

FINAL TECHNICAL REPORT

AN EXPERIMENTAL TEST OF PLANT CANOPY REFLECTANCE MODELS ON COTTON

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ABSTRACT

Extensive data on the plant parameters necessary to evaluate any model are presented for a cotton crop. The variation of the bidirectional reflectance function with observer altitude, observer azimuth, and sun altitude angle is presented for a high density cotton crop having leaf area index of 19. A comparison with the quantitative behavior obtained from the Suits model is accomplished in the wavelength region from 400 nm to 1050 nm.

INTRODUCTION:

This initial project was undertaken at Pan American University in an effort to provide a needed comparison of some current mathematical models of vegetative canopies. The objectives of these models are to: (1) relate the observed changes in spectral reflectance to the causative factors, (2) establish a data base definition necessary to construct realistic models, (3) make predictions about such things as optimum conditions for discrimination, and (4) provide other workers in agricultural or remote sensing with usable models for building more complete models on photosynthesis, crop yield predictions, or satellite crop inventory.

The position taken in this study was to obtain complete data on the reflectance of cotton over a wide range of observer angles and sun angles, and also to gather sufficient plant structure data to enable others to use the data for their models. The atmosphere problem was neglected and data was taken only on clear to 5% cloudy days so that the incoming diffuse component of solar radiation could be neglected.

ORIGINAL OBJECTIVES:

1. Collect plant parameters for implementing model calculations of Suits¹, Smith² and Beeth³.
2. Collect field spectroradiometer data for the bidirectional reflectance function of cotton.
3. Implement model calculations for the mathematical models and compare them to the canopy field data.
4. Evaluate the features of the different models.

The objectives 1 and 2 were carried out successfully with the exception that Beeth's model has not been published at this time. The preprints of Beeth's paper indicate that the data collected for Smith's model are sufficiently detailed to implement the model of Beeth when it becomes available. Data were sent to both Smith and Suits in an effort to obtain model calculations in objective 3. The calculations based on our programming of Suits' model are compared qualitatively to our field data. We have Smith's program, but it requires much more computer time than is currently available.

The general features of the models are compared and experimental data are used to evaluate the model predictions. The general trends in the behavior of the bidirectional reflectance function as measured in the field are presented. Observer azimuth variation with other angles constant and exchange of observer and sun are discussed.

EXPERIMENTAL DETAILS

The radiance measurements as a function of wavelength were carried out using a wedge-filter type radiometer made by Instrumentation Specialties Company. The spectroradiometer was an Isco Model SR equipped with a 1.82m fiber optics probe for which we measured a 19° field of view. Absolute reflectance of the cotton was obtained by alternately measuring the radiation reflecting from a flat white panel, freshly spray painted with a white latex paint. The ratio of canopy radiance to panel radiance was calculated and multiplied by the true panel reflectance at that wavelength to give the absolute reflectance of the canopy. The panel reflectance was determined from plywood squares of the same wood painted with the same paint at the same time as the panel. A Beckman DK-2A was used at the USDA Agricultural Research Service (USDA, ARS) in Weslaco, Texas, using a standard MgO ratio method⁴, to find the absolute reflectance of our plywood squares.

The fiber optics probe was connected to a drafting-machine mechanism to allow it to be easily directed through azimuthal angles. The entire mechanism was mounted to the top of a demountable scaffolding placed in the cotton field such that it was 4.9m above the top of the cotton canopy. This gives a field of view of slightly more than 1.59m in diameter looking perpendicular to the canopy.

The canopy was double planted SP-37 cotton having rows separated 0.20m planted 0.81m apart such that there were 88,000 per acre. The average ground area for a single plant was $4.60 \times 10^{-2} \text{m}^2$. The areas of single leaves were measured on an optical planimeter made by Kyokuto Boeki Kaisha Ltd. of Japan for Far East Mercantile Co. Ltd., Model AAM-5. Five "typical" plants were stripped in 0.20m layers with leaf angle,

leaf azimuth and leaf area measured on each leaf. Fig. 1 shows results of these measurements averaged for whole plants. Histograms, Fig. 2 and Fig. 3, show the leaf densities and leaf angles in individual layers averaged over all 5 plants. The plants were stripped from 3 hours before to 3 hours after solar noon during the same time period reflectance was being measured for the canopy. The azimuthal distribution of leaves around the main stalk of the plants is shown in Fig. 4. The soil reflectance did not greatly affect canopy reflectance because of the very large LAI, but it is included for the sake of completeness in Fig. 5. The canopy showed no row structure and for purposes of model verification, i.e., homogeneity and uniformity, the high density cotton was an ideal field. Most agricultural crops have LAI's of 2-6 or less, so our data is not representative of common crops; however, it is useful as an extreme case of a crop that shows no row structure and has sufficient density that there is little soil contribution to the reflectance.

It is important to note here that the single leaf data were only available in 50 nm increments and so the analog record of the spectroradiometer was digitized in 50 nm increments. The chlorophyll absorption at 687 nm and the water absorption at 970 nm are observed in the adjacent data points. One can hardly look at several analog records without noticing the fine structure apparent on the record. This fine structure probably contains much information that isn't being utilized in a discrete digitization of data such as was performed here.

PLANT PARAMETERS

88,000 plants/acre

459.9 Cm²= Area of base of plant=(A_b)

Plant No.	No. Leaves (N)	Height (h) (Cm ²)	Total Leaf Area (Cm ²)	Single Leaf Area	LAI	N
				σ (Cm ²)		
				$\frac{\text{Total Leaf Area}}{N}$	$\frac{LAI}{h \cdot \sigma}$	
1	101	166	11665	115.5	25.4	1.32×10^{-3}
2	64	160	7199	112.5	15.7	0.87×10^{-3}
3	101	156	10562	104.6	23.0	1.4×10^{-3}
4	71	160	8050	113.4	17.5	0.94×10^{-3}
5	82	190	7420	90.5	16.1	0.94×10^{-3}
A V E R A G E	83.8	166	8979	107.3	19.5	1.102×10^{-3}

Figure 1. Some representative data from field cotton plants that were stripped. Considerably more data was taken (i.e. leaf azimuth and slope angle) which is not shown here.

