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An assessment of the utility of a non-metric digital camera for measuring standing trees☆

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Abstract

Images acquired with a commercially available digital camera were used to make measurements on 20 red oak (*Quercus* spp.) stems. The ranges of diameter at breast height (DBH) and height to a 10 cm upper-stem diameter were 16–66 cm and 12–20 m, respectively. Camera stations located 3, 6, 9, 12, and 15 m from the stem were studied to determine the best distance to be used with the maximum wide angle setting on the camera. Geometric mean diameter estimates from the 12 and 15 m distances were within ± 4 cm at any height (95% χ^2). Though unbiased, measurement variation was found to increase with stem height. Using camera derived heights and diameters, volumes were found to be within 8% of volumes calculated using taped measurements of individual stems two times out of three — an improvement over existing DBH-height volume equations. This preliminary work demonstrates the ability of using a digital camera to acquire stem diameters and heights. Some limitations of the current technology are also noted. By combining equipment and procedural modifications with improved data flow from imagery to information, terrestrial digital imagery may revolutionize stem or even plot level data collection. Published by Elsevier Science B.V.

Keywords: Diameter measurement; Digital camera; Forest inventory; Instrumentation

☆ Tradenames are used for informational purposes only and do not imply any endorsement by the US Department of Agriculture.

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1. Introduction

Tree diameter measurements are needed for virtually all inventory and modeling aspects involving forests. Growth, volume/biomass, health, value assessment, habitat evaluation, etc., are all estimated and modeled using tree diameter measurements. Diameter at breast height (DBH) is commonly collected. This is probably due more to ease of collection than to the quality of this measurement as an estimator. However, formulation of volume equations, intensive inventories (Cost, 1979), and some sampling strategies (Gregoire et al., 1987; Van Deusen and Lynch, 1987) require measurement of diameters that are not easily accessible. Direct measurement of these points can be costly, both in time and money. Climbing the tree or felling the stem is labor intensive, dangerous, and sometimes incompatible with the desired objectives. For instance, cutting the tree would not allow tree growth to be monitored over time. And spikes (often used for climbing) will affect future stem growth precluding unbiased repeated measurements. A dendrometer should be efficient and not disrupt a stem's normal growth in addition to being 'simple to use, portable, relatively inexpensive, accurate at all tree heights, and operable independently of distance from point of measurement' (Avery and Burkhart, 1983). Optical dendrometers, which allow measurements to be taken visually from a remote location, have been developed to fill this niche. More details on the design, results, and history of optical dendrometers can be found in Grosenbaugh (1963), Brickell (1976) and Clark (1998).

Among the instruments tested as optical dendrometers (but not used in practice) are conventional film cameras. Marsh (1952), one of the first to document the use of a camera to measure tree diameters, obtained diameters within ± 63.5 mm for oblique photos and ± 20.3 mm for horizontal photos. Ashley and Roger (1969) designed a frame device to attach the camera to the tree stem in order to resolve some of the scale and orientation problems. They reported standard errors within ± 7.6 mm for measurements of placed targets (every 1.5 m, up to 30 m on a flat surface) in a laboratory setting. A simpler method using a camera with a 135 mm lens in conjunction with a clinometer and tape for calculation of slope distance was presented by Bradshaw (1972), where 26 diameters ranging from 30 to76 cm at points from 1.2 to 26 m in height were measured with an accuracy of ± 9.9 mm. Crosby et al. (1983) photographed 40 eastern white pines (*Pinus strobus*) with a 35 mm camera and a 200 mm lens using a telescoping rod to measure height and a scale attached to the rod was used to determine the photo scale. Sixty measurements obtained from the remaining 20 stems resulted in average errors of 0.063 and 0.089% for black and white photos and slides, respectively, with standard deviations (S.D.) of 1.91 and 2.40% on diameters smaller than 50 cm. A prototype camera produced by Minolta using the autofocus capability of a 500 mm lens as a rangefinder (solving the scaling problem) was tested by Takahashi et al. (1997). Here, a mean error of $+0.15$ mm and S.D. of 0.49 mm [4.9 mm] was attained for diameters between 13 and 35 cm at heights of 1.2, 3.2, and 5.2 m. In another experiment, 29 diameter measurements of hinoki (*Chamaecyparis obtusa*) stems were obtained with a mean error of $+1.6$ mm and S.D. of 4.6 mm after corrections for bark and systematic errors. Problems with using conventional cameras as optical dendrometers include the following: the expense of film and development, the time delay due to development, complicated calculations, improper exposure, and problems of orientation.

