Technical Report No. 133

DESIGN OF FIELD SPECTROPHOTOMETER LAB

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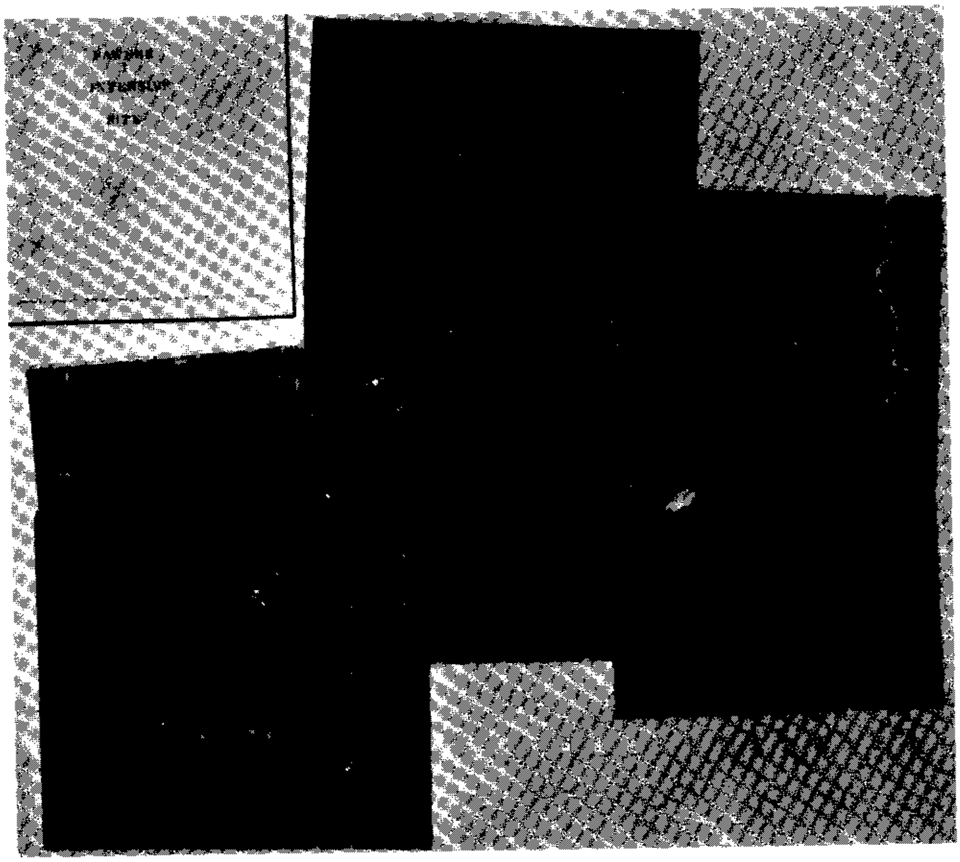
GRASSLAND BIOME

U.S. International Biological Program

October 1971



FRONTISPIECE. PAWNEE SITE OF THE IBP GRASSLAND BIOME. Kodak Ektachrome Infrared Aero. #8443 color mosaic copied and printed in color. Original film scale 1/12,000. Flown on June 28, 1969, with a Zeiss RMK-A mapping camera.

PUBLICATION NOTE

The following report is from a thesis submitted to the Graduate Faculty of Colorado State University in partial fulfillment of the requirements for the degree of Master of Science. The material has also been published as Science Series No. 2, Watershed Sciences Department, Colorado State University.

Pearson will be using this technique and information in his dissertation work now in progress. Therefore, please be extremely careful not to distribute this technical report beyond your program.

ABSTRACT

DESIGN OF FIELD SPECTROPHOTOMETER LAB

The IBP Grassland Biome Program of the National Science Foundation has funded a ground based remote sensing study of the feasibility of determining the percent cover of standing green vegetation for a shortgrass prairie ecosystem by measuring the spectroreflectance of an undisturbed patch of vegetation. The equipment assembled for this study include: a spectroradiometer, with telescope viewing optics; a computer based digital data acquisition system; and calibration and logistical support systems. The determination of spectroreflectance is made by measuring with the spectroradiometer the spectroradiance reflected from a white panel painted with barium sulfate and then measuring the spectroradiance reflected from the 'in situ' sample. The ratio of these two spectroradiances at each wavelength is the spectroreflectance of the sample. Several tests have been completed which assess the suitability of the spectroradiometer for measuring spectroreflectance of various objects as well as determining percent cover of prairie vegetation.

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ACKNOWLEDGEMENT

I would like to thank the National Science Foundation (Grant GB-13096-A) which, through its International Biological Program, has provided the funding for the spectrophotometer laboratory herein described, and Dr. Lee D. Miller for his guidance and support of this remote sensing project and for providing his computerized remote sensing library for use in the Selected Bibliography section.

I was fortunate to have the able assistance of fellow students, K. Jon Ranson, Ralph R. Root, and C. Jim Tucker in the construction and subsequent testing of the equipment and methods used in the laboratory.

Finally, I would like to thank the members of my family for their aid and help to me during my work in this endeavor, especially my wife, Cindy, for her assistance and understanding during the preparation of this thesis.

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I. INTRODUCTION

The recent development of interest in remote sensing has led numerous investigators to devise methods of remote sensing surveying and applications to the problems found in the present day natural resource scene (Colwell, 1968). In particular, the application of remote sensing techniques to vegetation study has been advancing rapidly, mainly in the agricultural areas (Silva et al., 1971), (Meyer and Chang, 1971), for two reasons: 1) economic--crop land is worth more than uncultivated land and 2) simplicity of interpretation--a cultivated crop tends to be more homogeneous within fields and similar between separate fields, while undisturbed land tends to be inhomogeneous everywhere.

Until recently there had not been enough resources available to sponsor a ground study of a natural prairie scene using remote sensing methodology. However, the United States International Biological Program (IBP), funded by the National Science Foundation, was started a few years ago to study natural ecosystems by several different methods, including remote sensing. The IBP Ecosystem Analysis Program has been subdivided into several ecological biomes and the Grassland Biome Program has sponsored* this study. This biome was organized to study a typical prairie ecosystem, its components, driving forces, internal processes and interactions using systems analysis techniques and to formulate a computerized model for digital simulation of the ecosystem.

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* Research sponsored by the National Science Foundation Grant GB-13096-A.

Two important functions of the ecosystem, and the model, which need to be determined are the amount of incoming solar energy and the primary forage production of the plants in the ecosystem. Primary production of an ecosystem has traditionally been measured by the increase in plant biomass per unit of land area measured in units such as kilograms per hectare. This determination has been made by the destructive sampling or clipping of a measured area which, when sampled and weighed, gives the desired measurement (dry biomass, root biomass, total biomass, etc.). Unfortunately, once an area has been sampled, it cannot be used again, preventing remeasurement of a fixed set of plots throughout a growing season. It is evident that a nondestructive sampling technique would be very beneficial for determination of primary productivity.

The point quadrat method, which was first described in 1963 (Warren Wilson, 1963), can be used to nondestructively determine the amount of ground cover over a specified area. This method uses a grid of uniform spacing placed above the sample area with a pin which drops from grid intersection points into contact with the vegetation canopy. When the pin touches a component of the vegetative cover, a "hit" is recorded, and a miss is recorded if no vegetation is touched. After numerous insertions of the pin the percentage of ground cover is computed by dividing the number of hits by the total number of insertions and multiplying by 100.

The two parameters estimated by variations of the point quadrat method are leaf area index and percent cover. Leaf area index is defined as the total amount of leaf area per unit ground area (which can have a value greater than one if the vegetation has a dense cover value with several levels of leaves in the canopy). Percent cover is defined as the vertical projection of the plant canopy onto the ground surface and is expressed as a percentage of the study area (with a maximum value of 100%). These two parameters have been correlated to total standing dry biomass for the prairie ecosystem by another research effort in the Grassland Biome Program (Knight, 1971) so that primary productivity estimates can be made by nondestructive means.

The main advantage of the point quadrat method is its simplicity of design and operation. A major disadvantage which more than outweighs the advantages is the length of time and the amount of field effort needed to obtain the data. It is evident that a better, more efficient, nondestructive method of obtaining percent cover data is needed and should be devised using remote sensing techniques. It is for this reason that the field spectrophotometer laboratory described in this thesis was proposed, funded and constructed by the Grassland Biome Program of the IBP. Initial investigations were conducted at the Pawnee Site*.

The primary purpose of the field spectrometer is to determine the two or three optimum wavelength bands (less than .1 micrometers wide) of visible and near visible electromagnetic radiation (.2 to 1.6 micrometers) to be used by a simple hand-held radiometer for remote determination of percent cover. This radiometer would measure the radiance from a grass plot in only these optimum wavelength bands and then would measure the irradiance incident on the plot in these same optimum bands. Using these measurements the operator could then go to a nomogram or table to obtain the percent cover of functioning green vegetation on the plot.

Since the construction of the field spectrophotometer and the initial field experimentation in the summer of 1970, several other secondary projects have been proposed and undertaken. They include: measurement of

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* The Pawnee Site is located 20 miles northeast of Fort Collins, Colorado, on the Central Plains Experimental Range and on the Pawnee National Grasslands.

spectroreflectance of several important grassland constituents throughout the growing season, measurement of the spectral light quality of incoming solar radiation inside a clump of *Bouteloua gracilis* (blue grama), and measurement of the spectrotransmission loss of sunlight in the gas analyzer plastic domes of the photosynthesis experiment for the Grassland Biome Program, IBP. A complete description of each of these experiments is included later in this thesis.

II. THEORY OF OPERATION

The field spectrometer laboratory primarily obtains a measurement of spectroreflectance which is an estimate of the parameter termed bidirectional spectroreflectivity of electromagnetic radiation in the wavelength region from .2 to 1.6 micrometers (2000Å to 16000 Å). This parameter is defined as the ratio of radiance from an object to the incident irradiance on the object and is determined for each infinitesimally small wavelength intervals in the wavelength band of interest for certain specified solid angles of illumination and reflection (Fig. 1) (Willow Run Laboratories, 1968, p. I-80). If it is further assumed that the incident radiation is coming from the entire upper hemisphere (2π steradians solid angle) then

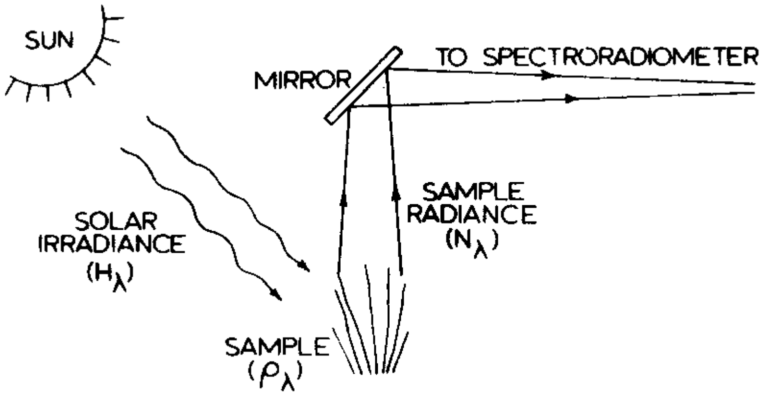


Fig. 1. SPECTRAL ENERGY FLOW DIAGRAM. Schematic drawing of energy flow from sun which is reflected off of the sample to the spectroradiometer.

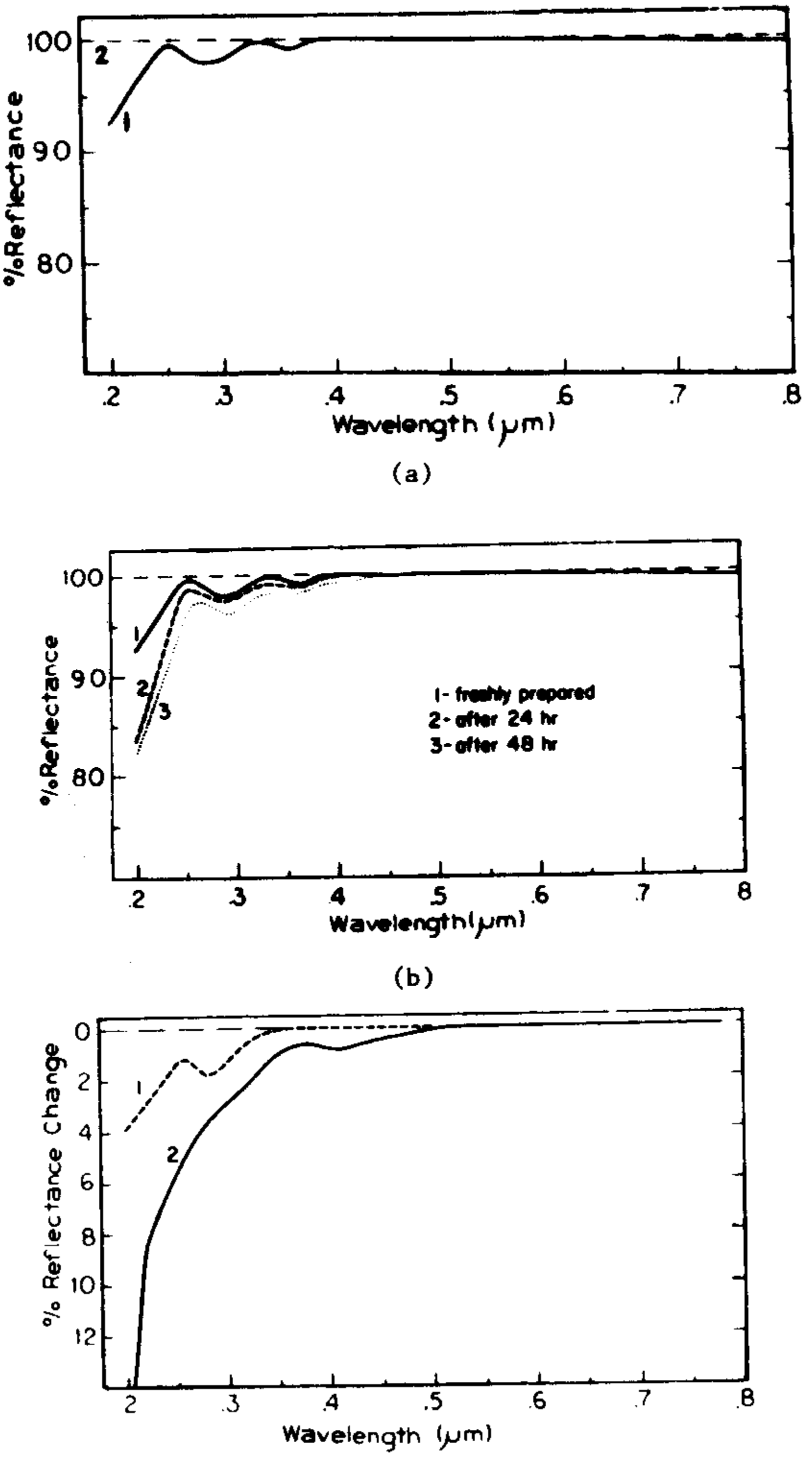
another term can be defined called directional reflectance as the ratio of the radiance reflected into a specific solid angle to the incident irradiance coming from the entire upper hemisphere. Directional reflectance can be expressed mathematically as:

$$\rho_\lambda = C\ N_\lambda/H_\lambda \qquad (1)$$

Where ρ_λ is the directional spectroreflectance at wavelength λ, N_λ is the spectroradiance (watts-cm^2-micrometer-steradian) at wavelength λ, H_λ is spectroirradiance (watts-cm^2-micrometer) at wavelength λ, and C is a constant which contains the solid angle viewed in the radiance measurement (Holter, 1970, p. 131).

The actual field measurement scheme employs a spectroradiometer with a variable, narrow field of view (see section on spectroradiometer) rather than a radiometer such as the Eppley Pyranometer which accepts radiation from anywhere in the hemisphere above its detector plate (Gier, 1951). Since irradiance, H_λ, is a measure of total radiation incoming to a point on a reflecting surface from the entire hemisphere above that surface (in this case, the ground surface), H_λ has to be measured indirectly.

A value for H_λ can be determined by measuring the sunlight reflected from an aluminum panel coated with a barium sulfate ($BaSO_4$) paint manufactured by the Eastman Kodak Company. The $BaSO_4$ was chosen for its high diffuse reflectance and durability relative to Magnesium Oxide (MgO_2), which previously has been used as a reflectance standard (Fig. 2). Furthermore, the $BaSO_4$ surface is approximately a Lambertian reflector which has directional reflectance properties (Grum, 1968). A diffuse reflector is one in which not all of the reflected energy leaves at the same angle as the angle of incidence and a Lambertian reflector is one in which all of



(c)

Fig. 2. COMPARISON OF THE SPECTROREFLECTANCE OF MAGNESIUM OXIDE (MgO_2) TO BARIUM SULFATE ($BaSO_4$). All curves show the ratio of the spectroreflectance of magnesium oxide to barium suflate. (a) for freshly prepared MgO_2 (1) and $BaSO_4$ (2); (b)for MgO_2 at varying periods of time after preparation; (c)for $BaSO_4$ (1) and MgO_2 (2) after exposure to intense ultraviolet radiation for 2.9 megalux hours. (Curves courtesy of Eastman Kodak Company.)

the incident energy is reflected and ρ_λ will be constant for all outgoing directions and angles from normal assuming a sufficiently large reflecting surface (large enough area to fill the solid angle of radiance for all view angles sampled) (Smith, 1966, p. 184). Therefore, by measuring the spectroradiance from the Lambertian surface at any arbitrary direction and applying equation 1 to that set of spectroradiance values the total spectroirradiance incident to the reflecting Lambertian surface can be determined. The unknown sample being radiometrically compared to $BaSO_4$, however, is usually not considered as being Lambertian or even diffuse and therefore another concept has to be considered.

If the sample surface dA has specular or bidirectional reflectance properties, that is, the radiance at some direction and normal angle depends not only on the intensity of the incident radiation, but upon the angles of incidence and reflection, then the spectroreflectance data must be labeled for a specific solar angle (solid angle $d\Omega_i$, normal angle Θ_i, direction Φ_i) and a specific viewing angle (solid angle $d\Omega_r$, normal angle Θ_r, and direction Φ_r) (Fig. 3). Therefore, in order to properly ratio reflected radiation to incoming radiation the white panel measurements must be made under the same angular constraints as those used in the sample measurements. For this reason the reflecting mirror is set up so that the same view angle (vertical) is maintained for both the white panel and sample measurements and the measurements are made as close together in time as possible so that the sun's angle or intensity will not change due to movement in the sky or to clouds intercepting or reflecting the incident radiation.

The ratio of the radiance from the unknown sample to the radiance from the white panel for a certain pair of viewing and solar angles, and a certain wavelength, gives a true spectroreflectance relative to that of

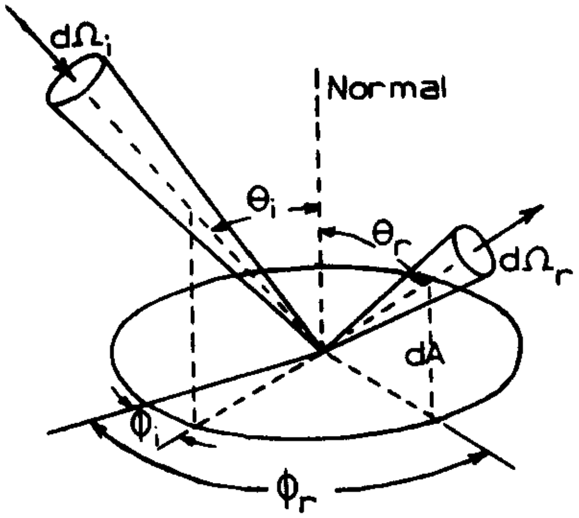


Fig. 3. BIDIRECTIONAL REFLECTANCE. A schematic drawing of bidirectional reflectance from the area dA for incident electromagnetic radiation in the solid angle $d\Omega_i$ which is at angles ϕ_i and θ_i reflected into the solid angle $d\Omega_r$ which is at angles ϕ_r and θ_r. (Willow Run Laboratories, 1968.)

$BaSO_4$ which can be used as an estimate of the bidirectional spectroreflectivity of the object under study (Holmes, 1970, pp. 314-319).

The same general concept holds true when the fiber optics probe is used (see section on spectroradiometer) except that its viewing port has an acceptance angle of 2π steradians which allows the measurement of spectroirradiance directly. However, when measuring spectroreflectance using the fiber optics probe, the white panel and the same technique for telescope viewing must be used for much the same reasons listed above.

The properties of the sample object which determine its spectroreflectivity are numerous and varied and none will be described in detail, however, a few will be mentioned. They include: chemical elements which comprise the object, chemical compounds formed by these elements (Franklin, 1970), the physical state of the object (solid, liquid, or gas), the temperature of the object, and surface coatings or films on the object (Watson, 1970). If the object is biotic, further properties are significant: angle of view (Fig. 4), time of year, time of day, species of plant, amount of moisture stress the plant is under, etc. (Olson, 1962, 1968). It is easy to see that since there are so many variables involved in determining an object's spectroreflectivity that the spectroreflectivity can differ greatly from one object to another, or even between similar objects for different conditions (e.g., aspen leaves in midsummer vs. fall). The techniques of remote sensing in the visible and near visible regions of the electromagnetic spectrum rely on these differences in order to remotely distinguish one type of object, or object condition, from another. A bibliography listing is included (Appendix I) for further reference.