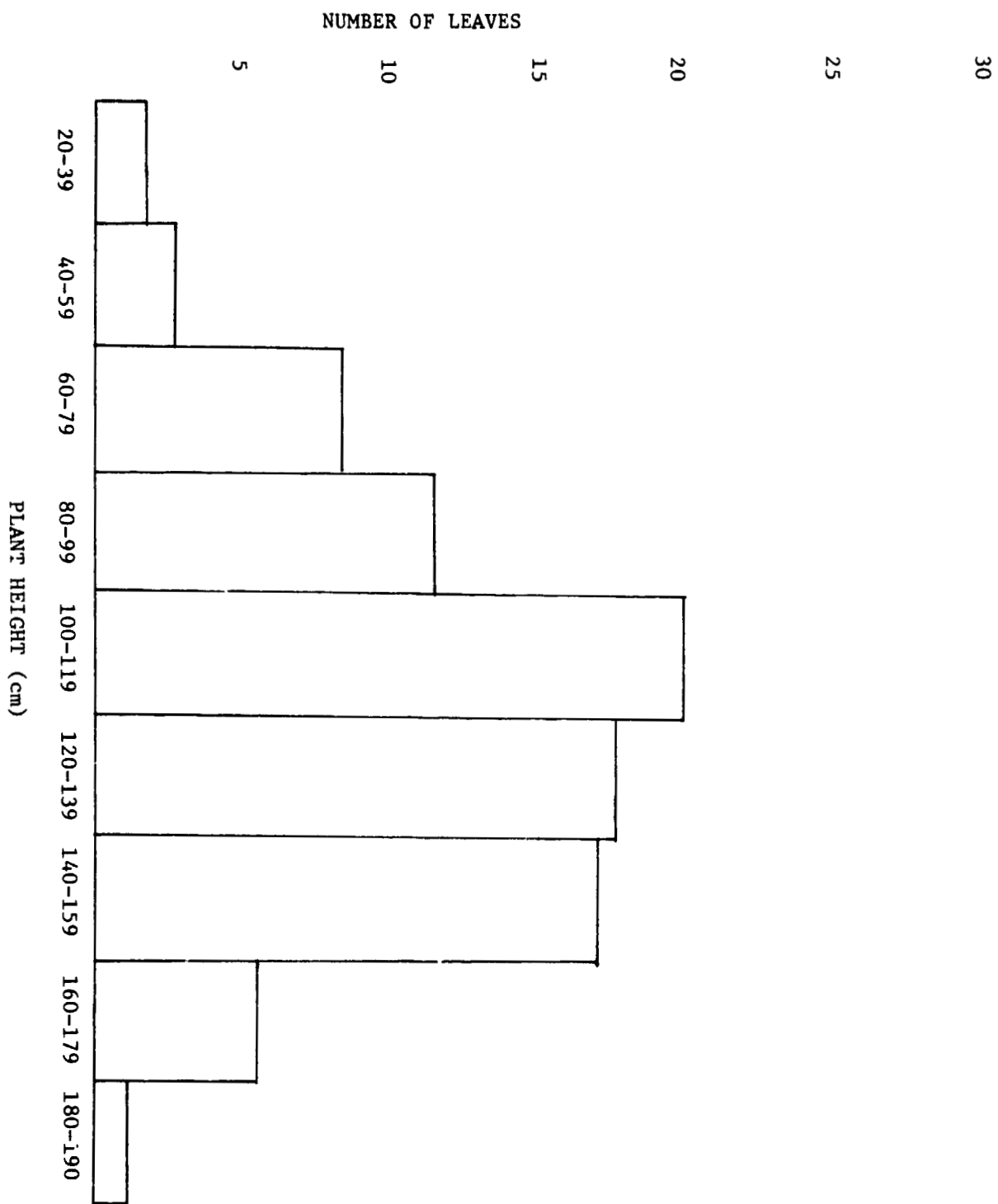


FIGURE 2. LEAF DENSITY AS A FUNCTION OF THE PLANT HEIGHT. The concentration of leaves on the top of the plants indicates that lower leaves were being sloughed as they were deprived of sunlight.

Number of Leaves vs. Leaf Slope

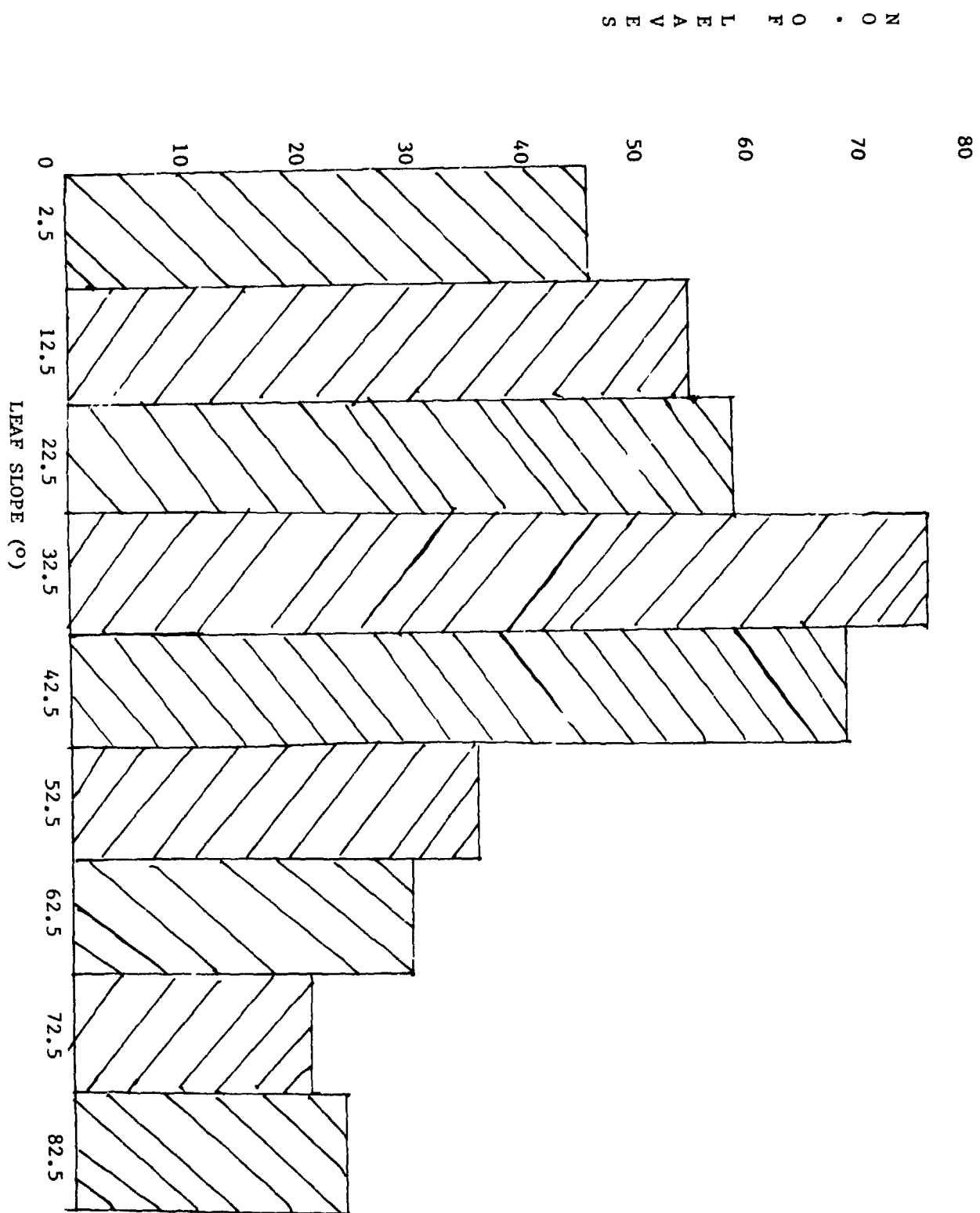


Figure 3. Leaf slope angles averaged over 5 plants.

