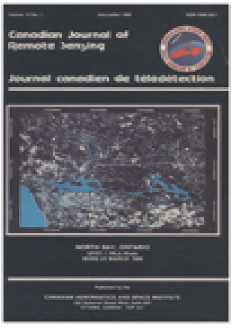

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GROSS-MERCHANTABLE TIMBER VOLUME ESTIMATION USING AN AIRBORNE LIDAR SYSTEM

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RÉSUMÉ

Une étude préliminaire visant à déterminer l'utilité d'un laser aéroporté comme moyen employé par les gestionnaires forestiers pour le calcul du volume forestier marchand brut a été effectuée près de la National Aeronautics and Space Administration (NASA) Goddard Space Flight Center, Wallops Flight Facility, au moyen du lidar océanographique aéroporté (LOA) de la NASA. Le volume forestier mesuré a été mis en régression avec la section efficace du lidar le long d'un profil de la forêt. On a constaté que ce profil de la section efficace du lidar constituait une variable très importante dans l'estimation du volume forestier marchand brut. La stratification des essences d'arbres a permis d'obtenir des résultats beaucoup plus satisfaisants, soit une valeur globale de R^2 de 0,921, pour un niveau de confiance de la régression de 99 %.

SUMMARY

A preliminary study to determine the utility of an airborne laser as a tool for use by forest managers to estimate gross-merchantable timber volume was conducted near the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center, Wallops Flight Facility utilizing the NASA Airborne Oceanographic Lidar (AOL) system. Measured timber volume was regressed against the cross-sectional area of an AOL-generated profile of forest at the same location. The AOL profile area was found to be a very significant variable in the estimation of gross-merchantable timber volume. Significant improvements were obtained when the data were stratified by species. The overall R-squared value obtained was 0.921 with the regression significant at the one percent level.

INTRODUCTION

Foresters were among the first to recognize the value of data obtained from aerial platforms (and later orbital platforms). Among the usable products these platforms yield are aerial photographs and sketch maps, as well as Landsat images and computer tapes. These products are used to assist in formulating management plans for forested lands. Of these products, only aerial photography offers foresters the capability of making direct biometric analyses of certain forest stand or individual tree characteristics. However, in computing timber inventories from aerial photographs, large errors can result due to difficulties in measuring tree heights in a forested situation. Thus the use of aerial photography inventorying techniques in the United States have generally been confined to providing reconnaissance surveys to optimize ground inventory efforts.

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A new technology, using an airborne lidar (light detecting and ranging) system, potentially offers the capability of directly measuring tree heights using laser light. When a series of these tree height measurements are merged, a canopy profile results. This profile may then be compared directly to the actual volume of the trees in question.

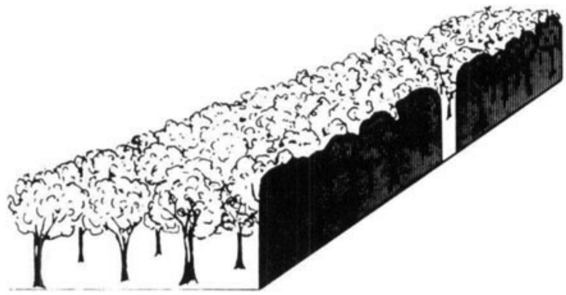

Figure 1
Profile conceptualization

The use of the canopy profile cross-sectional area (conceptualized in Figure 1) as a variable to estimate timber volume was first proposed by R. Hugershoff in the late 1920's (Spurr, 1960) and later and later refined by Smith (1969) and Maclean and Martin (1984). The profiles were generated using aerial photographs mounted on a stereoplotter considered advanced at the time of each study. Hugershoff demonstrated that the cross-sectional area of the canopy profile was apparently related to the amount of standing timber at the site of the profile, though the results were somewhat erratic. Smith used a spot densitometer with a 0.1 mm by 3.5 mm aperture to measure film densities. The canopy profile area and film density profile area were then related to timber volume. This methodology was demonstrated in a monotypic, even-aged stand of southern pines. Maclean and Martin used a scanning micro-densitometer to measure and record film densities. After alignment of the densitometric data with the photogrammetric data, the film densities were used to adjust the cross-sectional area for canopy micro-openings (those openings too small to measure with the stereoplotter). Maclean and Martin also demonstrated that using the natural logarithm of timber volume and data stratification by predominant species significantly improved the results from the regression analysis. An uneven-aged, northern hardwoods cover type was used in the Maclean and Martin study. Regressions of individual hardwood species in the Maclean and Martin study produced R-squared coefficients of between 0.75 and 0.87.

Aldred and Bonner (1985) used an airborne lidar system to generate traditional stand characteristic measurements to stand height and crown density. The system yielded an accuracy of plus or minus 4.1 m of actual stand height with 95 percent confidence, and categorized stands into 20 percent crown density category with 62 percent accuracy. They reported that results could be improved, however, with the use of a faster pulsing laser and an inertial navigation system for better ground track re-occupation.

