Forest Biomass, Canopy Structure, and Species Composition Relationships with Multipolarization L-Band Synthetic Aperture Radar Data

Steven A. Sader
NASA Earth Resources Laboratory, National Space Technology Laboratories, NSTL, MS 39529

ABSTRACT: The effect of forest biomass, canopy structure, and species composition on L-band synthetic aperture radar data at 44 southern Mississippi bottomland hardwood and pine-hardwood forest sites was investigated. Cross-polarization mean digital values for pine forests were significantly correlated with green weight biomass and stand structure. Multiple linear regression with five forest structure variables provided a better integrated measure of canopy roughness and produced highly significant correlation coefficients for hardwood forests using HV/VV ratio only. Differences in biomass levels and canopy structure, including branching patterns and vertical canopy stratification, were important sources of volume scatter affecting multipolarization radar data. Standardized correction techniques and calibration of aircraft data, in addition to development of canopy models, are recommended for future investigations of forest biomass and structure using synthetic aperture radar.

INTRODUCTION

ORGANIC MATTER STORAGE and forest production, especially in tropical regions, are important factors in the flux of atmospheric CO_2 and its potential impact on global climatic change. Accounting for changes in the global carbon budget partially depends on better estimates of biomass or organic carbon density. Biomass estimates of tropical forests have been used in models of the terrestrial biota (Whittaker and Likens, 1973; Brown and Lugo, 1982), but the data base for deriving biomass estimates is poor (Brown and Lugo, 1982; Brown and lugo, 1984). Recently, remote sensing estimates of forest area have been integrated into global forest surveys and inventory programs (Lanly, 1982). However, cloud cover in tropical regions causes gaps in data coverage by satellite systems (e.g., Landsat) which are often employed to derive the forest area estimates (Sader *et al.*, 1985).

SYNTHETIC APERTURE RADAR STUDIES OF FOREST VEGETATION

Investigations using Synthetic Aperture Radar (SAR) are of particular interest for tropical forest monitoring because active microwave systems can penetrate clouds and record the amount of energy returned from surface features. In perpetually cloud-shrouded life zones, where sensors that operate in visible and infrared wavelengths have limited utility, microwave sensors may provide information about forest area and structure that would be otherwise unobtainable.

Recent investigations have reported qualitative comparisons of SAR signals and forest targets with data collected from Seasat and SIR-A (Wu, 1981; Wu, 1984), SIR-B (Mueller *et al.*, 1985), and aircraft systems (Hoffer *et al.*, 1985; Ford and Wickland, 1985; Paris, 1985b; Evans *et al.*, 1986). Physical models of radar backscatter from vegetation components have been derived from experimentation with agricultural crops (Attema and Ulaby, 1978; Fung, 1979; Hoekman *et al.*, 1982), but knowledge concerning the physical relationship between radar backscatter and forest vegetation is lacking (Hoekman, 1985).

Investigations of vegetation structure are important to understanding the potential role of microwave sensors for deriving estimates of forest biomass and vegetation structure. Crown shape, leaf size, leaf mass per volume, and age class were related to X-band (3 cm) backscatter differences in HH polarization (Hoekman, 1985). In deciduous forests, the leaves were believed to be most important as scatterers of X-band waves; however, L-band waves (24 cm) with HH polarization penetrated through leaves and were scattered back from the branches of trees (Sieber, 1985). Plant height, density, geometry, and presence or absence of standing water at the surface influence the SAR response, but incidence angle and polarization can also have a significant effect (Ormsby and Blanchard, 1985; Ulaby and Wilson, 1985; Hoekman, 1985; Pampaloni and Paloscia, 1985). Riom and Letoan (1981) reported that image intensity of L-band HH polarization SAR data was highly correlated with tree height in a pine forest. Similar results for pine plantation age classes and SIR-A (HH polarization) data were reported by Wu (1984).

Microwave scatterometer experiments (C-band, 6 cm) with deciduous tree species revealed a dominant VV return near the canopy top, but HH response was higher near the base of the canopy (Paris, 1985a; Wu, 1985). High cross polarization responses of forest vegetation are the result of volume scatter and multiple reflection from randomly oriented structures (leaves, stems, and branches). Cross-polarization and ratios of cross and like polarizations could lead to isolation of canopy angular orientation properties (Paris, 1985a).

OBJECTIVE

The investigation was directed to the evaluation of multipolarized SAR data relationships to various forest canopy structure characteristics, including average tree height, basal area, average diameter at breast height, and number of stems per unit area. Of primary interest was the relationship between SAR digital values and above-ground green weight woody biomass. As a precursor to a SAR study to be conducted in a tropical environment, a local test site was selected in southern Mississippi pine-hardwood and bottomland hardwood forests to evaluate forest biomass and radar measurements. Analysis of forest composition and structure on SAR polarization response will facilitate the extension of the research into a tropical study site selected in Costa Rica.

STUDY AREA

The lower Pearl River drainage basin forms the border between Hancock County, Mississippi and St. Tammany Parish, Louisiana along the Gulf Coast approximately 50 km northeast of New Orleans, Louisiana. By the Holdridge system of classification, the area is a warm temperate moist life zone (Hold-

PHOTOGRAMMETRIC ENGINEERING AND REMOTE SENSING,
Vol. 53, No. 2, February 1987, pp. 193–202.

0099-1112/87/5302–193$02.25/0
©1987 American Society for Photogrammetry and Remote Sensing

ridge *et. al.*, 1971). Elevations range from 3 metres above sea level in the floodplain to approximately 15 metres in the surrounding uplands. Water regime, soil, and microrelief influence the distribution and composition of flora. The area is now part of the Pearl River Wildlife Management area administered by the Louisiana Department of Wildlife and Fisheries (White, 1979). The dense Pearl River bottomland forest approaches biomass levels[1], canopy height, and structure found in some tropical life zones.

Dominant canopy hardwoods in the lower Pearl River basin include sweetgum (*Liquidambar styraciflua* L.), Laurel oak (*Quercus laurifolia* Michx.), water oak (*Quercus nigra* L.), Blackgum (*Nyssa sylvatica* var. *biflora* (Walt.) Sarg.) red maple (*Acer rubrum* L. var. *drummondii*),and hickories (*Carya* spp.) Other common species occupying the midstory and understory were American hornbeam (*Carpinus caroliniana* Walt.) and American Holly (*Ilex opaca* Ait.). Frequently flooded, poorly drained soils are less diverse in floristic composition and are dominated by water tupelo (*Nyssa aquatica* L.), baldcypress (*Taxodium distichum* (L.) Rich.), and ash (*Fraxinus spp.*).

Also included in the investigation are pine and pine-hardwood stands in the vicinity of the NASA-NSTL installation and Devil's Swamp, adjacent to and east of the Lower Pearl River basin. Soils here are somewhat poorly or poorly drained, fine sandy loams supporting primarily longleaf pine (*Pinus palustris* Mill.) and slash pine (*Pinus elliotti* Englem.). Many low quality hardwoods are present, especially yaupon (*Ilex vomitoria* Ait) and Southern bayberry (*Myrica cerifera* L.), forming dense understory patches in abandoned pine stands damaged by hurricanes.

