SPECIES AND CULTIVAR DISCRIMINATION OF CEREALS BY FIELD SPECTROSCOPY

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Harvey L. Glick

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HARVEY LEONARD GLICK

A dissertation submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements of the degree of

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Very often, with research projects of this nature, there are a number of people whose names do not appear on the final manuscript, but who were instrumental in the completion of the project. I would now like to express my gratitude.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF TABLES (continued)

ABSTRACT

Glick, Harvey L. M.Sc., The University of Manitoba, September 1979. Species and Cultivar Discrimination of Cereals by Field Spectroscopy. Major Professor: K. W. Clark

Oblique measurements of spectral reflectance (350 nm - 750 nm) were made from plant canopies of wheat (cv. Sinton, Neepawa), barley (cv. Bonanza, Klondike) and oats (cv. Harmon, Hudson) in a replicated field experiment conducted in 1977. Comparisons of reflectance were made between species and cultivars to determine if it is possible to discriminate between closely related species and cultivars and to determine the optimum combinations of wavelength and stage of growth that maximize the potential for discrimination.

Seasonal changes in reflectance from wheat and barley were inversely related to changes in the concentration of chlorophyll in the leaves. Discrimination between wheat and barley was possible at tillering and at anthesis in the 600 nm - 700 nm waveband. Discrimination between wheat and oats and between barley and oats was not possible until anthesis, although discrimination was possible at almost all wavelengths.

Comparisons of reflectance from cultivars within a species indicated that a potential exists for discriminating between cultivars by remote spectral measurements.

INTRODUCTION

A long time goal of scientists within the cereal industry has been to accurately monitor grain production on a regional and national scale. Since the advent of the National Aeronautics and Space Administration's (NASA) resource satellite program, remote sensing techniques have been used in crop surveillance programs of various types. The analysis of remotely sensed crop reflectance data can provide information about important agronomic parameters like acreage, vigour, maturity and yield, which are at present difficult to determine by traditional survey methods.

At present, the development of instrumentation has perhaps outpaced our interpretative skills. While some studies have successfully demonstrated that different crop types (ie. broadleaf vs sod) can be distinguished by their spectral characteristics, the ability to distinguish more closely related crops, such as the small grains, has yet to be realized. Clearly there is a need for additional research to provide basic information about crop reflectance to improve our interpretative and analytical skills.

The purpose of this study was to compare the spectral properties of small grain crops in situ in the visible region (350 nm - 750 nm). This thesis provides information on the relationship between crop reflectance and the type of crop, the stage of maturity and the physiological state of the crop.

LITERATURE REVIEW

Introduction

The ability to monitor crop growth by remote sensing requires an understanding of the spectral properties of plant canopies and of the individual components within the canopy. Literature concerning visible reflectance from both single leaves and from plant canopies will be reviewed.

Single Leaves

An understanding of the way solar radiation interacts with leaves is still unclear. Most current theories are extensions of the theory proposed by Willstatter and Stohl (1918) for visible light. Based on the concept of internal reflectance (Coblentz, 1913) and an understanding of the absorptive role of chlorophyll, Willstatter and Stohl formulated their theory on the internal structure of leaves and the potential reflecting surfaces that were offered. They hypothesized that leaf reflectance must occur at interfaces within the leaf where critical reflectance was possible. The spongy mesophyll, with large intercellular spaces and irregular cell wall orientation, seemed to them best suited to satisfy the requirements of critical reflectance.

Studies by Pokrowski (1925), Shull (1929) and Gates *et al*. (1965) demonstrated that reflectance from the dorsal (lower) surface of most leaves was greater than reflectance from the ventral surface in the visible region. Since the spongy mesophyll is oriented towards the dorsal surface, these results supported the Willstatter - Stohl theory of critical reflectance.

Mestre (1935) suggested that reflectance occurred both at the leaf surface and within the leaf. Surface reflectance would be specular from leaves with a glossy cuticle and obey Fresnel's law of reflectance, and it would be diffuse from leaves with a 'tormentose' surface according to Lambert's cosine law. Mestre was unable to show that the internal scattering of light in leaves was due to small particles in the cell since there was no tendency for increased reflectance at shorter wavelengths, as would be expected from Rayleigh's equation. Instead he was forced to conclude that the "internal reflections proposed in the Willstatter - Stohl theory must be the major source of the scattering power of leaves".

In 1965, a comprehensive review on the spectral properties of plants was published by Gates et al. They concluded that internal reflectance was the result of critical reflection of light at the cell wall - air cavity interface in the spongy mesophyll of leaves. They also reported a decrease in reflectance at 680 nm and an increase in reflectance at 550 nm as chlorophyll developed in maturing oak tissue. In addition, their data showed that the absorption edge of the reflectance curves at 680 nm shifted progressively toward longer wavelengths as the tissue matured. Gates et al. theorized that the spectral properties of leaves in the visible region were related to pigment development. After investigating the spectral characteristics of numerous plants, they concluded that " qualitatively all green leaves have similiar spectral characteristics, quantitatively they differ considerably ".

Sinclair et al. (1973) investigated the relationship between reflectance and transmittance of light at visible and infrared wavelengths and the observed internal structure of the leaf. They concluded that the Willstatter - Stohl theory was unable to satisfactorily explain the effects of leaf reflectance at near infrared wavelengths. They presented results of dorsal and ventral measurements of soybean leaf reflectance as evidence. The Willstatter - Stohl theory would predict a higher reflectance from the dorsal surface of a soybean leaf. Sinclair et al. reported significantly higher levels of reflected radiation from the ventral side of soybean leaves at 1040 nm - 1070 nm. They proposed that "the difference in prediction capability of the Willstatter - Stohl theory was attributed to the fact that the theory was developed on the basis of results obtained only from the visible wavelengths, rather than results obtained in both the visible and reflective infrared wavelengths". In fact Sinclair et al. did observe higher levels of reflectance from the dorsal surface of soybean leaves at visible wavelengths (640 nm - 650 nm).

The authors also compared the spectral properties of both sunlit and shaded leaves of apple (Malus pumila). In both cases the ventral surface of the leaves was more reflective at infrared wavelengths. In addition they observed that reflectance was greater from sunlit leaves (dense mesophyll with several layers of stacked palisade) than from shaded leaves (lacunose mesophyll) in the infrared region (1040 nm - 1070 nm). These results further contradicted the Willstatter - Stohl theory which stresses the importance of a lacunose mesophyll.

Based on these findings Sinclair et al. postulated a diffuse reflectance theory, based on the microfibrillar structure of cell walls, which predicts that "for the shorter infrared wavelengths, the greater the number of layers of cellular material the incident radiation encounters at a perpendicular angle, the greater will be the reflectance". The Willstatter - Stohl theory would predict reduced reflectance. Reflectance measurements from dehydrated corn leaves were used to test their theory. Dehydration caused a reorientation of the cell walls to an angle perpendicular to the incident radiation. A statistically significant increase (up to 15%) in reflectance was observed as the corn leaves went from a turgid to a dessiccated condition, at infrared wavelengths. The diffuse reflectance hypothesis also satisfactorily explains the higher levels of reflectance obtained from the ventral surface of dorsiventral leaves and the higher levels of reflectance obtained from thicker sunlit apple leaves. A schematic drawing of the proposed diffuse reflectance pathway of light is illustrated in Figure 1.

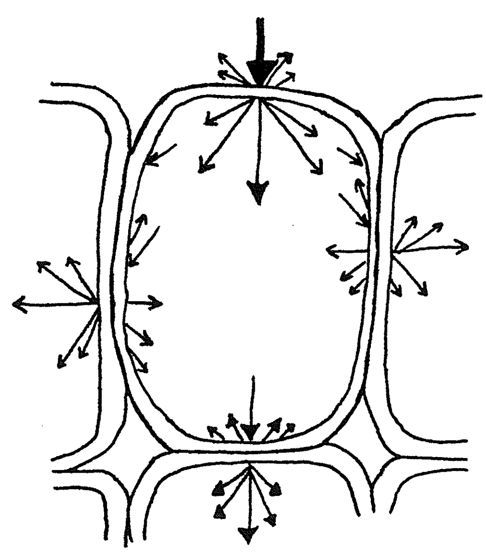

FIGURE 1. Schematic drawing of the pathway for the hypothesized diffusive reflected and transmitted radiation from cell walls. After Sinclair et al., 1973.

Thomas et al. (1966) reported that an inverse relationship existed between reflectance and cotton leaf moisture content at visible and infrared wavelengths. The effect was most noticeable at 1450 nm, a water absorption band. The increased reflectance as moisture deficit increased was related to changes in the size and shape of the cells and the intercellular spaces. They also reported that reflectance was more closely related to water content than to relative turgidity.

Gausman et al. (1969) also investigated the mechanism of leaf reflectance in cotton plants. They reported that the number of intercellular spaces in the spongy mesophyll was positively correlated to near infrared reflectance. An increase in the total mesophyll air spaces increased reflectance, as predicted by the theory of critical light reflection. These results were supported by Knipling (1970) who, on the basis of theoretical models, suggested "that the important parameter in determining the level of reflectance was the number or total area of the air - wall interfaces and not the volume of air spaces".

Gausman (1977) suggested that leaf components such as stomata cell walls, crystals, nuclei and chloroplasts may contribute to the reflectance of near infrared light, particularly in the 700 nm - 1100 nm waveband.

Thomas and Gausman (1977) reported that the 550 nm wavelength seemed best suited for relating reflectance to either total chlorophyll or carotenoid concentration. For most crops investigated chlorophyll was the most important independent factor affecting visible reflectance, although carotene may become influential later in the growing season.

While still unclear, the general understanding of reflectance from single leaves incorporates diffuse reflectance from cell walls and from the cell wall - air cavity interface, as well as small amounts of specular surface reflectance. Reflectance from leaves is modified by selective absorption of radiation by plant pigments and water.

Plant Canopies

Measurements of hemispherical reflectance from single leaves are basic to our understanding of vegetative reflectance. However, data from single leaves are unable to satisfactorily explain the directional reflectance from a plant canopy without modification. Unlike the relative simplicity of single leaf measurements, a plant canopy is a complex composite of shaded and sunlit soil and leaf surfaces at various angular orientations (Richardson, 1975).

Myers et al. (1966) reported that measurements of total reflectance from a cotton canopy (measured with a field spectroradiometer) were higher than measurements of total reflectance from a single cotton leaf (measured with a lab spectrometer) in the visible and infrared wavelengths (400 nm - 1600 nm). They suggested that this was due to changes in transmission through the top of the canopy, changes in light quality within the canopy, multiple internal reflections and reinforcement of reflectance from the top of the canopy.

Colwell (1973) reported that hemispherical reflectance from leaves alone was insufficient to completely describe vegetative or canopy reflectance. He cited data from Steiner and Guterman (1966) that shows measurements of hemispherical leaf reflectance from aspen and birch leaves were larger than the directional canopy reflectance (by up to 18%) in the 710 nm - 790 nm region

Monteith (1965) suggests that radiation scatter between leaves of a crop canopy by multiple reflection is important in explaining reduced canopy reflectance. The amount of scattering increases with the irregularity of the leaf surfaces and with the solar elevation angle, since more light can penetrate the canopy as solar elevation increases. Similiar results were reported by Davis (1957) who showed that grass canopies exhibited a reduction in reflectance as solar angle increased.

Egbert and Ulaby (1972) reported on the effect of solar altitude, incident look angle and azimuth look angle on the spectral reflectance from a grass canopy. They noted that the angular variations of canopy reflectance can have a significant effect on remote reflectance measurements.

Studies on leaf transmission by Kasangi and Monsi (1954) have shown that solar radiation exhibits a changed spectral composition after transmission through vegetation. Stanhill (1962) found that the extent of difference in the quality of transmitted solar radiation depended on the proportion of radiation transmitted through the leaves and the proportion that reaches the ground as unaltered sun flecks.

The effects of canopy density and geometry on reflectance are not well understood. While most studies were concerned with fully developed canopies, investigators are now looking at changes in reflectance as the canopy develops.

At early stages of canopy development, Alekseev and Belov (1960) reported a smoothing out of the reflectance curve between 450 nm and 900 nm due to the moderating influence of the soil background. Similiar results were reported by Archybasheus (1961) from aerial measurements of developing cotton plants.

The influence of the soil background on observed reflectance diminishes as the canopy develops. Idso et al. (1977) reported that the effect of soil background becomes negligible when the leaf area index (LAI) of wheat exceeds 2.5. Chance and Lemaster (1977) calculated from theoretical models that crop reflectance from canopies become insensitive to changes in LAI when the LAI exceeds 2.2 in the visible region and 6.2 in the infrared region.

A number of mathematical crop models have been developed to quantify the theoretical reflectance from crop canopies (Allen and Richardson, 1968; Allen et al., 1970; Idso and de Wit, 1970; Suits,1972). These models can be traced back to the two parameter Kubelka - Munk theory, which itself is an extension of the one parameter Bouger - Lambert law for transmission of light through a medium.

It is clear that a number of parameters in addition to hemispherical reflectance from single leaves are necessary to satisfactorily explain the complexities of vegetative or canopy reflectance. These additional parameters include:

1) leaf transmission
2) leaf area and geometry
3) non - leaf canopy components
4) background characteristics
5) solar angle
6) look angle

Applications

With the advent of NASA's resource satellite program in 1972, the number of investigations involving the application of remote sensing techniques to determine crop growth has increased. The focus of these investigations has been to determine whether solar radiation reflected from a crop is an accurate indicator of crop growth.

The Large Area Crop Inventory Experiment (LACIE), one of the early crop surveillance programs, utilized existing techniques of remote sensing, data processing and interpretation to provide estimates of crop yield (MacDonald, 1974). Although the results were encouraging, applications have been limited primarily due to a lack of information concerning the cause - effect relationship between crop reflectance and crop and environmental parameters. As a result, ground based crop reflectance experiments have become instrumental in providing much needed information to augment larger airborne surveillance programs.

Under field conditions reflectance from a crop canopy is affected by crop type, foliage density and geometry, plant height, vigour and maturity. In addition environmental factors such as soil type, moisture availability, soil salinity and nutrient status as well as atmospheric factors such as wind, cloud cover and solar angle indirectly affect crop reflectance in situ (McCllelan, 1963; Thomas _et al_., 1966; Myers and Allen, 1968). These characteristics can be exploited to advantage by remote sensing, since differences in spectral radiation reflected by a crop may be an accurate indicator of crop species, crop vigour and crop productivity.

Studies attempting to identify crop species on the basis of measurements of spectral radiation are inconclusive. Difficulties exist due to the dynamic nature of crop growth. Since the spectral properties of leaves are closely related to cell structure, their reflectance changes with maturity. Thomas et al. (1966) reported that reflectance at 550 nm from greenhouse grown cotton decreased with age. These findings were also reported by Gausman et al. (1971) for both field and greenhouse cotton. They noted that leaf age had less influence on leaf reflectance in the field.

Verhoef and Bunnik (1974) suggested that the differences among spectral reflectance properties of different crops were largely related to differences in canopy geometry. They noted that these differences in reflectance in the visible region were due to differences in pigment concentration and ground cover.

Leamer et al. (1978) compared the seasonal changes in reflectance of two wheat cultivars (one spring wheat and one winter wheat) at three planting densities. Reflectance at 550 nm decreased slightly with age for all treatments and no discrimination between cultivars was possible. Similiar results were obtained at 650 nm, although soil reflectance differed markedly from the wheat reflectance at this wavelength. At 750 nm the two cultivars differed in reflectance at all three densities on each date of measurement during the season, but the relationship was not constant and was very difficult to interpret.

Mack et al. (1978) reported that the spectral regions near 480 nm and near 650 nm were useful in differentiating crop species, noting that crop reflectance is extremely sensitive to changes in growth and development.

These two spectral regions are in agreement with findings of Radziminsky and Kharin (1973) who reported that the greatest contrast (maximum variability) in plant spectral reflectance using visible multiband photography occurred in two distinct wavebands, one at 480 nm - 520 nm and the other at 640 nm - 700 nm.

Rao et al. (1978) compared the reflectance of several grain crops in the field with a spectrophotometer accurate to 1 nm. Differences in reflectance in the visible region were observed for comparisons of soil vs oats (750 nm) and for comparisons of soybeans vs fababeans (380 nm, 750 nm). No differences were observed in comparisons among wheat cultivars. The reflectance values used however, were averaged from heading to maturity and did not account for reflectance during the early part of the growing season.

Idso et al. (1977) reported that measurements of canopy reflectance could be related to grain yield. Measurements of shortwave albedo taken every 20 minutes each day during the season from six differentially irrigated durum wheat fields showed that final grain yield is a linear function of the minimum albedo value reached just prior to head ripening. This technique however, is dependant on the crop type and the prevailing environmental conditions, and would require the development of a seperate model for each crop being investigated.

MATERIALS AND METHODS

Introduction

The primary objective of this study was to obtain accurate measurements of reflectance from several small grain crops (wheat, barley, oats) and to monitor the seasonal changes in reflectance as these crops matured. The methods and materials used in this study were selected to facilitate the realization of this objective and still maintain a degree of practicality. Ancillary agronomic parameters were recorded to improve our understanding of the causative factors that influence vegetative reflectance.

Experimental Design

The field plots were arranged in semicircular fashion (Figure 2). All the plots in each of the two arcs were equiidistant from the field laboratory which housed the light sensitive detector. The distance between the detector and the two arcs was 24.4 m and 30.5 m, respectively. The centre of the arcs was directly in line with the viewing mirror in the field laboratory. Plots in the front arc were 2.44 m long and 0.73 m wide at the front. Plots in the back arc were 3.05 m long and 0.91 m wide at the front. The two different arc distances and plot sizes had no effect on the spectral measurements (Brach *et al.*, 1977). Since the field of view of the telescope was completely filled by plant material during all measurements, it was not necessary to correct for differences in distances to the detector.

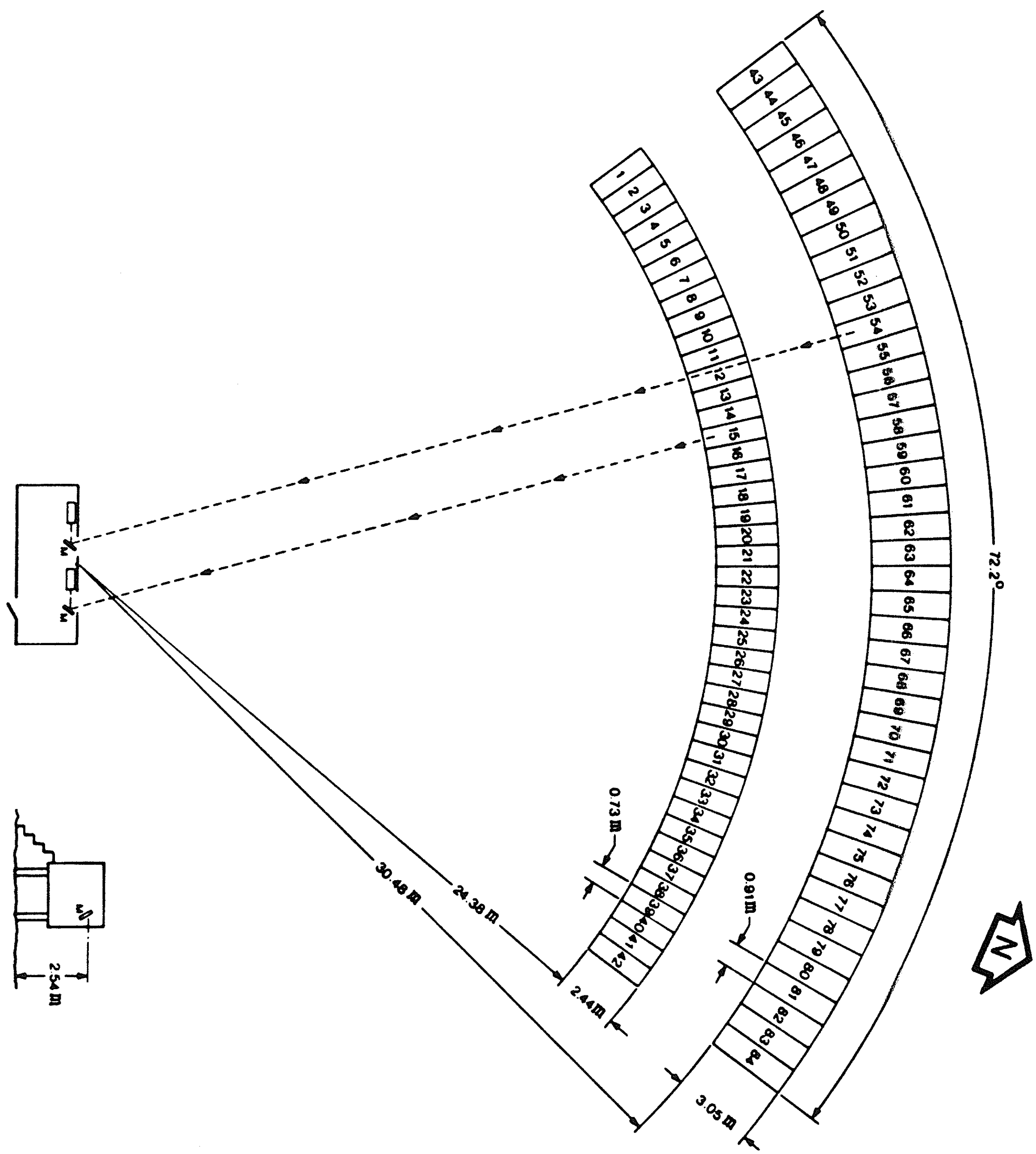

Figure 2. Field Layout for 1977 Experiment.

