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Technical note / Note technique

A low-cost field and laboratory goniometer system for estimating hyperspectral bidirectional reflectance

C.A. Coburn and D.R. Peddle

Abstract. The derivation of the bidirectional reflectance distribution function (BRDF) from earth-surface features provides a more complete basis for the estimation of both surface composition and physical structure than is possible using single-angle reflectance measurements. With the increase in number of remote sensors capable of multi-angular earth observation and the increased use and sophistication of canopy BRDF models, the need for field and laboratory BRDF data and validation has correspondingly grown to ensure proper calibration and improved understanding of the directional reflectance properties of earth-surface features. Goniometers are specialized devices for near-surface measurement of bidirectional reflectance factors and are typically used in the field but can also be used in controlled laboratory settings. Current goniometer systems are often prohibitively expensive, however, and are not always robust for use in different field environments or the laboratory. This paper presents the University of Lethbridge Goniometer System (ULGS) as a low-cost, flexible, and capable alternative for estimating BRDF in a variety of field and laboratory situations. The ULGS uses an analytical spectral devices full-range hyperspectral spectroradiometer sensor (ASD-FR, 350–2500 nm) to acquire 217 unique angular hemispherical measurements (–60° to +60° zenith angle over the full 360° azimuth with an angular resolution of 10° in both dimensions). The system is manually operated, reducing the significant overhead (cost, design, and weight) associated with computer and robotic control systems. BRDF results are presented as example applications for three different field and laboratory targets: (*i*) a Lambertian calibration panel, (*ii*) a field grassland site in a river valley coulee, and (*iii*) laboratory-based measurements of a moss sample from Fluxnet-Canada. It was concluded that the ULGS hyperspectral goniometer is capable of estimating the directional reflectance properties of non-Lambertian structured canopies. Compared with other goniometer systems, the ULGS is considerably more accessible due to its much lower cost and feasibility to construct and its portability and versatility, yet it sacrifices little in terms of the quality and speed of BRDF data acquisition.

Résumé. La mise au point d'une fonction de distribution de la réflectance bidirectionnelle (FDRB) à partir des caractéristiques de la surface terrestre fournit la base la plus complète possible pour l'estimation de la composition et de la structure physique de la surface comparativement aux mesures de réflectance à angle unique. Avec l'accroissement du nombre de capteurs de télédétection capables d'effectuer des mesures multi-angulaires d'observation de la terre et grâce à l'utilisation plus répandue des modèles de couvert FDRB et à l'amélioration de ces derniers modèles, les besoins pour des données de terrain et en laboratoire FDRB et pour la validation ont augmenté parallèlement afin d'assurer un étalonnage approprié et une meilleure connaissance des propriétés directionnelles de la réflectance des caractéristiques de la surface de la terre. Les goniomètres, qui sont des instruments spécialisés pour mesurer les facteurs de réflectance bidirectionnelle près de la surface, sont utilisés couramment sur le terrain quoique ces derniers puissent être aussi utilisés dans un environnement contrôlé en laboratoire. Toutefois, les systèmes actuels de goniomètre sont souvent très chers et pas toujours robustes pour utilisation dans différents environnements de terrain ou en laboratoire. Dans cet article, on présente le système de goniomètre de l'Université de Lethbridge (ULGS), un système à faible coût, flexible et qui constitue une alternative valable pour l'estimation de la FDRB dans une variété de situations sur le terrain et en laboratoire. Le système ULGS utilise un spectroradiomètre hyperspectral ASD-FR (« analytical spectral devices full-range ») opérant entre 350–2500 nm pour acquérir 217 mesures hémisphériques angulaires uniques (avec un angle zénithal de –60° à +60° à travers les 360° en azimut et une résolution angulaire de 10° dans les deux dimensions). Le système est opéré de façon manuelle réduisant ainsi significativement les coûts d'investissement (coût, conception et poids) associés aux systèmes d'ordinateur et de contrôle robotique. Les résultats FDRB sont présentés comme des applications types pour trois cibles différentes de terrain ou en laboratoire : (*i*) un panneau d'étalonnage lambertien; (*ii*) un site de prairie dans un val de vallée de rivière; et (*iii*) des mesures en laboratoire d'un échantillon de mousse de Fluxnet-Canada. Il a été possible de conclure que le goniomètre hyperspectral ULGS est capable d'estimer les propriétés de la réflectance directionnelle des couverts structurés non-lambertiens. Comparativement aux autres systèmes de goniomètre, le système ULGS est nettement plus accessible en raison de

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son faible coût et de sa faisabilité de construction, jumelé à sa portabilité et sa versatilité et ce, sans faire de concessions en termes de qualité et de vitesse d'acquisition de données FDRB.
[Traduit par la Rédaction]

Introduction

Reflectance is an inherent property of a target and is independent of time, location, illumination intensity, atmospheric conditions, and weather (Nicodemus et al., 1977; Peddle et al., 2001). Accordingly, the characterization of earth-surface features based on their reflectance is a central concept in remote sensing. Many previous studies have indicated that the vast majority of these surfaces are non-Lambertian, that is, they reflect energy in different amounts at different angles (Deering et al., 1992; Sandmeier et al., 1998a; Peddle et al., 2001). Therefore, a given surface may yield different reflectance values when viewed from remote platforms at different orientations to the surface. As a result, simple characterizations of surface reflectance need to be extended to include the angular distribution of reflectances for all possible view angles. When reflectance is measured from all possible angles, a bidirectional reflectance distribution function (BRDF) is resolved (Nicodemus et al., 1977). Reflectance anisotropy as a function of illumination and view geometry is a fundamental property of any terrestrial surface and is best quantified (or estimated) in terms of the BRDF (e.g., Peddle et al., 2003). Accordingly, surface BRDF is an important distinguishing attribute in surface feature and pattern recognition (Combal et al., 2002).

