

A Laboratory System for Multiangular Spectral Measurements of Vegetation

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Abstract

Accurate characterization of the directional spectral properties of vegetation is important for interpreting optical remote sensing observations and parameterizing radiative transfer models. We present a newly developed laboratory goniospectrometer for acquiring spectrally resolved bidirectional reflectance factor (BRF) measurements to characterize the bidirectional reflectance distribution functions (BRDFs) of vegetation. The system was designed to be versatile and easily configurable to accommodate various needs in vegetation remote sensing. For small targets, such as leaves and branches, it uses Köhler illumination to produce a small, homogeneous illumination footprint within the receiver field of view (FOV). By changing the illumination and receiver optics, the system is also configurable for measurement of larger targets, such as patches of short-statured vegetation. In this study we demonstrate its capabilities by using the configuration for small targets. Measurements of a Spectralon white reference panel demonstrate that the system is geometrically precise and spectrally stable, provides a usable signal over 400–2300 nm, and reproduces previously reported directional reflectance patterns. Measurements of Scots pine and silver birch branches further demonstrate the applicability of the system to small and structurally complex vegetation elements. The system provides a flexible laboratory platform for characterizing the directional spectral properties of vegetation and generating reference measurements for physically based interpretation and modeling of optical remote sensing observations.

1. Introduction

Information on the spectral reflectance properties of vegetation elements is essential for interpreting optical remote sensing observations and parameterizing radiative transfer models. Vegetation reflectance is inherently directional, and the signal observed by a remote sensing instrument depends on both illumination and viewing geometry. At the canopy scale, this directional behavior results from complex interplay between canopy structure and the bi-directional scattering properties of individual vegetation elements. Characterizing the spectral and directional reflectance properties of these elements can therefore improve the physical interpretation and modeling of remotely sensed canopy reflectance.

In recent years, there has been growing interest in compiling spectral libraries of forest and other vegetation elements, including leaves, woody elements, and short-statured vegetation communities. However, most existing spectral libraries are restricted to specific viewing and illumination geometries and therefore provide limited information on the directional scattering properties of the measured targets. Laboratory and field goniospectrometers have been developed to characterize directional reflectance at different spatial scales (e.g., Combes et al., 2007; Dangel et al., 2003; Harms et al., 2017; Lanevski et al., 2022; Peltoniemi et al., 2022; Yao et al., 2024), but comprehensive measurements of BRDF of vegetation elements across the visible to shortwave-infrared spectral range remain limited, particularly for small and structurally complex vegetation elements.

Requirements for collection of vegetation spectral BRDF information are diverse. Measurements of small elements, such as leaves and branches, require that the measured area is precisely defined and the measured signal does not originate from outside of the target. This is conveniently achieved by having an illumination footprint that is smaller than the receiver's FOV (e.g., Combes et al., 2007). Measurements of larger targets, such as patches of short-statured vegetation, may benefit from a

configuration in which the illuminated area is larger than the receiver's FOV, to ensure adequate signal levels and representativeness of the measurements when measuring heterogeneous vegetation communities. Especially the design of a system for measuring directional reflectance characteristics of small vegetation elements presents several instrumental challenges. The illumination and viewing geometries must be accurately controlled while maintaining a sufficiently strong spectral signal and homogeneous illumination over a small target area. Fiber-coupled spectroradiometers may introduce an additional source of uncertainty because differences in the effective FOV of individual detectors can produce spectral discontinuities across detector transitions. These challenges complicate accurate characterization of the directional spectral properties of small vegetation elements and motivate the development of laboratory systems specifically designed for such measurements.

To address various needs in remote sensing research and enable collection of multiangular spectral libraries of various types of vegetation elements, we present a newly developed laboratory goniospectrometer system for characterizing the spectral BRDF of vegetation and other targets. For small individual canopy elements, the system combines automated control of illumination and viewing geometries with a Köhler illumination system that produces a small, homogeneous illumination footprint within the receiver FOV. A dedicated receiver-optics configuration was further developed to minimize spectral discontinuities associated with varying detector FOVs. For larger vegetation targets, the system uses a larger illumination source coupled with a focusing lens to produce a homogeneous conical illumination beam at the target.