A line from the detector bisecting the two arcs was 27°44' west of the north - south axis. The plots were seeded in rows perpendicular (east - west) to the viewing axis of the telescope. Each treatment was replicated three times. A pathway of 3.66 m between the two arcs and the area between the field laboratory and the plots were seeded with a cover crop of fall rye which was kept closely cropped throughout the season.

Treatments

A total of 7 treatments were used in this study (Table 1). Each treatment consisted of a field plot seeded with a particular cultivar. Differences between treatments were due solely to differences in the type of plant material present.

Treatments were hand seeded on May 14, 1977 into a seedbed that received minimal cultivation and no fertilization. All treatments were sown at a depth of 3.8 cm in rows spaced 30.48 cm apart. Seeds were spaced 1.22 cm apart within the rows giving a population density of approximately 200,000 plants per hectare. Seeding rates were selected to obtain a dense, bushy stand of plant material that would completely fill the viewing area of the telescope. No attempt was made to simulate commercial seeding practices.

Instrumentation

Measurements of radiant energy (350 nm - 750 nm) reflected from the crop were made using the electro - optical system illustrated in Figure 3. Hardware components of the system included a flat, front surfaced mirror (M), a Schmidt - Cassegrain telescope (TE), a telecompressor (TC), a

TABLE 1. List of treatments used in this study.

Number	Description of treatment
1.	Bonanza; 6 - row malt or feed barley
2.	Klondike; 6 - row feed barley
3.	Harmon; common oats
4.	Hudson; common oats
5.	Neepawa; awnletted, hard, red, spring wheat
6.	Sinton; awned, hard, red, spring wheat
7.	Wakooma; amber durum wheat

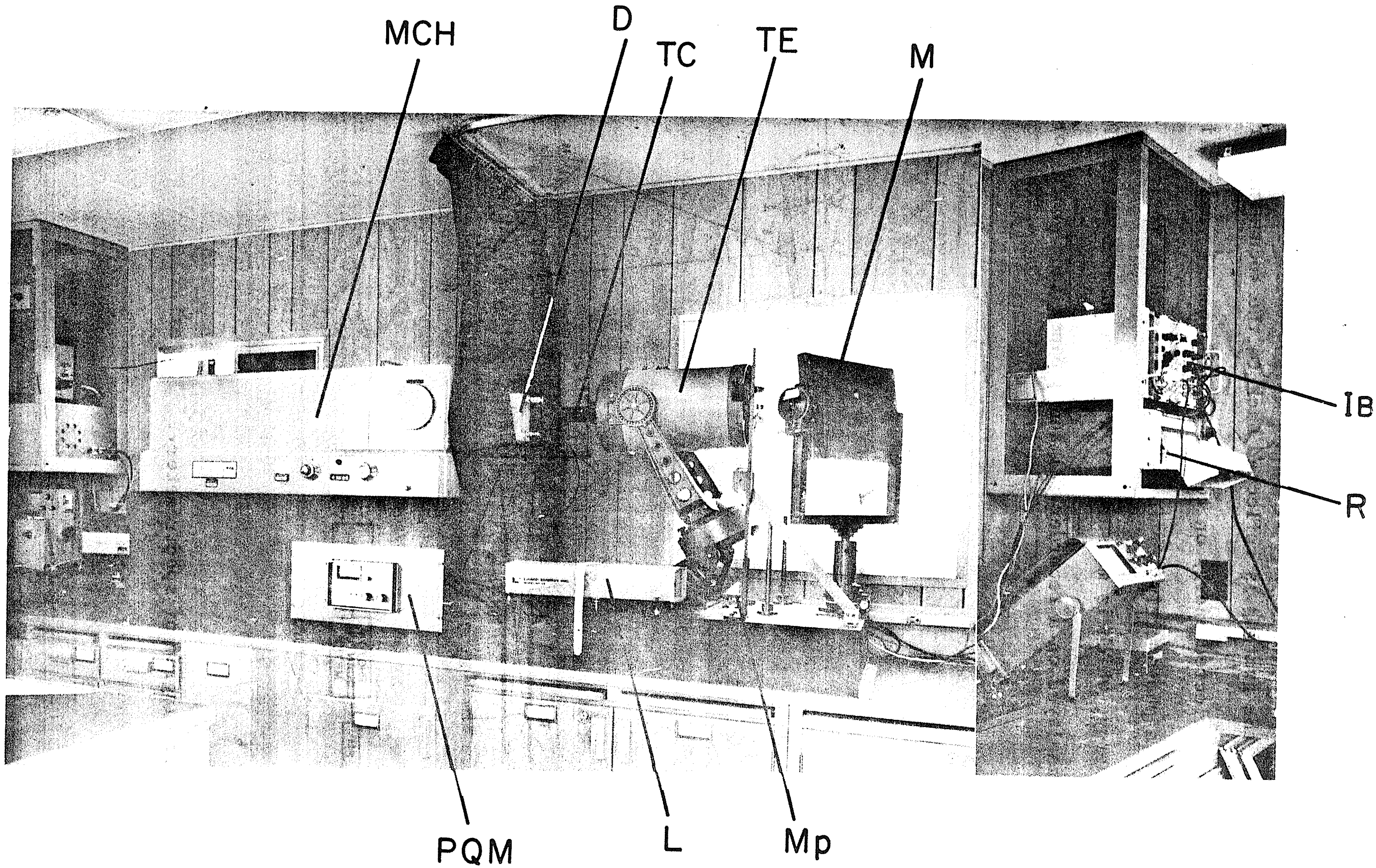

Figure 3. Optical System Used to Measure Crop Reflectance.

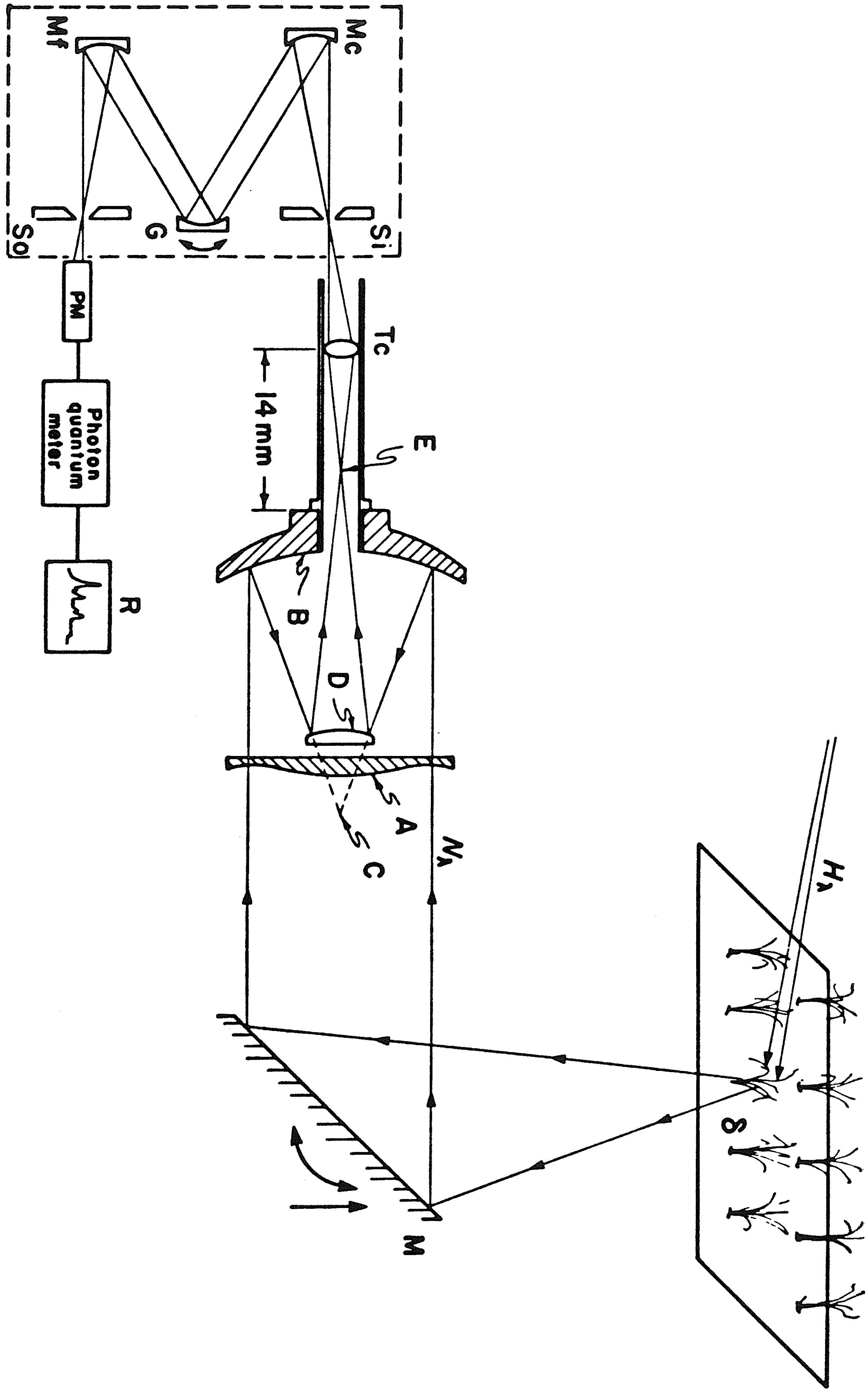

Figure 4. Schematic Drawing of Pathway for Visible Radiation Through the Optical System.

monochromator (M), a photomultiplier detector (PM), a photon quantum meter (PQM) and a two channel analog recorder. The optical path of reflected radiation through the system is schematically illustrated in Figure 4 (Brach et al., 1977).

Measurements of incident atmospheric radiation (350 nm - 750 nm) were obtained using a similiar but separate optical system. A roof mounted pyroheliometer attached directly to a telecompressor lens eliminated the need for a mirror and telescope. Monochromators in the two systems were wavelength synchronous, thus insuring that both optical systems were detecting light energy of the same wavelength at any given time during a measurement.

Measurement of Spectral Reflectance

Radiant energy reflected by the crop was measured on clear (less than 3/5 cloud cover), calm (less than 20 km per hr wind), sunny days several times throughout the growing season. Measurements were performed between the hours of 800 and 1700, local daylight saving time, between June 6 and August 10.

Prior to each spectral measurement the folding mirror was adjusted to the proper angle. The telescope was then focused on the upper third of the crop so that the desired plant treatment completely filled the viewing area. It was assumed that the reflectance measured in this way was from the upper horizontal surface of the canopy.

Spectral measurements were manually initiated. Radiant energy from the plant canopy as well as from the atmosphere were measured synchronously at 2 nm increments from 350 nm - 750 nm. The resulting data was recorded graphically in the form of relative output from each sensor as a function of wavelength. These will subsequently be referred to as analog crop spectral curves. For each analog curve, the exact time of day as well as estimates of wind speed and cloud cover were recorded.

Growth Stages

Growth stage measurements for a particular treatment were made each day that measurements of spectral reflectance were performed. A growth stage from 1 through 10 was assigned to a treatment on the basis of visual assessment (Table 2; USDA-FAS-LACIE, 1976).

Plant Height

Measurements of plant height (cm) were recorded for all treatments concurrently with measurements of spectral reflectance. Using a metre stick the distance between the base of the plant and the tip of the uppermost leaf was measured. After heading the distance between the base of the plant and the tip of the inflorescence was measured. Six plants measured at random within each treatment were used to compute a mean plant height for each treatment.

Leaf Area

Measurements of leaf area were made with an optically integrating leaf area meter[1]. Two plants from each treatment were sampled at random. Green leaves were separated from the stem and their area (cm^2) was measured. The leaf area index (LAI) was then calculated by multiplying the combined leaf area of the two plants by their germination percentage and dividing this product by the total area of soil covered by the two plants.

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[1] Lambda Instruments model LI - 300.

TABLE 2. List of growth stages used in this study

Number	Description of growth stage
1.0	Not planted
2.0	Planted, no emergence
3.0	Emergence, 1 - 3 leaves
4.0	Tillering
5.0	Boot
6.0	Heading
7.0	Anthesis, fully headed
8.0	Ripening, yellow leaves
9.0	Physiological maturity
10.0	Harvested

Chlorophyll Determination

The procedure for chlorophyll determination was based on the absorption of light by aqueous acetone (80%) extracts of chlorophyll (Arnon, 1948). The plant material selected for LAI determination was also used to measure chlorophyll. The concentration of chlorophyll in the leaf tissue was determined by measuring the optical density of the acetone extracts at 663 nm with a spectrophotometer[2]. Measurements of chlorophyll were performed concurrently with measurements of spectral reflectance.

Photographic Measurements

A complete photographic record was manitained for all treatments throughout the experiment. Exposures were made with a 35 mm format camera using a colour reversal slide film (ASA 64). A Kodak grey card (18% reflectance) was positioned adjacent to the treatment being photographed for accurate calibration. Each treatment was photographed just prior to the measurement of spectral reflectance.

Analysis of Data

1. Calibration

The optical equipment in the field laboratory was calibrated on June 14, 1977. The calibration was performed between the hours of 2300 and 300, local daylight saving time, to minimize the chance of the detectors receiving any atmospheric light radiation.

A high irradiance lamp[3] was placed 50 m away from the detector. The lamp had previously been calibrated (Optronics Laboratories) so that the spectral irradiance (microwatts/cm^2) at a distance of 41.8 cm at

[2]Bausch and Lomb, model Spec 20.

[3]Optronics, model S-310.

each wavelength was known (Table 3). The spectral irradiance of this lamp was then measured (350 nm - 750 nm) by the optical detectors in the field laboratory. After correcting for differences in distance between source and detector, a separate calibration factor for converting relative spectral output into energy per unit area was calculated for each 4 nm increment between 350 nm and 750 nm. In effect these calibration factors were determined by comparing the laboratory calibrated irradiance with the irradiance measured by the detector in the field. These derived calibration factors were incorporated into computer programs designed to calculate crop reflectance.

2. Digitization

Analog spectral curves from both the atmosphere and from the crop were manually digitized to facilitate analysis. The transformation of analog spectral curves to digital coordinate pairs (wavelength vs relative sensor output) was performed on a 91 cm by 122 cm digitizing table which had a resolution of 0.04 cm[4]. The resulting digital output was stored directly on computer disk.

3. Calculation of Crop Reflectance

A useful way of describing the reflectivity of an object is to express it as a percentage of the incident radiation upon it which is reflected back to space (Barrett and Curtis, 1976). Subsequently, the term crop reflectance refers to the ratio of reflected to incoming solar radiation expressed as a percentage.

The amount of incident radiation was measured by a hemispherical

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[4]Talos digitizing table, model Smart-1.

Table 3. Spectral irradiance of lamp S-310 (microwatts/cm^2) at a distance of 41.8 cm. when operated at 8.0 amperes

Wavelength (nm)	Spectral Irradiance
300	0.279
320	0.547
350	1.244
370	1.893
400	3.387
450	6.883
500	11.520
550	16.600
600	21.740
650	26.27
700	30.11
750	33.26

detector mounted on the roof of the field laboratory. In this way the amount of solar radiation incident to the crop was determined.

The amount of radiation reflected from the crop was more difficult to determine. When radiant energy is incident upon an object with a non - homogeneous surface (eg. a plant canopy) radiation is reflected from the surface in a myriad of directions. Thus the amount of radiation received at the detector is in fact only a fraction of the total radiation reflected by the object. Clearly it becomes necessary to relate the amount of radiation received at the detector (I) to the total amount of reflected radiation (Io).

Initially this was done by assuming that plants exhibit a Lambertian type of reflectance (Brach _et al._, 1977). Based on this assumption, the total radiation reflected by the crop could be calculated using Lambert's cosine law:

$$I = Io \times \text{cosine}(\text{scattering angle}) \quad (1)$$

where I = radiation received at the detector

Io = total radiation reflected by the crop

The cosine of the scattering angle was calculated by using the equation cited by Turner and Spencer (1972):

$$\cos(sc) = \cos(z) \times \cos(elev) + \sin(z) \times \sin(elev) \times \cos(deltaz) \quad (2)$$

where sc = scattering angle

z = zenith angle of the sun

elev = zenith angle of detector

deltaz = difference between crop azimuth and solar azimuth

By rearranging equation (1) it was possible to calculate the amount of radiation reflected by the crop.

The accuracy of calculating crop reflectance in this way was then tested. A standardized metal reflectance plate (anodized aluminium) designed by the Engineering and Statistical Research Institute, Agriculture Canada, Ottawa, was used as a test object. The plate was designed to simulate crop reflectance and was standardized to reflect between 22% and 29% in the visible region. Accurate calibration of this plate was performed by the National Research Council of Canada (Figure 5). These results were then compared to the reflectance from the plate calculated by Lambert's cosine law from measurements taken in the field laboratory (Figure 6 and Figure 7).

It was immediately apparent that the calculated values of reflectance from the plate were not identical to the values of reflectance obtained from the laboratory calibration. These conflicting results suggested that our initial assumption that the plate behaved as a Lambertian reflector was not valid. Also, it has been suggested that plants are not true Lambertian reflectors (Suits, 1972; de Boer, 1973; Colwell, 1973).

A more empirical approach was then applied in a second attempt to standardize the calculation of crop reflectance. Techniques of multiple regression were used to determine a numerical factor that would satisfactorily relate the amount of radiation received at the detector to the total amount of radiation reflected by the plate. The ratio of plate reflectance from the laboratory to the calculated plate reflectance from the field at four wavelengths (450 nm, 550 nm, 650 nm, 750 nm) was regressed to the zenith angle of the sun and to the cosine of the scattering angle. Four distinct regression equations were obtained for each of the four wavelengths (Table 4). Using linear interpolation, these four equations were used to calculate correction factors for the entire range of the visible spectrum. Thus at any given wavelength, reflected radiation received at the detector was multiplied by the specific regression factor appropriate for that wavelength, according to the equation:

$$Io_{590\ nm} = I_{590\ nm} \times \text{Regression Factor}_{590\ nm} \quad \ldots\ldots\ldots\ (3)$$

where $Io_{590\ nm}$ = total radiation reflected by the crop at 590 nm
$I_{590\ nm}$ = radiation received at the detector at 590 nm
Regression $\text{Factor}_{590\ nm}$ = correction factor specific for 590 nm

Using equation (3) the amount of radiation reflected by the plate was calculated and plotted a second time (Figure 8 and Figure 9). It should be noted that Figures 6 and 8 and Figures 7 and 9 originate from the same relative sensor output, respectively. Only the method of calculation of reflectance differs.

