CALCULATING FOREST BIOMASS WITH SMALL FORMAT AERIAL PHOTOGRAPHY, VIDEOGRAPHY AND A PROFILING LASER

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ABSTRACT

This paper reviews an aerial sampling technique that could reduce the cost of calculating standing forest biomass in remote regions by collecting a geographically distributed set of large scale transects that include a limited number of permanent plots. The biomass of these plots is calculated from allometric equations and extrapolated to the transects as a function of tree species, crown diameter and height.

Two kinds of aerial imagery sampling techniques were tested over a mixed hardwood /conifer forest in Crooksville, Ohio. Thirty-one 28-meter diameter plot sites were established along two transects within the test site and the dbh (diameter at breast height) of trees measured. Each transect was flown at 4,000 feet AGL with a small format photogrammetric camera, then at 1,000 feet AGL with global positioning system (GPS)-logged dual-camera video (wide-angle/zoom), and a profiling laser. The photogrammetric images were used to create 3D models of the terrain from which average tree heights and forest volumes could be calculated. The video / laser coverage was used to visually identify the species of individual trees, measure their crown diameters in a 2D geographic information system (GIS) and estimating their heights from the laser profile.

Due partly to an automatic georeference and mosaicking program developed for the video coverage during the project, it proved the more accurate / cost effective approach and this paper concentrates on its results. Average dbh values of one hectare transects calculated from the video are compared to those measured on site, showing a strong positive correlation given the small sample size. A much larger test of 635 plot sites has just been completed in Bolivia, which should allow us to refine the techniques.

INTRODUCTION

The 1997 UN Convention on Climate Change in Kyoto, Japan established a framework for assigning economic value to carbon sequestered in biomass. This could benefit efforts to preserve tropical forests in developing countries if their carbon content can be accurately measured and monitored. Field methods with extensive permanent plots can estimate biomass in a forest to known levels of precision, but these plots are expensive to reach and maintain in isolated areas. The resulting costs that can vary from approximately $0.05 to $0.50 per ton depending on inventory frequency, accessibility, spatial variability of carbon pools, labor costs and scale, making the process least practical in some of the areas most worthy of preservation.

President Clinton has asked for voluntary efforts on the part of American industries to comply with the goals set forth in Kyoto. As part of an effort to respond to the President's request, the Electric Power Research Institute (EPRI), in collaboration with The Nature Conservancy (TNC), Fundacion Amigos de la Naturaleza (FAN), and the government of Bolivia, have established the Noel Kempff Mercado Climate Action Project. ??? hectares of forest have been withdrawn from logging or agricultural development and added to the Noel Kempff Mercado National Park in northeast Bolivia as an experiment in carbon sequestration as an economically viable, low-cost option for mitigating climate change. In order to determine and monitor the standing forest biomass of this region, TNC contracted with the Winrock International Institute for Agricultural Development to develop a stratified sample of ground sites where individual trees could be measured over time. Winrock established 635 nested plot sites in five basic vegetation strata, measuring the diameter of all woody stems 5 cm to 20 cm in an inner plot of 4 meters radius, and the diameter of all woody stems greater than 20 cm in a larger nested plot of 14 meters radius. These dbh values and tree counts were then extrapolated to a per hectare estimate of standing biomass for the region using standard allometric equations. Setting up 635 plots in a tropical rainforest with few access roads is a major undertaking in cost and mobilization of personnel. Winrock determined that it could reduce this time and cost in future projects of this type if it could establish fewer sites and use aerial sampling to capture the variability of the terrain. For this reason, they contacted the Department of Forestry and Wildlife Management (FWM), University of Massachusetts, where we have worked for several years in developing low cost methodologies to monitor natural resources with small format aerial surveys. We had previously developed a sampling method for classifying forest vegetation using Landsat satellite imagery and low level, GPS-logged, dual camera videography as part of the southern New England Gap Analysis Project (Slaymaker et al, 1996,). We have also worked for the last five years with Conservation International to adapt these techniques to monitoring tropical forests in Africa, Asia and South America (Slaymaker & Hannah, 1997). During these projects, we developed a combined package of videography and digital imagery that utilizes GPS-based mosaicking techniques to provide a more quantitative analysis of forest development and change detection.

FWM is presently engaged in a three-year NSF grant in conjunction with the Computer Vision Research Laboratory (CVRL) of the Department of Computer Science at the University of Massachusetts, a leading research facilities in machine vision and image classification techniques. The purpose of this project is to automate and improve our forest classification methodology through the use of terrain reconstruction and classification techniques that delineate the structure of forests as well as their vegetation communities. Mapping vegetation types in complex terrain has become more successful as computer processing power increases and large amounts of ground truth data can be obtained (either by large-scale video transects (Slaymaker et al., 1996) or by field sites (Schriever et al., 1995;)). However, the structure and age of a forest ecosystem is often more important for habitat, and resource assessment. Wildlife often respond more to the structural variables in a forest (stems/ha, basal area, height of the canopy, etc.) than to the species composition of the forest (Chadwick et al., 1986). Significant forest management practices, such as thinning, affect both the wildlife habitat value and quality and value of timber produced by a stand, but are often imperceptible to satellite and smaller scale aerial imagery after only a year or two. In addition to mapping vegetation types, wildlife biologists and foresters need to be able to map forest structure, stand age and biomass (Short and Hestbeck, 1995). Remote sensing techniques have successfully measured active biomass or chlorophyll activity using normalized vegetation or leaf area indexes (Spanner et al., 1990), but only limited success has been obtained mapping forest structure variables, or standing biomass. CVRL has been working on automatic georeferencing and pixel-specific digital elevation modeling techniques that may increase our ability to extract structural information from large scale sampling data. Given its large database of stratified ground sites, the Noel Kempff Mercado expansion zone was an excellent project to apply these techniques to a tropical forest. Given the size of the area however, we felt a smaller test of a temperate forest was warranted first. Therefore, with support from Winrock, NSF, and additional matching funds from The National Fish and Wildlife Foundation, we established a test site in Crooksville, Ohio to determine the relative accuracy and economics of using large scale aerial sampling of the forest canopy as an extension of Winrock's plot based strategy for estimating biomass.