The lidar system used in this study was the National Aeronautics and Space Administration's (NASA) Airborne Oceanographic Lidar (AOL) system. This system is currently mounted in a NASA P-3A aircraft at Goddard Space Flight Center's Wallops Flight Facility, Wallops Island, Virginia. Previous studies in which the AOL was utilized for terrain mapping purposes produced results which indicate that the system is capable of measuring ground elevations beneath tree cover to an accuracy of 0.50 m root mean square (Krabill, et. al. 1980). That investigation compared AOL-generated elevational data to conventional photogrammetric data over the same profile line. That study also indicated that the AOL-measured elevational data had an accuracy of 0.12 m root mean square over open terrain.

The primary objectives of this study were to: apply lidar technology to the generation of accurate and precise forest canopy profiles; utilize methodologies successfully used in previous photogrammetrically-based studies for application to lidar profiles for the estimation of merchantable timber volume; explore new techniques to improve upon the profile area/timber volume relationship. The research performed by Aldred and Bonner (1985) was performed concurrent to the study reported herein. This report represents a preliminary study in the realm of the recommendation of Aldred and Bonner that "Analysis of laser data should be extended to other forest stand variables such as volume and biomass" (p. 57).

METHODOLOGY

Because of the favorable results of the previous studies, a NASA-funded project was undertaken to determine the applicability of profile data generated by the AOL system to timber volume estimation.

Lidar is the light equivalent of radar. The AOL system was originally developed and successfully used for near-shore ocean bottom mapping (Hoge, et. al. 1980). Results from early missions over terrestrial targets indicated that tree canopies yield a return waveform with characteristics similar to the bathymetric returns over water. Therefore it might be possible for the AOL to measure tree heights in the same way it measures water depth.

The AOL measures tree height using laser light as a differential altimeter. A short pulse of laser light approximately 7 nanoseconds (ns) in duration is emitted, and reflected out of the aircraft through a series of mirrors. When the laser pulse is intercepted by the forest canopy, a portion of the pulse is reflected back to the aircraft. Of the remaining energy, some proceeds through the canopy and is reflected off the forest floor and back to the aircraft as a secondary return pulse. The time difference between the initial return from the tree canopy and the secondary return can be converted to a height measurement using the known value of the speed of light. System precision allows approximately plus or minus 0.30 m distance estimates with any single pulse. Further details on the AOL hardware may be found in Hoge, et. al. (1980). Figure 2 is an example of data obtained with the AOL operating over a forested area near Fredricksburg, Virginia. The line labeled as 'Canopy' traces the initial return of the lidar from the canopy. Points indicated as 'Individual laser hits' represent secondary returns of sufficient magnitude to indicate good interaction of the pulse with the ground. The smooth 'Ground level' line is the output of a ground tracking filter used during data processing. The AOL system acquires and records data at the rate of 500 laser pulses per second. The aircraft typically flies over a target area at velocities of between 80 and 100 m/sec, providing an along-track data density potential of at least five measurements per meter. A beam divergence of 5 mR and flying height of 150 m above the canopy resulted in a nominal pulse footprint 0.7 m in diameter. Integration of all tree-height measurements over discrete units along the ground track of the aircraft, yields specific profile areas which can be correlated to ground measurements of timber volume. The NASA AOL system also simultaneously records information from the onboard LTN-51 Inertial Navigation System (INS). Pitch, roll, and heading parameters from the INS are utilized to correct for aircraft attitude changes during subsquent processing of lidar-ranging data.

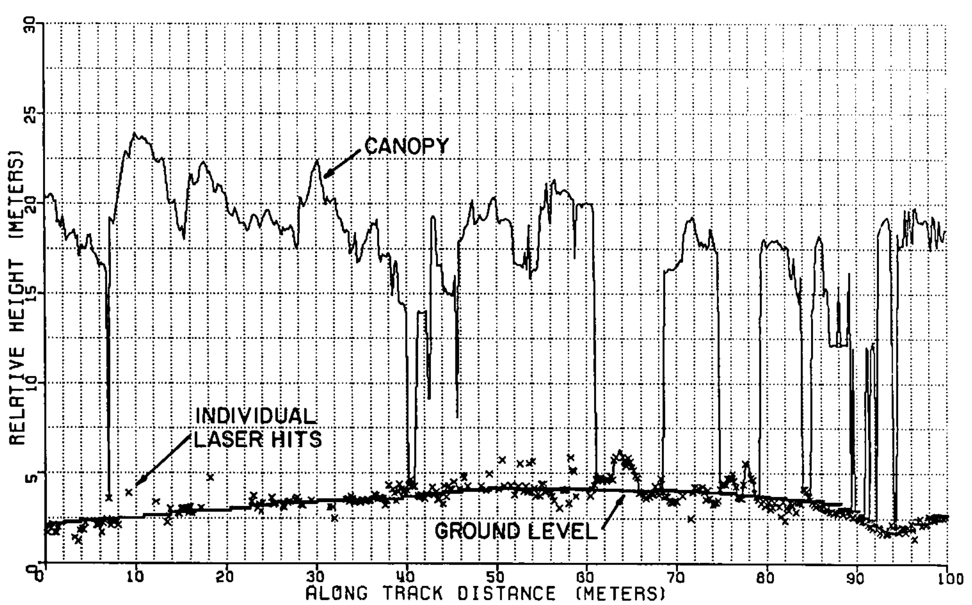

Figure 2
AOL data taken over forested terrain

A 35 mm, half-frame Flight Research Camera recorded overlapping color aerial photographs concurrent with collection of the AOL profile data. This photographic record was used in conjunction with the INS positional information to obtain accurate locational information for the establishment of sample plots along the ground track of the aircraft.

