AVIRIS Imagery for Forest Attribute Information: Anisotropic Effects and Limitations in Multi-Temporal Data

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Abstract-Hyperspectral data can provide valuable forest information, such as forest species, stand density, biochemistry, and forest structure. It is also well known that optical radiometric properties of forest objects vary with the angles of illumination and view angle. The anisotropy of the forest canopy can restrict the determination of the forest parameters of interest. In high relief areas such as Vancouver Island, Canada, the impact of illumination effects presents numerous additional complexities. In this paper, we present the results of a study undertaken to assess forest attribute determination from AVIRIS data acquired over the Greater Victoria Watershed District Test Site (GVWD) on Vancouver Island, B.C., Canada on two dates. A comparison of data from a number of test plots is carried out using AVIRIS imagery acquired in 1993 and 1994. Inventory information (such as stem density, species distribution, biomass, etc.) for these plots is known as a result of field sampling and data fusion of the AVIRIS Hyperspectral data with high spatial resolution (1 m) MEIS data and AirSAR data. For GVWD, the dominant forest species is Douglas Fir. Similarly aged stands on different slopes and at various aspects provide a sampling of view angles. Acquisitions at different times of the day sample the variation in illumination angles. AVIRIS reflectances from 1993 and 1994 are used to determine the limitations imposed by a range of off-nadir angles and BRDF effects.

INTRODUCTION

In an era of global concern about the sources and sinks of greenhouse gases, forests are seen as an important biome in the health of the planet. Under the Kyoto Protocol, Canada has agreed to reduce its greenhouse gases by 6% below 1990 levels [1]. Canada contains 10% of the world's forests. Forests are an important repository of carbon, an attribute that can be determined from knowledge of forest biomass. Depending upon the successional stage and available nutrients, forests may be viewed as a sink or a source for greenhouse gases. The Canadian National Forest Inventory (CanFI) contains more than 20 parameters characterizing the forest, including distribution of forest types, forest age, and forest volume. A summary of Canadian forest attribute requirements may also be found in [1].

Traditionally, estimates of forest biomass are carried out by ground samples in which measurements are made of individual tree diameter, height, and species for a group of trees within a fixed radius. Allometric equations are then used to compute the timber volume of each tree. These equations were derived from previous experiments in which trees were harvested and their volume directly measured either on that site or on similar sites. In conducting a volume experiment, there is a trade off between getting sufficient ground samples and the precision of the volume estimates. Large-scale, destructive harvesting and measurement will give precise volume estimates and tree structure, but are very expensive. Traditional ground sampling will give more samples, but with poorer estimates of individual tree volumes. If the samples are in a homogeneous stand, then these samples can be used to calibrate remote sensing techniques.

Investigators have tried optical techniques to estimate timber volume or biomass, as for example in [3], [4], [5], [6] and [7]. In [8] with Thematic Mapper (TM) imagery and airborne Multi-detector Electro-optical Imaging Scanner (MEIS) 3-meter imagery, a regression equation is derived between a normalized difference for TM 4 and 5, ND (4,5), and timber volume for 7-hectare samples. The regression was found to be valid over the range 50 m^3/ha to 300 m^3/ha. At higher timber volumes, Gemmell and Goodenough [8] predicted that Thematic Mapper data could not give accurate volume estimates because of the high crown closures and insensitivity of the vegetation index. Data from synthetic aperture radars have also been used in computing above-ground biomass in forests. In references [9], [10] and [11], relationships between timber volume and radar backscatter for P-band (68 cm) HV SAR imagery have been developed. In Bhogal et al [9], a data fusion technique utilizing 1-meter MEIS data was used to compute stem densities at more than 90 plots and compute the biomass using allometric equations appropriate to the test site. In this test site (Greater Victoria Watershed District - GVWD) having high relief and pronounced topography (with slopes exceeding 45 degrees), the results showed a trend between radar backscatter and biomass for P-band. The r^2 was less than 0.5 for these radar backscatter and biomass curves, and reflected the difficulties in working in a high relief area where sub-surface and surficial geology, aspect and slope effects heavily influence the radar backscatter.

In the present work, we attempt to determine the limitations in computing above-ground forest biomass in selected plots in the GVWD test site using MEIS, LANDSAT 5 TM and AVIRIS data. To the best of our knowledge,

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AVIRIS data have not been used for computing forest biomass in high relief sites such as ours. We assess the implications of BRDF in AVIRIS imagery acquired at noon and 15:00 (Pacific Daylight Time) over 1993 and 1994 for extraction of forest attributes such as canopy closure and biomass and compare the results with other optical and radar sensors.