METHODOLOGY

We set up aerial transects over a mixed hardwood/conifer forest managed by American Electric Power (AEP) in Ohio. AEP provided forestry support personnel to assist Winrock in measuring thirty-one plot sites along two aerial transects over the forest (Figure 1). The center of each plot was established within known tree stands that represented samples of mature and regenerating hardwoods, thinned hardwoods, and conifer plantations. Three criteria were used to select plot locations: 1) at least 100 m from roads, 2) along the target transects, and 3) in an area which was representative of the vegetation around it within a 100 m radius. Using a GPS receiver, the field crews navigated to each plot and marked the center with a four-foot metal stake. Estimates of understory vegetation, standing litter and soil biomass were collected from clip plots, but the vast majority of the standing biomass for each plot was estimated directly from the dbh values of measured trees, using species-specific allometric equations (Table 1). Equations of this kind are available for temperate tree species of the U.S. (Tritton and Hornbeck, 1982) and tropical tree species (Crow, 1978; Brown et al., 1984, 1989). Equations for temperate trees exist for individual species and for groups (e.g., all pines, all hardwoods) and have been generated over many different studies by measuring the trees, then actually cutting them down, drying and weighing them. Regression equations were developed to describe above ground biomass as a function of dbh alone or dbh and height. The differences in the equations reflect variations in wood density and tree allometry (relative mass in each component). The conifer/broadleaf distinction is usually the most important for both of these factors when grouping species, therefore the equations for tropical species are usually for all species in a single group. (In Bolivia only hardwoods and palm-trees are distinguished.)

Table 1. Biomass equations used for the Ohio test site.

Species	**Equation**	**Source**	**dbh range and mass**
Hardwoods	y = 0.5 + ((25,000*dbh^2.5)/(dbh^2.5+246,872))	Schroeder et al., 1995[1]	1-85 cm kilograms
Conifers	y = 0.5 + ((15,000*dbh^2.7)/(dbh^2.7+364,946))	Schroeder et al., 1995	3-71 cm kilograms
White Pine	y = 3.2031-(0.2337*dbh)+(0.006061*dbh^2)	Monteith 1979[2]	5-50 cm kilograms
Yellow/Tulip Poplar	y = (Exp(0.45689 + 2.6087 * (Log(dbh))))*0.454	Monteith 1979	5-50 cm kilograms
Elm	y =0.5 + ((25,000*dbh^2.5)/(dbh^2.5+246,872))	Schroeder et al., 1995	5-50 cm kilograms
Black Locust	y =0.5 + ((25,000*dbh^2.5)/(dbh^2.5+246,872))	Schroeder et al., 1995	5-50 cm kilograms
Red Pine	y =Exp(-2.3684 + 2.5303 * (Log(dbh)))	Monteith 1979	5-50 cm kilograms
Red Oak	y = (2.4601*(dbh^2.4572))*.454	Monteith 1979	5-50 cm kilograms
Black Cherry	y = (1.8082*(dbh^2.6174))*.454	Monteith 1979	5-50 cm kilograms

Where: y = biomass in kilograms, Exp = raised to the power of, dbh =diameter at breast height.

Dbh and species were the principal measures used by Winrock to calculate tree biomass in their plot sites.

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[1] Schroeder, P., S. Brown, J. Mo, R. Birdsey and C. Cieszewski. 1997. Biomass estimation for temperate broadleaf forests of the United States using inventory data. Forest Science 43:424-434.

[2] Monteith, D.B. 1979. Whole-tree weight tables of New York. *In* Biomass Equations for Major Tree Species of the Northeast. Northeastern Forest Experiment Station. General Technical Report NE-69. L. M. Tritton and James W. Hornbeck. USDA, 46 pg.

Therefore, our goal in an aerial survey was to find if measurements of crown diameter made from the air could be sufficiently correlated to stem diameter to accurately calculate the dbh of trees visible in the canopy. The USDA Forest Service recently completed a forest health survey of the Northeast U.S. in which both dbh and crown diameter measurements were taken from over 7,500 different tree specimens. Two measurements were made from each crown, its largest diameter and a second value directly perpendicular to the first measurement. Dr. Barbara O'Connell of the USDA in Radnor, PA, provided us with records for 1997 and 1998. We correlated the data and developed regression equations between average crown diameter and dbh for each species found at the Ohio test site (Table 2).

Two approaches were taken to aerial coverage of the sites, essentially 3D and 2D. In the 3D approach, a small format photogrammetric camera was used to develop a bundle adjusted 3D model of each transect using a CVRL developed auto digital elevation modeling program called Terrest (paper reference?). This photographic coverage was flown at an altitude of 4,000 ft. above ground with a calibrated Hasselblad MKW camera. Images were exposed onto 70 mm film and digitally scanned at a resolution of 40 centimeters per pixel, with 80% overlap between frames. A Trimble real-time differential GPS (DGPS) was used for in-flight navigation and georeferencing data. An on-board computer recorded the GPS data and fired the camera at predetermined geographic locations. It also recorded the exact time of each exposure and the corresponding output from a Watson digital gyroscope, which was mounted on the same plane as the camera so that its precise orientation in space could be determined. The excessive overlap was necessary to maintain radiometric consistency in the 3D model generated from the coverage and was made practical by the use of a small format camera and automated digital image handling techniques. Working within this 3D space in a "fly-through" image-processing program, it was easy to identify and measure individual crowns, but very computer intensive and time consuming. However, CRVL is working on a program that may automate this procedure.