Since the airborne data were to be directly related to the timber volume of the trees intercepted by the profile, extreme care was exercised in matching ground sampling with the photographic record of the ground position of the laser measurements. After establishing the ground trace of the laser data in the field, the line was divided into contiguous plots 30.48 m along track and 26.55 m, centred, cross track. Photographic enlargement prints (203 × 254 mm, nominal scale of 1:600) of the Flight Research Camera photos were made to allow for accurate positioning of control points in the ground track re-occupation process. These control points were chosen at places where the ground track of the laser crossed identifiable features such as roads or large canopy openings. The INS data from the aircraft were then used to generate a series of distances and magnetic azimuths with which the ground track of the laser was re-occupied. By using the INS information over relatively short distances (no more than 800 m between ground control points), aircraft motions of roll, pitch, and yaw could be accounted for on the ground, yet INS drift could effectively be ignored. The authors highly recommend this procedure for further studies of this nature. Using the photographs, control points were established to within 0.5 m. A 50 m fibreglass tape and compass were used to traverse between the control points, with an estimated locational error at any point of no more than 1.5 m cross track and 0.8 m along track. The dimensions of the contiguous plots (30.48 m along track and 26.55 m, centred, cross track) were chosen to encompass the expected locational error mentioned above and to ensure that an adequate number of trees were sampled on each plot by enclosing an area of 0.08 ha. The units for profile cross-sectional area in this study are, therefore, square meters per plot. Gross-merchantable timber volume was compiled in cubic meters per hectare. Hereafter these will be shortened to square meters and cubic meters respectively.

For every merchantable tree found on a plot, three critical factors were recorded during the ground survey: tree species, tree diameter at breast height (DBH), and merchantable tree height. The sites for this particular study were less than one kilometer apart, and located near Girdletree, Maryland approximately 30 kilometers southeast of Salisbury, Maryland on the Delmarva Peninsula. Because the sites were so close to each other, they are indicated by the same locator in Figure 3. The area is primarily third growth loblolly pine (*Pinus tadea*) plantations and naturally occurring mixed hardwoods and loblolly pine stands. Among the hardwoods the predominant species are a variety of oak species (*Quercus, spp.*), tulip poplar (*Liriodendron tulipifera*), sweetgum (*Liquidamber styracifula*), and blackgum (*Nyssa sylvatica*). Site number one was a relatively young mixed hardwood and natural loblolly pine stand. The area had been selectively cut approximately 15 years ago, leaving all hardwoods and most smaller loblolly pines. Since that time in areas that were cut heavily, loblollys that were released from suppression have become the predominant species. Most areas, however, are dominated by oaks. Overall tree vigor appeared high with no indications of abnormalities. Site number two was an over-mature loblolly pine plantation. The site appeared stagnant in terms of total net growth. Most of the new growth on the site was in the form of shade-tolerant hardwoods that are currently overtopped but growing into the canopy.

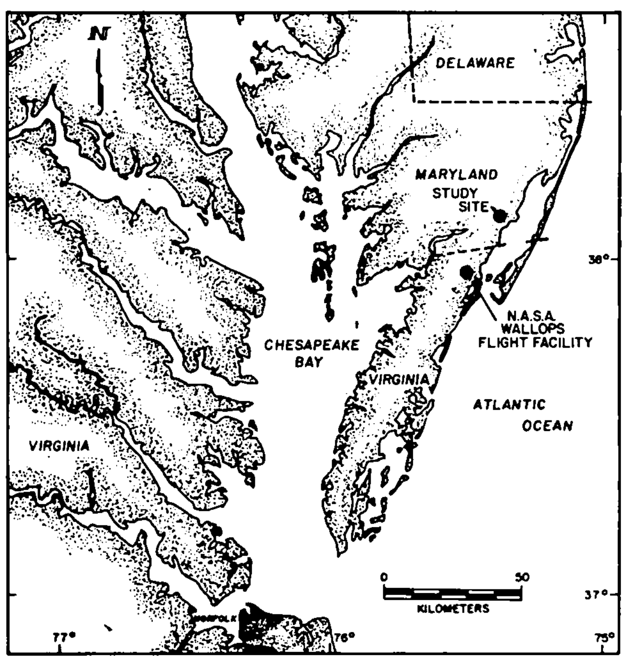

Figure 3
Study site location

Ample evidence, in the form of dead and down stems, of the overall loblolly senescence was available.

Tree DBH was measured to a precision of 3 mm at 1.37 m above ground level. All trees in excess of 127 mm were measured. Plots near or traversing man-made breaks in the forest cover (i.e. roads, open fields) were not considered. Merchantable tree-heights were measured from a 0.3 m stump to a minimum diameter limit (152 mm for trees greater than 203 mm DBH, 102 mm for trees between 127 mm and 203 mm) to a precision of 1.5 m using a Suunto clinometer. Trees with boles that forked below the minimum diameter limit were treated as three separate units (one below the fork and two above) provided the bole had a minimum 127 mm diameter 0.3 m above the fork. The measurements for individual trees were converted to a cubic foot volume using an existing table (Forbes, 1955, p2.3). The individual tree volumes were summed by species for each plot.