Changes in technology have brought about the re-emergence of the camera's usefulness for the purposes of mensuration. The manufacturing and medical industries actively use digital imagery to rapidly and accurately measure products with great precision (Clarke 1995). There is no manual processing or time delay involved with digital imagery. And digital images can be manipulated and measured faster, easier, and with less expensive equipment than conventional photographs.

This paper shows how digital remote sensing technology can be used to measure tree diameters and heights. An explanation is given on the methods of determining the image resolution and on how field measurements were taken. Diameters and volumes measured with the digital camera are compared with conventional caliper measured values. Finally, sources of error are explained and areas for further development are set forth.

2. Methods

2.1. Image resolution

All of the camera studies mentioned thus far have used analog cameras. The resolution of a conventional photograph is determined by the 'grain' of the film, more specifically the reactant chemicals in the film emulsion. And the resolution of the resultant diameter measurement is based on the magnification of the image, the precision of the device used to measure the image, and the user's ability to distinguish the endpoints of measurement. In the context of a digital image, the measurement resolution is dependent on the size and arrangement of the CCD (charge-coupled device) elements and the algorithms used in the analog-to-digital conversion and measurement of the output image.

The size of the resultant image pixels, for the camera used in this study (Kodak DC-120), was empirically determined by imaging an object of known dimension and applying an elementary scale equation, shown by

$$\frac{d}{D} = \frac{f}{L_0} \tag{1}$$

where d is the image measurement representing the real world length D (the object space dimesion), f is the focal length of the camera, and L_0 is the horizontal distance between the lens and the object.

Numerous images were captured perpendicular to the measured object varying L_0 but keeping f constant. D was measured using a steel tape to the precision of ± 1.6 mm, L_0 was measured with a nylon tape (± 12.7 mm), and f as reported by the camera manufacturer is 7 mm (at maximum wide angle). The image measurement d was solved for in Eq. (1) and divided by the number of pixels representing each measurement. Using least squares estimation, the image pixels were determined to be 5 μm in both the row and column dimensions since digital images are represented by square pixels.

The current image measurement technique calculates length from point coordinates representing the pixel centers. This defines an image measurement precision of ± 1 pixel. This results in an object space resolution (D) of ± 0.7 mm/m (L_0) for an object space plane that is perpendicular to the camera axis: from 10 m away, diameter can be recorded in 7 mm increments only.

2.2. Stem sampling methods

Species homogeneity was considered when selecting our sample trees to reduce variation caused by morphological differences (e.g. cross sectional shape, taper, bark texture, branching pattern, etc.). Red oak (*Quercus* spp.) was selected due to its moderate bark and form variation, and because of data constraints from concurrent studies. Northern red oak (*Quercus rubra* L.), black oak (*Quercus velutina* Lam.), and scarlet oak (*Quercus coccinea* Muenchh.) were the species sampled in this study. Five stems in each of four diameter classes (16–30, 31–45, 46–60, >60 cm) were investigated.

In addition to diameter measurements, more comprehensive information regarding timber products (e.g. sawlogs, pulpwood bolts) or health indicators (e.g. live crown ratio, biomass) will eventually be desired from these images. This requires data capture from the entire stem and major branches. The shortest focal length (maximum wide angle) was used to reduce the total number of images required for imaging the entire tree. This reduced the precision of individual diameter measurements but increased areal coverage. Four orthogonal directions, least obscured by understory vegetation, from each stem were selected to set up the camera stations and a paint mark was made on each tree for orientation reference. Data were captured at approximate distances of 3, 6.1, 9.1, 12.2, 15.2 m (corresponding to 10, 20, 30, 40, 50 ft) to study camera-to-object distance and viewing angle effects. The inclination angle of the camera was determined using a clinometer. Viewing angle and distance measurements were recorded on data sheets for each image.

After image acquisition, the stems were felled and diameters were measured with metal calipers (perpendicular to camera station directions) at breast height (1.4 m) and every 1.2 m from the height of 2.4 m to the termination of a dominant stem. Height measurements were made from the uphill contact point of the ground and stem. This resulted in two perpendicular caliper measurements at each height that corresponded to diameter measurements made from camera images.

2.3. Diameter extraction procedures

Kodak Picture Transfer software (provided with the camera) was used to transfer the images from the camera to a desktop computer. Images were stored in native Kodak format, which allows information such as the quality setting, exposure time, and date/time to be associated with each image. At this point the images were uncompressed, as needed, to their 3686 Kb size and converted to a format that is compatible with other image processing software used for image measurement and manipulation.

