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# DIRECTIONAL RADIANCE DISTRIBUTIONS ABOVE AND WITHIN A FOREST CANOPY

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## ABSTRACT

A multidirectional field radiometer was adapted for measuring directional radiances both above and below a boreal forest canopy to examine the total forest canopy system optical-reflective radiative transfer characteristics and to validate plant canopy models. Analyses of the reflected radiances above the canopy reveal a highly anisotropic bidirectional reflectance distribution function (BRDF) with a substantial forwardscatter but a considerably stronger backscatter. The characteristics of the forest BRDF vary with solar zenith angle, as has been observed to be the usual case in all other green plant canopies previously examined. However, the anisotropy was found to be considerably greater at the larger solar zenith angles for the Maine spruce-hemlock forest than has been observed for other land surfaces, at least for the limited range of solar zeniths available in September. But at the smaller solar zenith angles, the forest was found to have slightly less anisotropy in the near-infrared spectral band than a scrub oak plant community and less anisotropy than a prairie grassland. Keywords: Bidirectional reflectance, BRDF, boreal forest, anisotropy, transmittance.

## INTRODUCTION

Satellites offer the capability for truly synoptic viewing and thus are useful in regional, continental and global scale earth system parameter measurement and monitoring; but current satellite remote sensing techniques suffer from several important drawbacks. Among the more notable are 1) satellite measurements are generally limited to one viewing direction at a given observation time, that is, unidirectional rather than multidirectional or hemispheric reflectance is measured, and 2) it is generally impractical or impossible to obtain data for the same area except during one overpass, at one time of day (solar zenith angle)—that is, illumination, atmospheric and surface conditions must remain constant for a multidirectional dataset of a given area. An understanding of the characteristics of the reflectance anisotropy of earth surfaces is imperative for the full realization of the potential of future off-nadir pointing sensors as well as for utilizing *current* satellites that only have "one look" (whether one view angle or one time of day) at a surface target.

Measurements have been made in recent years of the bidirectional reflectance distribution of a variety of land surfaces. But measurements of the bidirectional reflectance distribution functions (BRDFs) of forest canopies have been rare, particularly near-canopy level meas-

urements. The logistical difficulties of making measurements above forest canopies, plus the complexity of natural forest stand geometry as compared to that of row crops, are likely primary reasons for the paucity of forest canopy measurements at field sites. Kriebel [1], Kimes et al. [2] and Kleman [3] used helicopters to acquire their data sets. Ranson et al. [4] set up a miniature, artificial forest canopy made up of potted balsam fir trees on a turntable and thereby simulated the effects of changing view angle and solar angles with different simulated forest floor backgrounds.

In this study measurements of the directional distribution of optical-reflective radiant energy in three spectral bands were preliminarily examined for a spruce-hemlock forest canopy. The primary objective of the study is to characterize the bidirectional reflectance of a coniferous forest canopy (above the canopy) and the directional distribution of the radiation transferred through the canopy to the ground level (below the canopy). This paper reports on early results from the first field campaign of this study.

## EXPERIMENT SITE AND INSTRUMENTATION

The field experiment was conducted in September, 1989 in the vicinity of a 25m meteorological tower (45° 21.21'N, 68° 44.49'W) that was established and is maintained by the University of Maine at Orono. The site, which is in the International Paper Company's Northern Experimental Forest at Howland, Maine, is predominately spruce and hemlock, (92% by stem count) with some white pine and red maple. Near the tower the average height of all trees was measured at 14.5 m with a tree density at just over 1200 trees per hectare and a diameter-at-breast-height of about 18 cm (Nelson, [5]).

The Portable Apparatus for Rapid Acquisition of Bidirectional Observations of the Land and Atmosphere, or PARABOLA field radiometer (Deering and Leone, [6]) was employed to measure the directional radiances in essentially the complete  $4\pi$  irradiance field both above and below the spruce-hemlock canopy under cloudless and overcast sky (below canopy only) conditions. The PARABOLA is a three-channel (0.650-0.670, 0.810-0.840, and 1.620-1.690  $\mu\text{m}$ ) radiometer with a scanning head that turns on two axes, which enables the acquisition of radiance data for almost the complete sky- and ground-looking hemispheres in 15° instantaneous field-of-view (IFOV) sectors in 11 s.