Past studies have relied on the entire profile cross-section, from ground to canopy top, as the major independent variable. The mensurational significance of this variable is two-fold. First, the area of the profile incorporates three sensitive indicators of merchantable timber volume that can be measured using remote sensing: total tree height, crown diameter, and crown closure into a single variable. Second, the variable is a measure of the total amount of the forest's potential growing space occupied by the dominant and co-dominant trees in the stand, thus directly measuring the major contributors to merchantable timber volume. Each of the three variables is directly analogous to measurements commonly taken by foresters when gathering information on the ground. It has been shown that the union of these three factors into a single variable yields a sensitive indicator of gross-merchantable timber volume (Maclean and Martin, 1984). It would also be expected (though not tested in this study) that this variable would be a very good indicator of total biomass or total woody biomass.

A drawback in combining the above three variables is that it allows a potentially major ambiguity to arise under certain circumstances. The profile area of a forested stand characterized by an open canopy, with tall trees and average crown diameters along a specific ground distance may be no different than a forested stand characterized by a dense thicket of shrubs or saplings several meters in total height (see Figure 4). The merchantable timber volume in the first stand would be real and measurable while the second stand would have no merchantable timber volume because of insufficient tree height or bole diameter. It should be noted that if total biomass or total woody biomass were the major concern, this ambiguity would not be of consequence and the entire profile variable would be appropriate. The proposed variable modification involves the exclusion of that portion of the cross-section lower than a certain level above the ground (as an example, ten meters above ground level is indicated in Figure 4). Figures 5 and 6 show the actual AOL-generated profiles and ground measured timber volumes from the two sites in this study. The ground level, ground level plus ten meters, and tree canopy lines are labeled in the figures. Heights above ground level from 10 m to 20 m inclusive, at 2.5 m increments were analyzed for the best relationship with volume. The use of species indicators to improve regression analysis was also studied.