The recognition of angular data as a fundamental dimension of remotely sensed data provides unique and important information content, in the same way that spectral, spatial, temporal, and radiometric considerations have been exploited (Barnsley et al., 1994). This has given rise to new airborne and satellite sensors, innovative image-analysis algorithms, the development of sophisticated and powerful canopy reflectance models, and the increased interest in multi-angle spectral measurements. Accordingly, information about angular reflectance characteristics of non-Lambertian surfaces from a variety of illumination and view angles is important for their correct characterization with respect to fundamental spectral signature development, experimental validation, surface modeling, and various forms of image analysis and accuracy assessment (Sandmeier and Deering, 1999; Combal et al., 2002).

A variety of studies have demonstrated that the measurement of BRDF is an important component in support of studies that seek to characterize earth-surface features from remotely sensed data (Barnsley et al., 1994). For example, the derivation of biophysical variables such as leaf area index (LAI), biomass, net primary productivity, and fraction of absorbed photosynthetically active radiation (fAPAR) from remotely sensed data would be improved if a true estimate of the canopy BRDF was known (Chen, 1996; Sandmeier and Deering, 1999; Combal et al., 2002). Further, the development of canopy BRDF models has significantly contributed to an improved understanding of the angular interaction of solar energy with surface vegetation targets and areas (Li and Strahler, 1985; 1992; White et al., 2002; Peddle et al., 2004) for which field and laboratory goniometer measurements can serve as an important source of model input and validation (Chen and Leblanc, 1997).

With the development of airborne (e.g., airborne solid-state array spectrometer (ASAS), compact airborne spectrographic imager (CASI)) and satellite (e.g., Systeme pour l'Observation de la Terre (SPOT), multi-angle imaging spectroradiometer (MISR)) sensors capable of off-nadir imaging, as well as the across-track capabilities of sensors with wide fields of view (FOV) such as the moderate resolution imaging spectroradiometer (MODIS) and advanced very high resolution radiometer (AVHRR), a relatively coarse estimation of surface BRDF is possible (Barnsley et al., 1994). These sensors, and future designs with similar or improved capabilities, will be expected to provide more accurate characterizations of the surface BRDF and allow for improved estimates of biophysical parameters by taking advantage of angular reflectance information.

The estimation of BRDF using ground instruments is becoming increasingly important for the validation of remote sensing image products and canopy BRDF models. Acquiring BRDF data will assist remote sensing scientists in developing a more thorough understanding of the relationship between spectral properties, physical controls, and angular characteristics of various targets (Sandmeier, 2000). The main constraints in gathering these data, however, are the cost and availability of instruments to perform the measurements (Sandmeier and Deering, 1999). This paper briefly reviews these systems and, in response to the identified problems, we present an alternative, low-cost hyperspectral goniometer system. The University of Lethbridge Goniometer System (ULGS) was designed to make BRDF measurements accessible to the mainstream remote sensing community based on a low-cost design that focused on ease of construction, portability, versatility, and simplicity of use. The system development and specifications are described, and examples of its use presented for field and laboratory BRDF applications.

Bidirectional reflectance distribution function

The estimation of the bidirectional reflectance distribution function (BRDF) was defined by Nicodemus et al. (1977) as the intrinsic property of a surface that describes the angular distribution of radiation reflected by the surface for all angles of exitance and under any given illumination geometry. The BRDF of a surface is, by definition, a function of infinitesimal differentials, and therefore all direct measurements are approximations of the BRDF function:

$$\rho = \frac{dL_r(\theta_r, \phi_r, \lambda)}{dE_i(\theta_i, \phi_i, \lambda)} \quad (1)$$

where ρ is the BRDF; d*L* is the differential radiance and d*E* is the differential incident irradiance for a given zenith angle (θ) and azimuth angle (ϕ) for any wavelength (λ); and the subscripts i and r denote irradiance and radiance, respectively (**Figure 1**).

In theory, the BRDF is a deterministic quantity of a surface that can be estimated by measuring the wavelength-dependent ratio of radiance to irradiance from a hemispherical perspective (Nicodemus et al., 1977). However, this classical definition of the BRDF, as representing a fundamental surface property, is limiting when applied to natural surfaces (Snyder, 2002a). In practice, a definition that incorporates scale is required for applied remote sensing. For example, a definition of BRDF at fine spatial resolutions (e.g., single tree) should include the effect of plant structure, and coarser spatial resolution BRDF measurements should include parameters that describe the effects of canopy architecture (Snyder, 2002a). This modification to the strict definition of BRDF is more tenable in a remote sensing context when complex, three-dimensional structured surfaces are under investigation. In this case, the BRDF estimated for a natural surface is a sample of the actual BRDF and is modified by the effect of canopy structure, multiple scattering, shadow, background effects, measurement conditions, detector noise, and parallax present in natural circumstances (Snyder, 2002a). These factors contribute to the difficulty of measuring BRDF in field studies and result in field measurements rarely exhibiting invariance properties such as reciprocity (Snyder, 2002b).

