Validation of Bidirectional and Hemispherical Reflectances from a Geometric-Optical Model Using ASAS Imagery and Pyranometer Measurements of a Spruce Forest

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Aircraft imagery and ground measurements acquired for a spruce forest stand in Howland, Maine as part of the 1990 Forest Ecosystem Dynamics Multisensor Aircraft Campaign (FEDMAC) are used to validate the Li–Strahler geometric-optical forest canopy reflectance model and to demonstrate that both spectral bidirectional reflectance factors and hemispherical reflectance can be estimated with some success. With the geometric-optical model, a vegetated surface is treated as an assemblage of partially illuminated tree crowns of ellipsoidal shape, and through geometric-optics and Boolean set theory, the proportion of sunlit and shadowed canopy and background is modeled as a function of view angle. The model is driven by ground measurements of spectral reflectance and tree crown shape, size, and spacing. Atmospherically corrected multiangular radiance measurements of the FEDMAC spruce site from the Advanced Solid State Array Spectroradiometer (ASAS) were found to fit the shape of the modeled reflectance function quite well along the principal and cross-principal planes. Furthermore, integration of the modeled reflectance functions yielded spectral surface albedos (hemispherical reflectance), which, when extended to the full solar spectrum, were found to agree closely with pyranometer measurements obtained at the spruce site.

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INTRODUCTION

The anisotropy exhibited by forest canopies is determined by the canopy structure, shape and density, shadowing patterns, multiple scattering interactions within the canopy, leaf angle distributions, and the specularity of the foliage. Although dense, uniform canopies have primarily been modeled with homogeneous plane-parallel or three-dimensional radiative transfer models (Verhoef, 1984; Gerstl and Simmer, 1986; Kimes et al., 1987; Kimes, 1984; 1991; Nilson and Kuusk, 1989; Myneni et al., 1989; Verstraete et al., 1990), simpler geometric-optical models have been used with some success to model nonuniform and / or sparse forests (Li and Strahler, 1985; 1986; 1992a,b; Strahler and Jupp, 1990a,b; Abuelgasim and Strahler, 1993). These models are designed to accommodate the complex shadowing patterns caused by sparse canopies or canopies with significant height variations. By modeling the interplay between sunlit and shadowed components of the canopy, realistic bidirectional reflectance distribution functions of the vegetated surface can be determined.

The Li–Strahler geometric-optical model represents these shadowing effects by modeling a scene or pixel as an assemblage of ellipsoidal tree crowns. Geometric-optics and Boolean set theory are used to determine the areal proportions of shadowed and sunlit canopy and shadowed and sunlit background associated with a view angle and solar zenith angle. Independently determined spectrally characteristic signatures for each of these shadowed or sunlit components are weighted by these areal proportions and are used to determine the spectral bidirectional reflectance factor of the canopy. Although the signatures are applied uniformly to the areal proportions and the model does not include an

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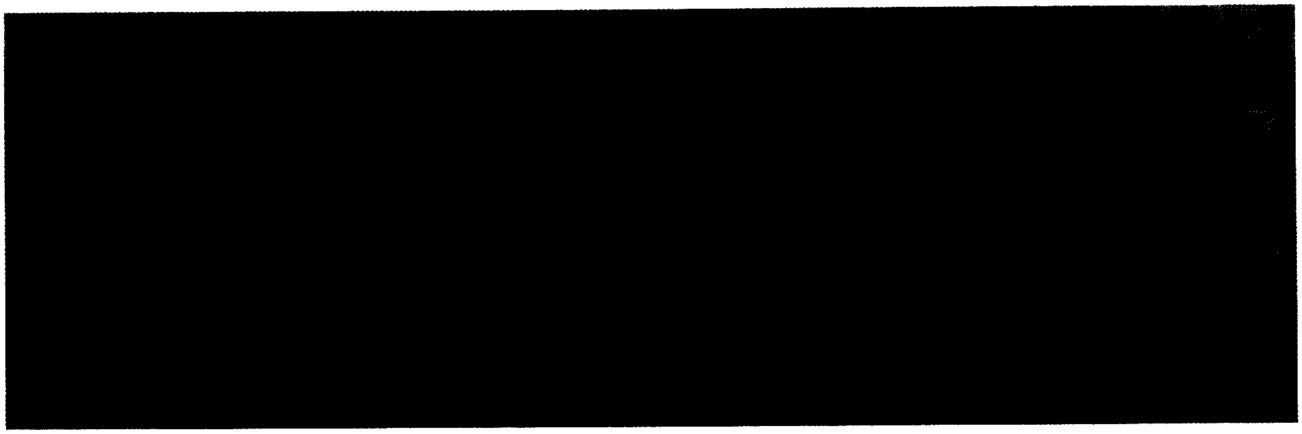