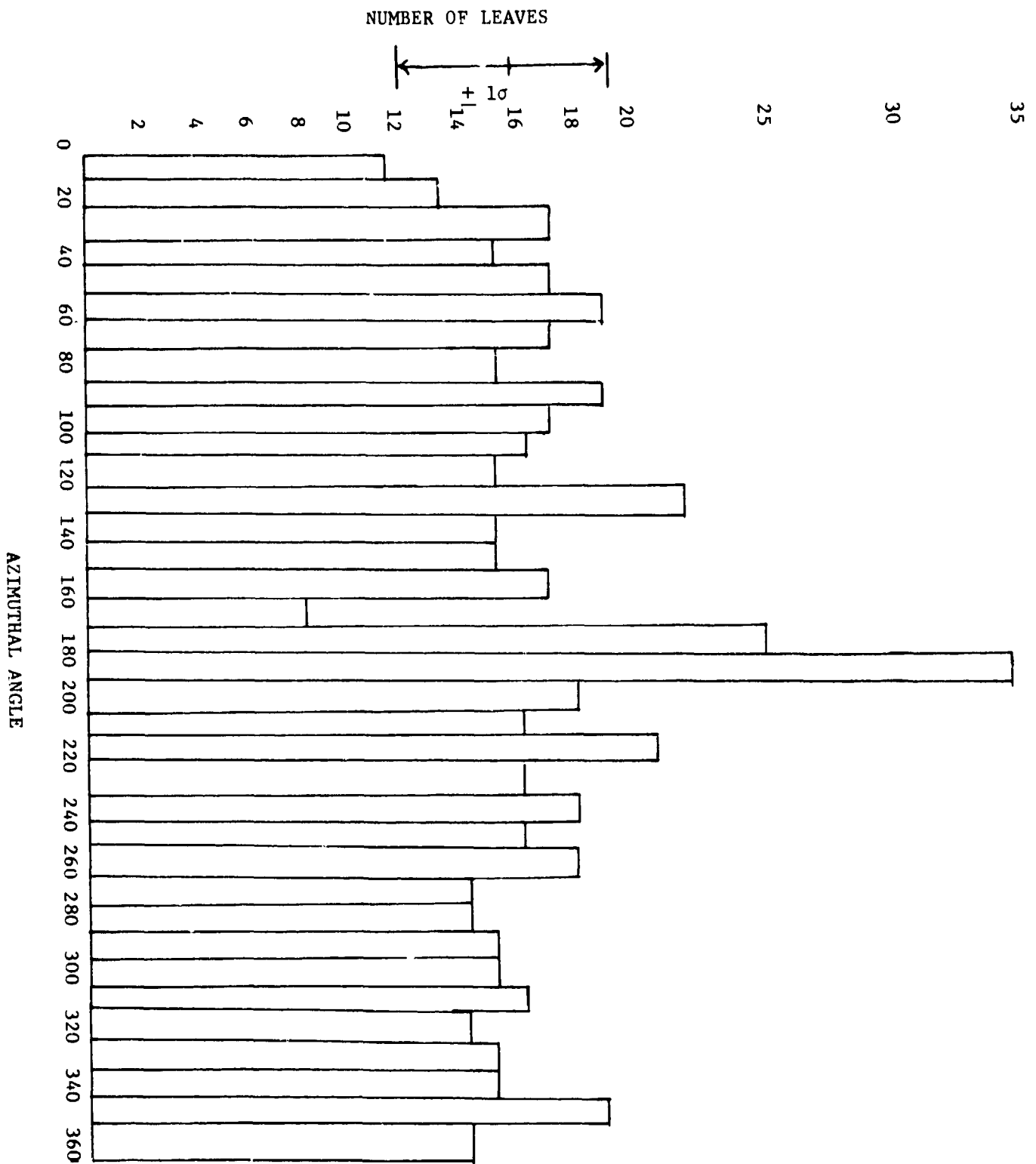


FIGURE 4. The azimuthal distribution of leaves around the main stalk of the plants.

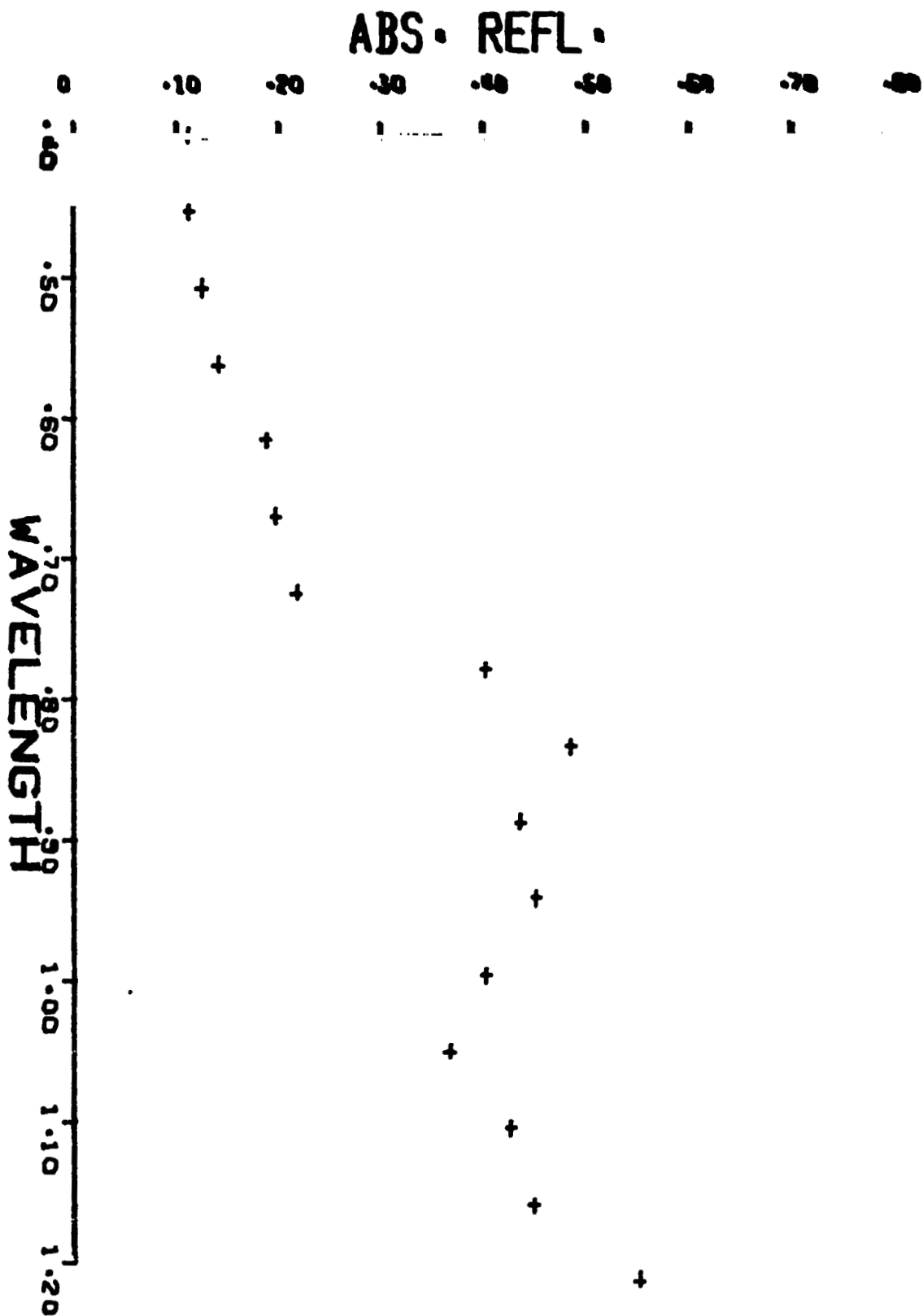


FIGURE 5. Absolute reflectance of dry clay soil located in cotton field at USDA, ARS Experimental Farm, measured during August, 1973.

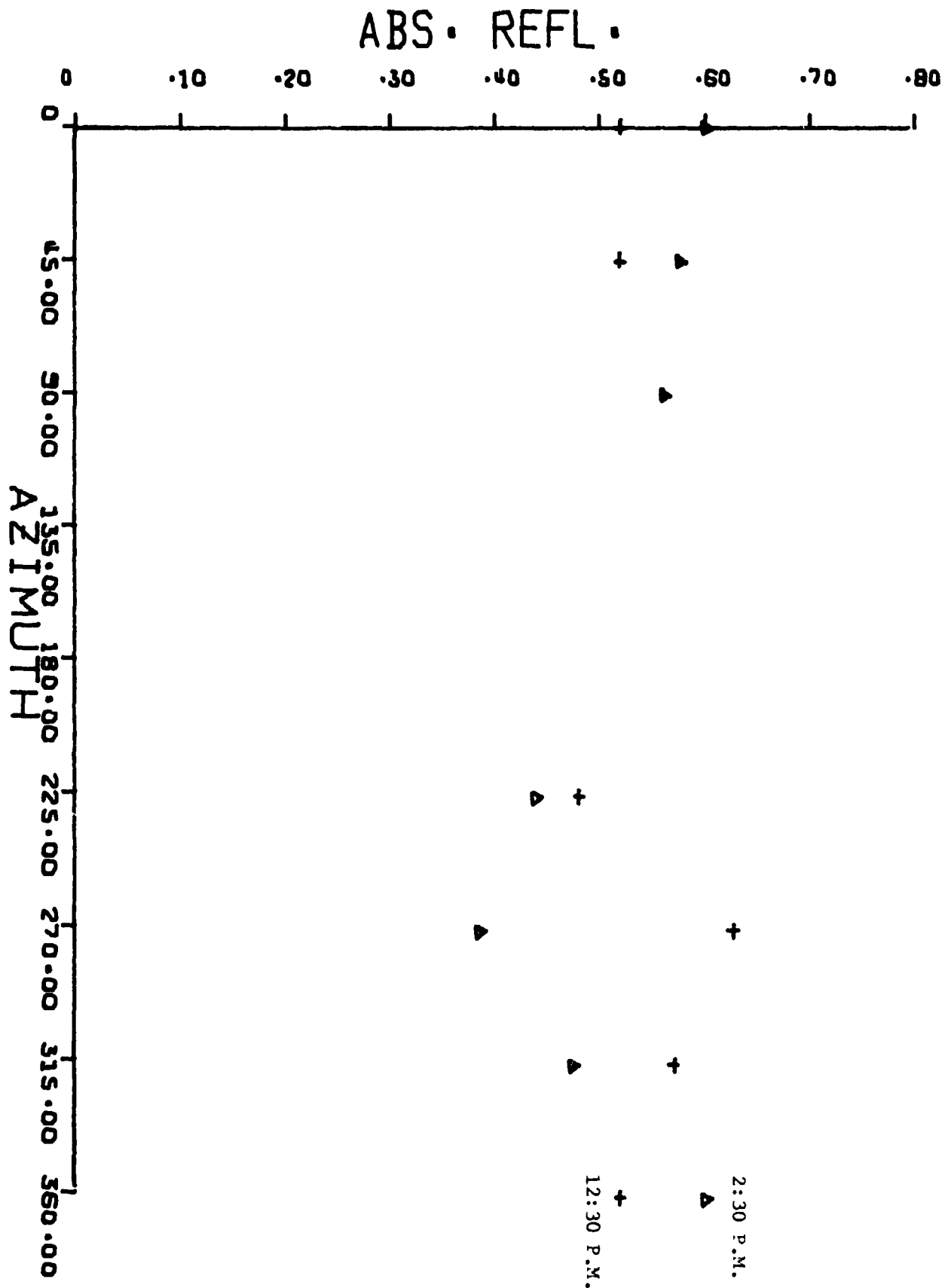


Fig. 6. The dependence of the reflectance on azimuthal variation is demonstrated at 850 nm for two readings. The observer angle for both readings is 30° ; the time at which the readings were taken are indicated on the graph.