In this study, we describe the design and measurement capabilities of the system. We further evaluate its geometric and spectral performance in the measurement configuration for small targets, using measurements of a Spectralon white reference panel, and compare the measured directional dependence of BRF with previously published reference measurements. Finally, we demonstrate the system using branch samples of Scots pine

(*Pinus sylvestris* L.) and silver birch (*Betula pendula* Roth), illustrating its applicability to spectrally and structurally complex vegetation elements. The system provides a new laboratory capability for acquiring spectrally resolved multiangular BRF measurements of different types of vegetation elements and supporting the physical interpretation and modeling of optical remote sensing observations.

2. Materials and methods

2.1 The mechanical goniospectrometer system

The laboratory goniospectrometer system has two motorized arms that enable automated adjustment of the view zenith and azimuth angles (Figure 1). Illumination can be provided either through a fiberoptic cable and a lens system held on an automated motorized arm (ideal for small vegetation elements such as tree leaves and branches) (Figure 1), or by mounting the illumination source directly on a large, manually adjustable aluminum arc (Figure 2) (see Section 2.2 for more details). To ensure stability and precision, the entire structure is mounted on a honeycomb optical tabletop (1HT12-18-20, Standa).

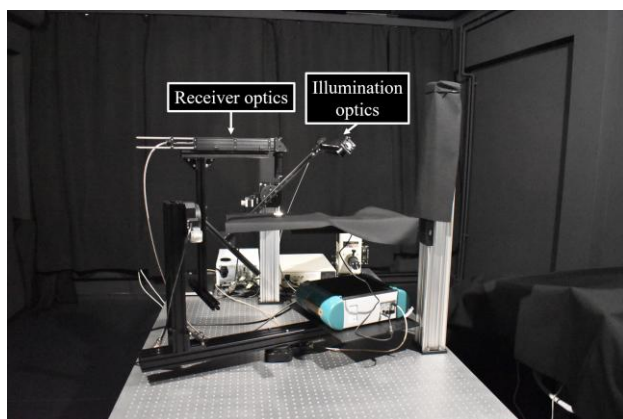


Figure 1. Photograph of the goniospectrometer setup that is ideal for small targets such as tree leaves and branches.

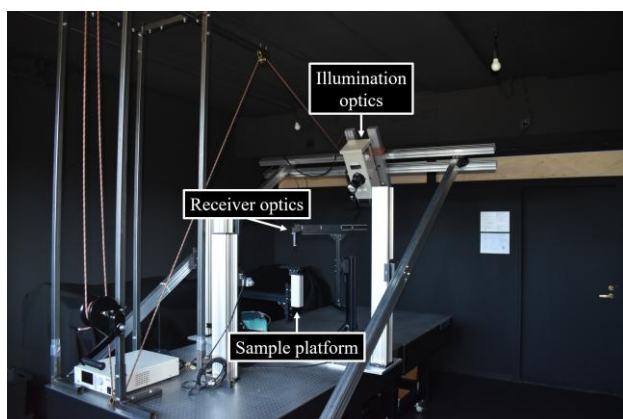


Figure 2. Photograph of the goniospectrometer's large, manually adjustable illumination setup used for larger targets, such as patches of short-statured vegetation.

The system uses three motorized heavy-duty continuous 360° rotation stages with an on-axis load capacity of 50 kg (HDR50/M, Thorlabs). The stages are fitted with top-plate adapters that provide additional mounting points for the lever arms (NR360SP9/M, Thorlabs). The motors are controlled using

a three-channel benchtop controller with USB connectivity, allowing multiple motor units to be operated from a single PC (BSC203, Thorlabs). The controller provides out-of-the-box software support for the rotation stages and enables the development of custom motion-control applications in various programming environments.

The lever arms rotated by the stages are constructed from combinations of aluminum optical rails (Thorlabs), which are well suited for building rigid, parallel assemblies using right-angle brackets and plates. Owing to the modular design of the optical rails, the measurement distance can be adjusted between 10 and 50 cm. Each rotating lever is also equipped with a counterweight. In particular, the motor controlling the view azimuth angle supports a large steel platform that holds the spectroradiometer and can simultaneously serve as a counterbalance if needed (Figure 1).

