A data collection platform for rapid and repeatable positioning of a down-looking radiometer was constructed using commercially available instrumentation and hardware. The platform also accommodated a second radiometer to measure irradiance at the same instant the other radiometer measured target radiance. Stepper motors position the down-looking radiometer at programmed view zenith and view azimuth angles. A Polycorder and stepper motor interface control the stepper motors while data acquisition is the sole responsibility of the Polycorder. Less than 15 min is required to measure target radiance from a full set of measurements consisting of 182 combinations of view zenith and view azimuth angles. Positioning accuracy of the viewing radiometer is within ± 0.2° for a nominal 15° angular movement. The system has proven to be dependable, easy to use, highly mobile, and adaptable.

INTRODUCTION

Numerous field studies of spectral reflectance from vegetation have been conducted during the past two decades. Radiance measurements of the crop/soil scene in these studies have, for the most part, been taken from a nadir-looking view angle where the sensor is pointed perpendicular to the scene. By definition, this view zenith angle is 0° (Fig. 1). Smith (1980) reported several key research issues identified through workshops conducted by NASA for the optical-reflective regime. A critical need was to obtain multidirectional spectral measurements to gain an understanding of the complex interaction of sunlight with crop canopies. For complete, homogeneous vegetation canopies, Kimes (1983) indicated that the directional reflectance factor increased as the off-nadir (zenith
Figure 1. Diagrammatic representation of the sensor view zenith angle \( \theta_v \) and the view azimuth angle \( \phi_v \).

data collection process. Thus, data need to be acquired rapidly to minimize these effects on the interaction of sunlight with crop canopies. Deering and Leone (1986) reported on a unique field instrument called the PARABOLA that could acquire radiance data for the sky and ground hemispheres in 11 s. Unfortunately, this is specialty equipment developed by NASA which is not commercially available. This paper describes a data collection platform designed to simultaneously measure incident irradiance in the horizontal plane and target radiance at programmable view zenith and azimuth angles using commercially available instrumentation and hardware. Rapid and repeatable positioning of the target viewing sensor was desirable.

**DESIGN AND CONSTRUCTION**

The data collection system consists of a boom mounted platform, a stepper motor interface (SMI), and a control and data acquisition device (Fig. 2). The platform is leveled with leveling motors and the down-looking radiometer is positioned with stepper motors. An Omnidata Polycorder\(^1\) (Model 516-B with 32K memory and version 5.5 operating system) controls the platform via instructions sent to the SMI and logs voltages generated by the radiometers. Smith (1980) indicated that simultaneous measurements of irradiance and target radiance should be made to understand spectral data acquired under hazy or scattered cloud conditions. Thus, the platform was designed to accommodate two radiometers.

Platform design evolved around utilization of existing instrumentation and data logging equipment. Exotech\(^1\) Model 100BX four-band radiometers were used. The radiometer used to measure target radiance had a 15° circular field of view (FOV); the radiometer that measured incident irradiance had a 180° FOV. Several constraints were placed on design of the platform. These were: 1) weight, 2) platform leveling, 3) combination of view zenith and azimuth angles, and 4) execution speed of the Polycorder for digital control.

Figure 3 shows the platform with the radiometers attached. Platform weight was of concern:

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\(^1\)Trade names are mentioned for the benefit of the reader. They do not imply endorsement by the authors or the Agricultural Research Service.
Figure 2. Schematic of data collection system components.

Figure 3. Data platform with radiometers attached.
because the platform was to be mounted on the end of a mobile boom. Weight was minimized by constructing the platform with aluminum materials. However, mild steel and brass components were used for hinge joints to level the platform.

Since the upward looking radiometer was attached perpendicular to the horizontal plane of the platform, a level platform was required to assure reliable irradiance data. The leveling mechanism consisted of two 12 V DC reversible gear motors (Barber-Coleman Model FYQF-63310-9) that turned screws to tilt the platform. One motor and screw assembly tilted the platform with respect to its longitudinal axis; the other assembly controlled the tilt about the latitudinal axis. An out-of-level state with respect to the platform axes was sensed by two sets of paired mercury switches (Micro Switch Catalog No. AS412A1). Each set consisted of two parallel, opposing direction switches mounted perpendicular to its pivot axis (Fig. 4). Each switch operated an indicator light on a console in the vehicle; thus, two indicator lights were associated with each set of mercury switches. A center position toggle switch was mounted between the two indicator lights. The platform was leveled by pushing the toggle switch toward the glowing light to energize the leveling motor. The platform was level when the indicator lights did not glow.

