EFFECT OF POLARIZATION ON RADAR BACKSCATTER IN RELATION TO SLASH PINE STAND BIOMASS USING AIRCRAFT AND SIR-B DATA

Yousif Ali Hussin
International Institute for Aerospace Survey
and Earth Sciences (ITC)
Enschede, The Netherlands

Robin M. Reich and Roger M. Hoffer
Department of Forest Sciences
Colorado State University
Fort Collins, CO 80523, USA

Abstract:

L-band multipolarized (i.e. HH, VV, VH and HV) multiple incidence angle aircraft Synthetic Aperture Radar data were analyzed in relation to the biomass and other stand parameters (e.g. basal area, diameter at breast height, tree height, and stand volume) for 35 slash pine plantations. The purpose was to determine if there are statistically significant relationships between slash pine stand biomass or other stand parameters and L-band (24.5 cm.) radar backscatter, and if so, to determine the effect of radar polarization on such relationships. The study site in northern Florida has very little topographic relief, thereby minimizing the effects of topography on the radar backscatter. The results show significant correlation between the cross polarized (e.g. HV and VH) and VV-polarized radar data and biomass, as well as several of the other stand parameters. The correlation between the HH-polarized data and the stand parameters was very low. These results indicate that future Shuttle Imaging Radar Systems (e.g. SIR-C, which will have cross-polarized radar sensors) should be able to obtain better results in attempting to estimate forest biomass than were obtained with previous satellite radar missions which obtained only HH- polarized SAR data.

KEY WORDS: Forestry, Radar, SAR, Forest Stand Parameters, SIR-B.

1. INTRODUCTION

It is generally accepted that biomass refers to the amount of living matter, couched in terms of unit area or volume, in the habitat in which the plant occurs. For the purpose of this study forest biomass is defined as the total weight (or mass) of a tree which includes the bole, limbs, branches, and leaves. Estimates of biomass are important for two reasons. First is the increasing emphasis on complete tree utilization and the use of wood as a source of energy or raw material for producing wood products (e.g. paper, furniture, etc.). Second is the fact that forest biomass (e.g. leaves, branches, etc.) and the organic matter stored in the forest soil as a result of forest growth, control the rate of the exchange of carbon dioxide (CO_2) between the forest and the atmosphere. This is a very important issue in terms of its potential influence on global climate changes, especially in tropical regions. It has been found that the amount of CO_2 in the atmosphere has increased by 40-80 parts per million since 1860 (Woodwell, 1984). Since biomass is generally expressed in terms of dry weight of the above ground portion of the tree, it is very difficult to measure in the field. Consequently, researchers tend to estimate forest tree biomass using several sampling techniques, such as the basal area ratio method (Madgwick , 1981), sub-sampling with regression (Valentine et al., 1984), or remote sensing (field spectral data, MSS and TM Landsat Data, AVHRR data, and Synthetic Aperture Radar data) techniques (Tucker, 1979; Tucker et al., 1981; Tucker et al., 1983; Markham et al., 1981; Holben et al., 1980; Hoffer et al., 1986).

Several recent studies have attempted to evaluate the relationship between the forest biomass and radar backscatter, based on satellite and aircraft data, using various combinations of incidence angles and polarizations (Hoffer et al., 1986; Wu and Sader, 1986; Wu, 1987; Sader, 1987; Wu, 1988; Hussin and Hoffer, 1989). Hoffer et al. (1986) showed a significant relationships between radar backscatter of L-band HH-polarized SIR-B satellite data and various forest stand characteristics, (i.e., age, cords/acre, biomass), and stand age. Riom and LeToan (1981), using L-band, HH polarized data, showed a similar relationship between radar backscatter, tree height and forest stand age. Sader (1987), working with L-band quad polarized data, found a high correlation between forest stand parameters such as height, DBH, and BA, and radar backscatter of L-band HV-polarized data. No significant relationship was observed between these stand characteristics and either of the like-polarized (HH or VV) data. Wu (1987a) found no significant correlation between height and radar backscatter for any polarization but a highly significant correlation with age. In another paper, Wu (1987b) reported that no particularly meaningful correlation existed between height and BA and radar backscatter at any polarization. Hussin and Hoffer (1989), using multipolarized L-band data at 35-45° incidence angle data, concluded that there were statistically significant relationships between the radar backscatter and DBH, volume, basal area, height, density and age for slash pine plantations. The correlation was significantly influenced by the polarization, with the HV polarized data having the highest correlation with the stand parameters.

The objectives of this study were to :

- Determine if there are statistically significant relationships between radar backscatter and slash pine stand biomass.