Table 2 Regression equations generated from USDA forest health survey data.

	Species	Regression	# of points
1	Hardwoods	$\hat{y} = 1.25310 + .03280\,x$	4452
3	White ash	$\hat{y} = 1.00709 + .03693\,x$	369
4	White pine	$\hat{y} = 2.08342 + .04305\,x$	626
5	Yellow/Tulip poplar	$\hat{y} = 1.31445 + .04100\,x$	448
6	Elm	$\hat{y} = 2.11935 + .02495\,x$	329
7	Black locust	$\hat{y} = 6.89910 + .01185\,x$	99
8	Red pine	$\hat{y} = 0.12001 + .05036\,x$	379
9	Red oak	$\hat{y} = 1.04406 + .03877\,x$	540
10	Black cherry	$\hat{y} = 1.70664 + .04169\,x$	219
		Total number of points	7461

The “2D” approach utilized video coverage of individual crowns at a much larger scale in conjunction with laser rangefinder data. Two Canon ES 500 Hi8 camcorders were then flown over each site at an altitude of 1,000 ft. above ground, providing of video coverage at two different scales. One camera was set at wide-angle coverage providing a swath approximately 320 meters wide, with 50 centimeter per pixel resolution. The other camera was set at 12X zoom, recording a 26 meter wide swath at 4 cm per pixel resolution, a sufficient scale to identify individual tree species (Figure 2). A Horita time code generator wrote the Trimble GPS time code and frame number to each video frame as a record of their geographic locations. It also logged the output from the Watson digital gyroscope and a pulse-modulated laser mounted in a vertical mode to provide a continuous profile of the canopy by sending a series of 248 pulses per second along the flight path. The laser beam was approximately one meter wide at the canopy surface and the instrument was set to record the last return on each pulse for maximum penetration to the ground. It was bore-sighted to the large scale zoomed video to identify sensor penetrations that clearly reached the forest floor and provided a measure of canopy height along each flight line (Figure 3).

This instrument package is a further modification of a system we have been developing over several years (Slaymaker et al., 1996, Slaymaker & Hannah, 1997), that can be attached to the window and door of any Cessna aircraft without additional modification (Figure 4). For the Bolivia coverage, we replaced the Hi8 cameras with a DV digital system and plan to replace that with higher resolution progressive scan cameras that will download directly to an on-board raid array.

ANALYSIS

At the inception of this project, we did not know how well the video / laser combination would work, as compared to a full 3D reconstruction from the calibrated camera. However, as the imagery was compiled and interpreted, it became obvious that the 2D approach was the most cost effective and accurate. The principal reason for this was that the identification of individual tree species and measurement of their crowns remained a manual photo-interpretation task. Work is being done at CVRL to automate these tasks within the 3D environment, but it has not yet matured to a useful stage. At present, the 3D reconstructions are computer intensive and time consuming to produce even with automatic, pixel specific, digital elevation models. Tree crown and heights can be easily identified and measured in a 3D “fly-through” image processing environment, but species identification is more problematic at the 40 centimeter per pixel resolution. Also, the manipulation of these models, even at that resolution, is frustratingly slow and difficult with the desktop computers presently available to most photo-interpreters.

However, other work within the NSF project had developed an automated geo-referencing and mosacking program that utilized the Watson gyroscope and laser data to rectify each video frame into an accurate strip of the ground (Zhu et al., in press). This made it practical to construct strip mosaics of the zoom video and delineate hectare size plots of 20 by 500 meters (Figure 5). At a pixel resolution of 4 centimeters, species could easily be identified and each crown fitted with a circle that averaged its diameter (Figure 6). Combined with the laser profile, this produced a simple model of the forest from which dbh values and heights, could be calculated (Figure 7).

For the purposes of this test then, we concentrated our analysis on manually measuring crowns within one-hectare linear strips from the zoomed video coverage, calculating the dbhs and percent canopy coverage for all visible trees within those strips. This was easily accomplished within a 2D GIS environment using the “object edit” program in TNTMIPS (Figure 6). Circles were fitted over each tree as CAD drawings, which preserved the center coordinates and diameter of each circle in the file database. After a first pass to draw the crown diameters, that file was edited for species type in conjunction with the laser data to attach a height value to each tree. Trees not directly measured by the laser were labeled with an average height for the stand, an average emergent height, or average understory height based on their size and shadow cast. The database for these drawings was then exported to Excel, where a dbh value for each tree was calculated from their crown diameters and the regression equations developed in Table 2. Because the circles in the CAD drawings tended to overlap, they were then converted to vector files with contiguous polygons that could be summarized to determine the percent coverage of canopy in each hectare plot.

Unfortunately, several of the plot sites in the Crooksville study were made within very localized stand conditions, which meant that the video strips had to hit them directly or pass within that stand in order to make a valid comparison. Inasmuch as the original GPS coordinates for the plots were not differentially corrected, this was as much a matter of luck as accurate aircraft aiming. The conifer stands were the most difficult, with only a half-hectare captured of one. We do not expect this to be a problem in Bolivia where the plots coordinates are differentially corrected and we will be using real time DGPS with an Oministar satellite. We were able to analyze and compare 10 video strips, most of which spanned the distance between two sites in a homogeneous community, although the size of the strip had to be reduced in several cases to fit within the stand type. When a strip crossed a road or natural non-forest clearing, the plot was collapsed then reopened on the other side so that only normal or thinned breaks in canopy coverage were included. The average dbh for each strip was then compared to the average dbhs for their corresponding sites.