Angle, distance, and tree/side identification data were manually entered into the computer and associated with corresponding images. A single height value was needed as a reference for each image. For images including the base of the stem, the contact point of the stem and ground (B_0) was defined as zero. For upper images, a matching point (a) was selected and height calculated from the lower overlapping image (Fig. 1). Heights to the desired diameter measurements were input into a custom-written diameter extraction program that output the corresponding image filenames and coordinate values. The left and right edges of the stem, corresponding to diameter end points, were determined visually and input into the program that calculated the diameters.

2.4. Analysis methods

Diameter estimates from the camera images were paired with the caliper using the geometric mean of perpendicular diameters. The arithmetic mean of opposite camera image estimates served as a single diameter measurement. This was done to minimize the effects of stem lean and anomalies.

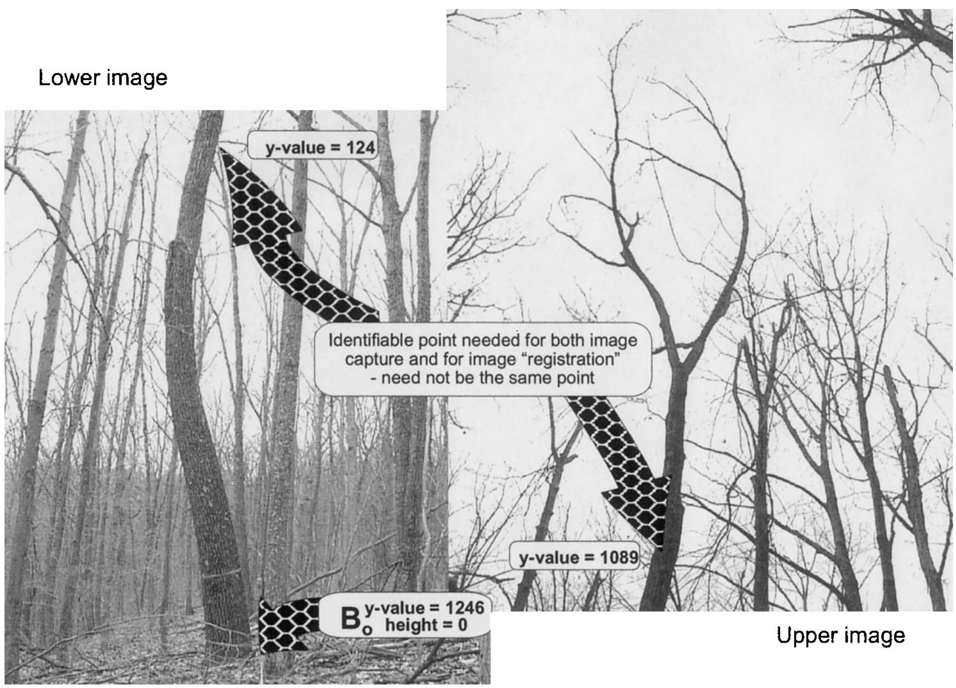

Fig. 1. Upper and lower images at single camera station showing location and image row value of B_0 and identifiable point a and row values for each of the images.

The volume of each stem was estimated by accumulating the volume of each stem section calculated using Smalian's formula, (Eq. (2))

$$Volume = \frac{\pi}{4 \times 10\,000} \frac{D_l^2 + D_s^2}{2} l \qquad (2)$$

where D_l and D_s are the large and small end diameter (cm), respectively, l is the length of section (m). The large end geometric mean diameter (GMD) for the 0–1.4 m section was calculated by adding the difference between the 1.4 and 2.4 to the 1.4 m GMD.

The maximum anticipated error (Bell and Groman 1971) derived from a χ^2 test (Freese 1960) is represented as:

$$E = \sqrt{\frac{\sum_{i=1}^{n} [(x_i - \mu_i)^2] r^2}{\chi_n^2}} \qquad (3)$$

where E is the expected deviation from the true value unless a $1 - \alpha$ chance has occurred, x_i and μ_i are the camera and 'true'(caliper) estimates of the i^{th} observational unit, respectively, r^2 is the value of the standard normal deviate at a set α level, and χ_n^2 is the chi-square value with n degrees of freedom.

Analysis of variance (ANOVA) was performed on the paired differences $(x_i - \mu_i)$ to examine the effects of distance and height for selecting the best data collection protocol. Diameter (four classes, 15 cm increments), height (four classes, 5 m increments), distance (five classes, 3 m increments), and distance/height interaction were all fixed effects to be examined. There were no random effects. Analyses were performed including all of the effects and each effect separately. An analysis was also conducted for cubic meter (m^3) volume using distances as treatments. Because each stem was included at each distance, repeated measures tests were used to account for the effects of the subjects (stems). Orthogonal contrasts were examined for differences among the means. The analyses were run using the SAS proc mixed function with compound symmetry used for the correlation matrix and adjusted for unbalanced data.

