DIURNAL REFLECTANCE CHANGES IN VEGETATION OBSERVED WITH AVIRIS

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1. INTRODUCTION

Among the most important short-term dynamic biological processes are diurnal changes in canopy water relations. Plant regulation of water transport through stomatal openings affects other gaseous transport processes, often dramatically decreasing photosynthetic fixation of carbon dioxide during periods of water stress. Water stress reduces stomatal conductance of water vapor through the leaf surface and alters the diurnal timing of stomatal opening. Under non-water stressed conditions, stomates typically open soon after dawn and transpire water vapor throughout the daylight period. During stress periods, stomates may close for part of the day, generally near mid-day. Under prolonged stress conditions, stomatal closure shifts to earlier times during the day; stomates may close by mid-morning and remain closed until the following morning — or remain closed entirely.

Under these conditions the relationship between canopy greenness (e.g., measured with a vegetation index or by spectral mixture analysis) and photosynthetic fixation of carbon is lost and the remotely sensed vegetation metric is a poor predictor of gas exchange. Prediction of stomatal regulation and exchange of water and trace gases is critical for ecosystem and climate models to correctly estimate budgets of these gases and understand or predict other processes like gross and net ecosystem primary production (Kittel et al., 1995).

Plant gas exchange has been extensively studied by physiologists at the leaf and whole plant level and by biometeorologists at somewhat larger scales (Gates, 1980), (Nobel, 1983). While these energy driven processes follow a predictable if somewhat asymmetric diurnal cycle dependent on soil water availability and the constraints imposed by the solar energy budget, they are nonetheless difficult to measure at the tree and stand levels using conventional methods.

Ecologists have long been interested in the potential of remote sensing for monitoring physiological changes using multi-temporal images. Much of this research has focused on day-to-day changes in water use, especially for agricultural applications (Moran et al., 1997). Ustin et al. (1998) showed seasonal changes in canopy water content in chaparral shrub could be estimated using optical methods. Vanderbilt et al. (1991) followed asymmetric diurnal changes in the reflectance of a walnut orchard, but could not attribute specific reflectance changes to specific changes in canopy architecture or physiology.

Forests and shrub lands in California experience prolonged periods of drought, sometimes extending six months without precipitation. The conifer and evergreen chaparral communities common to the foothill region around the central valley of California retain their foliage throughout the summer and have low transpiration rates despite high net radiation and temperature conditions. In contrast, grasslands and drought resistant deciduous species in the same habitat are seasonally dormant in summer. Because of differences in the mechanisms of drought tolerance, rooting depth and physiology between different plant communities in the region, it is likely that they display differences in diurnal water relations. The presence of diverse plant communities provides an opportunity to investigate possible diurnal landscape patterns in water relations that could be observed by an airborne hyperspectral scanner. This investigation of AVIRIS data collected over forest and shrub land represents the continuation of a prior investigation (Ustin et al., 1992) involving spectral mixture analysis of diurnal effects in the same AVIRIS data set.

2. METHODS

Eleven AVIRIS hyper spectral data scenes, Table 1, were collected over a common test site during a 3 hr 20 mn interval bracketing solar noon on 22 September 1989 from the NASA-Ames ER-2 aircraft (Flight 89-167) flying at an average altitude of 19.7 km (65,000 feet) above ground level (AGL).

Table 1. **AVIRIS data collection times (Pacific daylight time) and solar directions (degrees).**

Scene number	1058	1061	1064	1067	1070	1073	1076	1079	1082	1085	1090
Collection time	11:50	12:10	12:30	12:51	13:09	13:30	13:49	14:10	14:30	14:50	15:10
Solar elevation	45.53	47.20	48.18	48.48	48.48	48.19	47.22	45.52	44.05	41.52	39.29
Solar azimuth	151.2	161.4	168.6	176.5	183.5	191.2	198.3	205.7	212.2	218.5	223.9

2.1. Site description

The test site, located at (41°21'00"N, 121°57'30"W), approximately 10 km southeast of volcanic Mt. Shasta in the Cascade Range of north-central California, is volcanic in origin with a cinder cone, Black Fox Mountain, bordering its eastern edge. The site averages 1,200 m above sea level and slopes 1.5% to the southeast, displaying minimal topographic relief. The sandy, highly reflective soils appear either light gray or light red, contain little clay and little organic matter and appear to have little water holding capacity. The area is dominated by extensive stands of mature Ponderosa pine (Pinus Ponderosa) and extensive mixed stands of 'shrub' containing primarily manzanita (Arctostaphylos manzanita) and ceanothus (Ceanothus thyrsiflorus) and smaller amounts of Christmas berry (Heteromeles arbutifolia). Other species observed at locations northeast of and immediately outside of the test site — and which may also grow in small stands of minor importance within the test site — include white fir (Abies concolor), California black oak (Quercus kelloggii) and tanbark oak (Lithocarpus densiflora).

