Digital Terrestrial Photogrammetric Methods for Tree Stem Analysis

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Abstract.—A digital camera was used to measure diameters at various heights along the stem on 20 red oak trees. Diameter at breast height ranged from 16 to over 60 cm, and height to a 10-cm top ranged from 12 to 20 m. The chi-square maximum anticipated error of geometric mean diameter estimates at the 95 percent confidence level was within ± 4 cm for all heights when obtained at a distance of 12 m or greater. Error increased with increased stem height from ± 3 to ± 7 cm for heights from 1 to 20 m. In general, the error is equivalent to three times the instrument precision, which varies with distance. Two-thirds of the volume estimates were within 8 percent of "actual" volumes.

Diversifying values and increased accountability are forcing today's natural resource managers to make complex and defensible decisions. Information requirements to make these decisions are expanding in magnitude and variety, especially in forestry. Multiple resource inventories are being developed to maximize the efficiency of data collection for multiple objectives (Lund 1998). Analyses involving the health, volume, growth, change, and potential of forest resources at some level require information about individual stems. Collecting the large amounts of data required for these purposes is slow and expensive. In this paper, a method is set forth using a non-metric digital camera to capture raw data from an individual stem that can later be used for customized analysis. Diameter and height measurements were derived in this study to examine the effectiveness of this method for determining stem volume.

CAMERA INFORMATION

The camera falls into the optical fork (Grosenbaugh 1963) category of optical dendrometers, which are devices that allow measurements to be taken visually from a remote location. With optical forks, two lines of sight passing through two tangential points on the tree stem representing the diameter and intersecting at a point in front of "the observer" are used to determine an angle. This angle is scaled using the distance to the point of measurement (range) to determine the stem's diameter. "The observer" in respect to the camera is the image plane, and the point of intersection is the focal point of the lens.

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In conventional photography, the image plane consists of an area of film coated with a light-sensitive emulsion. In the case of the Kodak DC120™ digital camera, this image plane takes the form of an 850 x 984 element CCD (charge-coupled device) array that produces a resultant image that is 960 x 1,280 image pixels in dimension (Kodak 1997). Each element in the DC120 CCD array is 7.8 x 5.0 microns in dimension (Kodak 1997). These 836,400 packets are then transformed to produce the final 3,686,400 digital output values (1,280 x 960 (pixels) x 3 (colors)). Although the size of the CCD elements was reported, the image pixel size had to be empirically derived since the details of the interpolation algorithms are proprietary. The procedure used to do this can be found in *Clark et al.* (1998). The resultant image pixel dimension was found to be 5 microns.

The image processing software used for image measurement did not allow for sub-pixel mensuration, so the precision of the camera can be defined as a linear function of the distance from the imaged object. Equations 1 and 2 were used, substituting 5 microns for d, 7 mm for f, and setting L_o at 1 m. Solving for D resulted in an object space precision in the horizontal and vertical directions of ± 0.7 mm per meter from the object (fig. 1).

$$s = \frac{d}{D} \qquad (1)$$

$$s = \frac{f}{L_0} \qquad (2)$$

where s = scale
d = image space distance
D = object space distance
f = focal length
L_o = horizontal distance from focal point to imaged object

