as a Function of the Observer Azimuth Angle for a Solar Zenith Angle of $\theta_s=30^\circ$. Errors are calculated between soybean field reflectance and the Suits spectral reflectance model.

Figure 3. Mean Reflectance and Transmittance for Single Leaves of Wheat. (Gausman et al 1973)

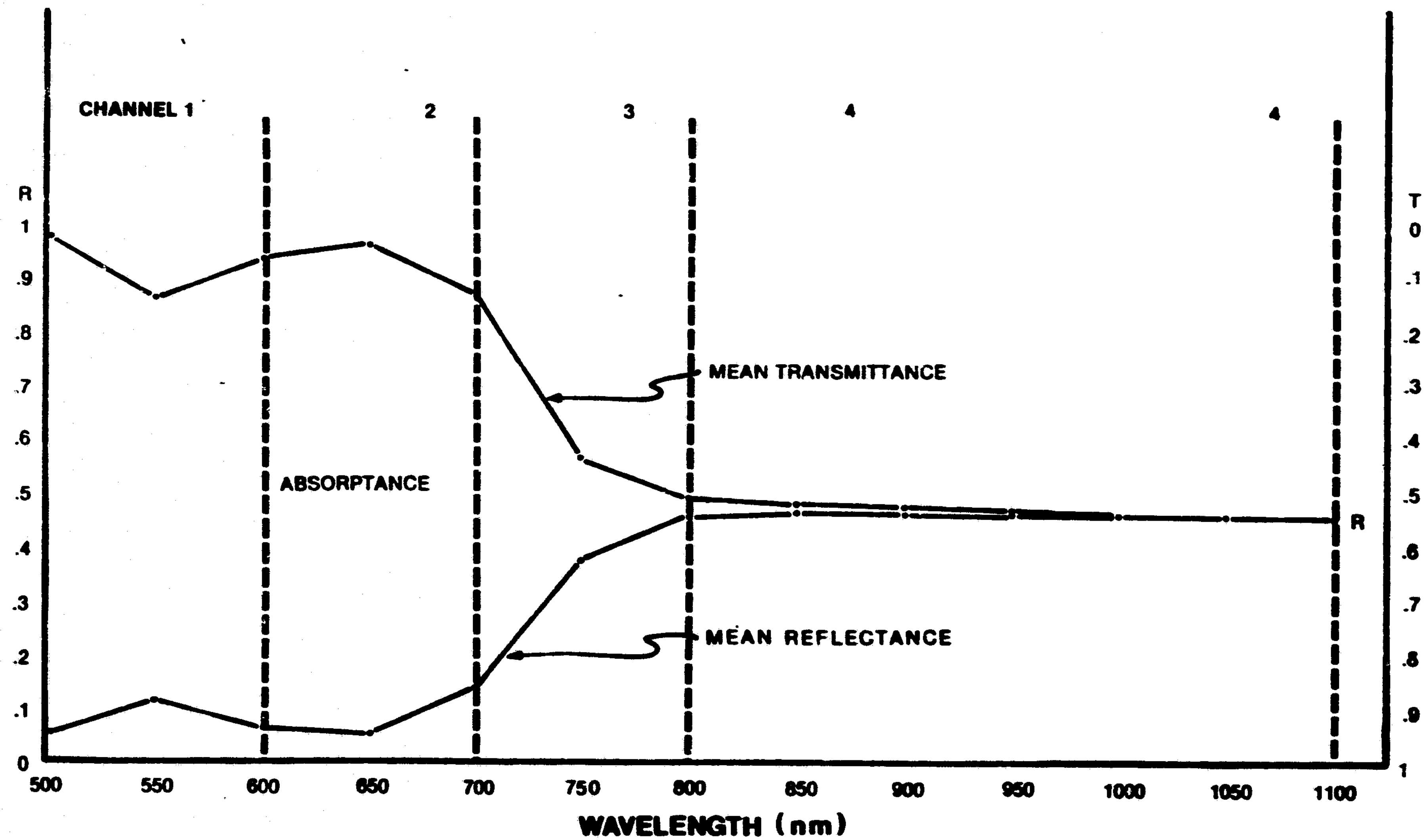
CHANNEL 1
2
3
4
4
R
1
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
T
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1
MEAN TRANSMITTANCE
ABSORPTANCE
MEAN REFLECTANCE
R
500
550
600
650
700
750
800
850
900
950
1000
1050
1100
WAVELENGTH (nm)