We observed that within the test site, Ponderosa pine appears to grow preferentially on light red soils while the light gray soils tend to support (a) shrubs or (b) very sparsely distributed grasses making these areas appear essentially as 'bare soil.' Clear cut areas display light red soils. The shrub and bare soil areas display no evidence of having previously been clear cut — all of which suggests a link between cover type and soil parent material. During AVIRIS data collection, all soils appeared dry; meteorological data suggested that no rain had fallen during the three days prior to AVIRIS data collection.

2.2. AVIRIS data analysis.

All scenes were co-registered to the first scene (1058) using a second order polynomial and more than 20 randomly selected control points. The root mean square (RMS) image rectification error of each scene was less than 1.0 pixel in both the X and Y dimensions. The data were not corrected for atmospheric effects. The solar elevation and solar azimuth corresponding to each scene were determined from the data collection time and geographic location of the scene center point. The dimensions (470 x 399 pixels) of the almost flat, almost horizontal test site were selected in order to exclude from the analysis process adjacent sloping terrain and its corresponding radiance data values which vary asymmetrically as a function of solar azimuth direction relative to solar noon (Vanderbilt et al., 1991).

Sixteen spectral classes were derived from an unsupervised cluster classification analysis involving five AVIRIS wavelength bands — band numbers 13 (512.9 nm), 18 (562.1 nm), 30 (680.3 nm), 50 (838.8 nm), and 139 (1653 nm) — of the first scene (1058). These wavelength bands, for these data collected in 1989, represent the approximate center wavelength positions of the Landsat Thematic Mapper bands 1, 2, 3, 4 and 5. A sixth band, also included in the cluster analysis, provided information of the spatial texture of the scene as represented by a 3x3 variance filter of AVIRIS band 30. The result obtained from the cluster analysis of each pixel of the first scene (1058) was assumed to apply to the corresponding pixel in each of the 10 other overlaid and registered AVIRIS images.

Analysis of color infrared photography, collected with the AVIRIS data, helped establish the correspondence between the 16 spectral classes and eight information classes: bare soil, shrub, and six Ponderosa pine classes — each class distinguished by its apparent crown closure: 100-90%, 89-80%, 79-70%, 69-50%, 49-30% and low density pine. The number of pixels within each of the eight information classes is shown in Table 2.

The mean spectrum of each information class was determined as the average within each wavelength band of all AVIRIS spectra in that class. Thus, for example, the mean spectrum of bare soil was obtained by averaging

27329 individual bare soil spectra, Table 2. The mean spectra do not include effects due to per pixel slope and aspect; these effects were assumed to be inconsequential for the comparatively flat test site.

Table 2. Number of pixels in each information class.

Information class	Ponderosa pine crown closure						shrub	bare soil
	percent							
	100-90	89-80	79-70	60-50	49-30	<30		
Number of pixels	10198	8215	39623	19723	11668	60982	9792	27329

2.3. Ancillary data.

Sun photometer data were collected continuously in eight wavelength bands between 400 nm and 1100 nm on September 22, 1989 between approximately 6 hr 30 mn and 17 hr Pacific daylight time using an instrument constructed at the University of Arizona. The data were analyzed by Dr. Carol Bruegge of JPL who estimated the atmospheric optical depth and aerosol optical depth for each wavelength band as a function of time during the day.

The water potential of needles on branches harvested from several Ponderosa pine trees was estimated with the aid of pressure bomb measurements collected continuously between approximately 6 hr and 17 hr on September 22, 1989. Each of the sampled trees was mature, located apart from a nearby extended stand of Ponderosa pine and was either an isolated tree or a member of a small group of trees. Both sunlit and shaded branches were measured between 6 hr and approximately 10 hr; after 10 hr only shaded needles were measured.

3. RESULTS

Fig. 1 shows both the first scene (1058) of AVIRIS data as well as the results from its classification represented with the aid of a gray scale for which the darkest gray level corresponds to the Ponderosa pine 100-90% crown closure class and the lightest gray level, the bare soil class. The bottom-to-top direction in each image represents a northeast compass direction. The homogeneous area approximately 80 columns x 150 rows represented by an intermediate gray level and located in the extreme upper right corner of the image is a Ponderosa pine plantation. Recent clear cut areas appear as sharply defined bright areas usually amid dark areas such as near the bottom right of Fig. 1b.