METHODS

Application of Existing Biomass Equations

A computer program entitled "Total-Tree Multiproduct Cruise Program," designed for implementation on IBM-compatible[2] micro-computers, was acquired (Clark *et al.*, 1985a). Regression equations stored in the program estimate the green weight of wood and bark (excluding foliage) in the total-tree-above-stump. Regression equations were developed for ten species that account for 77 percent of the commercial hardwood volume in the Gulf and Atlantic Coastal Plain (Clark *et al.*, 1985b). The equations were developed from sacrificed trees in four age classes (10, 20, 40, and 60 years) on 25 0.1-acre (0.04 ha.) circular plots. Six of the plots were located on bottomland sites in the vicinity of the Pearl River study area. The soft-hardwood species included green ash (*Fraxinus Pennsylvanica* Marsh.), blackgum, red maple, sweetgum, water tupelo, and yellow-poplar (*Liriodendron tulipfera* L.). Hard-hardwood species were Laurel oak, water oak, white oak (*Quercus alba* L.), and two or three hickories. No one particular hickory species exhibited dominance over the others.

Regression equations were combined to form one equation for each hardwood group. Hard-hardwoods have relatively high specific gravities (0.53 to 0.80), large deliquescent crowns[3], and green weights (wood and bark per cubic foot of wood) of 33 to 39 kg (73 to 85 pounds). Soft-hardwoods have lower specific gravities (0.30 to 0.52), higher moisture content, green weights of 27 to 33 kg (60 to 72 pounds), and smaller excurrent crowns (Clark *et al.*, 1985b). The form of the regression equations for hardwood trees less than 28cm (11.0 inches) dbh was as follows:

$$y = a\,(D^2Th)^b$$

where y = component weight in pounds,
D = tree dbh in inches,
Th = total tree height in feet, and
a,b,c = regression coefficients.

For trees greater than 28cm (11 inches) *dbh*, the equation was $y = a(D^2)^b(Th)^c$. Regression coefficients used in the computation of green weight of above stump total tree wood and bark combined are provided in Table 1.

Point Sampling Inventory

Four timber cruising options were available for implementation of the program including fixed plot, strip cruise, point sample, and 100 percent tree tally. The point sampling method was chosen as the easiest to perform in the field, and the accuracy of the method was considered to be adequate for the purposes of the investigation. In point sampling, the probability of a tree to be tallied is proportional to the stem basal area. Large trees tend to be sampled in greater proportion than smaller trees with lower biomass. The sample points are analogous to plot centers, and a prism (angle gauge) is used to subtend a fixed angle of view to "sight in" a tree (Avery 1967; Avery and Burkhart, 1983). Point sampling is best executed on relatively flat terrain such as the terrain conditions that exist in the Pearl River - NSTL study area. Point sampling produces very acceptable results compared to other cruise methods if the sample is representative (Phillips and Saucier, 1981).

The forest measurement sites were delineated on aerial photos, and their area was estimated using a dot grid. Transect lines were located at least 20 metres from any forest-road or forest-river bank boundary. A total of 44 sites were cruised. A wide range of stand structure conditions and species compositions were represented, but few samples were selected in low biomass stands. Twelve to 15 prism plots per site were sampled in even aged pine stands, and approximately 20 points were sampled in uneven aged natural hard-wood stands. The number of sample points measured in this study was chosen to comply with the recommendations of Avery (1967) for conducting point sample timber cruises. A 10-factor prism was used to locate "count" trees around each prism plot center. Borderline trees were measured to determine if they should be counted in the plot based upon their critical angle distance-diameter breast height relationship. Diameter breast height (dbh) and total height[4] of each count tree in a plot were entered in the appropriate location on the field tally sheet. Hardwoods were tallied by species group: hard-hardwoods and soft-hardwoods.

After the data were entered into the computer and checked for errors, the output option for calculation of green weight biomass was selected. From this output, a secondary summary was generated to list green weight biomass, mean *dbh*, mean total height, mean basal area, and number of stems for each species group, by size class, and for all size classes combined (total).

Table 1. Regression Coefficients (*a*, *b*, *c*) for Estimating Green Weight of Above-Stump Total Tree Wood and Bark Combined with *Dbh* and Total Height as Independent Variables (extracted from Clark *et al.*, 1985b).

	Trees < 11.0 in dbh		> 11.0 in dbh				
	a'	b	a''	b	c	R^2	$(S_{Y \cdot X})$
Soft-hardwoods	0.27499	0.93190	0.07785	1.19503	0.93190	0.99	0.0792
Hard-hardwoods	0.37894	0.92237	0.12821	1.14833	0.92237	0.99	0.0733

[1]According to Brown and Lugo (1982), total forest biomass in relatively undisturbed tropical forests ranges from approximately 40 to 538 tons per hectare. One of the forest plots measured in the Pearl River basin reached 398 metric tons per ha, or 74 percent of the high range of tropical forest biomass.

[2]Mention of trade names is intended for information only and does not constitute endorsement of products by the U.S. Government.

[3]Deliquescent branching without a continuous main axis as compared to excurrent branching with a continuous main axis from which lateral branches arise.

[4]Height was not measured for count trees less than 10cm (4.0 inches) *dbh*.

Synthetic Aperture Radar Data Acquisition

Multipolarized L-band (24.6-cm wavelength) synthetic aperture radar data were collected over the South Pearl River floodplain and NSTL vicinity on 11 Sept. 1984 at approximately 11:30 AM. The Convair 990 aircraft operated by NASA-Ames Research Center was flown at an altitude of approximately 9,144 metres (30,000 feet) above mean terrain. The SAR system developed by the Jet Propulsion Laboratory (JPL) can simultaneously transmit and receive like polarization (HH and VV) and cross-polarization (HV and VH) echo signals (Thompson, 1983). The four SAR polarizations (HH, HV, VH, and VV) were digitally correlated at JPL, and the digital tapes were shipped to NSTL. Two flight lines flown in a south-north orientation were available for processing. Data were collected from 15 to 60 degrees off nadir. Swath width was approximately 7.5 km, and the ground range and azimuth pixel of the raw data was 10 metres. The sky was partly cloudy, but there was no precipitation in the area during the morning prior to the flight.

Scene Illumination Correction

All computer processing at NSTL was performed on a Perkin-Elmer 3200 MPS computer using the Earth Resources Laboratory Applications Software (ELAS) package (Graham *et al.*, 1981). The SAR data received from JPL were uncalibrated and were not corrected for gain in antenna pattern and range-induced variation. The raw data exhibited an obvious image grey level gradient unrelated to the land surface backscatter characteristics (Figure 1a). Because the field measurement sites were selected across the entire width of the SAR data, a scene illumination correction was applied to reduce error which could have been introduced in the analysis of uncorrected data (Blom and Daily, 1982). A 100-line section representing continuous forest was selected for computation of column means and standard deviations perpendicular to the grey level gradient. Coefficients derived from the sample were applied to the entire data set, resulting in an image that appeared evenly illuminated (Figure 1b).

Median Value Filtering and Resampling

The speckling effect of the SAR data was filtered using a 5 by 5 moving window median value filter (Figure 1c). Median value filters may be superior to mean filters for removing multiplication noise (Blom and Daily, 1982), especially when automatic classification routines are to be used. The method of filtering was not considered to be critical to the investigation; however, the median filtered image appeared to minimize edge effects and speckle compared to a mean filter technique, also attempted. The filtering and subsequent resolution degradation of the multipolarized SAR data to 30 meters (Figure 1d) was considered to be appropriate for analysis with forest biomass and stand structure measurements collected by point sampling. Also, the 30-meter resolution was selected to facilitate comparisons of SAR and Thematic Mapper data planned for a follow-on investigation. Although some preprocessing was required to produce a suitable data set, results of subsequent data analyses can be stated only in terms of scene dependent digital values.

Polarization Selection and Ratioing

Individual SAR polarization HH, VV, and HV were selected for digital processing. Because the cross polarizations (HV and VH) were found to yield approximately equal results as determined by visual comparison of images and comparison of digital values for several sample areas, only one cross pole (HV) was retained for the analysis. Other forest studies have reported HV and VH to be nearly equal (Ford and Wickland, 1985; Wu, 1983; Hoffer *et al.*, 1985). Three polarization ratios (HH/VV, HV/VV and HV/HH) were generated through simple mathematical operations.