The down-looking radiometer was mounted to positionable brackets located at the end of the platform opposite the upward looking radiometer. Stepper motors (Crouzet Model 82936) position these brackets (Fig. 5). One motor, fixed to the platform with its output shaft normal to the horizontal plane of the platform, pivots a u-shaped bracket to attain the view azimuth angle. The other motor, fixed normal to the legs of the u-shaped bracket, moves the other bracket to which the radiometer is mounted. This motor pivots the radiometer to change the view zenith angle.

Reference points were required for repeatable positioning of the down-looking radiometer. The radiometer reference positions chosen were a $0^\circ$ view zenith angle and a $0^\circ$ view azimuth with respect to the platform. To establish the reference

Figure 4. Paired mercury switches to monitor platform leveling.
azimuth position, a Hall effect digital sensor (Radio Shack\textsuperscript{1} Catalog No. 276-1646) was permanently fixed to the underside of the platform and above the u-shaped bracket. The reference zenith position was established with another Hall effect sensor mounted on one leg of the u-shaped bracket. The south pole of a magnet greater than 300 gauss is required to activate these sensors. Thus, a magnet was attached to the u-shaped bracket such that it was directly beneath the Hall effect sensor on the platform when the bracket was rotated 90° counterclockwise (0° view azimuth). The other magnet was glued to the down-looking radiometer housing at a location to align it with its Hall effect sensor when the radiometer had a 0° view zenith angle. Hall effect sensors were selected because

\begin{table}[h]
\centering
\begin{tabular}{|l|l|l|}
\hline
\textbf{Polycorder Digital Output Number} & \textbf{Signal High} & \textbf{Signal Low} \\
\hline
1. PC select 1 & Accepts timer control from the Polycorder for motor \#1 & Accepts control from the Hall effect sensor for motor \#1 \\
2. PC select 2 & Accepts timer control from the Polycorder for motor \#2 & Accepts control from the Hall effect sensor for motor \#2 \\
3. CW/CCW & Motor direction is counter clockwise & Motor direction is clockwise \\
4. PC timer 1 & Activates motor \#1 & Holds motor \#1 \\
if PC select 1 is high, then & & \\
5. PC timer 2 & Activates motor \#2 & Holds motor \#2 \\
if PC select 2 is high, then & & \\
\hline
\end{tabular}
\caption{Polycorder Digital Output Channels and Their Control Functions}
\end{table}
Table 1b. Hall Effect Sensor Digital Output and Its Control Functions

<table>
<thead>
<tr>
<th>Hall Effect Sensor Signal</th>
<th>Digital Output High</th>
<th>Signal Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor #1 (view)</td>
<td>if PC select 1 is low, then activates motor #1</td>
<td>holds motor #1</td>
</tr>
<tr>
<td>Sensor #2 (azimuth)</td>
<td>if PC select 2 is low, then activates motor #2</td>
<td>holds motor #2</td>
</tr>
</tbody>
</table>

They generate a digital output and have no signal bounce.

The stepper motors are permanent magnet two-phase 12 V DC. Motor shaft rotation is 7.5° for each electrical pulse applied to the motor. Each motor has a heavy duty gear box with a 50:1 gear ratio. Therefore, 50 electrical pulses are required to rotate the output shaft 7.5°. Each motor has the capability of full or half step operation. Motor movement is smoother in the half step mode; thus, 100 motor pulses are required for a 7.5° angular movement. Since the time of rotation was to be minimized, a high speed frequency was desired. A frequency of 167 pulses for 1.2 s was determined to move the radiometer through a 15° angle with minimal inertial interference. However, the Polycover could only activate a digital output channel 48 times per second; thus, a stepper motor interface (SMI) was built to assist the Polycover in controlling the stepper motors.

The SMI contains the following electronic components for each stepper motor: a clock pulse generator, a stepper motor driver (Motorola SAA1042), and a multiplexer chip. The clock sends a pulsed digital signal to the driver chip on command from the Polycover which determines the frequency of electrical pulses sent to the stepper motors. The driver chip also requires digital inputs to select either full/half step motor operation and motor rotation direction. The full step mode is selected from a low "0" state; a high "1" state selects the half step mode. The motor's rotation is nominally clockwise (CW) and is selected when the input is held low "0"; counterclockwise (CCW) rotation is selected with the input in the high "1" state. Each multiplexer chip utilizes two digital output lines from the Polycover and a digital signal line from the respective Hall effect sensor. These signals switch stepper motor control between the Polycover and the Hall effect sensor. A fifth Polycover digital output controls the rotation direction of both stepper motors.