Upon comparison with the laboratory calibrated reflectance for the plate (Figure 5), it can be seen that the field measured reflectance is similiar to the laboratory measured reflectance, indicating that the empirically derived regression factors are satisfactory in the calculation of reflectance. Calculation of crop reflectance was performed in a similiar fashion. The assumption had to made that reflectance from the crop canopy was affected by zenith angle and scattering angle in the same way as it was from the reflectance plate.

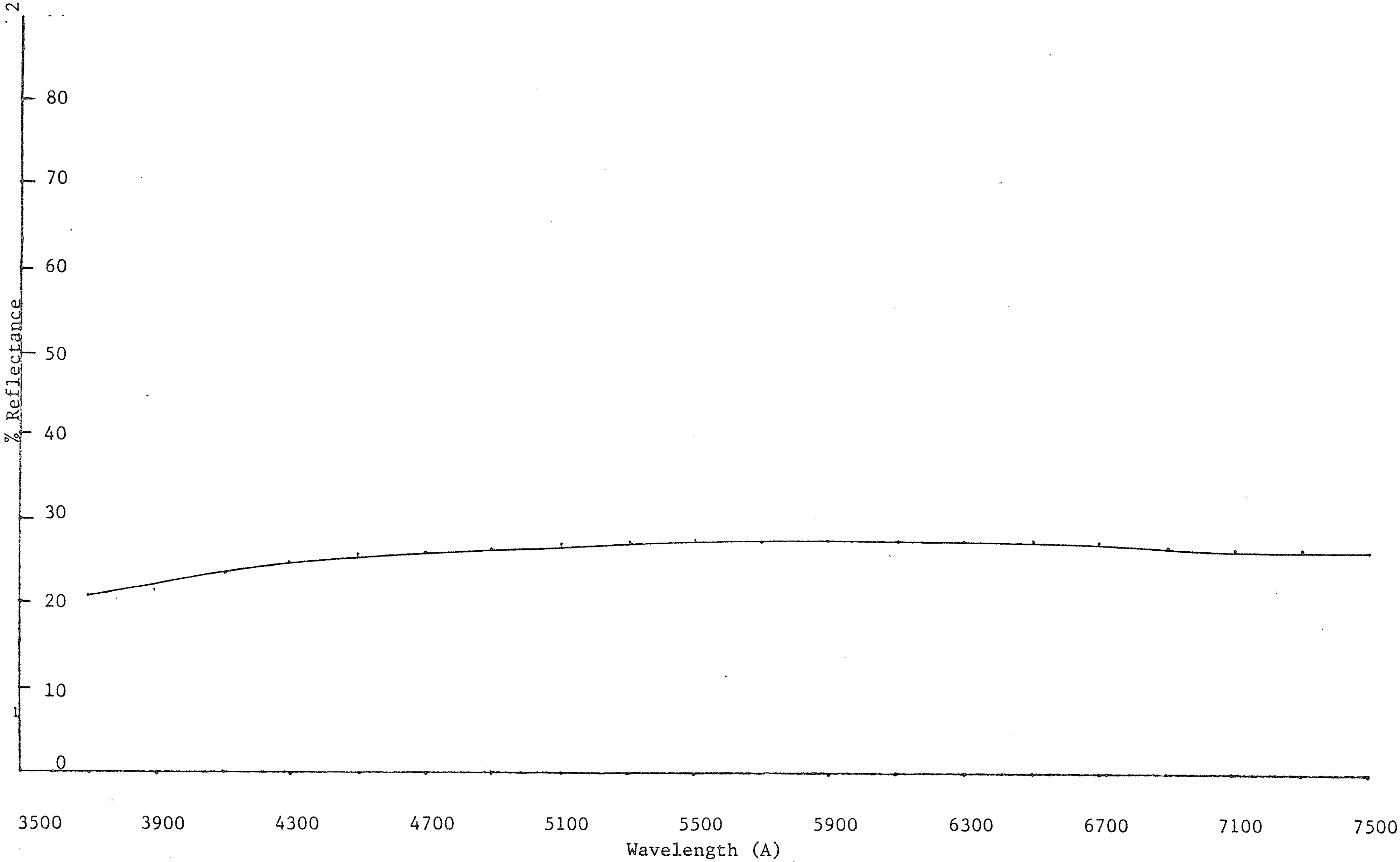

Figure 5. Calibration curve of the standard reflectance plate.

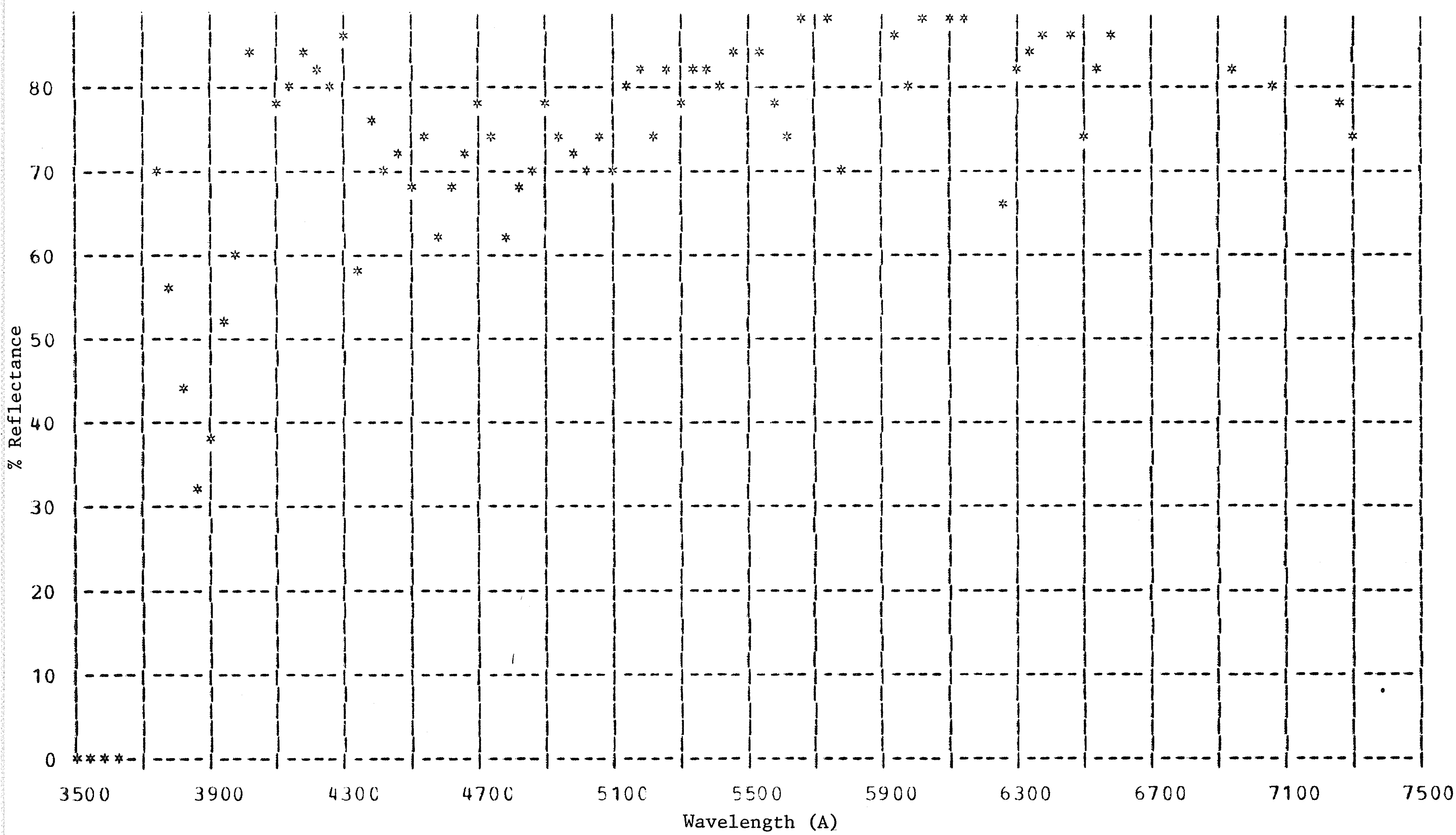

Figure 6. % reflectance from the standard reflectance plate measured at 13:32, June 7, 1977, assuming the reflectance plate acts as a Lambertian reflector.

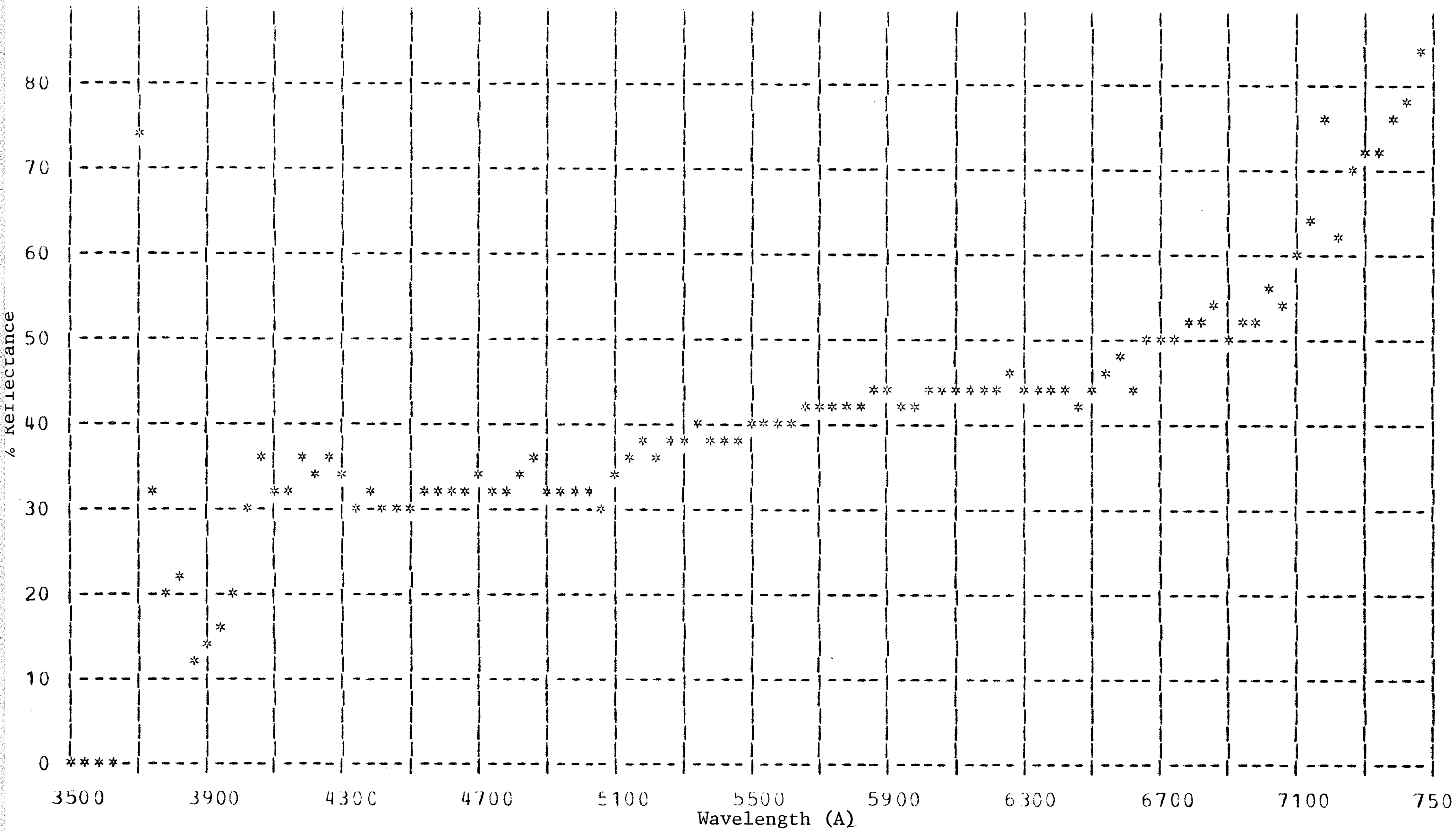

Figure 7. % reflectance from the standard reflectance plate measured at 8:37, June 22, 1977, assuming the reflectance plate acts as a Lambertian reflector.

TABLE 4. List of regression equations used to convert energy received at the sensor to energy reflected by the standard plate.

Wavelength	Regression Equation
450 nm	0.629 + 0.9171 (zenith angle[1])^2
550 nm	0.5361 + 0.6878 (zenith angle)^2
650 nm	0.1935 + 2.111 (zenith angle) - 2.228 (zenith angle) x (cosine scattering angle)
750 nm	0.4601 + 0.571 (zenith angle)^2 - 0.788 (zenith angle) x (cosine scattering angle)

[1]Zenith angle in radians.

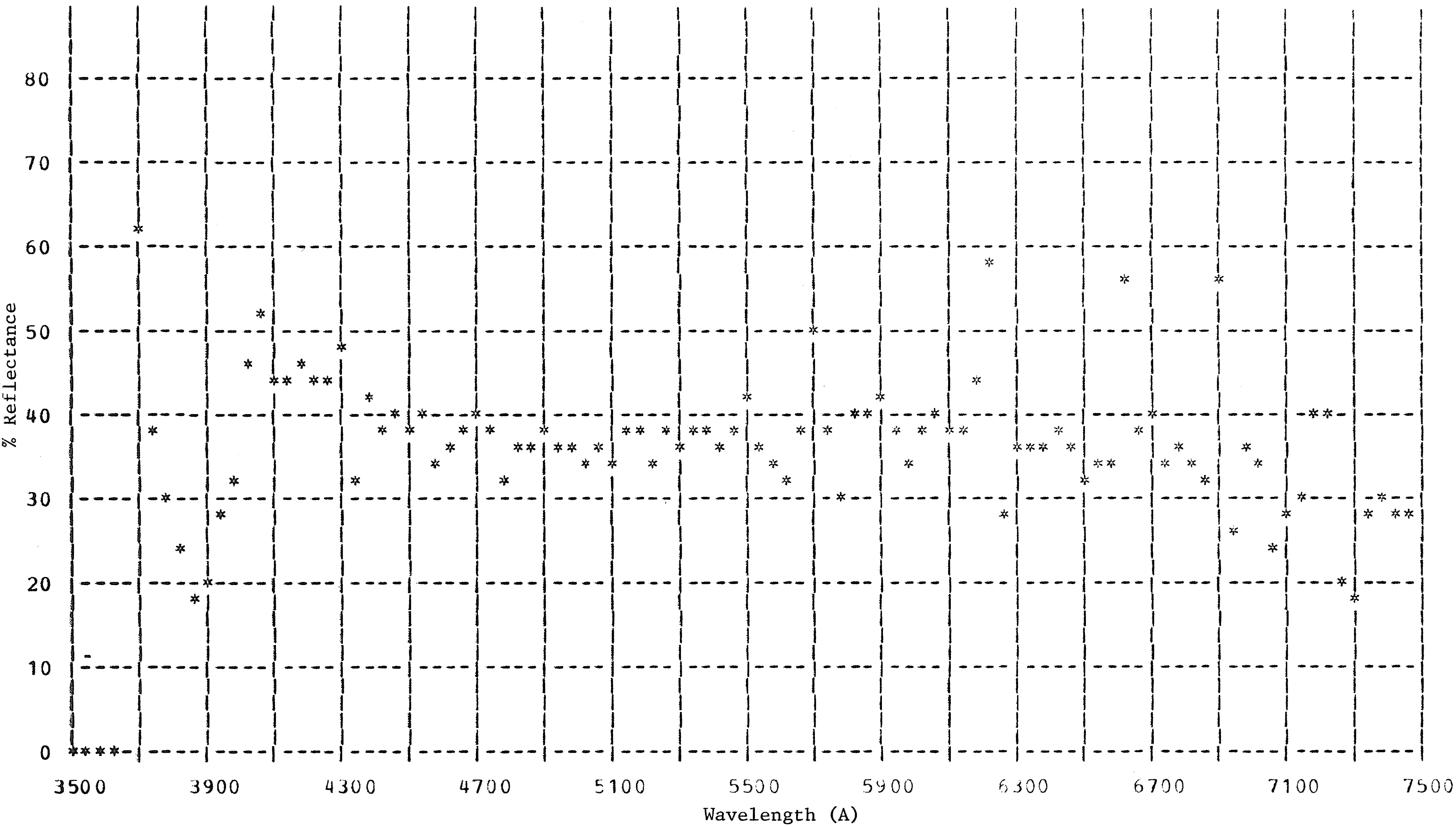

Figure 8. % reflectance from the standard reflectance plate measured at 13:32, June 7, 1977, after empirical correction for zenith and scattering angle.

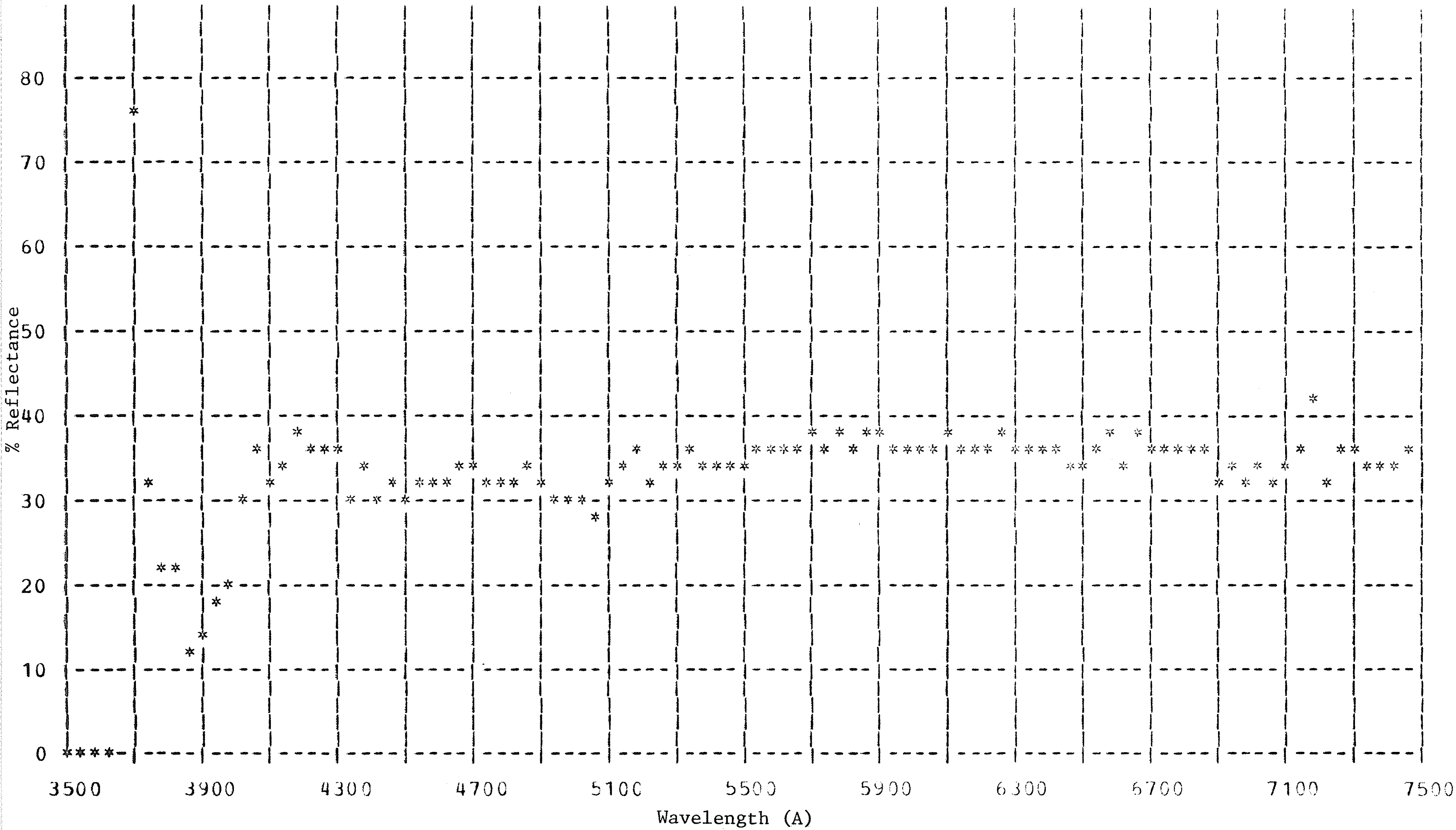

Figure 9. % reflectance from the standard reflectance plate measured at 8:37, June 22, 1977, after empirical correction for zenith and scattering angle.