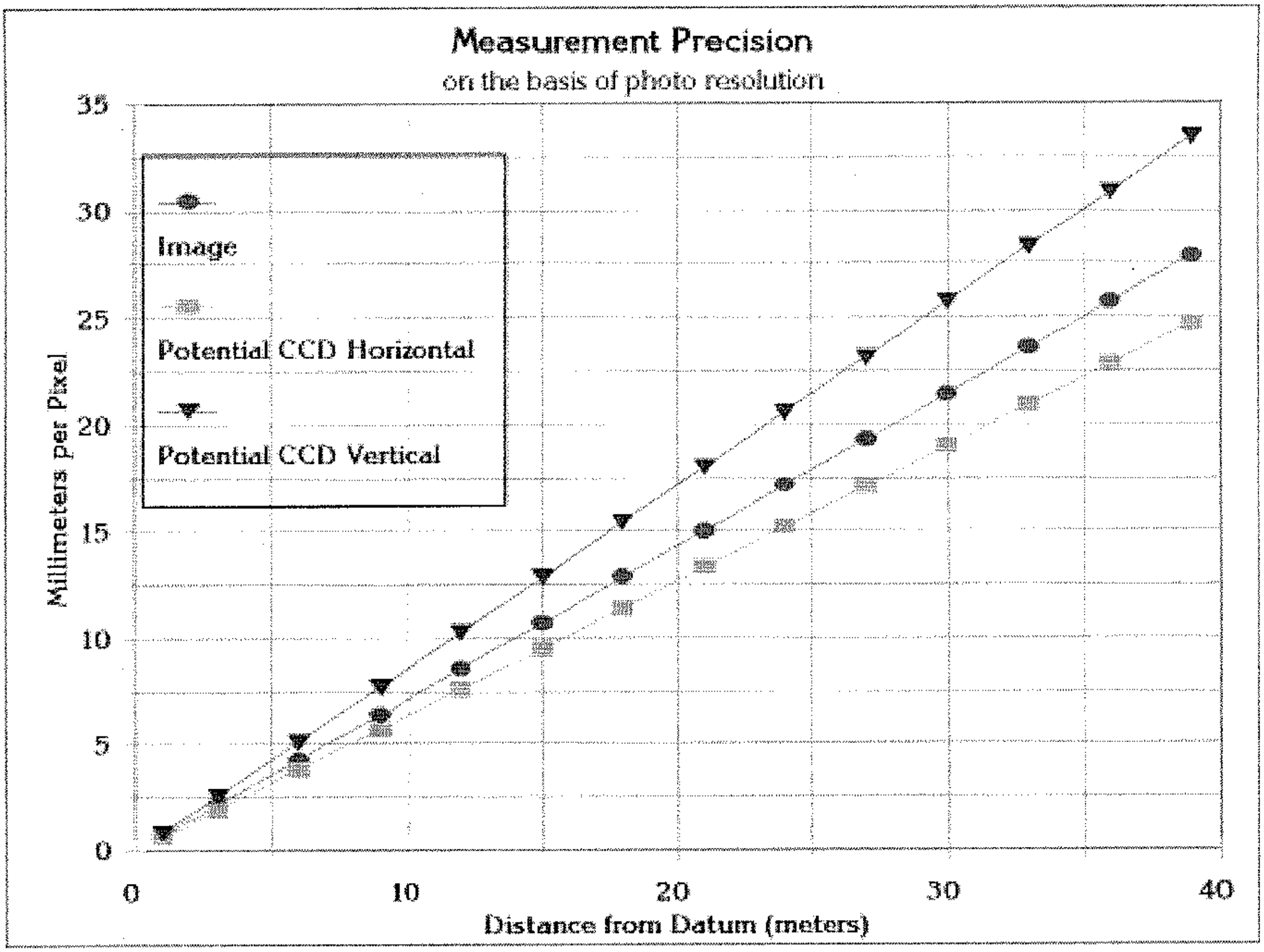

Figure 1.—*Measurement precision based on pixel size for the Kodak DC-120 digital camera. Resolution is calculated from the product of the pixel dimension and the distance of the focal point from the datum plane divided by the focal length of the camera. The focal length of the DC-120 set at maximum wide angle is 7 mm. Image pixel size is empirically determined to be 5 microns. Potential horizontal and vertical CCD "pixel" size is calculated from the product of the CCD element size (7.8 x 5.0 microns) and the array dimensions (850 x 984 pixels) and dividing by the image array dimensions (960 x 1,280). This calculation results in 4.4 and 6.0 micron "virtual pixel" vertical and horizontal dimensions, respectively. This is an estimate since the interpolative techniques are unknown.*

FIELD DATA INFORMATION

Stem Selection

Red oak (*Quercus spp.*) was selected for this study due to its moderate variations in bark and form distinctions. Northern red oak (*Quercus rubra*), black oak (*Quercus velutina*), and scarlet oak (*Quercus coccinea*) were the species sampled in this study. This species criterion was imposed to reduce variation due to morphological dissimilarity among species. Five stems were selected from each of four diameter strata, (16 - 30 cm), (31 - 45 cm), (46 - 60 cm), and (> 60 cm), to observe effects due to size. Two stems in each category were collected on a shallow-soiled ridgetop near Radford, VA; the remaining three stems were located on a moderately well drained midslope in Asheville, NC.

Image Collection Procedure

The DC120 features a 3x magnification, but the shortest focal length was used in this study to capture the maximum length of stem per image. Distance between the stem and the camera station was one of the main criteria investigated. Inversely related to this was the angle of inclination of the camera. To study the possible effects of this angle/distance relationship, data were captured at distances of 3, 6, 9, 12, and 15 m.

At each stem a quick visual survey was made to select four orthogonal directions with the least amount of obstruction from understory vegetation or parts of adjacent stems. Using red spray paint, a mark was made on one face of the stem corresponding with the direction determined from the visual survey. This mark was used as an indicator of the direction of the first camera station and aided in orientation of the caliper measurements after the stem was felled. The second camera station was directly opposite the mark, and the third and fourth camera stations were perpendicular to the mark (fig. 2).

The camera was oriented with the widest dimension of the image plane in the vertical direction. The shortest focal length was used to capture the maximum amount of stem height per image. The shutter speed was set to auto-exposure + 1.5 stops for most images. In backlit conditions the exposure time was reduced, and conversely, in lower light conditions the exposure time was increased. The LCD monitor on the camera was used to view the image seconds after capture to determine if the exposure was correct. If it was not, the image was erased, exposure adjusted, and another image was acquired.

A nylon tape was secured at the stem's base at a right angle to the plane of the stem axis and the camera station (B_o) (fig. 3). After the camera was adjusted on the tripod so that this point was visible through the viewfinder, this distance was measured and recorded to the nearest 0.5 inch. A handheld clinometer was used to measure the inclination angle (θ) (fig. 3) to the nearest ± 5 percent slope, and this angle was recorded. Overlapping images were captured of the entire stem face before locating the antipodal camera station and repeating the process.

In Situ Data Collection

In situ data were collected to determine the accuracy of image-derived measurements. After all imagery was acquired, the stems were felled. Height measurements were made from the uphill contact point of the ground and stem. The downed stem was then measured with a nylon tape to determine the exact points at which to measure diameter. Steel calipers were used to measure diameters perpendicular to the camera station locations, resulting in two perpendicular measurements at each height (fig. 2). Therefore, one caliper measurement corresponds to two camera measurements for each directional diameter. Diameter measurements were taken at 1.4 m (diameter at breast height [dbh]) and every 1.2 m from the height of 2.4 m to a 10-cm top or to the end of the merchantable stem.