The three objects of interest in the initial laboratory experiments conducted at the Pawnee Site are: live, green vegetation; dead, brown vegetation; and bare soil. The spectral reflectivities from each of these

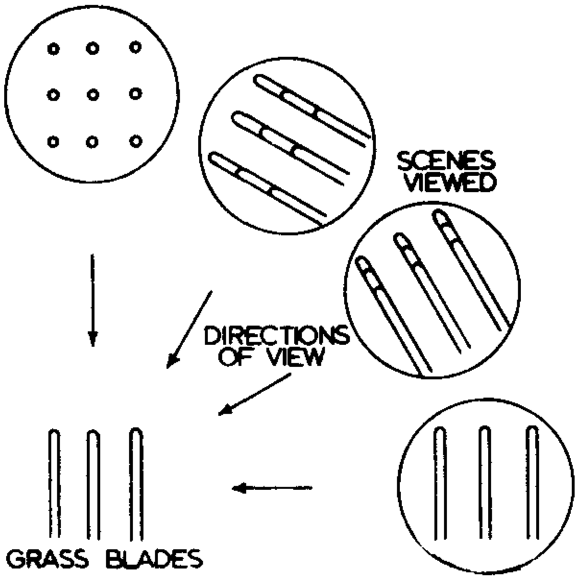


Fig. 4. COMPOSITE REFLECTANCE OF GRASS AS A FUNCTION OF VIEW ANGLE. Schematic drawing showing the reason that a grass clump has bidirectional reflectance properties (Hoffer et al, 1966).

objects viewed individually differ greatly in shape and reflectance value, especially in the region from .6 to .8 micrometers (Fig. 5a). The diversity of shape and value for these curves gives a method of distinguishing between them when viewed individually (Krinov, 1947) (Orr, 1962).

The discrimination becomes more difficult when the objects are not resolved seperately, but are viewed together in some undisturbed natural assemblage. The composite spectroreflectivity from the combination of all three objects at any wavelength will be a function of the individual spectroreflectivity curves of each of the constituents as well as their relative amounts in the area viewed (Fig. 5b). More specifically:

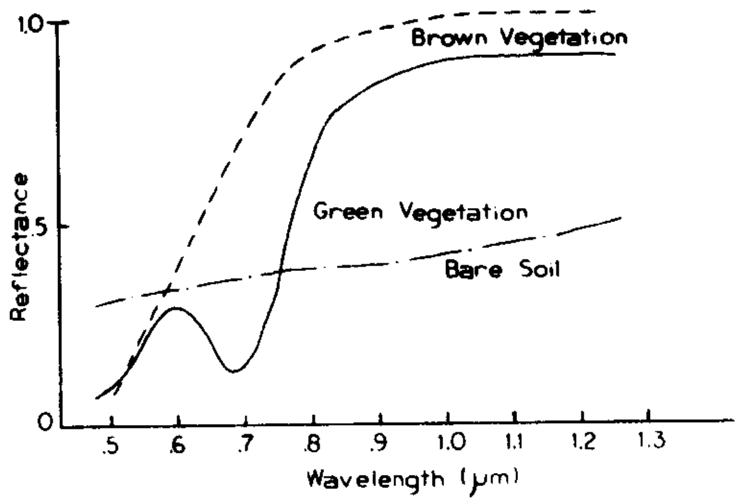
$$C_\lambda = \alpha g_\lambda + \beta d_\lambda + \gamma s_\lambda \tag{2}$$

where C_λ = composite reflectivity at wavelength λ;
α = relative amount of green vegetation;
β = relative amount of dead vegetation;
γ = relative amount of bare soil;
g_λ = reflectivity of green vegetation at λ;
d_λ = reflectivity of dead vegetation at λ; and
s_λ = reflectivity of bare soil at λ.

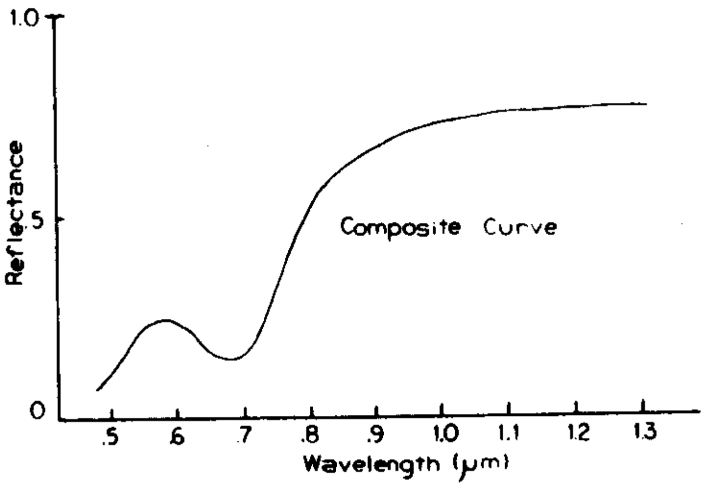
A remote sensing method of determining the relative amounts of green vegetation, dead vegetation, and bare soil in a large field of view where none can be resolved individually can be based on the diversity of shapes and values of the objects' spectroreflectivity curves. If it can be assumed that only these three objects constitute the field of view then:

$$\alpha + \beta + \gamma = 1 \tag{3}$$

or rearranging $\gamma = 1 - \alpha - \beta$



(a). for three individual constituents of a clump of blue gramma sod.



(b). for a specific combination of the three constituents.

Fig. 5. SPECTROREFLECTANCE OF THE SURFACE COMPONENTS OF BLUE GRAMMA SOD.

substituting into (2)

$$\begin{aligned} C_\lambda &= \alpha g_\lambda + \beta d_\lambda + (1-\alpha-\beta)s_\lambda \\ &= \alpha g_\lambda + \beta d_\lambda + s_\lambda - \alpha s_\lambda - \beta s_\lambda \\ &= \alpha g_\lambda - \alpha s_\lambda + \beta d_\lambda - \beta s_\lambda + s_\lambda \\ &= \alpha\ (g_\lambda - s_\lambda) + \beta(d_\lambda - s_\lambda) + s_\lambda \end{aligned}$$

rearranging

$$\alpha(g_\lambda - s_\lambda) = C_\lambda - s_\lambda - \beta(d_\lambda - s_\lambda)$$

and finally

$$\alpha = \frac{C_\lambda - s_\lambda - \beta(d_\lambda - s_\lambda)}{g_\lambda - s_\lambda} \tag{4}$$

Equation 4 is a relationship for α in terms of β and several reflectance terms all measured at wavelength λ. Since the relative amounts of the constituents (equation 3) are not a function of wavelength, an estimate of α can be made by simultaneously solving equation 4 for a pair of different wavelengths. However, because of the errors involved in measuring each of the reflectance values, the estimate of α will resultingly be in error. This error can be reduced by solving for α with several pairs of wavelengths rather than just one and averaging the results together. However, the magnitudes of g_λ, d_λ, and s_λ must first be known for the wavelengths used in the computation (Miller and Pearson, 1969).

The values of spectroreflectances of each of the constituent components (green vegetation, dry vegetation, and bare soil) must be determined by either viewing each of the components in the area of interest separately with a small field-of-view or by another method (Miller and Pearson, 1971, p. 9). Once the spectroreflectance of each of the constituent components has been determined, the relative amounts of each of the constituent components can be determined for an unknown area by solving equations 2,3, and 4.

III. DESIGN OF THE SPECTROPHOTOMETER LABORATORY

In order to properly field test the equations and objectives set forth in the previous section, a field-portable spectrometer laboratory was constructed which could measure radiant intensity of 'in situ' samples. The equipment comprising the field spectrometer laboratory can be classified in four categories: 1) spectroradiometer, 2) computer controlled digital data acquisition system, 3) maintenance and logistical support equipment, and 4) spectroradiation calibration equipment. Each of these categories will be discussed separately in detail as well as their combination into the functioning spectrometer laboratory.

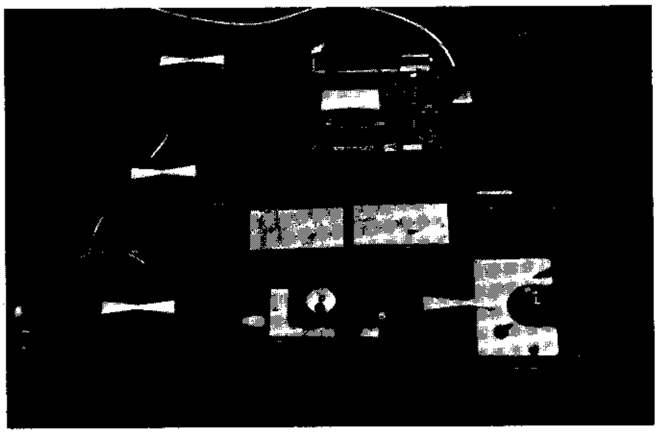
Spectroradiometer

The heart of the system is the spectroradiometer which measures the intensity of visible and near visible electromagnetic radiation in the wavelength region from .18 to 1.6 micrometers. The instrument chosen is an EG&G Model 580-585 spectroradiometer with high sensitivity detector heads, telescope, and fiber optics probe. This instrument was selected partly because of its telescopic viewing optics which allow the operator to radiometrically view a sample from a distance without disturbing it in any way. Previous to the introduction of the EG&G 580-585 spectroradiometer system, most spectroreflectance measurements were made by bringing the sample into the laboratory and inserting the material into the sample chamber of a laboratory type spectrophotometer. However, this instrumentation allows the direct observation of 'in situ' samples which can be spectrally changed by removing them to be measured elsewhere at a later time.

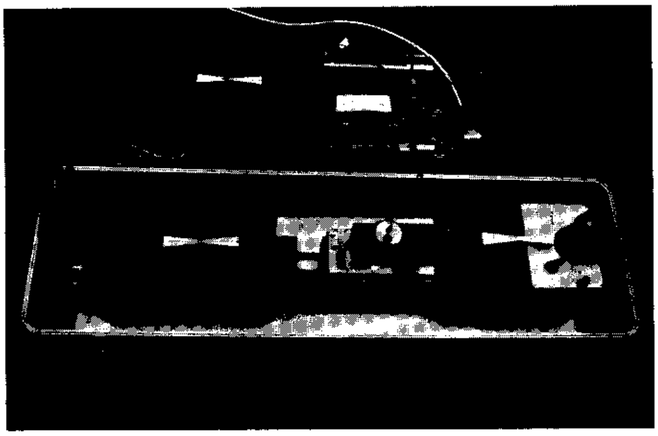
The spectroradiometer system is composed of the following modular subsystems:

1. a reflective telescope for viewing the sample (lower right, Fig. 6a);
2. a monochromator housing which accepts one of three gratings used to select the wavelength being sampled (lower center and middle; Fig. 6a);
3. a high sensitivity, near infrared detector head (lower left, Fig. 6a) and a separate power supply and cooling controller (upper left, Fig. 6a);
4. a high sensitivity, ultraviolet-visible detector head (middle left, Fig. 6a);
5. an indicator unit through which the radiant intensity signal is amplified (upper middle, Fig. 6a); and
6. a 1 meter fiber optics probe which replaces the telescope (upper left, Fig. 6a).

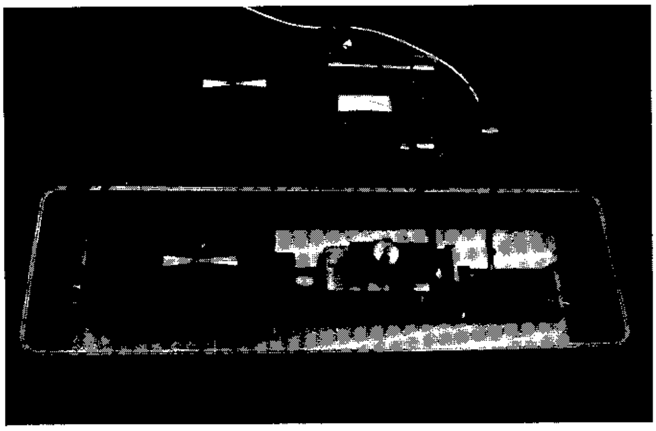
The telescope is the module that selects the variable field-of-view 2° to 7.5' (Table 1), and projects the image onto a diffuser disk for input to the monochromator grating. The telescope can be used to measure either radiance or irradiance from ground sample areas as large as the size of the optical folding mirror situated over the sample down to a few millimeters in diameter. This feature allows the direct study of whole grass plots down to a few grass blades (for smaller study areas, the fiber optics probe is used in place of the telescope). The optical design of the telescope is a combination of refractive and reflective optics with quartz refractive elements to allow transmission of a broad band of radiation (from .2 to 3.2 μm). The telescope has a movable first surface mirror which either reflects the viewed image through an eyepiece for operator viewing of the object being measured or allows the radiation to pass to the monochromator grating, and a variable aperature wheel which defines one of five fields of view. The hooded filter holder which attaches onto



(a). total system



(b). with telescope in protective field box



(c). with fiber optics probe in protective field box

Fig. 6. EG&G MODEL 580-585 SPECTRORADIOMETER. (a) Composite view showing all components; (b) system configured for use in the trailer (Fig. 12a); (c) system configured for use at a remote location (Fig. 12b).

Table 1. TELESCOPE FIELDS-OF-VIEW. Circular areas subtended for various fields-of-view and object to radiometer distances.

Telescope Field-of-View	Distance Multiplication Factor (SINE of FOV)	Plot Diameter Viewed Distance to Target 10 m	 100 m	Solid Angle Viewed (Steradians)
7.5'	.00219	2.2 cm	219 cm	3.763×10^{-6}
15 '	.00436	4.4 cm	436 cm	1.507×10^{-5}
30 '	.00873	8.7 cm	873 cm	5.96×10^{-5}
1 °	.01745	17.45 cm	1745 cm	2.395×10^{-4}
2 °	.03490	34.9 cm	3490 cm	9.56×10^{-4}

the front of the telescope has a sliding mount for one of the Corning Optical filters supplied with the instrument to eliminate second and higher order wavelengths from being measured.

The fiber optics probe, which can be used in place of the telescope, allows the viewing of objects as small as 3 mm in diameter such as individual grass blades. The radiation being measured passes through the aperature port in the side of the viewing head into an opal glass diffuser which transmits the light to the bundled optical fibers in the probe. The instrument end of the probe is attached to a set of input optics which contain a holder for the Corning Optical filters mentioned previously and a diffuser for the light input to the monochromator. Because of the glass diffuser in the side viewing head and the material used in the optical fibers, both of which absorb ultraviolet, the spectrotransmission range is limited to .35 to 1.2 μm.

The module, which selects the wavelength of radiation being sampled is the monochromator grating and attached wavelength transducer that outputs a voltage proportional to the grating setting. In order to cover the entire spectral range of the instrument, three different gratings (ultraviolet, visible, and infrared) are used (Table 2). The gratings are inserted into the monochromator housing which contains optics that focus the light onto the grating rulings. The housing also contains mounting locations for the fixed entrance and exit slits that determine the spectral band width used for any particular experiment (Appendix II). It should be noted that the narrower slits reduce the amount of radiation passing through to the detector head so that a compromise must be made between spectral resolution and minimum detectable radiation levels.

The final element in the optical path is the high sensitivity detector head. In order to measure radiation throughout the complete spectral

Table 2. GRATING CHARACTERISTICS. Optical characteristics for each of the three gratings used in the spectroradiometer and the IR gratings included in the proposed long wavelength capability.

Grating	UV	Visible	Near IR	Mid IR*
Wavelength coverage (micrometers)	.2-.4	.35-.8	.7-1.6	1.4-3.0
Blaze wavelength (micrometers)	.25	.5	1.0	2.0
Scattered light (%)	.3	.05	.1	.2
Blaze efficiency (%)	30	55	57	57
Exit Slit Width (mm)	Effective Bandwidth (micrometers)			
3.00	.01	.02	.04	.08
1.50	.005	.01	.02	.04
.75	.0025	.005	.01	.02

* Available from manufacturer but not yet used in these experiments.

range of the spectroradiometer there are two different detector heads, visible-ultraviolet, and near infrared. The visible detector head houses an S-10 photomultiplier tube with a wavelength sensitivity from .2 to .75 micrometers and the near infrared houses an S-1 photomultiplier tube with a sensitivity from .7 to 1.6 micrometers (the manufacturer now markets an infrared detector head sensitive to 3 micrometers, well up into the near infrared region). In order to reduce "dark current" in the infrared detectorheads below that of the lowest radiation level detectable, both of the infrared heads are cooled by thermoelectric cooling elements to a temperature of -15 ±5° C.

The overall sensitivity of the two detector heads available ranges from the measurement of sunlight to the measurement of starlight because the signal output of the detector heads is a current ranging from 10^{-11} to 10^{-6} amperes which is sent to the indicator unit (Fig. 7). The reason the mid IR response is so different from the two ranges we presently have is that the mid IR capability uses a different indicator unit which has a larger dynamic range than the indicator unit used for the shorter wavelengths.

The response time of the photomultiplier tubes is so short (1 nanosecond rise time) that the system can be used to measure the light output of a device, such as a laser, which has a very short pulse length. However, for such rapid events, it is recommended that the photomultiplier tube be connected directly to an oscilloscope or similar display unit which can respond to this type of short duration signal, since the time constant of the standard indicator unit described below is on the order of 0.1 seconds.

The indicator unit houses a low-level current amplifier which boosts the low output current from the photomultiplier tube up to a signal level

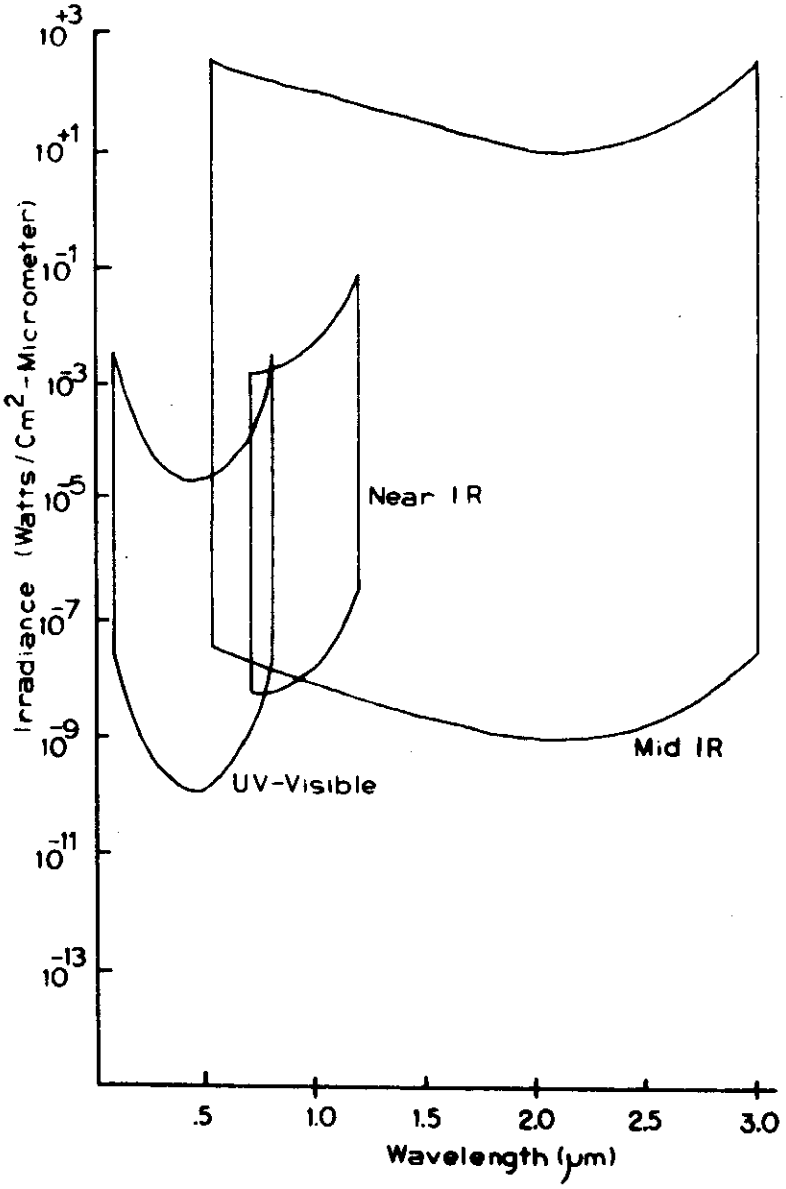


Fig. 7. SPECTRORADIOMETER DETECTOR SENSITIVITY CURVES. Note the wide dynamic range of the irradiance sensitivity of the various detectors available. (Curves courtesy of EG&G, Inc.)

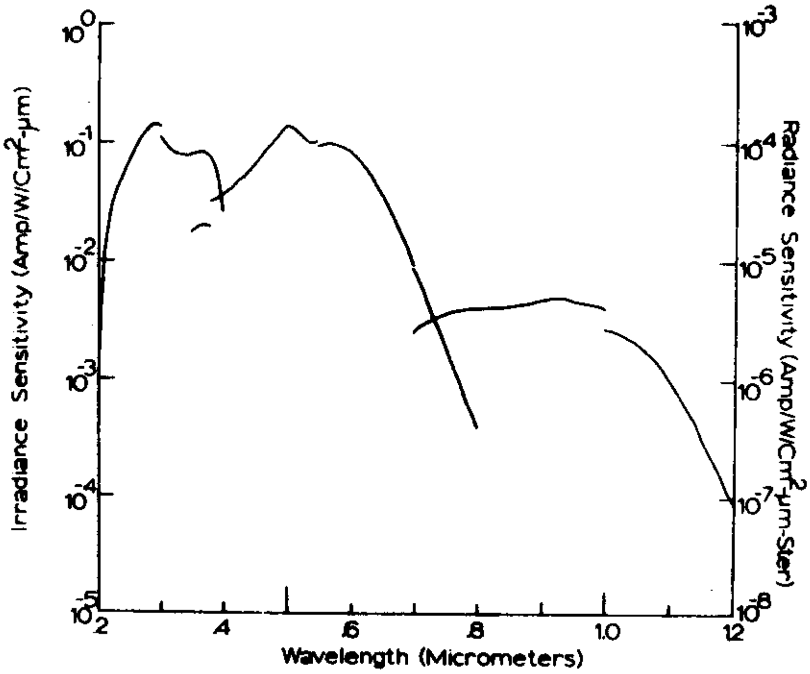
which can be detected by a galvanometer. The indicator unit is capable of either measuring directly in amperes the current output from the photomultiplier, or integrating this current with a capacitor to display in coulombs a measure of the total light output by a short term event such as the flash of a camera flash bulb.

In order to be able to convert the photomultiplier current to the equivalent radiation intensity viewed, the spectroradiometer system has been calibrated by the manufacturer for both absolute spectroradiance and spectroirradiance in all configurations and wavelengths used in normal operation (Fig. 8). Since the expense of factory calibration is high (∿ $700.), the decision was made to assemble a calibration capability to periodically check the response of the spectroradiometer for both intensity and wavelength. A more complete discussion of the calibration equipment and methods is included below.

