Multispectral Sensing of Agricultural Resources

IV Field Spectroscopy

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Field spectroscopy is the general term describing the techniques, instruments, and considerations necessary to obtain reflectance, emissivity, and radiance spectra of vegetation and soils in natural environment. A major point is that the measurements are made with objects in their natural environments; crops are viewed on large or small scale as they grow in the field under ambient micrometeorological conditions, soils are viewed as they are, plowed, harrowed, raked, and so on. The measurements are made under the natural irradiance with all the variabilities associated with cloud cover, a point that must be considered in calibration efforts. The advantage of field spectroscopy to the agriculturalist who desires in situ measurements is obvious; he cannot transport samples to the laboratory spectrophotometer, there to mount them for a specific measurement and hope to reproduce the many variables of the natural environment. On the other hand, many of the niceties of optical design built into the laboratory instrument and taken for granted are not present in the field - the solar irradiance at the scene of view replaces the lamp as a source, for example. This means that the optical nature of the data gathering process must be carefully considered in order to have meaningful data.

The discussion to follow is concerned with the wavelength range from 0.35 to 16 microns. Atmospheric absorption rules out other optical portions of the electromagnetic spectrum in a practical sense. Radar or microwave spectroscopy has sufficiently different instrumentation considerations to warrant separate treatment. The same holds for x-ray or gamma spectroscopy.

There is a natural division of the 0.35 to 16 micron wavelength range from a field spectroscopy point of view. From 0.35 to about 4 microns the scene of view is reflecting solar direct and scattered irradiance. From about 4 microns to the end of the 8 to 14 micron atmospheric window, the scene is emitting radiation as a grey body with some emissivity variation as a function of wavelength. There is some overlap of reflective and emissive behavior in the vicinity of 4 microns. These aspects pose different calibration problems and view angle problems in each spectral region, and have strong influence on instrument design choices.

The discussion of field spectroscopy opens with what may be called exterior parameters, those points to be taken into account assuming an adequate instrument is at hand. This leads naturally to the problems of instrument calibration in the face of the variabilities of the field experiment. This in turn requires consideration of the scan time, spectral resolution, and sensitivity of the field spectrometer. These features, together with signal-to-noise ratio properties, are discussed in conjunction with specific wavelength ranges of interest in agriculture. Finally, there is a brief review of instrument types available and under design. It should be emphasized at this point that most instruments that have been used in the field to date are not stock catalog instruments - they have been designed for field spectroscopy specifically, often as prototypes. The existence of a well-accepted, time-tested line of instruments, such as one finds in laboratory spectrometers, spectrographs, and spectrophotometers is still some years and a considerable amount of user demand in the future. In this vein it is mandatory for one embarking on field spectral measurements to have more than a casual acquaintance with instrumentation. As a closing point in the section on instrument types, various forms of data readout are discussed with a view to what the experimenter wishes to accomplish; a balance is sought between the time required to gather data and the time necessary to analyze these data.

Geometrical Parameters of Field Measurements

Several vital features of accurate field spectroscopy can be discussed with only the more gross specifications of instrument performance kept in mind. These specifications are field of view, effective aperture, focusing capabilities, and polarization sensitivity.

To begin, field of view is best defined in terms of the procedure used to measure this quantity. In order to map out the field of view of a particular instrument, a small radiation source is located on the nominal optical axis of the instrument. The source may be a tungsten lamp in the visible and near infrared portions of the spectrum. From about 3 to 16 microns a hot object such as a soldering iron behind an aperture plate will suffice, or direct viewing downward onto a surface of known emissivity cooled to 77°K in a small dewar half-filled with liquid nitrogen will serve the purpose. While the instrument is held fixed, and focused on the source, the source is moved measured amounts in the plane perpendicular to the optical axis, and relative instrument signal output is monitored. In this way loci of constant instrument response can be found. Simple trigonometry converts loci positions into degrees off the instrument axis. The resulting intensity profiles can be changed into power contours through appropriate calculations. Some typical field of view calibrations for instruments used in the field are shown in Figure 4-1.

Effective aperture area is the cross-sectional area, at the instrument optical entrance, of the bundle of rays emanating from a small source in the field of view. The word "effective" is used to indicate that only those rays which proceed to a detector in the instrument are included. The larger the effective aperture, the more radiation is collected from the sources in the field of view.

The focusing capabilities of an instrument depend on the specific task at hand. As a general rule for field measurements, if the scene of view is much closer than one meter (with an attendant small field of view area), it may be more reasonable to transport a standard spectrophotometer to the field location or design a special purpose arrangement of detectors and optical components than to insist on stringent short focus requirements for general purpose field instruments. General purpose instruments, then, should have focusing capability from a meter or so to infinity; along with this, reflex optics enabling the experimenter to determine both the scene of view and instrument focus just prior to measurement are most desirable.

In most spectrometers there will be some sensitivity to the polarization of the incident radiation. Whenever radiation reflects from or refracts through a medium such as a mirror surface or prism the intensity after this event will generally be a function of the polarization of the incident electromagnetic waves. Since experiments have been reported [1] indicating reasonably strong polarization effects in radiation reflected from vegetation and soils, polarization sensitivity of an instrument is an important parameter in field work. At least one instrument currently in use in field spectroscopy is extremely sensitive to polarization degree and direction. This is not a drawback, providing the instrument polarization axis is known; in fact this feature allows measurement of polarization properties of natural objects. In the visible and near infrared regions it is not difficult to calibrate an instrument in this respect with a bright source and a commercial polarizer. Polarizers are also available for the emissive range.

Now that the gross geometric properties of measuring instruments have been discussed it is possible to pass on to exterior geometric arrangements in the field experiment environment. The general experimental conditions are drawn in Figure 4-2. Clouds are included to emphasize the effect they may have on the experiment. The field of view of the instrument at the ground plane is shown cross-hatched. Important angles are the altitude and aximuth of both the sun and the instrument (θ_s, ϕ_s and θ_i, ϕ_i), the orientation angle of the instrument with respect to its optical axis, η, and the lay of any row structure in the crop or soil being observed. Sun angles are measured directly or computed from the time of observation and latitude-longitude of the test site, using navigational tables.

To emphasize the geometric effects one may observe and illustrate the need for knowledge of the geometric parameters, three field spectral experiments are shown in Figures 4-3, 4-4, and 4-5. These data were taken in the summer of 1966 at the Purdue University Agronomy Farm with a Perkin-Elmer SG-4 rapid scan grating spectrometer. The field of view of this instrument was extremely small even at large viewing distance, as can be seen by reference to Figure 4-1. Figure 4-3 shows the effect of a small field of view on data gathered on a windy day. The spectrometer was set for a fixed wavelength and was held on a fixed scene for many seconds. The "noisy" variations in the response are the result of leaf motion in the field of view about 35 feet from the instrument aperture. Further, the gross effects of scattered cumulus cloud cover are manifest. Note that significant change due to cloud cover takes place in a few seconds or less. Figure 4-4 shows several spectra taken in the 3 to 4 micron region at the border of the reflective-emissive behavior. The day was one of light overcast with the sun occasionally breaking through for short intervals. The total spectral scan time was fifteen seconds and the curve shows that even in this region of the spectrum cloud cover variability can affect results in short times of a second or so, to the extent of at least doubling the instrument response.

Figure 4-5 shows measurements at several fixed wavelength settings of the Perkin-Elmer spectrometer. In this experiment the instrument was manually panned out along a soybean row four times, once at each wavelength setting. The day was clear, so cloud cover was not a factor. Again, the minor variations of the recording are due to the small field of view with respect to the crop leaf size. At some wavelengths (1.12 and 1.26 microns) the response appears to be independent of view angle while at others there is significant variation as θ_i is increased.

It is possible to collect most of these parameters into a concise notation which clarifies what is being measured and how much power is flowing into the instrument aperture. The amount of power flowing into the instrument aperture in the wavelength range λ to $\lambda + \Delta\lambda$ is

$$\Delta P = \tau_a(\lambda)\ \overline{N_\lambda}\ A_a \Omega_f\ \Delta\lambda \quad \text{(watts)} \tag{1}$$

where A_a is the effective instrument aperture, Ω_f is the solid angle of the field of view, and τ_a is the transmittance of the atmospheric path from the scene to the instrument aperture. A quantity N_λ, called spectral raidance, is defined as the radiant power, wavelength range λ to $\lambda + \Delta\lambda$, from a source of incremental surface area flowing into a solid angle increment about a given direction from the source surface normal. This geometry is shown in Figure 4-6. The quantity $\overline{N_\lambda}$ in Eq. (1) is the average spectral radiance over the field of view of the spectrometer. It is averaged in two senses, both over the field of view area variety of source types and over the great variety of angles between surface normals and the instrument optical axis. The relation between $\overline{N_\lambda}$ over a heterogenous scene in the field of view, such as a one meter square of corn field, and normal incidence reflectance measurements on one corn leaf segment in a DK-2 spectrophotometer are not well understood at present. Indeed, the study of the scattering and emission of radiation from rough or heterogenous surfaces is an active research discipline in its own right.