Office Procedure

Images were downloaded from the 10 megabyte removable storage card in the camera into a computer for processing using the Kodak Picture Transfer™ software that accompanied the camera. The images were transferred and stored in the native KDC format because this format also allows information such as the quality setting, exposure time, and date/time to be associated with each image. A TWAIN module provided with the camera was

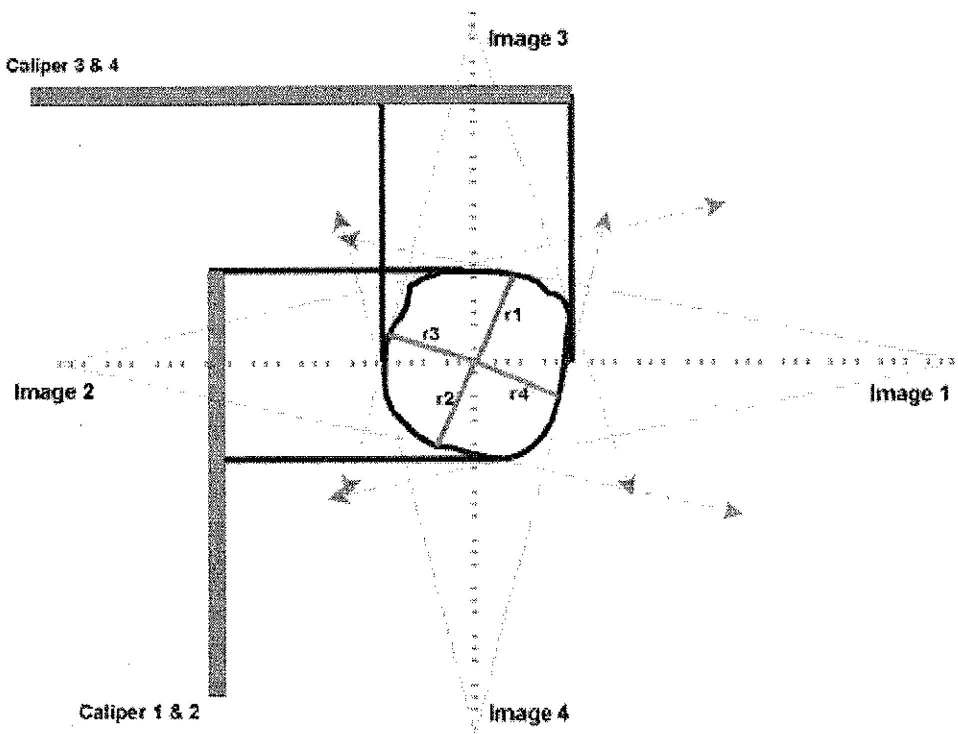

Figure 2.—*Orientation of caliper measurements and camera stations for the procedure used in this study.*

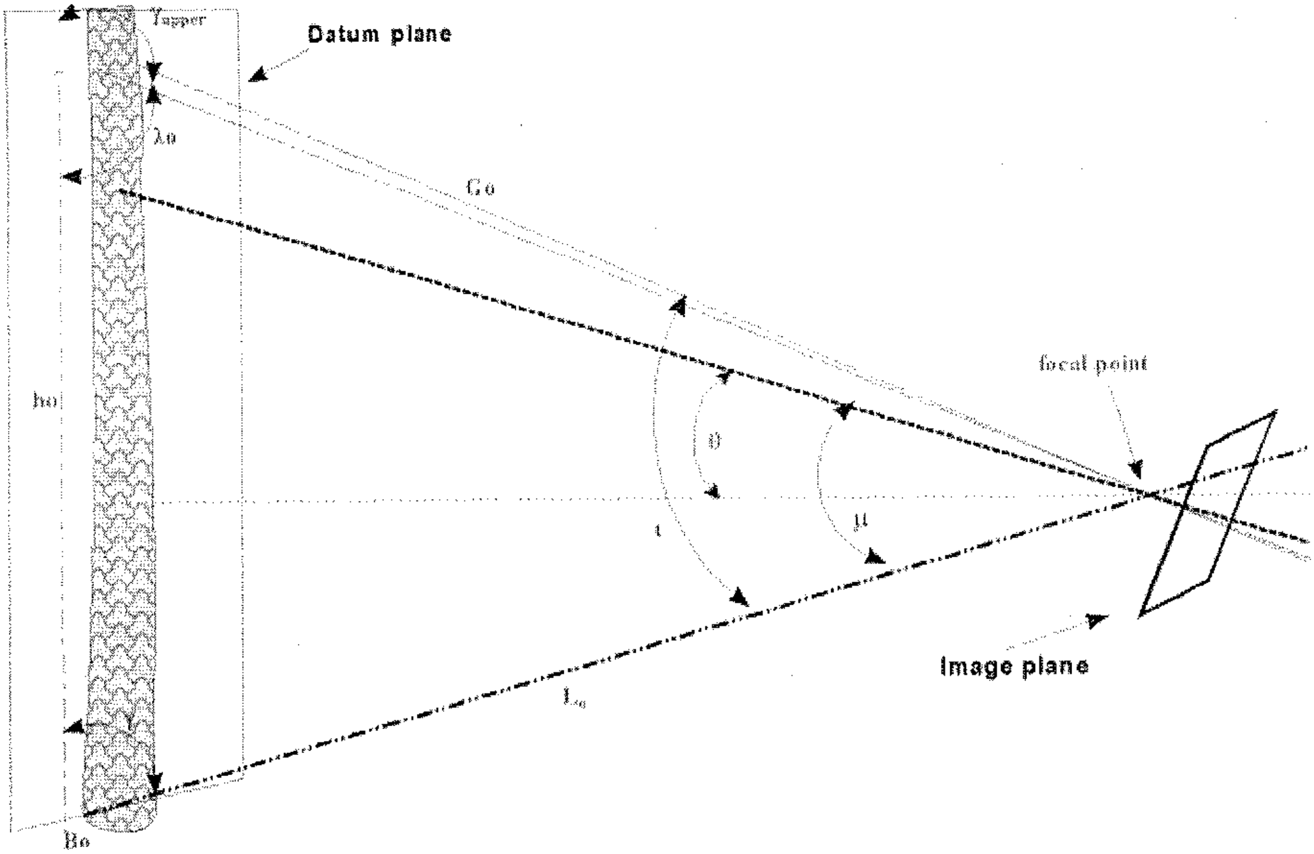

Figure 3.—*Diagram of object space showing measured or calculated angles, distances, and points.*