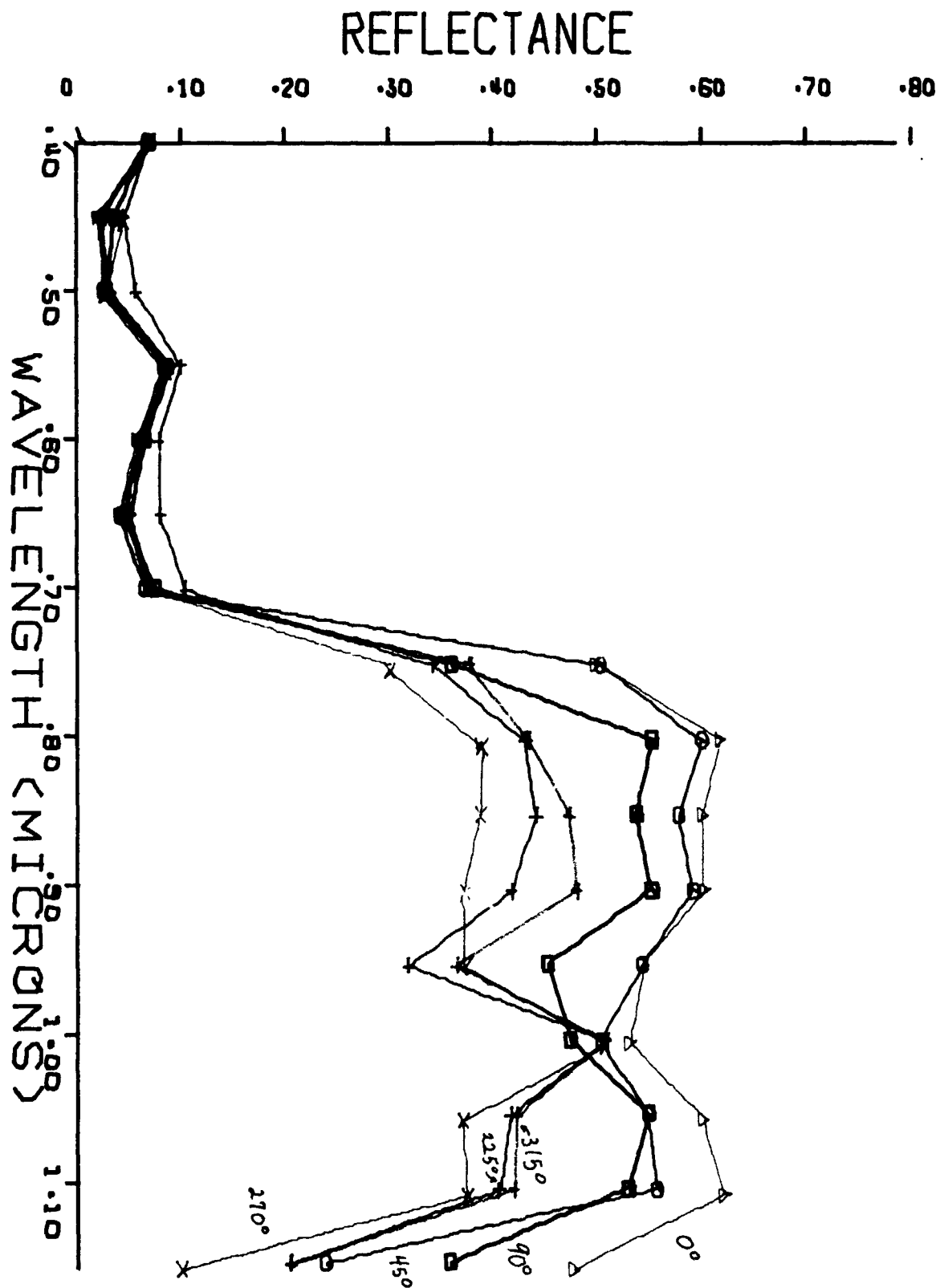


FIGURE 7. The azimuthal variation of the absolute reflectance of cotton with an observer look angle of 30° from the perpendicular and a sun angle of 15° past zenith. Azimuth is measured from a magnetic compass.

RESULTS OF FIELD SPECTRORADIOMETER MEASUREMENTS

A. OBSERVER AZIMUTH

The azimuthal variations in the reflectance is shown in Fig. 6 for two cases. The latitude was $25\frac{1}{2}^{\circ}$ so that the sun was about 4° from zenith at local solar noon. The curves indicate a minimum when the observer is looking at the crop facing the sun. The minimum is almost nonexistent in the visible. The complete spectra scans are shown in Fig. 7, so that the trends at other wavelengths can be seen. The curves in Fig. 6 are for different general orientations of the sun, i.e., both before and after solar noon. The detailed shapes of the curves are probably related to the fact that a strong heliotropism is observed in cotton. During the time the field studies were being made, time-lapse photographic records were made to give qualitative evidence of heliotropic response of cotton. The films indicate a tremendous amount of movement in the plants due to heliotropic response and effects of the wind. The general change in orientation of the leaves during windy days would perhaps cause the bidirectional reflectance function to show different behavior from that found on calm days. On a very windy day the spectroradiometer was set at a fixed wavelength to see if leaf flutter caused fluctuations in radiometer readings. There was not more than 2% fluctuation due to any wind effects and/or instrument instabilities. The effects of windy compared to calm conditions were not investigated.

On the studies of azimuthal variations the reflectance panel readings were made before and after each series of seven measurements on the canopy. In the worst case a canopy reading would be 20 minutes from a standard reflectance panel reading. This effect alone can cause up to 10% variation in an absolute reflectance value and probably

accounts for much of the variation observed in the azimuthal data.

B. OBSERVER ALTITUDE ANGLE

The dependence of reflectance on observer look angle is shown in Fig. 8. The observer azimuth in these plots was either north or north-east. The data indicate a definite increase in reflectance with observer look angle increase at 850 nm. The behavior persists in the visible part of the spectrum as seen in Fig. 9.

C. SUN ALTITUDE ANGLE

The reflectance viewed by an observer looking normal to the crop surface will decrease as the sun altitude angle increases. This data is shown in Fig. 10 and Fig. 11. The negative angles are for the hours before solar noon.

The behavior of the reflectance with changing azimuth appears to be quite large in the infrared portion of the spectrum. By comparison, the variation in the reflectance with sun angle is much less in the IR and much greater in the visible.

D. EXCHANGE SYMMETRY

The practice of assuming a symmetry with respect to interchange of sun and observer positions was questioned in this study.

The data presented in Fig. 12 indicate that this practice is questionable. Error bars indicate the average deviations due to time lags effects in reflectance panel measurements made before and after canopy measurements. The values are probably pessimistic.