Goniometer systems

To provide the necessary data for the approximation of BRDF, a near-surface sensor instrument must be capable of acquiring reflectance data throughout the full range of hemispherical positions over a target. A goniometer is a device used to position a sensor at these different angles and azimuths. Goniometers have two main components: a sensor for measuring radiance (usually a spectroradiometer) and some form of apparatus to position the sensor. There are two main and fundamentally different goniometer designs that use different sensor–target geometries, with each approach suitable for different applications and measurement objectives: (*i*) a sensor that rotates its view around a fixed centrepoint, thus viewing outwards from the centre of the sphere and acquiring sensor data from a different target field of view for each measurement (e.g., PARABOLA); and (*ii*) a fixed-target, movable sensor in which the same target area is viewed but from a different angle and azimuth for each measurement using a sensor that is moved throughout the hemisphere at a fixed distance from the target.

The PARABOLA was the first goniometer system routinely used for measuring BRDF (Deering and Leone, 1986; Deering et al., 1992). This instrument is a dual-axis, up-and-down-looking, three-band radiometer that rides on a cable suspended above the target. The PARABOLA is positioned over top of the surface, and the instrument is rotated to sample the BRDF. As a result, different targets are viewed at each zenith and azimuth combination. This approach makes the fundamental assumption of homogeneity over the area encompassed by the different target FOVs and therefore requires great care in site selection and instrument deployment. As a result, the limitations of this assumption prevent the PARABOLA from being used over many common surfaces that characteristically possess heterogeneity and surface complexity.

Most goniometer systems, including the ULGS, maintain a constant target and vary the view azimuth and zenith angles. The apparatus used to gather data on these single-target systems consists of a base ring and moveable arch structure (**Figure 2**). Reflectance measurements are made by moving the sensor along the arch to acquire a full set of different zenith angle measurements at a given azimuth, and then moving the arch to acquire another set of zenith measurements at the next azimuth. Systems that use this approach include the Field Goniometer (FIGOS) from the Remote Sensing Laboratories at

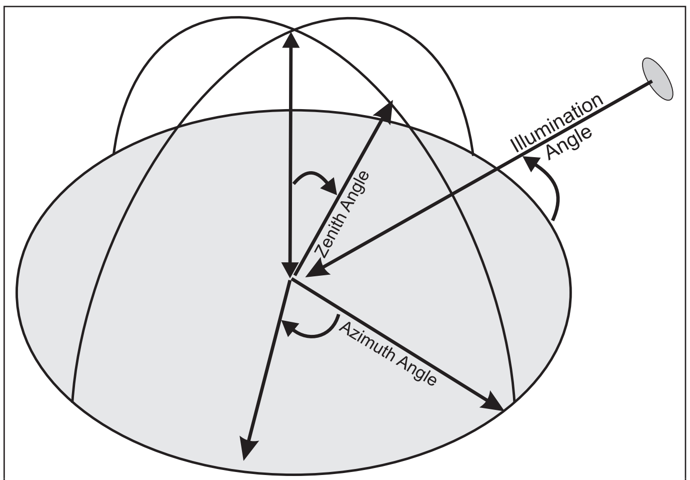

Figure 1. Geometry of incident and reflected energy.

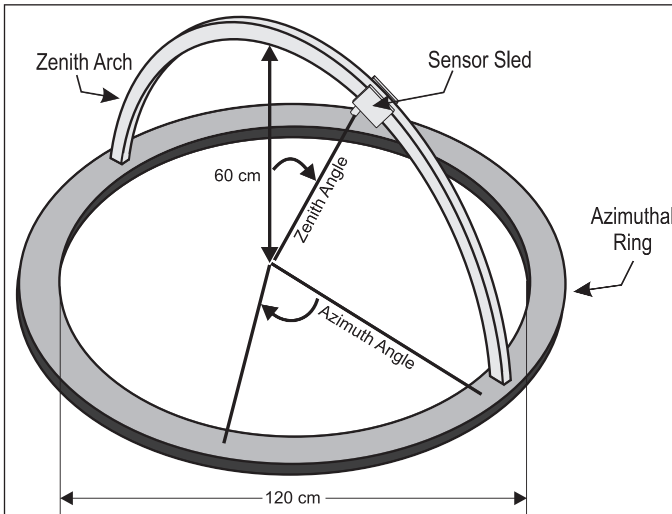

Figure 2. ULGS goniometer system layout and dimensions.

the University of Zurich (Sandmeier and Itten, 1999), the Sandmeier Field Goniometer (SFG) available from the National Aeronautics and Space Administration (NASA) Stennis Space Flight Center in Mississippi (Sandmeier, 2000), and the Automated Spectro-Goniometer (ASG) at the University of Colorado (Painter et al., 2003).