Selection of Forest Measurement Polygon Locations

With the aid of aerial photos, the boundaries of each field sample location were delineated interactively on the image display screen and stored in a polygon file. The forest sample areas were carefully selected in the SAR data to insure that subsequent statistics generated from the data would be representative and would not include variation beyond the boundary of the field measurement zone. The average size of selected sample areas was approximately 6 hectares. Forest sample areas were selected across the entire swath width of the SAR data. A statistics file was created consisting of mean digital values and standard deviations in each SAR channel for 44 forest sample sites.

RESULTS AND DISCUSSION

Estimated green weight biomass ranged from 25 to 398 metric tons/hectare[5] and basal area ranged from 4 to 42 m^2/ha. Mean *dbh* ranged from 6.9 to 20.1 cm, and mean heights of the forests were approximately 4.6 to 19.8 metres. The number of stems ranged between 524 and 4812 per ha. Pine sites had lower mean biomass (202 tons/ha) compared to hardwood sites with 261 tons/ha. Coefficients of variation in individual tree sites were greater in pine-hardwood and hardwood stands.

The forest measurement sites were partitioned into forest species composition groups based upon the proportion of biomass in pine, soft-hardwood, and hard-hardwood species. Total stand biomass, mean tree heights, diameters, and number of stems ranged widely both within and between forest composition groups. High correlation between biomass and mean height as well as biomass and diameter breast height (*dbh*) would be expected because height and *dbh* are the two independent variables used in the biomass prediction equations. Table 2 indicates a nonsignificant correlation between pine biomass and *dbh*; however, it was learned that one pine site was thinnned in May 1985, approximately two months before the field data were collected. The selective thinning eliminated many small diameter stems and resulted in an inflated mean diameter and reduced biomass for the stand as a whole. Exclusions of the sample resulted in a significant correlation coefficient ($p = 0.05$) for pine biomass and *dbh*. The biomass-*dbh* relationship was nonsignificant for pine-hardwood, suggesting that the inclusion of unmanaged or abandoned pine stands (with substantial hardwood component) may not have been representative of the stand conditions where pine biomass equations were developed. Total biomass was significantly correlated with all structure variables for hardwood sites, indicating an important difference in structure between forest composition groups. Although many of the forest parameters were significantly correlated with one another (Table 2), each provides a slightly different structural attribute which may influence SAR polarization response.

The percentage of crown to total tree green weight of all trees greater than 11 cm *dbh*, estimated from 24 hardwood sites in this investigation, was 28.0 ± 3.3 percent for hard-hardwoods compared to 17.4 ± 1.4 percent for soft-hardwoods. The percentage of crown biomass for a few of the older pine stands (20 to 30 years) was slightly higher than the soft-hardwood stands. Direct comparisons of crown biomass percentage between all pine and hardwood dominant sites would not be relevant because most of the pine stands were in young age classes compared to hardwood stands. Young age classes have smaller trees with higher percentage of crown to total tree biomass, but low total green weight compared to older stands.

The crown biomass was estimated as the green weight of wood and bark below 10 cm (4 inch) top diameter outside bark. Higher percentage of crown biomass for hard-hardwood species group may be attributed to the more extensive branching (deliquescent), higher specific gravity, and green weight of hardwood branches compared to soft-hardwoods. The difference in crown biomass and branching habits of pine dominant, soft,

[5]The total-tree multiproduct cruise program accepted measurements only in English units. Therefore, all measurements were converted to metric for reporting.

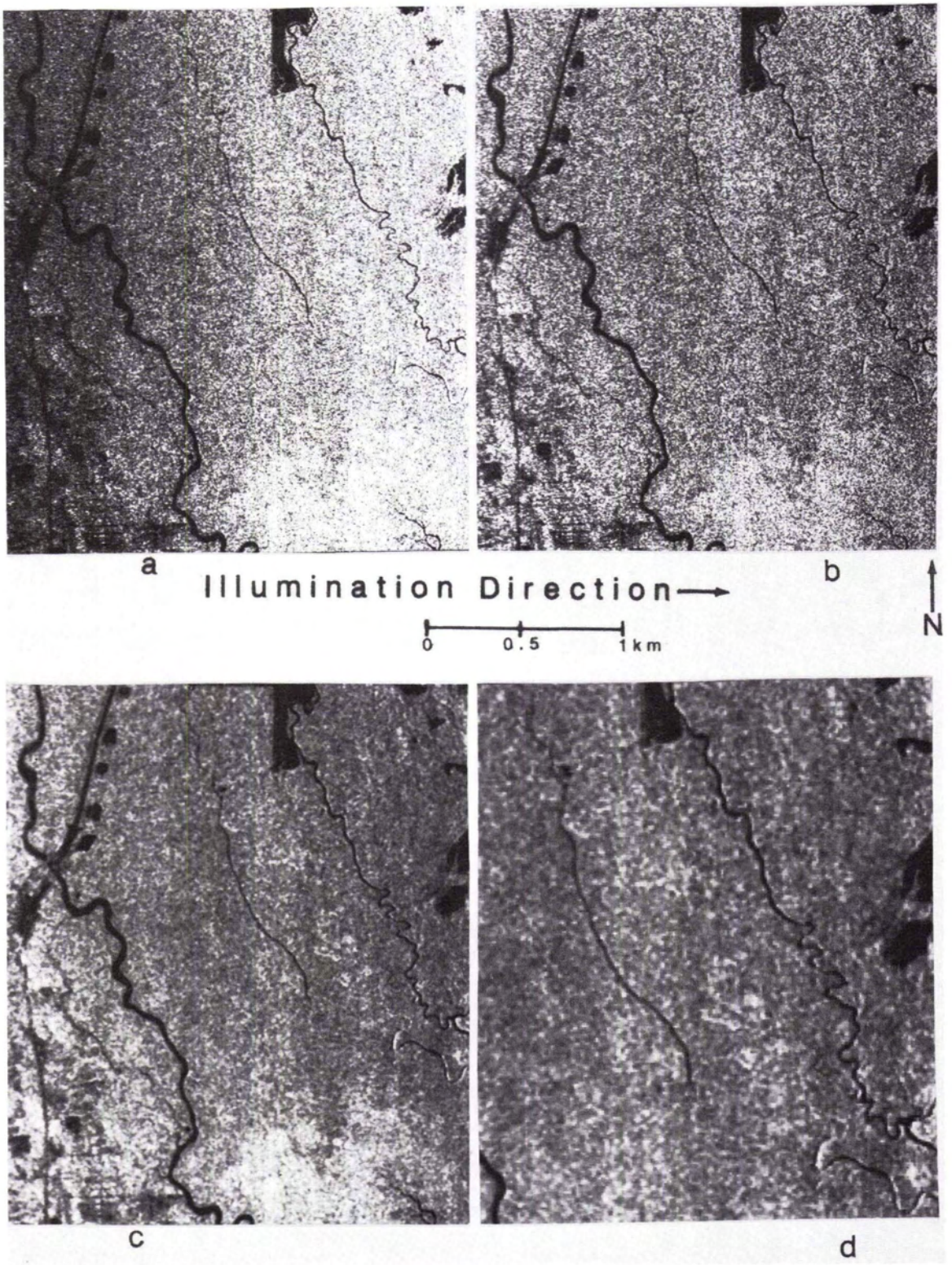

FIG. 1. Sequence of L-band multipolarization SAR preprocessed images (HV example): (a) 10-metre raw data; (b) 10-metre scene illumination corrected; (c) 10-metre median value filtered; (d) 30-metre, postfiltered and resampled.

and hard-hardwood dominant stands would be expected to yield differences in the SAR polarization backscatter.