Still, the experimenter is faced with the fact that the power flow into the field spectrometer is a measure of $\tau_a \overline{N_\lambda}$ simply multiplied by A_a and $\;_f$, parameters of the designer's choice. Some general functional aspects of $\overline{N_\lambda}$ can be stated and kept in mind when interpreting field spectroscopy data. For the reflective region, refering to Figure 4-2, $\overline{N_\lambda}$ is expected to be a function of θ_s, ϕ_s, θ_i, ϕ_i, atmospheric conditions, and the detailed geometry of the scene viewed. In the emissive region the same variables are important during the day, with the obvious simplification at night. In the reflective region $\overline{N_\lambda}$ is written as a product of the solar and skylight power per unit area into the scene ($H_\lambda \cos\theta_s$) in the $\Delta\lambda$ range and an average bidirectional reflectance for the scene. This bidirectional reflectance is averaged in the same involved sense as $\overline{N_\lambda}$. Then

$$\Delta P = \underbrace{\frac{\tau_a}{\pi} H_\lambda \cos\theta_s}_{\substack{\text{incident radiation,}\\ \text{modified by atmospheric}\\ \text{conditions}}} \overbrace{\overline{\rho_\lambda(\theta_s,\phi_s,\theta_i,\phi_i)}}^{\substack{\text{angular effects + detailed}\\ \text{scene geometry}}} \underset{\substack{\uparrow\\ \text{effective}\\ \text{aperture}}}{A_a} \underset{\substack{\nwarrow\\ \text{field}\\ \text{of view}}}{\Omega_f} \Delta\lambda \quad \text{(watts)} \qquad (2)$$

If the experimenter's major purpose is to correlate spectra with aircraft scanner data, then $\overline{N_\lambda}$ is the item of interest, for this is what an airborne reflective region scanner is sensing. On the other hand, if the experimenter's major purpose is to correlate field spectra with laboratory spectrophotometer data on natural objects, then $\overline{\rho_\lambda}$ is the item of interest, for it is the hemispherical integral of this quantity that is measured in the laboratory. Eq. (2) shows clearly that in order to interpret field spectra in terms of reflectance it is essential to measure concurrently the incident radiation spectrum.

In the emissive region an approximate form for $\overline{N_\lambda}$ can be written, based on radiation theory. Thus, the power flow into the instrument aperture is

$$\Delta P = \tau_a \, \overline{\epsilon(\lambda,T)} \, 1.19\text{X}10^4 \, \lambda^{-5} \left[\exp(14{,}388/\lambda T) - 1\right]^{-1} A_a \Omega_f \Delta\lambda \qquad (3)$$

λ in microns, T absolute temperature

If the scene of view were an isothermal Lambertian radiator, the quantity $\overline{\epsilon(\lambda,T)}$ would be the same as the conventional emissivity of the radiator. Even for nearly idealized flat, isothermal radiators there are a variety of emissivity quantities such as total, hemispherical, normal, and relative (angular) emissivities [2]. In a heterogenous, non-isothermal scene of a variety of sources at many angles, with semi-transparent objects overlapping opaque objects it is presumptive to link emissivity with $\overline{\epsilon(\lambda,T)}$ for the scene. Still, $\overline{\epsilon(\lambda,T)}$ in Eq. (3) serves to indicate departures from the standard black body curves that would result if $\overline{\epsilon(\lambda,T)}$ were unity.

The equations just given suffice for the estimation of order of magnitude of power into an instrument, in addition to providing concise statements of the variables.

It was pointed out that the reflectance or emissivity of a natural object as measured in the laboratory was difficult to extrapolate for the interpretation of spectra from a heterogenous field scene, and vice versa. This fact places a burden on the experimenter in the field to accurately describe both the field conditions and the instrument parameters in reporting his data. The description should include all the angles of Figure 4-2 and the obvious instrument variables; in addition, well-selected close-up and instrument range photographs of the detailed scene geometry are mandatory for adequate spatial description of the experiment. It is only through the correlation of many sets of such carefully defined field spectra that behavioral trends will emerge that will ultimately correlate with laboratory experiments and aid in the interpretation of aircraft scanner flight data.

Instrument Calibration

The power flowing into the aperture of a field spectrometer generally passes through foreoptics into the wavelength determining elements of the instrument. Following some form of wavelength discrimination, the power in the spectral range

λ to $\lambda+\Delta\lambda$ falls on a detector which transduces the optical power to an electrical signal. Electronic amplification of this signal follows, and finally results in an instrument response or output, usually a voltage signal. The first step in instrument calibration is to determine how the response is related to power flow into the aperture. The reflective region is considered first.

Standard quartz-iodine lamps of known spectral irradiance are commerically available. For such a source the number of watts per unit area per unit wavelength increment at a certain distance from the lamp is given by the supplier. Thus, if an instrument to be calibrated is set up in the laboratory viewing a standard lamp, the power flowing into the aperture in the wavelength range λ to $\lambda+\Delta\lambda$, call it $\Delta P(\lambda)$, is known. As wavelength selection is varied in the instrument, the response is recorded as a function of wavelength, response denoted by $R(\lambda)$. Then it is reasonable to define an instrument transfer function, $K(\lambda)$, by

$$\left\lceil R(\lambda) \right\rceil_{\substack{\text{std.}\\ \text{lamp}}} = K(\lambda) \cdot \left\lceil \Delta P(\lambda) \right\rceil_{\substack{\text{std.}\\ \text{lamp}}} \tag{5}$$

Now, having the transfer function, if the response from a scene of view is recorded in the field, the result is

$$\left\lceil R(\lambda) \right\rceil_{\text{scene}} = K(\lambda) \cdot \left\lceil \Delta P(\lambda) \right\rceil_{\text{scene}} \tag{6}$$

and minor algebra shows that

$$\left\lceil \Delta P(\lambda) \right\rceil_{\text{scene}} = \frac{\left\lceil \Delta P(\lambda) \right\rceil_{\substack{\text{std.}\\ \text{lamp}}}}{\left\lceil R(\lambda) \right\rceil_{\substack{\text{std.}\\ \text{lamp}}}} \left\lceil R(\lambda) \right\rceil_{\text{scene}} \tag{7}$$

Each quantity on the right hand side of Eq. (6) is known, hence $\left[\Delta P(\lambda)\right]_{\text{scene}}$ is determined.

This simple process will suffice for calibrating the instrument to determine $\overline{N_\lambda}$ only if one serious assumption is made. For this to work, it must be assumed that the spectrometer designer is able to make the instrument invariant to the environmental change from the air-conditioned, low-humidity laboratory to the ambient conditions in the field. At least three different spectrometers used in the field at present require this assumption to be made since they possess no internal calibration source. Spectra reduced to relative spectral radiance curves by this laboratory lamp comparison method are shown in Figures 4-7 through 4-10. The relative spectral radiance is found because gain settings in the signal amplifier must be different for the bright lamp source as compared with the lesser field radiance. The transfer function is changes by a constant factor for all wavelengths as gain is changed. Thus, the quantity $\left[\Delta P(\lambda)\right]_{\text{scene}}$ of Eq. (7) is multiplied by a constant factor. For absolute measurements of the scene radiance all instrument settings should be identical for both laboratory and field, or determined precisely for both laboratory and field and taken into account in the reduction arithmetic.

A serious problem prevents the use of this laboratory calibration technique in the emissive range unless special precautions are taken. Although standard black body sources are commercially available to provide the emissive range equivalent of the spectral lamp in the laboratory, the environmental changes from laboratory to field and the details of instrument design play significant roles in the spectrometer output. The spectrometer detector will "see" (interchange radiation with) the instrument optics and mechanical parts as grey bodies at ambient temperature. Through careful design the detector can be made to view only a limited area of surface of known temperature monitored by thermistor sensors. Without going into instrument details at this point, suffice it to say that an emissive range spectrometer will always contain a grey body that competes with the scene viewed in exciting the detector. This effect may be exploited by making a self-contained black body calibration source within the spectrometer.

The next calibration technique is related to the discussion of the previous paragraphs. The essence of this technique is that the calibration source is built into the spectrometer, and the detector alternately views the scene and the calibration source at a rapid rate, on the order of hundreds of cycles per second. The resultant detector signal is electronically demodulated to yield a response which measures the difference between scene response and source response.

$$\left\lceil R(\lambda) \right\rceil_{\text{scene}} - \left\lceil R(\lambda) \right\rceil_{\text{source}} = K(\lambda) \left\{ \left\lceil \Lambda P(\lambda) \right\rceil_{\text{scene}} - \left\lceil \Lambda P(\lambda) \right\rceil_{\text{source}} \right\} \qquad (8)$$

For the reflective range, K(λ) can be found by simply covering the aperture of the spectrometer, and is

$$K(\lambda) = \frac{\left\lceil R(\lambda) \right\rceil_{\text{source}}}{\left\lceil \Lambda P(\lambda) \right\rceil_{\text{source}}} \qquad (9)$$

If this is put into Eq. (8) the result is

$$\left\lceil \Lambda P(\lambda) \right\rceil_{\text{scene}} = \frac{\left\lceil \Lambda F(\lambda) \right\rceil_{\text{source}}}{\left\lceil R(\lambda) \right\rceil_{\text{source}}} \left\lceil R(\lambda) \right\rceil_{\text{scene}} \qquad (11)$$

which shows that this method is formally identical with the laboratory source calibration. There is an important practical distinction of this method, however. The instrument is viewing the source in the same environment with the field scene. Any variabilities of the components of the spectrometer are present for both source and scene viewing, and are subtracted out by the differential character of the measurement.