Figure 1. ASAS imagery along the principal plane at view angles −45°, −30°, −15°, 0°, +15°, +30°, +45° (9:12 EDT).

explicit treatment of diffuse irradiance, canopy multiple scattering or leaf specularity, such effects are implicitly introduced through component signatures that are either carefully modeled or measured in the field at the time and under the same initial conditions as the model run. If the atmosphere is relatively clear, measured sunlit crown component signatures can be corrected for solar zenith angle and used for other nearby model run times. At high solar or view zenith angles, the geometric-optical model incorporates the scene brightening effects of mutual shadowing. Mutual shadowing occurs at angles where only the tops of trees are illuminated and any shadows are lost in the lower part of the canopy and obscured by the other tree crowns. By performing a hemispherical integration of the bidirectional reflectance distribution function, the model can also provide an instantaneous hemispherical reflectance (or spectral surface albedo).

Directional radiances from the airborne Advanced Solid State Array Spectroradiometer (ASAS) serve as ideal validation data (Pinty and Verstraete, 1992) for the geometric-optical model. ASAS radiances are typically obtained in at least the principal plane and the cross-principal plane of the sun (Irons et al., 1991). Once atmospherically corrected, these aircraft measurements can be compared (both in relative position and in magnitude) with modeled bidirectional reflectance factors (BRFs) as long as the model has been carefully initialized with accurate tree shape measurements and component signatures measured in the field at the time of the ASAS overpass.

In this study, forest descriptive parameters, obtained during the 1990 Forest Ecosystem Dynamics Multisensor Aircraft Campaign (FEDMAC) in Howland, Maine, were used to initialize the Li–Strahler geometric-optical model. ASAS directional imagery, obtained during the same field project, were then used to validate the model bidirectional reflectances. In addition to the ASAS images, pyranometer data from an instrumented tower on the site were used to validate the model albedos. By combining the spectral hemispherical reflectances produced by the model (Brest and Goward, 1987; Brest, 1987), surface albedos were computed that could be directly compared to the pyranometer measurements obtained on the site at the times of the ASAS overpasses.

PROCEDURE

Validation Data

At 9:12, 11:10, and 13:52 EDT, 8 September 1990, the ASAS instrument was flown on a NASA C-130 aircraft at 4600 m altitude in the principal plane of the sun. The FEDMAC spruce site is in the vicinity of an instrumented meteorological tower maintained by the University of Maine at Orono (45°21.21′N, 68°44.49′W). ASAS images of the site were obtained at seven look angles from +45° to −45° (Fig. 1). The red Band 15 (band center 644.6 nm) and near-infrared Band 24 (band center 773.5 nm) were selected for this study. A fairly uniform region of vegetation was selected around the tower, and the mean brightness and variance for this area were obtained from each directional ASAS image. These brightnesses were then transformed to radiances with the NASA-provided radiometric resolution factors. Finally the values were atmospherically corrected using the Liang–Strahler (1994) radiative transfer model (which uses a two-stream approximation modified to incorporate a nonlambertian surface boundary). Aerosol optical depths over the site were measured in the visible and near-infrared at the time of the overpasses with tracking sunphotometers. Unfortunately, due to the low responsivity at that time of the ASAS red Band 15 sensor over thickly vegetated surfaces, the computed path radiances were greater than the ASAS radiances. Therefore, only the NIR ASAS Band 24 radiances could be used for