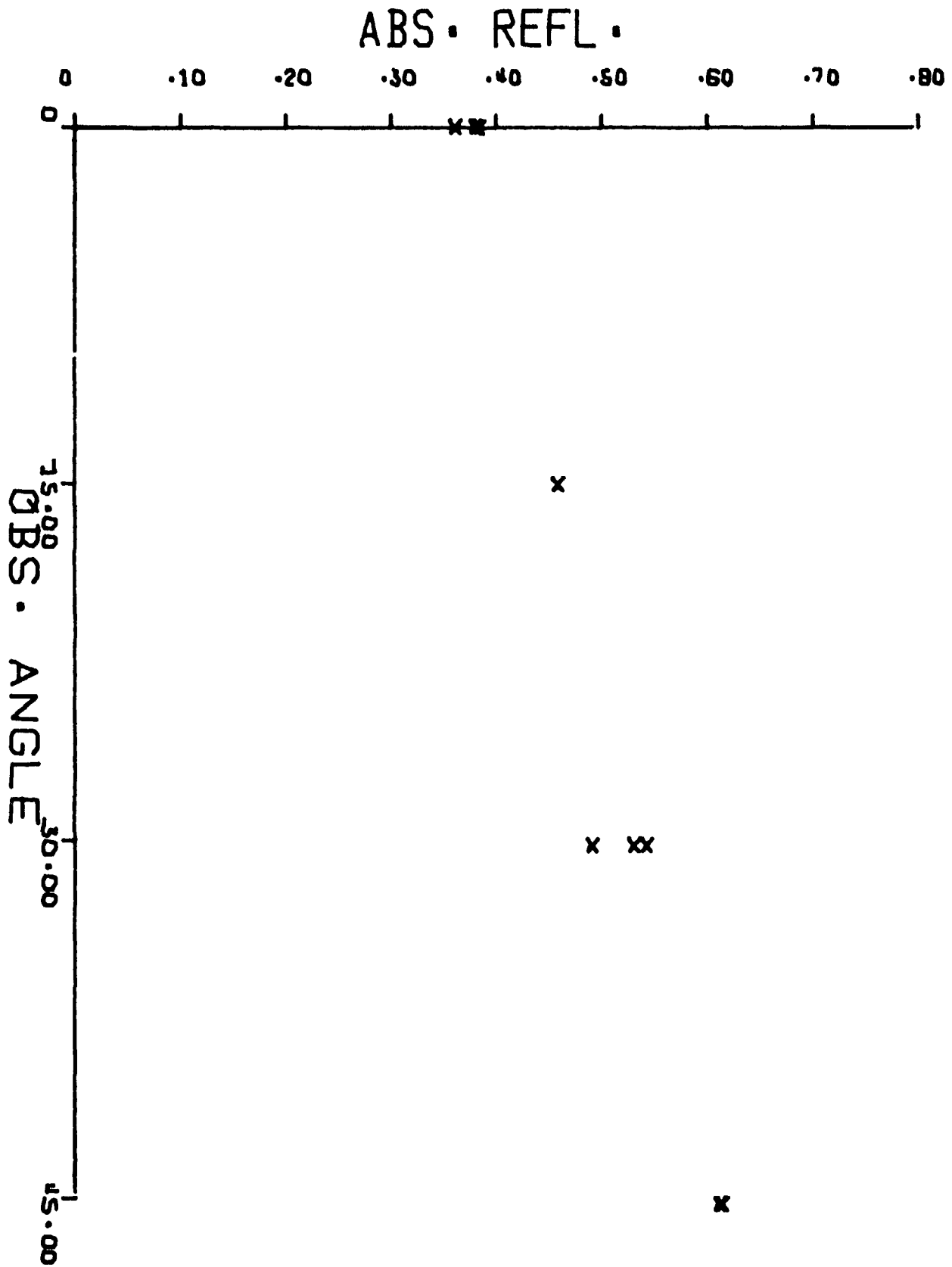


Fig. 8. The dependence of the reflectance on observer angle (from zenith) is illustrated at 850 nm. The reflectance values were obtained at varying times and azimuthal angles on three different days.

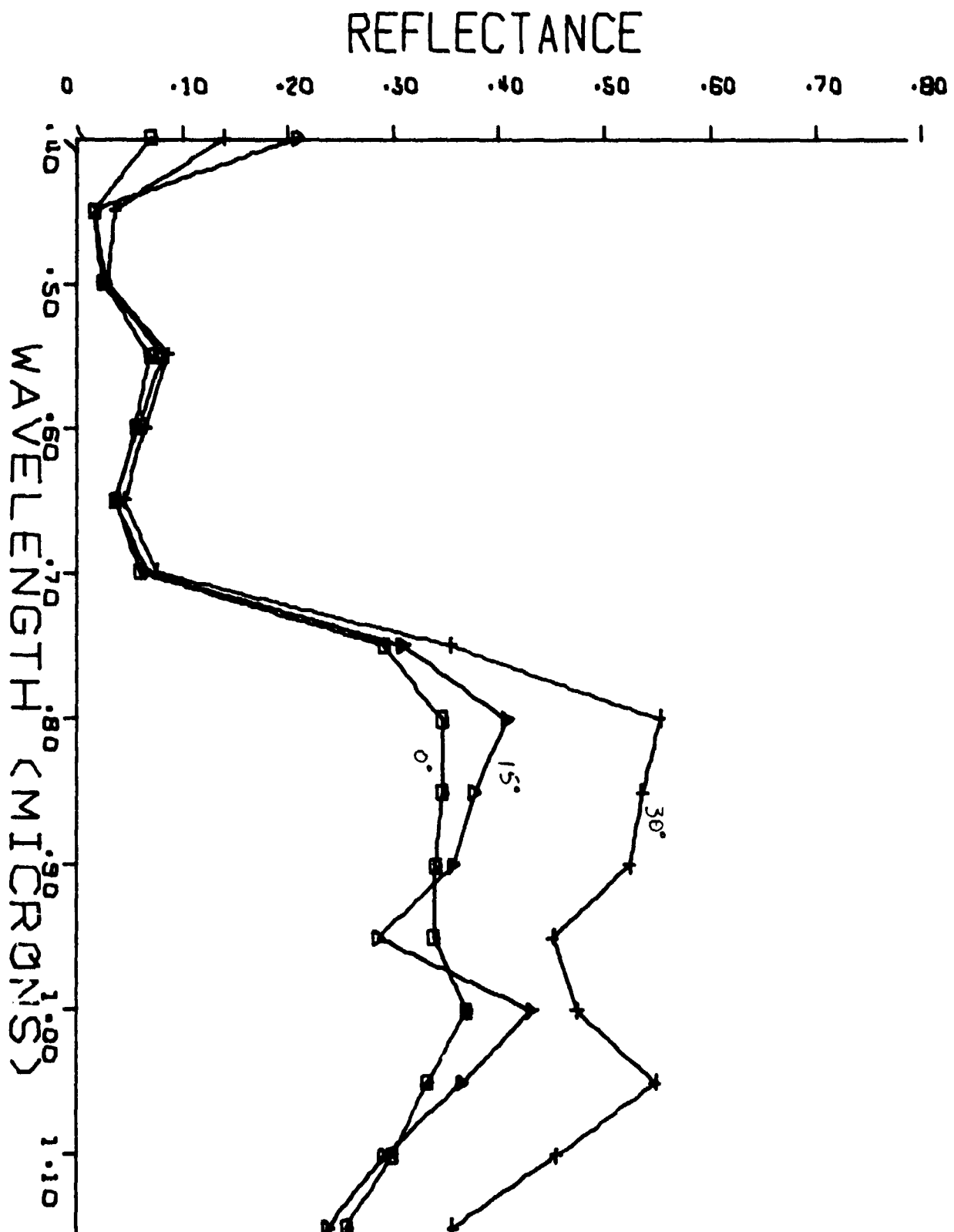


FIGURE 9. Variable observer altitude angle with constant sun angle of 15° and constant observer azimuth of 90°.