A comparison, Fig. 2a-b, of the mean spectra, when normalized by the mean soil spectra (a 'flat field' correction), derived from scenes 1058 and 1079 collected before and after solar noon at similar 45.5° solar elevations shows that the reflectance of shrub decreased at all wavelengths while that of Ponderosa pine 100-90% crown closure increased at all wavelengths. Two mean spectra for bare soil measured at similar solar elevations near noon, Fig. 2c, appear almost coincident, providing an indication that the temporal stability of the AVIRIS sensor is excellent. Use of the bare soil spectra to normalize the shrub and Ponderosa pine spectra was assumed to reduce the magnitude of the small variations in the data attributable to noise in the AVIRIS sensor. In addition use of such a flat field correction allows comparisons against a surface, the dry bare soil, that may reasonably be assumed to exhibit spectrally unchanging, Lambertian reflectance properties over the relatively short 3 hr 20 mn time period and limited range of solar elevations, 39° to 48°.

Fig. 3 shows the mean of each information class measured at two wavelengths at each of 11 data collection times. In the red wavelength region, the largest response at each data collection time is due to bare soil; the smallest, 90-81% cc Ponderosa pine. In the near infrared wavelength region, the largest response at each data collection time is due to shrub; the smallest, 100-91% cc Ponderosa pine. With few exceptions the maximum value of each curve occurs near solar noon, approximately 13 hr (1 PM) local time.

Figure 4 shows that during a 3 hr 20 mn time period bracketing solar noon, the normalized light reflected by Ponderosa pine having 90-100% crown closure increased approximately five percent while that of shrub decreased monotonically by approximately 25%. Fig. 4, similar to Fig. 2 but representing multiple data collection times, shows that for 100-91% cc Ponderosa pine at all measured times the response, normalized using the bare soil 'flat field,' is greater than the normalized response at 11 hr 50 mn; that of shrub monotonically decreases with increasing time from 11 hr 50 mn. Thus, starting from collection of the first scene, the normalized spectra of pine increase while those of shrub decrease. Fig. 4c shows that the response of bare soil, the data used to perform the 'flat field' normalization on the shrub and pine spectra, is greatest near solar noon, decreasing approximately in a symmetric fashion with time measured from noon. For each chart in Fig. 4, the response does not change with wavelength like that of a green leaf; each curve is comparatively smooth, revealing, for example, no abrupt changes near the location of the red edge at 700 nm.

A Langley plot analysis of the sun photometer data, Fig. 5a, shows that morning and afternoon data for each wavelength band appear to lie on the same line, suggesting atmospheric properties changed little during the period of AVIRIS data collection. This is supported by the results, Fig. 5b, showing the atmospheric optical depth at each wavelength changed little during the day. Dividing the optical depth into its Rayleigh and aerosol component parts, Fig. 5c, shows that the aerosol optical depth, particularly in the red and near infrared wavelength region, Fig. 5d, was extremely low, less than 0.02 throughout the period of AVIRIS data collection. These results show that the atmosphere was exceptionally clear — almost transparent throughout the day at these wavelengths. Its light transmitting properties in the red and near infrared wavelength region changed at most by 1% during the period of AVIRIS data collection. The data reveal no evidence of clouds.

The water potential of sunlit and shaded Ponderosa pine needles, Fig. 6, varied with time during the day, showing a large decrease from approximately -10 bars to -17 bars near 9 hr. The water potential of the shaded needles appears to trend upward from approximately -16 bars to -14 bars during the time period when AVIRIS data were collected.

4. DISCUSSION

These results, Fig. 4, reveal that during a 3 hr 20 mn time period bracketing solar noon the light reflecting properties of the two most important cover types within this test site changed substantially and differently: the normalized spectra of Ponderosa pine increased while those of shrub decreased monotonically with time. By normalizing these spectra using AVIRIS bare soil spectra from each of the 11 scenes, we have minimized effects in the results due both to sensor variation with time and to changing solar elevation. Because of this normalization procedure, we believe these results are real and not due to artifacts in the data.

If the canopy were unchanging and azimuthally symmetric, theory (Vanderbilt et al., 1991) shows that morning and afternoon canopy reflecting properties should exhibit mirror symmetry about solar noon. Assuming that canopy architecture is azimuthally symmetric (a reasonable assumption) and given that the atmospheric changes, Fig. 5, were insignificantly, data collected at identical morning and afternoon solar elevations should be identical — provided the canopy did not change. Yet comparing morning and afternoon results, Fig. 2, corresponding to a 45° solar elevation shows that during this 2 hr 20 mn time period the normalized spectra of Ponderosa pine increased by approximately 4% and shrub decreased by approximately 20%.

Thus, the AVIRIS images, when properly normalized and properly analyzed, show that the reflectance properties of the two canopies changed substantially and differently — and therefore that the two canopies changed. The canopy changes appear not to be due to asymmetric changes in the soil reflecting properties, as Figs. 3 and 4c show that these properties changed approximately symmetrically about solar noon. For a given set of illumination and observation directions, two canopy properties — architecture and the spectral scattering and absorbing properties of canopy components (leaves, stems, soil, etc.) — determine the canopy reflectance.