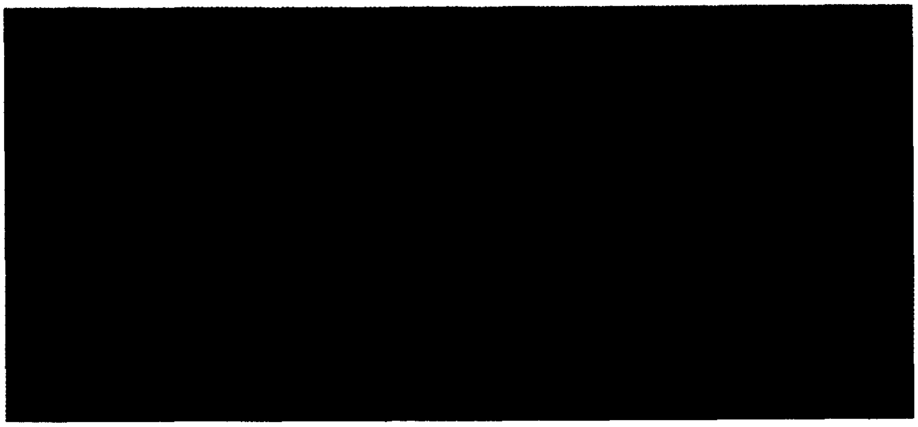


Figure 2. ASAS imagery along the cross-principal plane at view angles −45°, −30°, −15°, 0°, +15°, +30° (9:40 EDT).

the validation. Cross-principal plane ASAS images were obtained at 9:40, 11:28, and 13:12 EDT and subjected to the same processing (Fig. 2).

Upward and downward pointing Eppley PSP pyranometers were positioned at a height of 25.8 m on a boom extending 2.4 m west of the meteorological tower located on the spruce site. These data were ratioed to produce instantaneous full-spectrum surface albedos (0.3–3 μm) for the ASAS overpass times.

Model Initialization

In 1989 investigators from Boston University surveyed the spruce stand near the tower, and used variable radius plot sampling (Dilworth, 1977) to obtain tree height, diameter-at-breast height, crown width, and height-to-crown distance. These data were supplemented with tree heights collected by University of Virginia researchers. Based on the sample of 40 trees, the parameters used as input to the geometric-optical model were basal-area-weighted means of height-to-center-of-crown (9.9 m $\pm$ 2 standard deviations of 4.8 m), crown radius (2.2 m), crown vertical radius (3.6 m), and density (1161 trees / ha with a crown closure of 84%). This canopy, although dense, displays quite a bit of height variation (and therefore shadowing).

On 8 September 1990, handheld radiometer (Spectron Engineering SE590) measurements were collected for use as the sunlit and shadowed component signatures required by the model. Bands 97 (643.7 nm) and 141 (774.1 nm) were used to match the band centers of the ASAS channels. Spectralon panel measurements were also taken so that reflectance factors could be computed. The canopy component signatures consist of nadir measurements of crowns, which, since it is difficult to make measurements inside forest stands, were often at the edges of openings, where full foliage branches were within reach. The background component signatures were composites of nadir reflectances from litter, ferns, shrubs, moss, and grasses. A three-component version of the model was used (sunlit canopy, sunlit background, and shadows), so that the shadowed component represented the average of the shadowed background and shadowed canopy signatures. Although nadir radiometer measurements were used as characteristic component signatures in this study, ideally a series of directional radiometer measurements would have been made and then hemispherically integrated to produce a characteristic component signature. The radiometer measurements were collected at the site once in the morning and once in the afternoon. Given the fairly large solar zenith angles and the high density and crown coverage (84%), the crown components were determined to be the primary contributors to the scene reflectance rather than the background components. Therefore, the background and shadowed measurements collected closest to the ASAS overpass times were used to initialize the model, and no further attempt was made to correct for the exact solar zenith angle. On the other hand, the sunlit canopy component signatures were corrected geometrically to account somewhat for small changes in the solar zenith angle.