4. Statistical Methods

The basic output from the analysis consisted of digital and graphical values of percent reflectance as a function of wavelength for individual observations (ie. a particular treatment on a given day; Figure 10). However, since each treatment was replicated three times, data for a particular treatmeant at each stage of growth were combined and digital and graphical representations of the mean reflectance and mean reflectance plus or minus one standard deviation as a function of wavelength were produced (Figure 11). As well, all data from each species were combined to produce digital and graphical representations of mean reflectance and mean reflectance plus or minus one standard deviation as a function of wavelength.

This mean reflectance data was used in making several comparisons. These comparisons were made by calculating a Student's t value (Snedecor and Cochran, 1976) of the difference in reflectance of the two sets of data involved in the comparison. These t values were plotted as a function of wavelength.

The comparisons made were: 1) comparisons of reflectance from each species at different stages of growth, 2) comparisons of reflectance from different species at the same stage of growth, 3) comparisons of reflectance from different cultivars at the same stage of growth. The objective of these comparisons was to determine which species and which cultivars differed significantly from each other in mean reflectance, at what stage of growth they differed, and in which portion of the visible spectrum these differences occurred.

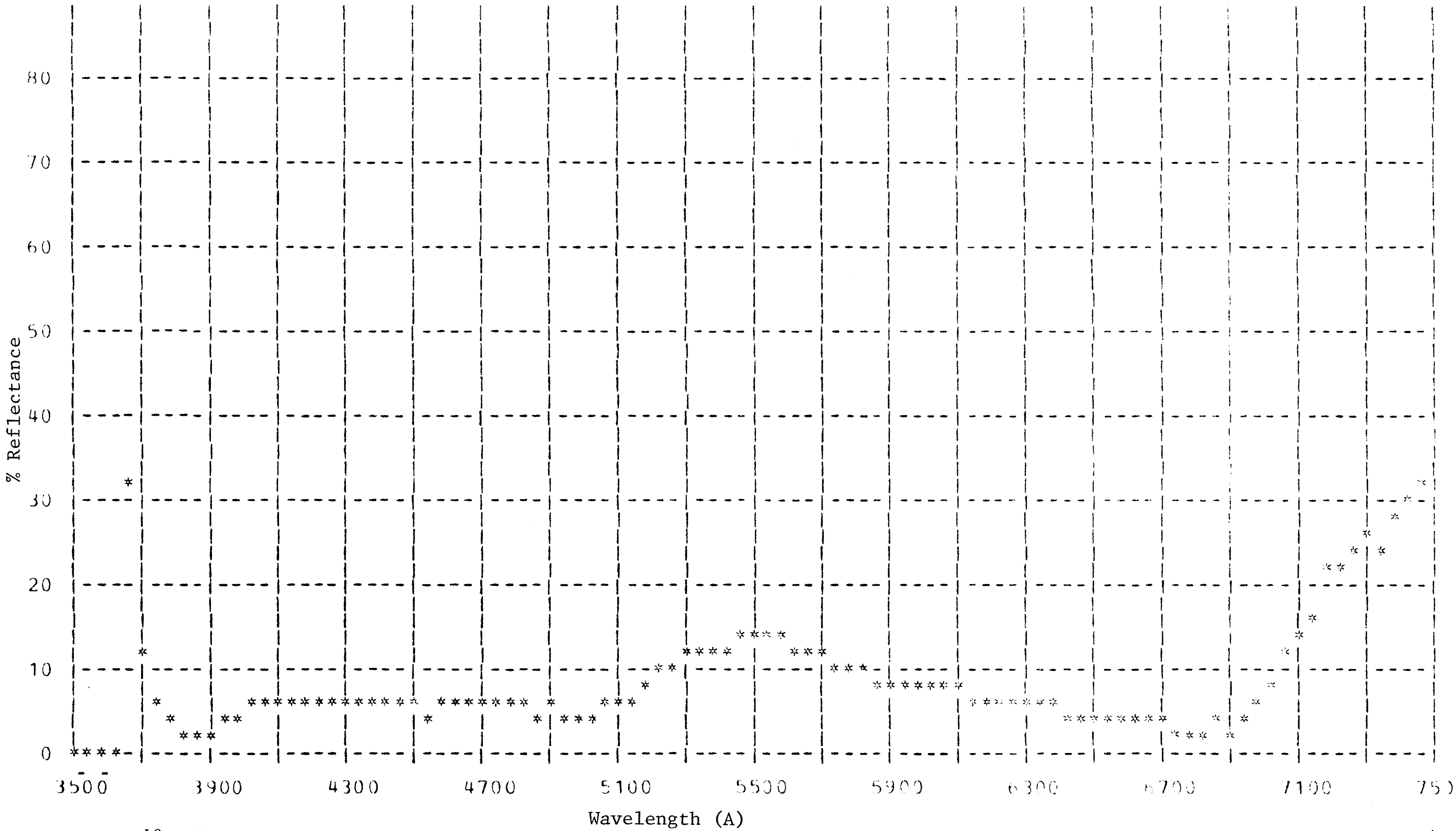

Figure 10. % Reflectance from Harmon oats as measured at 11:34, June 6, 1977.

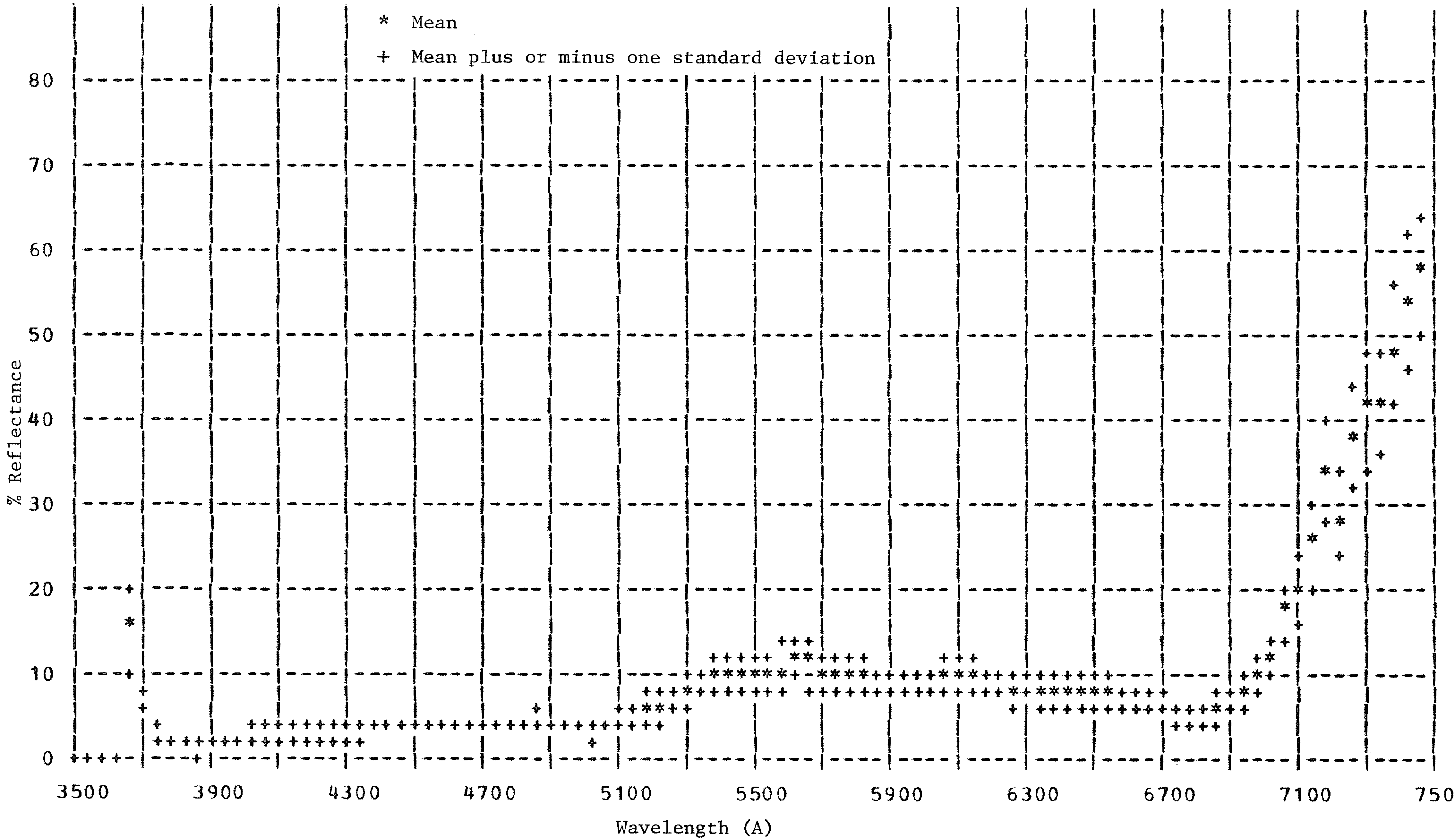

Figure 11. Mean reflectance and mean plus or minus one standard deviation for Sinton wheat at growth stage IV.

RESULTS AND DISCUSSION

Species Reflectance

1. Wheat

Reflectance measurements for wheat (cv. Sinton, Neepawa) were performed on five dates during the summer. The corrected mean reflectance spectra for wheat are listed in Appendix 1. These spectra illustrate the changes in the magnitude of reflectance from wheat during the growing season. The spectral regions of greatest change occurred at 550 nm, 600 nm and 700 nm (Table 5).

Reflectance decreased at most wavelengths as the wheat progressed from the early stages of tillering through heading. After heading, reflectance increased steadily, with very high values of reflectance observed as the wheat approached physiological maturity. These seasonal changes in wheat reflectance are largely related to changes in the chlorophyll concentration of the plants (Gates *et al*., 1965; Thomas *et al*., 1966; Wooley, 1971). Levels of chlorophyll in the leaves increased as the plants matured from tillering through heading. This increase in chlorophyll (and other pigments) increases the absorption of visible radiant energy by the plant and causes a reduction in the amount of reflected radiation. After heading, levels of chlorophyll decreased and were associated with a marked change in foliage colour. This decrease in chlorophyll concentration is responsible for the large increase in reflectance that occurred after heading.

Comparisons of the reflectance spectra from each of the five dates of measurement were made (Table 6). Reflectance from wheat at the first two dates of measurement (W_1 vs W_2) did not differ significantly at any wavelength. Since the wheat was at the same stage of growth for both dates of measurement, similiar reflectance was expected. Significant differences in reflectance were observed in comparisons of W_1 vs W_3, W_2 vs W_3, W_3 vs W_4, W_4 vs W_5. Each of these comparisons involved measurements of wheat reflectance at closely related but different stages of growth. In all these comparisons, significant differences in reflectance occurred in only two spectral regions; 450 nm - 550 nm (green band) and 600 nm - 710 nm (chlorophyll band). These differences suggest that the reflectance from wheat is a function of its stage of growth.

2. Barley

Reflectance measurements for barley (cv. Klondike, Bonanza) were performed on four dates during the summer. These four barley reflectance spectra are listed in Appendix 1. These spectra illustrate the changes in barley reflectance during the growing season.

The seasonal changes in the magnitude of reflectance from barley were similiar to those exhibited by wheat. Reflectance decreased from tillering through heading. After heading, large increases in reflectance were observed as the plants approached physiological maturity. Like wheat these seasonal changes in barley reflectance were largely related to changes in the concentration of chlorophyll (Table 7).

The reflectance data also show a shift in the wavelength at which maximum reflectance in the green spectral region occurs. This peak in the reflectance spectra, usually less than 20%, is due to a minimum of

Table 5. Days from seeding, growth stage, chlorophyll concentration and mean reflectance from wheat at three wavelengths.

Code	Days from Seeding	Growth Stage	Mean chlorophyll Concentration mgm/cm2	Mean Reflectance (%) 550nm	600nm	700nm
W1	13	4	34.2	5.3	10.9	14.4
W2	29	4	39.1	4.8	10.5	11.5
W3	46	6-7	43.9	3.2	7.9	11.2
W4	55	7	41.8	5.3	10.0	12.3
W5	76	8	-	10.3	20.1	24.0

Table 6. Wavelength range (nm) over which there was a significant difference in reflectance between five observation times of wheat.

Observation Time	Growth Stage	W1 4	W2 4	W3 6-7	W4 7	W5 8
W1	4		-	378-594**	-	460-514* 560-706*
W2	4			402-574**	-	435-700*
W3	6-7				418-550*	390-710**
W4	7					454-714*

* Difference significant at 5%

** Difference significant at 1%.

absorption by chlorophyll. A total shift of 12 nm (554 nm to 566 nm) was observed for this peak as the barley matured. A similiar shift in reflectance was reported by Collins (1974) at 670 nm for maturing wheat and sorghum. This green shift was not observed in wheat.

Comparisons of barley reflectance were made among the four dates of measurement (Table 8). Significant differences in reflectance were observed for comparisons of B_1 vs B_2 and B_2 vs B_3. These comparisons involved measurements of barley reflectance obtained at different stages of growth. The spectral region in which these differences occurred was from 450 nm - 680 nm. Significant differences in reflectance were also observed for the comparison B_3 vs B_4, even though the barley was at the same stage of growth on both dates of measurement. This difference illustrated the importance of accurately defining stage of maturity in the identification of species by field spectroscopy. These differences in reflectance occurred in the chlorophyll band (600 nm - 700 nm) and were probably due to a further deterioration of chlorophyll at the later date of measurement. These results indicate that like wheat, the spectral reflectance from barley is a function of the stage of growth at the time of measurement.

3. Oats

Reflectance measurements for oats (cv. Hudson, Harmon) were performed on four dates during the summer. The reflectance spectra for oats are listed in Appendix 1. These spectra illustrate the changes in oat reflectance during the growing season.

The seasonal changes in the magnitude of reflectance from oats were not consistent with the seasonal trends exhibited by wheat and by

Table 7. Days from seeding, growth stage, chlorophyll concentration, reflectance peak and mean reflectance from barley (cv Bonanza and Klondike) at three wavelengths.

Code	Days from Seeding	Growth Stage	Mean chlorophyll Concentration mgm/cm2	Peak Reflectance nm	Mean Reflectance (%) 550nm	600nm	700nm
B1	28	4	30.6	554	15.0	8.1	10.5
B2	39	5-6	40.6	558	10.2	6.2	8.9
B3	53	8	31.2	562	15.0	10.8	12.5
B4	59	8	-	566	14.1	17.3	19.2

Table 8. Wavelength range (nm) over which there was a significant difference in reflectance between four observation times of barley.

Observation Time	Growth Stage	B1 4	B2 5-6	B3 8	B4 8
B1	4		378-610**	374-426*	570-718**
B2	5-6			430-680*	430-718**
B3	8				598-698*

* Difference significant at 5%
** Difference significant at 1%.

barley (Table 9). Reflectance from oats at all wavelengths below 600 nm increased steadily from the early stages of tillering through to grain ripening. At wavelengths longer than 600 nm however, oat reflectance increased from tillering to heading, then decreased as the plants began to approach maturity.

Levels of chlorophyll in the oat treatments exhibited a seasonal pattern similiar to that observed for wheat and barley. The concentration of chlorophyll increased steadily up to heading and then decreased as the plants approached maturity. The relationship between oat chlorophyll concentration and oat reflectance is not clear. Unlike wheat and barley, the seasonal changes in reflectance from oats can not be satisfactorily explained by changes in chlorophyll concentration. Other factors such as the structure of the inflorescence and the geometry of the canopy may be involved.

The spectral region of greatest change during the season was from 600 nm - 700 nm. However, results of the comparisons of oat reflectance among the four dates of measurement show that few of these differences are significant (Table 10). The only significant differences were in comparisons of O_1 vs O_3 and O_2 vs O_3, in the 630 nm - 702 nm waveband. High standard deviations for oat reflectance may have contributed to the lack of significant differences.

The results indicate that oat reflectance is a function of the stage of growth of the plants at the time of measurement, although the relationship is not clear.

Table 9. Days from seeding, growth stage, chlorophyll concentration and mean reflectance from oats at four wavelengths.

Code	Days from Seeding	Growth Stage	Mean chlorophyll Concentration mgm/cm2	Mean Reflectance (%) 400nm	500nm	600nm	700nm
01	13	4	37.1	5.5	4.5	8.0	10.8
02	29	4	38.7	6.3	5.0	8.8	11.0
03	46	6-7	50.8	6.8	6.3	13.8	17.8
04	56	7-8	49.9	7.0	7.3	11.3	13.5

Table 10. Wavelength range (nm) over which there was a significant difference in reflectance between four observation times of oats.

Observation Time	Growth Stage	01	02	03	04
		4	4	6-7	7-8
01	4		-	594-742**	-
02	4			630-702*	-
03	6-7				-

* Difference significant at 5%

** Difference significant at 1%.

Comparison of Reflectance From Different Crops

1. Wheat vs Barley

Comparisons of reflectance from wheat (cv. Neepawa, Sinton) and from barley (cv. Bonanza, Klondike) at several stages of growth were made by calculating a Student's t (Table 11). Attention was focused on comparisons in which both the wheat and the barley were at the same stage of growth. It was felt that these specific comparisons were most directly related to the development of crop identification techniques.

At tillering (W_2 vs B_1) the mean reflectance from wheat was significantly greater than the mean reflectance from barley from 610 nm - 690 nm, the spectral region of chlorophyll absorption. Similiar results were observed at heading (W_3 vs B_2). Again mean wheat reflectance was significantly greater than mean barley reflectance from 606 nm - 690 nm.

At anthesis (W_4 vs B_3) and during grain ripening (W_5 vs B_4) mean wheat reflectance and mean barley reflectance did not differ significantly at any wavelength.

These data suggest the existence of two distinct temporal regions for describing comparisons of wheat and barley reflectance. From tillering to anthesis, the potential for discriminating wheat from barley exists due to differences in reflectance from the two crops in the 600 nm - 700 nm waveband. These differences are probably related to differing rates of chlorophyll synthesis in wheat and barley. After anthesis reflectance from the two crops was similiar, providing little potential for discrimination. The lack of significant differences late in the season may be related to the deterioration of chlorophyll, which would lessen the effect of different chlorophyll concentrations, and to the similiarity of the wheat and barley inflorescence.

2. Wheat vs Oats

Comparisons of reflectance from wheat (cv. Sinton, Neepawa) and from oats (cv. Hudson, Harmon) were made in the same manner as previously outlined (Table 12). Again, the comparisons of primary interest were those involving wheat and oats at similiar stages of growth.

At tillering (W_1 vs O_1, W_2 vs O_2) the reflectance from wheat exceeded the reflectance from oats, although these differences were not significant. The lack of significant differences may be due to the large standard deviation of the oat reflectance data.

At anthesis (W_3 vs O_3) reflectance from oats was significantly greater than reflectance from wheat at almost all wavelengths. After anthesis (W_4 vs O_4) these differences in reflectance were not observed.

These data show that reflectance from wheat and oats is similiar for much of the growing season. During anthesis however, the potential for discriminating wheat from oats does exist due to differences in their spectral reflectance. These differences in reflectance at anthesis may be caused by the large differences in the structure of the inflorescence of wheat (spike) and oats (panicle). However, since these differences in reflectance were not observed at any later stages of growth, the actual effect the inflorescence has on reflectance is not clear.

3. Barley vs Oats

Comparisons of reflectance from barley (cv. Klondike, Bonanza) and from oats (cv. Hudson, Harmon) were made at three stages of growth during the season. Comparisons of primary interest were those involving barley and oats at similiar stages of growth.