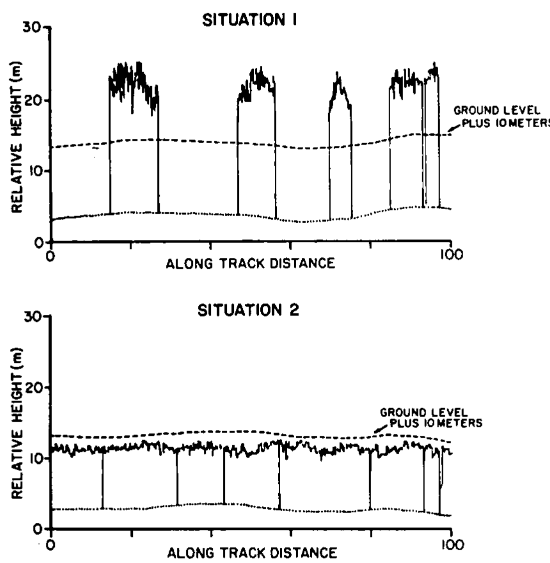

Figure 4
An artificial example with same profile area

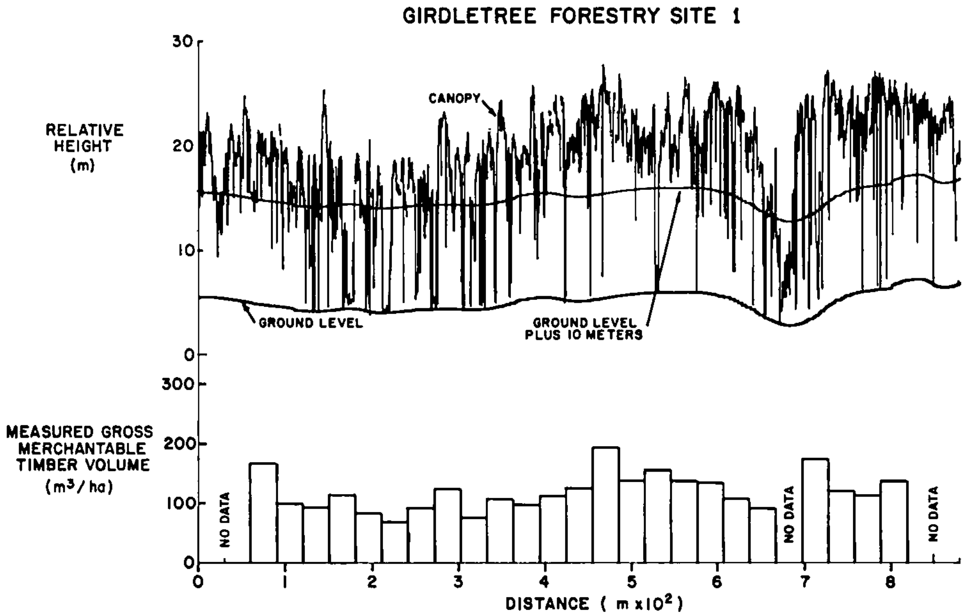

Figure 5
Mixed hardwoods and natural loblolly pine stand data

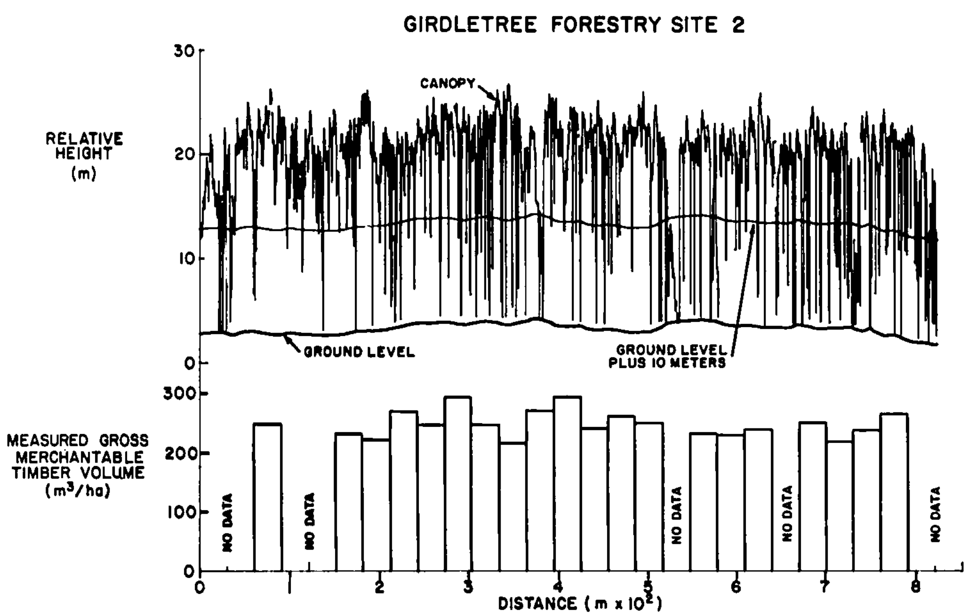

Figure 6
Loblolly pine plantation stand data

RESULTS

Test 1 — Entire profile versus partial profile

Preliminary data analysis tended to uphold the findings of Maclean and Martin (1984), that the natural logarithm of timber volume was an appropriate data transformation to improve the overall correlation with profile area. This transformation was not only appropriate to the entire profile area variable, but also to the partial profile variables. The partial profile areas were generated at the original laser data processing stage on a pulse-by-pulse basis concurrent with computation of the entire profile area.

Figures 7a–e show the effects on the overall relationship as the level of profile area exclusion is further and further removed from ground level, starting at ten meters and proceeding to 20 meters at 2.5 meter intervals. Note how the cluster highlighted 'moves' into a more linear arrangement the more severe the profile exclusion constraint is. This group of data is from the old-growth loblolly plantation. As can be seen in Figure 6, these trees are taller than those on site 1 (hardwoods and natural loblolly) but, because of age, many more openings to ground are evident. Hence, as the height elimination factor moves up through the intermediate levels of the canopy, very little profile area is being lost due to elimination of small trees from consideration (as is the case with the site 1 data). But the area that is being lost due to small tree elimination is tending to linearize the data from the loblolly plantation site while not greatly effecting the relationship of the data from site 1.

The simple correlation value for all of the data versus the natural logarithm of timber volume (Figure 7a) is only somewhat better than random (0.15), while the profile area excluding that which lies below 15 m (Figure 7d) exhibits the best simple correlation of 0.64. None of the profile area variables singly does a satisfactory job for predicting timber volume.

By using multiple regression of the profile variables noted in Figure 7 and backwards variable elimination techniques, the results outlined in Table 1 were produced. Each variable (zero-meter level and the ten-meter level) is highly significant when entered last, yet of little significance individually. The overall regression (the individual coefficients are significant at the one-percent level) and the R-squared value indicate that a reasonably large amount of the overall variance is described by this model.