The decision to incorporate a solar zenith angle dependency in the sunlit canopy signatures used by the geometric-optical model was driven by earlier studies which emphasized the importance of timely component signatures (whether they be measured or modeled) to capture all of the direct beam intensity, foliage specularity, and diffuse contributions at a specific solar zenith angle (Barker Schaaf and Strahler, 1993). The geometric-optical model computes the proportion of a pixel that is sunlit canopy at any given view angle under certain illumination conditions and multiplies that proportion by the characteristic reflectance or signature of sunlit canopy under those same illumination conditions. A reconsideration of the geometric-optics (Li, personal communication) suggests that, although the direct beam irradiation at larger solar zenith angles will be focused on a smaller area of an ellipsoidal crown (primarily the tips of the trees) due to mutual shadowing, an increased intensity of illumination will be reflected from that smaller area. If component signatures are based on

Table 1. Component Signatures

Components	*9:12 EDT 58.79°SZN*		*9:40 EDT 54.54°SZN*		*11:10 EDT 43.6°SZN*		*11.28 EDT 42.14°SZN*		*13:35 EDT 42.01°SZN*		*13:52 EDT 43.35°SZN*	
	Red	*NIR*	*Red*	*NIR*	*Red*	*NIR*	*Red*	*NIR*	*Red*	*NIR*	*Red*	*NIR*
Sunlit crown (C)	0.0396	0.4506	0.0366	0.4169	0.0307	0.3487	0.0299	0.3411	0.0335	0.3439	0.0342	0.3509
Sunlit background	0.0503	0.3248	0.0503	0.3248	0.0503	0.3248	0.0503	0.3248	0.0754	0.2463	0.0754	0.2463
Shadows	0.0017	0.0375	0.0017	0.0375	0.0017	0.0375	0.0017	0.0375	0.0023	0.0434	0.0023	0.0434

ground measurements obtained under exactly the same conditions as represented in the model, then they can be used as is. However, if either solar zenith angle independent component signatures or measured values obtained under different illumination conditions are being used for a model run, they will need to be corrected for the desired solar illumination and scaled to reflect this increased illumination intensity. Only then should they be applied to the areal proportion of sunlit canopy in the scene. In explicit terms, a measured or scaled value C represents the angle independent reflectance R_c of a sunlit lambertian crown surface scaled by the proportion of crown area projected onto the background $Proj(A_c)$ to the actual surface area of the crown A_c, which is sunlit from the point of view of the sun or

$$C = R_c \frac{Proj[A_c]}{A_c}.$$

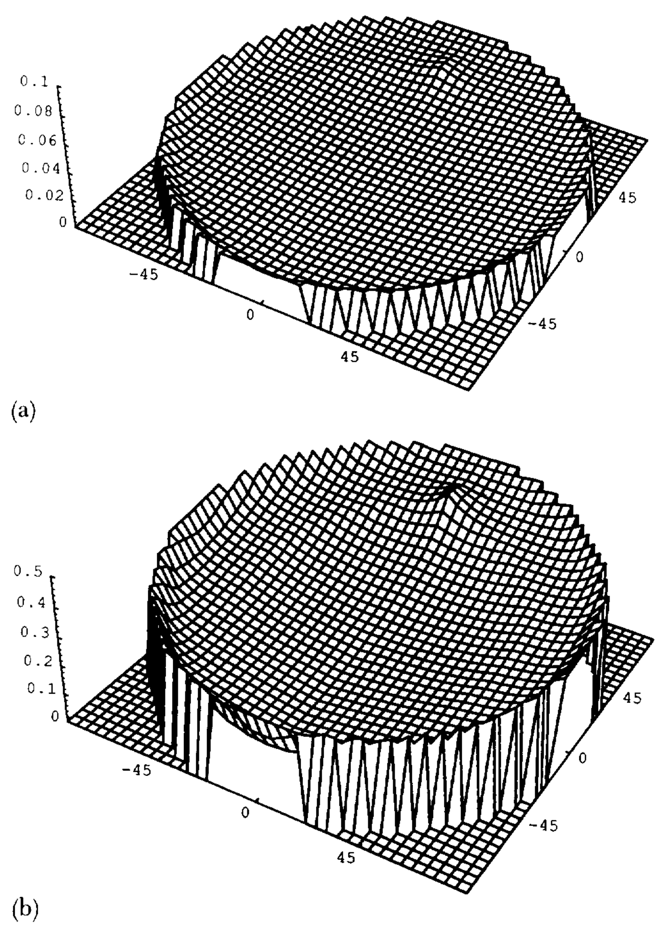
When a measured value has been obtained at a solar zenith angle somewhat different from the desired model solar angle, it can be used to retrieve an angle independent lambertian value (R_c), which can then be rescaled to the desired illumination angle. The values finally used for component signatures in the model simulations of the spruce canopy at ASAS overpass times are given in Table 1.