GVWD TEST SITE CHARACTERISTICS AND DATA

During the SEIDAM (System of Experts for Intelligent Data Management) field programs of 1993 and 1994, remotely sensed data from AVIRIS, MEIS, LANDSAT 5 TM, and AirSAR sensors were acquired. Data were acquired over two West Coast temperate forest sites on Vancouver Island, the Greater Victoria Watershed District (GVWD) and Clayoquot Sound.

The GVWD test site is the primary SEIDAM test site, as well as a supersite for the EOSD [1] and EVEOSD [2] Projects. Over 90 percent of the trees found in this test site are Douglas Fir. The average elevation of GVWD is about 400 meters above sea level, with slopes as great as 45 degrees for some of the plots. Except for the younger stands, the old growth forest in this test site is largely unmanaged, and most of our experimental plots are from unmanaged areas. The GVWD test site contains some of the oldest stands of Douglas Fir in the southern half of Vancouver Island. Studies in the GVWD test site conducted by the Canadian Forest Service have shown that trees having a diameter at breast height (dbh) of over 30 centimeters will seldom grow more than one millimeter per year in dbh [12]. Annual volume increments per hectare in Douglas Fir under the environmental conditions present at the GVWD range from 10 percent of standing volume at age 24 years, to about 5 percent by age 40, declining to zero after maturity is reached. Therefore, the change in biomass at each of the plots was assumed to be negligible over the two years of AVIRIS data acquisition and analysis.

It is assumed that leaf development is complete at the times of the AVIRIS flights, and foliage nutrient levels are stable [13], [14]. Thus, reflectance variations from the canopy due to illumination and view angles will be the dominant factors affecting estimates of crown closure and biomass. Table 1 summarizes aircraft and solar parameters:

Date	Flight Time (PDT)	Sun Alt. (deg)	Solar Elev. (deg)	Solar Angle wrt Aircraft (CW from heading)
Aug-93	12:11	49	156	168 (Sun behind)
Sep-93	15:10	42	221	233 (Sun behind)
Aug-94	12:20	57	153	345 (Sun ahead)

Table 1: Aircraft and solar parameters for AVIRIS data acquisition.

DATA PROCESSING

AVIRIS data were acquired by NASA in 1993 and 1994 using an ER-2 at an altitude of approximately 20 km and were subsequently radiometrically, spectrally and geometrically corrected for sensor characteristics at JPL. Details on the calibration of AVIRIS data to reflectance process may be found in [16]. For this analysis, reflectance values from 100 meter by 100 meter areas were used.

The airborne Multi-detector Electro-optical Imaging Scanner (MEIS) was flown on a Falcon Fan-jet. MEIS is capable of acquiring high (10-100 cm/pixel) spatial resolution multispectral images in eight spectral bands, two of which are typically fore and aft stereo pairs. Details pertinent to geocoding of the MEIS data may be found in [9]. Details on computing biomass, stem density, crown closure and other attributes using MEIS (50 meter by 50 meter plots) data may be found in [17] and [18].

LANDSAT 5 Thematic Mapper Data were acquired over the GVWD test site on August 4 1993. The TM data were precision georeferenced and orthorectified by using TRIM DEM data supplied by the Province of British Columbia. The location of the AVIRIS plots were determined using the UTM coordinates of each plot. Following a study on the optimum filtering kernel, it was determined that average reflectance from a 5 pixel by 5 pixel area (corresponding to a 125 meter by 125 meter area) was appropriate.

The NASA AIRSAR is a multi-frequency, multi-polarization synthetic aperture radar system. The radar flies on a DC-8 platform and operates in the C-band (5.7 cm wavelength), L-band (25 cm wavelength) and P-band (68 cm wavelength). The results from the AirSAR used in the current work can be found in [9].

ANALYSIS AND RESULTS

One-meter imagery from the MEIS was used to compute crown closure automatically [18]. This method offers the best opportunity to determine canopy attributes (such as crown closure) as compared with GIS data, which on a polygon basis, may have uncertainties of 20% or more, associated with the attributes [19].

The MEIS-derived attributes include stem density, tree spacing, average crown diameter, and crown closure. Biomass can be determined from stem density counts. Our previous work [9] using AirSAR data has shown clear trends in the relationship between SAR backscatter and biomass for these same plots. The multi-sensor data analysis presented in the current work is intended to determine the limitations on determining forest attribute information (e.g. biomass) from MEIS, TM, and especially, AVIRIS.

Using plots of size 50 metres by 50 meters, we have studied MEIS reflectances and their relationship to crown closure. The 875 nm channel (NIR) shows the best correlation with crown closure (r^2=0.70). A difference vegetation index has been computed and studied in relation to crown closure using 875 nm and 446 nm channels ($r^2 = 0.49$). The same difference vegetation index, when plotted against biomass shows virtually no correlation. The forest attributes of crown closure and biomass, when plotted against local slope and aspect (not shown here), show no correlation. These results are consistent with the canopy being unaffected by these terrain attributes except when slope and aspect pose stress on vegetation.