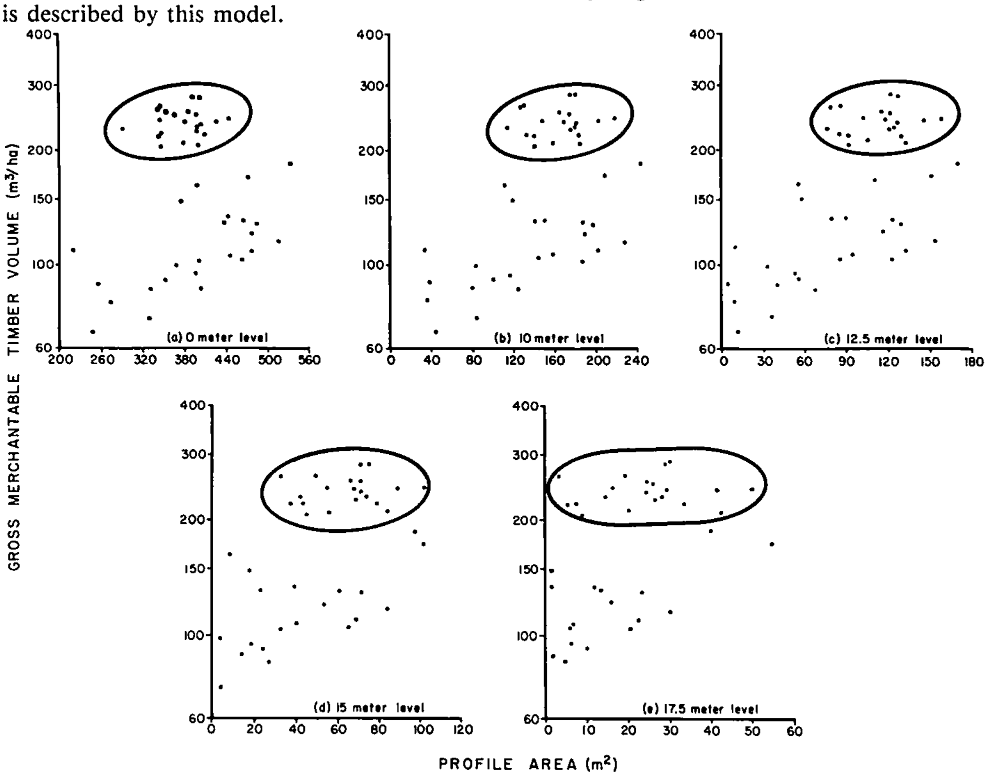

Figure 7
Effect of various profile exclusion levels

Table 1
Regression using natural log timber volume versus full profile area and 10 m exclusion level.

$$\text{Volume } (m^3/ha) = \exp(6.3953 - 0.0091X_1 + 0.0152X_2)$$

Variable	Coefficient	Stand.Dev of Coef.	T-Ratio
Constant	6.3953	0.2683	23.83**
X_1-Full Profile	−0.0091	0.0011	−8.10**
X_2-10 m Exclusion	0.0152	0.0015	10.12**

R^2 value = 0.721

Analysis of Variance

Factor	Deg. of Free.	SS	MS	F
Regression	2	5.96629	2.98314	52.86**
Residual	41	2.31366	0.05643	
Total	43	8.27995		

NOTE: ** — Significant at the one-percent level.

A similar analysis using un-transformed timber volume produced almost identical results in every aspect (Table 2). The final R-square and regression F values are marginally higher than the natural logarithm of timber volume. Plots of regression residuals versus both the independent variables and the predicted values confirm that the use of logarithmic variables and the predicted values confirm that the use of logarithmic timber volume is, however, more appropriate than un-transformed timber volume. Using the natural logarithm, the regression residuals show no evidence of lack of fit or hetereoschedasticity, nor is the assumption of normality violated.

Test 2 — Addition of predominant tree species as an independent variable

The previous study by Maclean and Martin (1984) indicated that stratification of the individual profile units by predominant species composition significantly improved the overall regressions. Two stratification methodologies were analyzed. The first involved the use of a measure of predominance of a single species. The measure of predominance should be a value that can be easily estimated from other than direct ground measurements to facilitate operational usage from a remotely-sensed data gathering aspect. The single most influential species in the relationship between profile area and timber volume in this study is loblolly pine. For this analysis the ratio

Table 2
Regression using untransformed timber volume versus full profile area and 10 m exclusion level.

$$\text{Volume } (m^3/ha) = 417.8773 - 1.5406X_1 + 2.4287X_2)$$

Variable	Coefficient	Stand.Dev of Coef.	T-Ratio
Constant	417.8773	41.3894	10.10**
X_1-Full Profile	−1.5406	0.1734	−8.89**
X_2-10 m Exclusion	2.4287	0.2309	10.52**

R^2 value = 0.731

Analysis of Variance

Factor	Deg. of Free.	SS	MS	F
Regression	2	149548	74774	55.72**
Residual	41	55041	1342	
Total	43	148496		

NOTE: ** — Significant at the one-percent level.