RESULTS

Bidirectional Reflectance Factor Comparisons

Initialized with the forest characteristics, the measured and corrected component signatures, and the appropriate solar zenith angle, the geometric-optical model was used to simulate the spruce site at the time of each ASAS overpass. The red and nearinfrared bidirectional reflectance distribution functions (BRDFs) modeled for the 9:12 EDT overflight are displayed in Figure 3. The three-dimensional BRDFs are displayed in a rectangular coordinate system where each view angle in the hemisphere is taken as a pair of polar coordinates and transformed onto the x–y plane as a vector of unit length. The corresponding reflectances are then plotted along the z-axis. The hotspot occurs where the viewing angle and solar zenith angle coincide, thus concealing shadows. The bowl occurs when the view angle moves opposite the solar zenith angle and more and more shadowing is revealed. Previous work (Li and Strahler, 1992a; Barker Schaaf and Strahler, 1993) has shown that the width of the hotspot is governed by the elliptical shape of the crowns. The shape of the bowl is governed by the density of the forest and the amount of mutual shadowing that is taking place. By extracting results along the principal plane, the modeled near-infrared BRFs can be compared to the ASAS BRFs (Fig. 4). The

Figure 3. Geometric-optical model bidirectional reflectance distribution functions [a) Red; b) NIR] at the time of the ASAS principal plane overpass (9:12 EDT).



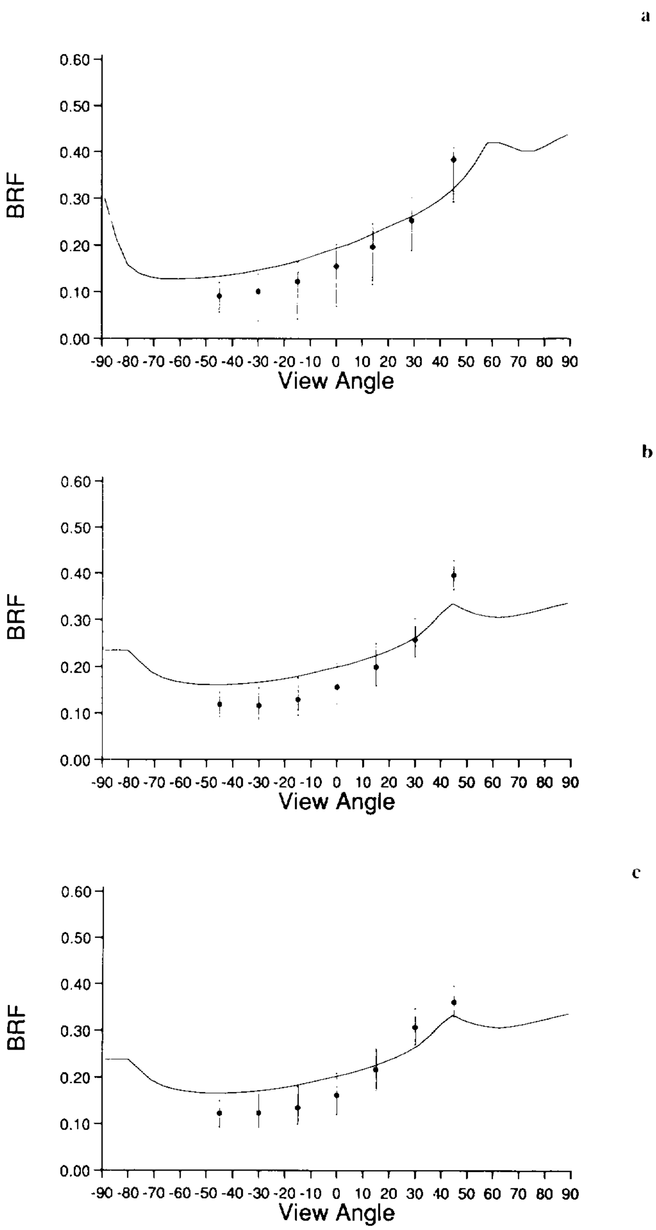


Figure 4. Mean NIR ASAS reflectances (•) compared with the modeled BRFs (—) along the principal plane: a) 9:12 EDT; b) 11:10 EDT; c) 13:52 EDT.