This style of goniometer usually incorporates a spectroradiometer as the sensor. The FIGOS goniometer is designed for the GER 3700 spectroradiometer (now available from Spectra Vista Corporation, Poughkeepsie, N.Y.), which provides a hyperspectral capability from 350 to 2500 nm at 10 nm nominal spectral resolution. The FIGOS has an angular resolution of 15° and can measure the 66 points it uses to estimate the BRDF in approximately 20 min. The more recent SFG instrument (Sandmeier, 2000) also uses the GER 3700 spectroradiometer and is a fully automated, computer-controlled goniometer that has a design similar to that of the FIGOS but can gather BRDF data faster (10 min for 15° zenith and 30° azimuth sampling). The ASG goniometer (Painter et al., 2003) was designed for measuring BRDF of snow surfaces. Although basically similar in design to the FIGOS and SFG goniometers, this instrument replaces the zenith arch structure with a large half-arch support and a rotating apparatus that controls the azimuth and zenith positions, further complicating the design and creating greater shadows.

University of Lethbridge goniometer system (ULGS)

The ULGS instrument has a design similar to that of the FIGOS and SFG goniometers in that it has a base ring and a rotatable arch for positioning the spectroradiometer sensor head above the target (**Figure 2**). The primary difference is that this low-cost instrument does not require computer-controlled positioning of these components. Instead, the sensor-head sled is simply positioned manually using precision-bored angular settings along the base ring and arch. Excluding a computer-controlled positioning system achieves several fundamental advantages: (*i*) dramatic reduction in cost; (*ii*) significantly less weight, making the system more portable for field use; (*iii*) significantly less developmental requirement; (*iv*) considerably less maintenance; and (*v*) no additional power requirements beyond that already needed for the spectroradiometer (usually a self-contained battery).

Spectroradiometer

Although any portable spectroradiometer can be used with the ULGS system, the current configuration uses an Analytical Spectral Devices, Inc. (Boulder, Colo.) FieldSpec® full-range spectroradiometer (ASD-FR), which provides hyperspectral data over the range 350–2500 nm. This spectroradiometer has a 512 element photodiode array for measuring radiation within the 350–1000 nm range and two cooled GaAs photodiodes for measurements between 1000 and 2500 nm. This instrument also has high spectral resolution (3 nm between 350 and 1000 nm and 10 nm between 1000 and 2500 nm) and rapid acquisition (10 spectra per second). The speed of sensor acquisition is an important consideration when acquiring BRDF data under natural (solar) illumination conditions to ensure change in solar geometry is negligible. This rate means that the total time required to acquire a full BRDF set is primarily a function of the time required for the operator to adjust the zenith position along the arch and the azimuth position along the base ring.

ULGS goniometer design

The overall design of the ULGS goniometer positioning system emphasized portability and flexibility for both laboratory and field use. The zenith arch rides in a track on the azimuth ring and is positioned over preassigned azimuth angles by way of marked, prebored indicators on both sides of the arch. Similarly, the sensor sled is located at preassigned zenith angles using marked, prebored positions and is securely held in place using an integrated clamp during measurements (**Figure 3**). The goniometer is constructed of medium-density fibre board (MDF), a dimensionally stable wood material that is coated with a highly absorbing flat black paint to minimize any reflection from the goniometer itself.

The ULGS system was designed to be compact; the radius of the azimuth ring and zenith arch is 60 cm. This allows for the direct measurement of samples in the laboratory or measurements of relatively short plant canopies in the field. To increase the utility of the instrument, extendable legs can be attached to the base ring to enable field measurements on sloped surfaces or for plant canopies up to 130 cm in height in the current design (**Figure 4**). Longer legs could easily be used to extend this capability. The zenith arch was designed so that it casts little or no shadow over the target area.

Although the system is capable of acquiring measurements at any angular precision, it is currently set to acquire measurements at 10° increments in both zenith and azimuth dimensions. The sensor sled and zenith arch design enables zenith angle measurements from –60° to +60°. The zenith angle is limited due to the design of the sensor sled that accommodates the ASD-FR pistol grip attachment. The size of the sled required to accommodate the pistol grip results in a maximum view angle of 70°. Although an alternate sled could be built to accept only the foreoptic, the incorporation of the pistol grip allows different instrument barrels and optics to be easily interchanged to alter the angular field of view (e.g., 1°, 5°, 8°, 12°, 18°) and for rapid conversion between hand-held spectra measurements and BRDF measurements.

A given zenith set therefore has 13 angles (including nadir), with 18 azimuths possible (effective azimuth range = 0–170°). Since the nadir position is the same for all 18 azimuths, however, this position is only measured once, resulting in 217 (13 × 18 – 17 or 12 off-nadir zeniths × 18 azimuths + 1 nadir) unique measurements taken for a complete hemisphere.

At the current 10° angular resolution, the acquisition time has averaged 20–25 min, which is adequate for laboratory