Similarly, the large manually adjustable aluminum arc is constructed using two opposing (continuous 360°) rotation stages fitted on vertical aluminum pillars that together with a winch allow the control of the illumination zenith angle (Figure 2). The aluminum arc supports counterweights at the ends of the arc for smoother and lighter movement.

A separate horizontal sample platform is positioned above the spectroradiometer and can be moved continuously along a large vertical aluminum rail (Figure 1). The sample platform is additionally equipped with a vertical adjustment stage for precise height positioning (Figure 2).

The automated and simultaneous control of the motorized goniospectrometer system and acquisition of spectra with the spectroradiometer are achieved using a PC running custom in-house scripts.

2.2 The illumination systems

The presented laboratory system has two alternative Quartz Tungsten Halogen (QTH) illumination sources, with maximum power of 250 W (Model 67009, Newport) or 1000 W (Model 66885, Newport). The two illumination sources have condensing and collimating optics that produce a collimated output. They are connected to power supplies that provide highly stable current and voltage for operating the QTH lamps (OPS-Q250 and OPS-Q1000, Newport, respectively).

For measurements of small targets or individual vegetation elements, the 250 W lamp is coupled through a fiberoptic bundle with a Köhler illumination system that provides a small area of perfectly homogeneous beam of illumination (5–25 mm in diameter) (Figure 3A). In principle, Köhler illumination aligns optical components (i.e., lenses) so that they do not produce an image of the illumination source at the target. This prevents the illumination source's structure (i.e., individual fibers of the fiberoptic bundle in this case) from appearing at the target, making the illuminated spot to have spatially invariant irradiance distribution (Figure 3B). The system is designed to produce an illuminated area smaller than the receiver's FOV, which helps to clearly define the measured area: an important property when measuring small targets such as tree leaves or branches (Figure 3C).

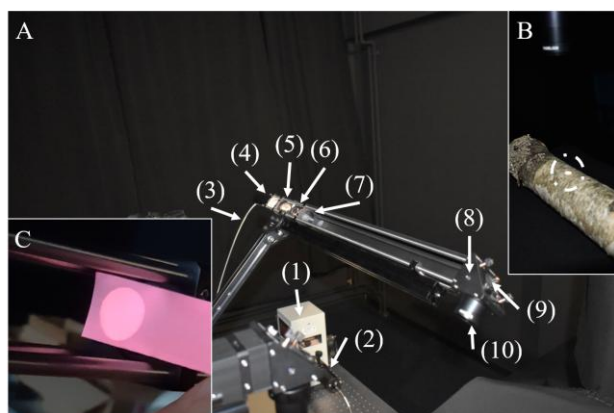


Figure 3. The Köhler illumination system: A) the QTH lamp and the optical component lineup (numbers correspond to the components listed in Section 2.2), B) image showing the perfectly uniform light beam after the first collimating lens, and C) 6 mm diameter perfectly homogenous light beam footprint on the surface of a measured branch sample.

The Köhler illumination system is constructed using a 30 mm cage system (Thorlabs, Figure 3A) and consists of the following components, listed in the direction of illumination: (1) a 250 W QTH lamp; (2) an aspheric lens assembly that focuses the beam onto the head of fiberoptic bundle (Model 60008, Newport); (3) a fiberoptic bundle (FG550LEC, Thorlabs); (4) an SMA fiber adapter plate (SM1SMA, Thorlabs); (5) a collimating (plano-convex or plano-convex aspheric) lens; (6) an iris diaphragm (CP20D, Thorlabs); (7) a focusing (plano-convex or plano-convex aspheric) lens; (8) a right-angle kinematic elliptical mirror mount (KCB1EC/M, Thorlabs); (9) a protected silver elliptical mirror (PFE10-P01, Thorlabs); and (10) a recollimating (plano-convex or plano-convex aspheric) lens. By selecting the focal lengths of the lenses and between-lens distances, the distance between the last lens and the perfectly homogeneous illuminated spot can be adjusted. Currently we use N-BK7 lenses manufactured by Thorlabs. The system also supports a 60 mm cage configuration (Thorlabs) with the same optical arrangement but using 50 mm diameter optics instead of 25 mm optics. This is beneficial to avoid illumination leakage when using lenses with long focal lengths (required for long illumination distances) that result in part of the illumination beam exceeding the 25 mm diameter.