At tillering (B_1 vs O_1) reflectance from oats was greater than reflectance from barley at all wavelengths except the green band (526 nm-574 nm), where reflectance from barley was greater. However, none of these differences in reflectance were significant (Table 13).

At anthesis (B_2 vs O_3) reflectance from oats exceeded reflectance from barley at all wavelengths. These differences were significant at most wavelengths with particularly large significant differences ($p = .01$) occurring in the chlorophyll band (582 nm - 702 nm)

After anthesis (B_4 vs O_4) these differences in reflectance were not observed. Mean barley reflectance did not differ significantly from mean oat reflectance at any wavelength at this stage of growth.

Like wheat, barley reflectance is similiar to oat reflectance for much of the growing season. At anthesis, when floral structures begin to affect reflectance, the potential for discrimination of barley and oats exists, due to large differences in reflectance. Again these differences may be due to the large differences in the structure of the inflorescence of these two crops.

Table 11. Wavelength range (nm) over which there was a significant difference in reflectance between wheat (W) and barley (B).

Observation Time	Growth Stage	B1 4	B2 5-6	B3 8	B4 8
W1	4	454-506* 578-690*	418-702**	382-478*	598-690*
W2	4	610-690*	422-538** 566-686**	-	598-698*
W3	6-7	366-574** 630-686**	606-698**	414-598**	394-710**
W4	7	606-690**	430-530* 562-698**	-	586-722*
W5	8	438-522** 570-714**	422-714**	422-514* 578-710*	-

* Difference significant at 5%
** Difference significant at 1%.

Table 12. Wavelength range (nm) over which there was a significant difference in reflectance between wheat (W) and oats (O).

Observation Time	Growth Stage	O1 4	O2 4	O3 6-7	O4 7-8
W1	4	-	-	-	-
W2	4	-	-	690-698*	-
W3	6-7	382-454* 522-554*	378-558*	378-738**	402-550*
W4	7	654-690*	-	-	-
W5	8	574-710*	578-622*	-	-

* Difference significant at 5%
** Difference significant at 1%.

Table 13. Wavelength range (nm) over which there was a significant difference in reflectance between barley (B) and oats (O).

Observation Time	Growth Stage	O1	O2	O3	O4
		4	4	6-7	7-8
B1	4	-	-	594-742*	674-686*
B2	5-6	430-594*	398-558*	422-718**	434-530* 662-686*
B3	8	386-406*	386-430*	382-418*	-
B4	8	582-718*	378-394* 598-698*	378-392*	-

* Difference significant at 5%
** Difference significant at 1%.

Comparisons of Cultivar Reflectance

Although the primary objective of airborne crop monitoring programs is the accurate identification of crop species, information about the particular cultivars present is also useful. Clearly the ability to distinguish cultivars of spring wheat from durum wheat as well as cultivars of feed barley from malt barley could increase the accuracy of estimates of grain acreage. Non-destructive cultivar identification techniques may soon be incorporated into breeding and licensing programs.

Comparisons of reflectance among cultivars of each species were made by calculating a Student's t. The procedure was similiar to the one used for comparisons of species with emphasis placed on comparisons of cultivars at similiar stages of development. However, since the number of degrees of freedom were lower in the cultivar comparisons, the test for significant differences in reflectance from cultivars was a much more rigourous test.

1. Wheat Cultivars

One cultivar of durum wheat (*Triticum durum* cv. Wakooma) was compared with two cultivars of hard red spring wheat (cv. Sinton, Neepawa). Results of the comparison of reflectance between Sinton and Neepawa are listed in Table 14.

During the early stages of tillering (S_1 vs N_1) reflectance from Neepawa was significantly greater than reflectance from Sinton from 610 nm - 682 nm. No significant differences were observed between the two cultivars during the later stages of tillering (S_2 vs N_2) and at heading (S_3 vs N_3).

At anthesis (S_4 vs N_4) reflectance from Neepawa was again significantly larger than reflectance from Sinton, this time in the 402 nm -

582 nm waveband. During grain filling (S_5 vs N_5) reflectance from Sinton became significantly larger than reflectance from Neepawa from 594 nm - 714 nm.

Sinton and Neepawa are two closely related cultivars. The fact that large differences in reflectance occurred at tillering and at anthesis through ripening is encouraging, although difficult to interpret. Both cultivars had similiar rates of chlorophyll production throughout the season, although the level of synthesis of other plant pigments was not measured (Table 15). However differences in the height of the plant canopies and the presence of long awns on Sinton may be responsible for some of the differences in reflectance.

Results of the comparisons of reflectance between Sinton and Wakooma and between Neepawa and Wakooma are listed in Tables 16 and 17, respectively. Due to differences in the growth pattern of the durum wheat treatments, comparisons were limited to the tillering and boot stages of growth.

At tillering, reflectance from Wakooma was significantly greater than reflectance from both Sinton (S_2 vs W_2) and from Neepawa (N_2 vs W_2). These differences occurred at 410 nm - 526 nm for both comparisons. At the boot stage of growth, reflectance from Sinton became significantly larger than reflectance from Wakooma at 578 nm - 746 nm (S_3 vs W_3). Data for Neepawa at this stage of growth was not available.

Although the results are not complete, the data suggest that the potential for discriminating such widely differing crops as durum wheat and spring wheat and between such closely related cultivars such as Sinton and Neepawa exists. These differences may be due to differences

Table 14. Wavelength range (nm) over which there was a significant difference in reflectance between Neepawa (N) and Sinton (S) wheat.

Observation Time	Growth Stage	N1 4	N2 4	N3 6-7	N4 7	N5 8
S1	4	610-682*	506-526*	402-610**	574-696*	-
S2	4	-	-	414-482* 526-602*	482-514*	-
S3	6-7	398-458*	406-498*	-	378-594*	390-510*
S4	7	-	-	-	402-582**	462-510*
S5	8	574-702**	562-706*	430-746**	570-714*	594-714*

* Difference significant at 5%
** Difference significant at 1%.

TABLE 15. Concentration of chlorophyll a, chlorophyll b and mean canopy height for Sinton and Neepawa wheat at five dates of measurement.

Crop	Measurement	Chlorophyll a (mgm/cm^2)	Chlorophyll b (mgm/cm^2)	Canopy Height (cm)
Sinton	1	24.4	9.9	27
	2	27.4	12.7	67
	3	28.9	13.3	112
	4	-	-	114
	5	-	-	114
Neepawa	1	24.3	10.7	26
	2	25.6	12.7	56
	3	31.6	13.5	100
	4	-	-	102
	5	-	-	103

Table 16. Wavelength range (nm) over which there was a significant difference in reflectance between Wakooma (W) and Sinton (S) wheat.

Observation Time	Growth Stage	W1 4	W2 4	W3 5	W4 5-6
S1	4	594-682* 710-746**	410-526* 650-746*	370-706*	466-590*
S2	4	-	402-526*	534-666* 706-746*	-
S3	5	378-470* 518-570*	378-526*	578-746*	390-422*
S4	7	378-430* 522-566*	378-526*	-	-
S5	8	578-702*	578-714*	442-726**	474-510* 558-722**

* Difference significant at 5%
** Difference significant at 1%.

in canopy height, inflorescence characteristics and the rate of pigment synthesis.

2. Barley Cultivars

Results of the comparisons from Klondike and Bonanza, two six - row barley cultivars, are presented in Table 18. At tillering (B_1 vs K_1), reflectance form Klondike was significantly greater than reflectance from Bonanza in the 434 - 490 nm waveband. As the plants began heading (B_2 vs K_2) reflectance from Bonanza became significantly greater in the 646 nm - 666 nm waveband and in the 694 nm - 746 nm waveband. However, due to the decreased sensitivity of the detector to wavelengths longer than 700 nm, differences in reflectance in this spectral region may not be meaningful.

During grain filling (B_3 vs K_3) no significant differences in reflectance were observed. As the crops approached physiological maturity (B_4 vs K_4) significant differences in reflectance were observed in the narrow 530 nm - 554 nm waveband.

These results suggest that closely related cultivars of barley may be discriminated on the basis of differences in reflectance from the two cultivars at selected times during the growing season. The factors causing these differences in reflectance are not clear.

3. Oat Cultivars

Results from the comparisons of reflectance from two oat cultivars, Harmon and Hudson, are listed in Table 19. Throughout the tillering period, reflectance from Hudson was significantly greater than reflectance from Harmon. During the early stages of tillering (Ha_1 vs Hu_1) these

Table 17. Wavelength range (nm) over which there was a significant difference in reflectance between Wakooma (W) and Neepawa (N) wheat.

Observation Time	Growth Stage	W1 4	W2 4	W3 5	W4 5-6
N1	4	-	402-522*	410-710*	562-678*
N2	4	-	416-526*	414-518*	-
N3	7	382-662* 702-746*	382-526** 562-714*	526-566* 614-746*	410-590*
N4	7	-	-	378-746*	454-526* 550-680*
N5	8	-	398-422*	430-506* 578-614*	470-510* 578-590*

* Difference significant at 5%
** Difference significant at 1%.

Table 18. Wavelength range (nm) over which there was a significant difference in reflectance between Bonanza (B) and Klondike (K) barley.

Observation Time	Growth Stage	K1 4	K2 5	K3 8	K4 8
B1	4	434-490*	406-610*	378-398**	570-690*
B2	6	490-590**	694-746**	514-542*	490-702*
B3	8	374-438** 578-618*	422-742*	-	-
B4	8	530-566** 598-702*	514-574** 598-726*	-	530-554**

* Difference significant at 5%
** Difference significant at 1%.

Table 19. Wavelength range (nm) over which there was a significant difference in reflectance between Harmon (HA) and Hudson (HU) oats.

Observation Time	Growth Stage	HU1 4	HU2 4	HU3 7	HU4 8
HA1	4	582-618*	370-642* 706-746*	402-740**	370-706*
HA2	4	-	386-606*	402-702**	486-674*
HA3	6	602-734*	-	402-590*	-
HA4	7	-	-	-	-

* Difference significant at 5%
** Difference significant at 1%.

differences in reflectance occurred in the 582 nm - 618 nm waveband. In the later stages of tillering (Ha_2 vs Hu_2) the differences in reflectance occurred in the much wider 386 nm - 606 nm waveband.

At anthesis, reflectance from the two cultivars became similiar and no significant differences were observed. No data was available for comparisons during grain ripening.

Although these two cultivars are closely related in appearance, in canopy height and in chlorophyll production, the data shows that a potential for discrimination exists at tillering. Again, the results are not complete and it is difficult to identify the factors responsible for these differences in reflectance.

SUMMARY AND CONCLUSIONS

1. Wheat, oats and barley reflect between 5% and 20% of the incident solar radiation in the visible wavelengths.
2. Reflectance of visible light from wheat and barley decreased from emergence to heading and then increased from heading to maturity. These seasonal changes in reflectance were inversely correlated with chlorophyll concentration.
3. Reflectance of visible light from oats exhibited greater variability (higher standard deviation) and fewer significant differences among growth stages. The relationship between the seasonal changes in oat reflectance and chlorophyll concentration was not clear.
4. A shift of 12 nm (554 nm - 566 nm) of the position of the peak reflectance in the green band occurred as barley matured. This green shift may be a useful indicator of barley maturity.
5. Reflectance from wheat was significantly greater than reflectance from barley in the chlorophyll absorption band during tillering and heading (Table 20). Thus wheat and barley could be discriminated as early as tillering and up until heading.
6. Reflectance from oats was significantly greater than reflectance from both wheat and barley at anthesis (Table 20). Thus, discrimination between oats and wheat and barley was possible only at anthesis.
7. In all three species examined, the potential exists for discriminating between cultivars on the basis of differences in their spectral reflectance patterns (Table 20).

Table 20. Summary of wavelength ranges (nm) over which there was a significant difference in reflectance between the three species and six cultivars used in the study.

Comparison	Tillering	Heading-Anthesis	Ripening
Wheat x Barley	610 - 690	606 - 698	-
Wheat x Oats	-	378 - 738	-
Barley x Oats	-	422 - 718	-
Bonanza x Klondike	434 - 490	-	530 - 554
Sinton x Neepawa	610 - 682	402 - 582	594 - 714
Harmon x Hudson	386 - 606	-	-

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APPENDIX I

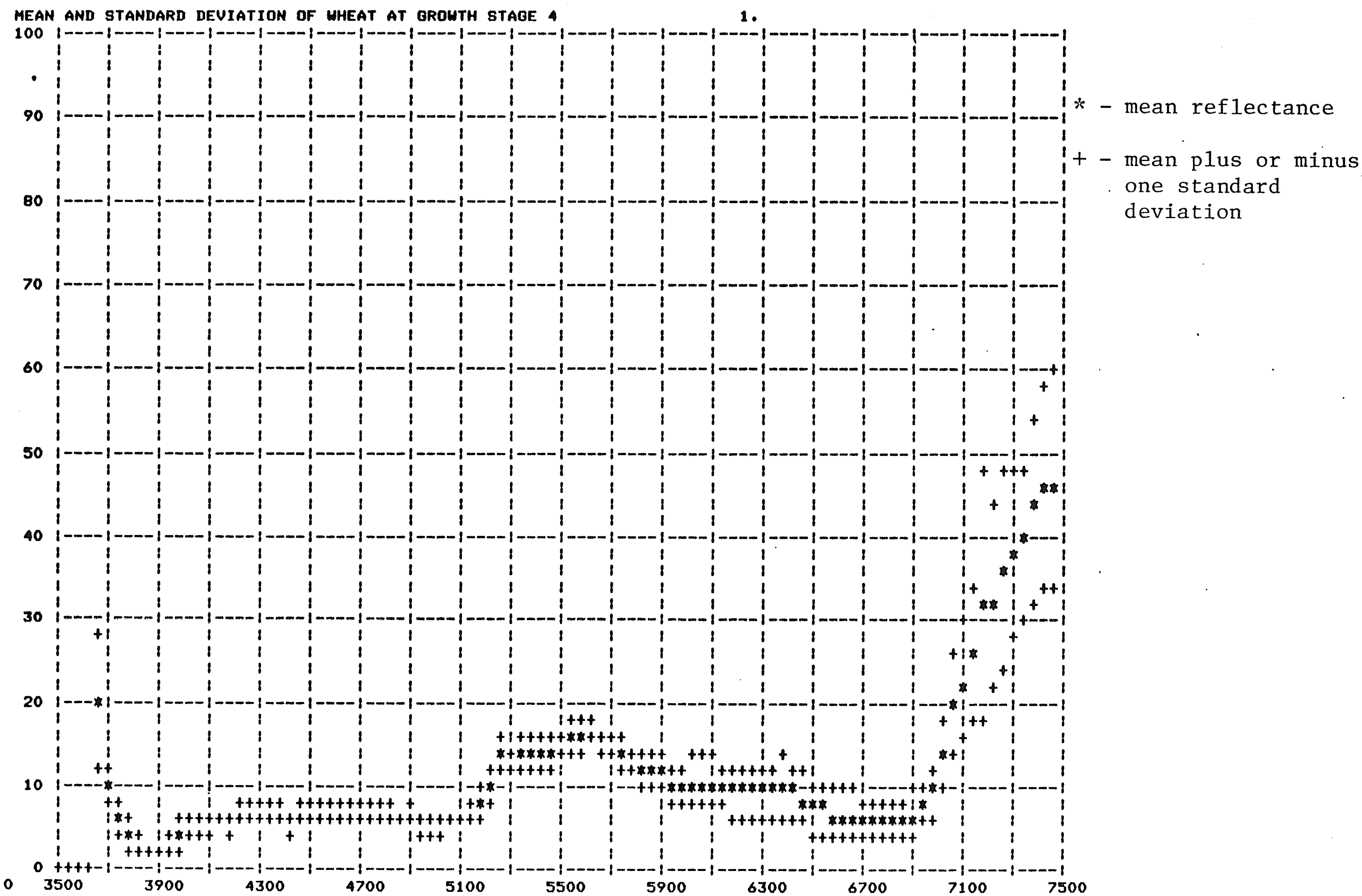

Figure I. Mean reflectance and mean plus or minus one standard deviation for wheat 13 days after seeding.

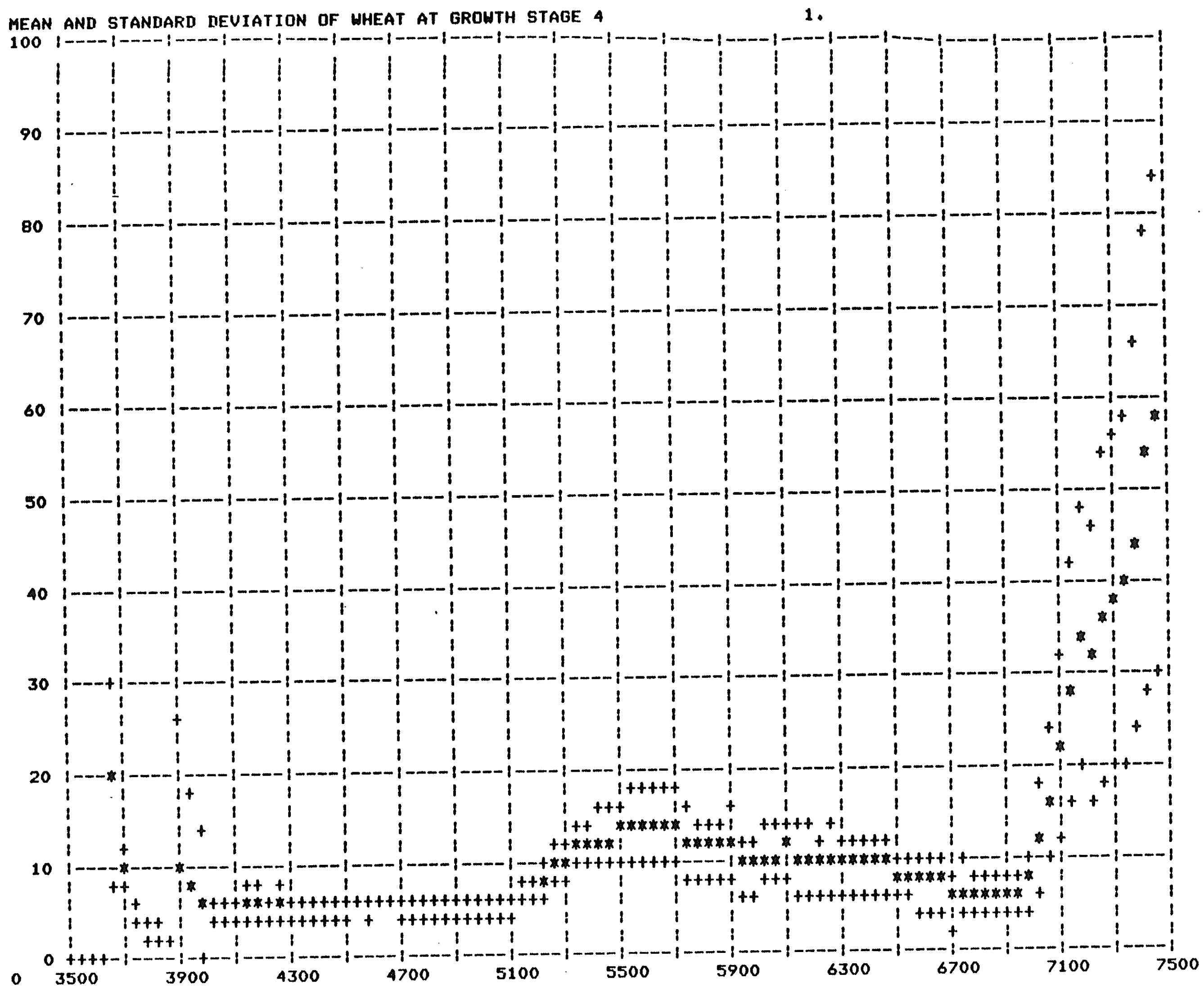

Figure II. Mean reflectance and mean plus or minus one standard deviation for wheat 29 days after seeding.