Pigments determine in part the spectral scattering and absorbing properties of canopy components. However, if the canopy reflectance changes were attributable entirely to changes in canopy pigments — pigment configuration changes with increasing water stress, for example, then the results, Fig. 4, should exhibit increasing evidence of pigment absorption as the canopy reflectance changed. The canopy reflectance properties, Fig. 4a-b, show only limited evidence of pigment absorption, decreasing, Fig. 4b, to 0.75 as a set of almost parallel lines. However, the evidence, albeit small, of differential pigment absorption can not be ignored. For example, near the red edge at a wavelength of 687 nm, the curve representing data collected at 3:10 PM trends downward approximately 5% over a wavelength interval of approximately 75 nm, a wavelength dependent change suggesting pigment involvement; yet this 5% change should be interpreted in light of the overall 25% decrease from data collected at 11:50 AM, which suggests that most of the 25% decrease is not wavelength dependent and therefore not pigment dependent. Thus, the results suggest that the changes in the reflecting properties of these two canopies are attributable less to pigment changes and more to changes in architecture at one or more of three scales — canopy, leaf and cell.

These results, Figs. 1-6, do not provide indication of the specific architectural changes which manifest the changes in the canopy reflectance. The measurements of pine needles, Fig. 6, suggest that shaded needle water potential decreased during the day, although not during the AVIRIS data collection time period. Changes in architecture at the canopy, leaf and cell scales attributable to the effects of decreasing leaf water potential are well documented for agricultural plant canopies. Other factors which could potentially affect the canopy asymmetrically about solar noon include the effects of wind. Wind speed which increases during the day presumably could potentially modify the architecture at the canopy and leaf scales, resulting in canopy asymmetric reflectance changes. Wind velocities at the test site during collection of AVIRIS data were not recorded. But memory indicates winds at ground level were light and variable in the high pressure weather system at the test site; we do not believe winds were a factor changing the architecture of the canopy or leaves in a diurnally consistent manner. Thus, in the absence of other identified sources of canopy change, we believe the asymmetric changes in the reflecting properties of the two canopies, changes evident in the results, Figs. 2-4, manifest the species specific response of these two canopies to their diurnally changing water status.

5. CONCLUSIONS

The results of this research show that during more than a two hour time period canopy reflectance properties changed substantially and asymmetrically about solar noon. The results show that the reflectance properties changed because the architecture of the plants changed at one or more scales — cell, leaf and canopy. There is no substantial evidence indicating the canopy changes may be attributed to changes in plant pigment properties. In the absence of other causes, we attribute the asymmetric changes in canopy reflectance properties to changes in canopy water relations.

6. Acknowledgement

We thank Dr. Carol Bruegge of NASA's Jet Propulsion Laboratory for her analysis of the sun photometer data.