The results are summarized in Table 3. The video strips are divided by tree type, showing the plot size, number of trees counted and the percent canopy coverage. You will note that canopy cover ranges from a low of 65% in a mature thinned hardwood stand to a high of 92% in an eight year old stand of regenerating trees. This is as we would expect and we anticipate that one of the advantages of using this kind of linear swath through the landscape is that the sample will be a more accurate reflection of the natural and man-made breaks in the canopy than may be captured by a series of 28 meter plots. The number of trees per hectare predicted by these strips is calculated and compared to the number of trees per hectare calculated from the corresponding plot sites. Two sets of columns are presented for both the video strips and the corresponding plot sites. The first column for the video estimates the total number of trees per hectare based on the measured percentage of canopy coverage. The second column estimated that number of based on the assumption of 100% canopy coverage, as would often be the case if the estimate were extrapolated from a single plot site. The first column of plot calculations shows the range of tree estimates for the two plot sites covered by the hectare video strip. These estimates are achieved by multiplying the outer plot count by 16.25 and the inner plot by 201.2, essentially extrapolating the site counts to a hectare sized area. The second column averages those two values after removing the understory of trees less than 7 cm in diameter, which we don't appear to be measuring in the aerial count, but which contribute only a small fraction to the standing biomass. What is striking about these two column sets is the difference between the calculated number of tree between sites that are supposedly within a homogenous stand of vegetation. Given that range of variability it is difficult determine which estimate of tree numbers per hectare is the more accurate, although it appears obvious that the video is undercounting the smaller trees in the 40 year re-growth and the plot site calculations tend to over estimate the percent of canopy coverage.

However, we do have very good correlations between the averages of measured and calculated dbh's for each stand, measurements that are not dependent on the estimation of a larger population from small sites. The last column divides the average measured dbh of the combined ground plot sites by the average calculated dbh of their video strips. A perfect ratio match would be a value of 1, and the admittedly small population of mature hardwoods represented here has a Pearson's sample correlation coefficient of r =.8757, indicating a very strong positive match between the measured and calculated values. We would expect an overestimate the dbhs of trees in the regeneration stands as indicated by sites A11-12 and B27-28, since our equations were developed from a mature population. Given a larger sample base, we could probably develop a correction factor to better characterize that type of stand.

It is difficult to directly compare the plot site values to video strip values when we don't have precise locations for the plots, but a review of size distribution within the mature hardwoods for both video strips and sites, indicates that we appear to be missing the smallest trees and overestimating the sizes of the medium size trees, but that this is somewhat canceled out by a consistent underestimate of the largest trees. These are also adjustments that could be corrected for in a larger ground sample population. Flying over the Noel Kempff Mercado expansion zone was completed in April of 1999, using progressive scan DV digital video. We had precise differentially corrected locations for most of the 635 plot sites and are confident of hitting at least 400 sites with sufficient accuracy to image the plot in the zoom. Crown diameters were not measured in the original plots established by Winrock, but we expect to develop regression equations directly from our analysis of the site images by identifying the major trees, or correlating the total structure of the 28-meter diameter of the trees to the site biomass values.

Table 3 Summary of measurements and dbh calculations for plot sites and video strips.

Forest Stand type with video strips used for interpretation	Size of video strips in Hectares	Number of trees counted in strips	% canopy coverage of strip	Calculated # of trees per hectare from video adjusted to canopy coverage	Calculated # of trees per hectare from video asuming 100% canopy coverage	Range of Calculated # of trees from plots includes >7 cm. dbh trees	Calculated # of trees per hectare from plots with trees >7 cm. dbh removed	Ratio of dbhs averages, sites divided by strips *
White Pine								
site B18-19	0.599776	151	70%	252	360	260-524	398	1.034229
Regeneration Hardwoods								
site_A11_A12	0.29864	361	92%	1209	1314	398-1591	975	0.452874
site B27_B28	0.40029	453	74%	1132	1529	1283-2586	1755	0.633954
Natural Hardwoods								
site A3-A4	1.000024	475	80%	475	594	329-1652	584	0.94121
40 year planting of Hardwoods								
site B25_B26	1.00018	659	82%	659	804	1234-1981	1194	1.102431
site_A10_A9	1.001	323	85%	323	380	788-1137	840	1.04557
site B21_B22	1	403	79%	403	510	739-1202	952	0.998811
site_A8	0.7035	158	68%	225	330	443	438	0.974026
Thinned Hardwoods								
site_A7	0.4001	129	65%	322	496	426	422	1.098875
site_A1-A2	0.9479	453	72%	478	664	475-1104	480	1.021324
				Average ratio of Mature Hardwoods, Natural, planted and thinned =				1.026035286
						Average deviation from mean =		0.048
						Pearson's Sample Correlation Coefficent r =		0.8757

* In order to compare the different approaches to calculating DBH (Diameter at Breast Height), the DBH measurements for the plots associated with each strip were combined and averaged. Trees with less than 7 cm diameter were considered understory and not included in the average. That combined averag was divided by the average of the DBHs calculated from crown diameter regression equations for each video strip. A perfect ratio match would be a value c

CONCLUSIONS

This paper reviews the results of a feasibility study to determine the usefulness of GPS-logged aerial sampling in calculating standing biomass in forests. Although based on a small sample set, it demonstrates that a positive correlation can be drawn between crown diameters in a temperate forest and their corresponding dbh measurements, and that these crowns can be measured from large-scale video mosaics of the canopy. At present this is a manual process in a GIS system, but work is proceeding on a program that will automate the process in a 3D environment. We are also adapting the Terrest automated terrain reconstruction program to work with digital video data, which may prove to be the best adaptation of both techniques. Approximately 20 hours of digital video was recently collected over the Noel Kempff Mercado expansion zone in northeastern Bolivia. Over the next year, we will be comparing this data to the series of 635 site plots established by the Noel Kempff Mercado Climate Action Project, and will be able to make a more precise determination of the extent to which the standing biomass in tropical forests can be successfully predicted from large scale aerial video.