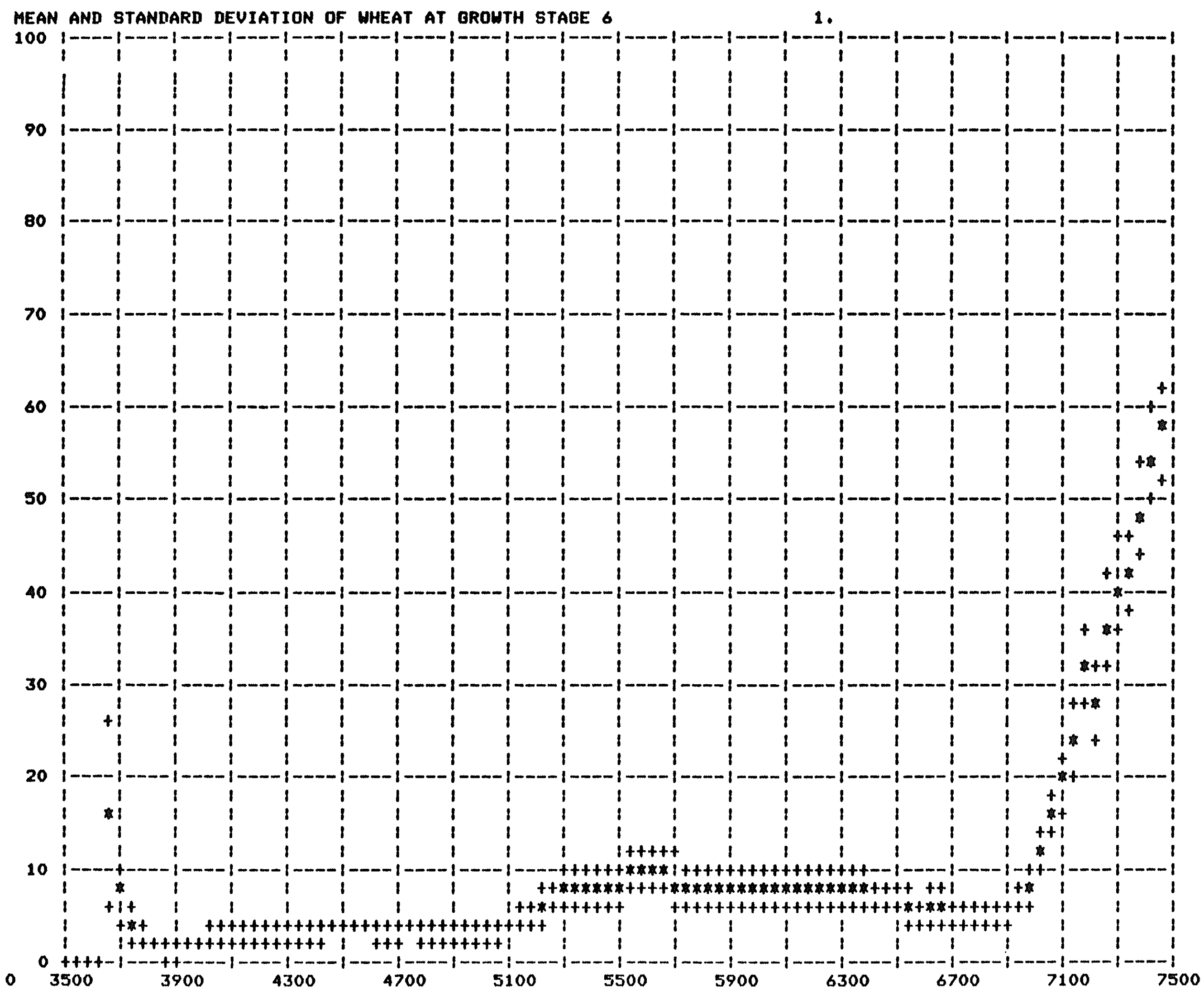

Figure III. Mean reflectance and mean plus or minus one standard deviation for wheat 46 days after seeding.

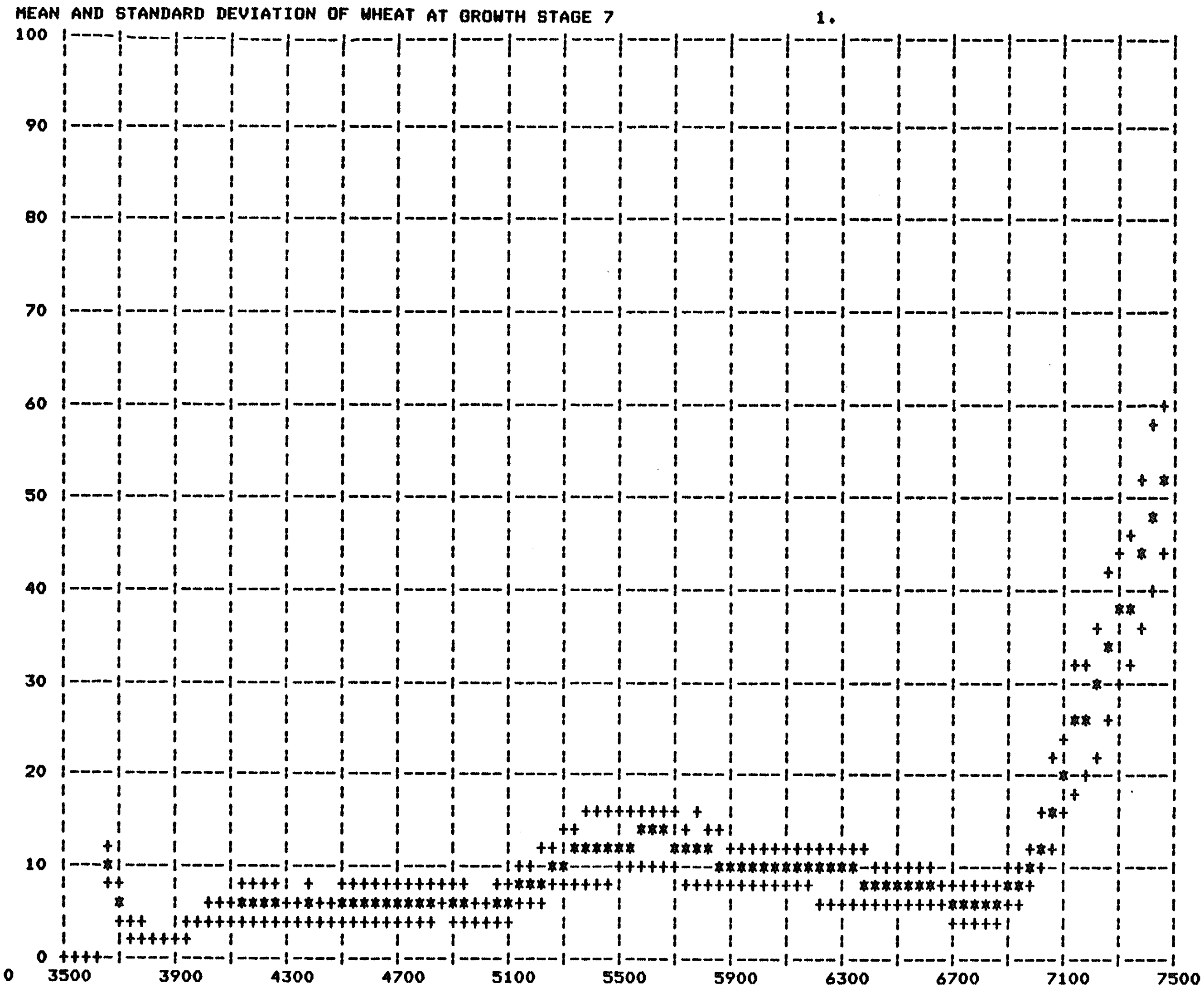

Figure IV. Mean reflectance and mean plus or minus one standard deviation for wheat 55 days after seeding.

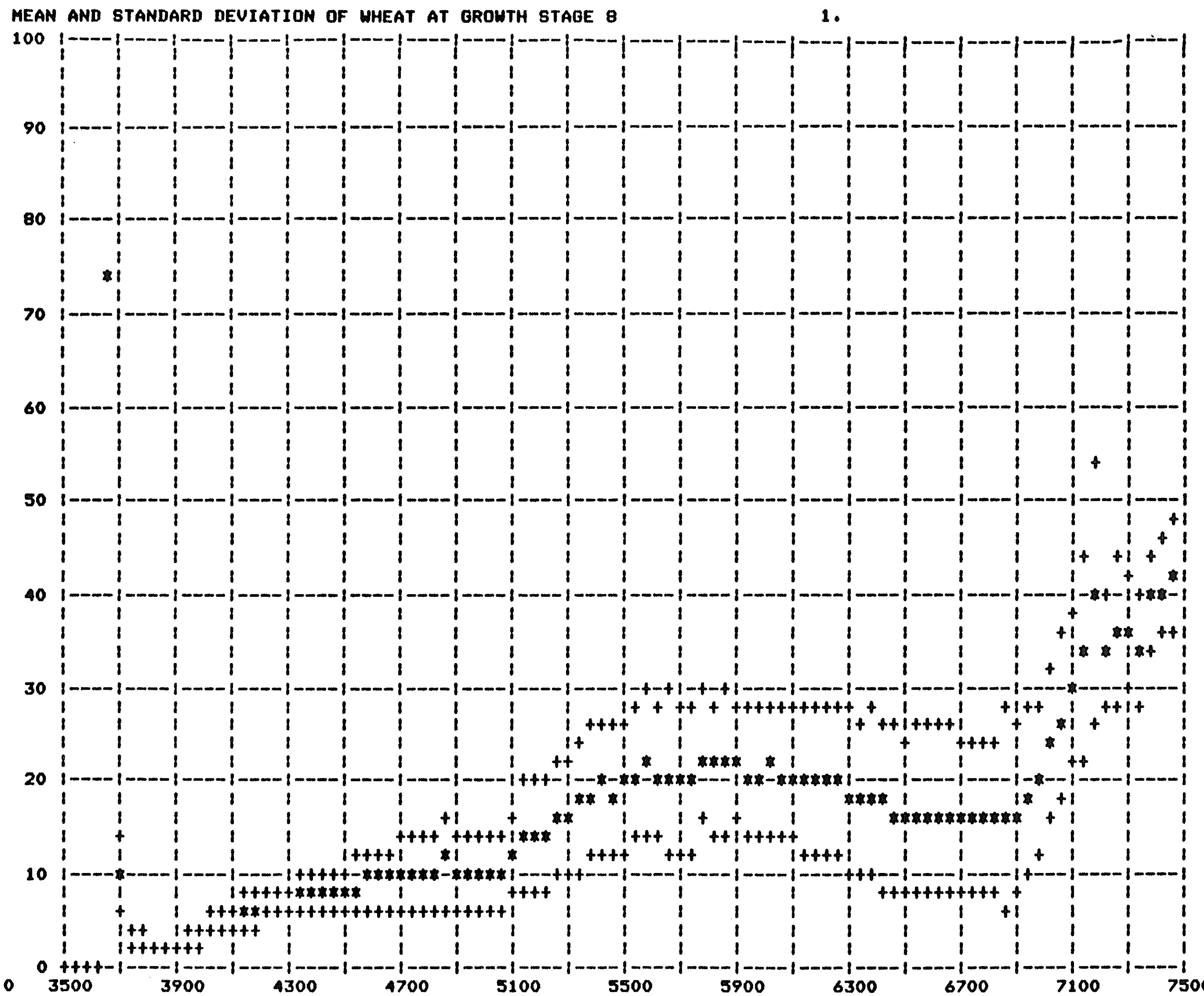

Figure V. Mean reflectance and mean plus or minus one standard deviation for wheat 76 days after seeding.

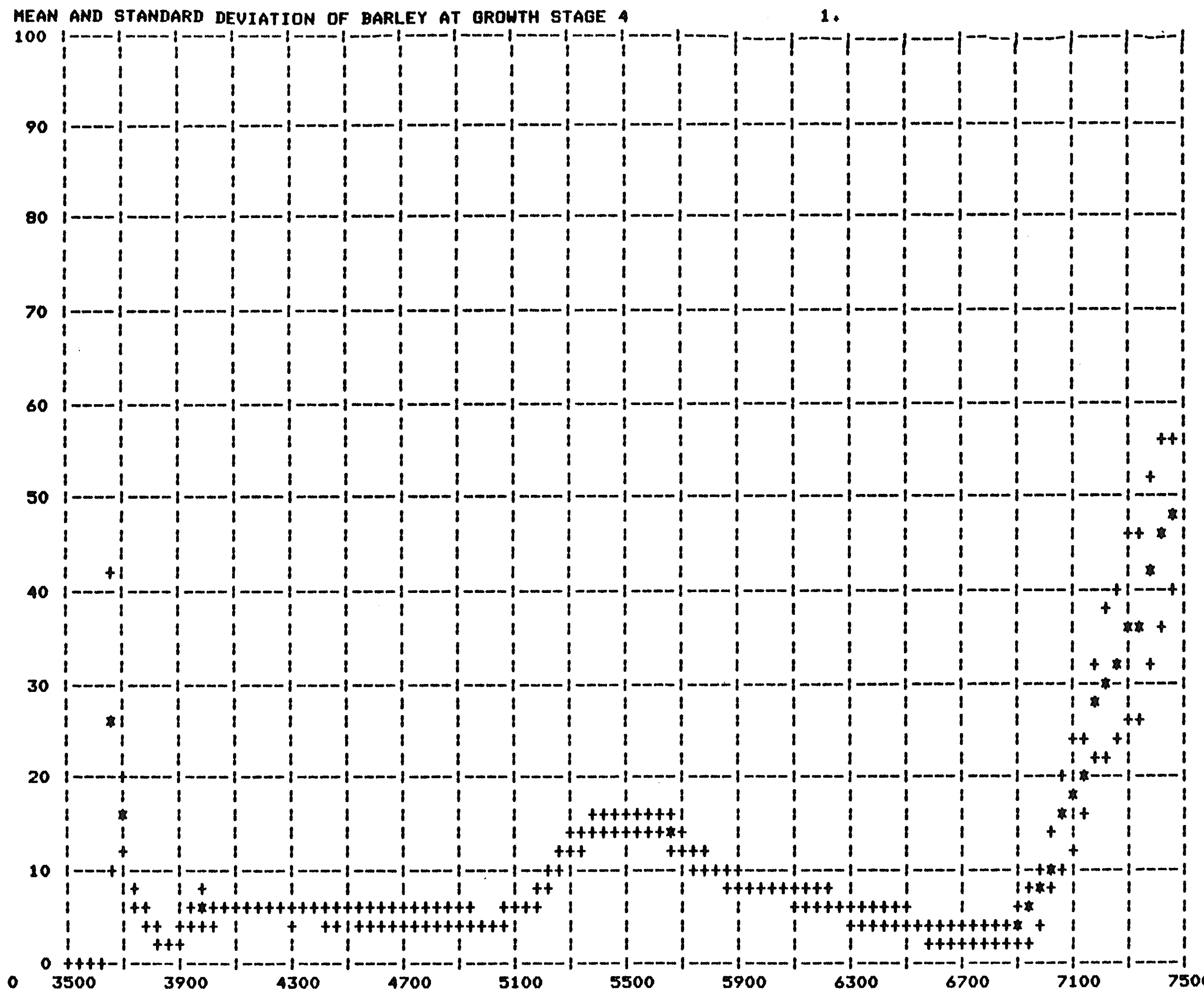

Figure VI. Mean reflectance and mean plus or minus one standard deviation for barley 28 days after seeding.

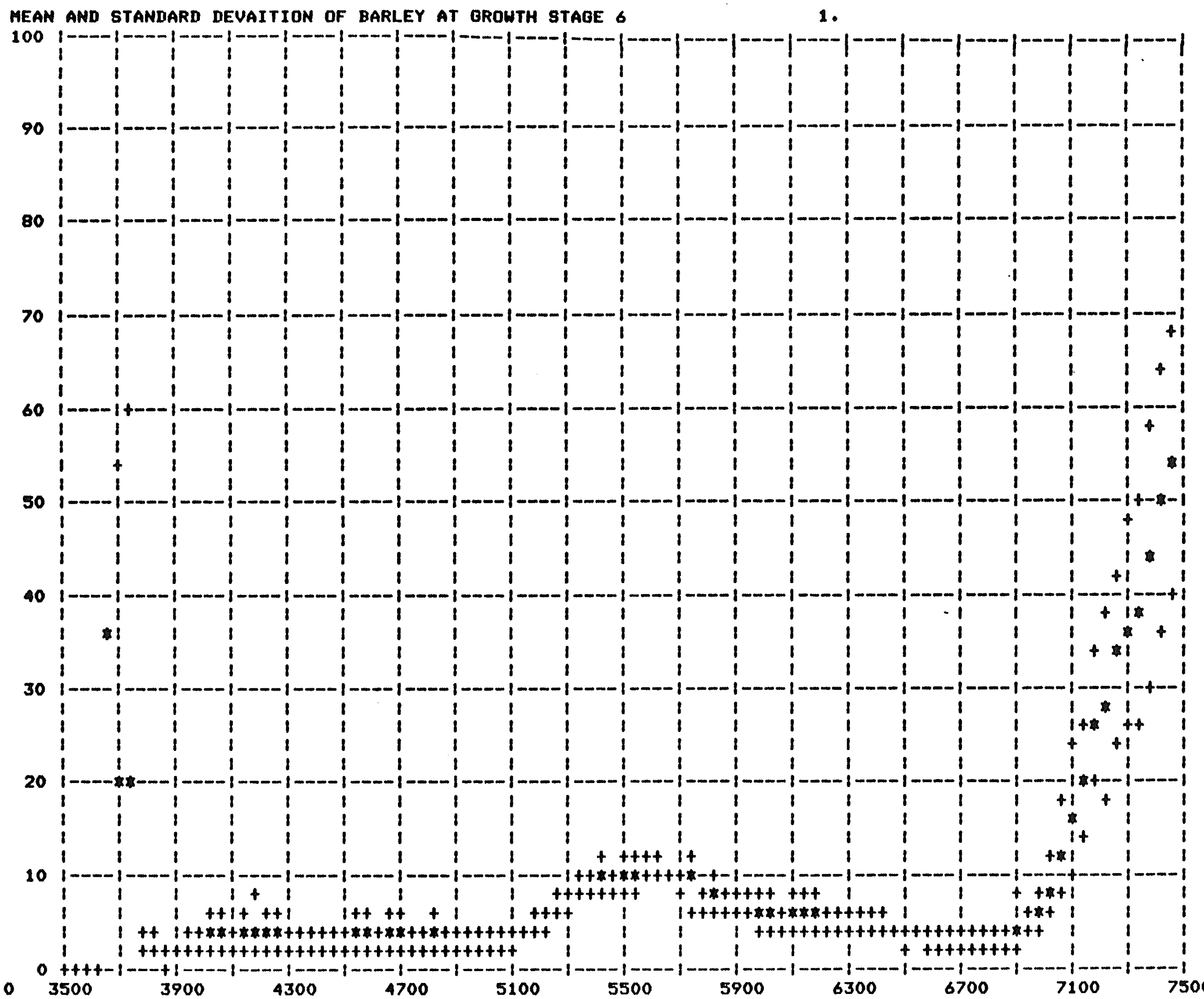

Figure VII. Mean reflectance and mean plus or minus one standard deviation for barley 39 days after seeding.