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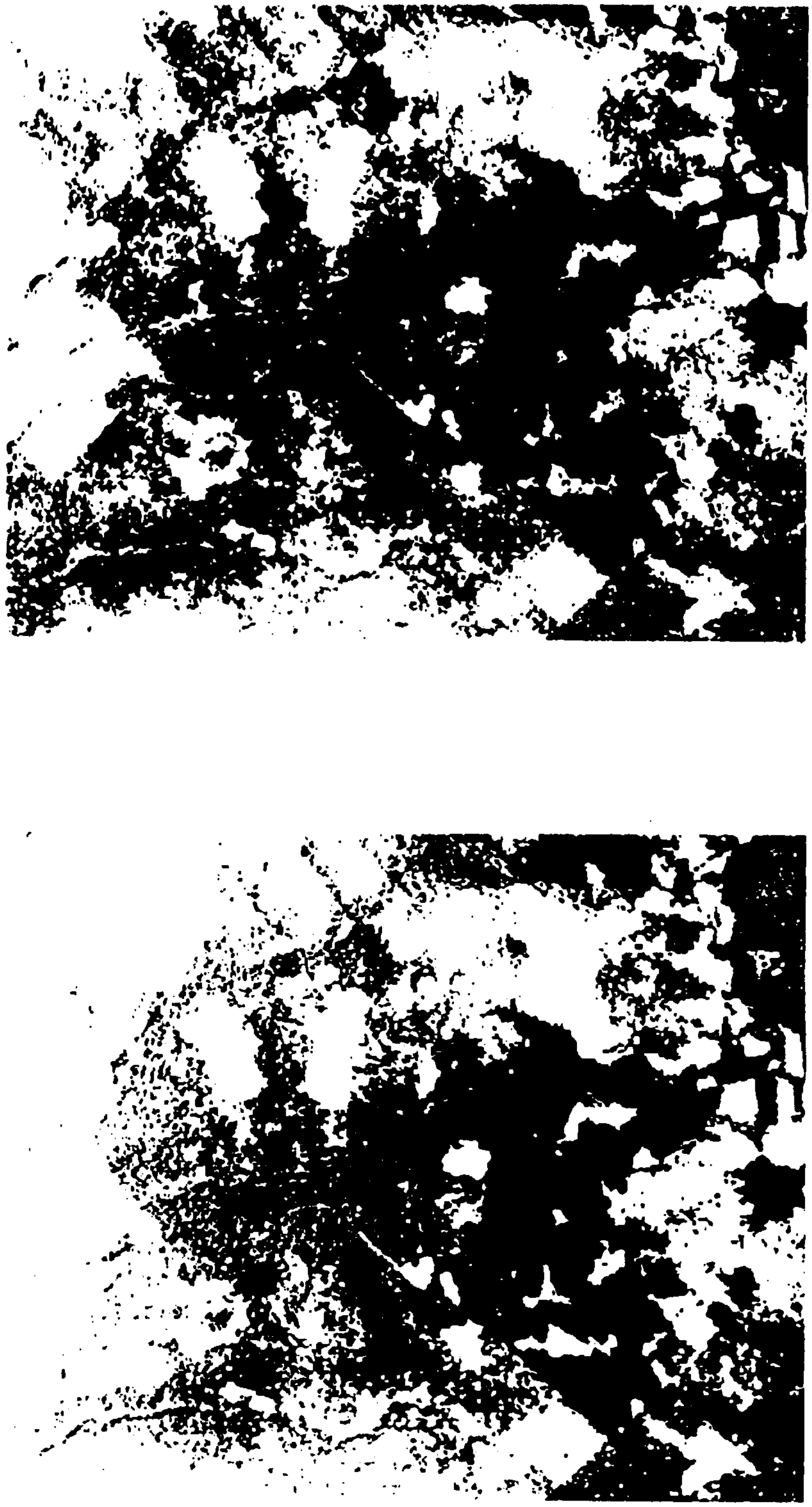

Fig. 1. The AVIRIS data (top) collected September 22, 1989 near Mt. Shasta, California were clustered to display (bottom) eight information classes: bare soil, shrub land and six classes of Ponderosa pine.

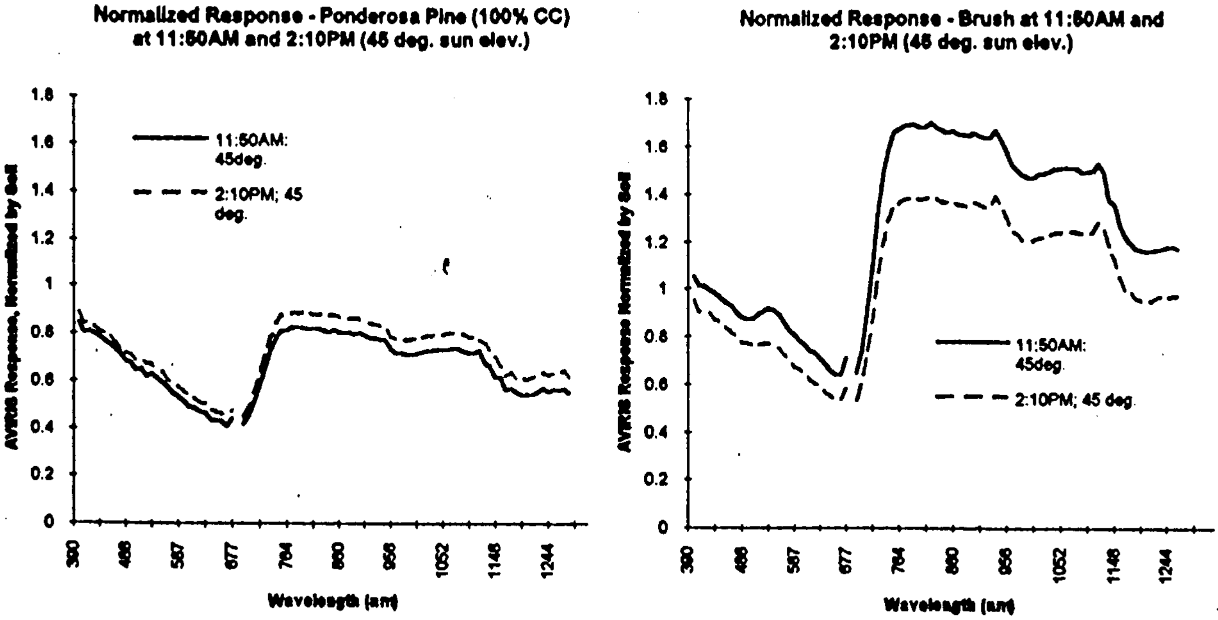

Fig. 2a-b. Mean spectra, normalized by the mean soil spectra collected before and after solar noon at similar 45.5° solar elevations, shows that the reflectance of shrub decreased at all wavelengths while that of Ponderosa pine 100-90% crown closure increased at all wavelengths.