ACKNOWLEDGEMENTS

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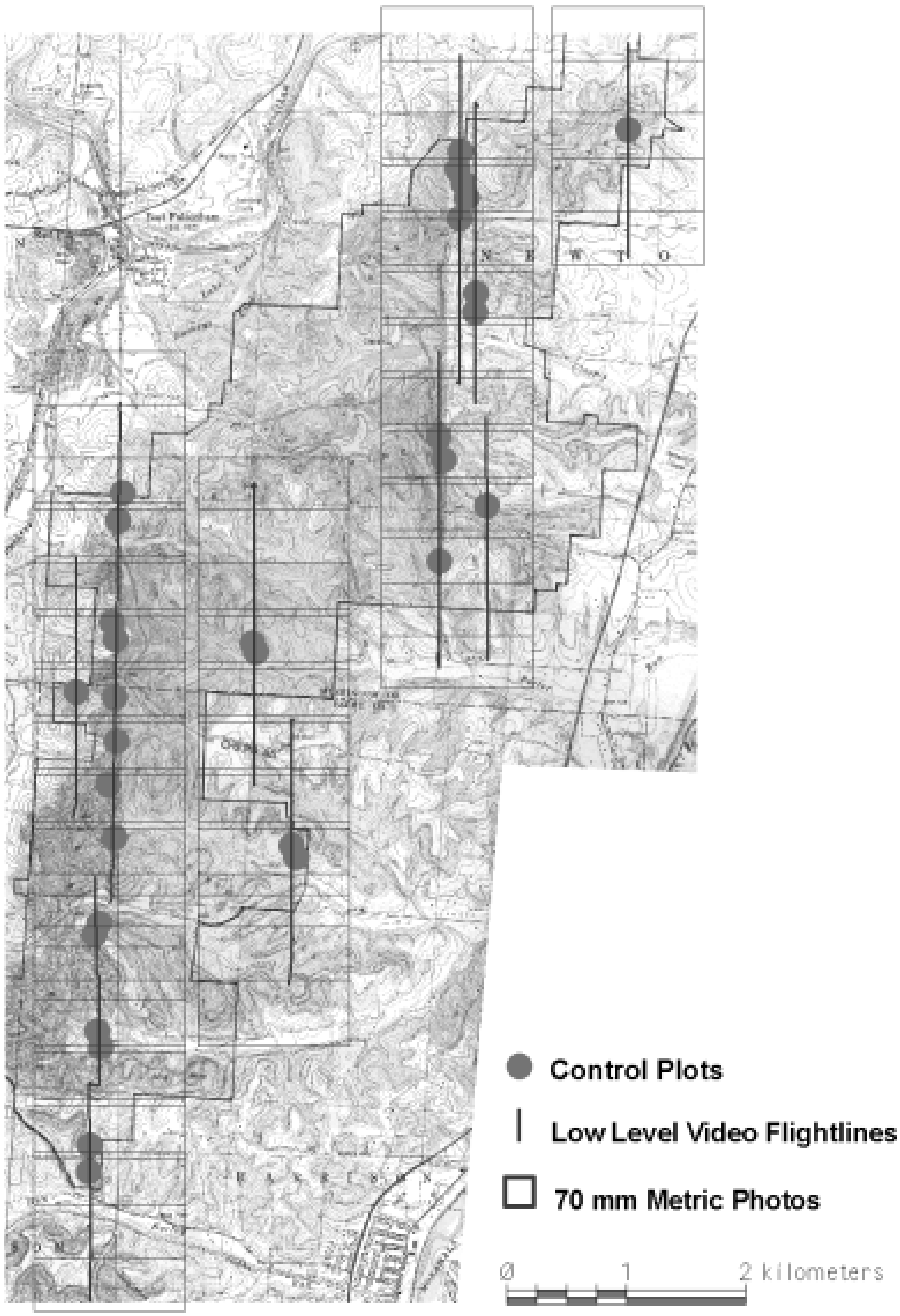

Figure 1 Plot sites and flight lines for Crooksville test.