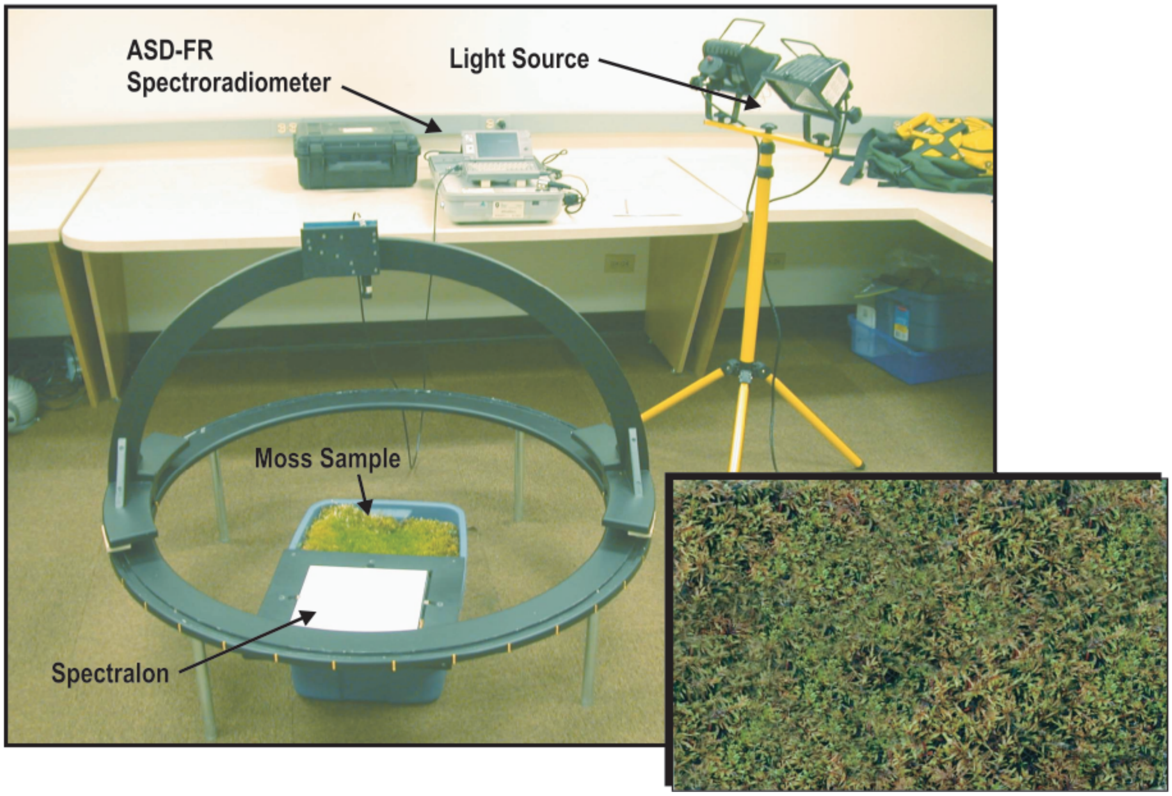

Figure 3. Setup of ULGS goniometer in the University of Lethbridge Spectroradiometer Laboratory. Fluxnet-Canada peat moss target, reference panel, illumination source (turned off), and ASD-FR spectroradiometer are shown. The inset is a close-up of the peat moss target (nadir).

measurements and also fast enough to ensure no significant change in solar illumination geometry during field acquisition.

Table 1 provides a general comparison of the ULGS and other fixed-target, movable sensor goniometers (i.e., PARABOLA is excluded from this comparison). This comparison is not intended to be comprehensive nor detailed but instead to provide an overview and basis for some broad observations. The other goniometers (FIGOS, SFG, ASG) possess similar characteristics and can be readily compared as a group. These categories for comparison are discussed elsewhere in this paper and are not repeated here, with **Table 1** serving as a useful summary of the main similarities and differences noted.

Example applications: field and laboratory BRDF estimates

BRDF measurement protocol

The purpose of this section is to provide several examples of ULGS measurements to demonstrate its use in different BRDF applications. It is not meant to be an extensive BRDF study, and therefore a detailed description of BRDF results is well beyond the intended scope of this paper. We also note that other investigators adopting this type of approach may choose to alter some of the ULGS design specifications to suit their particular purpose or for use with different types of spectroradiometers, reference panels, and illumination sources, as appropriate.

BRDF estimates from the ULGS goniometer for three different targets and settings were investigated: (*i*) measurement of a Lambertian reflectance calibration reference panel to serve as a test of panel reflectance characteristics (**Figure 5**), (*ii*) laboratory measurement of a moss canopy (*Pleurozium schreberi*) (**Figure 3**), and (*iii*) field measurement of a grass canopy (crested wheatgrass, *Agropyron cristatum*) (**Figure 4**). In all cases, hyperspectral target data were acquired at full angular resolution (10° in zenith and azimuth). A 5° foreoptic barrel was used on the ASD-FR to yield an FOV diameter of 5.24 cm based on a 60 cm distance from the sensor to the target (located at the centre of the plane formed by the azimuth base ring).

Illumination properties are important when estimating BRDF, particularly for field estimates due to changing solar position, weather, and atmospheric conditions. Therefore, time is of the essence in the field. In most field situations, a BRDF can be collected at reduced angular resolution to reduce the acquisition time from approximately 25 min to 15 min. This is not a concern in a controlled laboratory experiment. In this study, a 500 W halogen lamp was used as the source illumination. As the position of the lamp and optical properties of the illumination environment were constant, measurement time was less critical.

Figure 4. Field use of ULGS goniometer on a sloped surface at grassland meteorological station located in the coulees of the Oldman River valley in the southern portion of the University of Lethbridge campus. The inset is a close-up of the crested wheatgrass target (oblique view).