- Develop a mathematical model for predicting biomass on a per acre basis as a function of radar backscatter.

2. MATERIALS AND METHODS

2.1 Test Site Description

The test site is located in north eastern Florida, approximately 55 km west of Jacksonville. There is very little topographic relief in this area. The soils are mostly sandy and poorly to somewhat poorly drained. There are many swamps in the area having very poor drainage (Avers & Bracy, 1974). The climate of the area is humid subtropical with its high rainfall rate between June and September when the temperatures also reach the highest levels of the year (Howell et al., 1984).

A large part of the area is owned by three forest products companies and managed for the production of pulpwood and saw timber. The most common species in the study area is slash pine (*Pinus elliottii*). In the cypress swamps the dominant species are pond cypress (*Taxodium distichum var. nutans*), and bald cypress (*Taxodium distichum*). The mixed deciduous swamp areas are dominated by water tupelo (*Nyssa aquatica*), red maple (*Acer rubrum*), sweet gum (*Liquidambar styraciflua*) and water oak (*Querqus nigra*).

2.2 Data Utilized

Synthetic aperture aircraft radar data having an 11x11 meter ground resolution were obtained on September 14, 1984 from an altitude of 8000 meters. The incidence angle varied from 10 degrees for the earliest echos at near nadir to 55 degrees for the last echos at the farthest range of the scene. The L-band (24.5 cm) data were obtained by the NASA/Ames CV-990 Airborne Laboratory using the NASA/JPL aircraft SAR system capable of obtaining digital format data simultaneously for four polarizations (HH, VV, VH, & HV).

Color infrared photos (1:58,000) were available for this test site on two dates -- January 24, 1983 and February 5, 1984. The photos, obtained as part of the National High Altitude Photography (NHAP) program were used to locate the forest stands used to develop and validate the models.

A cloud-free frame of Landsat-5 Thematic Mapper data was collected on October 12, 1984. As of this date, the characteristics of the land cover were still about the same as they had been a month earlier when the radar data had been obtained. Therefore, the TM data was also used to help in the interpretation and to locate the forest stands.

1:24,000 scale forest stand boundary maps, which had been prepared by the companies that owned the forest lands, were a key element of the reference data used in this study. Both 7.5 minute and 30x60 minute USGS topographic maps (scale 1:24,000 & 1:100,000) were also utilized.

Forest inventory data that was related to the forest stand boundary maps had also been prepared by the forest products companies, and included, for each stand, the forest type, species, age classes, diameter classes, tree height, basal area per acre, density (number of trees per acre), and volume (cords per acre). This information was used to compare forest stand parameters to quad-polarized radar backscatter.

2.3 Stand Selection

An ERDAS image processing software and hardware system was used to locate, on the radar imagery, stands for which we had forest stand data. Fields selected were generally about 100-150 pixels in size. Since the radar backscatter is strongly influenced by differences in the incidence angle, a narrow strip having a 10 degree range of incidence angles was selected for the analysis. An incidence angle range from 35° to 45° was chosen for two reasons: first, because of the availability of field data and measurements on this particular part of the imagery, and secondly, because this is an intermediate range of incidence angles such that the penetration of the radar signal through the canopy would be moderate -- not as high as is the case at smaller incidence angles, nor as low as in the high angle range. Some earlier studies had indicated that the 35-45° range of incidence angle was better than either a steeper or shallower incidence angle when working with SAR data of forest canopies in this area (Wu, 1987b; Hoffer and Hussin, 1989;and Hussin and Hoffer 1989).

2.4 Forest Stand Biomass Measurement

The "Total-Tree Multiproduct Cruise Program" developed by US Forest Service-Southern Forest Experimental Station and the School of Forestry at the University of Georgia and was used to estimate the stand biomass for this study (Clark et al., 1985a and Clark et al., 1985b). The regression equations with the program are considered to be the best available, and have been used by other researchers to estimate the forest stand biomass of slash pine in the south-east (Sader, 1987 and Wu, 1987b).

2.5 Statistical Analysis

To test the relationships between the forest stand biomass or other parameters and the radar backscatter, correlations were determined for all four polarizations and stand parameters. This preliminary study showed that, in general, the HV polarized radar backscatter had a higher correlation with the varoius stand parameters of interest than any of the other polarizations, particularly the like-polarized data (i.e., HH or VV). Theoretically, the VH and HV cross-polarized data should have the same backscatter. In light of these results it was decided that the remainder of the current study would deal only with the HV polarized data set.