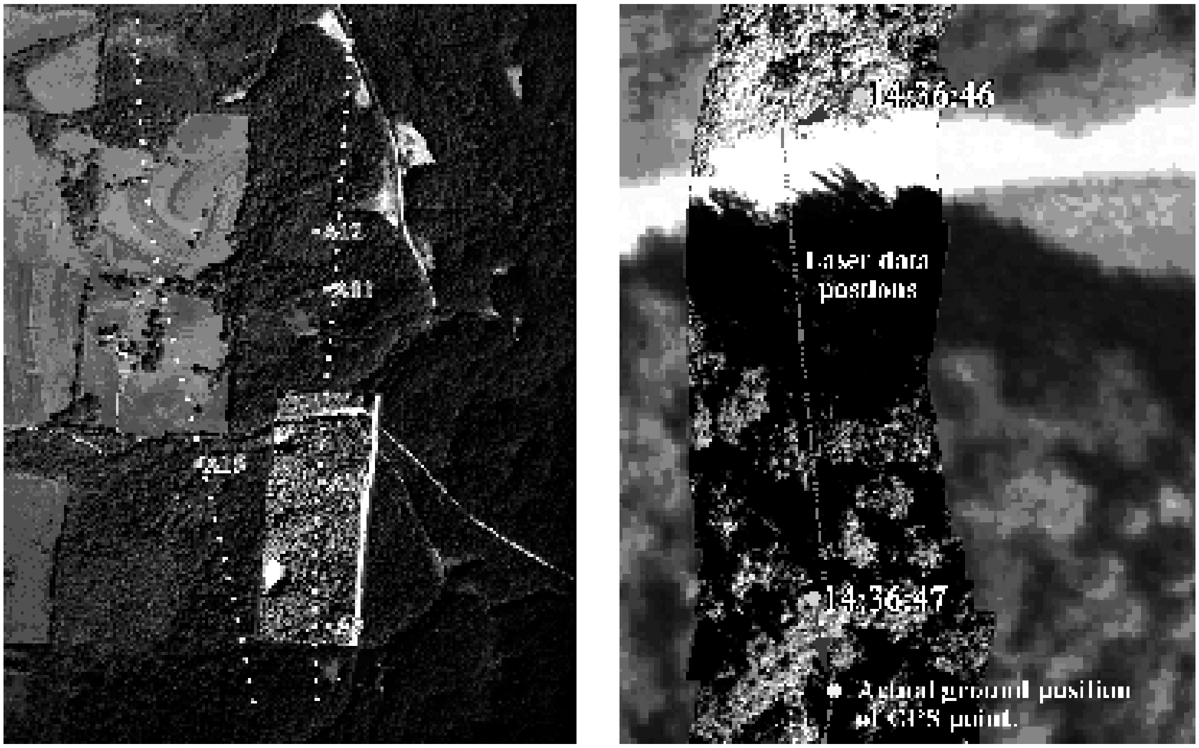

Figure 2. Wide-angle video mosaic superimposed on the 70 mm photographs, with detail showing the zoomed video mosaic. The ground coordinates of each GPS logged position are calculated from the orientation of the digital gyroscope.

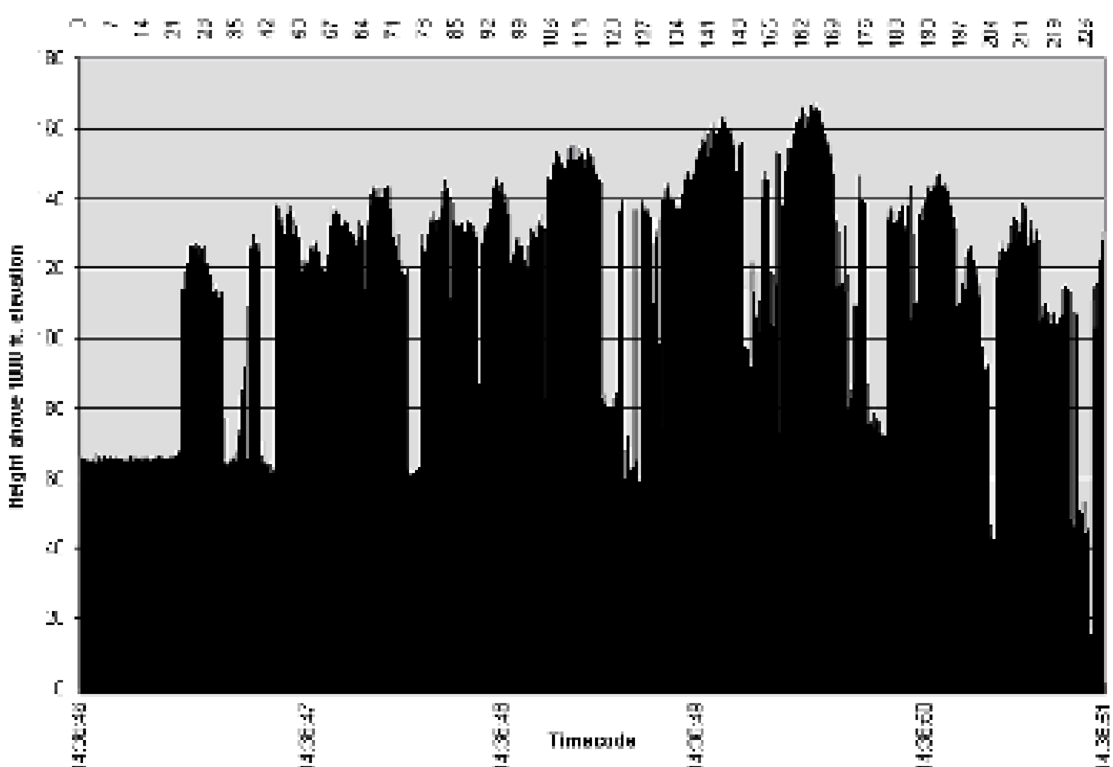

Figure 3. Laser profile of the video strip showing tree height in the stand.