subsequently used to convert the images to tagged image file format (TIFF) as needed. The camera offers several quality settings that compress the image to varying levels in the camera. The quality setting number three used in this study has an approximate file size of 240 kilobytes, which expands to 3,686 kilobytes when completely uncompressed to the TIFF format.

The images were sequentially numbered by the camera in the order they were captured. Great care was taken to ensure that the images remained in the same queue so that they could be matched with the correct angle, distance, face, and stem field data. Image measurements in this study were obtained using the University of Texas Health Science Center at San Antonio free ImageTool[1] program. Ancillary data were entered into an ASCII file that was accessible to diameter extraction software written by the author[2].

For each image, tree number, face number, image distance (L_o), and angle of inclination (θ) were transferred from field data sheets into this ASCII file. The image of the stem's base was viewed, and the image row value representing B_o was transmitted to the ASCII file and assigned a height value (fig. 3). Given that this was the base point, it was adjusted or estimated so that 0 was the highest point where the ground met the stem. On level ground, it was possible that all four base images per stem could have been set to 0; otherwise, the uphill (the side where the tape was secured) side of the faces perpendicular to the slope was set equal to 0. Point B_o for the upslope and downslope images was determined by averaging the distance between the high and low sides of the images showing the slope and subtracting from 0.

A point (a) was selected that could be identified in both the upper and lower images to determine B_o and L_o for the upper image. After the row values for point a from each of the images and the B_o value of the lower image were entered, B_o and L_o for the upper image were calculated by a module in the diameter extraction software. This height was transferred to the ASCII file along with the corresponding row value from the upper stem image. B_o for the upper image becomes the identifiable point with height

[1] *Available from the Internet by anonymous FTP from* ftp://maxrad6.uthscsa.edu

[2] *Contact author at* neclark@vt.edu *for code or other information related to measurement derivation.*