2.6 Model Development

For unthinned slash pine plantations, it is assumed that biomass (B) is directly related to the cubic foot volume which can be expressed as a function of the basal area per acre (BA) and the average stand height (H). In functional form this appears as

$$\hat{B} = f(BA,H). \qquad [Eq\ 1]$$

This form is not concerned with forecasting biomass, since both BA and H must be known. However, if predicted values are substituted in place of known values, the model can be used to estimate biomass. Therefore, if we assume that both BA and H can be described using radar backscatter (RB), we will obtain a system of equations with the following functional form:

Model 1

$$\hat{BA} = f(RB)$$
$$\hat{H} = f(RB)$$
$$\hat{B} = f(\hat{BA}, \hat{H}). \qquad [Eq\ 2]$$

This system of equations can be used to estimate BA, H and B directly from radar data. In some instances, however, information may be available on BA. In this case, the system of equations reduce to

Model 2

$$\hat{H} = f(RB)$$
$$\hat{B} = f(BA, \hat{H}) \qquad [Eq\ 3]$$

where H is estimated from the radar data. Finally, if information is also available on H, the system of equations would reduce to equation [1]. Thus, depending on the type of information available, one can select the system of equations that best suits their need.

2.7 Model Fitting

Prior to fitting the models, the data was split into two independent data sets of approximately equal sizes. One data set was used to develop the model while the second data set was used to validate the models.

In order to study the relationship between the radar backscatter and the forest stand biomass and the other parameters and to develop the regression models that can be used to predict the forest stand parameters from the radar backscatter, 35 slash pine plantation stands between 6 and 31 years of age were selected. A completely independent data set of 20 slash pine plantation stands having almost the same characteristics as the first data set were selected as a validation data set to test the models . Table 1 shows the characteristics of both the model development data set and the validation data set. The 1985 U.S. Forest Service inventory information and the measurements from the forest products companies who own the property were used as the data base for the forest stand parameters.

Table. 1 The Characteristics of the Model Development and Validation Data Sets.

Model Development Data Set.

Variables	Average	Std. dev.	Min.	Max.
Biomass (lb/a)	138284	48927	30981	212327
Height (ft.)	48.97	10.62	16	61
DBH (in.)	6.04	1.1	2.78	7.42
BA (sq.ft./a)	83.19	22.65	26.16	116.95
Age (years)	20.97	6.57	6	31

Validation Data Set.

Biomass (lb/a)	135912	50574	40570	221179
Height (ft.)	48.35	10.36	18	61
DBH (in.)	5.96	1.07	3.38	7.50
BA (sq.ft./a)	84.05	25.66	33	137
Age (years)	20.50	6.69	6	31

3. RESULTS AND DISCUSSIONS

3.1 Aircraft Radar Backscatter in Relation to Stand Parameters

The coefficients for both systems of equations [2 and 3] for the developmental data set were estimated using three-stage least squares (3SLS) after a suitable transformation. The resulting coefficients are shown in Tables 2 and 3. Both models generated predicted values that matched well with the observed values for the independent set of data (Table 4). As one would expect, the system in which information on BA was available fit better than the system in which BA was estimated.

Table 2 shows the first set of the regression models developed to predict biomass, DBH, and height using the radar backscatter. The model assumes that basal area is measured in the field. Figures 1,2,3, and 4 show the relationship between the radar backscatter and the untransformed predicted biomass and the other stand parameters (i.e. basal area, height, and DBH) using both sets of models. Comparing these results with those of Hussin and Hoffer (1989) using the same data sets, it became very clear that the transformation had significant affects of the on the relationship between the radar backscatter and the forest stand parameters. Both sets of equations accounted

Table. 2 The Coefficients for Model 1.

Variables	$(Biomass)^{-1/2}$	$1/(DBH)^2$	HT^{-1}	$(BA)^{-1/2}$
n	35	35	35	35
MSE	<0.001	<0.001	<0.001	<0.001
R^2	0.977	0.807	0.984	0.828
Constant	-0.00085	1.00907	0.04655	0.50702
RB	———	0.00959	-0.00064	-0.00440
RB^2	———	2.57E-5	2.23E-6	1.13E-5
HT^{-1}	0.16593	———	———	———
$BA^{-1/2}$	0.03210	———	———	———

Table. 3 The Coefficients for Model 2.

Variables	$(Biomass)^{-1/2}$	$1/(DBH)^2$	HT^{-1}
n	35	35	35
MSE	<0.001	<0.001	<0.001
R^2	0.977	0.807	0.986
Constant	-0.00066	1.01382	0.07418
RB	———	-0.00969	-0.00137
RB^2	———	2.61E-5	8.46E-6
RB^3	———	———	-1.71E-8
HT^{-1}	0.18894	———	———
$BA^{-1/2}$	0.03033	———	———

Table. 4 Bias and Sampling Error Percentages of Model 1 & 2.