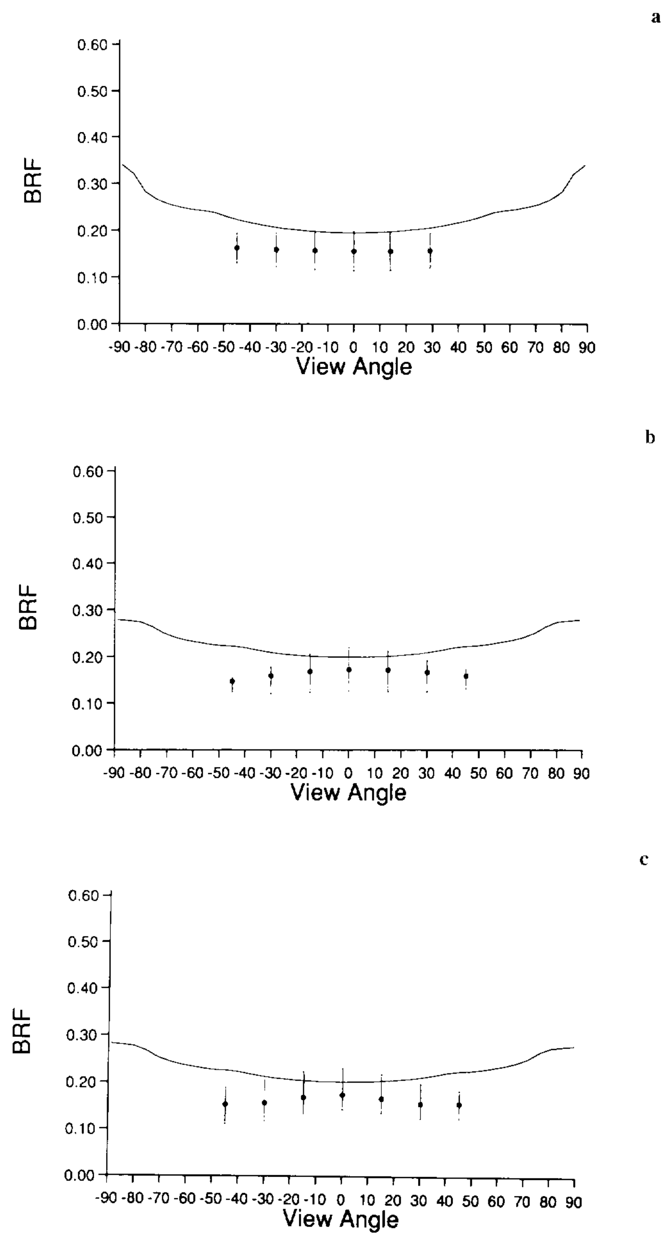


Figure 5. Mean NIR ASAS reflectances (•) compared with the modeled BRFs (—) along the cross-principal plane: a) 9:40 EDT; b) 11:28 EDT; c) 13:12 EDT.

model predicts somewhat brighter values in the forward scattering directions than were detected by the ASAS imagery. The model also slightly underestimates the hotspot value [which perhaps points to a need to more accurately model the coherent backscatter opposition effect (Hapke et al., 1993)]. However, the general shape and magnitude of the model results are very similar to those of the ASAS measurements. This close agreement is quite encouraging as the geometric-optical model has generally been used to simulate sparse canopies rather than high crown coverages such as exhibited in this spruce scene. However, this particular canopy does display a great variation in crown heights and therefore generates a great deal of shadowing that can be successfully simulated by the geometric-optical model.