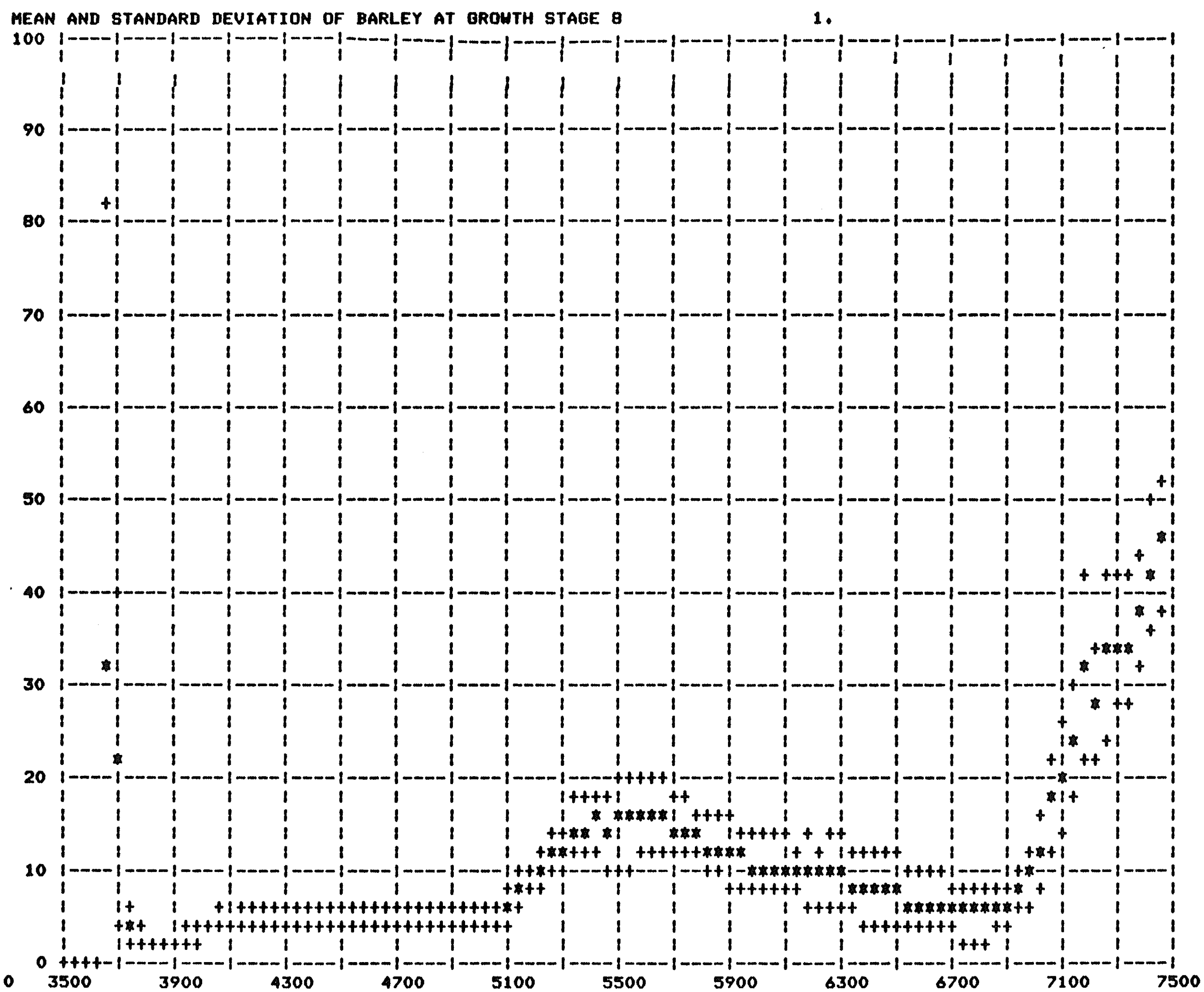

Figure VIII. Mean reflectance and mean plus or minus one standard deviation for barley 53 days after seeding.

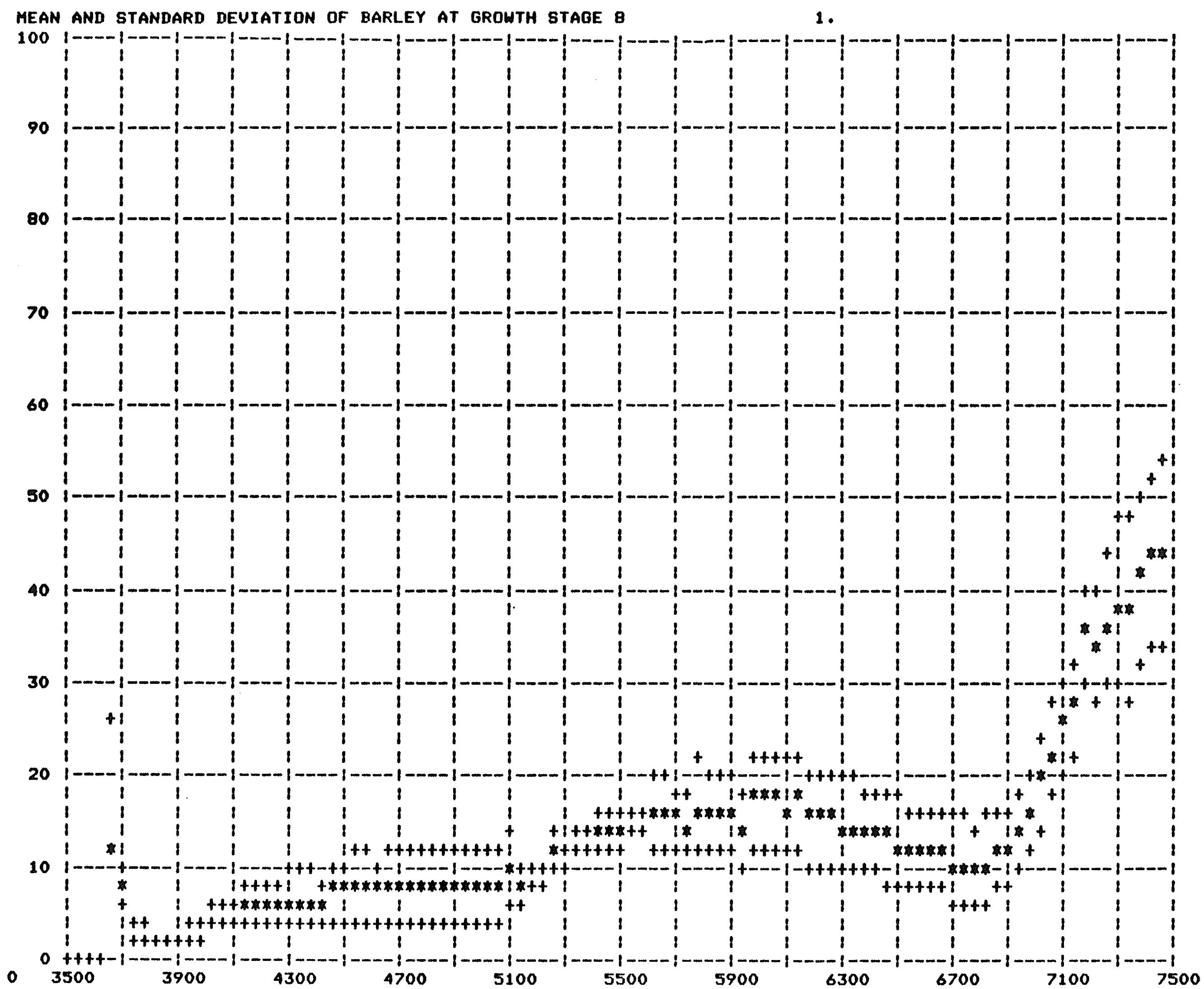

Figure IX. Mean reflectance and mean plus or minus one standard deviation for barley 59 days after seeding.

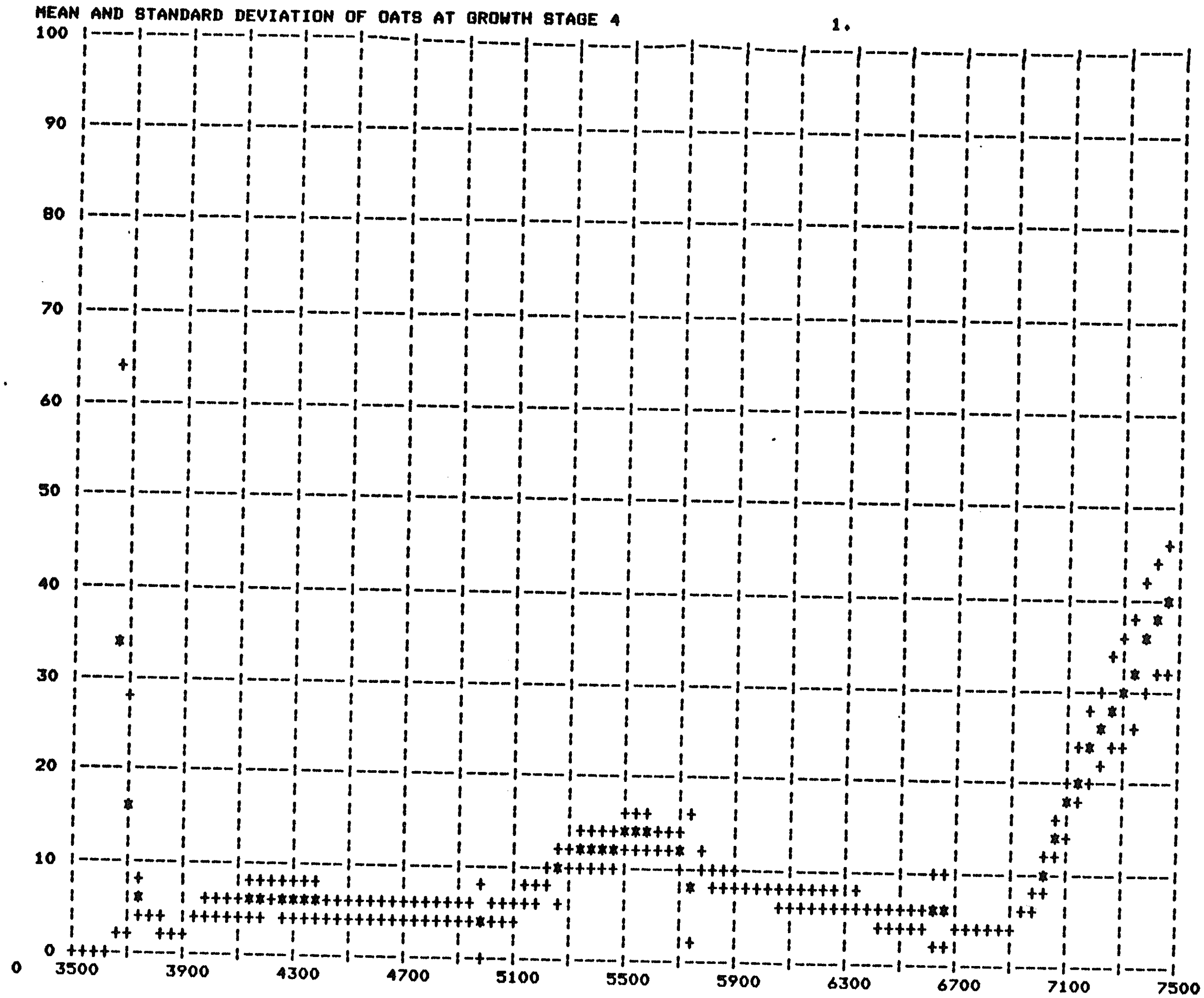

Figure X. Mean reflectance and mean plus or minus one standard deviation for oats 13 days after seeding.

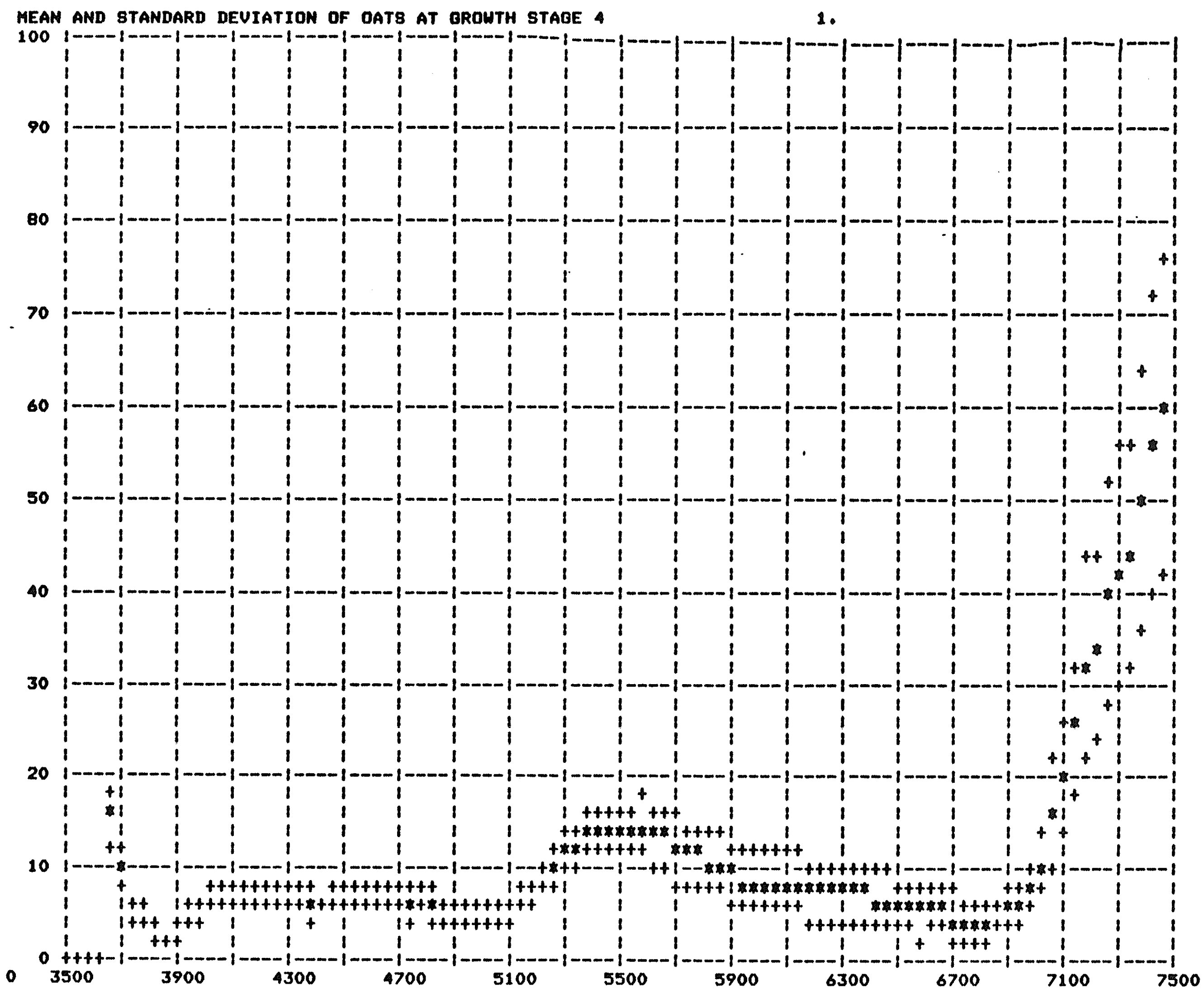

Figure XI. Mean reflectance and mean plus or minus one standard deviation for oats 29 days after seeding.

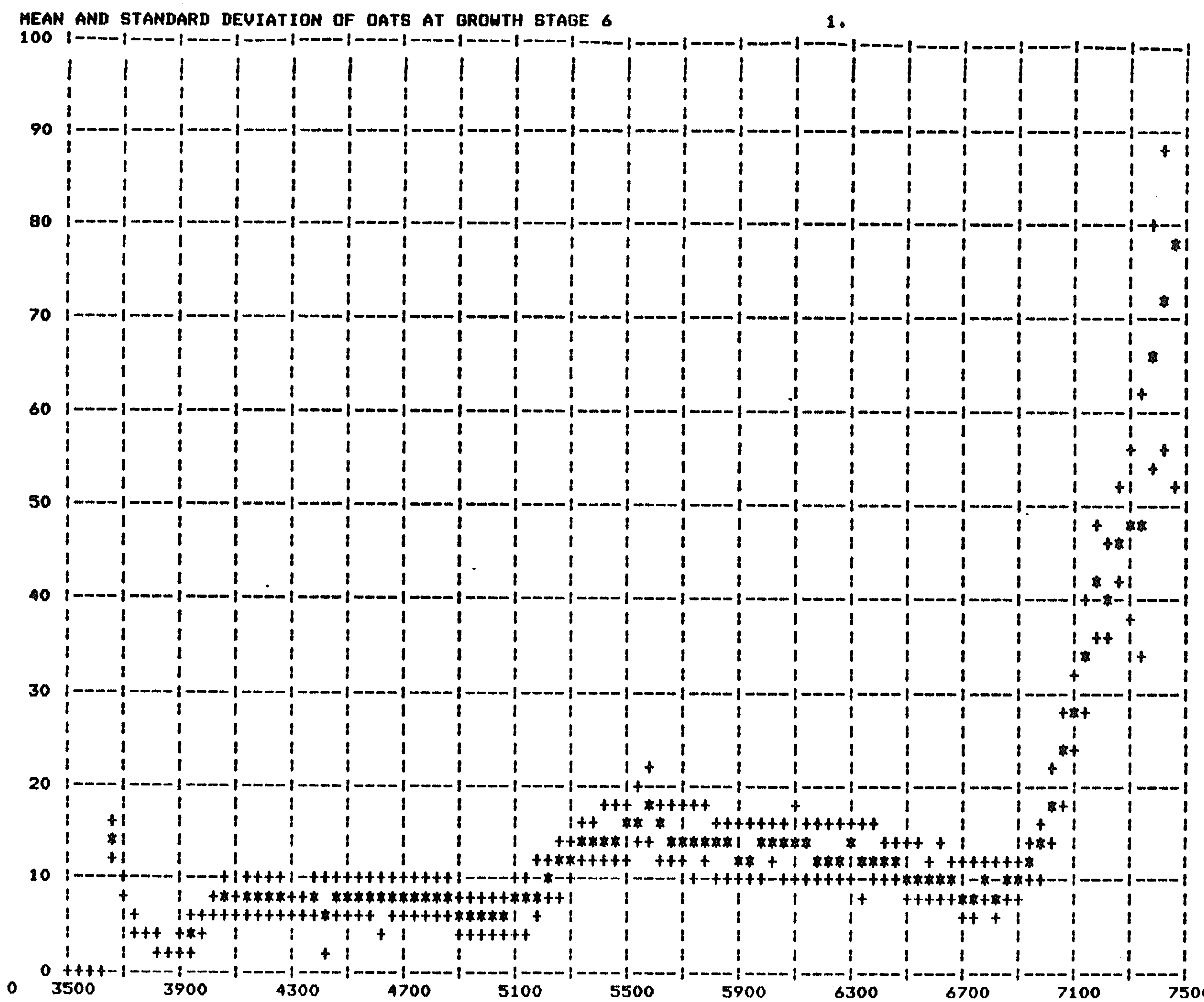

Figure XII. Mean reflectance and mean plus or minus one standard deviation for oats 46 days after seeding.