	Model 1 (BA Estimated)			Model 2 (BA Measured)		
Variables	**% Bias**	**% Sampl. Error**	**Bias/ RMSE**	**% Bias**	**% Sampl. Error**	**Bias/ RMSE**
Biomass (lb/a)	0.976	3.271	0.298	0.804	2.543	0.316
Height (ft)	4.171	5.417	0.770	2.934	2.694	1.089
DBH (in)	1.089	2.257	0.482	0.965	2.232	0.432
BA (ft^2/a)	1.204	3.636	0.331	――	――	――

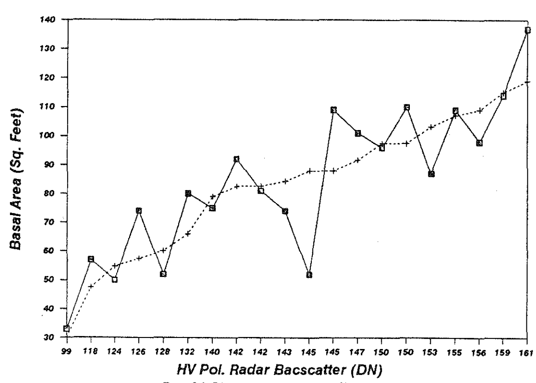

Figure 1. Relationship between measured and estimated basal area and HV radar backscatter.

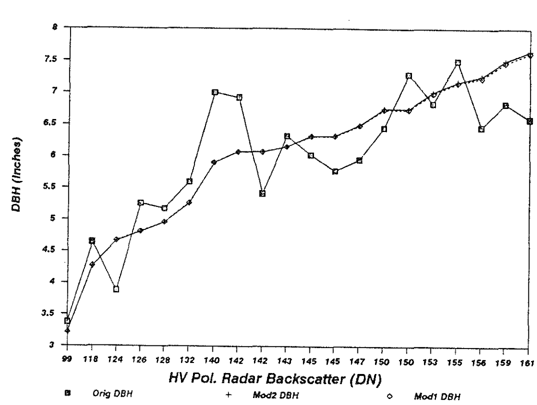

Figure 2. Relationship between measured and estimated DBH and HV radar backscatter.

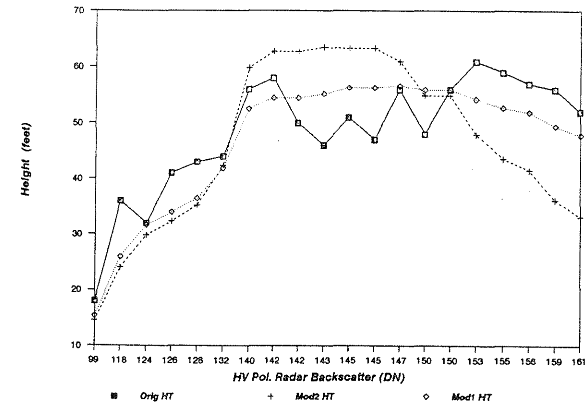

Figure 3. Relationship between measured and estimated heights and HV radar backscatter.

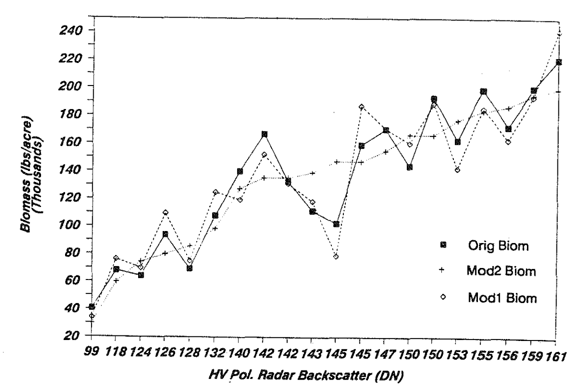

Figure 4. Relationship between measured and estimated biomass and HV radar backscatter.

for more than 97% of the variation in biomass (Table 2 and 3). However the R^2 values for the DBH and basal area models were less than 83% for both models.