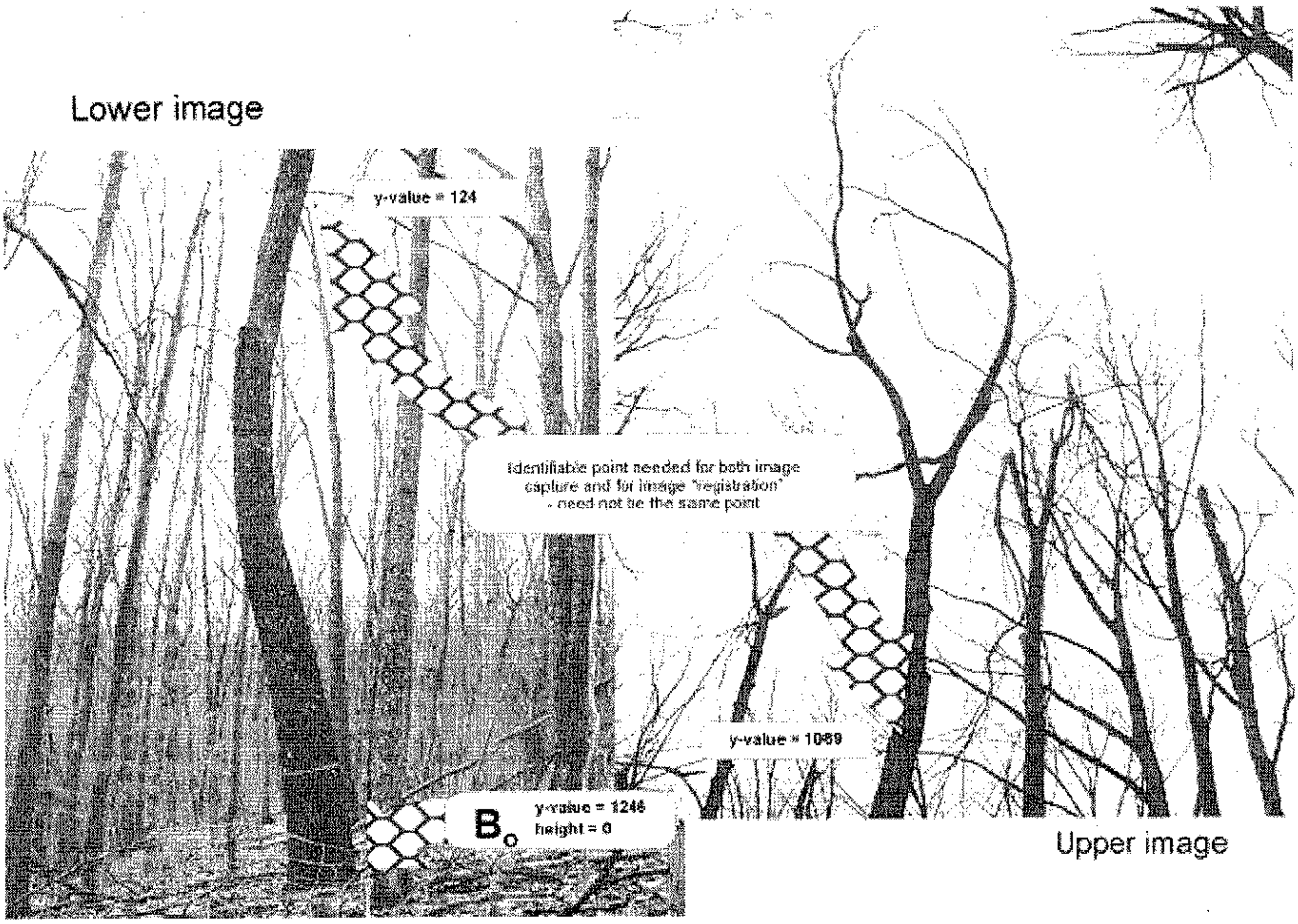

Figure 4.—*Upper and lower images at a single camera station showing location and image row value of* $\boldsymbol{B_0}$ *and identifiable point* ***a*** *and row values for each of the images.*

calculated from the lower image to *a*. L_0 for the upper image becomes the distance from the focal point to *a*, and γ becomes 180° minus the angle formed by the stem axis and the ray between the focal point and *a* in the lower image.

Diameters were derived from the raw image data using the diameter extraction software. Tree numbers and stem heights of the desired diameters were entered into an ASCII file. The program reads the ASCII file containing the field data and image information and the stem and height ASCII file, and it outputs the names of the images that contain the points that correspond to the desired diameters and their corresponding row values. The image coordinates representing the left and right edges of the stem at the respective row value were obtained with the ImageTool program and imported to the diameter extraction software.

There were two caliper measurements of diameter for each height and four camera measurements of diameter for each height. The two diametrical camera measurements for the same distance from the tree were arithmetically averaged. From this, the two perpendicular measurements for the camera were used to calculate the geometric mean diameter (GMD) of a circle with the same area as an ellipse with axes *a* and *b* (Equation 3). GMD at each height was also calculated by this same method substituting the two caliper measurements for *a* and *b*.

$$GMD = 2\sqrt{ab} \tag{3}$$

where *a* and *b* = perpendicular directional diameters
GMD = geometric mean diameter

Cubic foot volume (later converted to cubic meters) was then calculated using Smalian's formula (Equation 4) for each 1.2-m (4-foot) bolt and summed to report the total merchantable volume for the stem. English units are used here for the convenience of comparison to existing volume tables.

$$Volume = \frac{\pi}{4 \times 144} \frac{D_l^2 + D_s^2}{2} l \quad (4)$$

where D_l = large end diameter (inches)
D_s = small end diameter (inches)
l = length of section (feet)

Although Smalian's formula tends to overestimate volume, especially for the butt log, it serves only as a means of comparison rather than an accurate estimate of volume.

A chi-square test (Equation 5), such as introduced by Freese (1960) to determine whether a technique meets a certain accuracy requirement and modified by Bell and Groman (1971) to determine the maximum anticipated error, was used to measure the anticipated accuracies at the various distances and for different diameter classes.

$$E = \sqrt{\frac{\sum_{i=1}^{n} \left[\left(x_{i-\mu_i} \right)^2 \right] \bullet r^2}{X_n^2}} \quad (5)$$

where x_i = camera estimate of the i^{th} observational unit
μ_i = "true" estimate of the i^{th} observational unit
r^2 = value of the standard normal deviate at a set α level
χ_n^2 = chi-square value with n degrees of freedom

RESULTS

Field Data

There were 241 paired perpendicular diameter measurements taken with the conventional. Varying stem heights, damage incurred during felling, and human error accounted for unequal sample sizes within the various strata. Table 1 shows the number of field measurements taken by height category.

Image Data

Table 1 also shows the numbers of geometric mean diameter estimates that were derived from the image measurements. Missing GMD's are the result of at least one of the four image measurements being absent. This occurred in cases where the stem was occluded by objects in the foreground to the extent that a confident measurement could not be obtained. This visibility concern can be avoided in non-experimental situations where there are fewer restrictions on camera station location and tree height designation. There were no great differences in measurement attainability from the 6- to the 15-m distance class. The 3-m distance numbers fall off sharply after about the 11-m stem height mark, predominantly due to the sensitivity of the acute viewing angle to stem lean.

Table 1.—*Number of field and image collected diameter measurements obtained from 20 red oak stems (8 in Radford, Virginia / 12 in Asheville, North Carolina) in March/April 1998*

	Nominal distance of camera station (m)					
Stem height (m)	**3**	**6**	**9**	**12**	**15**	**Field**
1.4	18	18	18	18	18	18
2.4	19	18	18	18	17	19
3.7	19	19	19	19	19	19
4.9	19	18	19	19	19	19
6.1	17	18	18	18	18	19
7.3	17	18	18	18	18	19
8.5	17	18	18	18	18	19
9.8	16	19	19	20	19	20
11.0	12	18	20	20	19	20
12.2	9	17	17	18	15	20
13.4	4	11	14	14	10	15
14.6	3	10	9	11	12	13
15.8	2	6	7	8	9	10
17.1	2	4	3	4	4	6
18.3	0	2	1	0	1	3
19.5	0	0	1	0	1	2
	174	214	219	223	217	241

Analysis of Variance Results

Analysis of variance for an experiment with repeated measures was performed on the data to examine the various effects. The procedure was run using the SAS proc mixed function (Littell *et al.* 1996). The 20 stems were classified into four diameters (breast height) classes - (16 - 30 cm), (31 - 45 cm), (46 - 60 cm), and (> 60 cm), each containing five stems. The distances of 3, 6, 9, 12, and 15 m were studied as fixed effect as well as height in 1.2-m increments (16 levels) beginning at 1.4 m from the ground. Because every stem was an experimental unit for each of the treatments, repeated measures tests were used to account for the effects of the subjects (stems). Orthogonal contrasts were examined to determine significant differences among the means. Several models were run to determine the significant effects that contribute to error using this technique. Distance, diameter class, height, and distance/height interaction were used as fixed effects in the models. There were no random effects.