The internal source is always present in the emissive range instrument, whether designed into the spectrometer or not. It is customary design practice to have the detector "see" alternately the scene radiance and the radiance of an internal black body of controlled, or at least measured temperature. Eq. (8) still applies, thus a differential measurement is again employed, removing instrument component variation effects. The resultant output, when reduced, gives the radiance of the scene times the atmospheric transmittance. Even if the atmospheric transmittance is known, the measurement does not give the emissivity-like variable, $\overline{\epsilon(\lambda,T)}$, unless the average surface temperature is known for the objects in the field of view. The average surface temperature is one of the most difficult measurements to make correctly, even for a homogenous scene of uniform material. The reasonable course at the present time is to report scene radiance, if the atmospheric path effects are known, or aperture irradiance otherwise.

A third calibration method consists of placing a material of known reflectance or a black body source of known temperature near the scene of view. If the spectral scanning rate of the instrument is sufficiently fast, a spectral scan of the scene is immediately followed by a scan of the reflectance standard or the black body. In the reflective region this amounts to a comparison of scene reflectance $\overline{(\ \lambda)}$ with the standard providing the solar and skylight irradiance does not change during the total time required to take both spectra. In the emissive range this method essentially eliminates the effect of atmospheric transmittance between the scene and the spectrometer. For both the reflective and emissive ranges one of the major difficulties of the technique is the required size of the standards to fill the field of view. The effect of too small a field of view in gathering spectra of field vegetation was shown in Figures 4-3 and 4-5. If the field of view is large enough to average cut fine-grained detail, the standards will have to be of corresponding size.

A second difficulty with the reflectance standard or the black body is the difficulty of assuring the quality of the standard in the field environment. A large black body source must be maintained at uniform temperature in the face of variable solar irradiance, wind velocity, humidity, and so on. The reflectance standard is subject to subtle surface changes due to interaction of the surface material with ambient atmospheric gases. Further, to avoid time-consuming calibration of the reflectance standard in a spectrophotometer, it is desirable to have a standard which is stable and easily repaired when damaged. Standards tested in the summer of 1966 included white poster board, 3-M white velvet paint on poster board, barium sulfate slurries in a variety of vehicles, and flowers of sulfur. The flowers of sulfur proved to be a workable standard. The sulfur panel was constructed on quarter-inch wallboard in alternate coats of 3-M white velvet paint as a binder, and flowers of sulfur. This procedure was followed to a coating thickness of one quarter of an inch, with the last sulfur layer being quite thick. The entire surface, 30" x 30", was flat-pressed in a large hydraulic press. A protective layer of wallboard over the sulfue surface, and normal care in handling the panel led to a standard which stood up well in the field over the summer. The panel reflectance was nearly that of reported in a test of sulfur as a standard [3], and was measured with respect to magnesium oxide on a DK-2 spectrophotometer. A spectrum reduced with respect to this panel is shown in Figure 4-11.

One other modification of the reflectance panel method is feasible. A small reflectance standard can be placed close to the instrument aperture, and its spectrum taken immediately following the scene spectrum. This method has the advantage of small reflectance panel size, and the disadvantage of not including atmospheric transmittance effects over a distance of approximately twice the scene to spectrometer length. The disadvantage is relatively mild, and the method is the only one practical for an instrument with a large enough field of view to average out vegetation scene details.

The reflection standard calibration process results in data suitable for comparison with laboratory spectrophotometer data. The aircraft or satellite data measure irradiance at the scanner aperture which includes both solar irradiance and reflectance. At the present stage of remote sensing ideal field spectroscopy should include both scene radiance measurements against a built-in calibration source and solar irradiance measurements from a reflectance panel or an independent spectrometer measuring solar irradiance separately.

Calibration has long been the subject of investigation by workers in spectroscopy and radiometry. For further study on this subject, the reader is referred to the broad bibliographies of the Handbook of Military Infrared Technology. [7]

Internal Instrument Parameters

In addition to the geometrical parameters already covered, any field spectrometer will have other important characteristics of sensitivity, dynamic range, signal-to-noise ratio, resolution, and spectral scan rate. While these parameters involve details of the instrument design, it is important for the field experimenter to have an understanding of how these parameters affect his work and his choice of instrument.

Sensitivity is mainly a function of the choice of detector for a given optical system of certain aperture and field of view. The voltage, current, or conductance variation from a detector per unit of electromagnetic power incident must be sufficiently large to overwhelm noise signals inherent in any detector. An applicable discussion of specific detector types is given in Chapter 5. In a practical vein, the relation between sensitivity and field spectroscopy comes to a focus on the annoying but essential requirements of detector cooling. As a general rule, rapid-scan spectroscopy of reasonable resolution will involve liquid nitrogen or high-pressure gaseous nitrogen for cooling in the range from 1 micron to 5.5 microns, and liquid helium cooling in the range from 5.5 to 16 microns. For the visible and near infrared regions uncooled detectors often suffice. Cooling problems are not insurmountable, but they do impose the requirements of coolant availability and handling techniques.

The dynamic range of an instrument is a measure of the ability to take spectra of both bright and dim scenes. One usually wants to make maximum use of the linear ranges of the detector signal amplifier and the recording instrumentation (X-Y plotter, tape recorder, oscilloscope, and so on). For most common field scenes on a clear day the gain of the spectrometer amplifier is set to a fixed value such that the irradiance from the brightest scene gives a signal just below the saturation (overload) level of the amplifier and recording instruments. If the day is cloudy, this method of manual gain control requires continual resetting of the gain. Electronic automatic gain control can be built into the spectrometer circuitry, but field experience to date has shown that dynamic range problems are not severe, and manual gain control is sufficient for the normal variety of agricultural scenes.

Signal-to-noise ratio, resolution, and scan rate are interrelated parameters. Each parameter represents a desirable property which the experimenter would like to have as large as possible. A single example will suffice to show the interrelation and the resultant constraints. Figure 4-12 shows the structure of the Perkin-Elmer SG-4 spectrometer, and is self-explanatory. The signal-to-noise power ratio, S/N, is proportional to the width of the entrance slit, w, and inversely proportional to the bandwidth of the detector signal amplifier, Δf. Thus

$$S/N = \text{constant} \times \frac{w}{\Delta f} \tag{12}$$

The resolution of this instrument is limited by the entrance slit width for the normal slit widths used in the field. The resolution, r, is the ratio of wavelength, λ, to the wavelength difference, $\Delta\lambda$, of two spectral lines at λ that can just be distinguished from one another. In the spectrometer of Figure 4-12,

$$r = \frac{\text{constant}}{w} \tag{13}$$

which holds only for slit-limited resolution. The scan rate is limited by the ability of the detector amplifier to respond to sudden changes in detector irradiance, and this ability is determined by the amplifier bandwidth, Δf. Calling scan rate F,

$$F = \text{constant } \Delta f \tag{14}$$

When Eqs. (12), (13), and (14) are combined, it is clear that

$$(S/N)(r)(F) = \text{constant} \tag{15}$$

This relation shows that for a given design one may trade off resolution for scan rate, or signal-to-noise ratio for resolution, and so on. Since there is usually a minimum acceptable signal-to-noise ratio, Eq. (15) really comes down to a trade-off relation between scan rate and resolution.

The demonstrated rapid variability of the agricultural scene spectral radiance warrants emphasis on high spectral scan rate at the expense of resolution. This is consistent with the irradiance limited low resolution of aircraft scanners. Spectrometer manufacturers tend to emphasize resolution at the expense of scan rate for the demands of general spectroscopy.

Wavelength Range

Thus far it is apparent that field spectroscopy calls for a large field of view, rapid spectral scan spectrometer. The next topic covers the wavelength ranges which field experience has shown to be of interest. The reader should refer to Figures 4-7 through 4-10 for graphic support of the points to be made below.

First, the range from 0.4 to 1.1 micron is fascinating in the variety of spectra from agricultural scenes. The high near infrared reflectance of turgid vegetation compared with soils stands out clearly. The physiological variable, color, is contained in the spectral curves from 0.4 to 0.7 micron. The entire range certainly contains information of value in remote sensing and should be studied with as high a resolution as possible, consistent with scan rate requirements.

Next, the range from 1.1 to 2.0 microns may contain information in the amplitudes of the pronounced peaks between the 1.14, 1.38, and 1.87 water absorption bands. Spectral curve shape, on the other hand, seems to be the same for a large variety of targets. This is in contrast to the 0.4 to 1.1 micron region. It is reasonable to assume that a very gross spectrometer capable of measuring only the total irradiance between each absorption band will be necessary.