For measurement of larger targets the collimated illumination beam from a QTH lamp is directed to an aspherical or plano-convex focusing lens to provide a homogeneous conical beam. Both 250 W and 1000 W QTH lamps can be used here. The lamp size and the focal length of the focusing lens can be selected depending on the required power and opening angle of the conical illumination beam. To allow adjustment of the illumination zenith angle, the lamp housing, together with the optics, is mounted on the large aluminum arc described in Section 2.1 and shown in Figure 2.

2.3 The receiver optics

To minimize spectral discontinuities caused by the varying detector fields of view in the connected spectroradiometer (i.e., the 3×19 individual detectors within the Analytical Spectral Devices (ASD) FieldSpec4 Standard-Res fiberoptic bundle), the receiver optics for small targets also utilizes a 30 mm cage system (Thorlabs) and essentially follows a reversed optical design relative to the Köhler illumination system described in Section

2.2 (Figure 4). The alignment of the lenses makes sure that an image of the sample surface does not appear at the receiver's optics (i.e., at the head of spectrometer's fiberoptic bundle). The system consists of, listed in the direction of illumination: (1) a collimating (plano-convex or plano-convex aspheric) lens; (2) a lever-actuated iris diaphragm (SM1D25, Thorlabs); (3) a right-angle kinematic elliptical mirror mount (KCB1EC/M, Thorlabs); (4) a protected silver elliptical mirror (PFE10-P01, Thorlabs); (5) a focusing (plano-convex or plano-convex aspheric) lens; (6) a recollimating (plano-convex or plano-convex aspheric) lens; (7) an SMA fiber adapter plate (SM1SMA, Thorlabs); (8) an SM1-threaded adapter (AD64F, Thorlabs); and (9) a spectroradiometer. Currently we use N-BK7 lenses manufactured by Thorlabs also for the receiver optics. Note that with these components, the receiver optics accommodate any spectro(radio)meter with a fiberoptic bundle as a detector, and a standard SMA connector at the end of the bundle. The above design allows unrestricted movement of the goniospectrometer receiver optics and the illumination setups (described in Section 2.2). The measured signal also remains sufficiently strong between 400 and 2300 nm, although the spectroradiometer itself operates over a wavelength range of 350–2500 nm. This reduced usable spectral range results from signal losses introduced by the various optical components described in Sections 2.2 and 2.3.

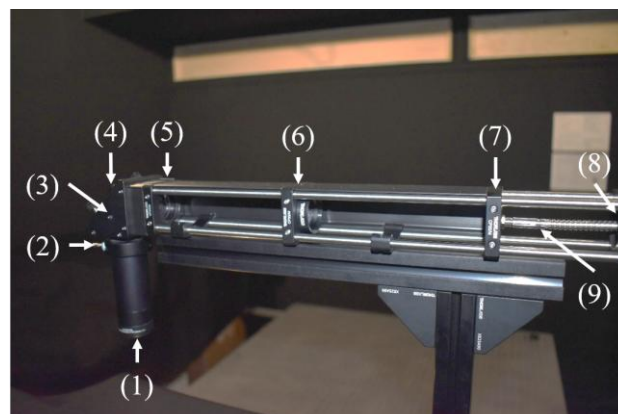


Figure 4. The receiver's optical component lineup. The numbers correspond to the components listed in Section 2.3.

For measurements of larger targets using the 1000 W QTH lamp configuration, the receiver optics can be replaced by the spectroradiometer's bare fiber mounted on a holder, with the FOV controlled using optically black tubes of varying lengths. This allows for free adjustment of the receiver FOV, contrary to the lens system in which the FOV is determined by the diameter of the first lens in the system.