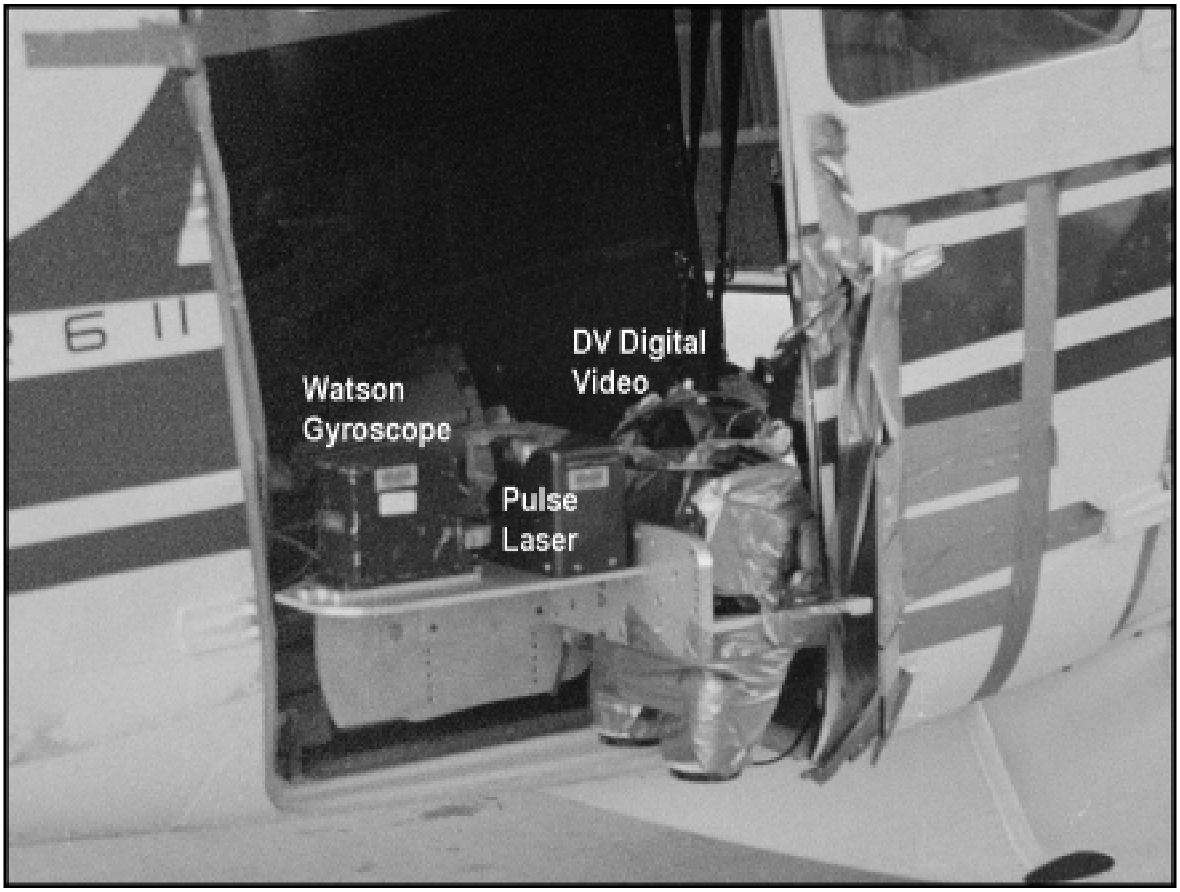

Figure 4 Camera system mounted out the side of a Cessna 206 in Bolivia. An airfoil has been attached to the forward door of the cargo bay to protect the cameras from the airstream.

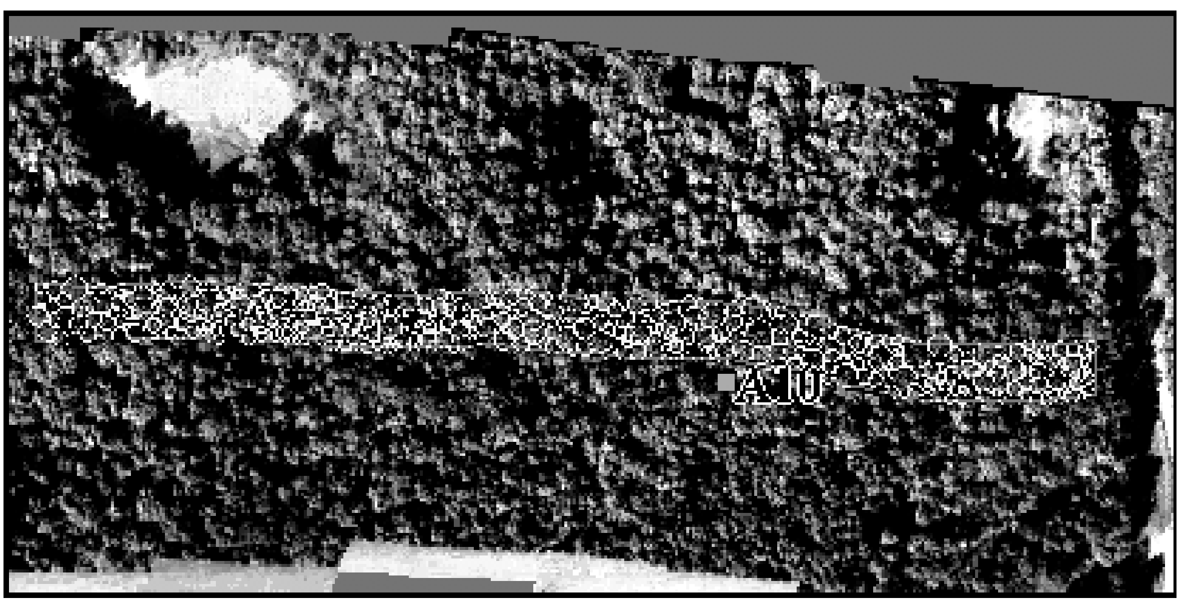

Figure 5. Zoomed video mosaic overlaid on wide angle mosaic with a one-hectare size strip plot**.** Crown diameters were measured by fitting circles over them in a GIS program.