Table 1a lists the five Polycover digital outputs and their associated control functions. Motor #1 signifies the view zenith angle stepper motor; motor #2 refers to the view azimuth stepper motor. Digital output #1, if high, selects Polycover timer control of motor #1 and, if low, selects the Hall effect sensor for control. Digital output #4 is significant only if output #1 is high. When both outputs #1 and #4 are high, then motor #1 is activated; if #1 is high and #4 is low, then stepper motor #1 holds its current position. The Hall effect sensor signal is significant only if digital output #1 and/or #2 is held low, as indicated by Table 1b. When both digital output #1 and the Hall effect sensor signal are low, motor #1 holds its current position; if digital output #1 is low and the sensor signal is high, motor #1 is activated.

Programming the Polycover to control the stepper motors is straightforward. In essence, it consists of outputting certain decimal numbers to the digital output ports in a binary format. For example, decimal 18 is equivalent to 10010 which turns output #1 high, #2 low, #3 low, #4 high, and #5 low. When the Polycover scans the digital inputs, highs and lows form a binary number which is interpreted as its decimal equivalent. The eight digital inputs are held high when not connected, thereby generating the binary number 11111111, which is equivalent to decimal 255. Consequently, the Polycover can determine if the down-looking radiometer is in its reference position by the decimal value. To move the down-looking radiometer + 15° in the view azimuth angle requires digital output #1 set high, #2 set high, #3 set low, #4 set low, and #5 set high (which is the binary equivalent of decimal 25) to be output for a duration of 1.2 s. The view azimuth motor rotates clockwise while the view zenith motor holds its position. This instruction is under the Polycover timer control. Another example is initializing the radiometer's view azimuth. Here digital output #1 is set high, #2 is set low, #3 is set high, #4 is set low, and #5 is set low. This is equivalent to decimal 20, which is the output by the Polycover to rotate the view azimuth motor counterclockwise until the Polycover senses a low state from the respective Hall effect sensor.

The down-looking radiometer was programmed to move in 7.5° and 15° angular incre-
ments to measure the complete existence hemisphere of upwelling target radiance. View zenith angles selected were 0°, 15°, 30°, 45°, 52.5°, 60°, and 67.5°. View azimuths defined a half circle, i.e., 0–180°, in 15° increments. View azimuths corresponding to a half circle were only considered because the platform would be mounted on a mobile boom with access to a field from its perimeter or a roadway through the field. With the boom perpendicular to the right side of the vehicle, a 0° view azimuth positions the viewing radiometer to “look” toward the front of the vehicle and parallel to the vehicle. Positioning the radiometer toward the rear of the vehicle and parallel to it defines a 180° view azimuth. A 90° view azimuth positions the radiometer to “look” perpendicular to the vehicle. A full measurement sequence, i.e., a full circle, requires rotating the boom 180° such that it extends from the vehicle’s left side. In this position, 180° is added to the view azimuth. Consequently, a view azimuth of 180° positions the radiometer towards the rear of the vehicle, 270° is perpendicular to the vehicle, and 360° is toward the front of the vehicle. This angle designation references the view azimuth to the vehicle which travels parallel to the rows. Adopting the coordinate system presented by Ranson et al. (1985), the view azimuth angle referenced to true north is calculated by

\[
\phi_v = V_{az} + \phi_t, \text{ if } \phi_v > 360, \phi_v = \phi_v - 360, \quad (1)
\]

where \(\phi_v\) is the view azimuth angle measured clockwise from true north, \(V_{az}\) is the view azimuth referenced to the vehicle, and \(\phi_t\) is the vehicle travel azimuth measured clockwise from true north.

The instantaneous FOV of the down-looking radiometer is circular at a 0° view zenith angle and elliptical for view zenith angles greater than 0° as long as the view zenith angle is less than \((\pi/2 - \alpha)\), where \(\alpha\) is one-half the FOV (Deering and Leone, 1986). Major and minor axis lengths of the off-nadir elliptical FOV are

\[
2a = \frac{2h \tan \alpha (1 + \tan^2 \theta_v)}{1 - (\tan \alpha \tan \theta_v)^2}, \quad (2)
\]

and

\[
2b = \frac{2h \tan \alpha}{\cos \theta_v [1 - (\tan \alpha \tan \theta_v)^2]^{1/2}}, \quad (3)
\]