The relationships between the HV polarized radar backscatter and stand biomass, height, basal area, and DBH for stands from 6 to 31 years old are depicted in Figures 1-4. In general, the tree height, DBH and biomass tends to increase more rapidly in stands from 6 to 19 years old and then levels off. The leveling off is due to crown closure. In examining Figures 1-4, one can see the effects of such changes in the stands on the radar backscatter. It would seem that as crown closure becomes more complete, there is less of the incoming radar signal being scattered down inside the canopy so there is less interaction between the radar signal and the individual trees, and thus there is not quite as strong a relationship between the radar backscatter and the various stand parameters. The data in Figures 1-4 would appear to support such a hypothesis.

Frome the results shown in Figures 1-4 and Tables 2-4, it is clear that there exist some very strong relationships between the measured stand parameters (i.e., tree height,DBH, basal area and biomass)and the estimated stand parameters based on the HV radar backscatter. As shown in Figures 1-4, the estimated values are very close to the measured values, which is very encouraging. As one would expect, the Model 1 results for biomass estimates were closer to the measured values than were Model 2 results (Model 1 results were based on basal area measured in the field whereas Model 2 results were based on estimated basal area).

Ultimately, the scientific community is looking for the ways to use satellite radar data to estimate forest biomass, and to determine if such an approach is even possible. The fact that these results show such good relationships between the HV polarized radar backscatter and slash pine stand biomass, as well as other stand parameters, is very encouraging.

3.2 A Comparison Between Satellite (SIR-B) and Aircraft Radar Backscatter in Relation to Stand Parameters

The twenty 6-31 year old slash pine stands that were used to produce the results in Section 3.1 were used again with HH-polarized SIR-B data to compare the satellite to the aircraft radar data in relation to stand parameters. Because the SAR aircraft data was not registered to SIR-B or to the Landsat TM data, approximately the same portion of each stand was delineated on both the aircraft and SIR-B data to produce the results in Sections 3.1 and 3.2. Figures 5-11 show the relationships between the 28°, 45°, and 58° incidence angle HH-polarized SIR-B data and forest stand parameters (i.e. age, height, DBH, number of trees per acre, volume (cords/acre), basal area, and biomass). Table 5 shows the correlation coefficients for the above relationships. The correlation coefficients in Table 5 indicate that, of the three incidence angles evaluated for the SIR-B data, the 45° data set had the highest r values. This is consistent with the aircraft results in Section 3.1 which indicated that the 35-45° range of incidence angles was better than either higher or lower incidence angles for classifying forest and other cover types. The correlation coefficients for the 45° SIR-B data are generally somewhat similar to those for 6-31 year old slash pine stands within the 35-45° range of incidence angles in the aircraft data (except for the height correlations, which were much better on the SIR-B data). Of particular significance, however, is the fact that the results shown by Hussin and Hoffer (1989) indicate that the HH-polarization is not as good as any of the polarizations having a vertical component (i.e., VV, HV, or VH) for relating SAR backscatter to forest stand parameters. This would imply that if the SIR-B data had been obtained with a VV, HV or VH polarization rather than the HH polarization used, perhaps the results shown in Table 5 for the SIR-B data would have been much better. It should also be noted that Hoffer et al. (1986) and Lee and Hoffer (1990) studied the relationship between forest stand parameters and radar backscatter of SIR-B data, and found better correlation coefficients than shown in Table 5.

Table 5. Correlation coefficients for the 6-31 year old pine plantation data, comparing the forest stand parameters and different incidence angles of HH-polarized SIR-B backscatter.

Stand Parameters	Radar Backscatter of Different Incidence Angles		
	28°	45°	58°
Age	0.56	0.63*	0.55
DBH	0.36	0.66*	0.39
Basal Area	0.24	0.48	0.24
Height	0.35	0.736*	0.732*
Cords/Acre	0.19	0.56	0.56
Trees/Acre	-0.51	-0.47	-0.45
Biomass	0.37	0.47	0.45

* significant at the .05 level of significance

It is believed that the difference is because of the relatively small number of stands which were available for this study, due to the limited area covered by the 35-45° incidence angle swath of the aircraft data.

4. CONCLUSION

- There are good positive relationships between HV polarized radar backscatter using aircraft data and slash pine stand parameters (i.e., biomass, height, basal area, and DBH).

- These results indicate that the stand parameters can be estimated with resonable accuracy using the L-band HV-polarized radar data.

- HV polarization had better correlation with stand parameters than the other polarizations.

- Using SIR-B multiple incidence angle HH-polarized data, only moderate relationships were found with the various stand parameters (e.g. DBH, volume (cords/acre), number of trees per acre, age, biomass, and basal area).

- The poor (if any) relationships shown between forest stand parameters and the HH-polarized aircraft data provides same interesting insight into the limitation of working with the HH-polarized L-band SIR-B satellite data, and indicates the potential benefits expected from the cross-polarized data that will be obtained during the SIR-C mission.