Comparison of SAR Data for Forest Composition Groups

Mean digital numbers (DN) for both like-poles and one cross-pole were plotted for each forest measurement site within each composition group. Each forest site was identified with a code followed by the incidence angle location of the site (in parentheses). For pine dominant sites, the HH and HV polarization response was higher than VV in six out of eight cases (Figure 2). The HV and HH polarization response was split; four cases had HV higher than HH and four exhibited the reverse. Site D5, in an area known as Devil's Swamp, was a four year old pine plantation with the lowest biomass, mean height, *dbh*, and basal

TABLE 2. LINEAR CORRELATION COEFFICIENT (r) OF FOREST STRUCTURE VARIABLES FOR PINE, PINE-HARDWOOD, AND HARDWOOD STANDS.

	Pine ($n=8$)	Pine Hardwood ($n=20$)	All Hardwood ($n=24$)	All Plots ($n=44$)
Biomass vs. Height	0.87**	0.80**	0.65**	0.70**
Biomass vs. Dbh	0.67	0.27	0.69**	0.59**
Biomass vs. BA	0.94**	0.93**	0.73**	0.80**
Biomass vs. Stems	0.32	0.34	0.54**	0.27
Height vs. Dbh	0.83*	0.48*	0.69**	0.54**
Height vs. BA	0.72*	0.73**	0.31	0.61**
Height vs. Stems	−0.03	−0.08	−0.50*	−0.22
Dbh vs. BA	0.52	0.30	0.26	0.29
Dbh vs. Stems	−0.29	−0.39	−0.84**	−0.74**
BA vs. Stems	0.61	0.55*	0.03	0.16

* Significant at $p=0.05$
** Significant at $p=0.01$

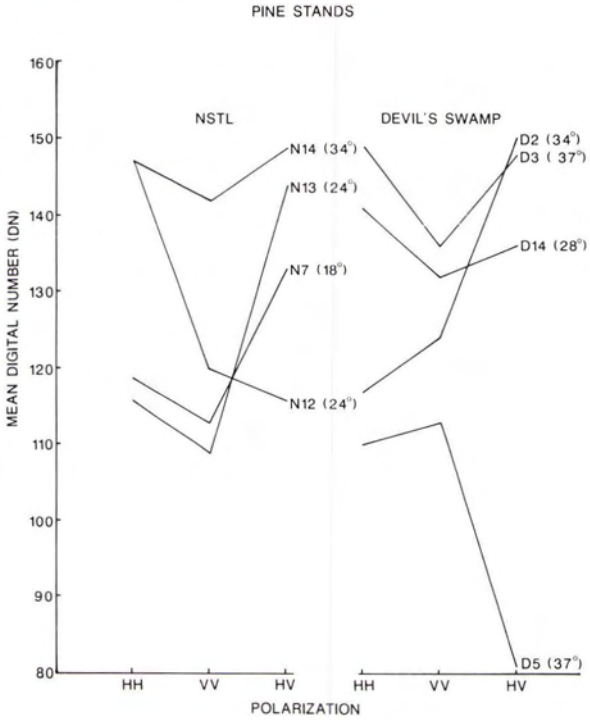

FIG. 2. Mean digital number of multipolarization L-band SAR data for eight pine stands located at various incidence angles.

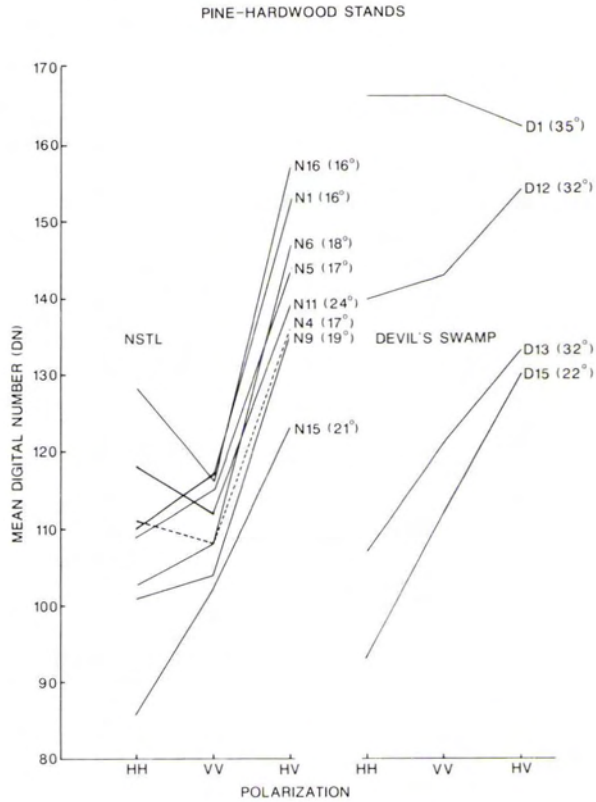

FIG. 3. Mean digital number of multipolarization L-band SAR data for 12 pine-hardwood stands located at various incidence angles.

area (BA) of all sites measured during the investigation. Site D5 had a mean digital number 30 counts lower than the site with the next lowest HV digital number (N12). Site N12 had the second lowest biomass and height, indicating that low biomass and stature (height and *dbh*) of young pine plantation (with little or no hardwood understory) lack sufficient volume scatterers that influence HV return. Sites N14, D3, and D14 were all actively managed pine plantations, that were frequently burned (1 to 3 year interval) and periodically thinned. These sites had grass understories with little or no hardwood competition. The SAR polarization responses of all three sites are very similar. Relatively high values in all three polarizations may indicate some penetration through the uniform single story canopy to the moist soil surfaces below.

Mean DN of pine-hardwood sites for each polarization were plotted in Figure 3. In eight out of 12 cases, the VV response was higher than HH. This trend was different from pine dominant sites where HH response was usually higher than VV. The HV response was higher than both HH and VV in all cases but one (Site D1). Higher HV response may indicate the effect of higher biomass, height, and *dbh* and the non-homogenous structure resulting from addition of substantial hardwood component in the pine-hardwood sites compared to pine sites. Site D1 had the highest DN of all sites and for all polarizations. Site D1 consisted of small diameter, low height and biomass, pine and soft-hardwood species on very poorly drained soils. The high moisture content of exposed soils in this sparse density stand likely contributed to the high DN in all three polarizations. Site D12 had high biomass but several poorly drained areas were noted during the field inventory. The relatively high HH and VV response may have been influenced by high soil moisture content, while the higher HV suggested strong backscatter from the standing biomass component. Several of the poorly drained, low to medium biomass stands exhibited high standard deviations around mean values (Figure 4).

Forest sites where soft-hardwood biomass outweighed hard-hardwood biomass (Figure 5) exhibited mixed results in regard to HH versus VV dominant digital numbers. The HV response was always highest compared to like-poles except for one case out of 15. The exception was site D10 in Devils Swamp, a poorly drained site with relatively low biomass, low height, and the second lowest mean *dbh* of all 44 sites. This site had a high basal area because it contained an estimated 4812 stems per hectare. The abundant small diameter stems may have masked the wet soil surface, reducing the potential high response that would have resulted if the wet soils had been more exposed. The low HV response suggests that the absence of larger trees may have been more important than high stem density in affecting volume scatter. The VV response was relatively high, perhaps indicating sensitivity to density of vertically oriented structures (tree branches and narrow crowns).