The PARABOLA radiometer head's support boom system was installed on the meteorological tower with a specially built set of mounting brackets that clamped onto two different sections of the tower. When joined with a steel cable harness, winch and pulley apparatus, the tower support provided a capability for limited azimuthal rotation of the boom about the base mounting pivot. The tower boom mount, extended the PARABOLA radiometer head approximately 8 m above the forest canopy, and almost 5 m away from the north side of tower.

Cloud cover during the period established for the experiment was highly variable. However, two days, September 16 and 18, yielded several periods of nearly cloudless skies for sampling. By employing these two days, clear-sky above canopy PARABOLA data were acquired for almost the complete range of solar zenith angles possible (nominally 45° to 80°) for the site's latitude and the time of year of the experiment.

Beneath the forest canopy the PARABOLA radiometer head with its leveling head apparatus was mounted on a tripod-mounted boom that was short enough to enable some movement between the trees. PARABOLA measurements were acquired for cloudless sky conditions with a moderate to heavy haze on September 9 for solar zenith angles ranging from 40° to 80°. A heavily overcast sky condition occurred on September 19 and PARABOLA measurements were acquired at 50° and 65° solar zenith angles for comparisons with the cloudless sky condition. Results of the below canopy measurements are not presented in this short paper.

## RESULTS AND DISCUSSION

### BIDIRECTIONAL REFLECTANCE

The bidirectional reflectance of the spruce-hemlock forest canopy at the Howland site was dominated by backscatter in all three spectral bands (red, near-infrared, and shortwave- or middle-infrared) over the two solar zenith angles as illustrated in Figure 1. Red band reflectances ( $0.662\mu\text{m}$ ) at the 54° solar zenith angle ranged from 1.5% at nadir to 5.9% at the 60° backscatter angle. Comparable values for the near-infrared (NIR;  $0.826\mu\text{m}$ ) and shortwave-infrared (SWIR;  $1.658\mu\text{m}$ ) were 18.4% and 6.8% at nadir and 43.7% and 21.7% at the 60° backscatter angle, respectively.

With a change in the solar zenith angle from 54° to 70° the nadir reflectances decreased as the depth of the shadowing increased. The 16° increase in solar zenith angle, resulted in decreases in nadir reflectance of 20%, 30% and 45% in the red, NIR, and SWIR bands, respectively.

Backscatter and forwardscatter bidirectional reflectance both increased at the farther off-nadir view angles, with the forwardscatter showing similar or larger percentage increases with the 16° larger solar zenith angle. In the NIR band, for example, as the nadir values *decreased* from 18.4% to 12.8% at nadir, reflectance at 75° off-nadir toward the backscatter direction *increased* from 41.0% to 63.8% in the region of the hotspot (a 56% relative increase). Correspondingly, the forwardscatter increased

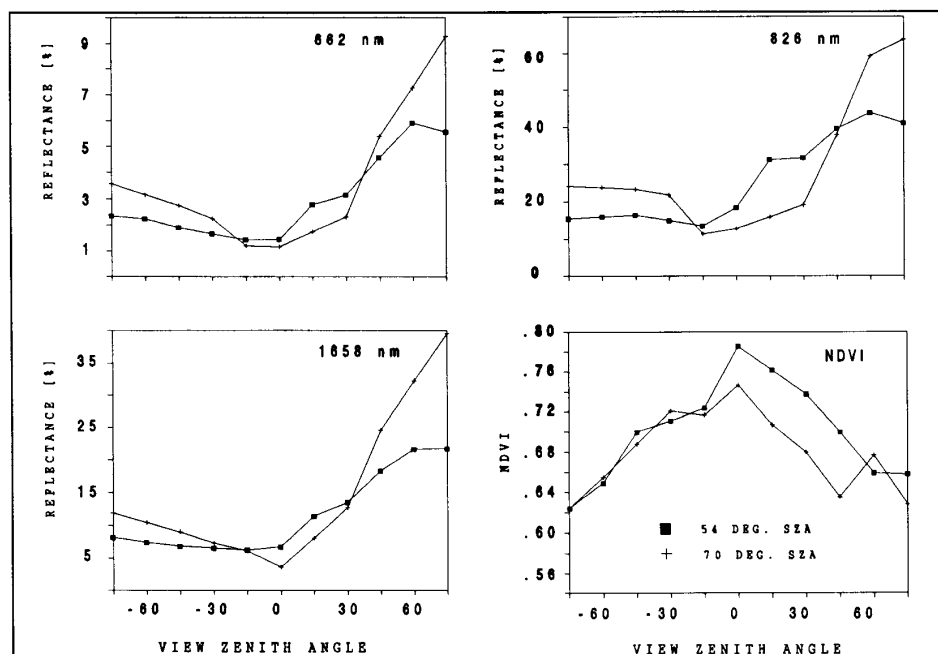


Figure 1. Howland Maine spruce-hemlock forest canopy reflectances in three spectral bands and Normalized Difference Vegetation Index compared for two solar zenith angles (54° and 70°).

from 15.5% to 24.3% (a 57% relative increase).