respectively, where \(h\) is the height of the radiometer above the target and \(\theta_v\) is the view zenith angle. When the \(x-y\) coordinate system is referenced to the center of the 0° view zenith angle footprint (circle), the center of successive elliptical footprints (Park and Ostroff, 1984) is located at

\[
x_c = \left[ h \tan (\theta_v - \alpha) + a \right] \cos (\phi_v - 3\pi/2) \quad (4)
\]

and

\[
y_c = \left[ h \tan (\theta_v - \alpha) + a \right] \sin (\phi_v - 3\pi/2), \quad (5)
\]

where \(\phi_v\) is the view azimuth angle. Table 2 gives the major axis \((2a)\) and the minor axis \((2b)\) for the elliptical FOV for the radiometer at 9.5 m above ground and center coordinates for the various view zenith angles at the 0° view azimuth angle. The maximum reach into a field with the boom fully extended and raised is approximately 4.6 m. One-half the minor axis of the elliptic footprint at the 67.5° view zenith is 3.45 m; thus, the upwelling radiance at that view angle for view azimuths of 0° and 180° with respect to the vehicle is not strongly influenced by field edge effects. However, at view zenith angles greater than 67.5° for those particular view azimuths, the upwelling radiance would not be representative of the target.

### FIELD PERFORMANCE

The Polycorder, stepper motor interface, and instrumentation platform are a viable and effective combination in the field. The platform is attached to the end of a boom mounted on a 1953 Willis Jeep. Maximum radiometer height is 9.5 m above the ground; the maximum reach into a field is 4.6 m with the boom raised, fully extended, and perpendicular to the vehicle. Boom controls are electric and hydraulic. The boom is constructed in two triangular truss sections such that one section telescopes inside the other. The inner section is ex-

<table>
<thead>
<tr>
<th>View Zenith ((\theta_v))</th>
<th>Major Axis ((m))</th>
<th>Minor Axis ((m))</th>
<th>Center Coordinates ((m))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2.50</td>
<td>2.50</td>
<td>0.0</td>
</tr>
<tr>
<td>15</td>
<td>2.68</td>
<td>2.60</td>
<td>0.2.59</td>
</tr>
<tr>
<td>30</td>
<td>3.36</td>
<td>2.90</td>
<td>0.562</td>
</tr>
<tr>
<td>45</td>
<td>5.10</td>
<td>3.56</td>
<td>0.9.84</td>
</tr>
<tr>
<td>52.5</td>
<td>6.96</td>
<td>4.16</td>
<td>0.12.98</td>
</tr>
<tr>
<td>60</td>
<td>10.56</td>
<td>5.14</td>
<td>0.17.66</td>
</tr>
<tr>
<td>67.5</td>
<td>19.00</td>
<td>6.90</td>
<td>0.25.95</td>
</tr>
</tbody>
</table>

*Radiometer height is 9.5 m.
tended and retracted via a 12 V DC electric winch. Microswitches mounted on the outer section limit the travel of the inner section in both directions. The boom is raised/lowered and rotated via hydraulic power. Hydraulic stabilizers were mounted at the rear of the vehicle on both sides to stabilize the vehicle when the boom is positioned perpendicular to the vehicle.

Leveling accuracy of the platform leveling mechanism and positioning accuracy of the down-looking radiometer were checked by mounting the platform on a workbench. A protractor graduated in 1° increments and encompassing a level gauge was used to determine the levelness of the upward-looking radiometer. Results from this test showed that the upward radiometer was out-of-level by less than 1° with respect to either axis of rotation when the mercury switches opened (leveling indicator lights stopped glowing). A helium-neon laser mounted to the platform in place of the down-looking radiometer was used to check stepper motor positioning. The platform was mounted at a known height above a level surface. As the view zenith and view azimuth angles were changed, the laser spots were marked on the surface. The angles traversed were calculated via trigonometric functions. View zenith angles varied from 14.8° to 15.1° while the view azimuth angle varied from 14.7° to 15.2° for nominal 15° movements. Gear box backlash was somewhat of a problem; however, it was found that backlash could be eliminated by continuing past the reference position an additional 15° for both view angles and then approaching it in the direction of the radiometer sweep.

Figure 6 shows the instantaneous FOV footprints of the down-looking radiometer in one quadrant. Very little of the upwelling radiance from the target is missed.