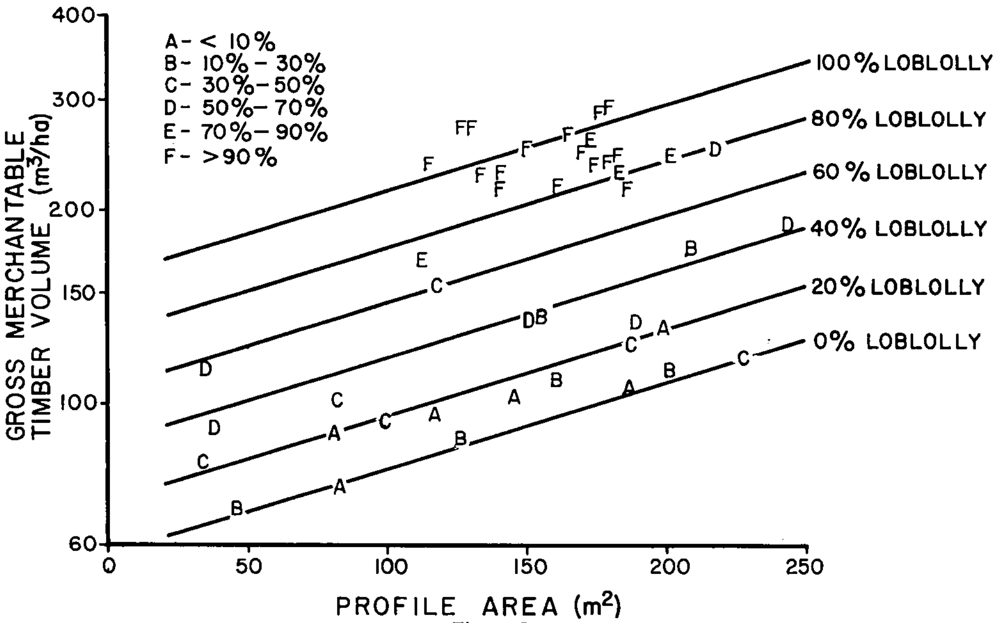

Figure 8
Stratification of 10 meter exclusion data by percent loblolly pine volume

of loblolly pine volume to total volume on each plot was calculated and entered as an independent variable in multiple regression analysis. Figure 8 is a plot of this information versus the natural logarithm of timber volume and the ten-meter level of profile area exclusion and gives an indication of just how strong a variable this is. These data have been grouped as shown for graphical purposes only.

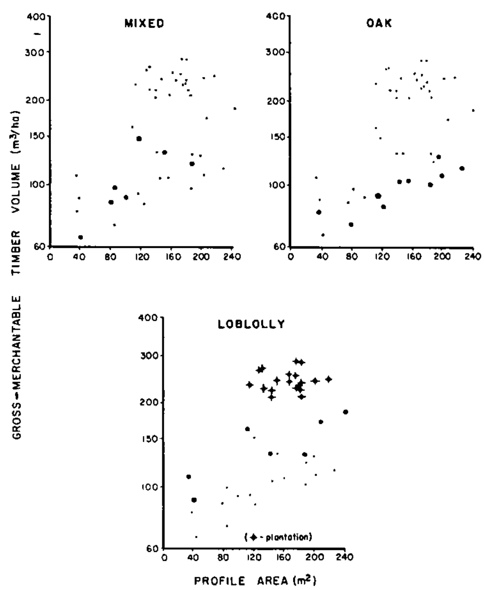

Figure 9
Stratification of 10 meter exclusion data by predominant species

The second stratification methodology involved the labeling of each plot according to the predominate species (or species group) thereon. Prior to stratification, criteria were established to govern the selection of an appropriate label for each plot of data. Any plot which contained 60 percent or more of the total gross merchantable volume of a particular tree species was assigned that species label. Plots on which no single species constituted at least 50 percent of the total volume were labeled 'mixed'. If at least 50 percent of the gross-merchantable volume on a plot was contained in one species and more than 40 percent of the gross-merchantable volume was contained in a second species, the plot was also labeled 'mixed'. A plot of these data appears in Figure 9. As can be seen, the general trend is for the 'mixed' and 'oak' plots to have far less timber volume per unit profile area than the loblolly pine plots.

The addition of the loblolly volume to total volume ratio to the profile area variables, and reiteration through the backwards elimination procedure culminates in the regression in Table 3. The R-squared value is approaching the 90 percent level and a very low standard deviation of volume about the regression line (approximately 60 percent of that observed in Table 1) exists. The graphical representation of this regression at several levels of loblolly volume percentage are shown in Figure 8. Each variable in this regression is significant at the one-percent level when added last, as is the overall regression.

Table 3
Regression using natural log timber volume versus 10 m exclusion level and percent loblolly.

$$\text{Volume } (m^3/ha) = \exp\,(4.0081 + 0.0032X_2 + 1.0012X_3)$$

Variable	Coefficient	Stand.Dev of Coef.	T-Ratio
Constant	4.0081	0.0731	54.82**
X_2-10 m Exclusion	0.0032	0.0004	7.12**
X_3-% Loblolly	1.0012	0.0659	15.19**

R^2 value = 0.890

Analysis of Variance

Factor	Deg. of Free.	SS	MS	F
Regression	2	7.37200	3.68600	166.4**
Residual	41	0.90795	0.02215	
Total	43	8.27995		

NOTE: ** — Significant at the one-percent level.

The second approach to stratification provided the means for analysis of the individual species groupings. The plots were labeled according to the procedure previously outlined and multiple regression was used to test the various slope and intercept values for statistical significance. The resultant regression coefficients have been plotted in Figure 10. The model intercept value is that for 'mixed' species plots and is significantly different from zero at the one-percent level. The first variable coefficient, representing the slope value for 'mixed' species plots is significantly different from zero at the 2.5-percent level. The remaining model coefficients allow for the testing of the other species slope and intercept values. From Figure 10 one would anticipate that no significant difference would exist between the 'mixed' species intercept and that for 'oak'. It would also appear that no significant difference exists between any of the slopes at the one-percent level. The results in Table 4 confirms both of these hypotheses.