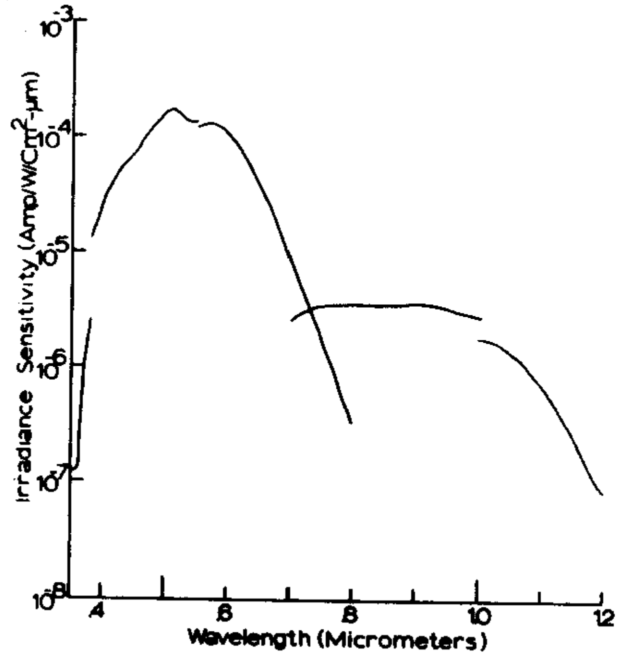
Digital Data Acquisition System

Because of the high wavelength resolution of the spectroradiometer system and the wide spectral range of operation, the spectroradiometer is capable of producing individual data curves with more than 300 discrete points per curve. In order to properly record and process this volumous data output, a digital data acquisition system was purchased which would be connected to the spectroradiometer data output lines. The main purpose of the system is to automatically scan the wavelength transducer output, take a reading when the wavelength transducer has changed a preselected amount, convert the intensity reading to optical units (spectroreflectance, spectrotransmittance, etc.) and output the data to the x-y plotter, tape punch, and teletype.

A normal hardwired coupler-based digital data acquisition system could do the data collection job, but a minicomputer system was actually



(a). using the telescope



(b). using the fiber optics probe

Fig. 8. SPECTRORADIOMETER CALIBRATION CURVES. Absolute spectroirradiance and spectroradiance calibration curves for the spctroradiometer. The breaks in the curves are caused by changing filters, gratings and detector heads during the scan from .2 to 1.2 micrometers.

less costly and much more flexible for this and future data acquisition applications. Therefore the system ultimately purchased was a digital data acquisition system based on a Hewlett-Packard 2114A minicomputer. The Hewlett-Packard system consists of:

1. an analog x-y plotter, interfaced to the computer through a digital to analog converter card, and used to plot the spectral curves as they are reduced on line by the computer (top of rack; Fig. 9);
2. a model 2114A digital computer (middle of rack, Fig. 9);
3. a digital multimeter for system maintenance and testing (below computer, Fig. 9);
4. a high speed (300 8-bit characters per second) punched paper tape reader used primarily for program input to the computer (lower middle of rack, Fig. 9);
5. a low level analog to digital converter for conversion of input analog signals from the spectroradiometer and other sensors (just below the paper tape reader, Fig. 9);
6. a high speed 120 8-bit characters per second) paper tape punch for data output (bottom of rack, Fig. 9);
7. a multiplexer for selecting under program control the analog input channel to be digitized (below paper tape punch, Fig. 9); and

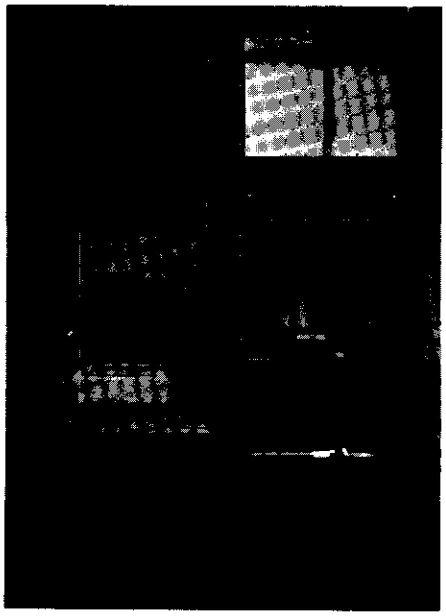


Fig. 9. COMPUTERIZED DIGITAL DATA ACQUISITION SYSTEM. The system is shown in a rack used for indoor laboratory operation during the winter months.

8. a model ASR-33 teletype for keyboard input and printed output from the computer (left, Fig. 9).

The computer has 8192 16-bit words of memory which can be programmed in either FORTRAN, ALGOL, BASIC, or Assembly (machine level, three letter, mnemonic code). The resulting compiled program can then be entered either in relocatable address form (the programs can be put anywhere in core) or in absolute address form (Assembly only), which allows a great deal of flexibility in determining optimum core memory utilization within the computer. Along with the compilers mentioned above, the supplied software includes an edit routine for modifying programs, a program library with mathematical functions and service subroutines (such as trigonometric and Boolien Algebra functions), a debugging routine to assist in checking out programs by use of memory dumps, trace printouts, etc., and a complete set of hardware diagnostic routines to aid in servicing and maintenance of the computer and its peripheral devices.

The computer hardware is designed with a 16-bit word size, two microsecond cycle time, and two arithmetic registers (accumulative) as well as six other control and service registers. The computer also has a priority interrupt input-output system which allows interruption of low priority computer activities by high priority input or output functions.

The following options have been installed in the computer, in addition to the basic hardware: a crystal controlled time base generator card for use with internal software clock to maintain a time signal independent of power line frequency, a power-fail interupt system to allow orderly shutdown and startup of the system if the power line voltage should drop or fail, and a two-channel, digital-to-analog converter card to produce two analog voltages from a 16-bit binary computer word (8 bits for each D/A channel).

The analog to digital converter system consists of a low-level channel multiplexer and a high speed analog to digital converter. The multiplexer at present is capable of switching between 8 input channels of analog data and is expandable in 8 channel increments up to 64 channels total. The analog-to-digital converter subsystem converts with an accuracy of 12 bits including sign (1 part in ±2048) with a 12 step binary amplifier system which accepts directly analog signals from ±10 millivolts full scale to ±10 volts full scale. The A/D converter can accept up to 8 low level multiplexers for a maximum input capability of 556 analog channels and will sample and convert at a maximum rate of 10,000 readings per second. The system operates completely under computer control with respect to the number and order of the channels sampled and the voltage range used by the A/D converter for conversion to digital numbers.

Addition of a magnetic tape system (or systems) which is contemplated, will allow the recording on an output medium which is compatable with the University's CDC 6400 computer and which will allow the system software to be put on magnetic tape for faster and more efficient use of the computer data acquisition system and its operating software (Fig. 10). Also, it is proposed that the computer can be directly connected to the CDC 6400 through a data line so that the Hewlett-Packard computer can call on the CDC for larger computing power as needed.

Maintenance and Logistical Support Equipment

In order to house the laboratory and provide it with the necessary mobility, a modified 13.5 foot travel trailer is used (Fig. 11). It features a full width work counter at the rear, on which to operate the spectroradiometer, with a door to allow the spectroradiometer to view the outside and a built-in instrument rack to hold the computer and its related peripheral equipment, a work area at the front alongside a space for the

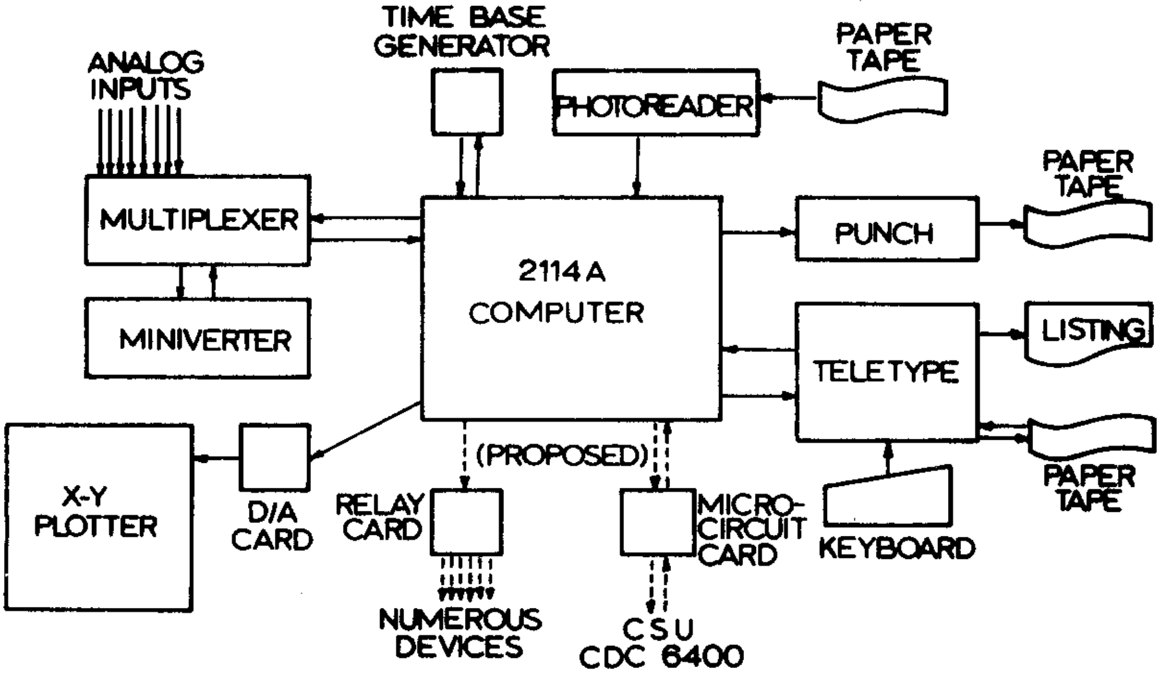
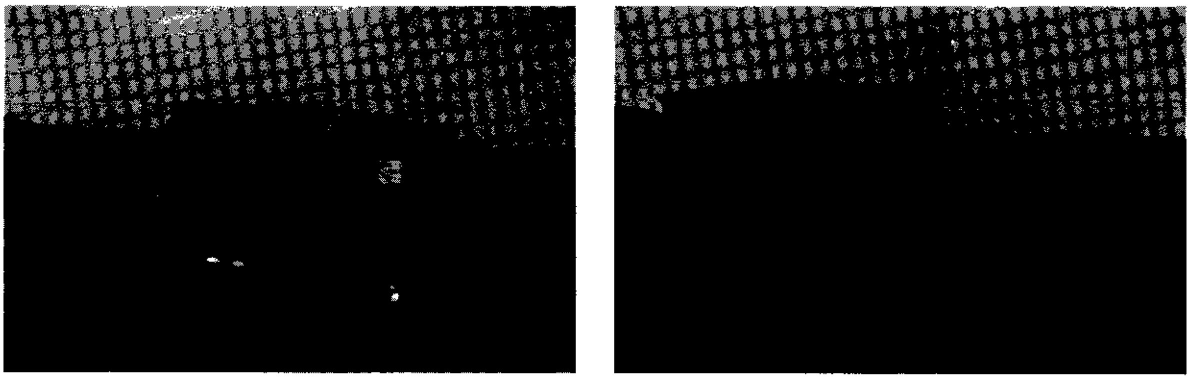


Fig. 10. **FUNCTIONAL DIAGRAM OF THE COMPUTER DIGITAL DATA ACQUISITION SYSTEM. Control signal and data flow diagram between the various components of the Hewlett-Packard system.**

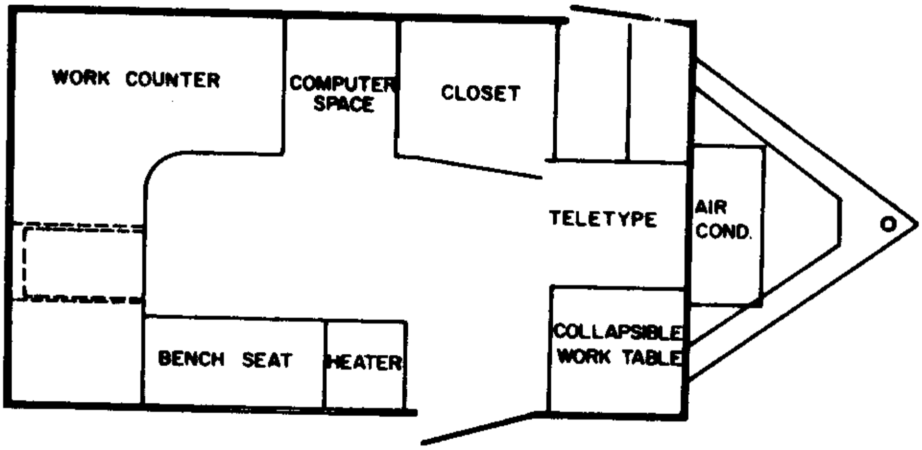
computer's teletype, a large closet storage area, a full height equipment storage area accessable from the outside, a cable locker on the rear bumper to store data and power cables, and numerous cabinets for storage of small pieces of equipment and supplies. The trailer has both heating and air conditioning (11,000 BTU/hour) to maintain the interior temperature of the trailer at 72° F. while maintaining a positive air pressure gradient to protect its equipment from outside dust and contaminants.

When the laboratory trailer is operated in remote locations, away from commercial power, a 3500 watt alternator is used to provide operating electricity. The laboratory is equipped with a 60 meter power cord which allows the generator to be placed away from the laboratory trailer because of the noise it produces.



(a)

(b)



(c) floor plan

Fig. 11. FIELD TRAILER AND SUPPORT EQUIPMENT. A tripod-mounted, first surface mirror (a and b) is used to fold the horizontal field-of-view of the spectroradiometer down onto the sample. A 3500 watt power plant supplies field power. A cable locker (not shown) has been added atop the rear bumper to store the trailer's main power cable (30 m), a remote site power cable (90 m), and a remote site data and communication cable.

In its primary mode of operation the spectroradiometer is maintained inside of the laboratory trailer to protect it from the environment (Fig. 12a). However, equipment has been assembled so that the spectroradiometer can be operated near the sample under study on the ground (Fig. 12b). This additional equipment includes an instrument box which protects the spectroradiometer from dust and vibration; a 110 volt power cable and a 28 conductor geophysical data cable, each 90 meters long for electrical connection to the laboratory trailer; and an intercom system for communications between the remote site and the trailer. When operated in this mode the spectroradiometer, fitted with the fiber optics probe, is used to study the objects of interest in great detail with the data being transmitted through the data cable to the data acquisition system. The remote site equipment is also capable of connecting five other instruments at the remote site (e.g. anemometers, thermistors, etc.) to the data acquisition system in the trailer for simultaneous recording of meteorological or other data.

Another trailer has been obtained to support the field spectrophtometer laboratory in addition to the laboratory trailer. The second trailer is 10 meters long and is equally divided into an airconditioned office portion and an equipment storage room. The office portion is primarily used for the writing of computer software and electronic maintenance of the field equipment and for the storage of field results and maintenance manuals for the laboratory.

The final pieces of logistical support equipment maintained as part of the spectrometer laboratory are: three, two-way citizens' band radios for communication with the personnel at a remote sample location and office trailer, and a shortwave radio to receive the National Bureau of Standard Station WWV for correct time reference.

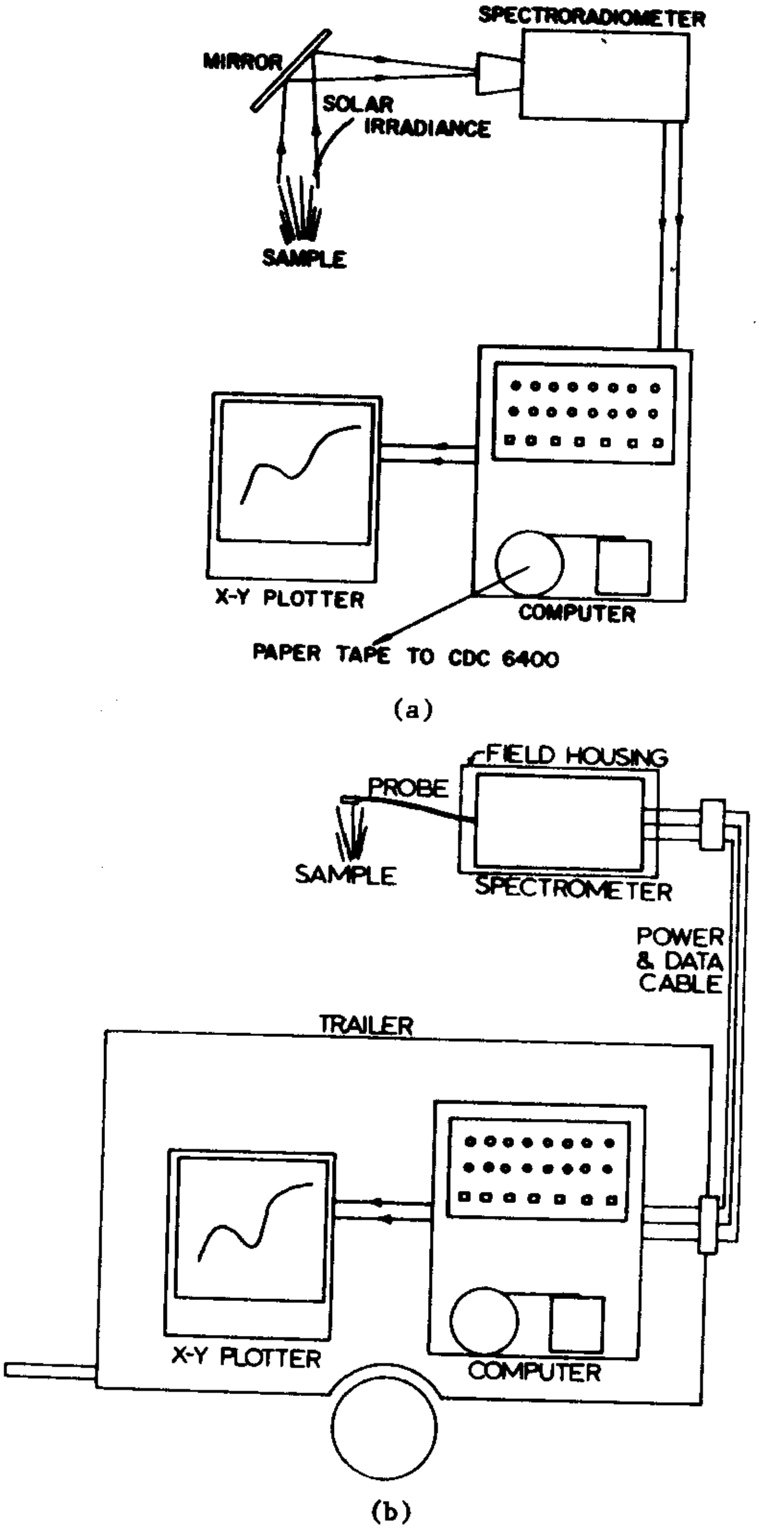


Fig. 12. DATA FLOW INTO THE FIELD SPECTROMETER. (a) Using the telescope with the spectroradiometer housed in the trailer. (b) Using the fiber optics probe at the remote site.

Spectrometer Calibration

The field spectrometer can be calibrated for intensity (both spectroradiance and spectroirradiance) and wavelength in the field. The equipment used includes:

1. a high amperage, current limiting D.C. power supply to drive one of five General Electric Q6.6A/T4/CL quartz iodine lamps for detector calibration (left, Fig. 13);
2. a lamp housing for the quartz iodine lamp with variable area aperature and cooling fan (center, Fig. 13);
3. a mercury-neon emission lamp used for grating wavelength calibration (lower center, Fig. 13); and
4. a power supply for the mercury-neon emission lamp (right, Fig. 13).

A wavelength calibration check is achieved by measuring the spectral emission of the mercury-neon bulb with the spectroradiometer. Mercury and neon emit radiation at discrete, known wavelengths and the spectroradiometer output curve for the lamp is compared against the known emission curves for these two gasses (when the lamp is warm, only the mercury lines are recognised) (Fig. 14). If a wavelength shift is found between these two curves for a particular grating the grating is adjusted so that the measured curve matches the known emission spectra.

After wavelength calibration, quartz iodine lamps operated at a known, constant current to produce a constant light output, are used to check the intensity calibration. Spectroirradiance is checked by directly illuminating the spectroradiometer with either the telescope or fiber optics probe attached at a set distance of 50 cm from the quartz iodine lamp filament. Spectroradiance is checked by illuminating the $BaSO_4$ white panel at 50 cm distance with the lamp and viewing the panel with the telescope of the spectroradiometer system.

Five quartz iodine lamps are initially calibrated by comparison with the spectroradiometer against an NBS calibrated lamp (Fig. 15). The

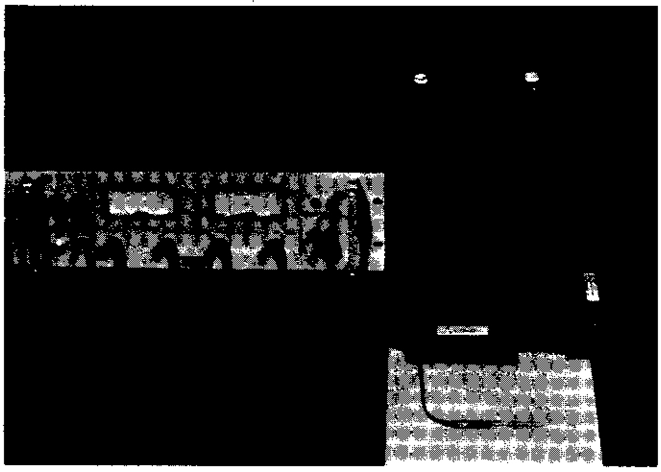


Fig. 13. SPECTRORADIOMETER CALIBRATION EQUIPMENT. The intensity calibration light housing (right center) is shown with its power supply (left) and the wavelength calibration lamp (lower right) is shown with its power supply (extreme right).