Spectral character in the 2.0 to 2.6 micron window and the 3.0 to 4.1 micron window is similar to that in the 1.1 to 2.0 region. Details of spectral shape within these windows do little to enhance target identification, though there may be information in the total power in each window.

In situ field spectral data on agricultural scenes are rare in the 4.5 to 5.5 micron window. Spectroscopic capability was not available to agricultural researchers until late autumn, 1966, for this wavelength range. One reported spectrum on grass indicates typical grey body emitter behavior, as expected [5]. Total power measurements in this window are available on natural objects that confirm this general tendency to appear as grey bodies. Even if significant fine spectral structure of the effective scene emissivity $[\overline{\epsilon(\lambda,T)}]$ were known to be present, there is a large amount of atmospheric band structure in this window range that may obscure interpretation.

In a similar vein, spectral structure in the atmospheric window from approximately 7 to 15 microns is not well explored for agricultural scenes. Again, total power measurements are common in this wavelength range, to be interpreted as radiation emanating from a grey body. There are recent data [6, 7] showing that restrahlen absorption bands can be detected in minerals; these may be of value in soil type evaluation. Still, the major application for information on radiance in this window is expected to be surface temperature radiometry for both crops and soils. Interpretation of apparent temperatures so measured has been discussed in Chapter 2.

Instrument Types and Data Readout

The specific spectrometer system of Figure 4-12 illustrates the general features of a broad class of field instruments. First, there are collecting optics or foreoptics which usually determine the field of view (in conjunction with an entrance slit or field stop) and the effective aperture. Details of collecting optics are available in standard optics texts. Next, there is a wavelength-selecting unit, for example, the grating monochromator in Figure 4-12. It is the manner of wavelength selection that is the distinguishing feature of field spectrometer designs; this feature will be discussed in the following paragraphs. The radiation passing through the wavelength-selecting portion goes on to the detector, possibly through a detector optics system. Detector types are common for most instruments and are discussed in Chapter 5. Finally, there are the electronic signal processing units, details of which are outside the scope of this chapter.

The most common monochromators employ a grating or prism as the dispersing element. These monochromators are amply discussed in standard spectroscopy texts such as that by Sawyer [8]. In field work over the range from 0.35 to

16 microns several gratings or prisms are required to cover the spectrum. If a single grating or prism mount instrument is utilized, it is necessary to change dispersing elements several times in the field environment in order to cover the spectral range on a chosen scene. One expensive way around this difficulty is an instrument with several gratings (or prisms) and dichroic mirrors to steer gross spectral ranges to the appropriate gratings. An alternate solution is the utilization of rapid-change modular monochromators with convenient plug-in gratings. Such monochromator units are commercially available today (Bausch & Lomb), but the collecting optics and detector arrangement must be tailored to the unit.

Another common wavelength selection method is the use of interference filters which pass only a narrow spectral range on to the detector. A large selection of fixed range filters may be mounted on a wheel and alternately placed in the optical path, essentially sampling the spectrum at the wavelengths of the filters. An interesting variation on this idea is the continuous filter, with wavelength selection determined by the location of the optical path on the filter surface. One instrument, the ISCO Model SR spectroradiometer, utilizes a continuous filter laid down in a line on a glass substrate for the spectral range from 0.35 to 1.05 microns. Continuous filters laid along the circumference of a wheel are available from Optical Coating Laboratories, Inc. These filter wheels cover the spectral range from 1.2 microns to well beyond the 16 micron limit discussed in this chapter. Several instrument proposals based on the filter wheel are being studied by remote sensing researchers, and one filter wheel instrument for aircraft use was designed and built at NASA, Goddard. Filter wheels below 1.2 microns are currently under development.

Still another form of wavelength-selection utilizes interferometer techniques, commonly based on the Michelson or Fabry-Perot interferometers, or a Soleil compensator-polarizer combinations. In this scheme different wavelengths of the incoming spectrum are converted to different audio frequencies at the detector, the amplitude of each frequency depending on spectral power inflow at the corresponding wavelength. The output might be called a "spectral symphony"; mathematically it is the Fourier transform of the input spectrum. This places the burden on the experimenter of performing the inverse Fourier transform to regain the original spectrum, either at general computational facilities or in an available special purpose computer. Three Block Engineering, Inc., interferometer spectrometers are currently in use in agricultural field spectroscopy.

Whatever the particular design features of an instrument, the agricultural experimenter is always faced with the decision of the mode of data recording in the light of subsequent reduction problems. Most instruments have outputs suitable for connection to conventional recorders such as x-y plotters or strip charts or oscilloscope-camera combinations. This recording mode is sufficient when a relatively small number of spectra are to be studies. The labor of manually reducing these data is more than compensated to the expense and de-bugging effort necessary to establish a more sophisticated data analysis system. On the other hand, if the experimenter intends to record field spectra over a growing season on a wide variety of crops and soils in order to establish statistical trends, the result will be hundreds or thousands of spectra. In this case the more sophisticated data handling system becomes a necessity, not a luxury. Analog or digital tape recording in the field is the mode of data gathering, and facilities are required for later playback and analysis of the tapes. An interesting report on data handling problems met by geophysical research workers in remote sensing is available [9]. It is good policy to gather data on a modest scale when first experimenting with a new field spectrometer, carefully checking for data consistency, calibration reliability, and proper instrument functioning with a reasonable number of simply recorded spectra.

Future Field Spectroscopy Plans

The field spectroscopy techniques discussed thus far result in one number for a given scene and given wavelength interval, or equivalently, one spectrum for the entire area covered by the field of view. As pointed out, this number can be reduced to an average scene radiance, a most involved average in terms of the multiplicity in variety and angular variation of the objects in the scene.

In the research work in the field the prime question is how the overall reflectance or emittance of the scene in, say, a two meter by two meter patch can be interpreted in terms of what is there including geometry, spatial layout and variety of surfaces. This in turn requires a knowledge of the location in the scene of the various levels of radiance, N_λ, for wavelengths of interest. For example, a corn field scene will include tassels, brightly irradiated top leaves, dimly illuminated lower leaves, stalks, and soil between rows, all of which contribute to the integrated radiance measured by the spectrometer.

One type of spectral instrument which, by its very nature, will yield a spatial map of the scene is the multilens camera. This instrument takes several simultaneous photographs of the same scene on a single plate, each through a bandpass filter of chosen wavelength limits. The resulting photos give a good qualitative view of the distribution of spectral radiance levels over the scene, but the problems of readily analyzing this distribution are significant, requiring accurate film calibration and a flying-spot scan of the photographic plate. In addition, the experiment is limited to the spectral range covered by the emulsion sensitivity.

A field spectrometer can be made which will have a relatively small field of view of about 5 milliradians or less. The area covered by this field of view can be scanned over a scene such as the two by two meter patch by a rotating mirror system in a rectangular, television-like raster. The outputs in various spectral bands would be detected and recorded in parallel, simultaneously, on magnetic tape. This tape may then be played back to create a digital line-printer image in the same manner that aircraft scanner digital printouts are now produced at the Laboratory for Agricultural Remote Sensing at Purdue University. In fact, the field spectrometer necessary to perform this imaging type measurement could be a reasonable modification of an airborne scanner system. Such a scanning field spectrometer is as technologically feasible today as a simple field spectrometer. What is needed is the impetus, the time, and money necessary for successful development. The research necessary to put remote sensing in agriculture on an operational basis has provided the impetus for field spectrometer development.