2.4 Optically black laboratory surroundings

The entire windowless laboratory is covered with nominally optically black materials to minimize stray light. It is worth noting that all materials used were acquired from relatively low-cost, non-specialty retail sources, yet they exhibit low reflectance across the optical region. The walls and other external structures are coated with black paint (Tela Taustamusta by Teknos), while the floor is covered with a durable, easily cleanable black surface (Eclipse Premium by Tarkett). Their mean directional-hemispherical reflectances, measured using an integrating sphere, were approximately 3% and 5%, respectively, across the measured spectral range. Surfaces that could not be painted (e.g., the optical honeycomb table, and aluminum parts of the mechanical goniospectrometer system) are covered with black

acrylic canvas fabric (Solid VV M100 by Sunbrella) with a directional-hemispherical reflectance of approximately 2% across the spectral range.

2.5 Measurements and data processing

To demonstrate the operation of the system, and to test its performance when measuring challenging small targets, we measured BRFs of a Spectralon white reference panel, as well as tree branch samples of Scots pine (*Pinus sylvestris* L.) and silver birch (*Betula pendula* Roth). The Spectralon panel (Labsphere Inc., serial no. 99AA05–0625–9144) had a nominal reflectance of 99%. The branch samples were collected from forests in Lohja, southern Finland (60°23'N, 23°53'E). We used the illumination and receiver configuration designed for small targets (Sections 2.1 and 2.2) in these measurements. For future reference, the serial number of the ASD FieldSpec4 StandardRes we used for measurements was 19404.

We performed measurements at two illumination-zenith angles (11° and 45°). The 11° angle was selected to be as close as possible to the standard 8° illumination angle used in integrating spheres. The current configuration and measurement distance allowed measurements no closer than 11° to the hotspot, and therefore use of 8° illumination-zenith angle would have prevented measurements at nadir view. Measurements closer to hotspot can be obtained in the future by increasing the measurement distance or using a narrower detector without lens optics. The 45° represents a mid-range angle that differs substantially from 11° and therefore demonstrates illumination angle dependencies in the measured BRFs. The measurements were conducted at 28 viewing angles for each illumination angle: eight azimuth angles (0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°) and three zenith angles (15°, 45°, and 75°), with additional nadir (0°) measurements at every other azimuth. In the principal plane the zenith angles that were not possible to measure due to the receiver obscuring the illumination were replaced by the closest possible angle, i.e., 15° was replaced by 22°, and 45° was replaced by 56°, for illumination zenith angles 11° and 45°, respectively. The diameter of the illumination beam was 6 mm, and the measurement distance was 13 cm.

We calculated the spectral bidirectional reflectance factor (BRF) of each sample using the sample and reference measurements and the BRF of the reference panel:

$$\text{BRF}(\theta'_i, \phi'_i; \theta'_r, \phi'_r; \lambda) = \frac{s_r(\theta'_i, \phi'_i; \theta'_r, \phi'_r; \lambda)}{s_{r,ref}(\theta_i, \phi_i; \theta_r, \phi_r; \lambda)} \times \frac{\cos \theta_r}{\cos \theta'_r} \times \text{BRF}_{ref}(\theta_i, \phi_i; \theta_r, \phi_r; \lambda), \quad (1)$$

where,
 ϕ_i = illumination-azimuth angle
 θ_i = illumination-zenith angle
 ϕ_r = view-azimuth angle
 θ_r = view-zenith angle
 λ = wavelength
 $\text{BRF}(\theta'_i, \phi'_i; \theta'_r, \phi'_r; \lambda)$ = BRF of the sample
 $s_r(\theta'_i, \phi'_i; \theta'_r, \phi'_r; \lambda)$ = sample measurement
 $s_{r,ref}(\theta_i, \phi_i; \theta_r, \phi_r; \lambda)$ = measurement of the reference panel
 $\text{BRF}_{ref}(\theta_i, \phi_i; \theta_r, \phi_r; \lambda)$ = BRF of the reference panel.