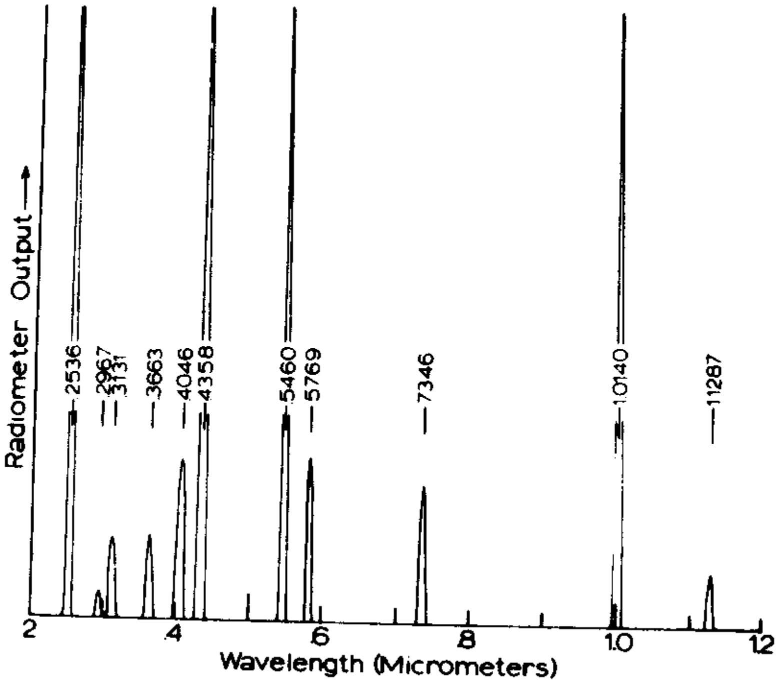


Fig. 14. CURVE USED FOR WAVELENGTH CALIBRATION. The curve was produced by the spectroradiometer viewing a mercury-neon lamp. Note that the curve peaks occur at the known emission wavelengths of mercury shown with each peak.

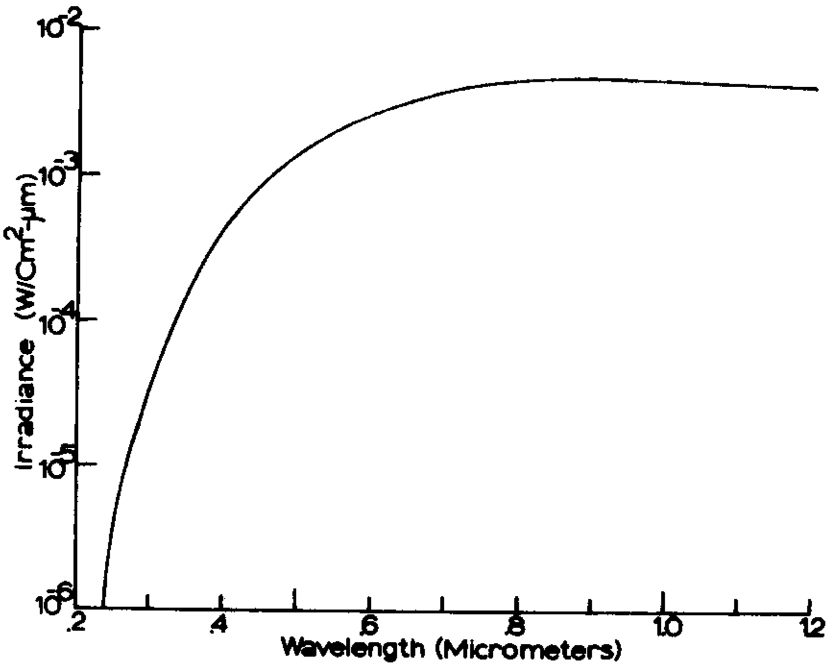


Fig. 15. QUARTZ-IODINE BULB CALIBRATION CURVE. Irradiant intensity curve for a typical quartz iodine bulb used to check the intensity calibration of the spectroradiometer. The bulb is operated in a lamp housing with a constant D.C. current of 6.5 amperes and a lamp to spectroradiometer spacing of 50 cm.

five bulbs are then separated into a working standard and four backup standards. Periodically the spectroradiometer is compared to the working standard and, if change is noted, it is then compared to the backup standards. If the change is measured with only the working standard, the bulb is assumed to have changed and it is replaced. If the spectrometer yields a difference with all five bulbs and the power supply and lamp housing, as well as the measurement geometry are correct, the spectroradiometer is assumed to be out of calibration and a new calibration curve is prepared for the instrument.

Connection of Equipment for Operation

All of the equipment in the system was purchased as separate pieces or subsystems. Assembling the laboratory and interfacing the various components together into a working configuration was necessary before operation could begin. There were several problems in making the individual pieces work together as intended.

The system is configured so that the source of the energy detected is the sun which illuminates either the white panel or the unknown sample of interest (detailed explanation in the succeeding section entitled Operational Procedure). The light reflected from the panel or sample is directed by use of a tripod-mounted first-surface mirror toward the spectroradiometer when the system is trailer mounted, or directly into the viewing port of the fiber optics probe when the spectroradiometer is carried to the sample site. The spectroradiometer converts the level of the radiance viewed to an analog voltage which, along with the analog voltage from the grating's wavelength transducer and an amplifier gain signal, is sent to the computerized data acquisition system. The computer system, through its multiplexer and A/D converter system scans these three voltages and samples and records them when the wavelength set on the grating has been changed by a programmed amount by the rotation of the grating.

At the completion of an entire wavelength scan sequence, the computer outputs the final results on the plotter, punch, and teletype. The output from the computer directly onto the x-y plotter produces an on-line graphic display of the spectroreflectance data. This allows the operator to determine, as the curves are being collected, whether they appear correct and to adjust the experimental procedure if they do not. The inexpensive (compared to magnetic tapes) high speed punch creates a computer compatable punched paper tape which can be used as input for further subsequent computer data analysis and reduction on the Hewlett-Packard 2114A or CDC 6400 computers. The current drawback with the paper tape as an input medium to the University's Central CDC 6400 is that the Computer Center can presently read paper tape only at a speed of 10 characters per second, via a teletype. The teletype in the trailer, mainly as a computer control device, also allows the presentation of tabularized data and numerical results for immediate review.

The hardware interfacing problems were encountered at the spectroradiometer-data acquisition system interface and the computer, x-y plotter interface. These two interfaces were those not worked out by the individual subsystems' manufacturers.

The major interfacing problem occurred at the connection of the spectroradiometer to the multiplexer. The outputs of the radiometer indicator unit and wavelength transducer were both designed to be 10 millivolts full scale. In order for the data acquisition system to distinguish 300 or more discrete wavelength points per curve, it had to resolve voltages differences of ±3 microvolts which is well down in the noise region affected by ground loops, common mode voltages and thermocouple effects in the input data lines. To reduce the ground loops, each of the low voltage components of the laboratory were tied to an external ground stake by the use of a length of #6 copper wire and the data signals were amplified to 1 volt full scale.

A pickup of 60 hertz A.C. noise from the power cables in the walls of the trailer also occurred on these low level data lines. For a low speed A/D converter (30 conversion/second or less) this 60 hertz pickup is not a major problem since the sampling rate is less than the Nyquist frequency (30 hertz) of the noise. However, since the multiplexer, converter subsystem converts at a maximum rate of 10,000 conversions per second; the 60 hertz pickup is an important consideration. The solution was to put a 5 hertz low-pass filter network on the multiplexer input lines to filter out the 60 hertz noise. The filter network for each channel is a two section RC low-pass filter with an effective attenuation slope of

12 db/octave which means that the 60 hertz will be attenuated roughly 40 db or to 1% of the original 60 hertz noise level. Since the peak to peak signal voltage level of the 60 hertz is roughly a millivolt, the low pass filter reduces its contribution to approximately a microvolt which is well below the desired signal resolving level of the data acquisition system.

The current from the spectrometer photomultiplier tubes is amplified a selectable amount by the indicator unit before it is output to the data acquisition system. The computer must know the amount of amplification so that the data can be properly converted to optical units. The indicator unit hardware was modified to output a voltage to the data acquisition system proportional to the gain setting of the amplifier. This indicator unit has two switches which determine the gain used, each switch generates a voltage which is summed together through the use of a summing amplifier and output to the data acquisition system.

The interface problem between the computer and the x-y plotter was easier to solve. The computer is a digital device and the x-y plotter is an analog device and a digital to analog (D/A) converter is included in the interface, as well as appropriate control signal generators, and conditioners for transfer of a "seek" signal to the plotter and a "flag" signal back to the computer. The D/A interface card used was designed to operate high speed syncronous devices such as oscilloscopes or television type displays rather than low speed asyncronous devices such as x-y plotters. Therefore, a timing circuit on the D/A card was changed and a plot-completed flag generator and conditioner were purchased and installed in the plotter mainframe. Also, a software driver was written for the plotter so that the computer could transmit data to the plotter in the proper format.

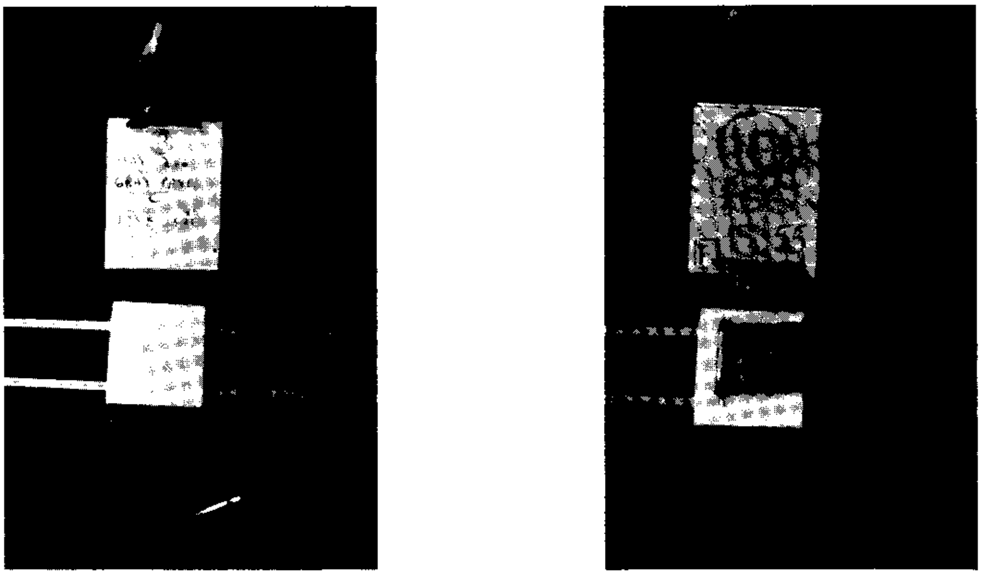
IV. OPERATIONAL PROCEDURE

The basic mode of operation of the spectroradiometer is to look out through the viewing door in the side of the trailer to the tripod-mounted first surface mirror (Fig. 12a). The tripod-mounted mirror is positioned over the sample of interest and adjusted so that spectroradiometer operator sees the image of the sample object to be measured when looking through the eyepiece on the telescope. Then the variable aperature wheel is set on the telescope for the desired field of view, and the $BaSO_4$ coated white panel is placed over the sample so that a determination of solar irradiance can be made.

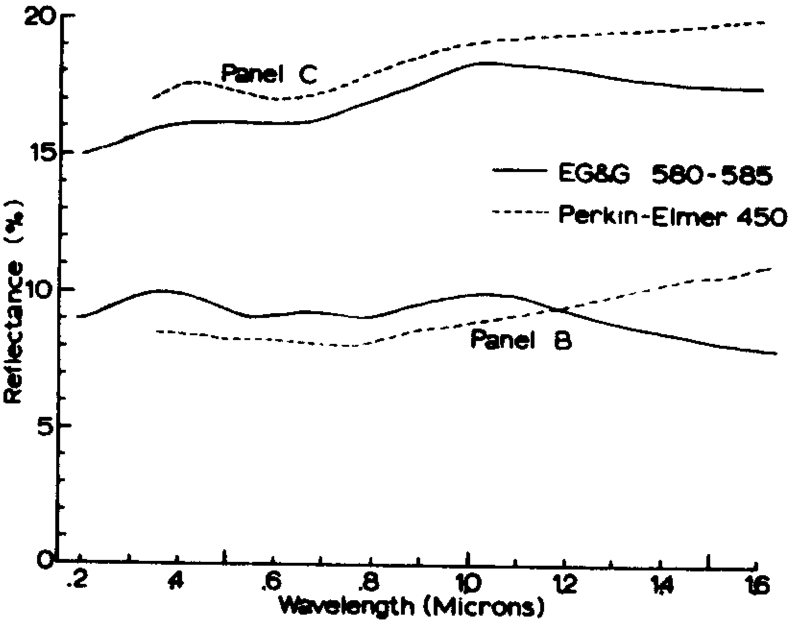
Once the spectroradiometer has been set up, the computer program (Appendix III) is started which first requests and punches out the header for the paper tape. Then the computer program requests the spectroradiometer constants being used for the measurement, namely: the wavelength range to be scanned, the wavelength interval ($\Delta\lambda$) to use between samples, and the appropriate conversion constants for the incoming signals from the spectroradiometer. Upon receiving this information, the data acquisition system starts sampling the wavelength signal and converts the intensity signal to radiometric units when the operator has changed the wavelength a programmed amount.

Once the white panel spectroradiance curve has been read into the computer memory, it is removed and the same procedure is repeated to measure the spectroradiance curve of the sample plot. As the spectroradiance curve from the sample plot is being read in, the computer calculates the ratio between the sample plot value measured and the white panel value stored in memory for every wavelength interval sampled and plots this spectral reflectance curve out on the x-y plotter. When both radiance curves have been read into the memory, the computer determines if the operator desires either of the original radiance curves plotted out and/or the tabularized data printed out on the teletype. If not, the computer punches out the data (wavelength, white panel spectroradiance, sample plot spectroradiance, and spectroreflectance) on the high speed punch. Finally, the computer halts, ready to take another set of measurements as soon as the spectroradiometer is set up on a new sample plot. Since $BaSO_4$ is used as the standard of reflectance in all of the data taken by the laboratory, all spectroreflectance values calculated by the computer are relative to the spectroreflectance of $BaSO_4$ and are not absolute spectroreflectances.

A series of test curves have been measured to assess how the data from the instrumentation and the experimental methods used compare to data from laboratory type spectrophotometers. Special Data Corporation canvas reflectance panels were chosen as standard reflectance samples because of their stability, ease of handling, and availability. Initially, the panels were measured by the field spectroradiometer using the method described above from .18 to 1.6 micrometers (Fig. 16). Next, these same panels were measured on a laboratory Perkin Elmer model 450 spectrophotometer over the same wavelength interval. The comparison of the reflectance curves obtained with the conventional laboratory spectrophotometer and our field spectrometer system show that both yield essentially the same curves for the test panels in the visible region (Fig. 16c) (Pearson and Miller, 1971).



(a) $BaSO_4$ reference panel (b) gray canvas sample panel



(c)

Fig. 16. SPECTROREFLECTANCE OF CANVAS CALIBRATION PANELS. A comparison of the curves taken by the field spectrometer and those taken by a laboratory Perkin-Elmer model 450 spectrophotometer. The four inch panels are gray reflectance standards fabricated by Data Corporation. Perkin-Elmer curves courtesy of the Colorado Seed Laboratory, Colorado State University.

Several other types of abiotic materials were measured by the field spectrometer under natural or artificial light and then remeasured for comparison by various laboratory spectrophotometers. All materials used as samples were flat diffuse surfaces which could be inserted into an entrance port of a laboratory spectrophotometer and also laid flat in the field for measurement by the field spectrometer. The materials included a green Munsel color chip (Fig. 17 and 18)and geologic materials (Fig. 19). In all cases the curves obtained normal to the surface under either natural or artificial light compare well with laboratory measurements, giving confidence in the use and accuracy of this system as a field spectrophotometer.

A final test demonstrates why field spectrometer measurement of rough 'in situ' natural materials, especially biological materials, under natural solar irradiance is so important from a remote sensing viewpoint. It also underscores the gross differences between laboratory spectroreflectance measurements of biological materials and measurements made 'in situ' in the field, indicating why laboratory measurements have been of limited value in predicting what an aerial camera or a multispectral scanner will measure. In determining the spectroreflectance of grass blades, pine needles, etc., in a laboratory, spectrophotometer samples are made up of a series of criss-crossed mats of the fresh foliage material assembled on a surface of very low reflectivity. Spectroreflectance of three different criss-crossed mats of Kentucky blue grass *(Poa pratensis)* on black construction paper were measured by the field spectrometer under artificial light to simulate laboratory curves (Fig. 20). These curves are reasonable replicates and show very high reflectance in the photo IR (.8 μm to 1.2 μm) due to the transmission and multiple reflection which takes place in the leaf mat. Three more spectroreflectance curves were measured for the same

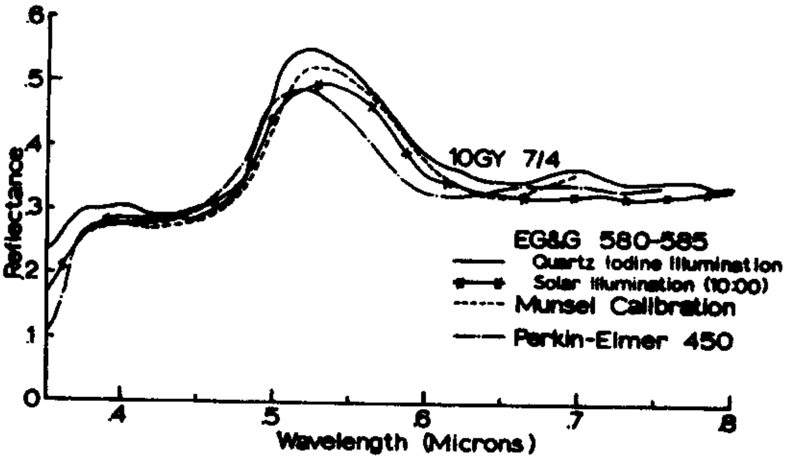


Fig. 17. SPECTROREFLECTANCE CURVES FOR A GREEN MUNSEL COLOR CHIP. A comparison of measurements of the same chip, including curves measured under artificial and natural sunlight by the field spectrometer, Munsel curves purchased with color chip, and Perkin-Elmer curves courtesy of Colorado Seed Laboratory, Colorado State University.

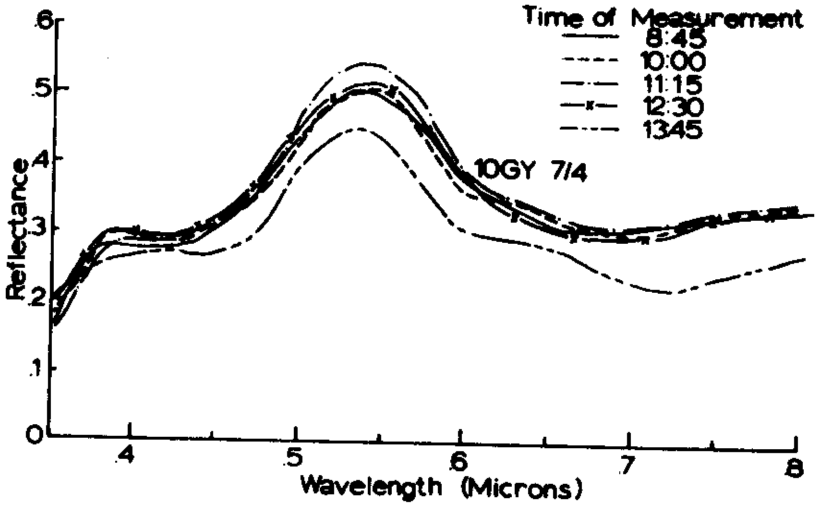


Fig. 18. SPECTROREFLECTANCE CURVES FOR A GREEN MUNSEL COLOR CHIP. A comparison of the curves obtained under natural solar illumination with the field spectrometer at different times of the day. May 13, 1971, at Fort Collins, Colorado, Mountain Standard Time.

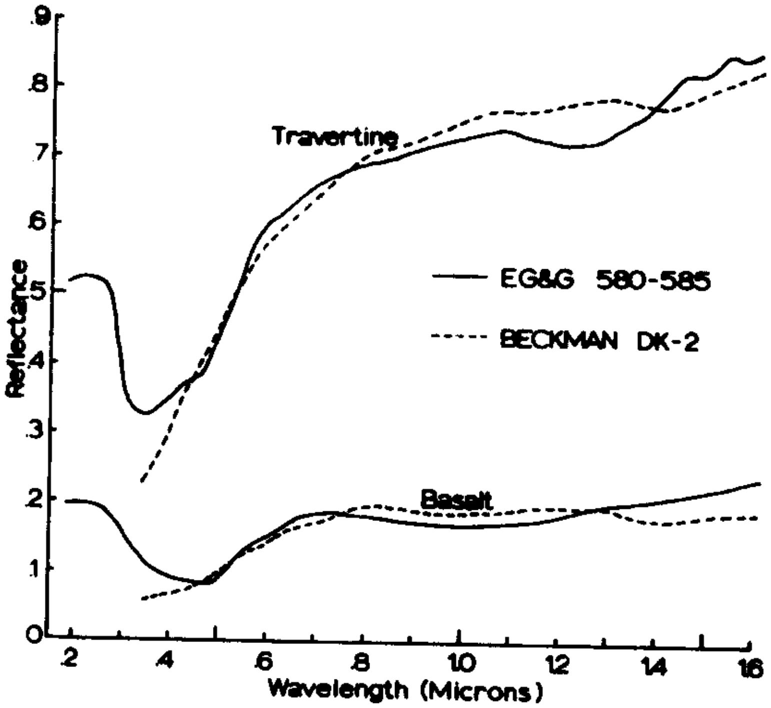


Fig. 19. GEOLOGIC SAMPLE SPECTROREFLECTANCE CURVES. A comparison of the measurements taken by the EG&G field spectrometer and Beckman DK-2. Beckman curves courtesy of Dr. C.L. Olson, University of Michigan.