- The system of equations presented in this study, when combined with an appropriate inventory design, could provide efficient estimates of the Total Biomass (T_B) on a regional scale. Because of the case in which basal area can be measured in the field using variable plot sampling and the importance of basal area in estimating biomass on a per acre basis, some form of double sampling with regression would probably be the best design.

- Further work is needed to test the feasibility of developing similar models for natural stands and for older age classes of plantations. Additional work is also needed to verify these results using sattelite SAR data, rather than using aircraft data as was done in the current study.

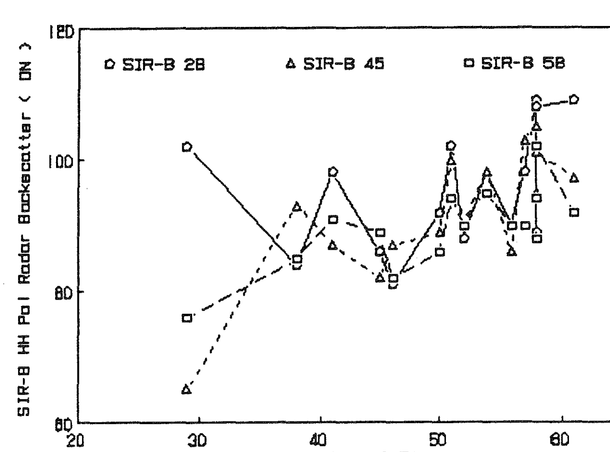

Figure 5. SIR-B multiple incidence angle HH-polarized radar backscatter from 6-31 year old slash pine plantations in relation to height.

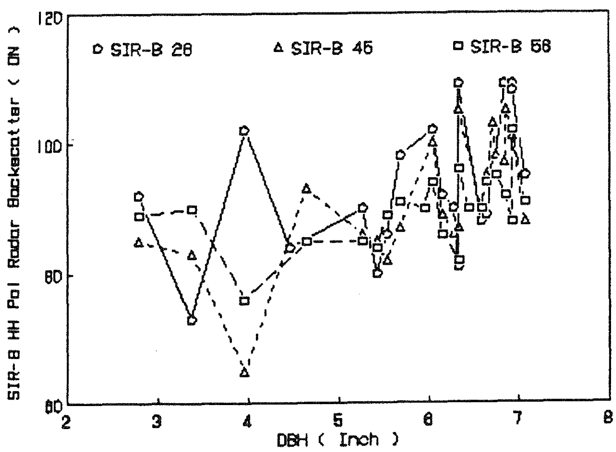

Figure 6. SIR-B multiple incidence angle HH-polarized radar backscatter from 6-31 year old slash pine plantations in relation to DBH.

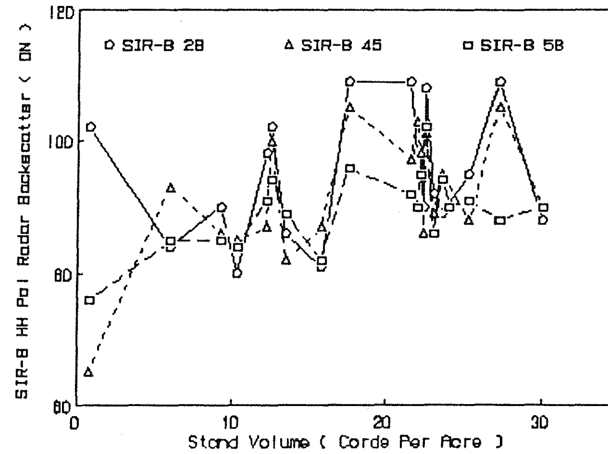

Figure 9. SIR-B multiple incidence angle HH-polarized radar backscatter from 6-31 year old slash pine plantations in relation to volume cords per acre.

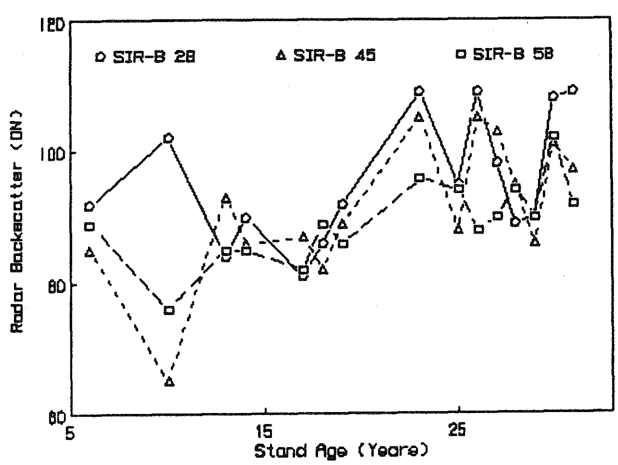

Figure 7. SIR-B multiple incidence angle HH-polarized radar backscatter from 6-31 year old slash pine plantations in relation to age.