For the Howland spruce-hemlock site we found significant view angle dependence in the normalized difference vegetation index, or NDVI ((NIR - Red)/(NIR + Red)), at both the 54° and 70° solar zenith angles. Also, there was some change in NDVI due to solar zenith angle change for the nadir to 45° backscatter view angle range over this relatively small range in solar zenith angles.

Recently, Kleman [3] measured directional reflectance factor distributions for two forest stands in Sweden, one pine and the other spruce, over a solar zenith angle range of 40° to 60°. The measurements for the spruce canopy were made over the solar zenith angle range of 47° - 50°. He reported stronger anisotropy for the spruce forest than the pine forest. We compared the Maine spruce-hemlock forest PARABOLA tower measurements with his spruce data acquired in Sweden from a helicopter. There are relatively small differences in the two radiometers' wavelength bands, and Figure 2 reveals that the directional reflectances for the two sites and instrument systems are quite comparable for all three spectral bands, but with higher reflectances at the Maine spruce-hemlock forest for nearly all view angles in all three spectral channels. It is noted that the canopy species composition and structure vary for these two forest sites. For example, at the Howland, Maine site there were approximately 1200 trees/ha with an average height of 14.5 m, while at Kleman's spruce site there were approximately 680 trees/ha with an average height of 18.5 m. These differences in canopy geometry and species composition may account for the observed differences in reflectance at the two sites.

#### ANISOTROPIC FACTORS

Kleman [3] concluded that "since spruce forest is among the most anisotropically reflecting vegetation types [*sic*] due to its geometrical structure and dense canopy, the stated values probably represent maximum values for the angular dependence that will be met in applications." Anisotropic factors from the PARABOLA data were computed by multiplying the nadir value by  $\pi$  and dividing that product by the hemispherical reflectance, as reported by Middleton, et al. [7], and are given in Table 1. For an isotropically reflecting surface this ratio is equal to 1.

The spruce-hemlock forest in Maine was indeed highly anisotropic for all three wavebands. At the 54° solar zenith angle the red spectral band exhibited the greatest anisotropy at 0.554. And, although the anisotropy increased considerably for all three spectral bands as the solar zenith angle is increased, at the 70° solar zenith angle the SWIR spectral band was substantially more anisotropic at 0.306 than the red band at 0.408.

In order to preliminarily evaluate Kleman's claim concerning spruce forest anisotropy, we compared our spruce-hemlock anisotropy with our data from a couple of other surface cover types from previous experiments: a semiarid scrub oak stand and a natural prairie grassland at its peak of "greenness". The principal deviation from Kleman's generalization occurs in the NIR spectral band,