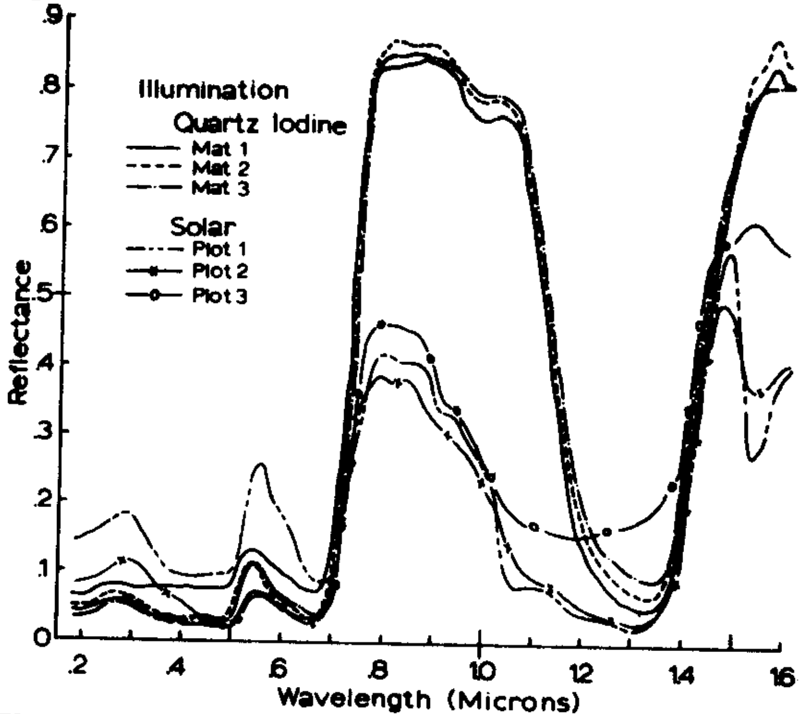


Fig. 20. SPECTROREFLECTANCE OF KENTUCKY BLUE GRASS (*Poa pratensis*). Comparison of three curves from leaf mats made by taping grass blades to a sheet of black paper which was illuminated by the quartz iodine source to three curves from 'in situ' grass plots in the lawn illuminated by the sun on May 13, 1971, between 10:00 and 14:00 hours MST at Fort Collins, Colorado.

grass 'in situ' in the lawn using natural solar irradiance and the tripod-mounted folding mirror to view the ground and sample plot normally (Fig. 20). The lawn was thick and lush but these curves do not replicate each other and are not similar to the three curves for the grass mats. The grass blades are oriented vertically in the spectrometer view of the natural samples and a significant amount of shadows and bare soil are viewed along with the tips of the grass blades. These 'in situ' spectroreflectance measurements of undisturbed biological materials interacting with incoming solar irradiance yield measurements similar to those of a multispectral scanner viewing the same patch of grass at the same angle and are quite different from laboratory curves.

Measurements of some abiotic materials such as road paving materials (Fig. 21) have been made by the laboratory to determine whether the laboratory would properly respond to reflectance samples of widely different spectroreflectivities. The curves produced by the field spectrometer are similar to curves reported several places in the literature (Robertson, 1970).

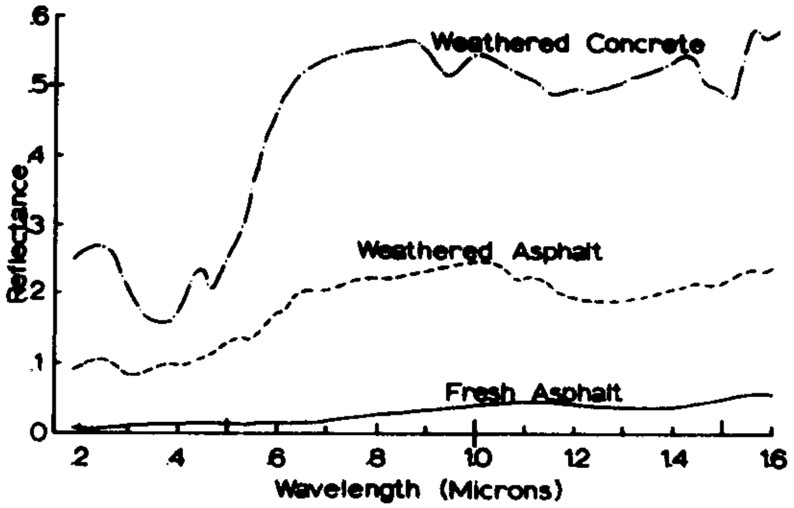


Fig. 21. SPECTROREFLECTANCE CURVES OF COMMON ROAD PAVING MATERIALS.

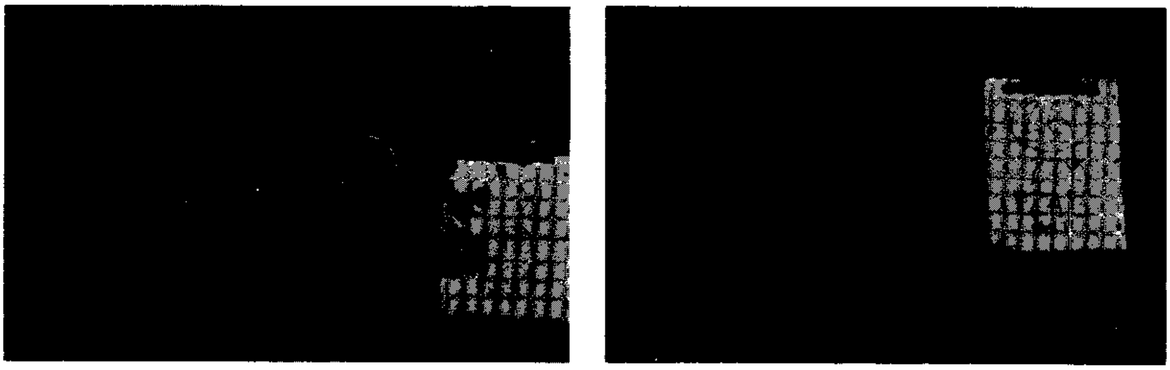
V. EXPERIMENTATION PERFORMED

Spectroreflectance of 'In Situ' Grassland Constituents

The first field experiment performed was to determine how effectively the field spectrometer in its initial field configuration could be used to catalog spectroreflectance curves for several constituents of the grassland, including both vegetation and soil. Photographs of the plant and soil samples were taken as they were measured (Fig. 22). The wire ring in each photograph denotes the field-of-view of the spectroradiometer when the curves were measured, and the numbers on the clipboard are, from top to bottom: a sample reference number (encircled), the Julian date of the experiment, and the Mountain Standard Time of the readings.

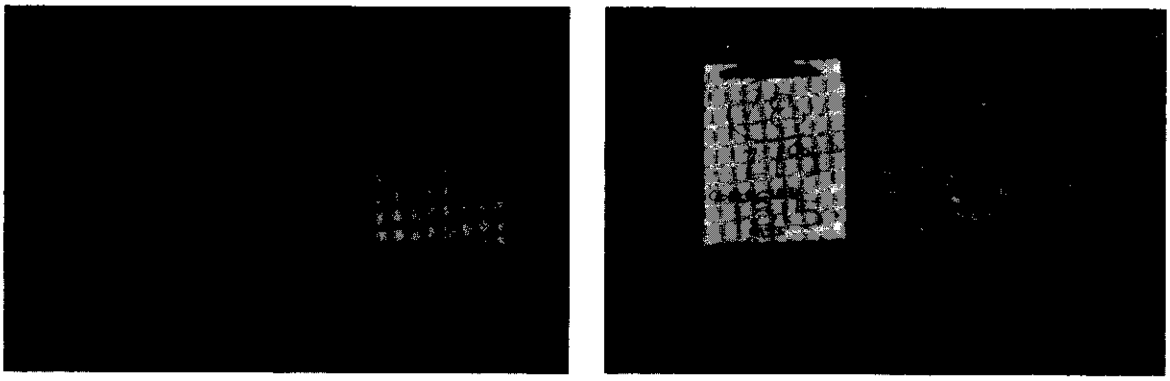
These photographs clearly show the reason for the differences which should be expected between laboratory and field spectroreflectance curves of natural materials. Laboratory measurements of the vegetation samples could be made for both the yellow infloresence and the green leaf and stem material (Fig. 22a). Yet, it would be difficult to construct the composite 'in situ' spectroreflectance of the plant from these measurements, and it is these spectral functions which determine the amount and spectral distribution of solar energy flowing into the ecosystem through its plants, soils, and animals.

The preliminary curves obtained were taken primarily to test the instrumentation for field operation and should not be relied upon for significant interpretation (Fig. 23). A future experiment is planned to measure the annual sequence of such curves at different periods during the growing



(a). Sample 25. *Chrysothamnus nauseosus* (Rabbitbrush) at 1200 hours MST

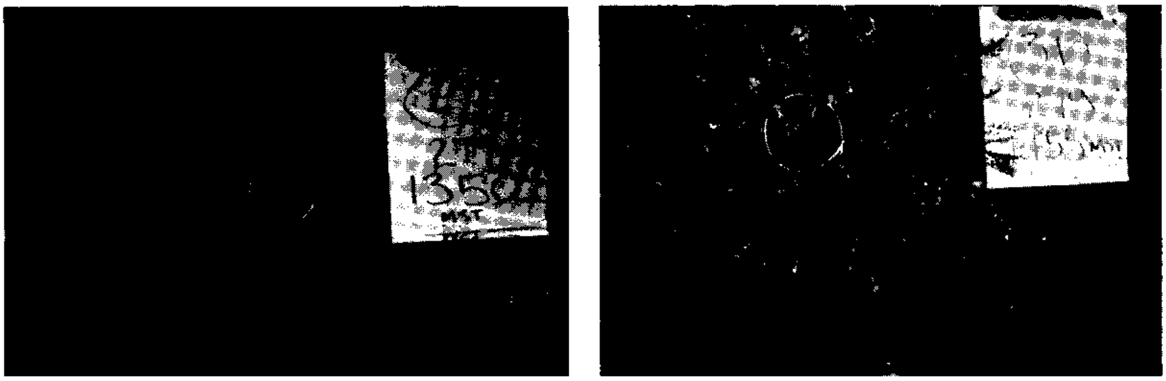
(b). Sample 26. *Eriogonum microthecium* (Buckwheat) at 1245 hours MST



(c). Sample 27. *Aristida logiseta* (Red threeawn) at 1300 hours MST

(d). Sample 28. Ascalon sandy loam soil at 1315 hours MST

Fig. 22. FIELD SPECTROMETER VIEWS OF SAMPLE GRASSLAND CONSTITUENTS. Sample grassland plants and soil as they were measured by the light quality laboratory on October 3, 1970, at the Pawnee Site. The area within the wire ring (approximately 8 cm in diameter) was the actual sample area viewed by the spectroradiometer.



(e). Sample 29. *Opuntia humifusa* (pricklypear cactus) at 1359 hours MST

(f). Sample 31. *Artemisia frigida* (fringed sagewort) at 1455 hours MST

Fig. 22. Continued

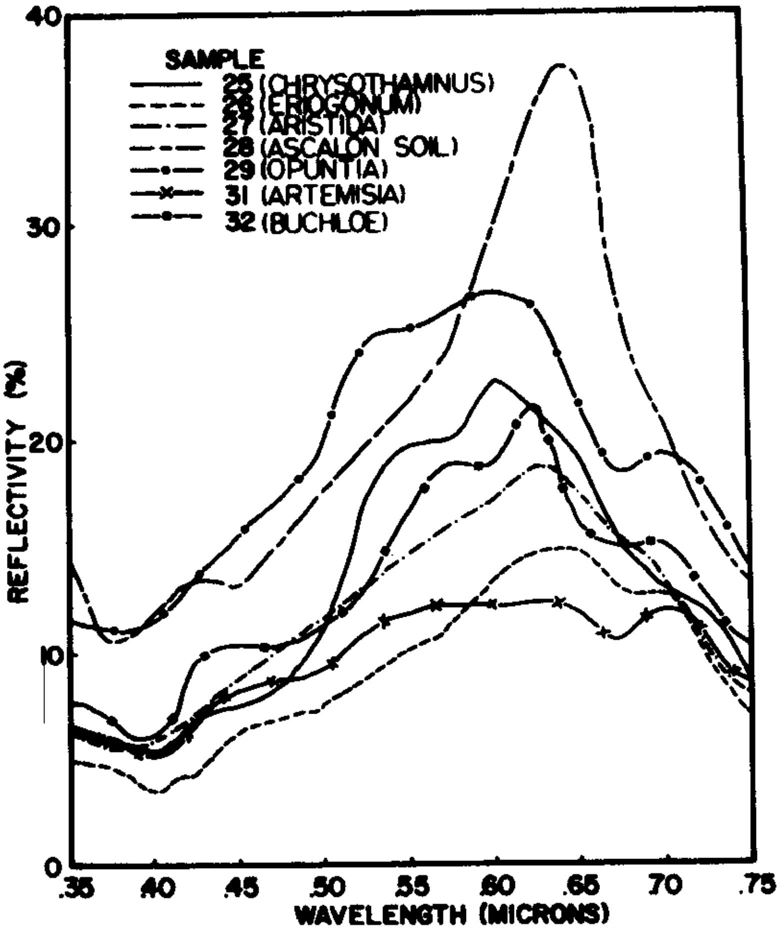
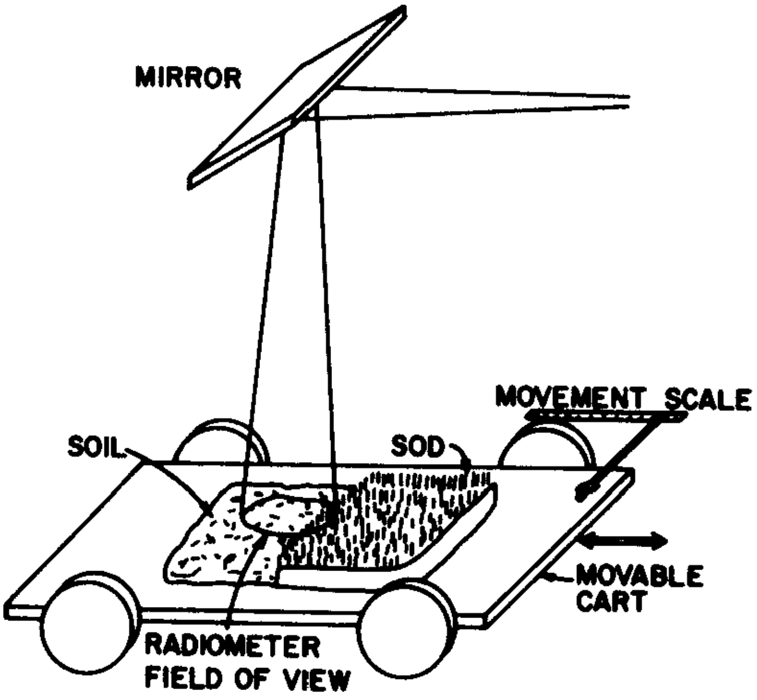


Fig. 23. SAMPLE GRASSLAND CONSTITUENTS' SPECTROREFLECTANCE CURVES. Spectroreflectance curves for several types of vegetation and soil on the Pawnee Intensive Site collected October 1, 1970, (Fig. 22); all measurements made normal to the underlying soil surface.

year over the interval of .35 μm to 1.2 μm for each of the major vegetation and soil constituents present on the Pawnee Site. This experiment will also be designed to obtain sufficient spectral measurements of the solar incoming to the Pawnee Site over the same wavelength intervals so that the flow of energy into the ecosystem and several of its major components could be accurately determined on a day by day or week by week basis. The curves do clearly show that the differences in spectroreflectance between various species can vary from 2% to 25% in some cases. These differences can be used to differentiate between the species from an aerial measurement viewpoint with colored films and more sophisticated remote sensors.

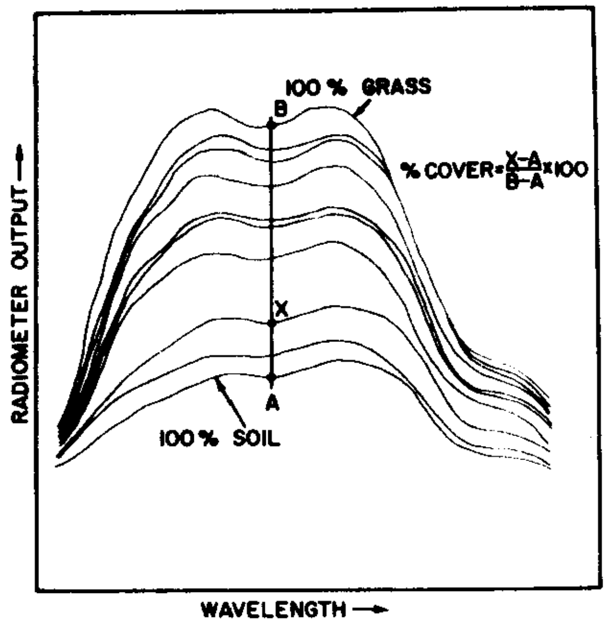
Feasibility Experiment for the Measurement of Percent Cover

A second experiment was intended to determine the response of the spectroradiometer to changes in percentage of grass in the spectrometer field-of-view. A dense clump of *Bouteloua gracilis* (blue grama) sod, approximating 100% cover, was placed on a movable cart underneath the tripod-mounted folding mirror (Fig. 24a). The area under and adjacent to the sod was covered by soil from the same area. The cart was then situated so that, when it was moved, the spectroradiometer "looked" at either soil or grass or part of each at the boundary between. The actual percentage of the vegetation and soil seen by the spectroradiometer in each setup was calculated from the geometry of the particular arrangement. The spectroradiometer output was plotted directly onto the analog x-y plotter for each set up of different grass and soil amounts (Fig. 24b). These curves represent the spectroradiance from the sample multiplied by the spectral detector function of this instrument. Since the detector curve is only a function of wavelength, it cancels out in the ratios to be taken. Limiting curves were obtained for 100% sod or grass and for 100% exposed soil. Using these limiting curves, a percent cover of green vegetation versus

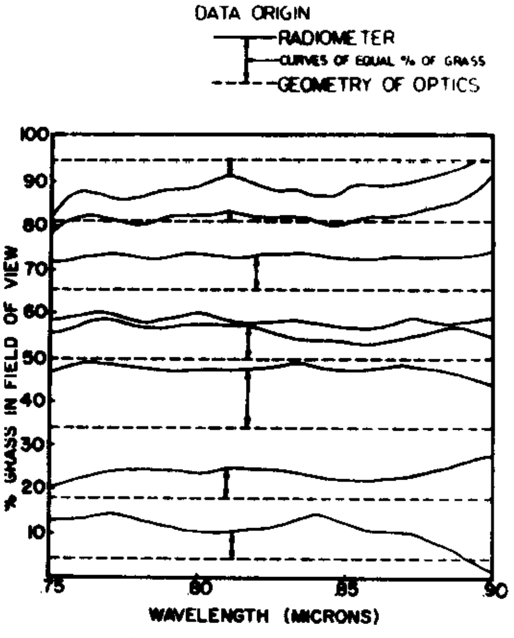


(a). Diagram of cart arrangement used in the preliminary expriment to determine percent cover using blue grama (*Bouteloua gracilis*) sod.

Fig. 24. PRELIMINARY COVER EXPERIMENT.



(b). Uncorrected spectroradiometer output from simple cover experiment. these curves are a product of the solar spectroirradiance, detector spectral sensitivity and sample spectroreflectance curves for a given wavelength.



(c). Comparison of the computed versus measured amounts of grass versus soil. The fairly uniform difference shown is caused by a small error in the measurement of the actual position of the cart which resulted in a slightly incorrect percentage of grass which the spectroradiometer viewed. The two experimental curves of ∿57% show the repeatability of the measurements.

Fig. 24. Continued.

soils for the intermediate setups can be computed at each wavelength using:

$$P_\lambda = \frac{X_\lambda - A_\lambda}{B_\lambda - A_\lambda}(100), \tag{5}$$

where P_λ = percentage of green vegetation versus soil computed at wavelength λ;

X_λ = spectroradiometer output from the unknown sample at λ;

A_λ = spectroradiometer output from 100% soil sample at λ; and

B_λ = spectroradiometer output from 100% grass sample at λ.

This equation was solved for all wavelengths on each intermediate curve for .7 μm to 1.0 μm representing different amounts of grass and soil. These curves of percent cover, computed as a function of wavelength, can then be compared with the known amounts of cover computed from the set up geometry (Fig. 24c). The two sets of curves agree reasonably well, and the error that exists can be explained by the irregular boundary between the sod and the soil and the crude scheme for measuring the position of the cart which had a standard error of roughly 2 cm. Note that when the boundary was set at roughly midway in the projected field-of-view at the beginning and end of the measurements, the resulting curves are quite similar (Fig. 24c, ∿57%) demonstrating the repeatability of the cart position scale. The main conclusion of this preliminary, simple experiment is that spectroradiance and spectroreflectance clearly do reflect changes in the percentage of grass and can be measured with the field spectrometer.

Measurement of Composite Grassland Spectroreflectance

The third and most complex experiment was to determine the spectroreflectance of several natural soil-grass plots. The area chosen was near the headquarters building of the Pawnee Site and consisted of several

8 cm diameter circular plots of various ratios of soil to grass and dead vegetation (Fig. 25). The normal spectroreflectance of each plot was determined from the spectrometer within the space of two hours (Fig. 26). Then photographs were taken of the plots with both color (Fig. 25) and color infrared film. The percentage of each of the components was determined by projecting the color infrared image onto a uniform dot grid (Appendix IV) and counting the number of dots touching each component (Table 3).