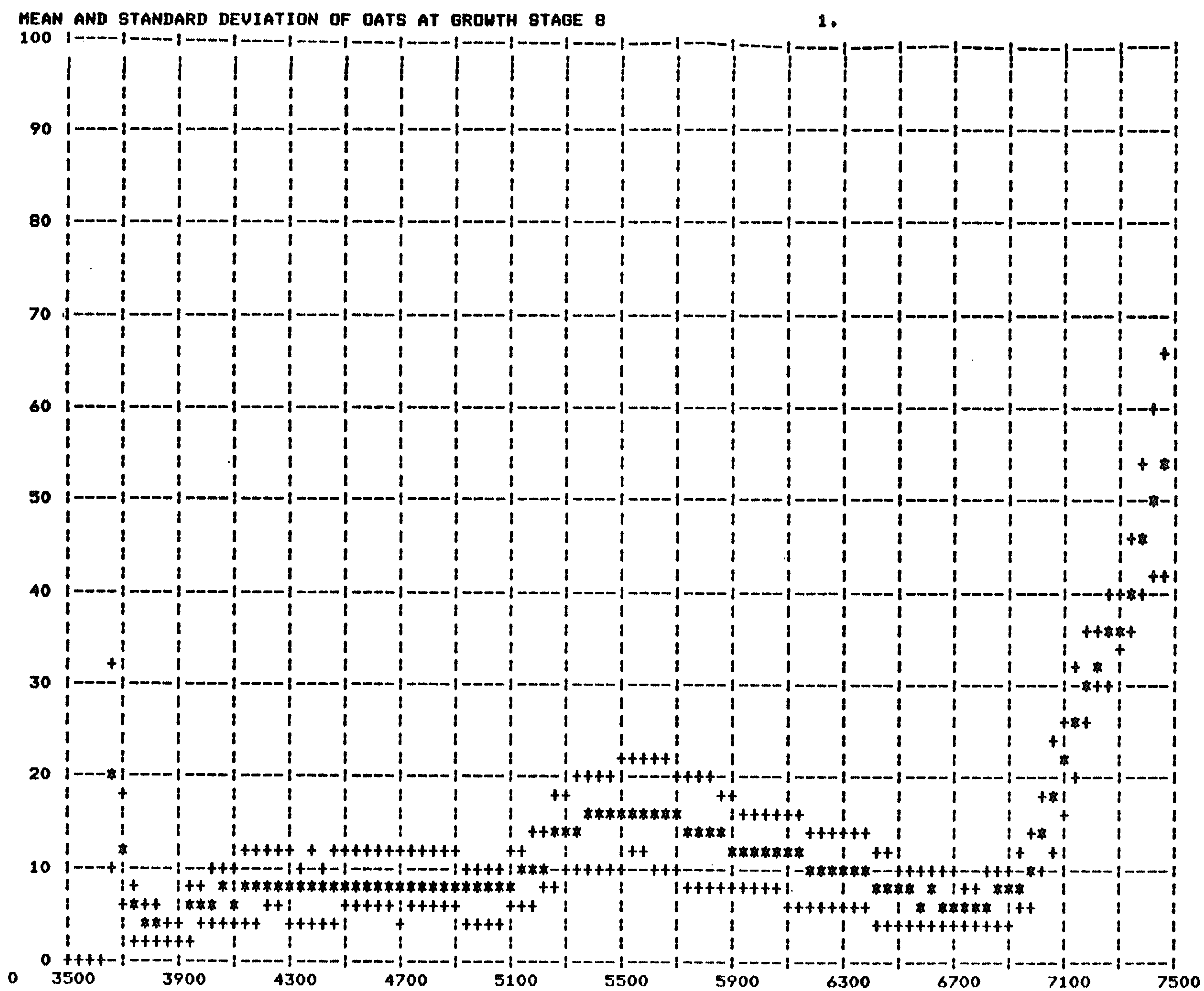

Figure XIII. Mean reflectance and mean plus or minus one standard deviation for oats 56 days after seeding.

APPENDIX II

COMPUTER PROGRAMS

Three computer programs were used in this study to assist in the analysis of reflectance data. These three programs were written in Fortran and are listed in their entirety. The first program was used to calculate reflectance (%) from the raw data. The second program calculated a mean and a standard deviation of reflectance for each treatment at each wavelength. The third program was used to calculate a Student's t for comparisons between species and cultivars, test the resulting t values for significance, and plot a 't profile' which was a curve of the t values plotted as a function of wavelength.

```
ote77
//PLANTSC JOB '0522,CM,98,T=10,F=43,L=4,C=0','H GLICK',MSGLEVEL=1
/*TSO SOIL
//  EXEC WATFIV
//GO.SYSIN DD *
$JOB WATFIV
C
C       DEFINITION OF VARIABLES
C
C     COSAZ  = COSINE OF THE AZIMUTH ANGLE OF THE SUN
C     COSSC  = COSINE OF THE SCATTERING ANGLE
C     COSZ   = COSINE OF THE ZENITH ANGLE OF THE SUN
C     CROPAZ = AZIMUTH ANGLE BETWEEN THE CROP AND THE SENSOR
C     CRRIR  = INTENSITY OF INCIDENT INFRARED RADIATION
C     CRRVIS = INTENSITY OF INCIDENT VISIBLE RADIATION
C     CRWIR  = INTENSITY OF REFLECTED INFRARED RADIATION
C     CRWVIS = INTENSITY OF REFLECTED VISIBLE RADIATION
C     DELTA  = ANGLE OF SOLAR DECLINATION (RADIANS)
C     ELEV   = ZENITH ANGLE OF THE VISIBLE SENSOR
C     FRIR   = CALIBRATION FACTOR FOR INCIDENT INFRARED RADIATION
C     FRVIS  = CALIBRATION FACTOR FOR INCIDENT VISIBLE RADIATION
C     FWIR   = CALIBRATION FACTOR FOR REFLECTED INFRARED RADIATION
C     FWVIS  = CALIBRATION FACTOR FOR REFLECTED VISIBLE RADIATION
C     LAMBDA = WAVELENGTH (ANGSTROMS)
C     NRWAVE = INTEGER RELATIVE WAVELENGTH OF INCIDENT VISIBLE RADIATION
C     NWWAVE = INTEGER RELATIVE WAVELENGTH OF REFLECTED VISIBLE RADIATION
C     OUR    = HOUR ANGLE (RADIANS, MEASURED WESTWARD)
C     PLOT   = PLOT NUMBER
C     PHI    = LATITUDE (RADIANS)
C     REFIR  = % REFLECTANCE OF INFRARED RADIATION
C     REFVIS = % REFLECTANCE OF VISIBLE RADIATION
C     RINTE  = RELATIVE READING OF INCIDENT VISIBLE RADIATION
C     RRIR   = RELATIVE READING FOR INCIDENT INFRARED RADIATION
C     RWAVE  = RELATIVE WAVELENGTH OF INCIDENT VISIBLE RADIATION
C     RWIR   = RELATIVE READING FOR REFLECTED INFRARED RADIATION
C     SONOON = SOLAR NOON IN TERMS OF CENTRAL DAYLIGHT TIME
C     SUNAZ  = AZIMUTH ANGLE OF THE SUN (RADIANS)
C     SINZ   = SINE OF THE ZENITH ANGLE OF THE SUN
C     THETA  = ANGLE FUNCTION OF THE DAY OF THE YEAR (RADIANS)
C     TIME   = TIME OF OBSERVATION (CDT)
C     TIMEA  = TIME OF OBSERVATION  (WHOLE HOURS CDT)
C     TIMEB  = TIME OF OBSERVATION (MINUTES)
C     TOP    = HIGHEST READING OF THE X COORDINATE
C     WINTE  = RELATIVE READING OF REFLECTED VISIBLE RADIATION
C     WWAVE  = WAVELENGTH OF REFLECTED VISIBLE RADIATION
C     ZENITH = ZENITH ANGLE FOR THE SUN
C
      DIMENSION LAMBDA(250),FWVIS(250),FWIR(250),FRVIS(250),FRIR(250)
      DIMENSION RWVIS(250),RWIR(250),RRVIS(250),RRIR(250),REFVIS(250)
      DIMENSION REFIR(250),CRWVIS(250),CRWIR(250),CRRVIS(250),
     1CRRIR(250),Z(125),NREFVS(250),NREFIR(259),CROPAZ(100),NWWAVE(250),
     2RWAVE(250), RINTE(250), WWAVE(250), WINTE(250), NRWAVE(250)
      INTEGER Z,P,Q,R,S,X
      READ(5,100)P,Q,R,S,X
```

```
  100 FORMAT(5A1)
      PHI = .8717
      ELEV = 1.4915
      SONOON = 13.4744
C
C     READ IN CROP AZIMUTH VALUES FOR EACH PLOT
C
      READ(5,21) (CROPAZ(I), I = 1,98)
   21 FORMAT(14(7F10.0,/))
C
C     READ IN CALIBRATION FACTORS FOR LIGHT SENSORS
C
      DO 2 I = 1,101
    2 READ(5,1) LAMBDA(I),FRVIS(I),FWVIS(I)
    1 FORMAT(I4,6X, 4F10.0)
C
C     READ IN REFLECTANCE OBSERVATIONS
C
   99 READ(5,10) PLOT, NDATE, MONTH, NYR, TIMEA, TIMEB, NDAY
   10 FORMAT(2X, F2.0, 3I2, 2F2.0, 2X, I4)
      TIME = TIMEA + TIMEB/60.
      WRITE(6,12) PLOT, MONTH, NDATE, TIME
   12 FORMAT(1H1,'PLOT NO ',F3.0,4X,'MONTH ',I3,4X,'DAY ',I3,
     14X,'TIME ',F6.2)
C
C     CALCULATION OF SCATTERING ANGLE
C
      NPLOT = PLOT
      THETA = .01721 * NDAY
      DELTA = .3964 + 3.631 * SIN(THETA) - 22.97 * COS(THETA)
     1 + .03838 * SIN(2* THETA) - .3885 * COS(2 * THETA)
     2+.07659 * SIN(3 * THETA) - .1587 * COS(3 * THETA)
     3- .01021 * COS(4 * THETA)
      DELTA = DELTA/57.2956
      OUR = (TIME - 13.4744)/12 * 3.1416
      COSZ = COS(DELTA) * COS(PHI) * COS(OUR) + SIN(DELTA)*SIN(PHI)
      ZENITH = ARCOS(COSZ)
      SINZ = SIN(ZENITH)
C     COSAZ = (SIN(DELTA) - (SIN(PHI) * COSZ))/(COS(PHI) * SINZ)
      SINAZ = -COS(DELTA) * SIN(OUR)/SINZ
      SUNAZ = 3.1416 - ARSIN(SINAZ)
      DELTAZ = CROPAZ(NPLOT) - SUNAZ
      WRITE(6,24) ZENITH, SUNAZ, CROPAZ(NPLOT), DELTAZ
   24 FORMAT(1H ,' ZENITH = ',F6.3,' AZIMUTH = ',F6.3,' CROP AZIMUTH = '
     1,F6.3,' DELTA AZIMUTH = ', F6.3)
      COSSC = COSZ * COS(ELEV) + SINZ * SIN(ELEV) * COS(DELTAZ)
      COSSC = ABS(COSSC)
      WRITE(6,25) COSSC
   25 FORMAT(1H ,' COSINE OF THE SCATTERING ANGLE = ', F6.3)
C
C     CALCULATION OF RADIATION INTENSITY FOR EACH WAVELENGTH INTERVAL
C
      READ(5,3) (RWAVE(I), RINTE(I), I = 1,115)
    3 FORMAT(23(5(F6.0,1X,F6.0,1X),/))
```

```
      WRITE(6,501) (RWAVE(I), RINTE(I), I = 1,5)
  501 FORMAT(1H , 5(F6.0,1X,F6.0,1X))
      WRITE(6,501) (RWAVE(I), RINTE(I), I = 111,115)
      READ(5,7) (WWAVE(I), WINTE(I), I = 1,125)
    7 FORMAT(25(5(F6.0,1X,F6.0,1X),/))
      WRITE(6,502) (WWAVE(I), WINTE(I), I = 1,5)
  502 FORMAT(1H ,5(F6.0,1X,F6.0,1X))
      WRITE(6,502) (WWAVE(I), WINTE(I), I = 116,120)
      WRITE(6,502) (WWAVE(I), WINTE(I), I = 121,125)
      TOP = 0.
      DO 8 I = 1,115
    8 IF(RWAVE(I).GT.TOP) TOP = RWAVE(I)
      DO 9 I = 1,115
      NRWAVE(I) = (RWAVE(I) - RWAVE(1))/ (TOP - RWAVE(1)) * 100. + 1.5
      IF(NRWAVE(I).LE.0)NRWAVE(I)=1
      LAMBDA(NRWAVE(I)) = (RWAVE(I) - RWAVE(1))/(TOP - RWAVE(1))*400+350
    9 RINTE(NRWAVE(I)) = RINTE(I)
      TOP = 0.
      DO 101 I = 1,125
  101 IF(WWAVE(I).GT.TOP) TOP = WWAVE(I)
      DO 102 I = 1,125
      NWWAVE(I) = WWAVE(I)/(TOP - WWAVE(1)) * 100. + 1.5
  102 WINTE(NWWAVE(I)) = WINTE(I)
C
C     CORRECTION FOR SOLAR ELEVATION ANGLE
C
      R450 = 0.629 + 0.9171 *(1.5708 - ZENITH)*(1.5708 - ZENITH)
      R550 = 0.5631 + 0.6878 * (1.5708 - ZENITH) * (1.5708 - ZENITH)
      R650 = 0.1935 + 2.111 * (1.5708 - ZENITH) - 2.288 *
     1(1.5708 - ZENITH) * COSSC
      R750 = 0.4061 + 0.571 * (1.5708 - ZENITH) * (1.5708 - ZENITH)
     1-0.788 * (1.5708 - ZENITH) * COSSC
      DO 6 I = 1,100
      IF(I.LE.25) FACTOR = R450
      IF(I.GT.25.AND.I.LT.50) FACTOR = R450 - (R450 - R550) *
     1(I - 25)/25
      IF(I.EQ.50)FACTOR = R550
      IF(I.GT.50.AND.I.LT.75) FACTOR = R550 - (R550 - R650) *
     1(I - 50)/25
      IF(I.EQ.75)FACTOR = R650
      IF(I.GT.75.AND.I.LT.100) FACTOR = R650 - (R650 - R750) *
     1(I - 75)/25
      IF(I.EQ.100) FACTOR = R750
      CRWVIS(I) = FWVIS(I) * WINTE(I) * FACTOR * 1.324/4
      CRRVIS(I) = FRVIS(I) * RINTE(I)
      IF(CRRVIS(I))4,4,5
    4 REFVIS(I) = 0.
      GO TO 6
    5 REFVIS(I) = CRWVIS(I)/CRRVIS(I)
    6 WRITE(6,11)LAMBDA(I), CRWVIS(I),  CRRVIS(I),
     1REFVIS(I)
   11 FORMAT(1H ,I5,5X,F10.5,F15.2, F15.8)
C
C     PLOTTING OF REFLECTANCE DATA
```

```
C
      WRITE(6,12) PLOT, MONTH, NDATE, TIME
      WRITE(6,24) ZENITH, SUNAZ, CROPAZ(NPLOT), DELTAZ
      WRITE(6,25) COSSC
      DO 51 I  = 1,100
   51 NREFVS(I) = REFVIS(I) * 50. + 1.5
      NREFVS(101) = 0
      ML = 1
      L = 51
   84 IF(MOD(ML - 1,5))31,42,31
   42 DO 43 K = 1,101
   43 Z(K) = P
      GO TO 40
   31 DO 44 K = 1,101
   44 Z(K) = R
   40 DO 61 K = 1,101,5
   61 Z(K) = Q
      DO 37 I = 1,101
      IF(NREFVS(I) - L)37,32,37
   32 K = I
      Z(K) = S
   37 CONTINUE
      LM = (L - 1) * 2
      IF(MOD(LM,10))38,201,38
  201 WRITE(6,202) LM, (Z(K), K = 1,101)
  202 FORMAT(1H , I3, 1X,101A1)
      GO TO 203
   38 WRITE(6,36) (Z(K), K = 1,101)
   36 FORMAT(1H , 4X, 101A1)
  203 IF(L.EQ.1) GO TO 71
      L = L- 1
      ML = ML + 1
      GO TO 84
   71 WRITE(6,72)
   72 FORMAT(1H0, 3X,'3500',6X,'3900',6X,'4300',6X,'4700',6X,'5100',
     16X,'5500',6X,'5900',6X,'6300',6X,'6700',6X,'7100',6X,'7500')
      GO TO 99
  444 STOP
      END
$ENTRY
```

```
$JOB WATFIV
C
C    THIS PROGRAM COMPUTES MEAN REFLECTANCE
C
      DIMENSION REFL(100,6)
      DIMENSION RMEAN(100),STD(100)
      READ 20,((REFL(I,J),I=1,100),J=1,6)
20    FORMAT(40X,F10.8)
      DO 30 I=1,100
      SUM = 0
      DO 31 J=1,6
      SUM = REFL(I,J) + SUM
31    CONTINUE
      RMEAN(I) = SUM/6.
30    CONTINUE
      DO 41 I=1,100
      VAR=0
      DO 32 J=1,6
      VAR=VAR + (REFL(I,J) - RMEAN(I)) * (REFL(I,J) - RMEAN(I))
      STD(I) = SQRT(VAR/5.)
32    CONTINUE
41    CONTINUE
      PRINT 50
50    FORMAT('1H1',1X,'WAVELENGTH',10X,'MEAN',25X,'STD')
      PRINT 51
51    FORMAT(' ',1X,10('-'),10X,4('-'),25X,3('-'))
      PRINT 55
55    FORMAT('0')
      DO 40 I=1,100
      IWAVE=350 + (I-1)*4
      PRINT 60,IWAVE,RMEAN(I),STD(I)
60    FORMAT(' ',4X,I3,10X,F12.8,15X,F12.8)
40    CONTINUE
      STOP
      END
$ENTRY
```

```
$JOB WATFIV
C
C    THIS PROGRAM COMPUTES T VALUES FOR TWO MEANS
C
      DIMENSION STD(100,2),RMEAN(100,2),VAR(100,2),KAZ(1,2), Z(101)
      DIMENSION SDBAR(100),TVAL(100),ATVAL(100), ITVAL(110)
      CHARACTER*2 ASTER/'  '/
      INTEGER Z,P,Q,R,S,X
      READ(5,100)P,Q,R,S,X
  100 FORMAT(5A1)
  999 PRINT 54
54    FORMAT(1H1)
      DO 11 J = 1,2
      READ 1
1     FORMAT(/)
   11 READ 10, (RMEAN(I,J),STD(I,J),I=1,100)
10    FORMAT(17X,F11.8,17X,F11.8)
      DO 20 I=1,100
      DO 30 J=1,2
      VAR(I,J)=STD(I,J) * STD(I,J)
30    CONTINUE
20    CONTINUE
      DO 400 I=1,100
      SDBAR(I)=SQRT((VAR(I,1)/3.) + (VAR(I,2)/3.))
400   CONTINUE
      DO 50 I=1,100
      IF (SDBAR(I).EQ.0) SDBAR(I)=SDBAR(I)+1
      TVAL(I)=((RMEAN(I,1) - RMEAN(I,2))/SDBAR(I))
50    CONTINUE
      PRINT 55
55    FORMAT(1X,'WAVELENGTH',25X,'T VALUE')
      PRINT 56
56    FORMAT(' ',10('-'),25X,7('-'))
      DO 60 I=1,100
      ATVAL(I)=ABS(TVAL(I))
      IWAVE=350 + (I-1) * 4
      IF(ATVAL(I).GE.4.604)ASTER='**'
      IF(ATVAL(I).LT.4.604.AND.ATVAL(I).GE.2.776) ASTER='*'
      IF(ATVAL(I).LT.2.776) ASTER='  '
      PRINT 58,IWAVE,TVAL(I),ASTER
58    FORMAT(' ',4X,I3,25X,F10.5,A3)
60    CONTINUE
      WRITE(6,555)
  555 FORMAT(1H1)
      DO 101 I = 1,100
  101 ITVAL(I) = (TVAL(I) + 4.) * 5. + 1.5
      ITVAL(101) = 0
      ML = 1
      L = 41
   84 IF(MOD(ML - 1,5))31,42,31
   42 DO 43 K = 1,101
   43 Z(K) = P
      GO TO 40
   31 DO 44 K = 1,101
```

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   44 Z(K) = R
   40 DO 61 K = 1,101,5
   61 Z(K) = Q
      DO 37 I = 1,101
      IF(ITVAL(I) - L)37,32,37
   32 K = I
      Z(K) = S
   37 CONTINUE
      LM = (L - 1)
      IF(MOD(LM,5))38,201,38
  201 LMM = 4 - (ML - 1)/5
      WRITE(6,202) LMM, (Z(K), K = 1,101)
  202 FORMAT(1H , I3, 1X,101A1)
      GO TO 203
   38 WRITE(6,36) (Z(K), K = 1,101)
   36 FORMAT(1H , 4X, 101A1)
  203 IF(L.EQ.1) GO TO 71
      L = L- 1
      ML = ML + 1
      GO TO 84
   71 WRITE(6,72)
   72 FORMAT(1H0, 3X,'350 ',6X,'390 ',6X,'430 ',6X,'470 ',6X,'510 ',
     16X,'550 ',6X,'590 ',6X,'630 ',6X,'670 ',6X,'710 ',6X,'750 ')
      GO TO 999
  444 STOP
      END
$ENTRY
-¦ *
```