The first model that was run included all the factors. Only height and the interaction term showed significant effects at the 95 percent confidence level. All subsequent models examined each effect separately. The model using the nominal distance as the only effect did not show any significant differences at the 95 percent level. It can be noted, however, that the average deviation from zero at the 3-m distance was greater than at any other distance (table 2). The largest standard deviation was also at the 3-m distance.

Height was stratified into four classes—(1-5 m), (6-10 m), (11-15 m), and (16-20 m)—to see if the significant effect was simply due to the extreme level of stratification. The analysis of variance showed no significant differences among the means. Even though the equal variance assumption was ignored, it is apparent that the maximum difference between any of the means does not approach even the smallest standard deviation. Table 2 shows that the standard deviations of these observations rise about 1.5 cm for every 5 m increase in height. This variance difference is readily apparent in the scatterplots of the errors by height at various distances (fig. 4). Visual interpretation of these plots shows that in every case the variance increases with height. The errors at the 3-m distance are more dispersed than at any other distance. The 95 percent range results from the ordered difference results bring the magnitude of these results to light (table 2).

Volume Results

Volumes were calculated as previously described. Volumes were calculated for each of the 20 stems in each of the distances, regardless of missing camera observations. Where there were missing field observations, only the section of the stem measured in the field was compared. For example, if the 1.4-m distance was not

Table 2.—*Summary statistics for camera minus caliper geometric mean diameter estimates in centimeters by distance and diameter for 20 red oak stems. Reported are the arithmetic means and standard deviations, the maximum anticipated error (E) using the chi-square test for accuracy, and the actual measurement range of the nearest 95 percent of the observations from the median observation.*

	Nominal Distance					
	3 meter	6 meter	9 meter	12 meter	15 meter	all
n	174	214	219	223	217	1048
Mean(cm)	-0.458	-0.111	-0.173	-0.132	-0.335	-0.232
Std. Dev.(cm)	3.039	2.301	2.178	2.133	2.074	2.337
E(cm)	5.5	4.2	4.0	3.9	3.8	4.7
95% range(cm)	(-5.8,6.8)	(-4.5,4.8)	(-4.6,4.8)	(-3.6,3.8)	(-3.3,3.8)	(-4.6, 5.3)

	Nominal Height			
	1- 5 m	6 - 10 m	11 - 15 m	16 - 20 m
n	369	360	263	56
Mean(cm)	-0.053	-0.459	-0.126	-0.458
Std. Dev.(cm)	1.346	2.07	3.134	4.058
E(cm)	2.5	4.3	5.7	7.0
95% range(cm)	(-2.8,2.8)	(-4.3,4.3)	(-5.1,6.7)	(-7.4,10.2)
Median	-0.25	-0.51	-0.51	-1.02