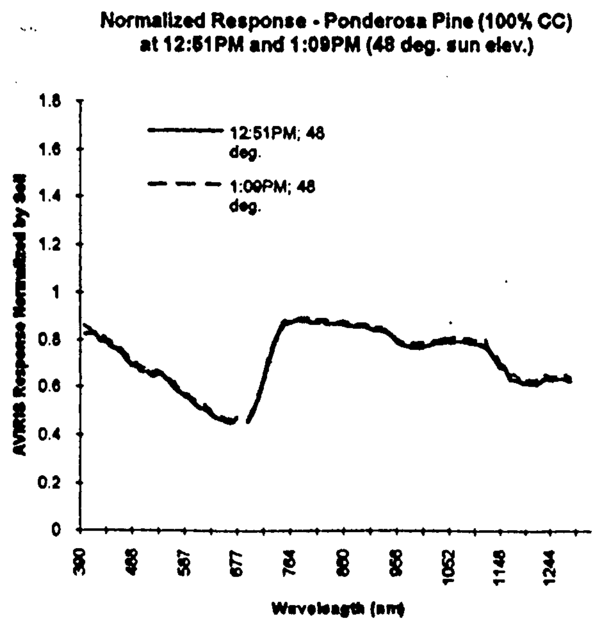

Fig. 2c. Two mean spectra for bare soil measured at similar solar elevations near noon, Fig. 2c, appear almost coincident, providing evidence that the temporal stability of the AVIRIS sensor is excellent.