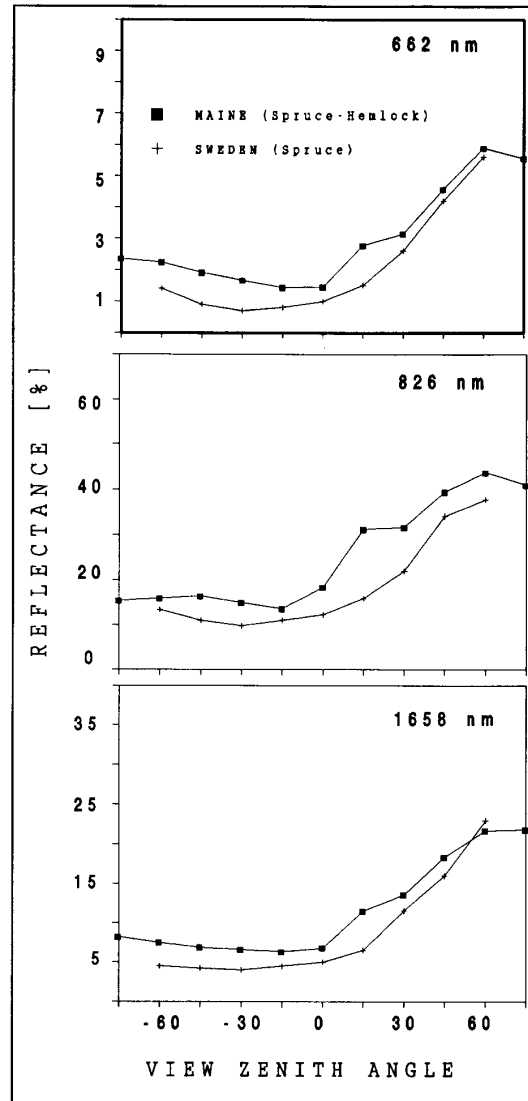


Figure 2. Maine spruce-hemlock forest reflectances compared with Sweden spruce forest (Kleman [15]) in three spectral bands (solar zenith angles 54° and 48.5°, respectively).

where both the shinnery oak and grassland show a somewhat greater anisotropy than the spruce-hemlock forest. For example, the spruce-hemlock forest anisotropy in the NIR was 0.786 versus 0.735 for the grassland. Anisotropy at small solar zenith angles could not be computed for the September spruce-hemlock data, but representative data for the grassland and shinnery oak sites are included to illustrate that the anisotropy can potentially be reversed (i.e., greater than 1, which results from nadir reflectance being

**Table 1.** Anisotropic factors ((nadir reflectance \*  $\pi$ )/hemispheric reflectance) compared for three vegetated surfaces for a range of solar zenith angles in the red (0.662  $\mu\text{m}$ ) and near-infrared (0.826  $\mu\text{m}$ ) spectral bands.

SITE	SOLAR ZENITH ANGLE	ANISOTROPIC FACTORS	
		.662 $\mu\text{m}$	.826 $\mu\text{m}$
<u>~ 70° Solar Zenith Angle:</u>			
Maine Forest	70	0.408	0.481
Shinnery Oak	71	0.600	0.650
Konza Prairie	70	0.530	0.660
<u>~ 55° Solar Zenith Angle:</u>			
Maine Forest	54	0.554	0.786
Shinnery Oak	58	0.840	0.780
Konza Prairie	55	0.611	0.735
<u>~ 15+° Solar Zenith Angle:</u>			
Maine Forest	--	--	--
Shinnery Oak	30	1.120	0.950
Konza Prairie	17	1.142	0.863

higher than far off-nadir values). Whether coniferous forests will exhibit such a reversal remains to be tested.

#### HEMISPHERIC REFLECTANCE

Total hemispheric reflectance, or albedo, is an important parameter in energy budget calculations for use in ecosystem and climate studies. The spectral hemispheric reflectances in the three spectral bands computed from the integration of PARABOLA directional measurements are given in Table 2 for the spruce-hemlock forest at two solar zenith angles. The spectral hemispheric reflectances are lower by approximately 10% - 15% for the larger solar zenith angle.

**Table 2.** Hemispheric spectral reflectance for spruce-hemlock forest canopy at two solar zeniths.

SZA	REFLECTANCE (%)		
	CH. 1	CH. 2	CH. 3
70°	2.9	26.5	12.0
54°	2.6	23.4	10.3

Since the total shortwave albedo is generally the desired parameter, a rudimentary computation was made for the spruce-hemlock forest using the PARABOLA wavebands and then compared with the measurements taken concurrently with the Eppley pyranometers. The red, NIR and SWIR hemispheric reflectances were weighted by factors of 0.45, 0.40 and 0.15 based on the percentages of the total insolation in three spectral regions: 0.4 - 0.7  $\mu\text{m}$ , 0.7 - 1.4  $\mu\text{m}$ , and 1.4 - 4.0  $\mu\text{m}$ . The three narrow band PARABOLA channels were assumed to represent these three broad spectral regions, based on analysis of alfalfa reflectance spectra. The sum of the products of these weighting factors and the corresponding hemispheric reflectances yielded the estimate of the total shortwave albedo. The PARABOLA estimates of the albedos were 12% and 14% for the 54° and 70° solar zenith angles which were quite comparable to the pyranometer values of 11% and 15%, respectively. Thus, the differences were nominally +9% and -7%, respectively. The use of high spectral resolution measurements of the forest canopy should result in a more accurate accounting for the weighting of the 3 discrete PARABOLA wavebands and enable the PARABOLA-derived albedos to more closely match those of the pyranometers.

These are only preliminary results and a complete analysis of the above- and below-canopy directional radiances is currently in progress. These data should yield important information on the manner in which the spruce-hemlock forest absorbs, transmits and reflects optical-reflective energy.

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