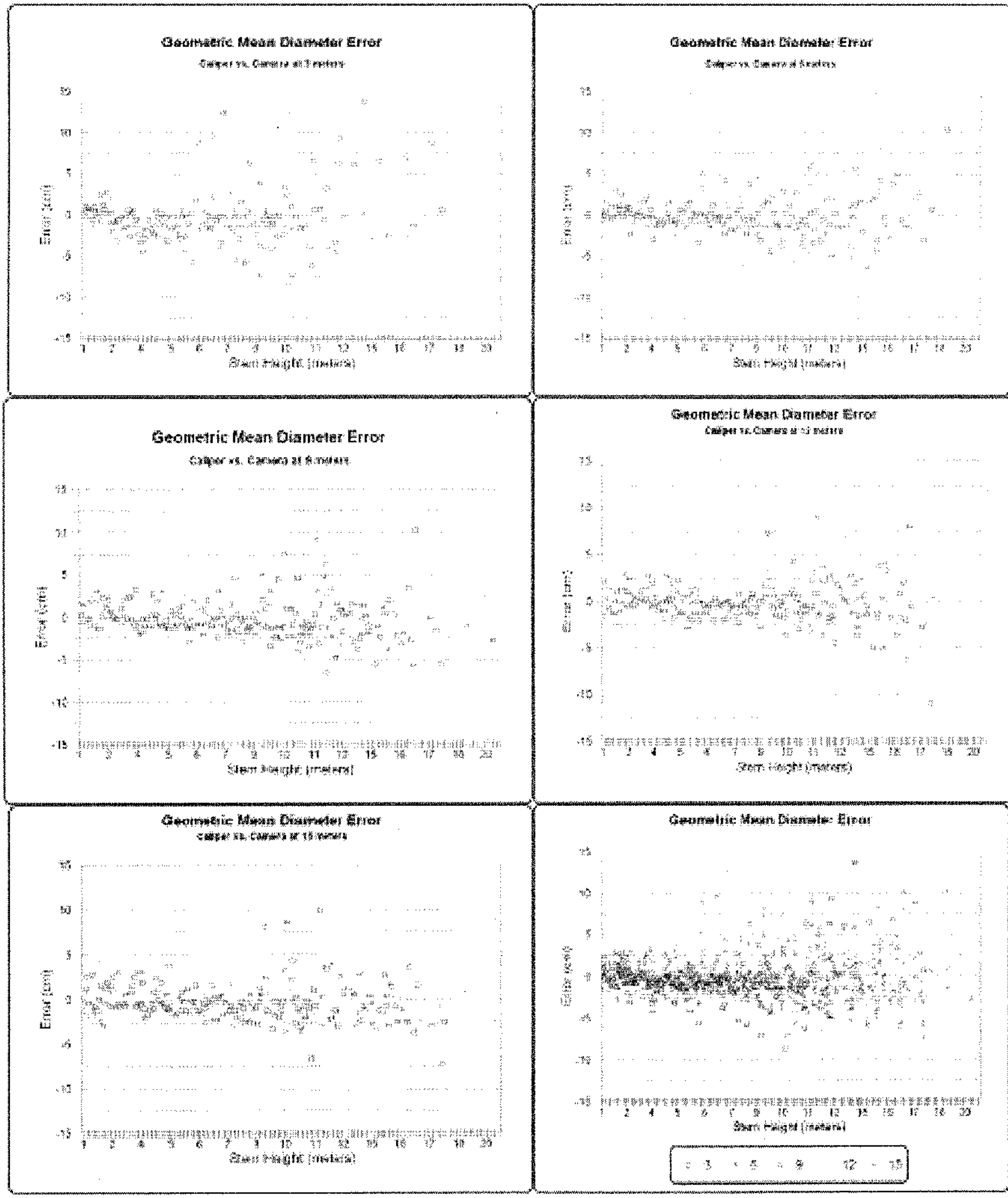

Figure 5.—*Scatterplots of geometric mean diameter error in centimeters by height for five distances from 3 to 15 m.*

recorded, only the stem section from 2.6 m to the measured top was evaluated for both camera and caliper. For the stem that split when felled, single caliper measurements were used up to 9.8 m. The GMD's were used when possible for the camera estimates, but directional diameters were used where the GMD's could not be calculated. Only distance was used as a factor since height is intrinsically related to volume and diameter was not found to have any significant effect. The 12-m distance resulted in the mean closest to zero and had the lowest standard deviation, although it is not significantly different from other distances in the 6- to 15-m range. The 3-m distance had the greatest standard deviation and also the largest difference of the mean from zero.

To better see the advantages of this system, the results were compared to results from an alternative method. The alternative method was using volume equations developed specifically for northern red oak in the southern Appalachian Mountains. The equations used (Equations 6 and 7) were for cubic foot volume, later converted to cubic meters, for wood and bark using dbh and height to a 4-inch top (10 cm) as independent variables (Clark and Schroeder 1986). This equation still requires an instrument to take upper stem measurements to obtain an estimate with any precision. For the comparison in this study, the GMD's from the caliper estimates were used along with the field-taped heights for equation input parameters. Because these are the same measurements used in "actual" volume calculations, any error comes from the model. Height to a 4-inch top was not acquired in the field for every tree. Diameter data were collected for some trees only up to the end of the merchantable stem. This is seen particularly in the larger diameter stems where the equations produce an underestimate of volume. For many of these stems without a clear dominant main stem, it is often difficult to determine which 4-inch top should be measured.

$$volume_{<11"} = 0.03592(d^2h)^{0.73586} \qquad (6)$$

$$volume_{<11"} = 0.01199(d^2)^{0.95561}h^{0.73586} \qquad (7)$$

where $volume_{<11"}$ and $volume_{>11"}$ = cubic foot volumes of wood and bark for stems less than 11 inches and greater than 11 inches, respectively.
d = diameter at breast height in inches
h = height to a 4-inch top in feet

Although the equation provides quite an accurate assess-

Table 3.—*Volume estimates for 20 red oak stems comparing camera estimates from the 12 meter distance, the average of all camera estimates, and the equation estimates to the "true" caliper estimates. The left four columns show the stem volumes in cubic meters, the next three columns from the left show the cubic meter differences, and the final three columns report the percent differences.*

	cubic meters				cubic meters			percent		
	caliper	12 m	AVG	equation	12-cal	avg-cal	equ-cal	12-cal	avg-cal	equ-cal
1	0.80	0.77	0.74	0.77	-0.03	-0.06	-0.03	-3.6	-8.0	-3.6
2	0.78	0.79	0.77	0.70	0.01	-0.01	-0.08	1.5	-1.0	-9.9
3	0.29	0.27	0.27	0.33	-0.02	-0.01	0.05	-7.2	-4.7	15.8
4	2.44	2.53	2.32	1.85	0.09	-0.12	-0.59	3.7	-4.9	-24.1
5	3.74	3.61	3.50	2.72	-0.13	-0.24	-1.01	-3.4	-6.3	-27.2
6	0.76	0.75	0.76	1.09	-0.02	0.00	0.32	-2.0	0.1	42.3
7	1.60	1.55	1.55	1.75	-0.05	-0.04	0.16	-2.8	-2.5	9.9
8	0.17	0.18	0.16	0.20	0.00	-0.01	0.03	1.7	-6.4	17.0
9	0.36	0.32	0.32	0.43	-0.03	-0.03	0.07	-8.6	-9.7	20.4
10	0.55	0.51	0.52	0.56	-0.04	-0.03	0.01	-7.8	-5.4	1.3
11	3.45	3.75	3.70	3.15	0.30	0.25	-0.29	8.8	7.3	-8.5
12	2.70	2.72	2.25	2.21	0.02	-0.44	-0.49	0.9	-16.5	-18.0
13	1.40	1.21	1.18	1.30	-0.18	-0.22	-0.10	-13.2	-15.4	-7.0
14	4.84	4.48	4.62	3.69	-0.37	-0.22	-1.15	-7.5	-4.5	-23.7
15	1.42	1.36	1.45	1.41	-0.06	0.03	-0.01	-4.1	2.4	-0.7
16	3.26	3.51	3.37	2.81	0.25	0.10	-0.46	7.5	3.2	-14.0
17	2.39	2.40	2.29	1.91	0.00	-0.10	-0.49	0.1	-4.1	-20.4
18	0.51	0.54	0.50	0.52	0.02	-0.01	0.01	4.9	-2.8	1.3
19	1.13	1.23	1.16	1.05	0.10	0.03	-0.08	8.5	2.3	-7.3
20	2.51	2.69	2.62	2.21	0.17	0.10	-0.30	6.9	4.1	-12.0
Mean	1.75	1.76	1.70	1.53	0.00	-0.05	-0.22	-0.79	-3.65	-3.42
Std. Dev.	1.34	1.34	1.32	1.02	0.14	0.15	0.38	6.31	6.08	17.56