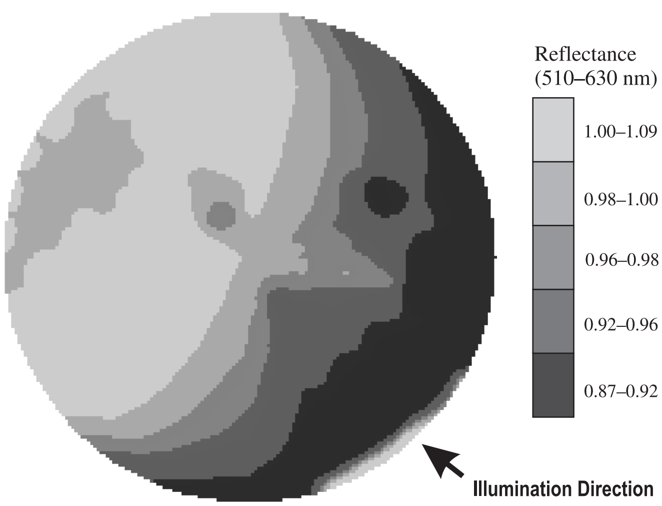

Figure 5. BRDF for the Spectralon reference panel showing near-Lambertian characteristics.

Table 1. Comparison of ULGS and other goniometer systems.

	ULGS	Other
Quality of spectra	High	High
Acquisition speed (full BRDF)	Moderate to high	High
Angular control	Manual	Computerized
Angular precision	Moderate to high	High
Laboratory capability	Yes	Not always
Field capability	Yes	Yes
Field portability	Excellent	Variable
Relative target size	Medium to large	Large
Sloped terrain	Yes	Most: no
Different sensors	Yes	Yes
Cost	Very low	Very high
Weight	Light	Moderate to heavy
Versatility	High	Low to moderate

Note: This is a general comparison intended to indicate main attributes of different goniometer system options. Individual goniometer systems may possess capabilities that differ from those indicated here.

The protocol used for gathering spectral reflectance data with the spectroradiometer followed the procedures outlined in Peddle et al. (2001). For each set of zenith measurements (i.e., each azimuth) for the grassland and moss targets, a separate measurement of a calibrated 12 in. × 12 in. (1 in. = 25.4 mm) pressed polytetrafluoroethylene (PTFE) reflectance panel (available commercially as Spectralon from Labsphere Inc., 1998) was first acquired at the nadir position to provide the normalizing input required for the computation of target reflectance. Each separate series of azimuth sets therefore has unique reference panel calibration spectra. The PTFE panel used offers nearly ideal Lambertian properties, as described in the next section.

These data were then processed to reflectance for each view position. The zenith and azimuth positions associated with each spectral measurement were then transformed from spherical to rectangular coordinates to facilitate improved visualization, graphing, and manipulation using the following equations:

$$x = \rho \sin \theta \cos \phi \quad (2)$$

$$y = \rho \sin \theta \sin \phi \quad (3)$$

where ρ is the diameter of the sphere, θ is the zenith angle, and ϕ is the azimuth angle. Once the data were transformed, BRDF surfaces were created using a thin-plate spline technique (Earth Resources Mapping, 2002). This technique maintains the original data points and provides a smooth interpolation (Hutchinson, 1993).

Reference panel Lambertian test

The use of PTFE reference panels to calibrate spectral measurements to reflectance is a standard operating procedure for field and laboratory measurements due to the near-Lambertian nature of the panel. In this study, detailed BRDF measurements of the reference panel were first obtained in the University of Lethbridge Spectroradiometer Laboratory with the ULGS goniometer to test the BRDF characteristics of this reference panel.

In theory, the BRDF should be constant across all zenith and azimuth view angles; in practice, however, it is not possible to have a surface that is perfectly Lambertian, and therefore a certain degree of anisotropy is expected. The results of these measurements (**Figure 5**) closely resemble those presented by Sandmeier et al. (1998b). The Spectralon panel is not perfectly Lambertian, with the small amount of anisotropy likely due to small variations in lamp intensity and possibly the presence of small foreign materials or particles on the panel surface.

Laboratory results: moss target

The laboratory studies were conducted with a pleurozium moss canopy collected from the Fluxnet-Canada Western Peatland site in northern Alberta and transported to the University of Lethbridge Spectroradiometer Laboratory using standard refrigerated shipment methods. The results of this experiment indicate that there was no pronounced hot spot; there was more of a region of low-angle, higher reflectivity around the southern edge, perpendicular to the source illumination angle (**Figure 6**). These results are similar to those for the moss canopy BRDF reported by Solheim et al. (2000).

When these data were plotted as a full spectrum for a variety of azimuth angles with a constant zenith, little difference was apparent in the visible wavelengths (**Figure 7**). The infrared wavelengths, especially between 750 and 1150 nm, showed a greater degree of variability with change in azimuth angle. In this region, the differences reflect the zone of higher reflectance, with the southern azimuths showing higher reflectance than the northern azimuths. This pattern was not always consistent. For example, the 50° azimuth was positioned with the higher reflectance group in the 750–950 nm range and was with the lower group between 1050 and 1150 nm.