Hard-hardwood HV mean digital values were highest in all cases but one (site H6) where HH polarization had a slightly higher digital number compared to the cross-pole (Figure 6). In

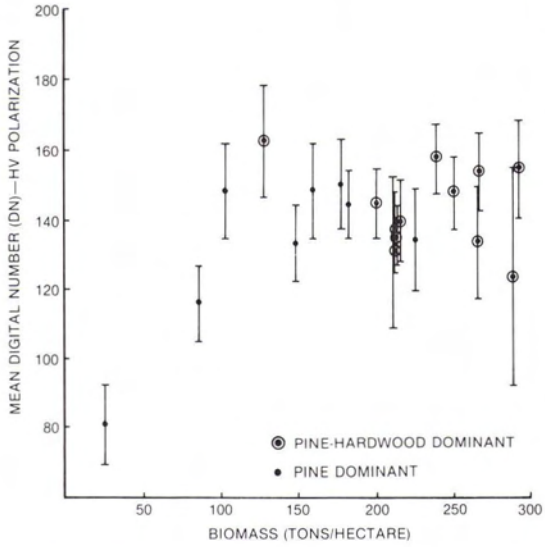

FIG. 4. Estimated biomass of pine and pine-hardwood stands and mean digital numbers of HV polarization data with one standard deviation.

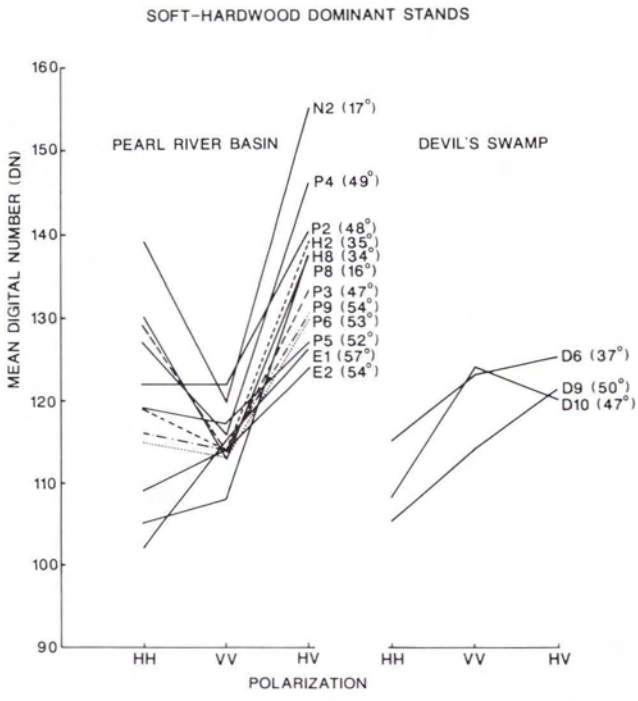

FIG. 5. Mean digital number of multipolarization L-band SAR data for 15 soft-hardwood dominant stands located at various incidence angles.

five out of seven cases the HH response was higher than VV. Site H6 is very similar to other nearby measurement sites in biomass, mean basal area, *dbh*, and stem density. The dissimilarity of this site compared to others was a low mean height of 11.6 m, compared to the next lowest hard-hardwood canopy of 13.1 m with a total biomass of 54 tons/ha lower than site H6. Site H6 had a uniform canopy structure with large diameter water oaks and very little understory. Pearl River hard-hardwoods had low HV/VV ratios compared to soft-hardwood sites. This can be attributed primarily to higher VV response of hard-hardwood sites: higher crown biomass compared to soft-hardwood sites may have contributed to this difference in VV response.

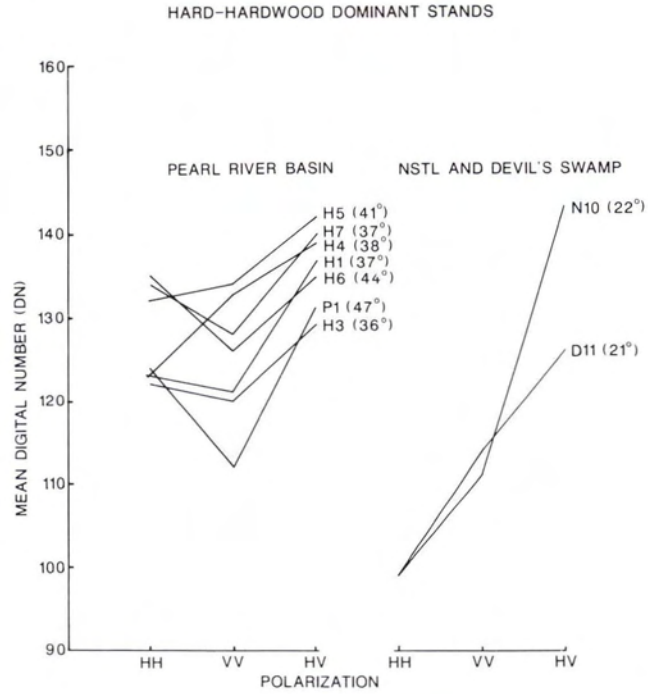

FIG. 6. Mean digital number of multipolarization L-band SAR data for nine hard-hardwood dominant stands located at various incidence angles.

LINEAR REGRESSION ANALYSIS

Linear regressions were performed to determine the degree to which each forest structure variable was correlated with multipolarization SAR data. There were few significant linear correlations between SAR data and individual forest structure variables of forest species composition groups (Table 3). Better results were achieved for pine dominant stands compared to other forest types. Correlation coefficients (r) were significant for biomass, mean height, *dbh*, and basal area for pine dominant stands using HV polarization only. The significance level achieved was $p=0.05$ for all but height which was significant at $p=0.01$. By combining all pine and pine-hardwood sites, the r values for HV polarization were significant at $p=0.05$ for biomass, and $p=0.01$ for height. Of the three ratioed polarizations tested, the HV/VV produced similar results compared to HV polarization. Pine *dbh* and HH/VV were significantly correlated at $p = 0.01$ ($r=0.87$), which was the only case where the ratio technique provided better results compared to HV polarization. All hardwood forest structure variables regressed against mean digital values of all SAR polarizations were nonsignificant except hard-hardwood *dbh* and VV polarization at $p=0.05$. As mentioned previously, the relatively high VV response for hard-hardwood sites may be attributed to high crown biomass and spreading branching patterns of large diameter oaks and hickories.

EFFECTS OF INCIDENCE ANGLE ON BIOMASS ESTIMATES

Mean incidence angle locations for all hardwood sites were 40.5 degrees ± 11.7 compared to pine and pine-hardwood sites located at 25.3° ± 7.4. Incidence angle effects on SAR data may have been masked to a certain extent by the variation in backscatter from differences in species composition and structure. Direct comparisons of relative radar backscatter between pine and hardwood sites cannot be made as a result of difference in incidence angle locations for the forest types. The penetration of SAR pulses at more acute angles to the moist soil surfaces was believed to have a strong influence on the multipolarization response for some pine and pine-hardwood stands.

Apparent angular dependencies were observed for SAR data. Some of the highest biomass sites were located at high incidence

TABLE 3. LINEAR CORRELATION COEFFICIENT (r) OF MULTIPOLARIZATION SYNTHETIC APERTURE RADAR DATA AND FOREST STRUCTURE OF SPECIES COMPOSITION GROUPS.