ment of volume for the reduced amount of work and man hours required, the standard deviations of the differences, both cubic meter and percent, are twice as large for the equation estimates as for the camera estimates (table 3). The percent difference numbers should be interpreted with caution since a small stem carries the same weight as a large stem. Comparison of the results from the 8 Virginia stems and the 12 North Carolina stems showed that standard deviations for the North Carolina stems were only one and a half times larger for the equation than the camera for estimates. This ratio increased to six for the Virginia stems. This indicates the effects that stand factors can have on morphological characteristics. Reliability of estimation is directly proportional to ability in matching the range (e.g., location, species, diameter classification resolution, form information, etc.) and resolution (e.g., region-level data to stand-level data, intensity of data input in model formulation) of the model used for estimation to the actual phenomena being estimated.

Chi-square Results

Error distributions failed to meet the normal distribution assumption that is inherent to the maximum anticipated error (E). Actual ranges found by ordering the data from smallest to largest, taking the sign into account, and examining the actual observations obtained using equation 8 are shown by the 95 percent range in table 2.

$$obs_{U\&L} = \left(\frac{n_t}{2}\right) \pm \left(\frac{(1-\alpha)n_t}{2}\right) \qquad (8)$$

where $obs_{U\&L}$ = upper and lower ordered observations representing the 1- α percent confidence level
n_t = sample size of group t

Comparison to the maximum anticipated error calculated disregarding the assumption shows that a reasonable approximation is still obtained using this method. The maximum anticipated errors decreased with increasing distance from the stem, asymptotically approaching ± 4 cm. The maximum anticipated errors increased from ± 2.5 to ± 7.0 cm with increasing heights from 1 to 20 m.

Sources of Errors

The mislocation of points used for diameter determination due to height and tangential differences was a cause of significant error. The diameter locations were not explicitly marked but were determined by the camera system and the conventional system independently. This source of error is magnified by stem lean—which was only accounted for in the averaging technique—and by the deliquescent branching structure of hardwood stems. The closer the camera station is to the stem, the farther the tangential points that define the edges in the image are from hypothetical caliper contact points.

Lens distortion, image plane deformation, and the orientation of the CCD array to the focal point are elements of the interior orientation of the camera that contribute to error. The greatest source of camera-related error was probably the apparent shifting of edges due to image interpolation in areas of low contrast between the stem and background reflectance.

Procedural errors of varying magnitudes and frequencies in the measurement or transfer at the ancillary data, image capture, image measurement, and calculation stages may have further contributed to error.

CONCLUSION

The conclusions of this study reveal that camera station distance should roughly be equal to the uppermost sample height to be measured using the averaging method set forth in this study. In general, shorter distances when inclination from camera station to measured point is less than 45 degrees produce the most precise results. Longer distances provide more consistent estimates with a decrease in precision at lower stem heights. The maximum anticipated error at the 95 percent confidence level for geometric mean diameters for stem heights up to 20 m on upland red oak stems using the methods set forth in this paper at a camera distance from the stem greater than 12 m is ± 4 cm. This maximum anticipated error increases with height from ± 3 to ± 7 cm at stem heights from 1 to 20 m. In this same height interval with a 12-m camera station distance, instrument precision varies from 0.8 to 1.6 cm. The expected measurement accuracy to instrument precision ratio is about 3, which is consistent with most other instruments. Volume estimates will be within 8 percent of taped measurements of individual stems two times out of three, which is an improvement over the 20 to 28 percent possible using applicable volume equations that are often not readily available. The method used in this paper provides the ability to easily formulate appropriate-scaled volume equations.

More work needs to be done to control measurement errors using the digital camera. Further experimentation using marked diameters and compensation for stem axis deviation from datum using perpendicular images should mitigate the gross errors greater than twice the image precision. The varying precision problem may be reduced by image interpolation and the image capture at longer focal lengths. The price paid for this increased precision would be a decrease in the extent of area coverage.

Comparison of this technique to results of higher precision instruments (e.g., pentaprism, rangefinder dendrometers, etc.) touting reliable diameter estimates to within ± 7 mm is not promising. However, with improvements to the automation process and ancillary data integration, this procedure has the potential to collect much more data, including spectral and spatial components that may be useful for the acquisition of other stem characteristics such as form, quality, and health information.

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