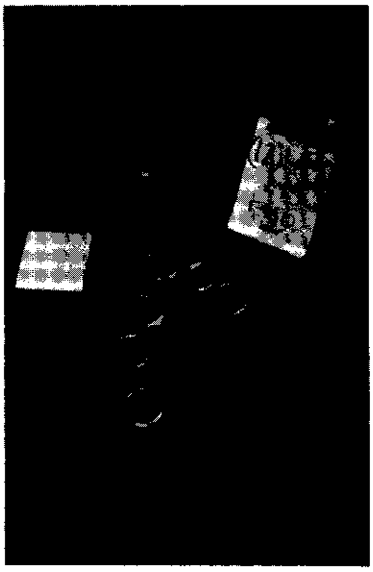
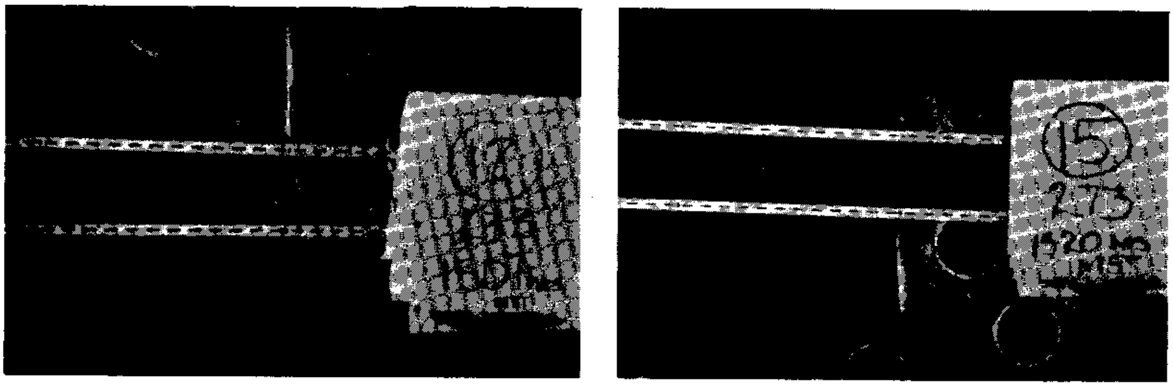
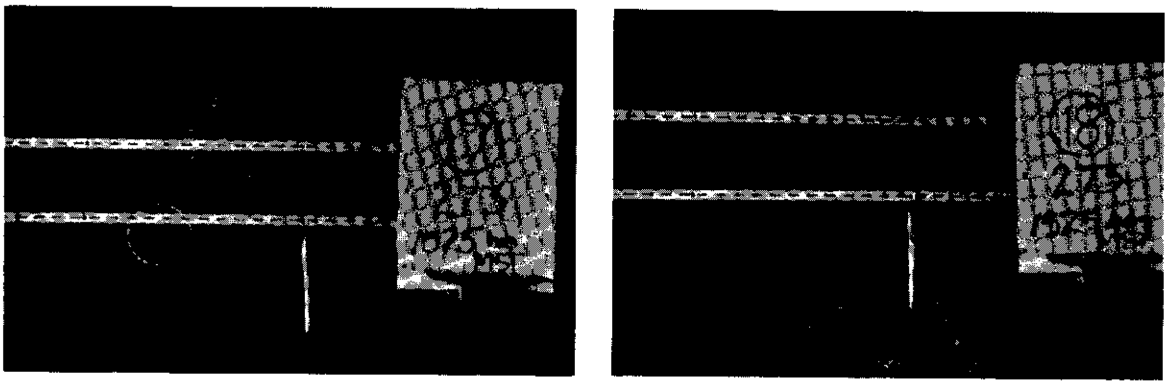


Fig. 25. GRASSLAND PLOTS OF 8 CM DIAMETER MEASURED BY THE FIELD SPECTROMETER. (a) areal distribution of the plots 12 to 19; (b-e) four of the plots measured where the actual area viewed by the spectroradiometer is shown by the circle.



(b). 0% green grass; 66% bare soil

(c). 32.7% green grass; 10.3% bare soil



(d). 12.4% green grass; 35.0% bare soil

(e). 37.4% green grass; 18.7% bare soil

Fig. 25. Continued.

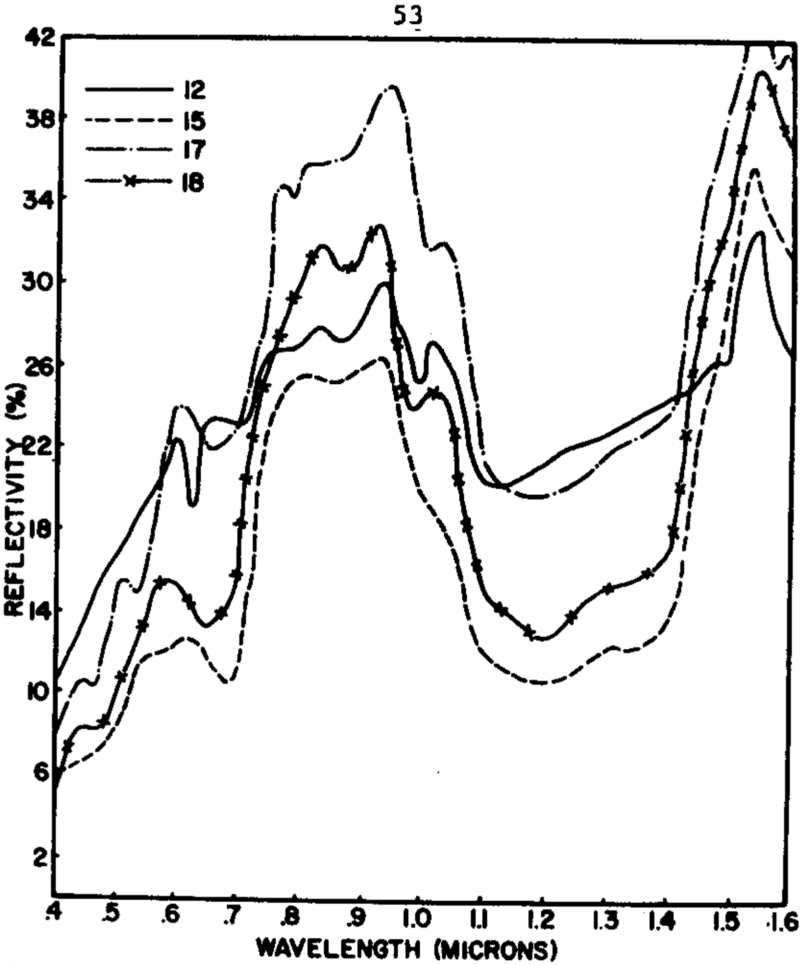


Fig. 26. SPECTRAL REFLECTANCE OF 8 cm GRASS-SOIL SAMPLE PLOTS. Table 3 shows the relative amounts of constituent components in each plot.

	VALUES IN PERCENT						
SAMPLE NO.	12	15		17		18	
GREEN VEGETATION	—0	11.1	327	8.7	124	11.2	374
PARTIALLY GREEN	—0	190		2.2		215	
INTERMEDIATE	—0	2.6		1.5		4.7	
MOSTLY DEAD	—0	1.4	19.5	0.4	8.9	0.4	15.0
DEAD VEGETATION	—0	18.1		8.5		14.6	
SHADOWS	—34.	37.5		24.0		28.9	
SOIL	—66	10.3		35.0		18.7	

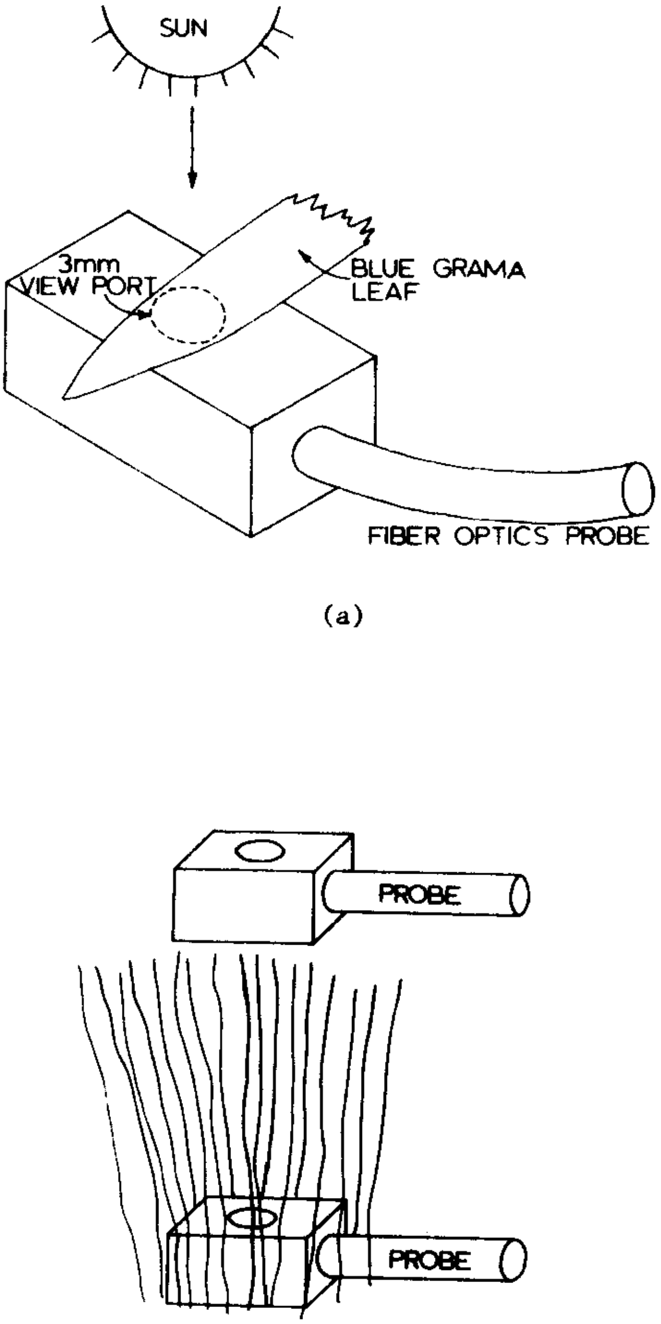
Table 3. VERTICAL PROJECTED COVER OF 8 cm CIRCULAR SAMPLE PLOTS. Actual cover values of 8 cm soil-grass plots measured by dot grid method (Fig. A2) from Ektachrome IR photographs taken September 30, 1970.

Determination of Spectral Light Quality Within a Clump of *Boutiloua gracilis*

Another experiment performed with the laboratory was the first in a series of measurements which will define the spectral light quality of sunlight within a clump of *Boutiloua gracilis* (blue grama grass) through out the growing year. The determination was made with the fiber optics probe extended through the viewing door onto a table covered with photographic darkroom cloth which held the sod sample (Fig. 27).

The first measurements performed were intended to give estimates of the spectral spectroreflectivity and spectrotransmissivity of the dormant brown leaves of blue grama. The measurements for transmission were made by taping a grass blade over the 1/8" viewing port on the fiber optics probe (Fig. 28a). The port was then directed toward the sun and the amount of light transmitted through the leaf was measured. Next, the leaf was removed and the spectroirradiance was obtained with the probe again directed

Fig. 27. DORMANT BLUE GRAMA GRASS CLUMP. Sample clump (14 cm in diameter and 23 cm high) used in the grassland canopy light quality experiment (note: fiber optics probe extending into the right center of the photo).



(a)

(b)

Fig. 28. FIBER OPTICS PROBE PLACEMENT FOR LIGHT QUALITY EXPERIMENT. (a) With blue grama leaf placed over viewing port for determination of spectrotransmittance (Fig. 29). (b) In and outside of the blue grama clump for determination of ratioed light intensity (Fig. 30).

toward the sun. The ratio of the transmitted light curve to the irradiance curve on a wavelength basis gave the spectrotransmittance curve (Fig. 29).

The measurements for estimation of spectroreflectivity were made by assembling a mat of grass blades on the same photographic cloth used on the table (Fig. 27) so that little shadow and no black cloth was visible. The mat was then inclined so that the incoming solar radiation was normal to the mat surface and the probe was placed above the mat looking down so that it cast no shadow on the grass blades. The resulting spectroradiance curve was read by the spectroradiometer and plotted on the x-y plotter. The spectroirradiance curve was determined by substituting a $BaSO_4$ coated aluminum panel for the grass mat in the same orientation and taking another reading. The ratio of radiance to irradiance on a wavelength basis gave the spectroreflectance curve (Fig. 29). The sum of spectroreflectance and spectrotransmittance subtracted from 1 for each wavelength gives spectroabsorbance of the sunlight by the leaf (Fig. 29).

Once these above parameters had been estimated, the spectral light quality inside the clump of blue grama sod was measured. A sample clump of blue grama having a diameter of $\sim$14 cm and a maximum height of $\sim$23 cm above the soil surface was chosen for the experiment. The fiber optics probe was held in this experiment so that its viewing side was horizontal with the viewing port sampling the upper hemisphere (anything above the horizon) (Fig. 28b). However, since the port has a cosine acceptance response, radiation coming from more than 60° off normal had an insignificant effect. The probe was first held above the clump so that a measurement of solar irradiance could be made. Next the probe was centered in the clump resting on the soil surface with the viewing port in the sunlight and another curve was measured (Fig. 28b). Finally the probe was moved slightly so that the viewing port was in the shade of one of the leaves. The wind was

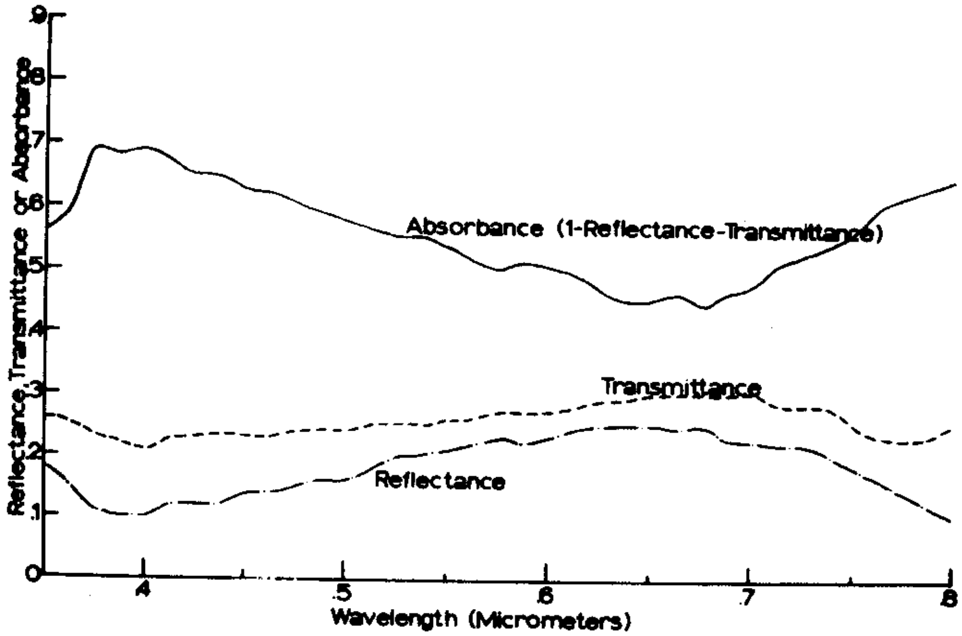


Fig. 29. SPECTRAL PROPERTIES OF DORMANT BLUE GRAMA GRASS (Fig. 27). Reflectance and transmittance were calculated directly from the spectrometer data and absorbance was computed by subtracting the sum of reflectance and absorbance from 1 for every wavelength. Measured at Pawnee Site, February 27, 1971, at 1400 hours MST.

blowing, and the shaded area moved quite a bit causing the loss of data in places. Both of these curves measured in clump were ratioed to the incoming solar reference curve yielding light quality curves in the sunflects and shadows of dormant blue grama (Fig. 30).

The three curves of the optical properties of dormant blue grama leaves appear to be reasonable with the minimum absorbance in the yellow-orange region giving the leaves their light brown color (Fig. 29). The light quality curves are informative in that they suggest that the average light intensity at the bottom of the clump (taken by averaging sunlit and shadowed areas) has a greater intensity than outside the clump (Fig. 30). The sunlit curve has a peak in the .65 to .7 micrometer region which is the same region as the peaks on the transmittance and reflectance curves. This may be explained by the fact that the upper leaves and stems reflect and transmit sunlight down to leaves below with a funneling action which, when

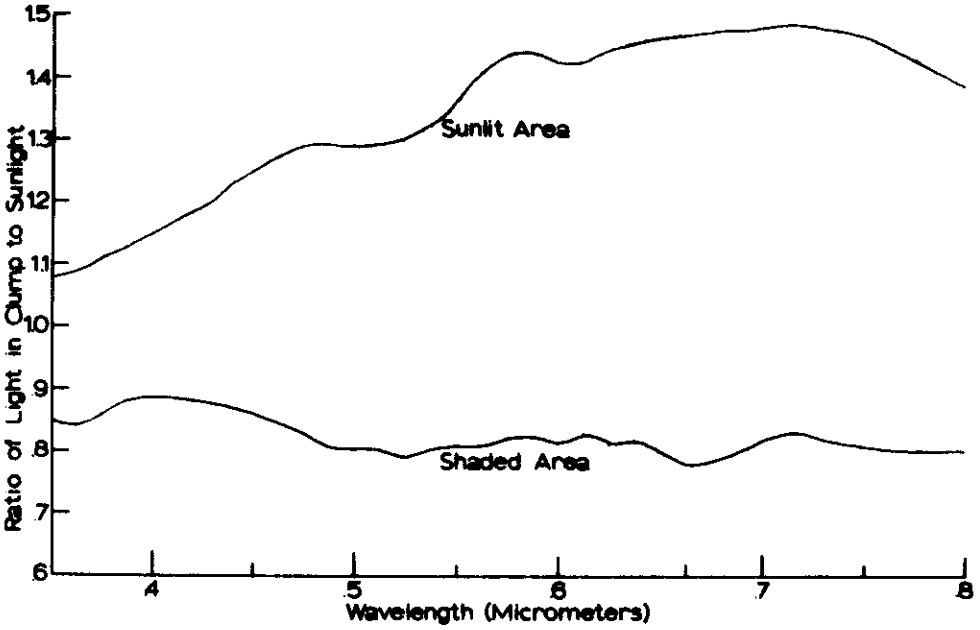


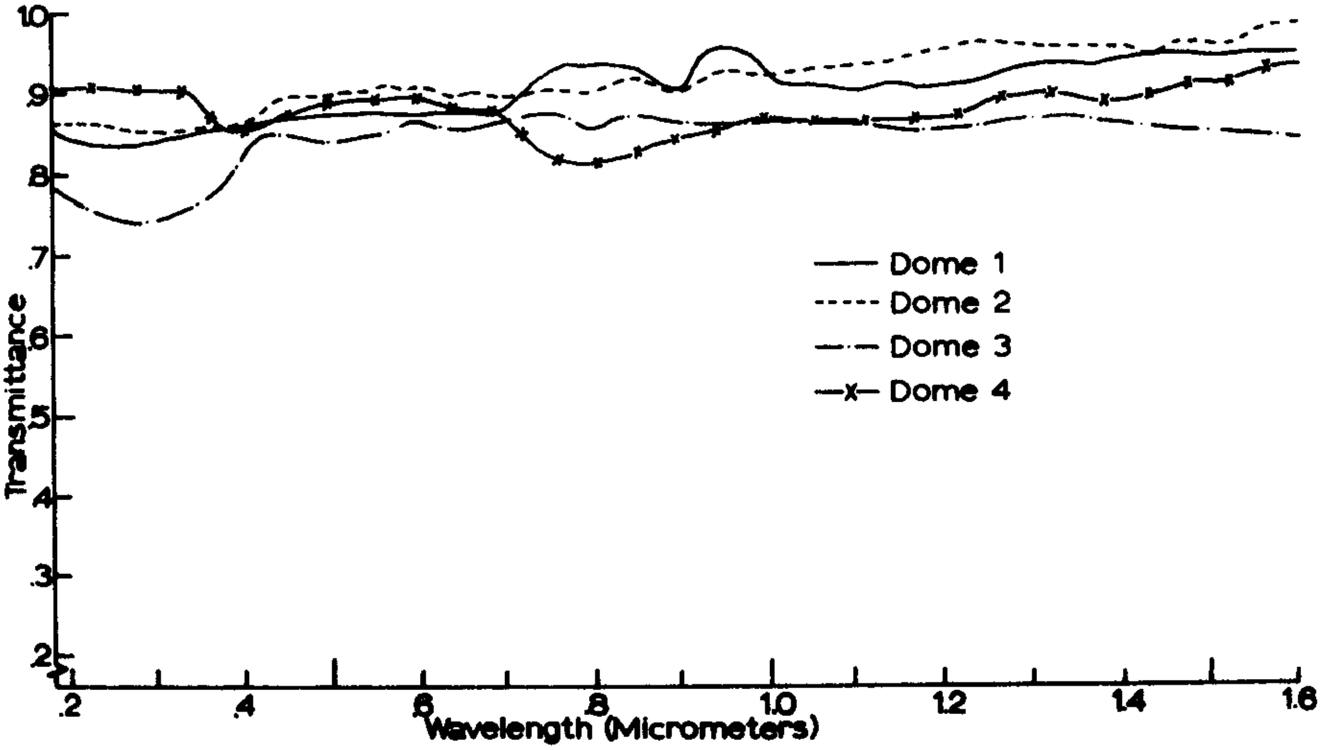
Fig. 30. LIGHT QUALITY WITHIN A CLUMP OF BLUE GRAM GRASS (Fig. 27). Curves of the light quality within the clump for both sunlit and shaded areas ratioed on a wavelength basis to the light quality outside the clump at the same time. Note that in the sunlit area the light intensity is more than outside the clump on a spectral basis, while in the shaded area the intensity is uniformly less than outside the clump.

added to the direct incoming sunlight gives a value greater than the original irradiance for any wavelength in the region sampled being lowest, 1.1 in the blue violet and highest, 1.5 in the red.

Spectral Transmission of the Grassland Photosynthesis Domes

The last field experiment performed by the laboratory was the determination of the spectrotransmission of the plexiglass gas analyser domes used by the photosynthesis group of the IBP Grassland Biome Program. In this exercise, the spectroradiometer's fiber optics probe was substituted for the telescope module and extended out of the trailer (Fig. 31a). The rear of the laboratory trailer was covered with black photographic cloth to minimize the stray reflected light reaching the dome. The end of the fiber optics probe was pointed upward and collected light from the total upward hemisphere according to a cosine function referenced to the zenith.