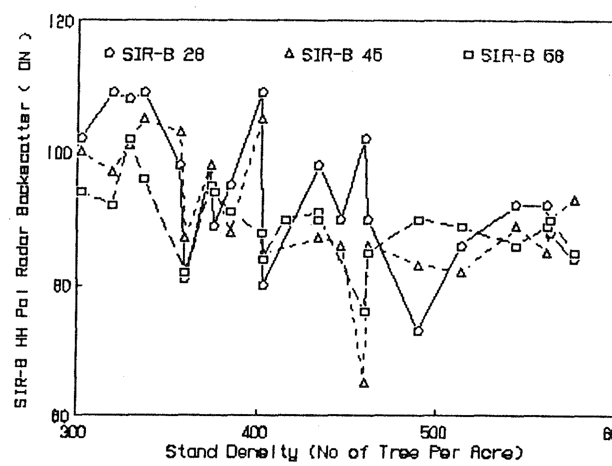

Figure 10. SIR-B multiple incidence angle HH-polarized radar backscatter from 6-31 year old slash pine plantations in relation to number of trees per acre.

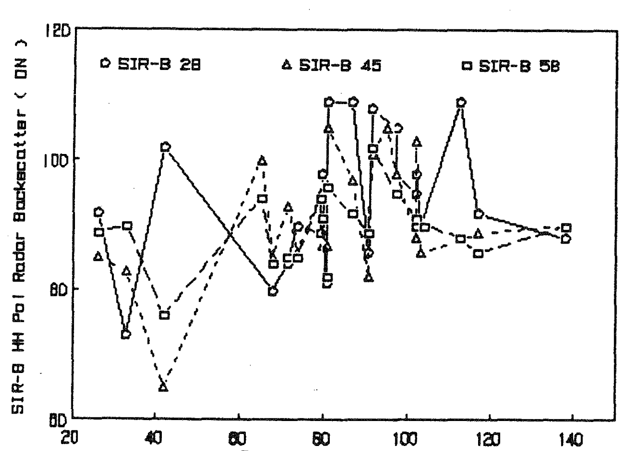

Figure 8. SIR-B multiple incidence angle HH-polarized radar backscatter from 6-31 year old slash pine plantations in relation to basal area.

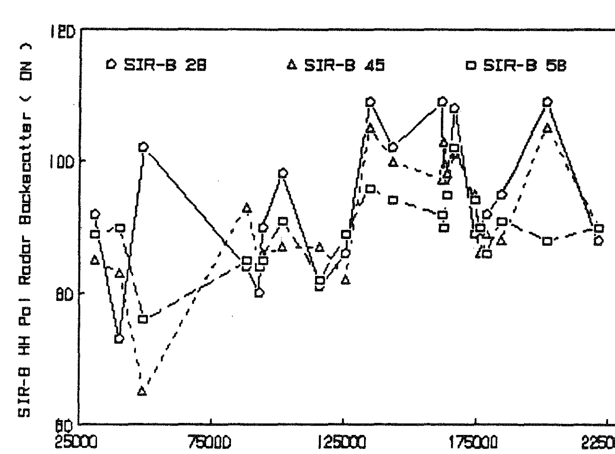

Figure 11. SIR-B multiple incidence angle HH-polarized radar backscatter from 6-31 year old slash pine plantations in relation to biomass.

5. ACKNOWLEDGEMENTS

This research was conducted under J.P.L. (Jet Propulsion Lab, Pasadena, CA.) Contract 9569552 as part of NASA Contract NSA-7-918. The authors express their appreciation to the J.P.L. engineers for their preprocessing of the radar data, and to the foresters of the U.S. Forest Service and Owens-Illinois, Champion, and Southern Resin corporations for providing the reference data used in this study.

6. REFERENCES

Avers, P.E. and K.C. Bracy. 1974. "Soil and Physiography of the Osceola National Forest". U.S. Dept. of Agriculture, Forest Service, Southern Region. pp. 94.

Clark, A., Burgan, T.M., Field, R.C., and P.E. Dress. 1985a. "User's Manual for Total-Tree Multiproduct Cruise Program". USDA, Forest Service, Southern Forest Experimental Station. General Technical Reports SE-31. 65 pp.