Primed symbols ($\theta'_i, \phi'_i; \theta'_r, \phi'_r$) denote the illumination and view angles in sample measurements, and their unprimed counterparts ($\theta_i, \phi_i; \theta_r, \phi_r$) correspond to the reference measurements. The white Spectralon panel was used as a reference. The reference measurement was performed at each illumination angle separately, i.e., $\theta'_i = \theta_i$, and $\phi'_i = \phi_i$. Nadir view was used in the reference measurements, i.e., $\theta_r = 0^\circ$, and the reference measurement was repeated at four different view azimuth angles and averaged for further calculations. BRF of the reference panel at nadir view was calculated using the panel's directional hemispherical reflectance, $\rho_{ref}(\theta_i = 8^\circ, \phi_i; 2\pi)$, measured with an integrating sphere and reported in its calibration certificate, and the ratio of signal from the reference panel at nadir view to the hemispherically integrated signal at 11° illumination as follows:

$$\text{BRF}_{ref}(\theta_i, \phi_i; \theta_r, \phi_r; \lambda) = \pi \frac{s_{r,ref}(\theta_i, \phi_i; \theta_r, \phi_r; \lambda)}{\cos \theta_r} \times \left[\frac{\sum_{\phi_r \in A} \sum_{\theta_r \in B} s_{r,ref}(\theta_i = 11^\circ, \phi_i; \theta_r, \phi_r; \lambda) \sin \theta_r d\theta_r d\phi_r}{\sum_{\phi_r \in A} \sum_{\theta_r \in B} \sin \theta_r d\theta_r d\phi_r} \right]^{-1} \times \rho_{ref}(\theta_i = 8^\circ, \phi_i; 2\pi; \lambda), \quad (2)$$

where, $A = \{0^\circ, 45^\circ, 90^\circ, 135^\circ, 180^\circ, 225^\circ, 270^\circ, 315^\circ\}$
 $B = \{15^\circ, 45^\circ, 75^\circ\}$.

Once the BRF of the reference panel at nadir view had been obtained, it was sufficient to measure the reference panel at nadir view for each measured sample.

3. Results and discussion

We first present the BRF measurements of the Spectralon white reference panel. Note that in these measurements the same panel was used as both sample and reference. The results therefore quantify the goniospectrometer's precision and ability to characterize view and illumination angle dependencies of BRF, but not the absolute accuracy of the measurements. Nevertheless, the results demonstrate that the laboratory goniospectrometer is stable, precise, and geometrically accurate. Despite producing a very small, homogeneous, point-like beam, the Köhler illumination system and the receiver optics provided a sufficiently strong signal over the 400–2300 nm wavelength range (Figure 5). In addition, the spectra indicate that the current receiver-optics configuration successfully minimized spectral discontinuities that are due to the spectrometer having three separate detectors at 350–1000 nm, 1001–1800 nm, and 1801–2500 nm, each of them receiving the signal through separate optical fibers having slightly different fields of view (Figure 5). Small discontinuities remained at very oblique viewing angles ($\pm 75^\circ$), but these could likely be further reduced through additional alignment or more frequent dark current measurements (Figure 5).

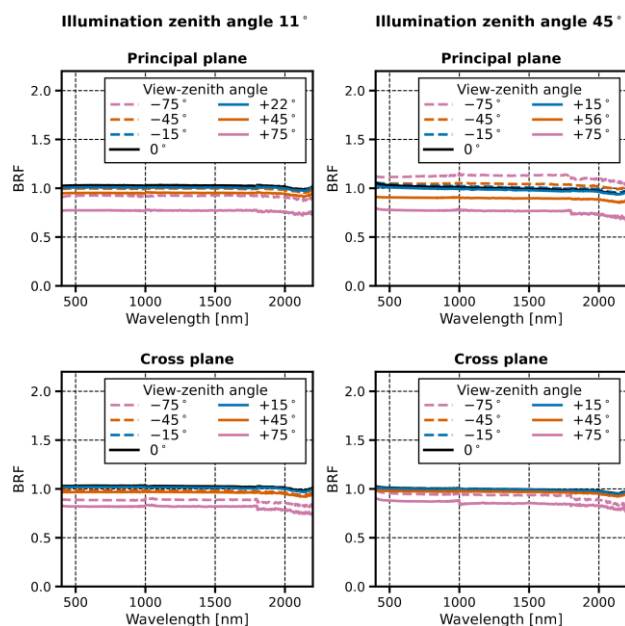


Figure 5. Full-range (400 nm to 2300 nm) BRF spectra of Spectralon white reference panel measured along the principal and cross planes at illumination zenith angles of 11° and 45°. In the principal plane, positive and negative view zenith angles correspond to the backward- and forward-scattering directions, respectively.