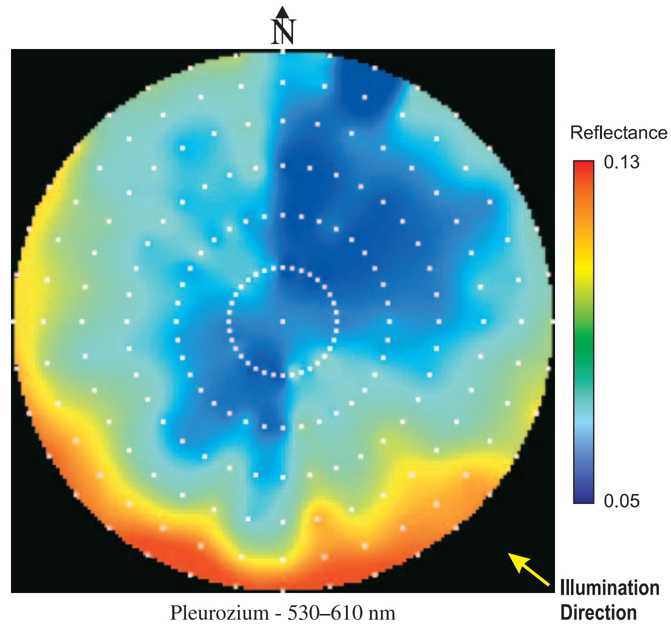

Figure 6. Laboratory-measured BRDF plot for the pleurozium surface within the green region of the electromagnetic spectrum. The hot spot is characterized primarily by higher reflectance values in the southern portion of the graphic, perpendicular to the illumination direction.

Field results: grassland target

The field data gathered for estimating the BRDF of crested wheatgrass were collected on 24 August 2004. At this time, the grass plants were starting to senesce and therefore did not display the same spectral signature as that of a healthy plant. Three BRDF measurement sets were acquired between 1200 and 1330 h (solar noon at 12:38 local time), with each measurement set requiring 20–25 min to complete. A comparison of these measurement sets (not shown) indicated each set was quite similar. Results from set 2 (acquired closest to solar noon) are presented here.

The results of this experiment (**Figure 8**) show a distinct hot spot located in the direction of solar illumination. **Figure 8** shows the planimetric projection of the BRDF data and gives a clear indication of the amount of variability possible with respect to different view angles.

When the data gathered by the ULGS were plotted for a single zenith angle for all azimuths, the differences in reflectance provided insight into the magnitude of the variation between azimuths (**Figure 9**). Measurements that corresponded to the hotspot (120°–140°) not only had higher overall reflectance but also showed greater differences within a given

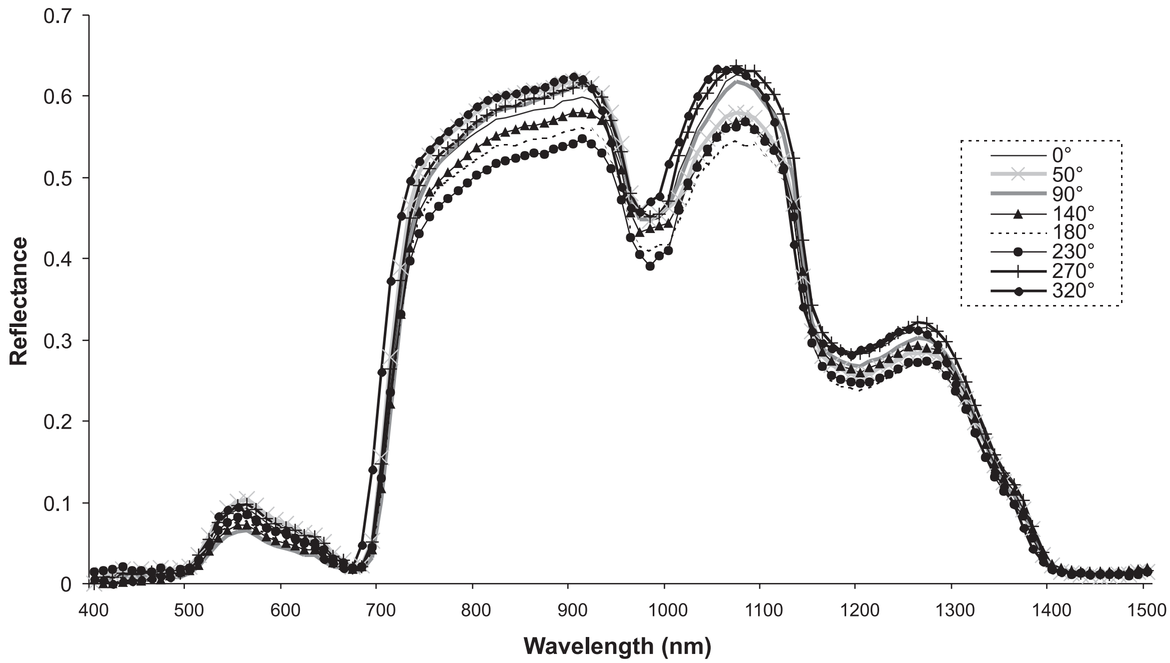

Figure 7. A full-spectrum representation of the pleurozium data at a constant 40° zenith for different azimuths.

spectrum. This further illustrates the spectral variability encountered with measurements taken over different azimuth positions (**Figure 9**).