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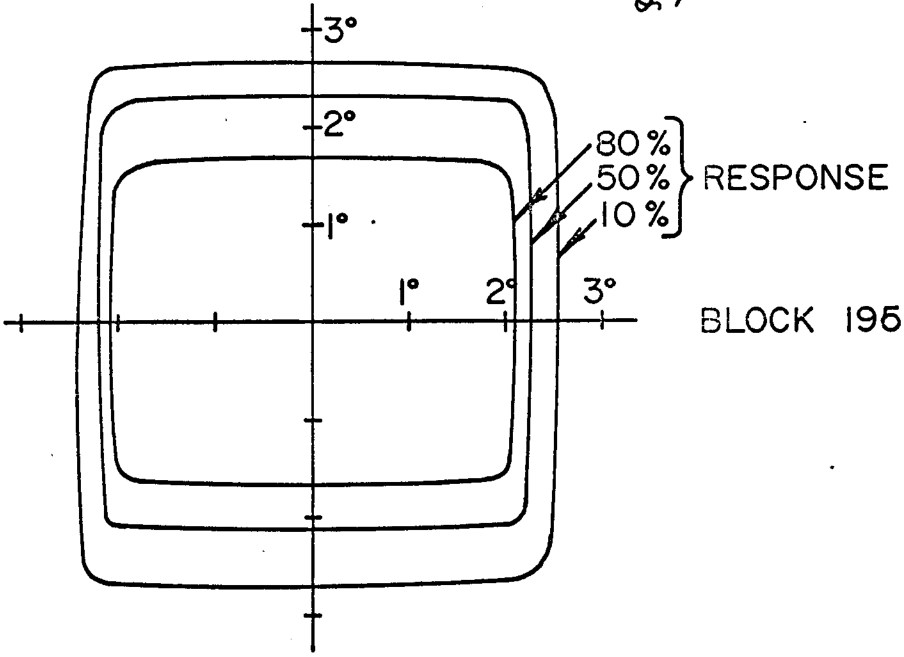
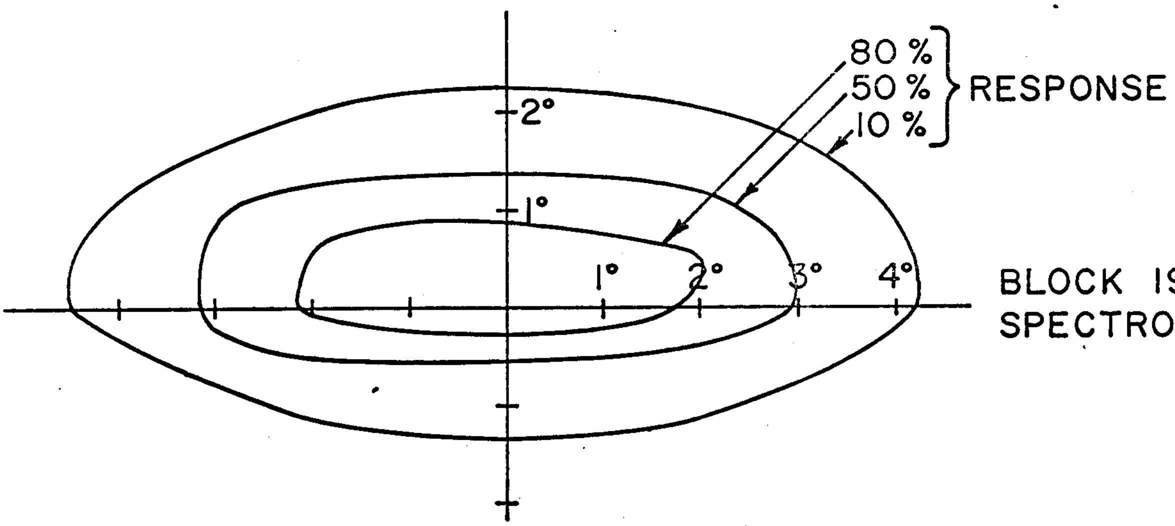
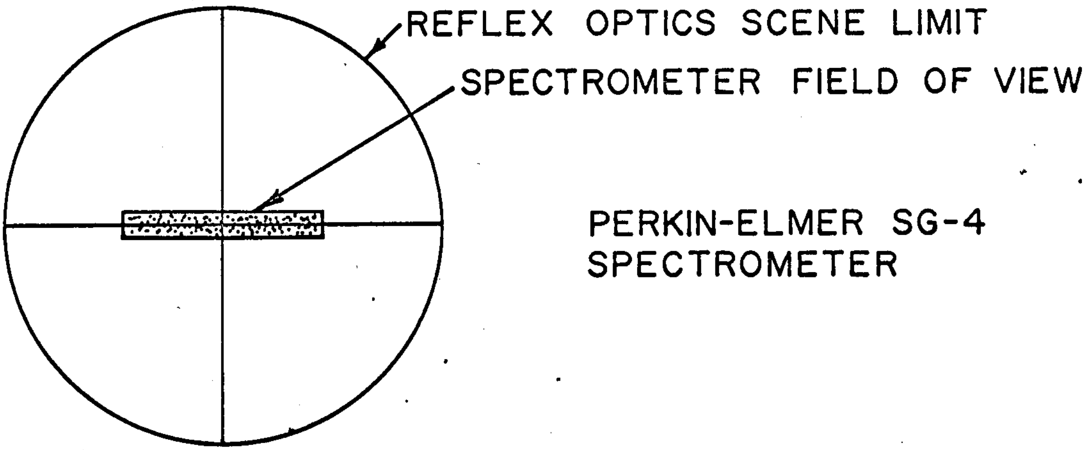
Figure 4-1. Fields of view for three spectrometers currently used in field spectroscopy. For the Perkin-Elmer SG-4, the spectrometer field of view at 10 meters viewing distance is a 21 by 3 centimeter rectangle.



BLOCK 195T SPECTROMETER



BLOCK 195E
SPECTROMETER



PERKIN-ELMER SG-4
SPECTROMETER

Figure 4-2. Geometrical parameters at the field spectroscopy site.

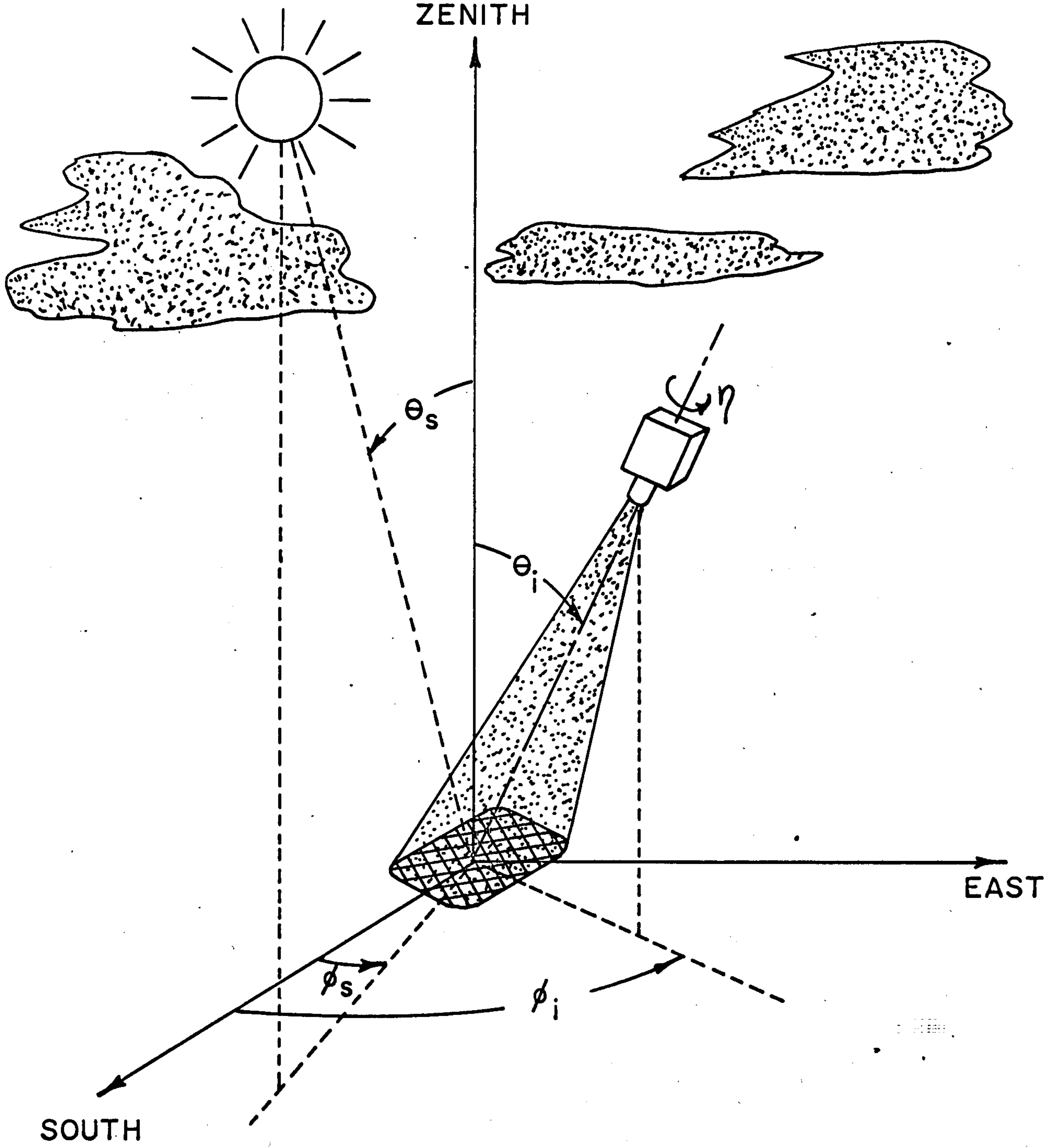

ZENITH
θ_s
η
θ_i
EAST
ϕ_s
ϕ_i
SOUTH

Figure 4-3. Spectrometer response at two wavelengths viewing a fixed scene (corn field) for a period of time, $\theta_i = 20^\circ$. The day was gusty with rapid leaf motion in the field of view.