Species Composition	Polarization						Independent Variable
	HH	HV	VV	HV/VV	HH/VV	HV/HH	
Pine ($n=8$)	ns	0.76*	ns	0.75*	ns	ns	Green Weight Biomass
	ns	0.84**	ns	0.86**	ns	0.75*	Mean Height
	ns	0.76*	ns	0.82*	0.87**	0.71*	Mean dbh
	ns	0.79*	ns	ns	ns	ns	Mean Basal Area
HdSh ($n=9$)	ns	ns	0.72*	ns	ns	ns	Mean dbh

ns – nonsignificant at $p=0.05$
* Significant at $p=0.05$
** Significant at $p=0.01$
HdSh — Hard-hardwood/soft-hardwood

angles. The mean digital number of the HV polarization data appears to decrease beyond green weight biomass of approximately 290 tons/ha (Figure 7). However, peak values in all polarizations occurred for hardwood sites located near 41 degrees and decreased (10 to 15 counts) for sites located near 57 degrees. In this angular range, SAR data were negatively correlated with biomass, but this observation may be of minor consequence considering the high scatter in the data. Digital numbers of hardwood sites increased slightly from 34 to 41 degrees, and only this angular range produced significant positive linear correlation between biomass and HV polarization data ($r=0.72$, D.F. = 6, $P=0.05$). Linear correlations for pine-hardwood biomass of sample areas between 16° to 32° and 32° to 37° were nonsignificant.

ASYMPTOTIC RESPONSE OF RADAR TO BIOMASS CHANGES

Comparison of Figures 4 and 7 suggest a relationship between all forest types and HV radar data. The available data indicate an increase in radar return (DN) with increasing biomass up to approximately 100 tons/hectare. Above 100 tons/hectare the relationship becomes asymptotic, that is, a relatively constant DN with increasing biomass beyond 100 tons. Biomass at 100 tons/hectare or less were measured only in pine dominant stands, while no pine stands greater than approximately 225 tons/hectare were measured. A horizontal line can be passed through the error bars of the other three forest types and the highest biomass point for the pine stands where the relationship appears to follow the same trend. The same asymptotic relationship was observed using HH and VV polarization data. These data suggest

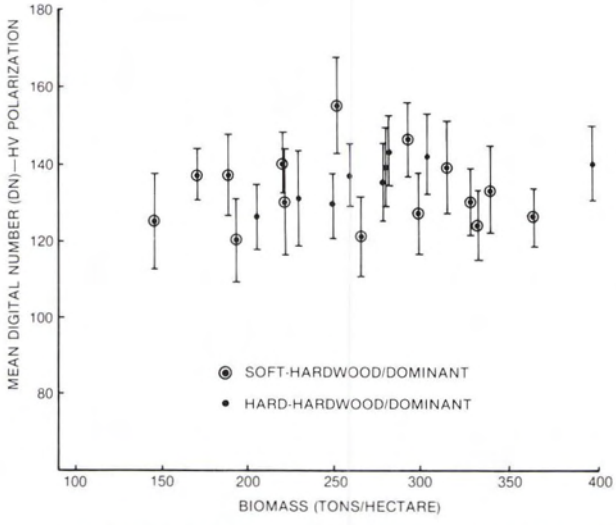

FIG. 7. Estimated biomass of soft-hardwood and hard-hardwood dominant stands and mean digital numbers of HV polarization data with one standard deviation.

that L-band radar was insensitive to biomass changes above approximately 100 tons hectare; however, the absence of an equal range of biomass data for all forest composition groups may be obscuring these relationships.

MULTIPLE LINEAR REGRESSION

Canopy roughness models have not been fully developed to explain the physical basis for SAR interaction in complex forest environments. In an attempt to integrate canopy characteristics, multiple linear regression was tested to analyze the effect of forest structure measurements on SAR data.

With four independent variables (biomass, height, *dbh*, and total stems), the correlation coefficient ($r=0.77$) for pine and pine-hardwood sites using HV and HV/HH polarization data was significant at $p=0.01$ (Table 4). Multiple linear regression using all stand structure variables provided an integrated expression of hardwood forest structure and achieved higher correlation (with HV/VV SAR data, $r=0.78$, $p=0.01$) than could be achieved using simple linear regression. The green weight of vegetation was not an effective variable to explain much variation in SAR polarization response for hardwood stands as was the case with other structure variables used in isolation. The improvement in r values and significance achieved at higher probability levels compared to linear regression suggested that SAR polarization response was affected by the volume scatter and multiple reflection that was better explained using three or four stand structure variables in addition to integrated biomass estimates of total green weight. The HV/VV ratio may have helped to isolate the canopy angular orientation properties of hardwood trees. The ratios did not improve the relationships or significance level for pine biomass and structure variables, in general.

The relationship between SAR data and forest structure may be better than the results of these analyses have shown. The problem rests with inadequate knowledge of the physical basis for these relationships and inadequate descriptors of canopy structure. In structurally non-uniform pine-hardwood, soft-hardwood, and hard-hardwood dominant stands, the use of whole stand mean digital numbers did not adequately typify the intra-stand variability that existed between various sites with similar biomass or similar structure but different biomass. Figure 8 (a and b) illustrates an example of forest sample areas (P4 and H5) with nearly equal total stand biomass but different species composition and structure. Sites E1 and H1 have equal mean *dbh* and nearly equal mean height for the total stand, but widely different structure and total biomass. Mean digital numbers for multipolarization SAR data vary considerably among these pairs, indicating the apparent effect of intra-stand species structural components on the radar response. Several other examples could be given to demonstrate this point. An integrated measure of this complex structure, or a measure of the projected area of the trees, may be a more relevant parameter than biomass (weight) and mean values of individual stand structure characteristics.

TABLE 4. MULTIPLE LINEAR CORRELATION COEFFICIENT (r) OF MULTIPOLARIZATION SYNTHETIC APERTURE RADAR DATA AND FOREST STRUCTURE VARIABLES OF SPECIES COMPOSITION GROUPS.

Species Composition	Polarization						Independent Variable (s)
	HH	HV	VV	HV/VV	HH/VV	HV/HH	
Pine and Pine-hardwood ($n=20$)	ns	0.77**	ns	0.75*	ns	0.77**	Biomass, mean height mean *dbh*, no. of stems (D.F. = 15)
All hardwood ($n=24$)	ns	ns	ns	0.78**	0.67*	ns	All five (D.F. = 18)
All Forest Stands ($n=44$)	ns	0.66**	ns	0.69**	ns	0.64**	All five (D.F. = 38)

ns – nonsignificant at $p=0.05$
D.F. - Degree of freedom
* Significant at $p=0.05$
** Significant at $p=0.01$