Elapsed time from start to finish for acquisition of a full set of hemispherical measurements is normally less than 15 min. At first glance, this does not appear to be any better than the time reported by Ranson et al. (1985) with their tower system. However, we acquire 182 combinations of view zenith and view azimuth angles compared to their 64. The 15-min time element consists of parking the vehicle, setting the rear stabilizer(s), leveling the platform, executing the Polycorder program to acquire a half circle of data, rotating the boom 180°, and executing the Polycorder program again to acquire the other half circle of data. Six minutes and 18 s elapse from start to finish for each half circle of data. The variable time element is due to stabilizing the vehicle, rotating the boom, and leveling the platform. Time required to take data for the seven view zenith angles at any view azimuth angle is 18.7 s. During this time, 5.1 s are required for positioning the radiometer at the desired view zenith angles. The remaining time is used by the Polycorder to scan the eight analog channels (integration time is set at 100 ms), convert time in hours:minutes:seconds to decimal hours, and store the data. On the average, this takes 2.2 s for each view zenith position. The other time-consuming operation is reinitializing the view zenith angle to 0° for each 15° rotation of the view azimuth angle; this takes 8.2 s. However, we believe this action is necessary to assure accurate positioning of the view zenith angle.

Data collection time could possibly be reduced by stepping the motors at a faster rate. However, this would require additional circuitry to provide ramping for the stepper motors, i.e., to accelerate the motor to running speed and decelerate the motor to a stop. Without this added circuitry, positioning accuracy would be jeopardized. A more logical approach to reducing the time would be through use of faster data acquisition and control hardware.

Directional reflectance factors for corn (Zea mays L) "Pioneer 3540," an erectophile variety, in
Figure 7. Reflectance factors for corn (Zea mays L., "Pioneer 3540" in TM Bands 1 ( ), 2 ( ), 3 ( ), and 4 ( ), as a function of view zenith angle for selected view azimuth angles. LAI = 2.7, dry soil, clear sky; north/south rows ($\phi_v = 0^\circ$); latitude = 40.8°, longitude = 102.8°; $\theta_s = 21^\circ$, $\phi_s = 215^\circ$, date: 6 July 1989 (Doy 187).

Thematic Mapper Bands 1, 2, 3, and 4 as a function of view zenith angle for selected view azimuth angles are shown in Figure 7. The data were measured on 6 July 1989 in a center pivot sprinkler irrigated field in northeastern Colorado. Row direction for this particular field was north/south. Vehicle access to the field (pivot road) was from the north such that the vehicle was traveling south ($\phi_v = 180^\circ$) for data acquisition. Data acquisition started 42 min after solar noon; the full circle measurement scheme was completed in 13 min. Mean solar zenith angle ($\theta_s$) was 21° and mean solar azimuth angle ($\phi_s$) measured clockwise from true north was 215°. Directional reflectance factors for the two radiometer system were calculated using a procedure similar to that reported by Duggin (1980) and described in detail by Neale (1987). Data trends are similar to those presented by...
Ranson et al. (1985). Maximum directional reflectance factors occurred at the 30° view azimuth angle for coincident view azimuth and solar azimuth angles.

SUMMARY AND CONCLUSIONS

A data collection platform was constructed to accommodate two Exotech radiometers such that one measured the irradiance at the same instant that the other radiometer measured target radiance from programmed view zenith and view azimuth angles. The upward-looking radiometer was mounted perpendicular to the horizontal plane of the platform. Platform leveling was accomplished with mercury switches and reversible gear motors that turned screws to tilt the platform with respect to its longitudinal and latitudinal axes. The platform was out-of-level by less than 1° with respect to either axis of rotation with this leveling mechanism. The down-looking radiometer was positioned with stepper motors controlled by a Polycorder which also logged the data. The Polycorder’s execution speed was inadequate for the stepper motors; hence a stepper motor interface was built and used in conjunction with the Polycorder to achieve desirable positioning time of the viewing radiometer. Positioning accuracy of the viewing radiometer for 15° nominal view zenith angle increments varied from 14.8° to 15.1° while the view azimuth angle increments varied from 14.7° to 15.2°. A full set of measurements consisting of seven view zenith angles at each of the 26 view azimuth angles are normally completed in less than 15 min, a time that includes rotating the boom 180° to acquire the second half of the circle and stabilizing the vehicle.

The data collection platform has been used for 2 years with minimal problems. Most problems have been associated with loose connectors. The system has proven to be easy to use, dependable, highly mobile, and easily adaptable in the field to newly desired view and azimuth angle sequences that are multiples of 7.5° of rotation.

The authors gratefully acknowledge the numerous hours that Walter M. Shannon, a former graduate student, devoted to the initial design and construction of the boom and data platform.

REFERENCES