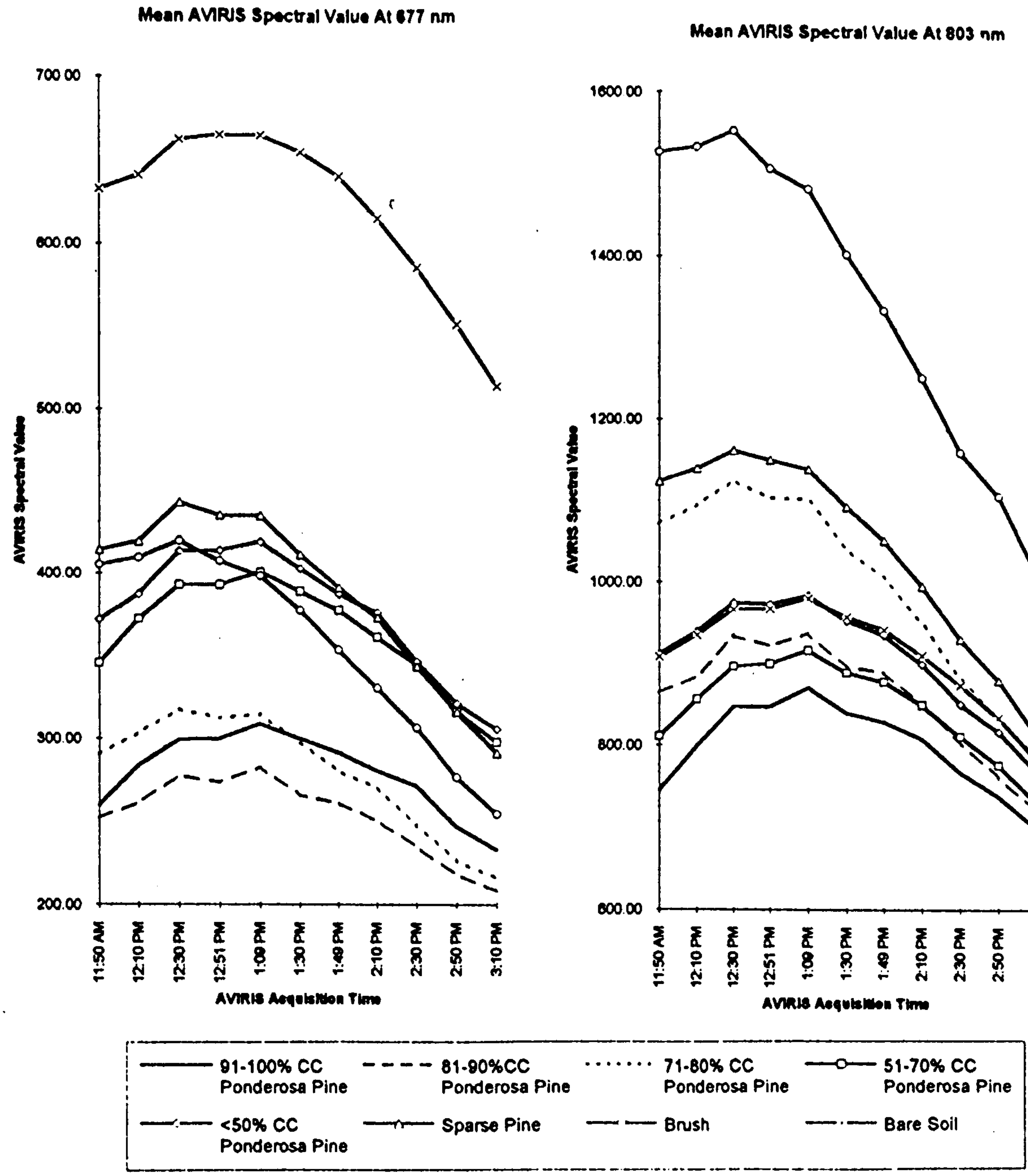

Fig. 3. AVIRIS data for eight information classes were collected within the test site approximately every 20 mn during a 3 hr 20 mn period. Solar noon occurred at approximately 13 hr.

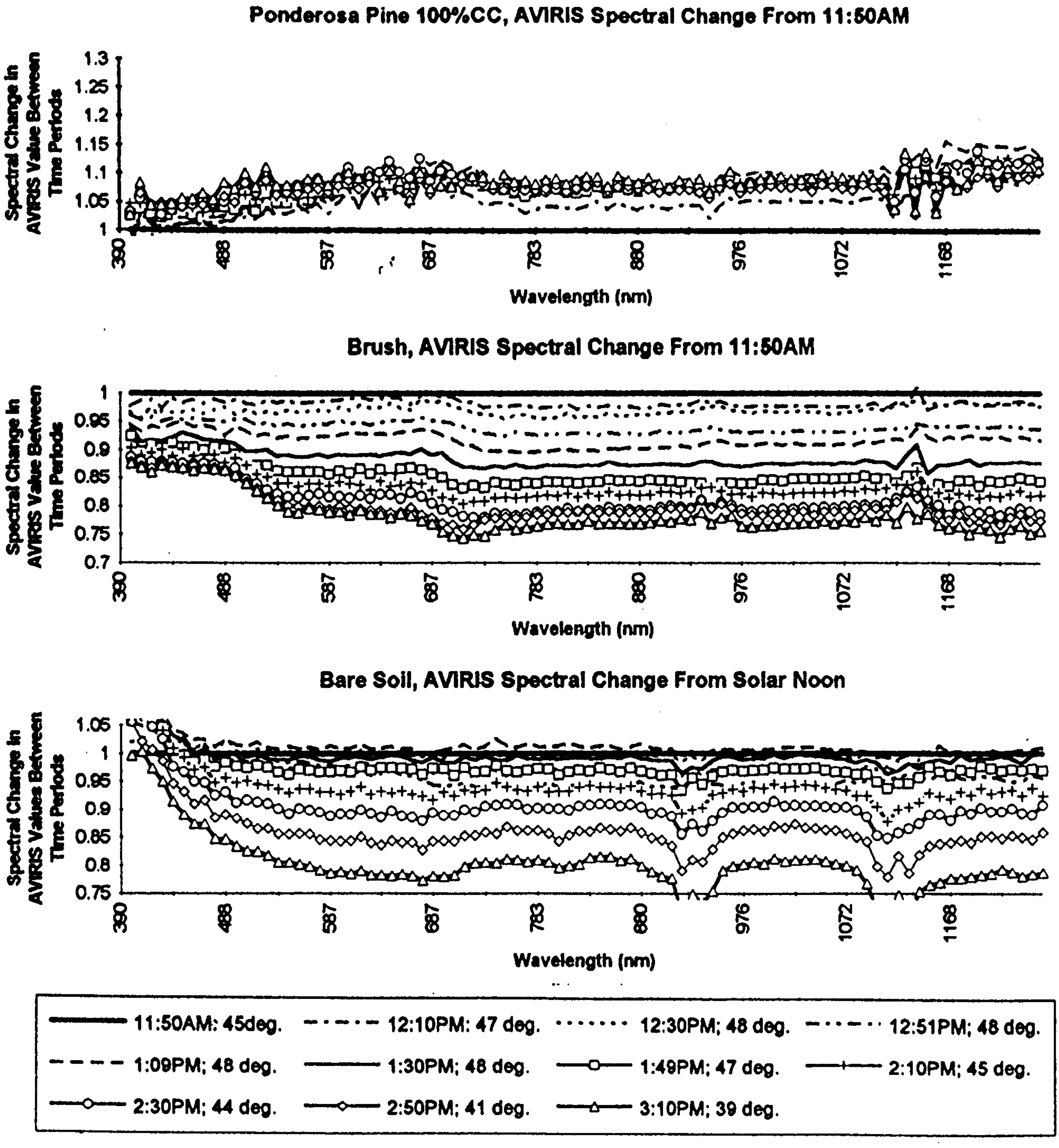

Fig. 4. The mean spectra of two information classes, shrub land and Ponderosa pine 100% crown closure, were normalized by dividing by the mean spectra of bare soil, thereby reducing effects in the results due to sensor variation.