We have observed much better correlations between mean tree height from GIS data and biomass (r^2=0.68) and age and biomass (0.47). Relationships between site index and biomass have a low r^2=0.27. This analysis (using high spatial resolution MEIS data) has enabled us to establish baselines for the AVIRIS work.

We constrain our analysis to TM data acquired in the same time frame as AVIRIS and MEIS, namely, August 1993. We have studied LANDSAT TM reflectances as a function of crown closure. As for the MEIS, the best correlation (r^2=0.29) is for the TM 4. We have computed and studied the DVI for these TM data and its relationship to crown closure and biomass. The poor correlations with DVI are evidence of saturation. Others (e.g.[20]) have observed correlations in Pine forests of western Japan. In [20] they only consider forest biomass not exceeding 200 tons per hectare. Our work considers forest biomass in excess of 600 tons per hectare.

We have examined the response of the sensor to known forest attributes as determined from GIS information and MEIS data. Three dates of August 29 1993, September 2 1993 and August 1 1994 have been used in this analysis (see Table 1). There are clear differences in atmospheric conditions on the three dates. Whereas the September 1993 and August 1994 data were acquired under nearly pristine (clear and cloudless) conditions, the August 1993 data were acquired within one hour of contrails being observed over much of the GVWD test site by field personnel as well as the ER-2 pilot.

For the multitemporal AVIRIS data, we have studied the response of the 875 nm channel against crown closure and biomass. For all three dates, the AVIRIS response at 875 nm appears to agree within 5 %. It is not possible to identify clear differences due to time of day. We also note that the behavior of the curves (e.g. slope reversal in crown closure and biomass plots) is consistent with observations in the MEIS and TM data.

Figures 1 and 2 show a difference vegetation index (DVI) computed using the 875 nm and 628 nm channels of the AVIRIS data and plotted against crown closure and biomass. We have chosen these two channels consistent with the considerations of [21] in relating AVIRIS reflectance to LAI. We observe some agreement between the September 1993 data and the August 1994 data. Once again, the difference in the August 1993 data relative to the other two dates is attributed to unstable atmospheric conditions. The crown closure and biomass curves show trends observed in MEIS and TM data that includes a slope reversal between the crown closure and biomass plots. The present work has yielded inconclusive results as far as off-nadir angle views are concerned.

Our study has indicated that the DVI for all three dates of AVIRIS appears to be independent of off-nadir angles. Ideally, a study of anisotropic effects would require reflectances at various off-nadir and aspect angles for targets having similar spectral signatures. Our AVIRIS data set consists of nearly identical flight lines flown on three different dates. We are not able to find similar targets in our test sites (such as logging roads, rock outcrops, gravel areas, etc.) at various off-nadir angles that have spectrally pure signatures. This limitation is caused in part, by the dimensions of candidate targets being much less than the AVIRIS pixel size of 20 meters by 20 meters.

We choose to get around this limitation imposed by the lack of spectrally pure targets by examining those plots which have similar biomass and canopy closure. We choose three biomass regimes of 50-78 tons/ha, 140-180 tons/ha and 300-368 tons/ha. The results appear in Figures 3, 4, and 6 where we plot the DVI for each of the three AVIRIS dates against each of the three biomass regimes. In all three plots, the best correlated curve is from August 1994,when the AVIRIS data were acquired at noon under nearly pristine conditions. The September 1993 data (acquired at 3 p.m. PDT), show downward slope with increasing off-nadir angle for the high biomass values of 300 tons/ha (Fig. 5). This change in behavior of the Sept. 1993 curve for high biomass values may be due also in part to changing contribution to the total reflectance from the old and new foliage in addition to the change in ambient light variations.

The curves for the September 1993 data are within 10% of the August 1994 data. The differences may be due to the time of acquisition and a greater reduction in the signal-to-noise ratio (compared with noon acquisitions from August 1994) as the path length to the target increases with increasing off-nadir angle. Finally, the August 1993 curve is noticeably different from the other two. As discussed earlier, there is evidence of atmospheric haze and remains of contrails on this date from several independent observers. Despite the time of acquisition (noon PDT), these kinds of atmospheric conditions would render a low signal-to-noise ratio as well as suspect results after an atmospheric correction is carried out using a default atmospheric profile (e.g. mid-latitude summer model for MODTRAN [12]).

CONCLUSIONS AND FUTURE WORK

We conclude that for AVIRIS (field-of-view of 35 degrees), anisotropy poses minimal constraints for extracting crown closure and biomass information for west coast forests.