We also compared our results with those of Bruegge et al. (2001) and Voss and Zhang (2006), who characterized the BRDF of Spectralon white reference panels at 632–633 nm along the principal and cross planes, respectively. Our measurements showed very similar angular patterns and successfully captured the substantial deviations of Spectralon from an ideal Lambertian diffuser (Figure 6).

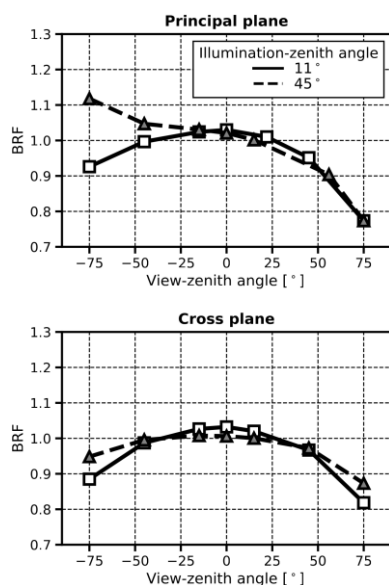


Figure 6. Principal- and cross-plane BRF of a Spectralon white reference panel at 632 nm for illumination zenith angles of 11° and 45°. In the principal plane, positive and negative view zenith angles correspond to the backward- and forward-scattering directions, respectively.

Next, we present measurements of two natural targets: branches of Scots pine and silver birch (Figures 7–8). These targets require a small, point-like illumination footprint because of branch

curvature, surface irregularity, and changes in the illuminated area with illumination angle. The measurements show that tree branches can exhibit highly anisotropic BRDFs (Figures 7–8), with strong forward scattering (Figures 7–8). Forward scattering was particularly strong for silver birch, which also exhibited pronounced anisotropy in the cross plane (Figure 8). Finally, we show directional-hemispherical reflectance spectra of all measured branch samples, obtained by integrating the BRF measurements over the hemisphere (Figure 9). These measurements demonstrate a tendency of increasing reflectance (decreasing absorption) as a function of illumination zenith angle. It is noted that two samples (pine, tree 3; birch, tree 3) deviated from this tendency, which is likely related to measurement uncertainties of these nonhomogeneous samples with surface irregularities. The strong anisotropy of these branch samples clearly demonstrates the need for vegetation spectral libraries that consider the view and illumination angle dependence.

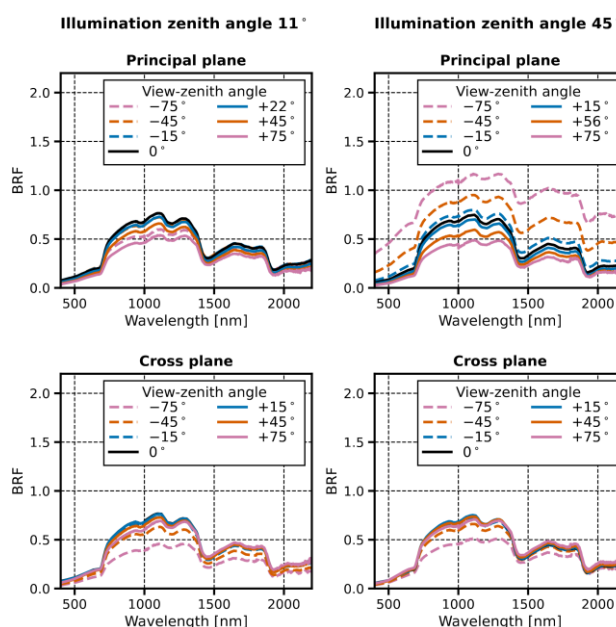


Figure 7. Full-range (400–2300 nm) BRF spectra of a Scots pine branch sample measured along the principal and cross planes at illumination zenith angles of 11° and 45°. In the principal plane, positive and negative view zenith angles correspond to the backward- and forward-scattering directions, respectively.