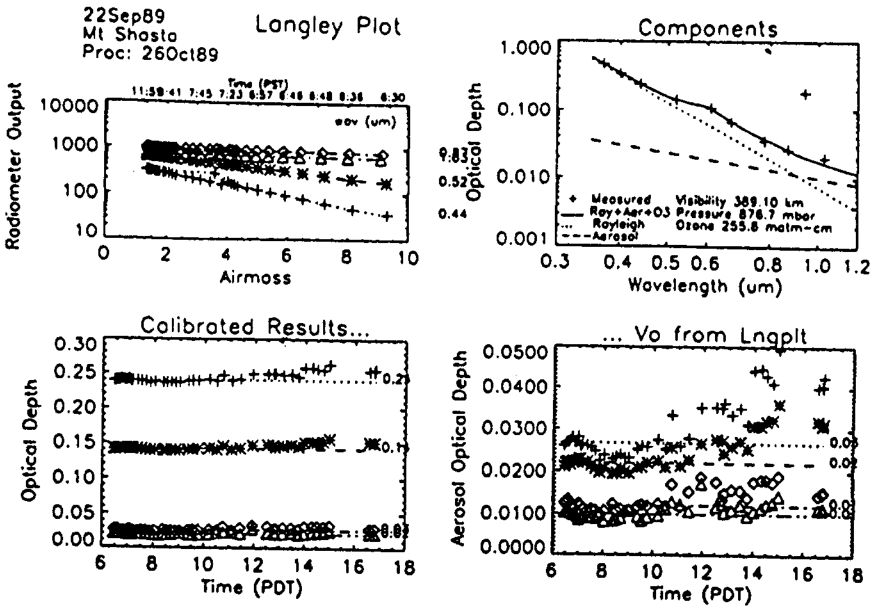

Fig. 5. Atmospheric optical depth and aerosol optical depth were estimated as a function of time from analysis of the sun photometer data.

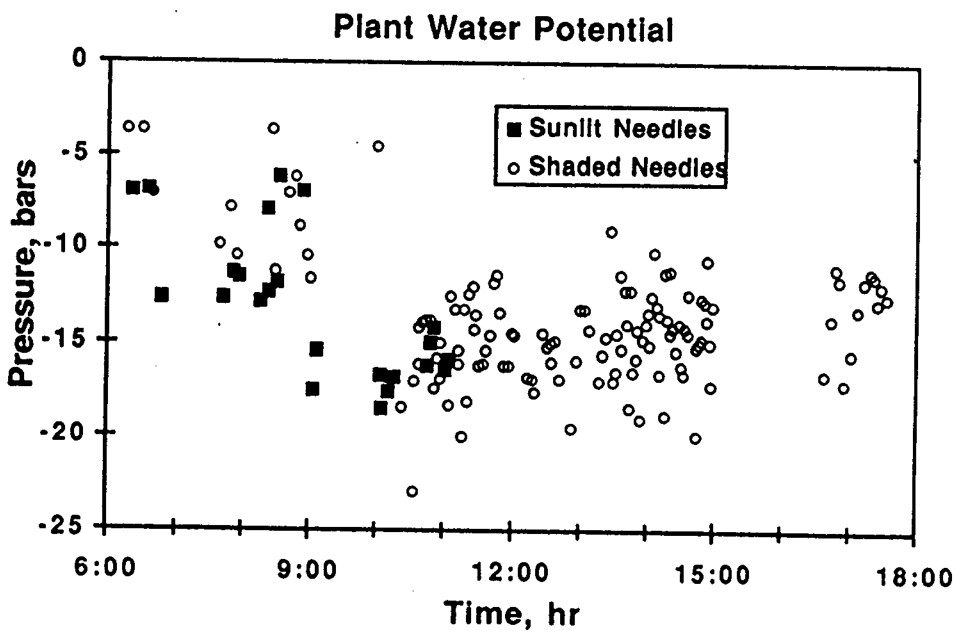

Fig. 6. The water potential of shaded and sunlit branches harvested from Ponderosa pine was measured during AVIRIS data collection.