3. Results and discussion

Table 1 shows the number of diameter measurements collected by height and camera station distance as well as the number of diameters collected using conventional calipers. All stems were at least 12.2 m in height. Unmatched stem heights, damage incurred during felling, and human error accounted for unequal sample sizes within the various height strata for the field measurements. Missing GMDs in the camera station columns are due to obstructed views of at least one of the four directional image measurements. This visibility problem is real with any optical dendrometer, but should lessen if camera station location and measurement height are not restricted in the sampling design.

Table 1
Number of field and image collected diameter measurements obtained from 20 red oak stems (eight in Radford, VA/12 in Asheville, NC) 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
Total	174	214	219	223	217	241

Whether grouped by distance or height, Kolmogorov–Smirnov normality tests reject the null hypothesis that the distributions of $x_i - \mu_i$ are normal. Violation of the normality assumption can cause considerable degradation of results when using the χ^2 statistic (Gregoire and Reynolds 1988). The actual ranges were found (95% range in Table 2) by ordering the data from smallest to largest taking the sign into account and examining the actual observations $(x_i - \mu_i)$ using:

$$obs_{U\,\&\,L} = \left(\frac{n_t}{2}\right) \pm \left(\frac{(1-\alpha)n_t}{2}\right) \tag{4}$$

where $obs_{U\&L}$ are the upper and lower ordered observations representing the $1-\alpha$ percent confidence level and n_t is the sample size of group t. The values are generally greater than the χ^2 maximum anticipated error, supporting the findings of Gregoire and Reynolds (1988).

Diameter was dropped from the ANOVA model because stem morphology and camera location prevent the isolation of this factor from other factors such as lower stem heights, smaller camera station to stem distances, tree lean, and lower inclination angles. Therefore, it would be difficult to ascertain the true source of error. Extremes were examined to evaluate whether there was any indication of diameter magnitude effects. There are a total of 35 diameter estimates that are greater than 60 cm (caliper measurement) and they all occur at stem heights below 7 m. Errors range from -3.0 to 3.2 cm with an arithmetic mean of -0.17 cm and a S.D. of 1.63 cm. The 67 estimates of calipered diameters less than 20 cm below

Table 2
Summary statistics for 241 camera minus caliper geometric mean diameter estimates in centimeters by distance and diameter for 20 red oak stems[a]

	Distance (m)						Height (m)			
	3	6	9	12	15	All	1–5	6–10	11–15	16–20
n	–	–	–	–	–	–	369	360	263	56
Mean (cm)	−0.458	−0.111	−0.173	−0.132	−0.335	−0.232	−0.053	−0.459	−0.126	−0.458
S.D. (cm)	3.039	2.301	2.178	2.133	2.074	2.337	1.346	2.07	3.134	4.058
E (cm)	5.5	4.2	4.0	3.9	3.8	4.7	2.5	4.3	5.7	7.0
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)	(−2.8,2.8)	(−4.3,4.3)	(−5.1,6.7)	(−7.4,10.2)

[a] Reported are the arithmetic means and standard deviations (S.D.), the maximum anticipated error (E) using the chi-square test (χ^2) for accuracy, and the actual measurement range of the nearest 95% of the observations from the median observation.

7 m have errors ranging from −2.0 to 2.7 cm, an arithmetic mean of −0.40 cm and a S.D. of 0.91 cm. No distance or height produced a mean error greater than 0.5 cm (Table 2). S.D.s decreased with increasing distance from the stem and with lower heights.

Neither repeated measures ANOVA models considering height or distance solely, show any significance with P-values of 0.10 and 0.91, respectively. The height/distance interaction term did indicate significance ($P < 0.01$) when examined alone and included in a model with height and distance. The results indicate that significant errors are more likely at the extremes of decreasing distance and increasing height.

4. Volume estimation

An advantage of using a camera as opposed to other instruments lies in the amount of data that can be collected in a short period of time. For single diameter measurements there are assuredly other instruments that are as capable and more efficient. However, for volume estimation, where more diameter measurements along the stem can provide greater accuracy, camera dendrometers offer a distinct improvement over other instruments. In addition, camera images can provide diameter and height estimates simultaneously. There is a trade off at a certain point, however, where the cost of collecting the data will surpass the benefit gained from having a more reliable estimate.