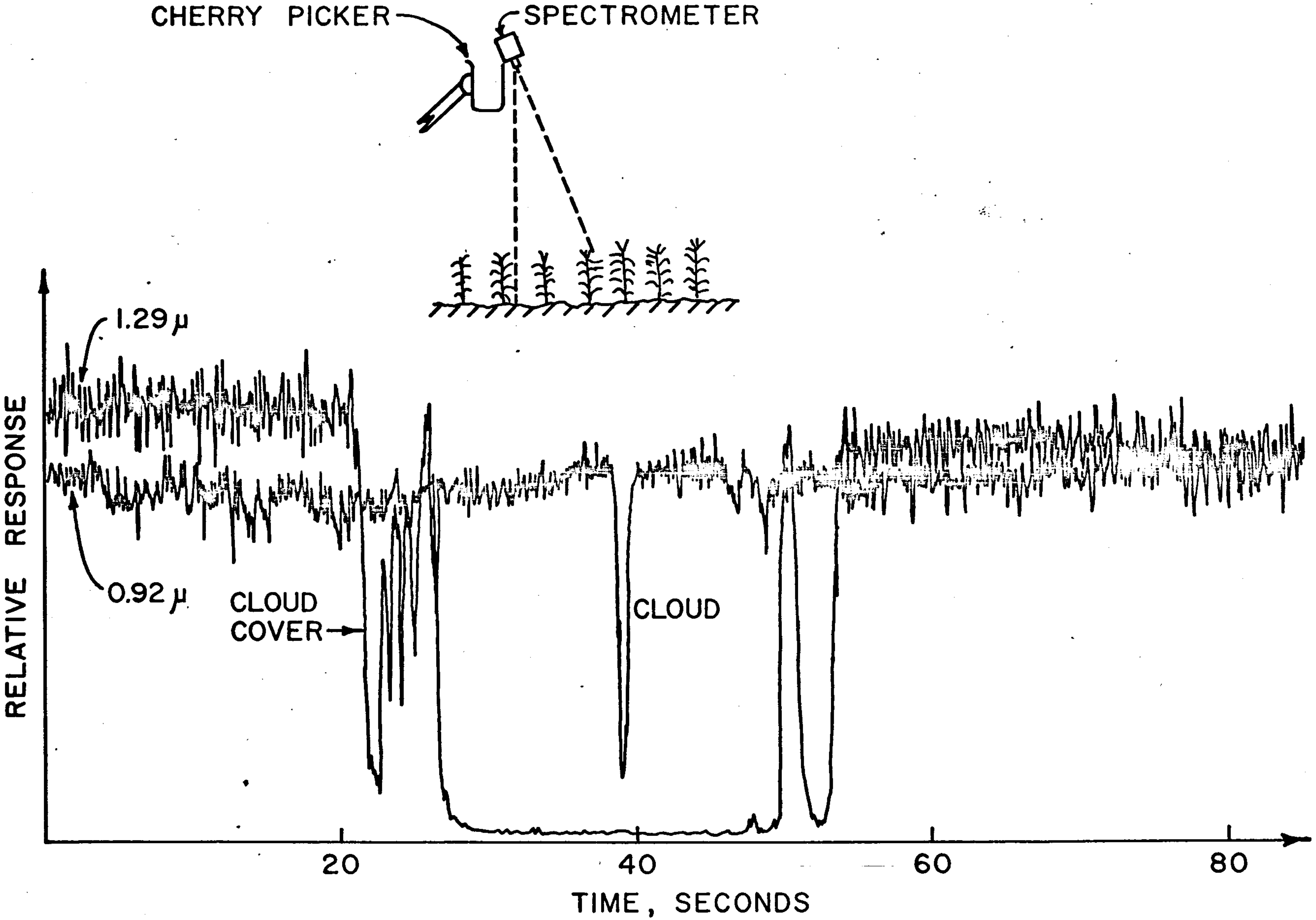

CHERRY PICKER
SPECTROMETER
1.29 µ
0.92 µ
RELATIVE RESPONSE
CLOUD COVER
CLOUD
20
40
60
80
TIME, SECONDS

Figure 4-4. Relative Spectral radiance of five subjects, showing the effect of solar irradiance variation near the long wavelength limit of the reflective region. Instrument gain settings were changed from spectrum to spectrum. Curves should be compared in functional form only.

8-11-66, 1340

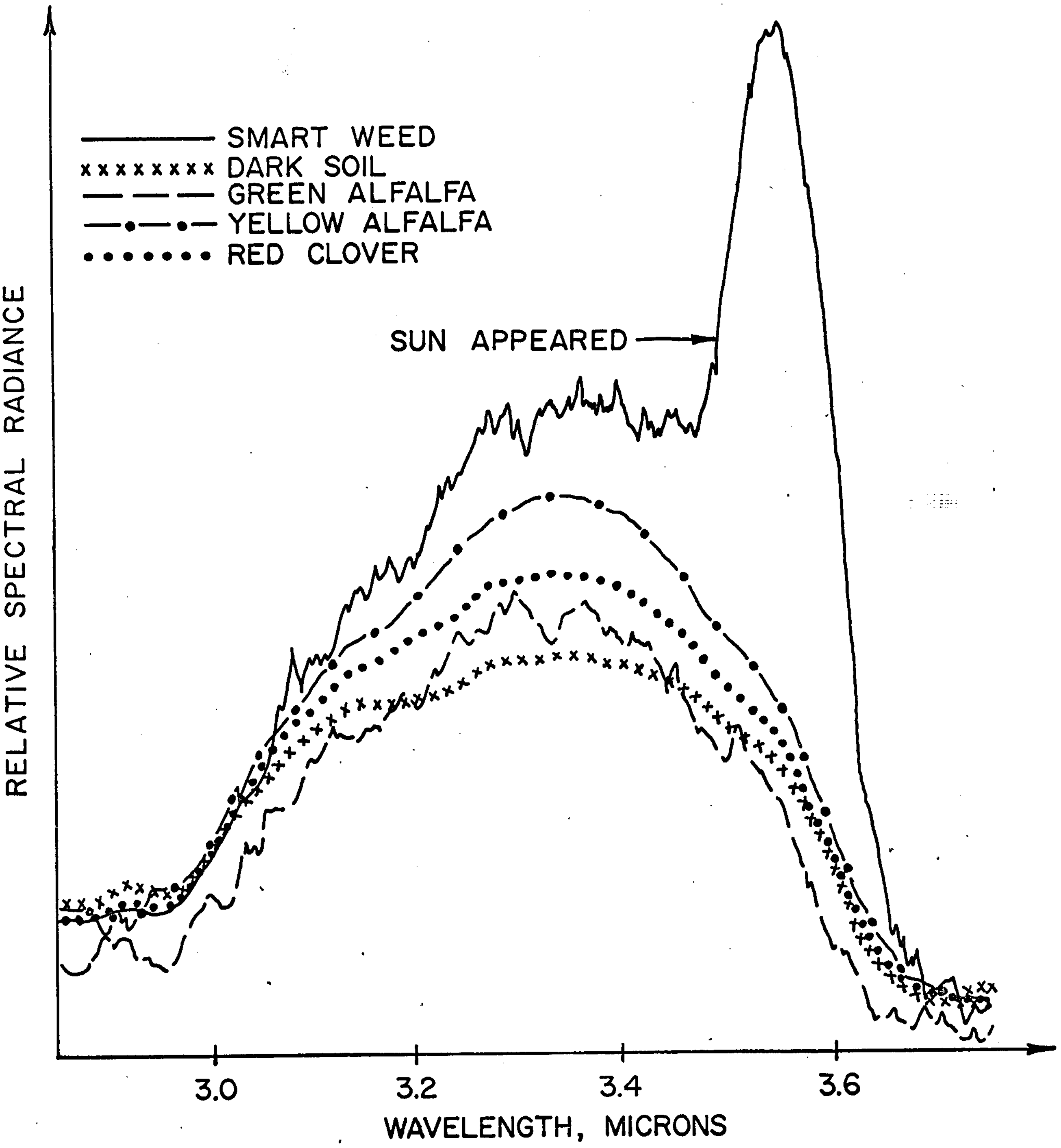
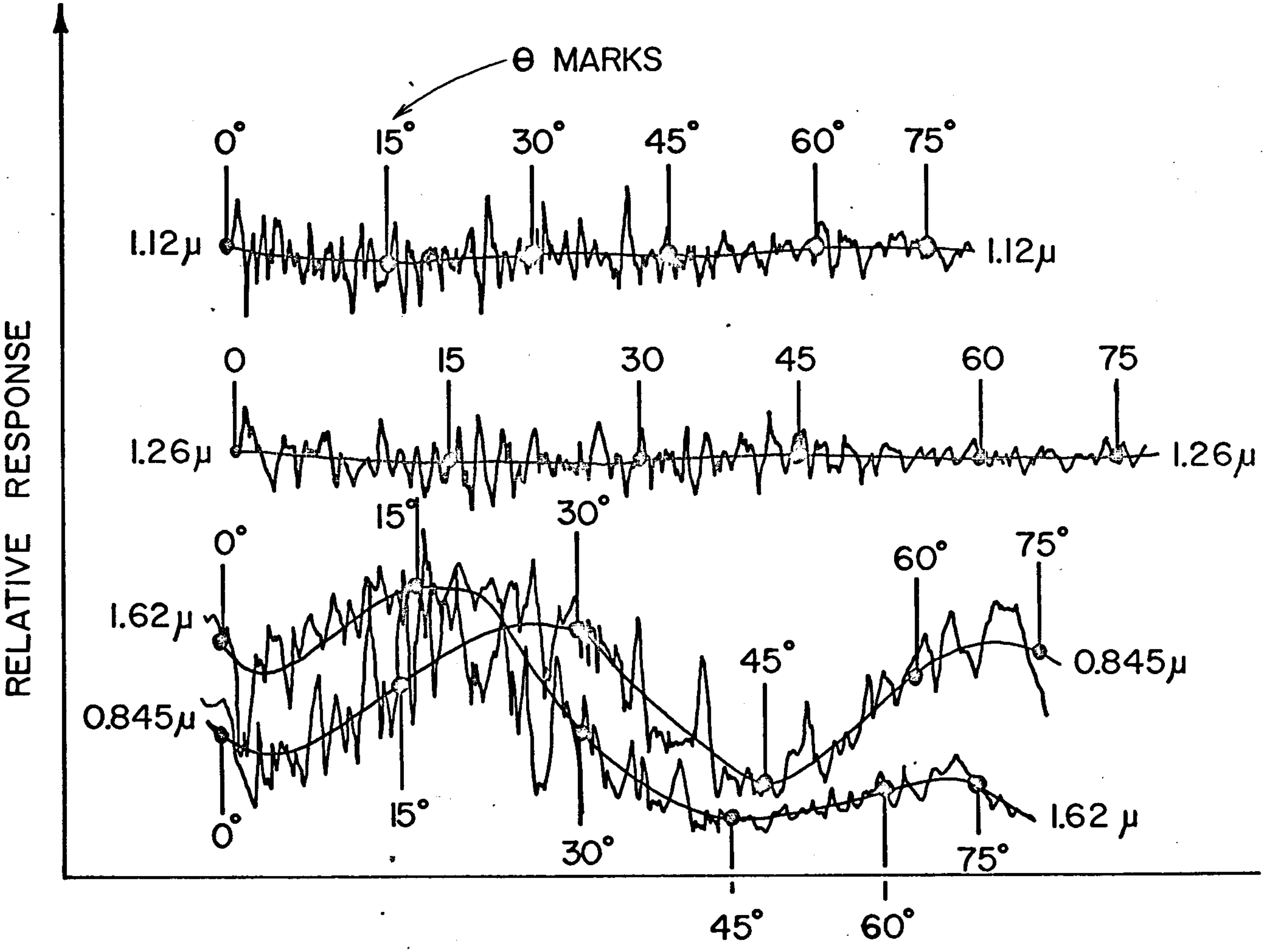