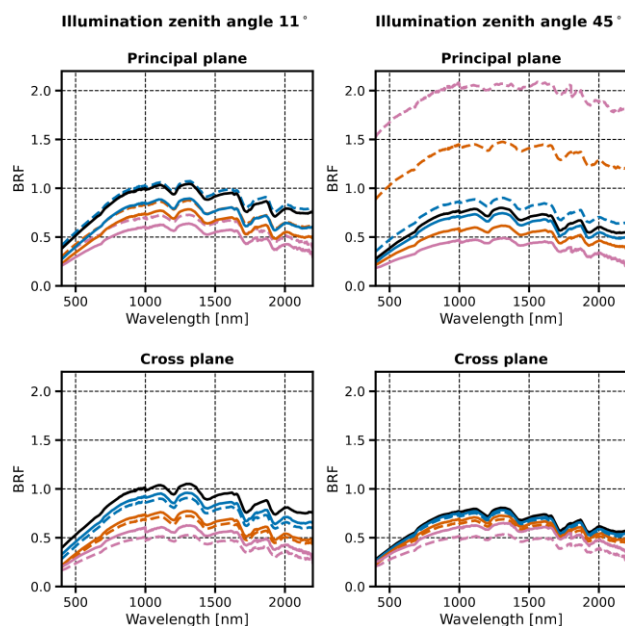


Figure 8. Full-range (400–2300 nm) BRF spectra of a silver birch branch sample measured along the principal and cross planes at illumination zenith angles of 11° and 45°. In the principal plane, positive and negative view zenith angles correspond to the backward- and forward-scattering directions, respectively. See Figure 7 for the legend indicating the line type and color corresponding to each view zenith angle.

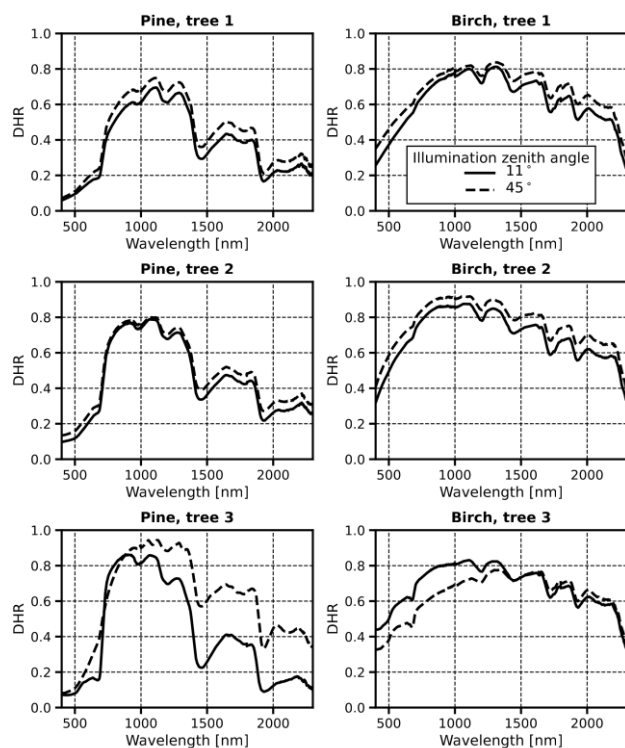


Figure 9. Directional-hemispherical reflectance (DHR) spectra for three samples of Scots pine and silver birch branches measured at illumination zenith angles 11° and 45°.

One measurement-related challenge remains: the measurements are time-consuming. For natural targets such as vegetation, an efficient sampling strategy is therefore needed when compiling spectral libraries, even though the laboratory goniospectrometer itself can characterize the BRDF of a target. One of the main

factors that such a sampling strategy must account for is sample drying, i.e., loss of moisture during measurement. Changes in moisture content can alter the spectral signature, especially in the case of foliage samples, even when the physical position of the sample remains unchanged throughout the measurement protocol.

4. Conclusions

We described in detail the design and measurement capabilities of a newly developed laboratory goniospectrometer system and evaluated its geometric and spectral performance. The system is precise and spectrally stable, while its flexible design enables characterization of the directional spectral properties of a wide range of targets and generation of reference measurements for physically based interpretation and modeling of optical remote sensing observations. By providing a detailed description of the system and its components, we also aim to support the development of similar systems and lower the barrier for researchers seeking to design and build goniospectrometers.

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