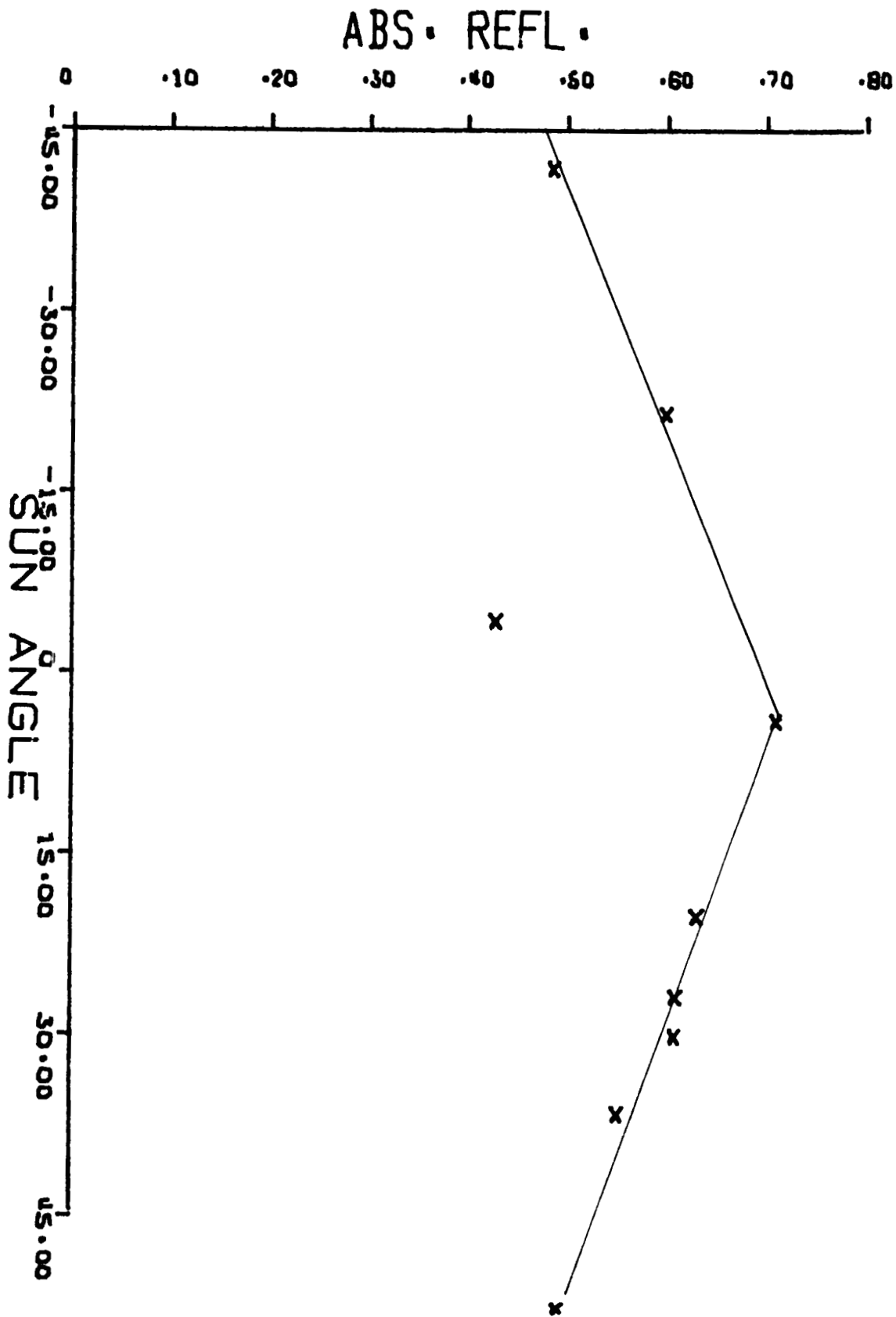


FIGURE 10. The dependence of the reflectance on sun angle is shown at 850 nm. The spurious point may have been caused by an unobserved cloud during the canopy measurement.

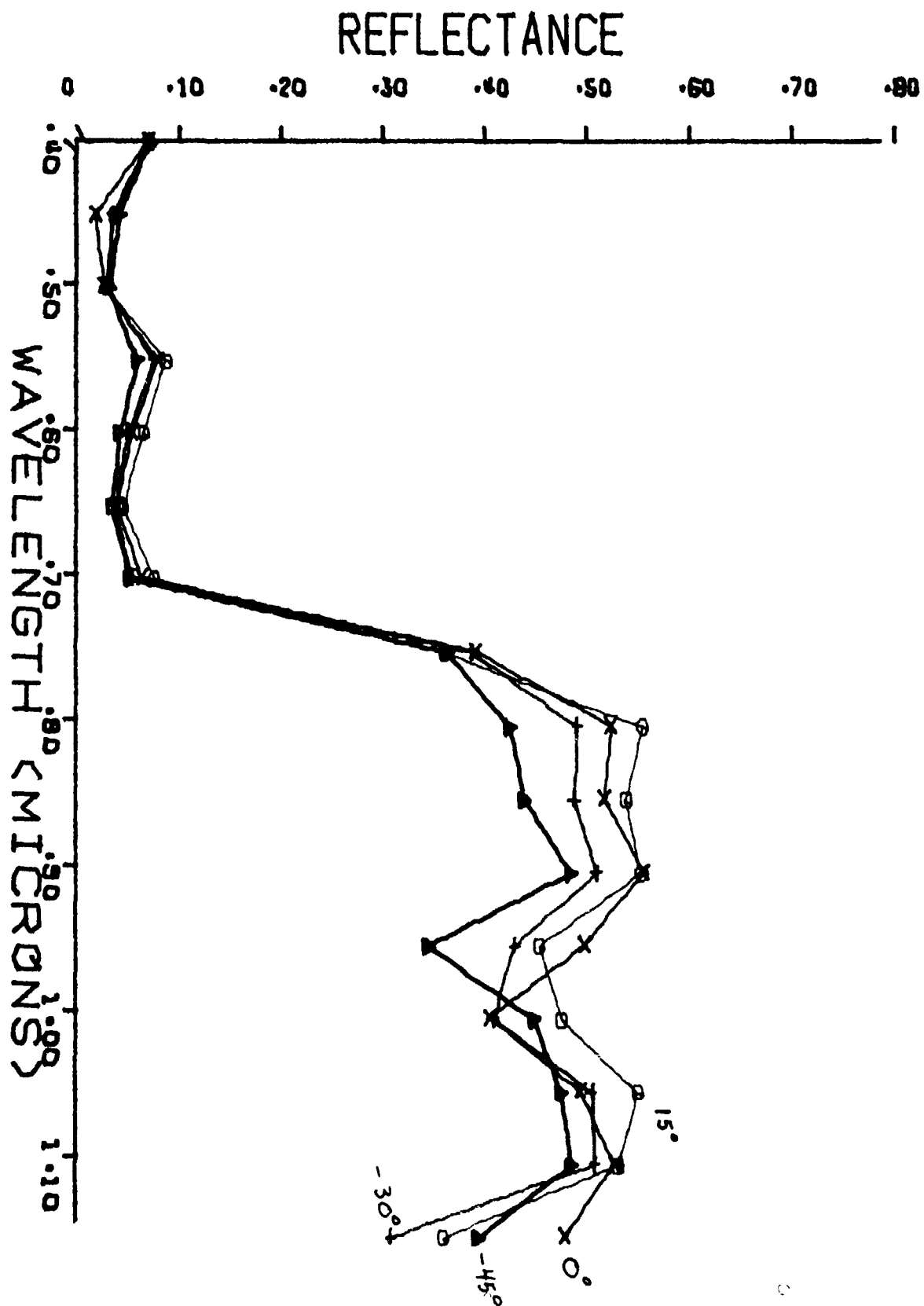


FIGURE 11. The reflectance with variable sun angle with observer angle fixed at 30° and azimuth 90° (looking east). The sun angle is indicated by each curve.