SMART WEED
xxxxxxxx DARK SOIL
GREEN ALFALFA
YELLOW ALFALFA
RED CLOVER
SUN APPEARED
RELATIVE SPECTRAL RADIANCE
3.0
3.2
3.4
3.6
WAVELENGTH, MICRONS

Figure 4-5. Angular sweeps along a soybean row at four fixed wavelengths. The spectrometer was manually panned from $\theta = 0^\circ$ to $\theta = 75^\circ$ at each wavelength setting. Smooth lines through the response curves are drawn in to show average trends.

8-3-66, 1450


RELATIVE RESPONSE
θ MARKS
0°
15°
30°
45°
60°
75°
1.12µ
1.12µ
0
15
30
45
60
75
1.26µ
1.26µ
0°
15°
30°
60°
75°
1.62µ
0.845µ
45°
0.845µ
0°
15°
30°
45°
60°
75°
1.62 µ

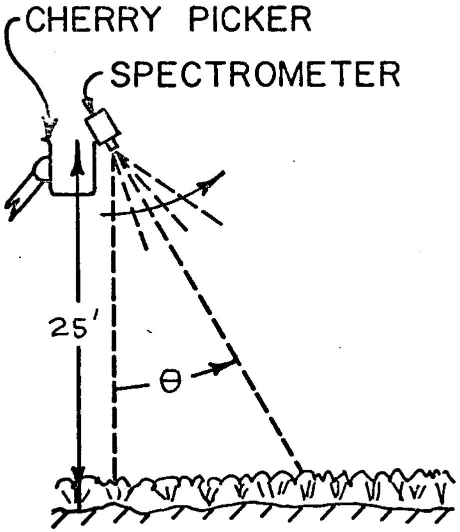
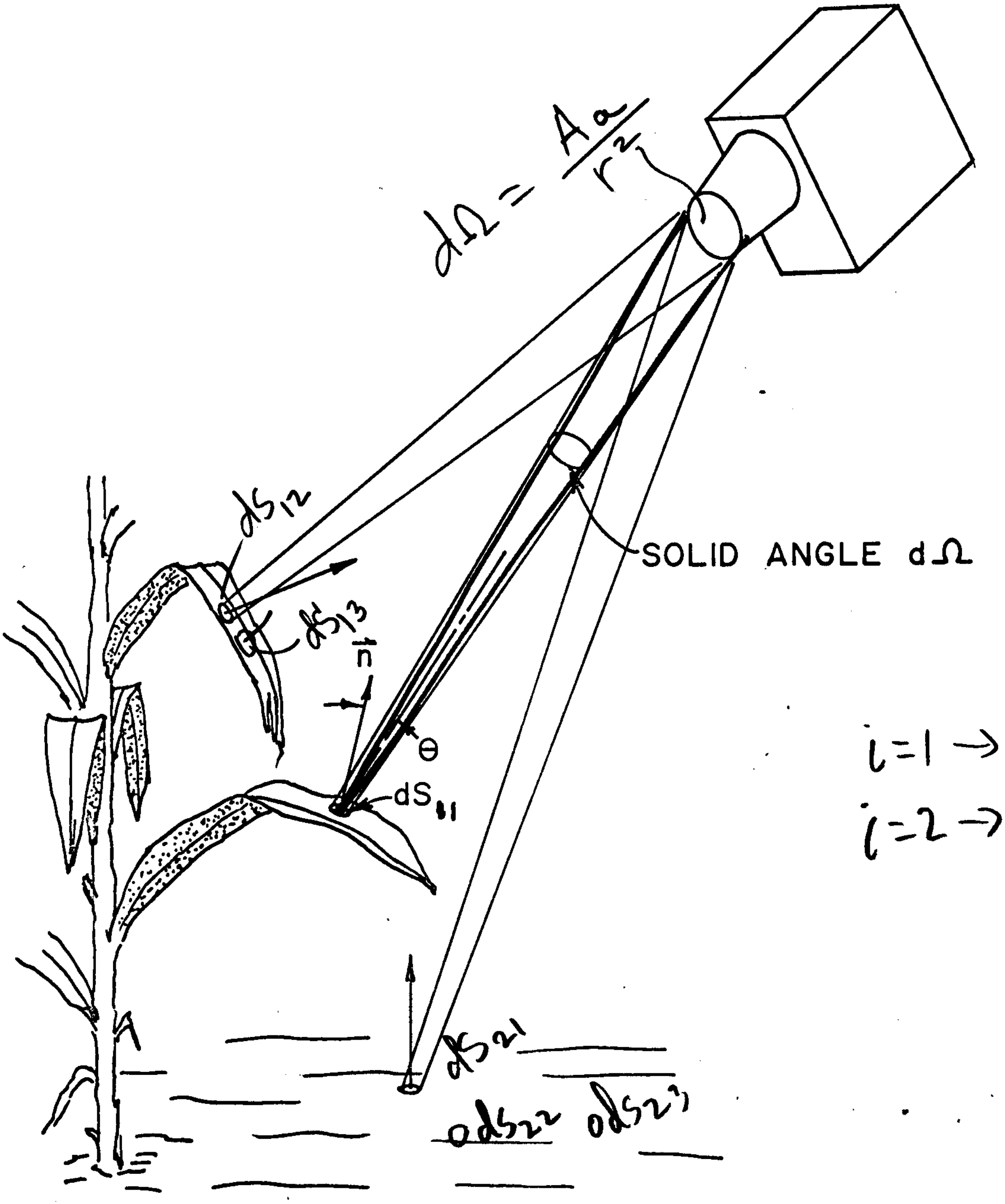

CHERRY PICKER
SPECTROMETER
25'
θ

Figure 4-6. Power flow from a surface element dS into a solid angle increment d in the wavelength range λ to $\lambda+d\lambda$ is

$$\Delta P = N_\lambda \underline{\cos\theta}\, dS\; d\Omega d\lambda$$

The spectral radiance is N_λ, generally a function of θ and λ. The irradiance at the spectrometer aperture comes from a variety of surface types over a broad range of angles with respect to surface element normals, n.



$i=1 \rightarrow$ corn leaf
$i=2 \rightarrow$ soil

Figure 4-7. Relative spectral radiance spectra for agricultural scenes in the range 0.4 to 1.05 micron. Curves should be compared in functional form only; gain settings were changed between spectra.

Figure 4-8. Relative spectral radiance spectra for agricultural scenes in the range 0.65 to 1.85 micron. Curves should be compared in functional form only; gain settings were changed between spectra.