Figure 1

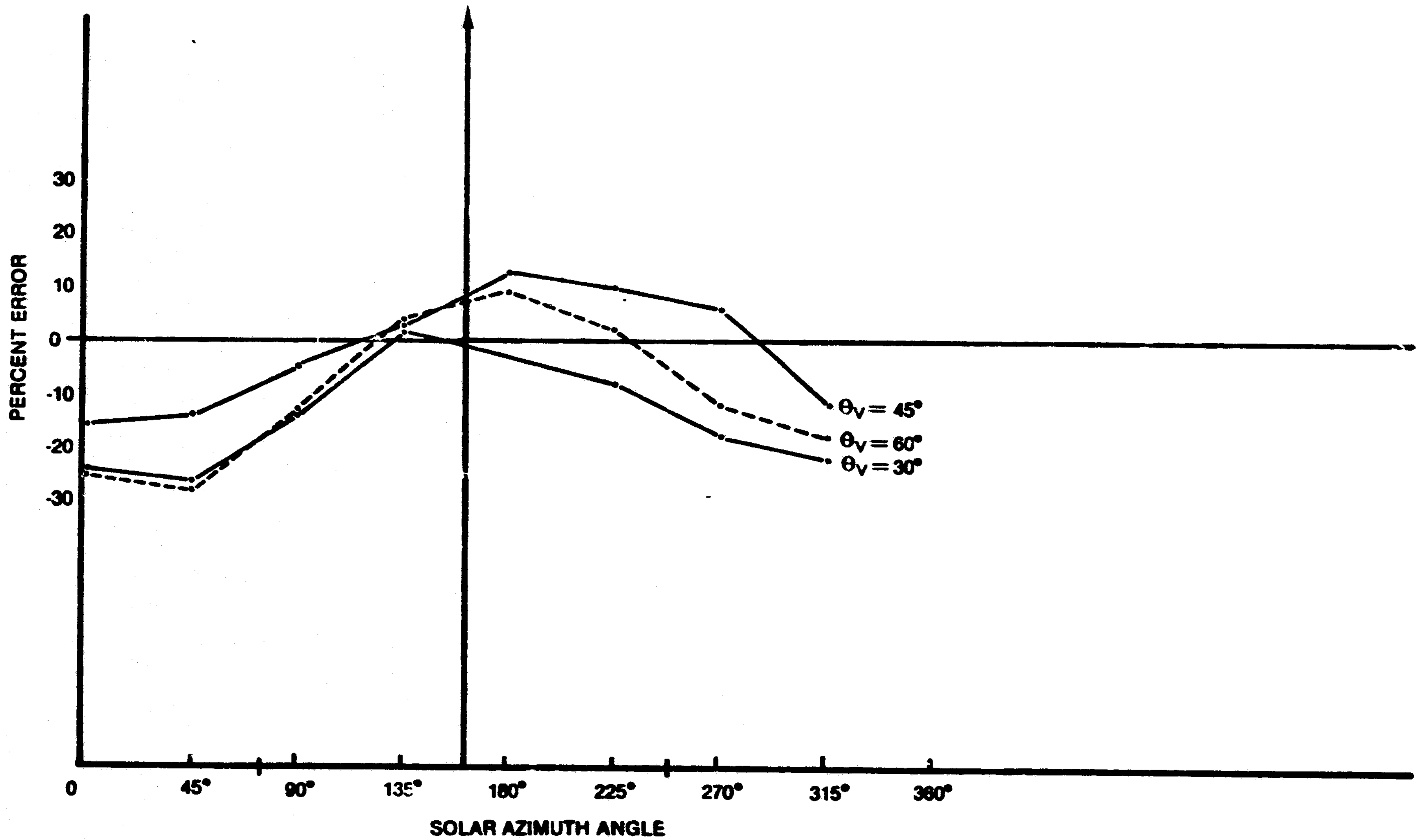
30
20
10
0
-10
-20
-30
PERCENT ERROR
$\theta_V = 45°$
$\theta_V = 60°$
$\theta_V = 30°$
0
45°
90°
135°
180°
225°
270°
315°
360°
SOLAR AZIMUTH ANGLE