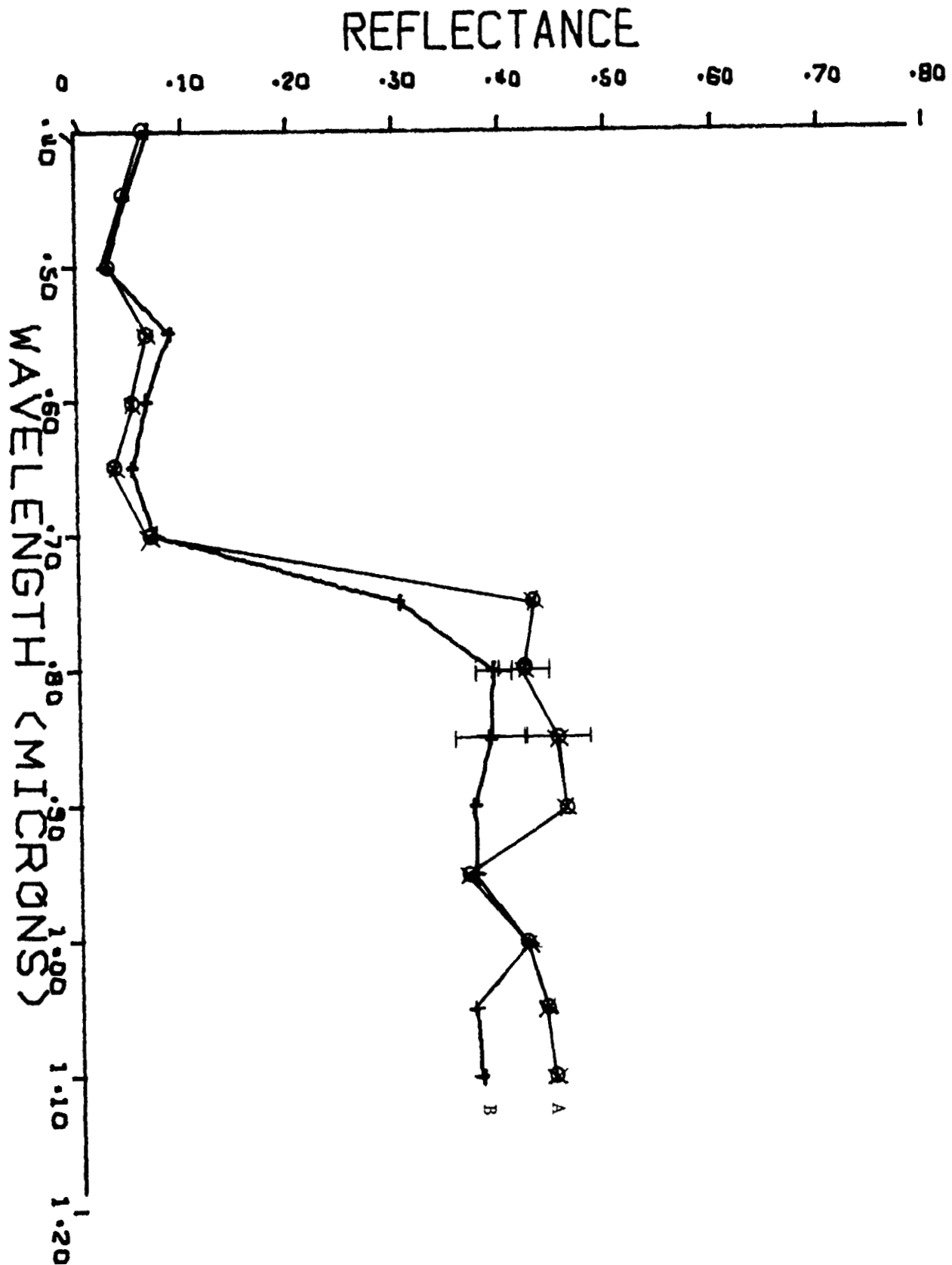


Figure 12. Interchange of sun and observer position. For plot (A) the sun angle was -30° and the observer angle was 15° . For plot (B) the sun angle was 15° and the observer angle was 30° .

MODEL CALCULATIONS:

The AGR equations presented in the paper by Sui+s¹ were programmed. These equations do not include the azimuthal contribution which was later added.²

As in the AGR model, the radiant flux that interacts with the canopy is divided into two kinds, specular and diffuse. The specular flux is that flux which arrives from a part of the sky or the sun and flows into the canopy in a straight line without interception by any canopy component or the soil. The diffuse flux is that flux which has been intercepted at least once. As specular flux enters the canopy and is intercepted by a component, the flux leaves the specular category permanently. It is either absorbed or contributes to the diffuse flux of the canopy.

In the following calculations the spectral flux density is symbolized by E_{λ} (s) for specular flow and E_{λ} (d) for diffuse flow. The diffuse flux density is again divided into upward and downward flow and is symbolized by E_{λ} (+d) and E_{λ} (-d) respectively. Since the canopy consists of different layers each with its own properties, the specification of the layer must be included in the nomenclature. Thus, for instance, E_{λ} (+d, i, x) represents the upward directed flux in the ith layer at level, x.

The calculation to determine E_{λ} (+d, i, x) in each layer is the same as in the AGR layer model using the equations

$$\frac{dE (+d, i, x)}{dx} = -a_i E_{\lambda} (+d, i, x) + b_i E_{\lambda} (-d, i, x) + c_i E_{\lambda} (s, i, x) \quad (1)$$

$$\frac{dE (-d, i, x)}{dx} = +a_i E_{\lambda} (+d, i, x) - b_i E_{\lambda} (-d, i, x) - c_i E_{\lambda} (s, i, x) \quad (2)$$

$$\frac{dE (s, i, x)}{dx} = +k_i E_{\lambda} (s, i, x) \quad (3)$$

The constants a_i , b_i , c_i , c'_i , and k_i are derived from measurements of canopy components of the i^{th} layer. If only one type of component occupies the i^{th} layer, then

$$a_i = \left[\sigma_h n_h (1 - \tau) + \sigma_v n_v \left(1 - \frac{\rho + \tau}{2}\right) \right], \quad (4)$$

$$b_i = \left[\sigma_h n_h \rho + \sigma_v n_v \frac{\rho + \tau}{2} \right], \quad (5)$$

$$c_i = \left[\sigma_h n_h \rho + \frac{2}{\pi} \sigma_v n_v \frac{\rho + \tau}{2} \tan \theta \right], \quad (6)$$

$$c'_i = \left[\sigma_h n_h + \frac{2}{\pi} \sigma_v n_v \frac{\rho + \tau}{2} \tan \theta \right], \quad (7)$$

and

$$k_i = \left[\sigma_h n_h + \frac{2}{\pi} \sigma_v n_v \tan \theta \right]. \quad (8)$$

where σ_h is the average area of the projection of the canopy component on a horizontal plane,

σ_v is the average area of the projection of the canopy component on two orthogonal vertical planes,

n_h is the number of horizontal projections per unit volume,

n_v is the number of vertical projections per unit volume.

The angle, θ , is the polar angle for incident specular flux.

The spectral transmittance, τ , and the spectral reflectance, ρ , are the hemispherical reflectance values obtained from measurements of component samples in the laboratory. The factor $(2/\pi)$ associated with the tangent of the specular angle in equations (6), (7), and (8) is the average value of the cosine of the azimuthal angle. The vertical projection is averaged for random, azimuthal orientations.

For values of the canopy parameters used in our study, there were problems encountered using the solution to Suits' equations. There is a term in the solution of both the upward and the downward diffuse flux that is exponentially increasing downward from the top of the canopy. This overwhelms other terms in the solution for leaf area index values greater than 2 or 3. Suits mentions in his original paper (Ref. 1) that the infinite case can be evaluated by taking certain coefficients to be zero. These are the coefficients of the terms that increase exponentially. It is not clear how one decides exactly when to go to the infinite case. The AGR⁶ model from which Suits' work originated shows the same behavior and for canopies having appreciable LAI's an "infinite case" solution must be used.

The σ_h and σ_v , horizontal and vertical component areas for the leaves, were originally found by photographing the leaves vertically with a background of a horizontal grid and likewise with the vertical orthogonal projections. The pictures were then printed using the same grid to insure proper scale and the prints were run through the same optical planimeter used for leaf area measurements. It was found that for a broad leaf such as cotton, this photographic procedure was not necessary. For the 18 leaves photographed the slope angles and areas were recorded. The σ_h and σ_v could then be calculated from the area of the individual leaf times the cosine and sine of the slope angle, respectively. The average for the leaves compared within 2% to the photographic method. Typical values found were $\sigma_h = 85.5 \text{ cm}^2$ and $\sigma_v = 58.6 \text{ cm}^2$ and average slope angle 34° .