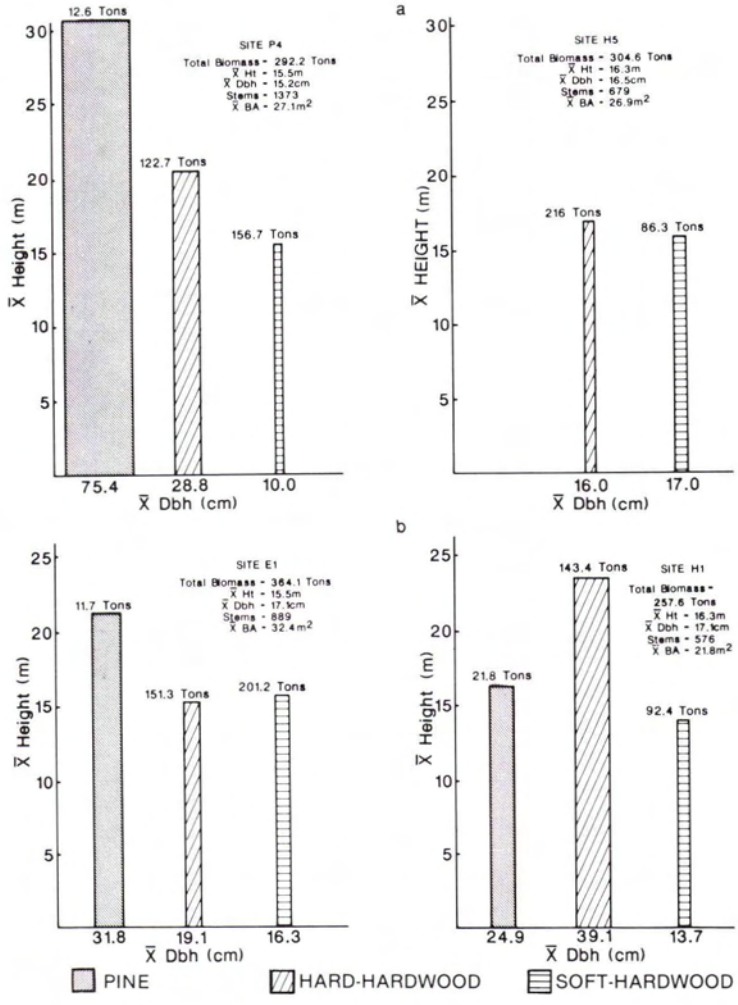

FIG. 8. Variation in species composition and structure for (a) a pair of hardwood forest stands with nearly equal total stand biomass and (b) a pair with widely different total stand biomass but nearly equal stand height and *dbh*.

SUMMARY AND CONCLUSIONS

Multipolarization synthetic aperture radar backscatter is influenced by the structure of the forest vegetation, including tree heights, diameters, spacing, orientation, and geometry. Factors believed to be of particular importance in influencing SAR polarization response in this investigation were

- Differences in canopy characteristics (branching patterns, crown weight, and area) between the hard hardwood and other forest composition groups;
- Variability in species composition and stand structure (heights, stem diameters, and density) within and between major forest composition groups;
- The distribution and amount of exposed wet soils and ground litter in some of the lower biomass and partially open forest sites; and
- Angular dependencies of SAR data collected from approximately 15 to 60 degrees off nadir.

Best results were achieved in pine plantations where strong relationships were observed between HV polarization and nearly all stand structures variables. The uniform canopy condition in

pine plantations should behave like Rayleigh scatterers, similar to agricultural crops, but this may not be the case with more complex pine-hardwood and hardwood forests. Non-uniform pine-hardwood and hardwood forests contained many scatterers of different types that influenced the SAR statistics. High HV response and large standard deviation to mean digital values were recorded in many of these structurally complex stands.

Hardwood forest structure variables did not explain much of the variation with multipolarized SAR data when the variables were tested separately in linear regression analysis. Scatter around regression lines was wide for SAR data, which may cast some uncertainty on their utility in predictive models of hardwood forest biomass.

Some of the relationships appeared to be non-linear, particularly hardwood biomass versus SAR polarization data. The radar data exhibited an asymptotic response to biomass increases beyond approximately 100 tons/hectare. Angular dependencies could be partially responsible for a negative relationship between SAR digital numbers and biomass above approximately 290 tons/ha. The best results for correlating hardwood biomass were achieved at incidence angles between 34 and 41 degrees using HV polarization. These results were difficult to interpret with only limited samples. More samples collected within narrow ranges of incidence angles (less than 10 degrees) would be recommended for future studies.

The terrain in the study area was nearly level and elevation range was very slight. Terrain was not considered to be an important factor except possibly as related to soil moisture. High soil moisture in poorly drained stands in Devil's Swamp appeared to influence SAR backscatter at lower incidence angles, especially when the forest canopies contained partial openings. The effect of surface moisture on multipolarization radar data was less apparent in high biomass stands primarily located at incidence angles greater than 30 degrees. The dense vegetation may have masked the surface moisture factor in these stands.

Ratios of SAR polarization data, particularly HV/VV, improved the relationship with five hardwood stand structure variables in multiple linear regression. The HV polarization yielded consistently high responses in mature forest conditions. The VV polarization was shown to be correlated to mean *dbh* in hard-hardwoods, yielding a relatively high response influenced by thick heavy branching and high crown biomass (directly proportional to stem *dbh*). The HV/VV ratio may have helped to isolate some of the hardwood canopy geometric orientation properties that also existed independently in both the HV and VV polarization. The use of SAR polarization ratio techniques should be investigated further to determine if improvement in definition of canopy structure can be achieved in other forest investigations.

Although multiple linear regression provided a better integrated measure of hardwood canopy structure, the use of mean values to describe forest biomass levels and stand structure characteristics was not optimal to typify the complexity and variation in forest composition and structure. Development of physical models of forest structure as a measure of canopy roughness would enhance future investigations of forest biomass using SAR data.

Results of this investigation are stated only in the context of scene dependent digital values on uncalibrated SAR data. Calibration and techniques for correcting uneven scene illumination and incidence angle effects are necessary for understanding the physical interaction of multipolarization SAR data with complex forest vegetation. Standardized procedures have not been developed for correction and calibration of the aircraft SAR data. Analysis of the aircraft SAR data without calibration and appropriate scene illumination correction may result in false conclusions concerning the utility of SAR for forest biomass estimation. Qualitative studies may be less affected by uncorrected and uncalibrated data such as visual interpretation of broad land-cover types of mapping of forest and non-forest zones for monitoring deforestation in the tropics.

ACKNOWLEDGMENTS

The project was supported by NASA-Terrestrial Ecosystems Program, RTOP 677-27-01. Special thanks to Sharon Hatch and Chris Swalm (Lockheed-EMSCO) for field data collection and data processing support, respectively. Other assistance provided by Jeff Luvall, Charlotte Timmons, and Janet Austill was greatly appreciated. Diana Lieberman and three anonymous reviewers offered helpful editorial comments concerning the manuscript.

REFERENCES

Attema, E. P. W., and F. T. Ulaby, 1978. Vegetation modelled as a water cloud. *Radio Sci.*, 13 (2): 357–364.

Avery, T. E., 1967. *Forest measurements*. The American Forestry Series, H. J. Vaux-Consulting Editor, McGraw-Hill Inc., New York, 290 p.

Avery, T. E., and H. E. Burkhart, 1983. *Forest Measurements*, McGraw-Hill, New York.

Blom, R. G., and M. Daily, 1982. Radar image processing for rock-type discrimination, *IEEE Transactions on Geoscience and Remote Sensing*, Vol. GE-20, No. 3, pp. 343–351.

Brown, S., and A. E. Lugo, 1982. The storage and production of organic matter in tropical forests and their role in the global carbon cycle. *Biotropica* 14(3): 161–187.

———, 1984. Biomass of tropical forests: A new estimate based on forest volumes. *Science*, Vol. 223, pp. 1290–1293.

Clark, A. C., T. M. Burgan, R. C. Field, and P. E. Dress, 1985a. *User's manual for total-tree multiproduct cruise program*. USDA-Forest Service, Southeastern Forest Expt. Sta. Gen. Tech. Report SE-31, Asheville, N.C., 64 p.

Clark, A., D. R. Phillips, and Douglas J. Frederick, 1985b. *Weight, volume and physical properties of major hardwood species in the Gulf and Atlantic coastal plains*. USDA - Forest Service, Southeastern Forest Experiment Station, Res. paper, SE-250, 66 p.

Evans, D. L., T. G. Farr, J. P. Ford, T. W. Thompson, and C. L. Werner, 1986. Multipolarization radar images for geologic mapping and vegetation discrimination, *IEEE Transactions on Geoscience and Remote Sensing*, Vol GE-24, No. 2, pp. 246–256.

Ford, J. P., and D. E. Wickland, 1985. Forest discrimination with multipolarization imaging radar. *Int. Geoscience and Remote Sensing Symposium Proceedings (IGARSS '85)*, 7–9 Oct., Univ. of Mass., Vol. 1, pp. 462–465.