(a)



(b)

Fig. 31. FIELD MEASUREMENT OF THE SPECTROTRANSMISSION OF PHOTOSYNTHESIS DOMES. (a) Set up for measurement of dome #2 (note: fiber optics probe extending from trailer to center of dome). (b) Transmission curves of four photosynthesis experiment domes.

Spectroirradiance was first read with the dome removed and then with the dome centered in place over the probe's collector. The ratio of these two curves on a wavelength basis is the spectrotransmission of the dome (Fig. 31b). The curves are ordered in transmission value by the length of time the domes have been exposed to direct sunlight (i.e., dome 3 has been exposed to sunlight about 200 hours which has an average transmission of ∿83% while dome 4, which has been exposed only about 10 hours, has the highest average transmission of ∿90%) (Dye, 1971). This aging of the domes is of significance in measuring photosynthesis as it would cause a 7% or 8% change in photosynthesis ratio under these domes.

VI. SUMMARY

The IBP Grassland Biome Program is an organization studying the shortgrass prairie ecosystem with systems analysis techniques. A need of the program is the amount of forage production by the plants in a typical prairie community. In order to fill this need, the Grassland Biome Program has constructed a field spectrometer laboratory with which to study the feasibility of obtaining primary production estimates using remote sensing techniques.

The spectrometer laboratory is designed to view samples 'in situ' without the disturbance necessary with other types of spectrometers. The laboratory is comprised of a spectroradiometer with telescope viewing capabilities, a minicomputer based digital data acquisition system, and maintenance and support equipment.

The experiments performed to date with the laboratory were intended to demonstrate the feasibility of measuring spectroreflectance using a spectroradiometer and the sensitivity of the spectrometer system to changes in vegetation cover amounts.

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VIII. APPENDIX. I. SELECTED BIBLIOGRAPHY

The following bibliography section has been generated from citations taken from Dr. Lee D. Miller's computerized remote sensing library. The bibliography listing is in four sections: Visible Remote Sensing Methods and Instruments; Light Interactions with Biotic Substances; Light Interactions with Abiotic Substances; and Solar Illumination.

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IX. APPENDIX II: Function of Grating Slits

The monochromator element used in the spectroradiometer is a set of interchangable diffraction gratings, one for each of the wavelength regions sampled. The grating surface has a series of closely spaced parallel etched rulings acting as a group of diffracting slits which disperse the light to an angle that is a function of its wavelength. A good discription of the optical characteristics of a dispersion grating can be obtained by referring to a good physics or optics text (Halliday and Resnick, 1963).

In order to select a certain wavelength from the dispersed light, a set of slits is used (Fig. A1). The entrance slit is used to limit the incoming illumination to the central portion of the grating. The quartz lens is used to focus the light into parallel paths which strike the grating surface. The grating set at an angle to the incoming light diffracts this light to angles according to its wavelength (the longer wavelengths are diffracted most) which are reflected off of the parabolic mirror and through the exit slit. By making the entrance and exit slits wider, more light will be allowed through the system. However, as the slit width is increased, a wider wavelength interval of light ($\Delta\lambda$) are allowed through the exit slit which reduces the wavelength resolution, and by narrowing the slits the reverse is true. By doubling the width of each of the slits its cross-sectional 1° area is doubled but because of dispersion from the grating the amount of light passed through is increased by a factor of approximately three.

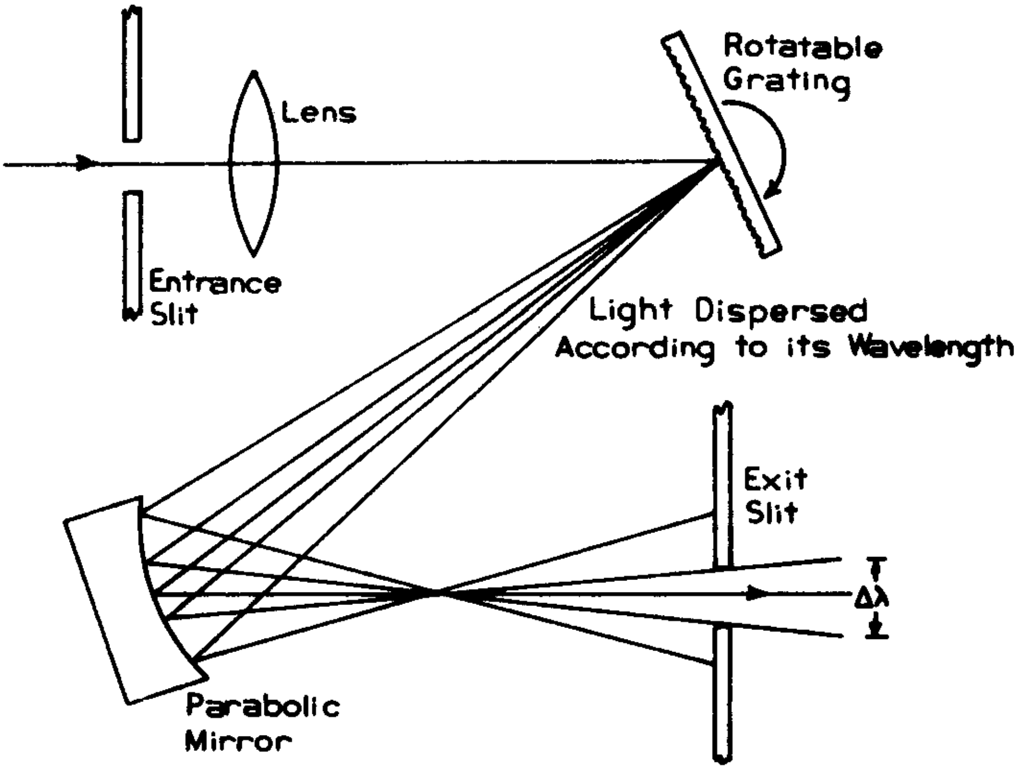
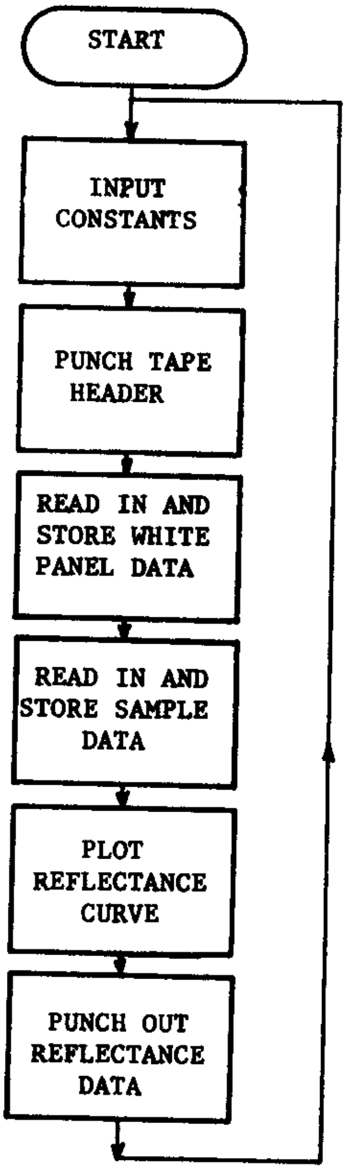


Fig. A1. MONOCHROMATOR GRATING. Schematic drawing of monochromator grating showing the function of entrance and exit slits.

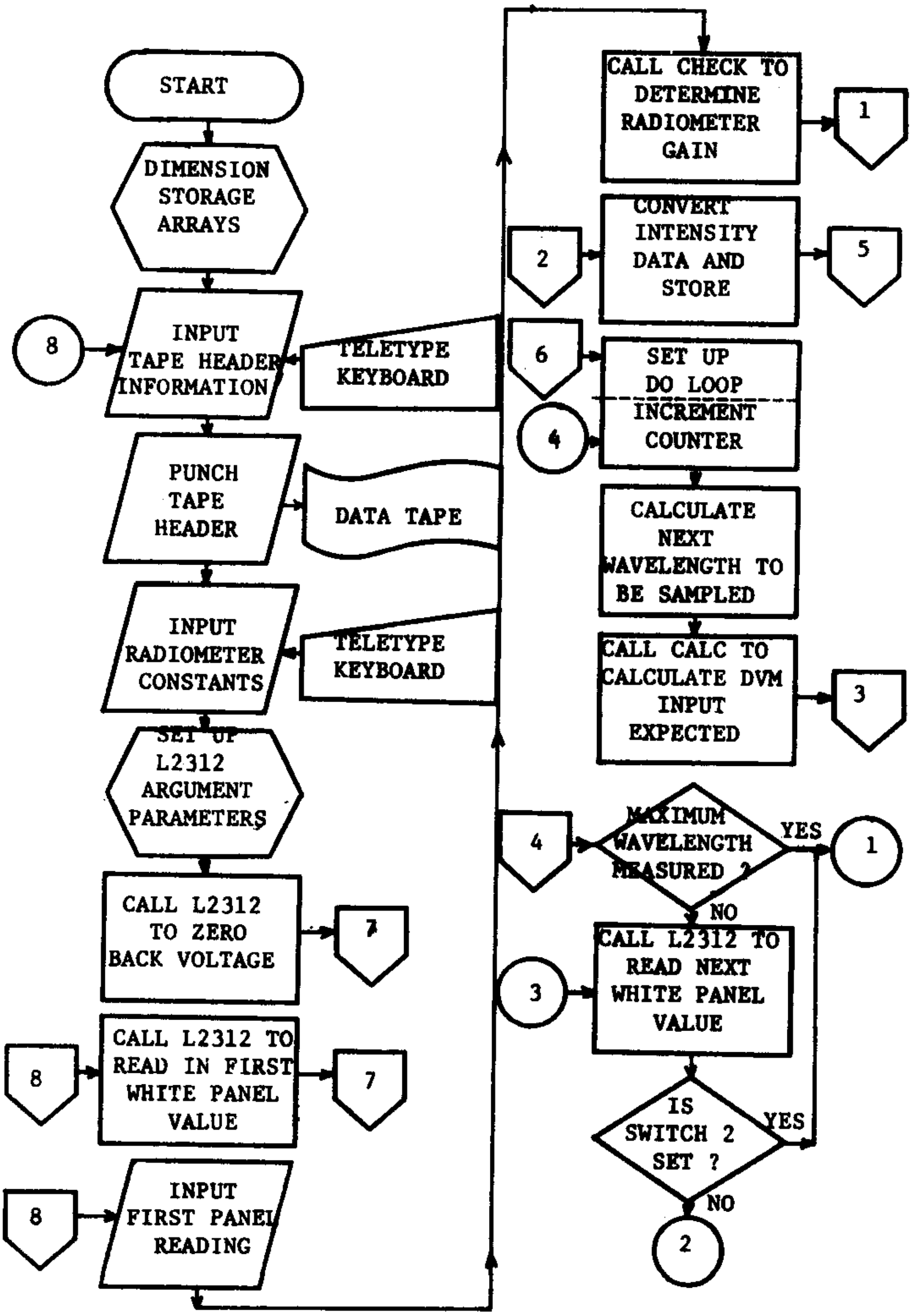
X. APPENDIX III: Data Acquisition Computer Program

A. FUNCTIONAL DIAGRAM OF DATA ACQUISITION PROGRAM

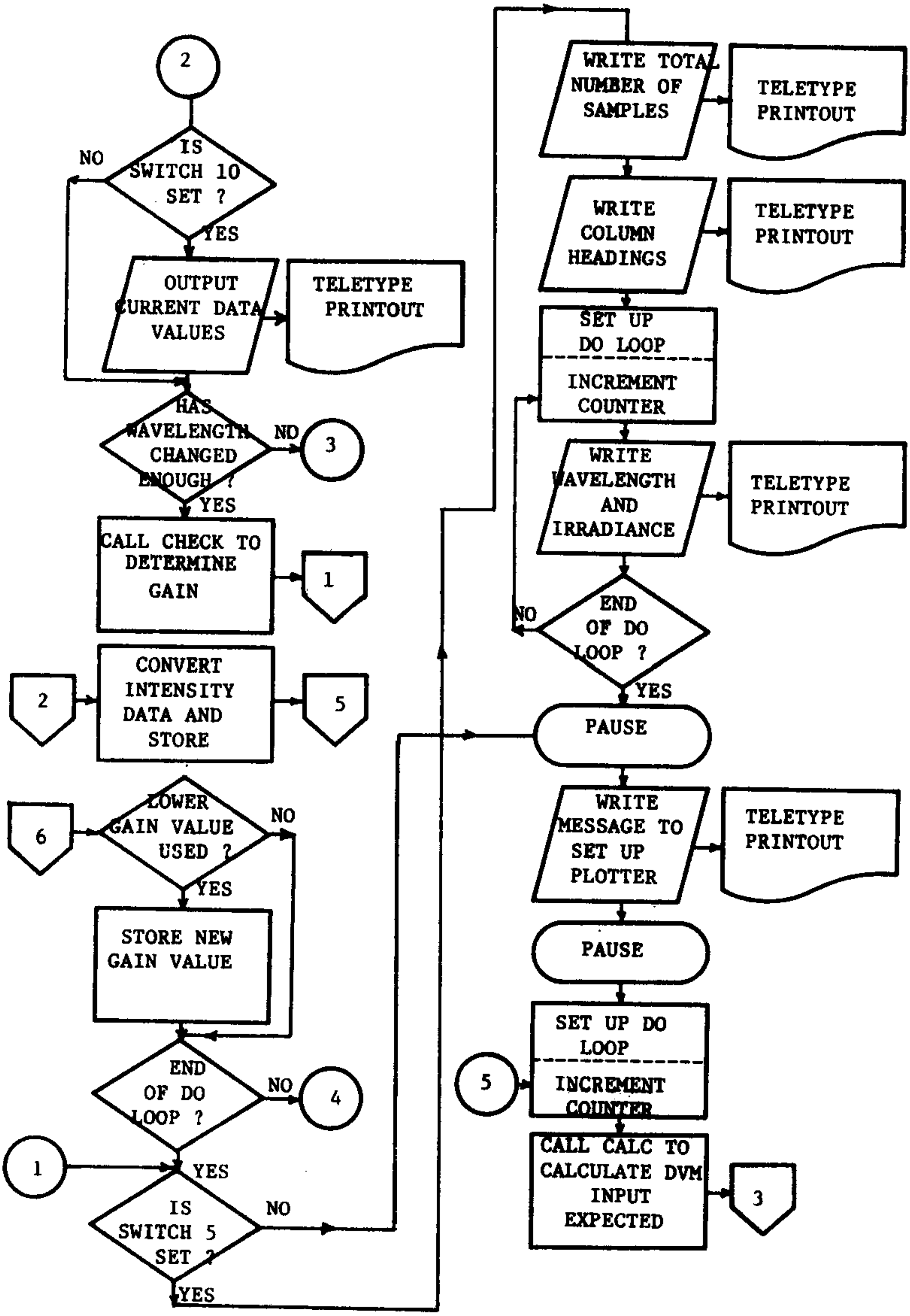


B. FLOW CHART OF DATA ACQUISITION PROGRAM AND SUBROUTINES

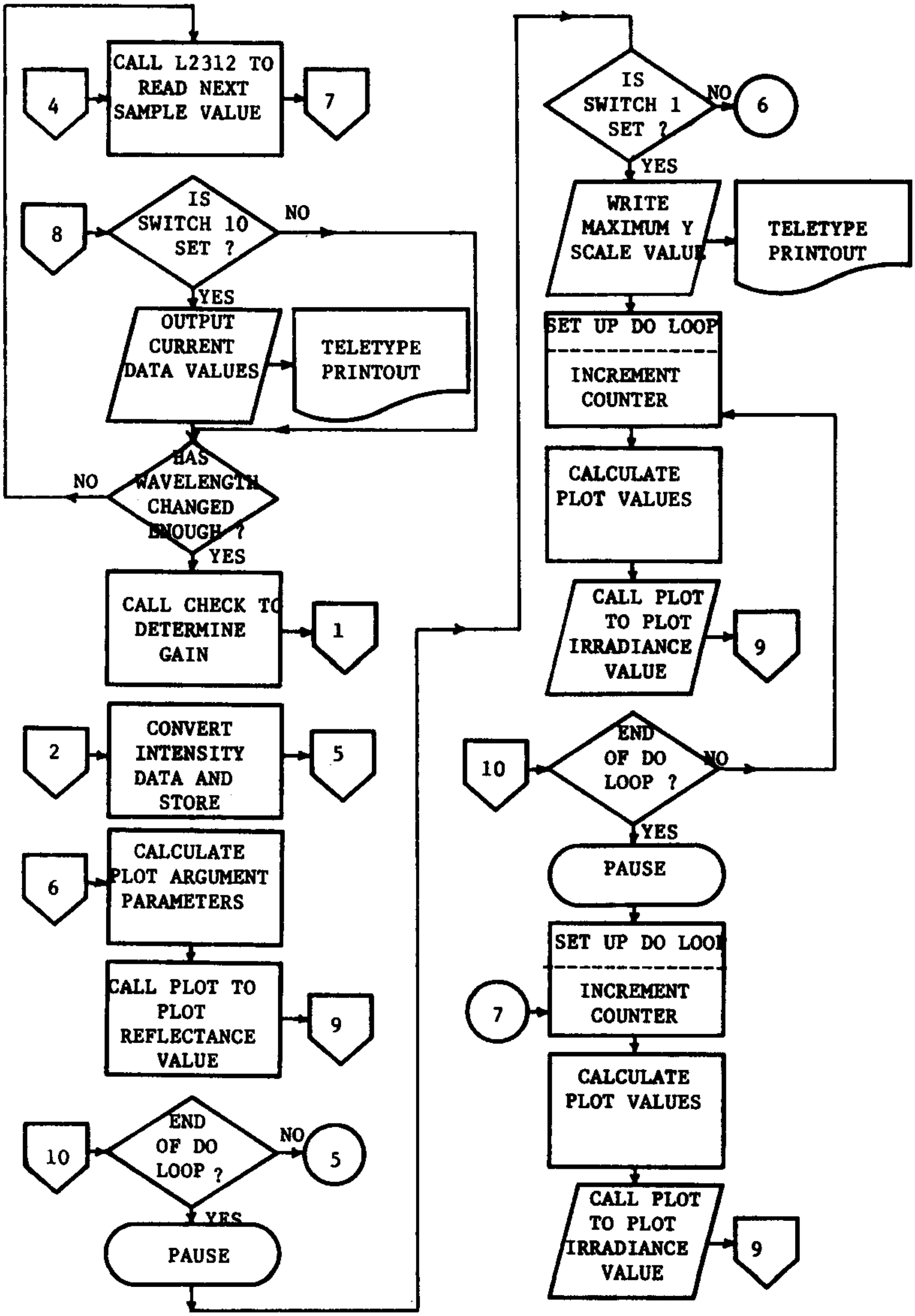
PROGRAM "SAMPL"



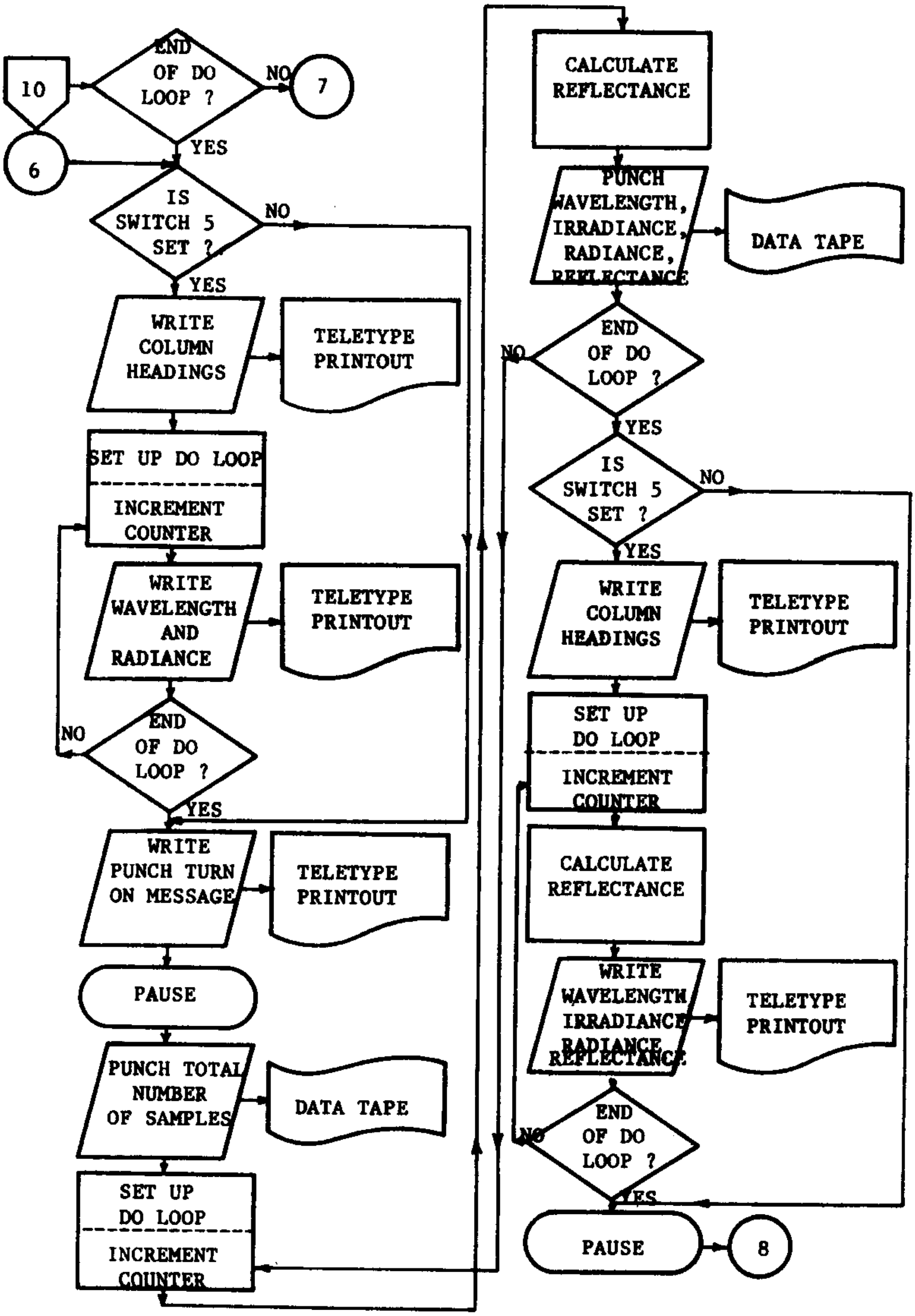
PROGRAM "SAMPL" CONTINUED



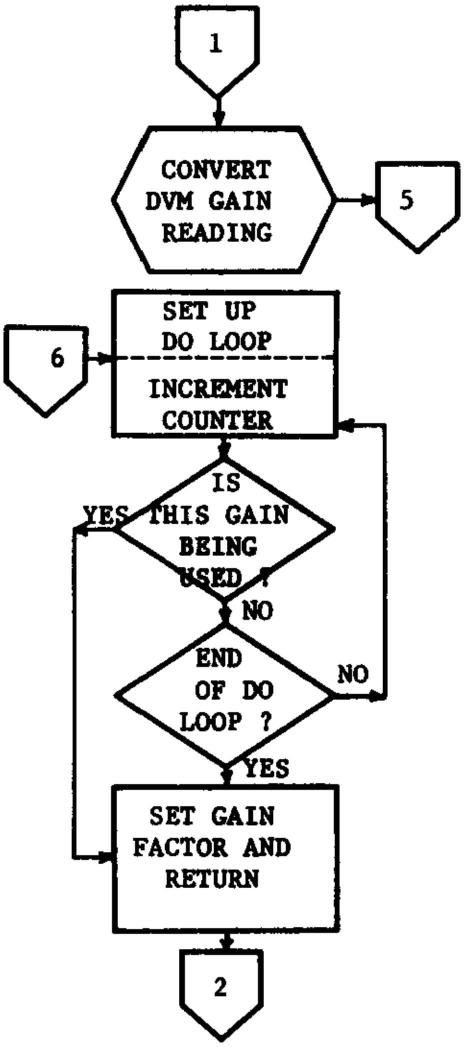
PROGRAM "SAMPL" CONTINUED



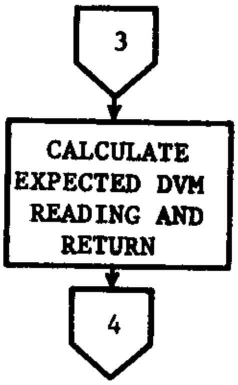
PROGRAM "SAMPL" CONTINUED



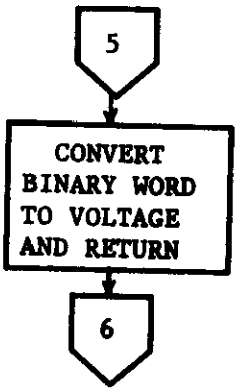
SUBROUTINE "CHECK"