The results of the Suits model calculations for a crop having an LAI value of 2 are shown in Figures 13 and 14. These results compare

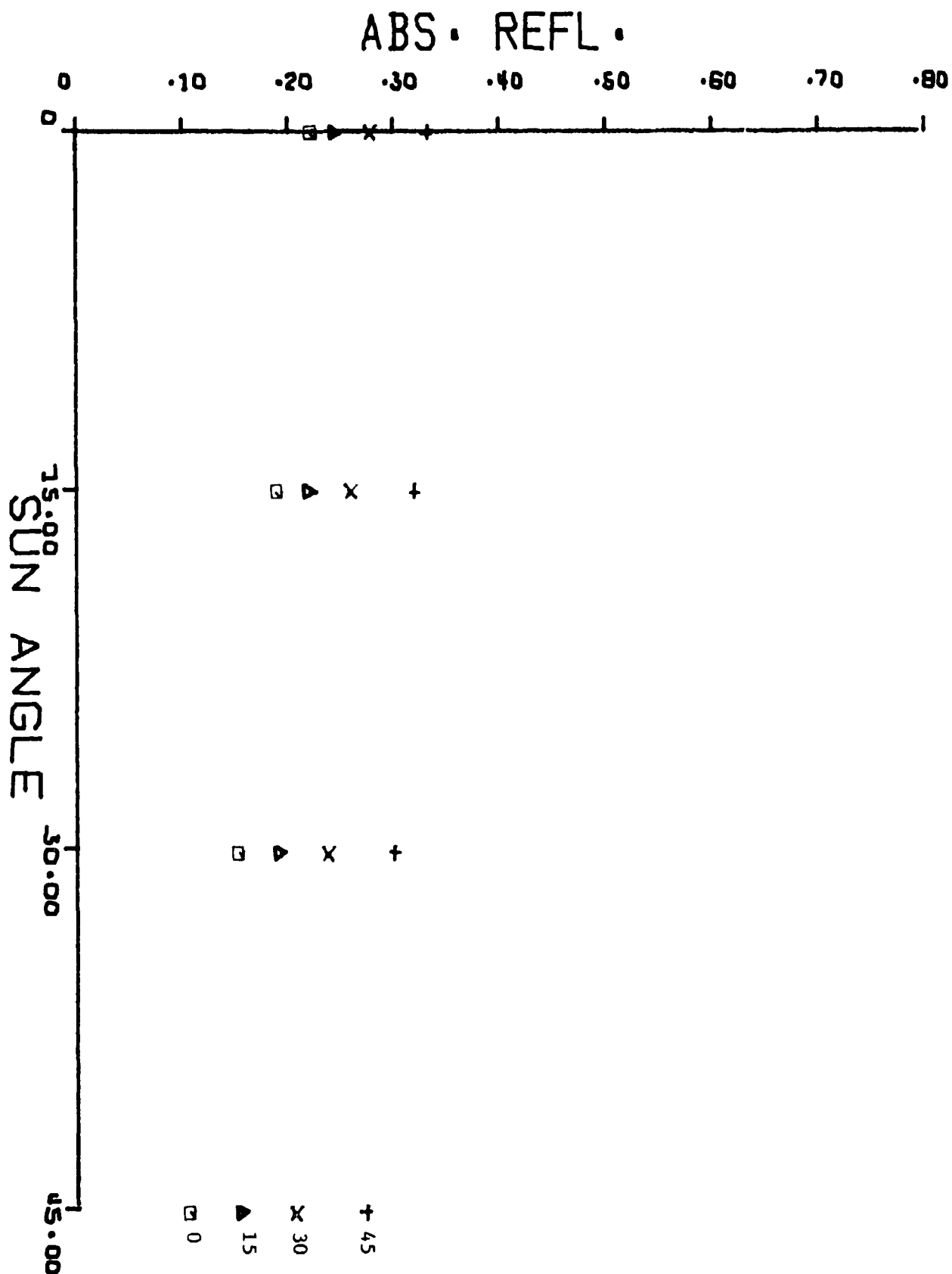


Fig. 13. Dr. G. Suits' canopy model predictions of the dependence of reflectance on sun angle at 850 nm for four different observer angles. The different observer angles for the readings are indicated on the graph.

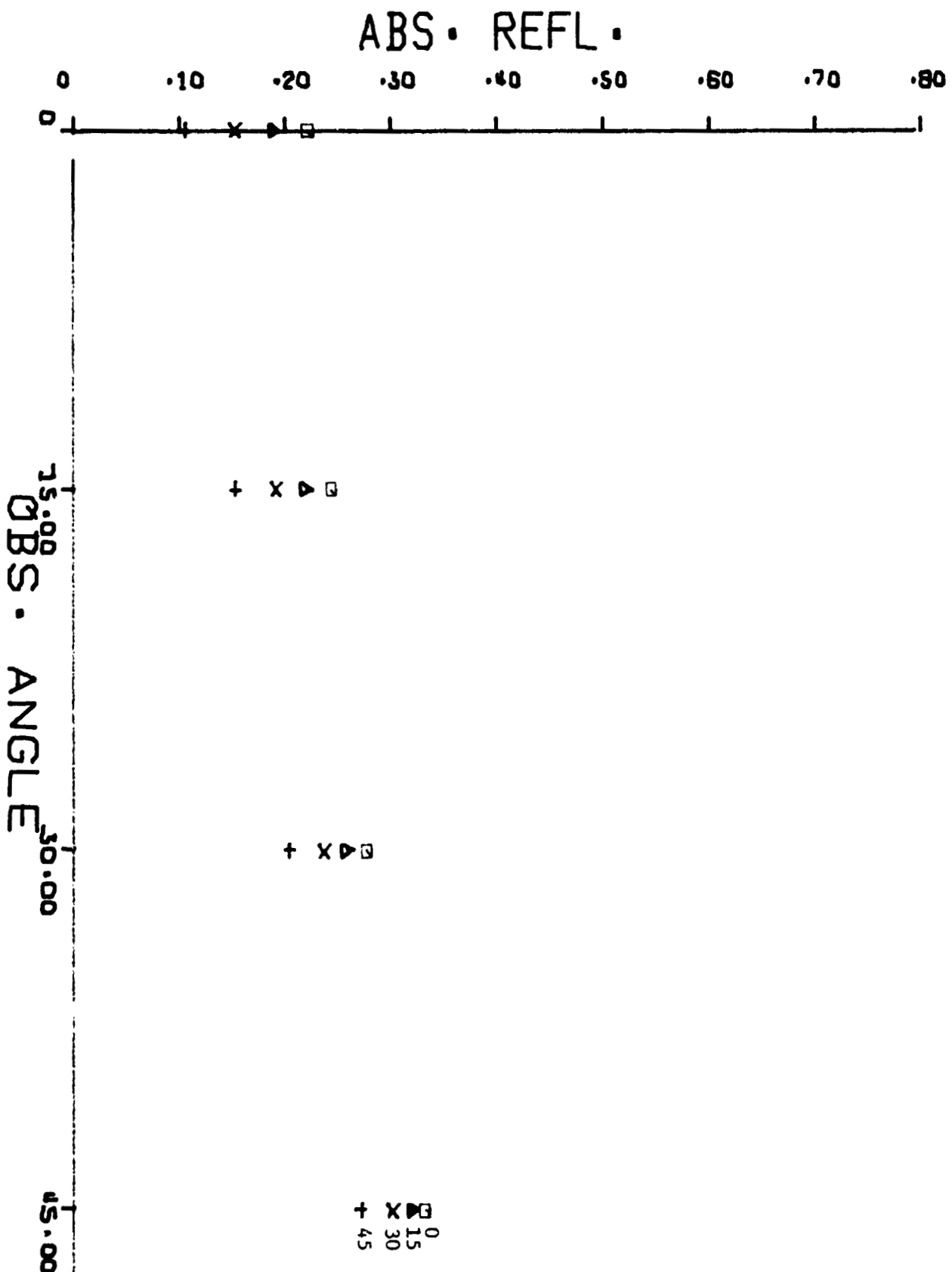


Fig. 14. Dr. G. Suits' canopy model predictions of the dependence of reflectance on observer angle at 850 nm for four different sun angles. The different sun angles for the readings are indicated on the graph.

qualitatively with that observed in the cotton crop. (See Figures 8 and 10.) Note that since there is no azimuthal angle being considered, the data in Figure 13 is symmetric about solar noon. On the observer angle, the effects of any "hot spot" have not been considered.

DISCUSSION:

Our data generally show the trends in observer angle and sun angle in qualitative agreement with Suits model. Quantitative comparison was not possible because of the finding that Suits' published model is suitable only for plants having a LAI of not more than about 2. It appears an "infinite case" solution needs to be wedded to the present solution.

The Smith model needs to have some simplifying work done on it so that it does not require enormous amounts of computer time.

The specific data on angular dependence of the bidirectional function needs to have experimental work done to reduce the errors to a level that specific angular dependence can be determined for the angles concerned. It is clear that without the specific knowledge of how physical parameters effect the bidirectional reflectance function, one can hardly use remote sensing to the extent of its capabilities. A recent paper of Malila, et. al⁶, shows that if a flight line is repeated every 10 minutes, within two hours the recognition reduces from over 90% to 0%.

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