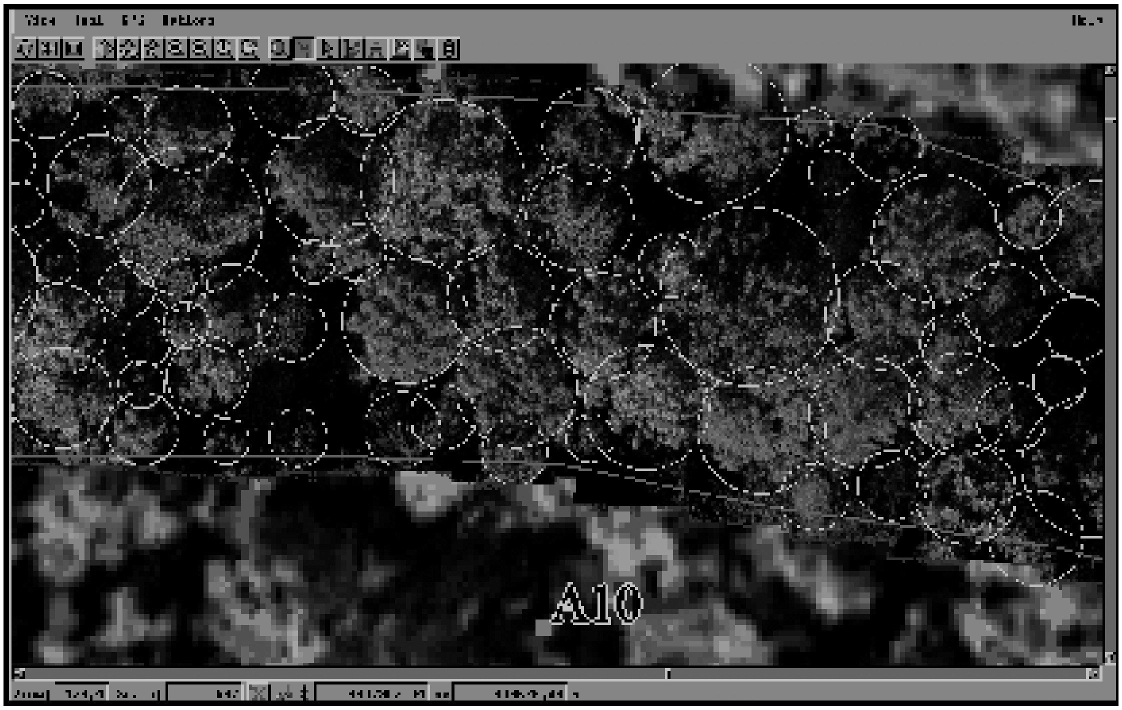

Figure 6. The detail and color discrimination of the zoomed video mosaics proved to be a greater advantage than the 3D modeling of a lower resolution surface. Draping the video strip over the terrain model combines the best features of both, but is a slow process most useful as a training tool.

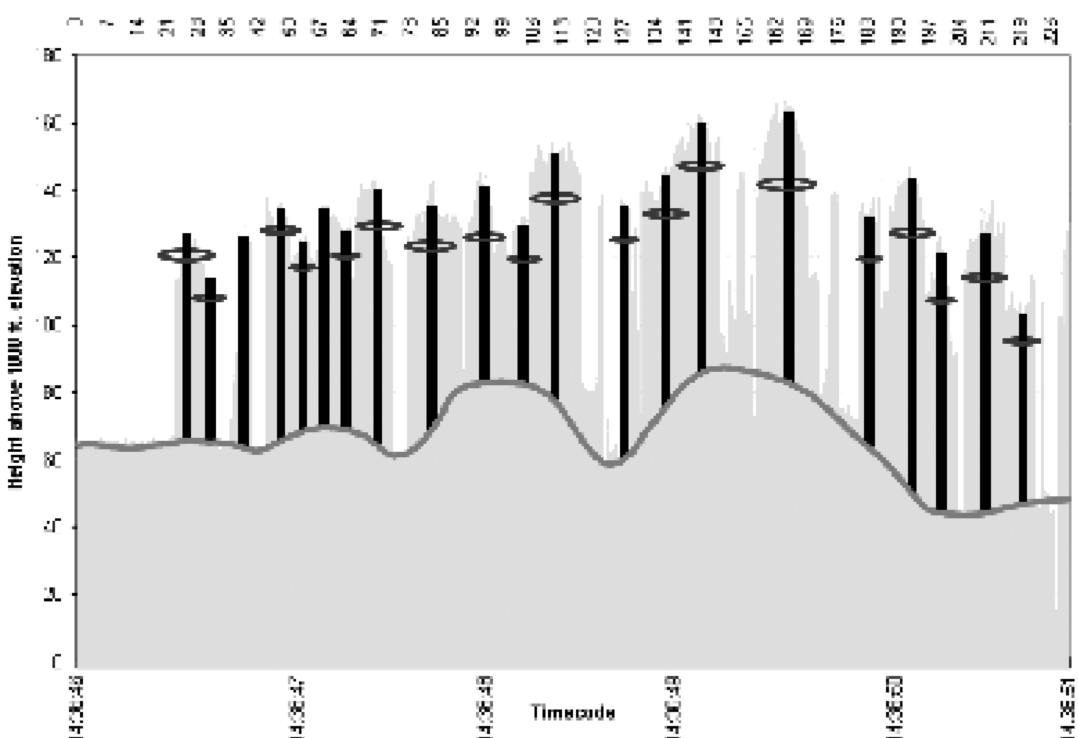

Figure 7. Combining these circles with the laser profiling data reduces the forest to a simple model of poles with height and diamete