Fung, A. K, 1979. Scattering from a vegetation layer. *I.E.E.E. Trans. Geosci. Electron.* 17, 1.

Graham, M. H., B. G. Junkin, M. T. Kalcic, R. W. Pearson, and B. R. Seyfarth, 1980. *Earth Resources Laboratory Applications Software (ELAS)*. NASA-NSTL-Earth Resources Laboratory, Report No. 183.

Hoekman, D. H., Krul, and E. P. W. Attema, 1982. A multilayer model for radar backscattering from vegetation canopies. *Proc. of the International Geoscience and Remote Sensing Symposium*, Munich, 1–4 June, 1982, Vol. 2, TA-1, pp. 4.1–4.7.

Hoekman, D. H. 1985. Radar backscattering of forest stands. *Int. J. Remote Sensing*, Vol. 6, No. 2, pp. 325–343.

Hoffer, R. M., S. E. Davidson, P. W. Mueller, and D. F. Lozano-Garcia, 1985. A comparison of X- and L-band radar data for discriminating forest cover types. *Proc. of Pecora 10 — Remote Sensing in Forest and Range Resource Management*, 20–22 Aug. 1985, Colorado State University, Fort Collins, Co., pp. 578–592.

Holdridge, L. R., W. C. Grenke, W. H. Hatheway, T. Liang, and J. A. Tosi, Jr., 1971. *Forest environments in tropical life zones: a pilot study*. Pergamon Press, New York, 747 p.

Lanly, J., 1982. *Tropical Forest Resources*. Food and Agr. Organization of United Nations, FAO Forestry paper 30, FAO-UNEP, 106 p.

Mueller, P. W., R. M. Hoffer, and D. F. Lozano-Garcia, 1985. Interpretation of forest cover on microwave and optical satellite imagery. *Proc. of Pecora 10 — Remote Sensing in Forest and Range Resource Management*, 20–22 Aug. 1985, Colorado State University, Fort Collins, Co., pp. 578–592.

Ormsby, J. P., B. J. Blanchard, and A. J. Blanchard, 1985. Detection of lowland flooding using active microwave systems. *Photogrammetric Engineering and Remote Sensing*, Vol. 51, No. 3, pp. 317–328.

Pampaloni, P., and S. Paloscia, 1985. Experimental relationships be-

tween microwave emission and vegetation features. *Int. J. Remote Sensing*, Vol. 6, No. 2, pp. 315–323.

Paris, J. F. 1985a. Active microwave properties of vegetation canopies. *Fundamental Remote Sensing Science Research Program. 1985 Summary Report of the Scene Radiation and Atmospheric Effects Characterization Project*, D. W. Deering, 1985. NASA Tech. Memo. 86234, pp. 148–154.

———, 1985b. On the use of L-band multipolarization airborne SAR for surveys of crops, vineyards and orchards in a California irrigated agricultural region. *NASA/JPL Aircraft SAR Workshop Proceedings*, 4–5 Feb. 1985, JPL Pasadena, Ca., Jpl Publication 85-39, 15 June 1985. p. 63.

Phillips, D. R., and J. R. Saucier, 1981. *Cruising procedures for estimating total stand biomass*, Georgia Forest Research paper, No. 14, Georgia Forestry Commission, 7 p.

Riom, J., and T. Le Toan, 1981. Relations entre des types de forests de pins maritimes et ra retrodiffusion radar en bande L. *Digest of ISP, Spectral Signatures of Objects in Remote Sensing*, Auigon, France.

Sader, S. A., A. T. Joyce, R. B. Waide, and W. T. Lawrence, 1985. Monitoring tropical forests from satellite and aircraft platforms: some limitations and new approaches. *Proc. of Pecora 10 — Remote Sensing in Forest and Range Resource Management*, 20–22 Aug. Fort Collins, Co., pp. 473–482.

Sieber, A. J., 1985. Statistical analysis of SAR images. *Int. J. Remote Sensing*, Vol. 6, No. 9, pp. 1555–1572.

Thompson, T. W., 1983. *A user's manual for the NASA/JPL synthetic aperture radar and the NASA/JPL L- and C-band scatterometers*, JPL publication 83-38.

Ulaby, F. T., and E. A. Wilson, 1985. Microwave atenuation properties of vegetation canopies. *IEEE Trans. on Geosci. and Remote Sensing*, Vol. GE-23, No. 5, ISSN 0196-2892, pp. 746–753.

White, D. A., 1979. *Plant communities of the lower Pearl River Basin*. Unpublished Ph.D. dissertation, Department of Biology, Tulane University, 153 pp.

Whittaker, R. H., and G. E. Likens, 1973. Carbon in the biota. *Carbon and the Biosphere*, G. M. Woodwell and E. V. Pecan (eds.), U. S. Atomic Energy Commission. Conf-720510, Nat. Tech. Inf. Serv., Springfield, Virginia, pp. 281–302.

Wu, S. T., 1981. *Analysis of results obtained from integration of Landsat multispectral scanner and Seasat synthetic aperature radar data*, NASA-NSTL Report No. 189, 53 p.

———, 1984. *Analysis of data acquired by shuttle imaging radar and Landsat-4 thematic mapper over Baldwin County, Alabama*. NASA-Earth Resources Laboratory, Report No. 228, NSTL, MS, 27 pp.

———, 1985. A preliminary report on the measurements of forest canopies with C-band radar scatterometer at NASA/NSTL. *Proc. of International Geoscience and Remote Sensing Symposium (IGARSS '85)*, 7-9 Oct. 1985, Univ. of Mass., Vol. 1, pp. 168–173.

(Received 6 January 1986; revised and accepted 12 September 1986)

Publications Available

Proceedings of the Second International Symposium on Spatial Data Handling. Available for $40.00 including shipping ($35.00 if check in U.S. dollars accompanies order) from IGU Commission on Geographical Data Sensing & Processing, P. O. Box 571, Williamsville, NY 14221. Checks should be drawn to the order of IGU Comm. on Geog. Data Sensing & Processing.

Nearly 50 technical articles are contained in this over 600-page volume. Included, among others, are papers from sessions on "Quadtree Representations of Spatial Data," "Automated Name Placement," "Storage and Accuracy of Digital Elevation Models," "Relational Database Approaches to GIS," and "Expert Systems for Spatial Data."

Proceedings of the First International Symposium on Spatial Data Handling. Available for $30.00 including shipping from Prof. Kurt Brassel, Geographisches Institut, Universität Zürich - Irchel, 8057 Zürich, Switzerland.

Proceedings, Auto Carto London, M. J. Blakemore (ed.). Available for £40.00 (£20.00 to libraries in *bona fide* educational organizations) from the Royal Institution of Chartered Surveyors (Land Surveyors Division), 12 Great George Street, London SW1P 3A, United Kingdom.

One hundred fifteen "long papers," 20 short papers, and 30 poster presentations were given at the Auto Carto London Conference, held 14-19 September 1986. The full text of the long papers and abstracts of the short ones were published in the *Proceedings*.

French - English Glossary on SPOT, Remote Sensing and their Applications (Working Document), S. Dyson. May be ordered from S. Dyson, "Bouygues", Miramont-de-Quercy, 82190 Bourg-de-Visa, France.

The *Glossary* contains over 3,500 entries; ten separate "mini-glossaries" on major applications of remote sensing; extensive referencing to source documents; useful annexes with lists of acronyms, official (50-entry) SPOT vocabulary, diagrams, and texts concerning the SPOT system; and an airy layout with plenty of room for additional notes and entries. Updates, including feedback received from purchasers, are planned.