Clark, A., Burgan, T.M. and R.C. Field. 1985b. "Total-Tree Multi-Product Cruise Program: Programmer's Guide for the IBM Mainframe Version. USDA, Forest Service, Southern Forest Experimental Station. Technical Paper. 31 pp.

Hoffer, R.M., D.F.Lozano-Garcia, and D.D. Gillespie. 1986. "Characterizing Forest Stands with Multi-Incidence Angle and Multi - Polarized SAR Data". COSPAR Symposium, Toulous, France, COSPAR Paper No. V.2.5. 6 pp.

Hoffer, R.M. and Y.A. Hussin. 1989. " Per-point and Per-field Contextual Classification of Multipolarization and Multiple Incidence Angle Aircraft L-band Radar Data". Proceedings of the 1989 ASPRS-ACSM Fall Convention, Cleveland, OH. 1989. Pp. 154-170.

Holben, B.N., Tucker, C.J. and C.J. Fan. 1980. "Assessing Soybean Leaf Area and Leaf Biomass with Spectral Data". Photo. Eng. and Remote Sensing. 26:651-656.

Howell, D.A., Houston, T.B., Allen, W.J., Genter, E., Weatherspoon, R.L. and K.C. Bracy. 1984. "Soil Survey of Columbia County, Florida". U.S. Dept. of Agriculture, Soil Conservation Service. Tellahassee, FL. 187 pp.

Hussin, Y.A. and R.M. Hoffer. 1989. " Relationships Between Multipolarized Radar Backscatter and Slash Pine Stand Parameters". Proceedings of the 1989 ASPRS-ACSM Fall Convention, Cleveland, OH. Pp. 184-196.

Madgwick, H.A.I. 1981. "Estimating the Above-Ground Weight of Forest Plots Using the Basal Area Ratio Method". New Zealand Journal of Forestry Science 11(3): 278-286 (1981).

Markham, B.L., Kimes, D.S., Tucker, C.J. and J.E. McMurtrey. 1981. "Temporal Spectral Response of a Corn Canopy". Photo. Eng. and Remote Sensing. 48(11): 1599-1605.

Riom, J. and T. LeToan. 1981. "The Relation Between Types of Maritime Pine Forest and L-band HH Polarization Radar Backscatter. Digest of ISP, Spectral Signature of Objects in Remote Sensing, Avignon, France. 10 pp.

Sader,S.A. 1987."Forest Biomass, Canopy Structure, and Species Composition Relationships with Multipolarization L-band Synthetic Aperture Radar Data". Photo. Eng. and Remote Sensing, 53(2):193-202.

Tucker, C.J. 1979. "Red and Photographic Infrared Linear Combination for Monitoring Vegetation". Remote Sensing of Environment. 8(2):127-150.

Tucker, C.J., Holben, B.N., Flgin, J.H. and J.E. McMurtrey. 1981. "Remote Sensing of Total Dry-matter Accumulation in Winter Wheat". Remote Sensing of Environment. 11:171-189.

Tucker, C.J., Vanprate, C., Boerwinkel, E. and A. Caston. 1983. "Satellite Remote Sensing of Total Dry Matter Production in the Senegalese Sahel". Remote Sensing of Environment. 13:461-474.

Valentine, H.T., Tritton, L.M. and G.M. Furnival. 1984. "Subsampling Trees for Biomass, Volume, or Mineral Content". Forest Science, 30(3):673-679.

Woodwell, G.M. 1984. "The Role of Terrestrial Vegetation in the Global Carbon Cycle: Measurement by Remote Sensing".John Wiley & Sons Publishing Company. 247 pp.

Wu,S.T. 1987a. "Parametric Analysis of Synthetic Aperture Radar Data for Characteristics of Deciduous Forest Stands". Technical Papers, ASPRS-ACSM Annual Convention, Vol. 1 (Remote Sensing). Pp 320-329.

Wu,S.T. 1987b. "Potential Application of Multipolarization SAR For Pine-Plantation Biomass Estimation". IEEE Transaction On Geoscience and Remote Sensing. GE-25(3):403-409.

Wu, S.T. 1988. "Parametric Analysis of Synthetic Aperture Radar Data for the Study of Forest Stand Characteristics".Proceedings of the 1988 ASPRS-ACSM Fall Convention, Virginia Beach, VA. Pp. 214-223.

Wu, S.T. and S.A. Sader. 1986. "Multipolarization SAR Data for Surface Features Delineation and Forest Vegetation Characterization". IEEE. Trans. Geos. and Remote Sensing, GE-25(1):67-76.