SUBROUTINE "CALC"

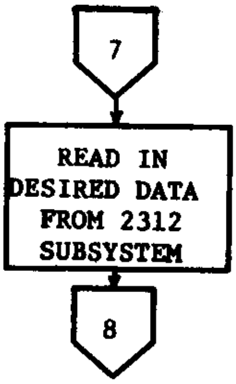


SUBROUTINE "VOLTS"

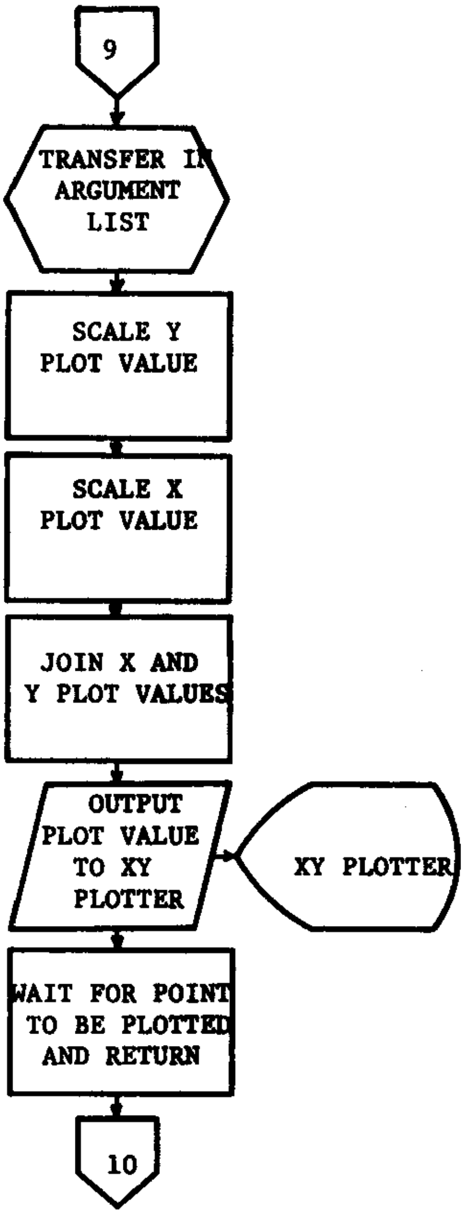


SUBROUTINE "L 2312"

(Supplied with 2312 Subsystem)



SUBROUTINE "PLOT"



C. Listing of Data Acquisition Program and Subroutines

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FTN,B,L
      PROGRAM SAMPL
C          THIS PROGRAM IS DESIGNED TO TAKE READINGS FROM THE
C          SPECTRORADIOMETER, CONVERT TO WAVELENGTH AND PHOTO-
C          MULTIPLIER CURRENT, COMPUTE REFLECTIVITY AND OUTPUT
C          THE DATA ON THE PUNCH, PLOTTER, AND TELETYPE
C
C
C     *******************************************************
C     *                                                     *
C     *              VARIABLE IDENTIFICATION                *
C     *                                                     *
C     *   IWAVE........ARRAY OF WAVELENGTHS SAMPLED         *
C     *   WHITE........ARRAY OF IRRADIANCE VALUES           *
C     *   GREEN........ARRAY OF RADIANCE VALUES             *
C     *   IDATA........TEMPORARY STORAGE OF DVM READINGS    *
C     *   ID...........CURVE NUMBER                         *
C     *   IS...........SAMPLE CODE                          *
C     *   IDA..........JULIAN DATE OF MEASUREMENT           *
C     *   IH,IM........TIME OF MEASUREMENT (24 HOUR CLOCK)  *
C     *   ILO,WMIN.....SHORTEST WAVELENGTH SAMPLED          *
C     *   ILM,WMAX.....LONGEST WAVELENGTH SAMPLED           *
C     *   IDL..........WAVELENGTH INCREMENT FOR SAMPLING    *
C     *   IH,IM........TIME OF MEASUREMENT (24 HOUR CLOCK)  *
C     *   TC...........WAVELENGTH TRANSDUCER CONSTANT       *
C     *                  (ANGSTROMS/VOLT)                   *
C     *   IUNIT........BCS UNIT REFERENCE NUMBER OF 2312    *
C     *                  SUBSYSTEM                          *
C     *   IRDGS........NUMBER OF READINGS TO BE TAKEN BY 2312 *
C     *   IMDLN........MODE OF SAMPLING BY 2312 SUBSYSTEM   *
C     *   IPGM.........STARTING GAIN RANGE AND CHANNEL NUMBER *
C     *                  FOR 2312 SUBSYSTEM                 *
C     *   RATIO........RATIO OF RADIANCE TO IRRADIANCE AT   *
C     *                  WAVELENGTH IWAVE                   *
C     *   G............GAIN CORRECTION APPLIED IN SUBROUTINES *
C     *   GTABL........TABLE OF GAIN CONSTANTS TO BE APPLIED *
C     *                  TO THE PHOTOMULTIPLIER DATA        *
C     *   GSET.........VOLTAGE OUTPUT BY GAIN CHANNEL OF    *
C     *                  RADIOMETER                         *
C     *   RGAIN........CURRENT GAIN BEING APPLIED TO THE DATA *
C     *   V............TABLE OF EXPECTED GSET VOLTAGES      *
C     *   RGNMX........MAXIMUM GN USED FOR IRRADIANCE DATA  *
C     *   PLOTM........10*MAXIMUM GAIN USED (FOR SCALING    *
C     *                  PLOTTED IRRADIANCE DATA)           *
C     *   IWOLD........LAST WAVELENGTH SAMPLED (BINARY)     *
C     *   IWNEW........CURRENT WAVELENGTH SAMPLED           *
C     *   IROLD........LAST RADIANCE SAMPLED                *
C     *   IRNEW........CURRENT RADIANCE SAMPLED             *
C     *                                                     *
C     *******************************************************
C
      DIMENSION IWAVE(200),WHITE(200),GREEN(200)
      COMMON IDATA(4),GTABL(12),IS(34)
      GTABL(1)=1.E-6
      GTABL(2)=3.E-7
      GTABL(3)=1.E-7
      GTABL(4)=3.E-8
      GTABL(5)=1.E-8
      GTABL(6)=3.E-9
      GTABL(7)=1.E-9
```

```
      GTABL(8)=3.E-10
      GTABL(9)=1.E-10
      GTABL(10)=3.E-11
      GTABL(11)=1.E-11
      GTABL(12)=3.E-12
C           TYPE IN CURVE IDENTIFICATION DATA
    1 WRITE(2,100)
      READ(1,*)ID
      WRITE(4,101)ID
      WRITE(2,102)
      READ(1,99)IS
      WRITE(4,103)IS
      WRITE(2,104)
      READ(1,*)IDA,IH,IM
      WRITE(4,105) IDA,IH,IM
      PAUSE
C           INPUT RADIOMETER CONSTANTS
      WRITE(2,106)
      READ(1,*)ILO,ILM,IDL,TC
C           ZERO MULTIPLEXER BACK VOLTAGE
      IUNIT=7
      IRDGS=4
      IDATA(1)=0
      IDATA(2)=0
      IDATA(3)=0
      IDATA(4)=0
      IMDLN=-4
      IPGM=037000B
      CALL L2312(IUNIT,IRDGS,IDATA,IMDLN,IPGM)
C
C           PASS 1---READ IN WHITE PANEL DATA
C
C           READ FIRST WHITE PANEL VALUE
      IRDGS=3
      IMDLN=-3
      IPGM=037001B
      CALL L2312(IUNIT,IRDGS,IDATA,IMDLN,IPGM)
      IWAVE(1)=ILO
      CALL CHECK(RGAIN)
      WHITE(1)=VOLTS(IDATA(2))*RGAIN*10.
C           CALCULATE SUCCEEDING WAVELENGTH VALUES,CONVERT
C           TO DVM READING EXPECTED AND TEST DVM INPUT
      RGNMX=RGAIN
      DO 50 I=2,200
      K=I-1
      IWAVE(I)=ILO+K*IDL
      CALL CALC(IWRDG,IWAVE(I),TC,ILO)
    5 IF(ILM-IWAVE(I))51,10
   10 CALL L2312(IUNIT,IRDGS,IDATA,IMDLN,IPGM)
C           SET SWITCH 2 TO MANUALLY END CURVE
      IF(ISSW(2))51,19
C           SET SWITCH 10 TO OBTAIN RUNNING DATA PRINTOUT
   19 IF(ISSW(10))13,12
   13 WRITE(2,14)IWAVE(I),IWRDG,IDATA(1),IDATA(2),RGAIN
   14 FORMAT(I5,3(O6,","),E8.1)
C           TEST WAVELENGTH TO SEE IF IT HAS CHANGED ENOUGH
   12 IF(IWRDG-IDATA(1))15,15,10
   15 CALL CHECK(RGAIN)
      WHITE(I)=VOLTS(IDATA(2))*RGAIN*10.
C           TEST FOR MINIMUM GAIN VALUE USED
```

```
      IF(RGNMX-RGAIN)50,50,25
   25 RGNMX=RGAIN
   50 CONTINUE
C           SET SWITCH 5 TO OBTAIN PRINTOUT
   51 I=I-1
      IF(ISSW(5))52,65
   52 WRITE(2,113)I
      WRITE(2,107)
      DO 60 J=1,I,10
      WRITE(2,108)IWAVE(J),WHITE(J)
   60 CONTINUE
   65 PAUSE
C
C           PASS 2---READ IN SAMPLE DATA
C
C           READ UNKNOWN SAMPLE WAVELENGTHS AND VALUES FOR
C           WAVELENGTHS SAMPLED IN THE FIRST PASS
      WRITE(2,112)
      PAUSE
      DO 70 J=1,I
      CALL CALC(IWRDG,IWAVE(J),TC,ILO)
   30 CALL L2312(IUNIT,IRDGS,IDATA,IMDLN,IPGM)
C           SET SWITCH 10 TO OBTAIN RUNNING DATA PRINTOUT
      IF(ISSW(10))31,35
   31 WRITE(2,14)IWAVE(J),IWRDG,IDATA(1),IDATA(2),RGAIN
C           TEST WAVELENGTH TO SEE IF IT HAS CHANGED ENOUGH
   35 IF(IWRDG-IDATA(1))40,40,30
   40 CALL CHECK(RGAIN)
      GREEN(J)=VOLTS(IDATA(2))*RGAIN*10.
C           PLOT REFLECTANCE VALUE
      WAVE=IWAVE(J)
      WMAX=ILM
      WMIN=ILO
      WPLT=WMAX*(WAVE-WMIN)/(WMAX-WMIN)
      RMAX=1.
      RATIO=GREEN(J)/WHITE(J)
      IF(RATIO-RMAX)69,69,68
   68 RATIO=RMAX
   69 CALL PLOT(WPLT,WMAX,RATIO,RMAX)
   70 CONTINUE
      PAUSE
C           SET SWITCH 1 TO PLOT RADIANCE AND IRRADIANCE
      IF(ISSW(1))80,73
   80 PLOTM=10.*RGNMX
      WRITE(2,115)PLOTM
      DO 85 N=1,I
      WAVE=IWAVE(N)
      WPLT=WMAX*(WAVE-WMIN)/(WMAX-WMIN)
      CALL PLOT(WPLT,WMAX,WHITE(N),PLOTM)
   85 CONTINUE
      PAUSE
      DO 87 N=1,I
      WAVE=IWAVE(N)
      WPLT=WMAX*(WAVE-WMIN)/(WMAX-WMIN)
      CALL PLOT(WPLT,WMAX,GREEN(N),PLOTM)
   87 CONTINUE
C           SET SWITCH 5 TO OBTAIN PRINTOUT
   73 IF(ISSW(5))75,93
   75 WRITE(2,107)
      DO 93 J=1,I,10
```

```
      WRITE(2,108)IWAVE(J),GREEN(J)
   94 CONTINUE
C           OUTPUT WAVELENGTH,WHITE PANEL,SAMPLE AND REFLECTIVITY TO
C           THE HIGH SPEED PUNCH
   93 WRITE(2,114)
      PAUSE
      WRITE(4,116)I
      DO 91 J=1,I
      RATIO=GREEN(J)/WHITE(J)
      WRITE(4,109)IWAVE(J),WHITE(J),GREEN(J),RATIO
   91 CONTINUE
C           SET SWITCH 5 TO OBTAIN PRINTOUT
      IF(ISSW(5))95,92
   95 WRITE(2,110)
      DO 92 J=1,I,10
      RATIO=GREEN(J)/WHITE(J)
      WRITE(2,111)IWAVE(J),WHITE(J),GREEN(J),RATIO
   92 CONTINUE
      PAUSE
      GO TO 1
   99 FORMAT(3442)
  100 FORMAT("INPUT CURVE NUMBER")
  101 FORMAT(I5)
  102 FORMAT("INPUT SAMPLE DESCRIPTION")
  103 FORMAT(1H",3442,2H ")
  104 FORMAT("INPUT TIME OF DAY (XXX,XX,XX)")
  105 FORMAT(I3,",",I2,",",I2)
  106 FORMAT("INPUT LAMBDA 0, L.MAX, D.L.,T.C.")
  107 FORMAT("WAVELENGTH (ANGSTROMS),AMPERES")
  108 FORMAT(8X,I4,",",8X,E10.4)
  109 FORMAT(I5,3(",",E10.4))
  110 FORMAT("WAVELENGTH",5X,"WHITE",9X,"SAMPLE",6X,"REFLECTIVITY")
  111 FORMAT(I5,7X,E10.4,4X,E10.4,4X,F6.4)
  112 FORMAT("SET UP PLOTTER")
  113 FORMAT("TOTAL # OF SAMPLES IS "I3)
  114 FORMAT("PUNCH!")
  115 FORMAT("MAX. VERT. PLOT VALUE =",E10.4)
  116 FORMAT(I3)
      END
      SUBROUTINE CHECK(RGAIN)
      DIMENSION V(12)
      COMMON IDATA(4),GTABL(12)
C           THIS SUBROUTINE READS THE GAIN CHANNEL FROM THE
C           SPECTRORADIOMETER AND DETERMINES RGAIN TO BE USED
C           IN CORRECTING THE INTENSITY DATA
C
C           READ ANALOG CHANNEL 3 TO DETERMINE AMPLIFIER GAIN
C           SETTING
      GSET=VOLTS(IDATA(3))
      V(1)=.06
      V(2)=.16
      V(3)=.26
      V(4)=.35
      V(5)=.46
      V(6)=.56
      V(7)=.66
      V(8)=.76
      V(9)=.87
      V(10)=.99
      V(11)=1.10
```

```
      V(12)=1.3
C            TEST GSET TO SEE WHICH RADIOMETER GAIN IS BEING USED
      DO 100 I=1,12
      IF(GSET-V(I))200,100
  100 CONTINUE
  200 RGAIN=GTABL(I)
      RETURN
      END
      SUBROUTINE CALC(IWRDG,IWAVE,TC,ILO)
C           THIS SUBROUTINE CALCULATES THE NEXT DVM BINARY WORD
C           EXPECTED FROM THE WAVELENGTH TRANSDUCER CHANNEL
      G=.7812
      IWRDG=IFIX((FLOAT(IWAVE-ILO)/TC)*G*32768.)
      RETURN
      END
      FUNCTION VOLTS(IDATA)
C           THIS FUNCTION CONVERTS THE DVM BINARY WORD FROM THE
C           INDICATOR CHANNEL TO ITS EQUIVALENT INPUT VOLTAGE
      G=.7812
      VOLTS=(FLOAT(IAND(IDATA,177740B))/(G*32768.))
      RETURN
      END
      ENDS
```

```
 ASMB,R,B,L,T
       NAM PLOT
       ENT PLOT
       EXT .ENTR,IFIX
AGMTS  BSS 4                  RESERVE SPACE FOR 4 FLOATING POINT NUMBERS
STORE  NOP                    RESERVE SPACE FOR INTERMEDIATE STORAGE
PLOT   NOP
       JSB .ENTR              GO TO .ENTR TO TRANSFER IN ARGUMENTS
       DEF AGMTS
       DLD AGMTS+2,I          LOAD IN Y VALUE
       FDV AGMTS+3,I          DIVIDE BY Y MAX
       FMP NORM               MULTIPLY BY 255.
       JSB IFIX               CONVERT TO FIXED POINT
       ALF,ALF
       AND MASKY              MASK OFF LEAST SIGNIFICANT BITS
       STA STORE              STORE TEMPORARILY
       DLD AGMTS,I            LOAD IN X VALUE
       FDV AGMTS+1,I          DIVIDE BY X MAX
       FMP NORM               MULTILPY BY 255.
       JSB IFIX               CONVERT TO FIXED POINT
       AND MASKX              MASK OFF LEAST SIGNIFICANT BITS
       IOR STORE              MERGE Y PLOT VALUE
       STC DA,C
       OTA DA
       SFS DA                 WAIT FOR DATA TO BE PLOTTED
       JMP *-1
       JMP PLOT,I             RETURN TO MAIN PROGRAM
NORM   DEC 255.
MASKY  OCT 177400
MASKX  OCT 000377
DA     EQU 14B
       END
```

XI. APPENDIX IV: Projected Dot Grid Method

The method used to photographically determine the percentage of each of several constituents in a circular plot is to take an Ektachrome IR photograph of the scene with a wire ring or similar device placed in the area to denote the area to be measured. After the slide is developed, it is placed in a 35 mm slide projector with a zoom lens and is projected onto a dot grid (Fig. A2). The size of the projected image is adjusted with the zoom lens so that the wire ring in the slide corresponds to the circular boundary on the dot grid. Then by counting the number of dots which touch each desired constituent and dividing these counts by the total number of dots, the percentage of each can be estimated.

The value of this method over the point quadrat method is that by using Ektachrome IR film, healthy, green vegetation will stand out from the abiotic and dead background material. Another advantage over the point quadrat method is that a permanent photographic record is rapidly obtained in the field at the same time as spectroreflectance curves and can later be reduced at the experimenter's conveniencs.

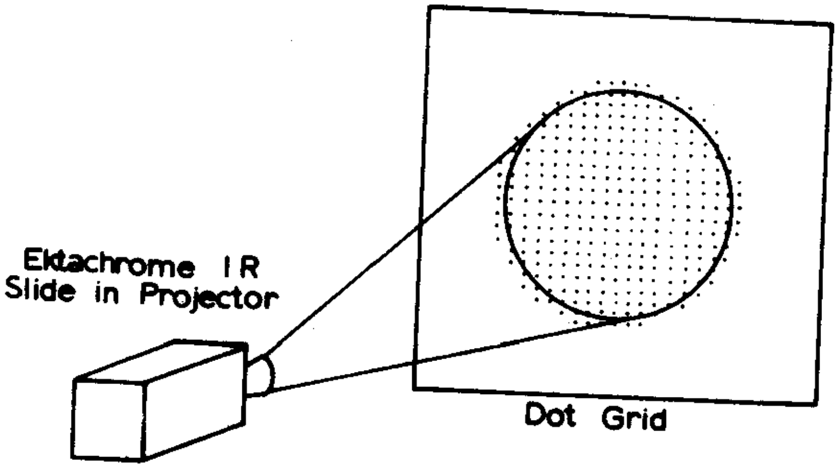

Fig. A2. PROJECTED DOT GRID METHOD OF MEASURING PERCENT COVER. A 35 mm Ektachrome IR slide, taken normal to the sample plot, is projected onto a dot grid where counts are made of the occurance of each component.