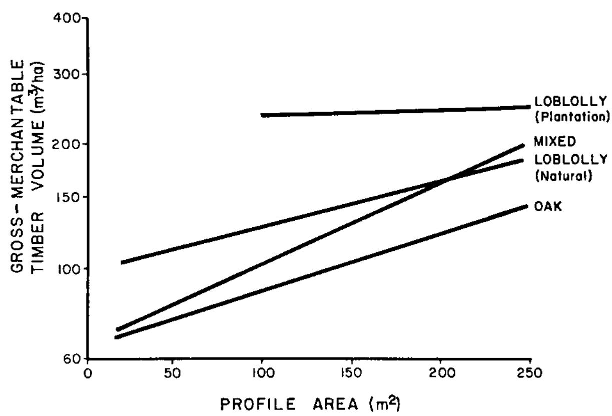

Figure 10
Graphical representation of regression coefficients

The addition of more variables must increase the regression sum of squares (SSR) at the expense of the error sum of squares (SSE). Whether this reduction is significant (i.e. whether the reduced model (RM) is as adequate as the full model (FM)) can be tested according to the procedure outlined by Chatterjee and Price (p.57). The ratio:

$$\frac{[SSE(RM) - SSE(FM)] \,/\, (p\text{-}k)}{SSE(FM) \,/\, (n\text{-}p)}$$

Where:

p = number of parameters in the full model
k = number of parameters in the reduced model
n = number of regression data points

is an F distribution with (p-k) and (n-p) degrees of freedom. Table 5 summarizes the findings for the regressions derived in this study. In each case the addition of the individual species parameters resulted in a significantly improved regression (at least at the five-percent level) as compared to those regressions in which no species stratification was performed.

Table 4
Regression using natural logarithm timber volume versus 10 m exclusion level and predominant species.

$$\text{Volume } (m^3/ha) = \exp(4.1656 + 0.0044X_4 - 0.0150X_5 - 0.0012X_6 + 0.4049X_7 - 0.0019X_8 + 1.2632X_9 - 0.0041X_{10})$$

Variable	Coefficient	Stand. Dev. of Coef.	T-Ratio
Mixed Intercept	4.1656	0.1336	31.18**
X_4 — Mixed Slope	0.0044	0.0011	3.91**
X_5 — Correction for Oak Intercept	−0.0150	0.1775	−0.08
X_6 — Correction for Oak Slope	−0.0012	0.0013	−0.86
X_7 — Correction for Loblolly Inter.	0.4049	0.1710	2.37*
X_8 — Correction for Loblolly Slope	−0.0019	0.0013	−1.42
X_9 — Correction for Plant. Lob. Inter.	1.2632	0.2341	5.40**
X_{10} — Correction for Plant. Lob. Slope	−0.0041	0.0016	−2.53*

R^2 value = 0.921

Analysis of Variance

Factor	Deg. of Free.	SS	MS	F
Regression	7	7.62867	1.08981	60.24**
Residual	36	0.65128	0.01809	
Total	43	8.27995		

NOTE: ** — Significant at the one-percent level.
* — Significant at the five-percent level.

Table 5

Significance test for added parameters.

	TEST A	TEST B
Reduced Model (Regression #)	1	3
Full Model (Regression #)	4	4
Number of Data Points	44	44
Parameters in Reduced Model	3	3
Parameters in Full Model	8	8
SS Error (Reduced Model)	2.31366	0.90795
SS Error (Full Model)	0.65128	0.65128
F-Distribution Deg. of Free.	(5,36)	(5,36)
Test Value	18.38**	2.84*

NOTE: ** — Significant at the one-percent level.
* — Significant at the five-percent level.

All regressions presented in the analysis have contained either the 10 m exclusion level or the full profile and the 10 m exclusion. These levels were chosen by the backwards variable elimination process because they offered the best overall correlation with the natural logarithm of timber volume. Individually, each species had a different level of profile area exclusion for a best single variable fit (ground level for mixed plots, 20 meters for oak plots, and 15 meters for loblolly plots). This would imply that a multi-exclusion level regression by species might offer a better solution. Normally this process would be done, but because of the limited number of data points, over-parameterization of the model would result.

The basic conclusion of this test is that inclusion of species information is highly desirable owing to the improvements that result in the overall fit of the model to the data and the much smaller confidence intervals that result around the regression line.

CONCLUSIONS

The results of this study, though limited in the total number of data plots, confirmed previous studies which found that the profile area of a forest canopy cross-section is a very good indicator of the total amount of gross-merchantable timber on a site. This study also confirmed the necessity to differentiate the data plots by predominant species. The new findings of this study involve the use of an airborne lidar system for data collection purposes. This study indicates the potential of a lidar profiling system, such as the NASA AOL, to go beyond the simple measurement of tree heights to the direct measurement of standing timber volumes; further, more rigorous, studies in this realm are warranted. The system is also capable of recording the location of that timber (through the use of aerial photography and aircraft INS data) more quickly than currently-used photographic methods.

Operational aspects of timber volume estimation using the AOL, and accuracy comparisons to more typical aerial photographic methods have yet to be studied. Of primary concern is the need for a broader study of the profile area-timber volume relationship for a variety of different cover types and for similar cover types in different geographical regions and growing conditions and the development of a satisfactory method of identifying the species composition for input to the observed relationships. A detailed time- and cost-analysis of an operational system similar to the NASA AOL must be performed. This analysis is required to determine the cost-effectiveness of this methodology compared to the more traditional methods of timber cruising.

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