Figure 4-9. Relative spectral radiance spectra for agricultural scenes in the range 1.9 to 2.8 microns. Curves should be compared in functional form only; gain settings were changed between spectra.

Figure 4-10. Relative spectral radiance spectra for agricultural scenes in the range 2.8 to 4.05 microns. Curves should be compared in functional form only; gain settings were changed between spectra.

Figure 4-11. Reflectance of soybeans. The two raw spectra include the instrument transfer function which cancels in taking the ratio of crop to standard panel response over the wavelength range. Instrument gain was reduced for the sulfur panel spectrum.

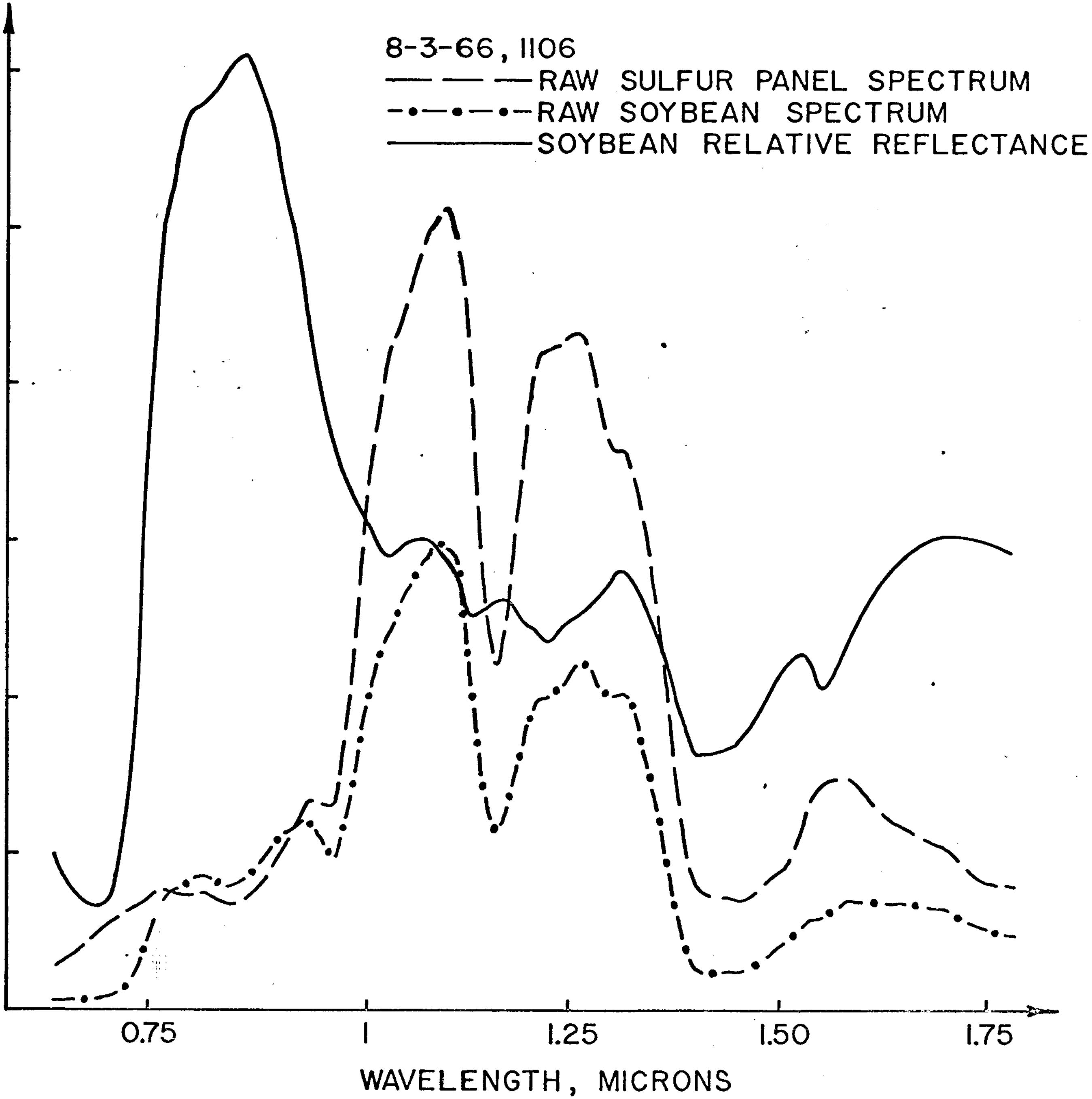
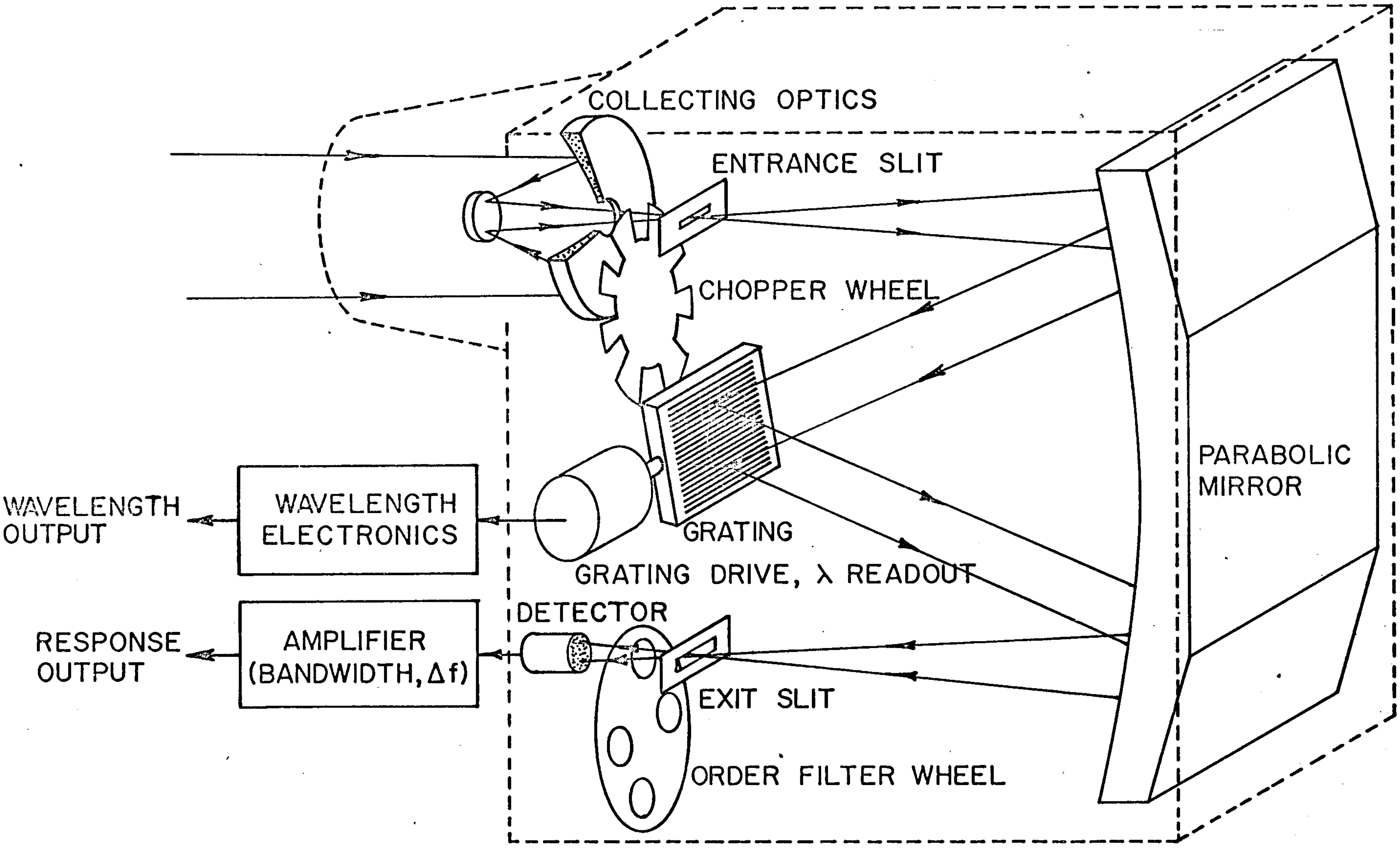

8-3-66, 1106
— — — RAW SULFUR PANEL SPECTRUM
-•-•-•- RAW SOYBEAN SPECTRUM
——— SOYBEAN RELATIVE REFLECTANCE
0.75
1
1.25
1.50
1.75
WAVELENGTH, MICRONS

Figure 4-12. A typical field spectrometer system. The diagram is based on the Perkin-Elmer SG-4 spectrometer, with several details of practical importance omitted.


COLLECTING OPTICS
ENTRANCE SLIT
CHOPPER WHEEL
PARABOLIC MIRROR
GRATING
GRATING DRIVE, λ READOUT
WAVELENGTH OUTPUT
WAVELENGTH ELECTRONICS
DETECTOR
RESPONSE OUTPUT
AMPLIFIER (BANDWIDTH, Δf)
EXIT SLIT
ORDER FILTER WHEEL