Figure 2

ORIGINAL PAGE IS
OF POOR QUALITY

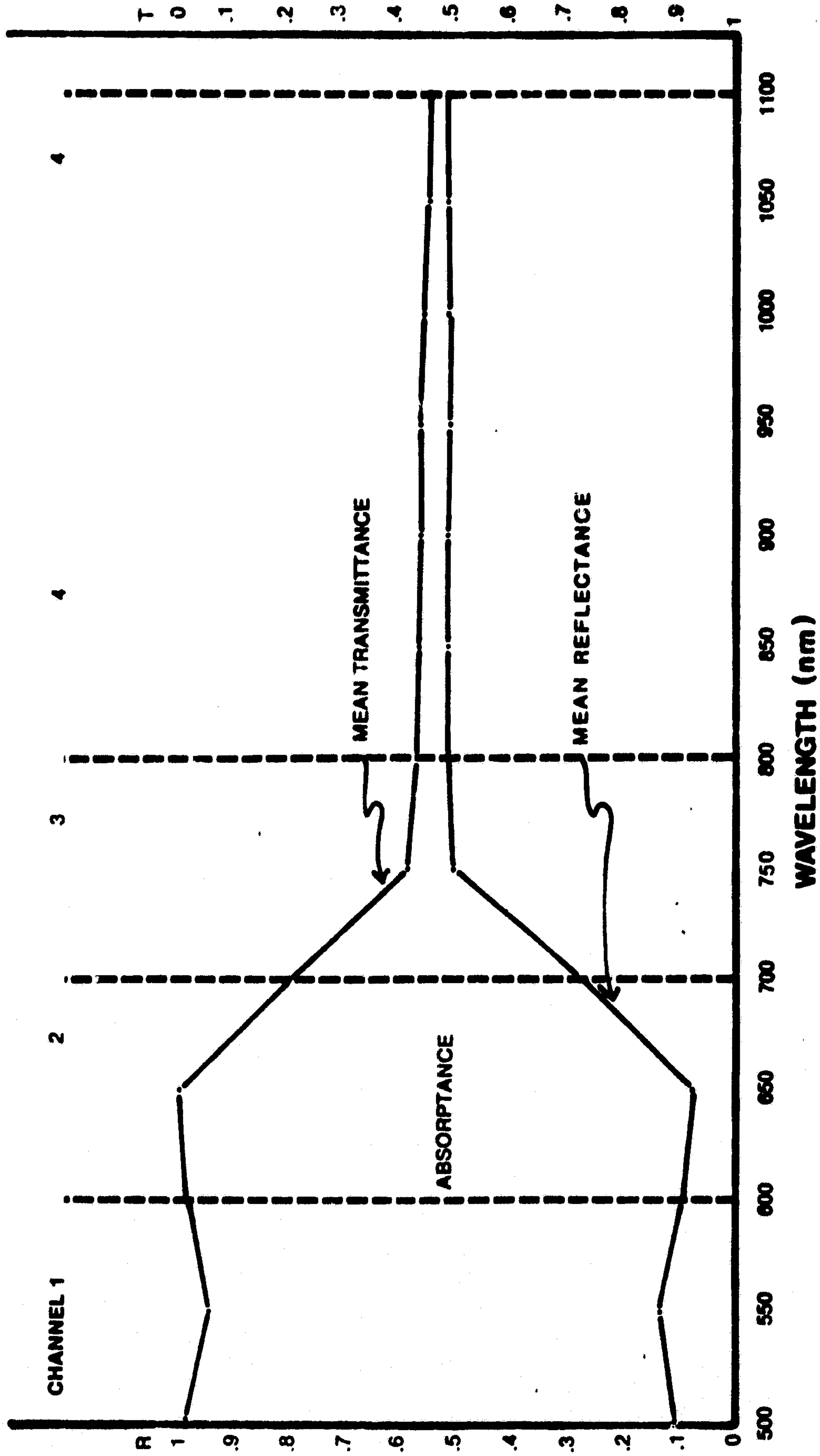

Figure 3