The modeling was repeated with solar zenith angles that correspond to the times of the cross-principal plane flights. In the cross-principal plane direction (Fig. 5), the model overemphasizes the impact of the mutual shadowing in the + to $-45°$ region by creating more of a valley shape than the flattened shape revealed by the ASAS imagery. ASAS images from even greater zenith angles would be needed to clarify whether scene eventually brightened due to mutual shadowing (as the model would suggest) or continued to darken. The overall magnitude of the directional reflectances in the cross-principal plane is somewhat overestimated by the model.

Hemispherical Reflectance Comparisons

A hemispherical integration of each geometric-optical model BRDF results in a spectral hemispherical reflectance or surface albedo. This spectral albedo, although an integrated value, captures the shadowing patterns of the scene caused by the interaction of realistic tree shapes and densities and the illumination conditions (Barker Schaaf and Strahler, 1993).

The pyranometer measurements obtained at the tower are full spectrum values. Therefore, the red and near-infrared model albedos need to be spectrally combined before a comparison is possible. Brest and Goward (1987) suggest that a red spectral albedo is representative of a 0.526 proportion of solar radiation incident at the surface, while a near-infrared albedo is representative of a 0.362 proportion and a mid-infrared is representative of a 0.112 proportion. Therefore, red, near-infrared, and mid-infrared spectral model albedos can be weighted by these proportions and added to estimate the broadband value. Unfortunately, since no mid-infrared handheld radiometer measurements were collected to use as component signatures, no mid-infrared model runs could be made. However, Brest and Goward (1987) use 0.5 of the near-infrared value as an appropriate approximation of the mid-infrared value of vegetation. Based on these assumptions, rudimentary full spectrum surface albedos were computed from the model results and compared with the pyranometer measurements taken at the site (Fig. 4). Despite the simplicity of the spectral combination scheme, the resultant model values are quite close in magnitude to the measured values.

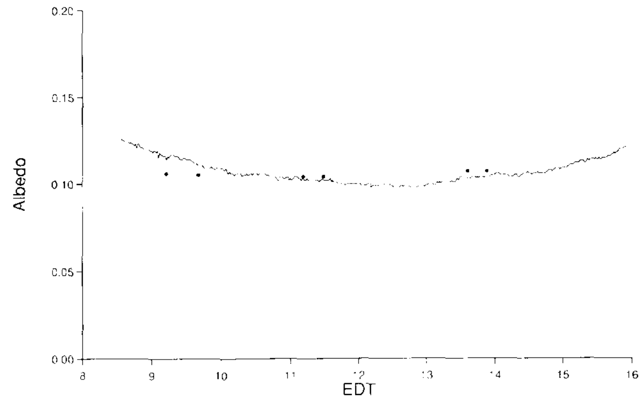


Figure 6. Measured (—) and modeled (•) surface albedos at ASAS overpass times.

CONCLUSIONS

The Li–Strahler geometric-optical model was validated with data collected from a spruce forest in Maine during the 1990 FEDMAC data collection effort. This field site tested the applicability of the model to canopies that are not necessarily sparse but do reflect a great deal of height variation (and therefore shadowing). Although modeled near-infrared BRFs agreed quite well with ASAS reflectances along the principal plane in both shape and magnitude, a comparison of the cross-principal plane values reveal that the model tends to overestimate the reflectance at mid-range viewing angles by overemphasizing the impact of mutual shadowing. Model spectral hemispherical reflectances were combined to produce full spectrum surface albedos that compared quite successfully with pyranometer measurements taken at the site at the same time as the ASAS overpasses. Given the simplicity of the model, the difficulties in obtaining realistic component signatures, and the high density of the coverage, the close agreement found between the measurements and model results is quite encouraging.

Such success demonstrates the adaptability of the geometric-optical model but also highlights its dependence on accurate sunlit and shadowed component signatures. Work is underway to produce a hybrid model that treats canopy scattering as a function of path length and gap probability (Li and Strahler, 1988; Strahler and Jupp, 1990a,b) and combines the scattering with the geometric-optical effects of the trees within the canopy. Such efforts will result in a model that obviates component signatures and does not suffer from a sensitivity to site and time specific spectral measurements.

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