An attempt to determine forest attribute information using high spatial resolution MEIS data, high spectral resolution AVIRIS data and LANDSAT 5 TM data has revealed similar trends in sensor response to crown closure and biomass. We have constrained our analysis to sample plots in the GVWD test site (one of the most productive forested areas in North America) for which extensive studies of AirSAR response to biomass have been carried out [7]. The AirSAR work has demonstrated that clear trends exist relating backscatter to biomass.

Weak correlation between difference vegetation indices (DVIs) and the response from MEIS, TM and AVIRIS may be due to a number of factors. A fully developed crown for Douglas Fir limits the correlation between reflectance and biomass. The crowns for the trees in our test site are fully developed by the age of 40 to 50 years. Thus, the relationship of crown closure to biomass becomes saturated after a certain age. Another limitation is be due to variable understory. Salal, a broad-leafed bush, is the dominant understory in our test site, and impacts the determination of DVI. Salal is not uniformly distributed our plots.

The weak correlations observed in our work for individual optical sensors imply that other remotely sensed data (data fusion) may be required for the computation of forest attributes such as biomass in stands of high density.

With respect to AVIRIS, our work demonstrates the difficulties associated with using data which have haze and contrail residue in the atmosphere. This is an important issue as increasing air traffic in the sky creates contrail remains which will adversely affect hyperspectral data applications.

Future work will include the following: a) use of interferometric SAR and LIDAR data to compute biomass; b) investigation into the atmospheric correction models (e.g. CAM5s, ATREM, MODTRAN); c) Modeling of reflectance to study anisotropic and BRDF effects with variable biomass.

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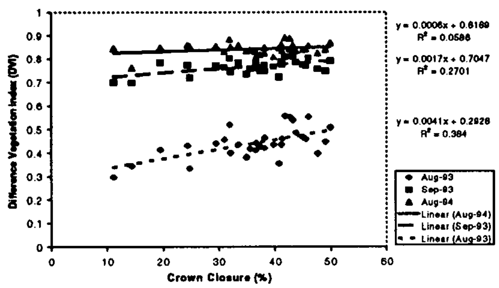

Figure 1: AVIRIS DVI against crown closure.

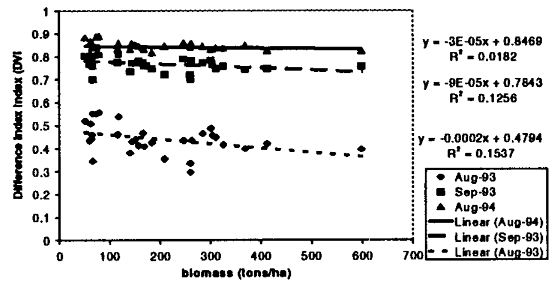

Figure 2: AVIRIS DVI against biomass.

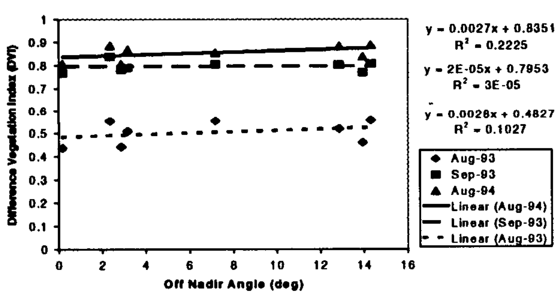

Figure 3: AVIRIS DVI for 50 to 80 tons/ha against off-nadir angle.

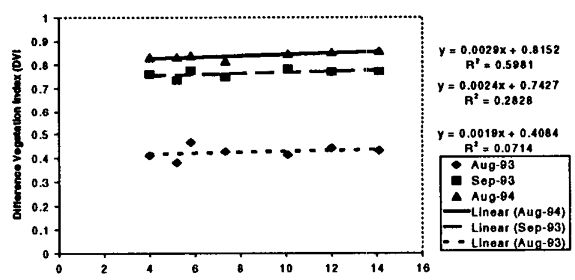

Figure 4: AVIRIS DVI for 140 to 180 tons/ha against off-nadir angle.

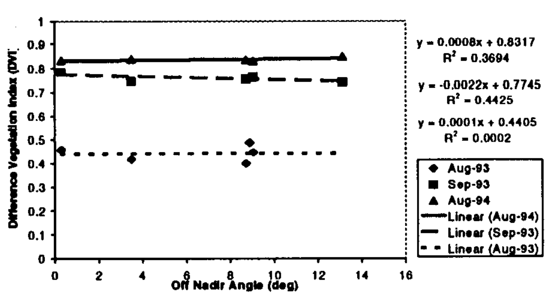

Figure 5: AVIRIS DVI for 300 to 368 tons/ha against off-nadir angle.