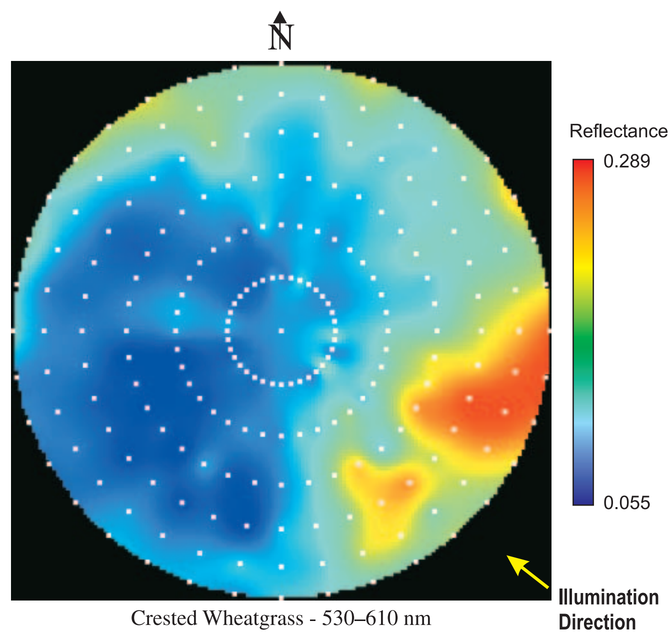

Figure 8. Field-measured BRDF plot for crested wheatgrass for the green region of the electromagnetic spectrum. Note the pronounced hot spot located near 120°.

Conclusion

The development of this low-cost field and laboratory University of Lethbridge goniometer system (ULGS) allows for the acquisition of BRDF data under a variety of conditions in support of remote sensing studies. The actual quality of an individual spectral measurement is primarily a function of the spectroradiometer sensor used and is largely independent of the goniometer platform. Accordingly, despite the low cost, the ULGS still yields very high quality spectra. The application of a low-cost approach has yielded usable data with this system, as demonstrated by the field and laboratory examples presented in this paper. The primary difference between this system and others currently in use is the relative simplicity and greatly reduced cost of the ULGS compared with the computer-operated type of goniometer.

The angular sampling resolution of the ULGS is high and can be adjusted. At 10°, the BRDF data provided greater detail than other goniometers (e.g., FIGOS and SFG) but resulted in longer acquisition times for BRDF sets. This is potentially only an issue in the field, however, and can be modified. For field use, reducing the angular resolution to 20° would provide a good balance between detail and length of acquisition time. Frequent measurement of the reference panel provided an indication of the magnitude of change in down-welling irradiance over the acquisition period.

The increasing availability of multiangular airborne and orbital satellite data and the increasing use of spectroradiometers for field validation of remotely sensed data require the collection of BRDF data for a wide variety of ground conditions. The development of instruments such as the ULGS capable of estimating the BRDF in a low-cost fashion will improve the availability and utility of these data and increase our knowledge of the reflectance characteristics of the earth's surface.

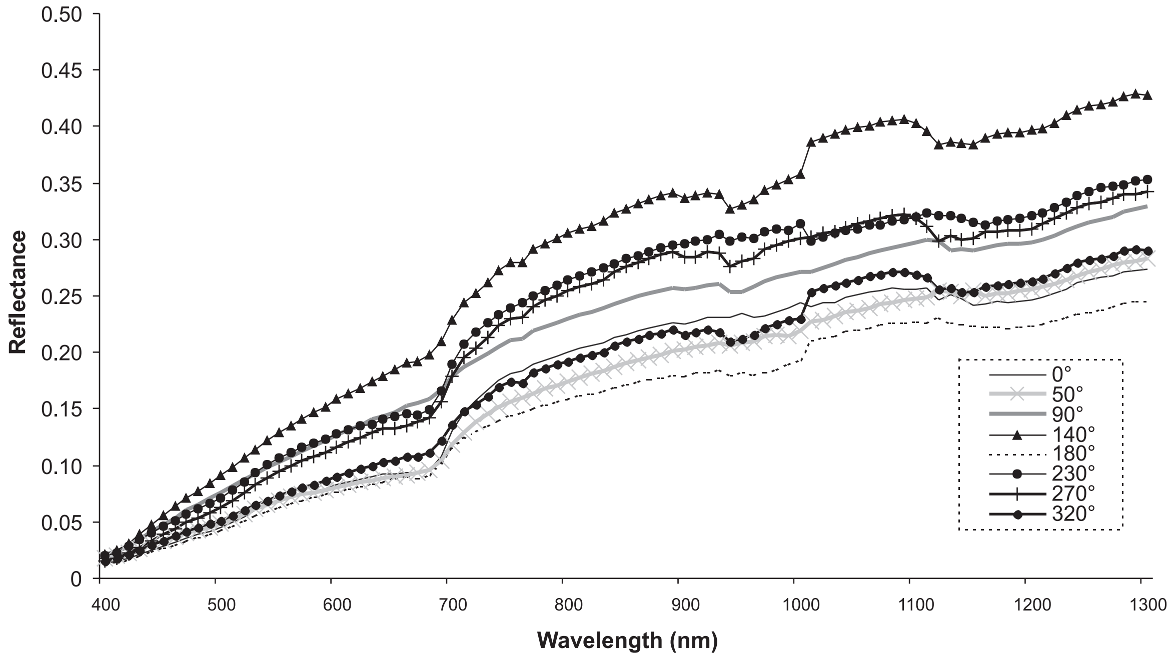

Figure 9. Full-spectrum representation of crested wheatgrass data at a constant 40° zenith for different azimuths.

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