Volumes were computed using camera and caliper GMDs with Smalian's formula and with:

$$\text{volume}_{<11''} = 0.03592(d^2h)^{0.73586} \tag{5}$$

$$\text{volume}_{>11''} = 0.01199(d^2)^{0.95561}h^{0.73586} \tag{6}$$

where $\text{volume}_{<11''}$ and $\text{volume}_{>11''}$ are cubic foot volumes of wood and bark for stems less than 11 in. and greater than 11 in., respectively, d is DBH in in. and h is height to a 4-in. upper-stem diameter in feet. These equations were developed by Clark and Schroeder (1986) for northern red oak (*Q. rubra*) in the southern Appalachian mountains. The results were converted to metric units before analysis. Volumes calculated from the calipered GMDs and taped lengths were considered 'truth'. Directional diameters were substituted for GMDs in cases where perpendicular diameters were unable to be measured.

It should be noted that even this relatively simple volume equation is not completely free from upper stem measurements. A dendrometer and hypsometer would have to be used in order to locate and measure the height of the 4-in., upper-stem diameter. In this study, the GMDs from the caliper estimates were used along with the field taped heights for equation input parameters. Because these are the same measurements used to compute the 'true' volume, the model is responsible for any resultant error. Height to a 4-in. top was not acquired in the field for every tree. Some stems lacked a dominant main stem and had multiple 4-in. tops. Diameter data was only collected for these trees up to the end of the merchantable stem. There is some indication in the data that the volumes of the larger diameter stems were underestimated.

Table 3 shows the results of these computations. While, the equation provides a reasonably accurate assessment of volumes, for less work and fewer man-hours, S.D.s of the m^3 differences are at least twice as large for the equation estimates than for the camera estimates. The explanation for this is that the camera and caliper estimates are from the same sample, whereas the equation estimates are derived from volumes expected within a larger sample population. More importantly, the m^3 mean error produced by the equation, while not being statistically significant, was quite a bit larger than the camera standard errors. This supports the creation of custom volume tables for the population being examined. Reliability of estimation is directly proportional to the ability to match 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.

A repeated measures ANOVA model was used to determine the effect of distance on volume measurement. The measurement variable is volume difference in m^3. A test of the null hypothesis that the means for all of the distances are the same is marginally not rejected at the 95% confidence level ($P = 0.0576$). Orthogonal contrasts, comparing each distance to the other four, show only the 3 m distance to be significantly different for volume in m^3 and %. The least squares mean deviations are -0.153 m^3 for the 3 m distance. Least squares means for the other distances range from -0.025 to 0.017 m^3.

5. Sources of errors

There are many factors that contribute to error using the methods described in this paper. There are errors related to collecting and recording incorrect field data assumed to be 'true,' error in field reference data measurement, various camera related sources of error, and error due to mislocation of points used for diameter determination because of height, line of sight, and tangential differences.

5.1. Procedural errors

Camera station set-up and ancillary data collection errors can occur at any stage in the process. Distance measurement with the nylon tape is hampered by underbrush that keeps the tape from being pulled taut for an accurate reading. Movement of the tape end at B_0 (Fig. 1) can cause error. The tape end was secured to the stem using a nail for this study to avoid this problem. Due to the pivot point of the tripod, the orientation of the focal point to the stem changes slightly as inclination angle is adjusted.

Incorrect inclination angle measurement could be caused by misreading or inconsistent positioning of the clinometer relative to the camera body, or a mistake during recording or transferring data. The clinometer used in this study reported

Table 3
Volume estimates for 20 red oak stems comparing camera estimates from the 12 m distance (12-cal), the average of all camera estimates (avg-cal), and the equation estimates (equ-cal) to the 'true' caliper estimates[a]

	Stem volumes (m^3)				Differences (m^3)			Differences (%)		
	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
S.D.	1.34	1.34	1.32	1.02	0.14	0.15	0.38	6.31	6.08	17.56

[a] 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.

the angle with decreasing precision in percent up to 150% and graduations were present at a $\times$/66 ft scale up to 200 ft.

There are image capture errors, related to incorrect exposure or focus, that can lead to improper location of diameter endpoints. Subjective (e.g. observer) error can occur at the image measurement stage. Attention was paid to locate the points used for diameter as near as possible to the pixel where there was the greatest amount of contrast from tree stem to background. In this experimental situation, where diameters at pre-defined heights had to be obtained, there were sometimes difficulties in locating edges due to obstructions or contrast situations where the edges were questionable (Fig. 2). Even when there appears to be a clearly defined

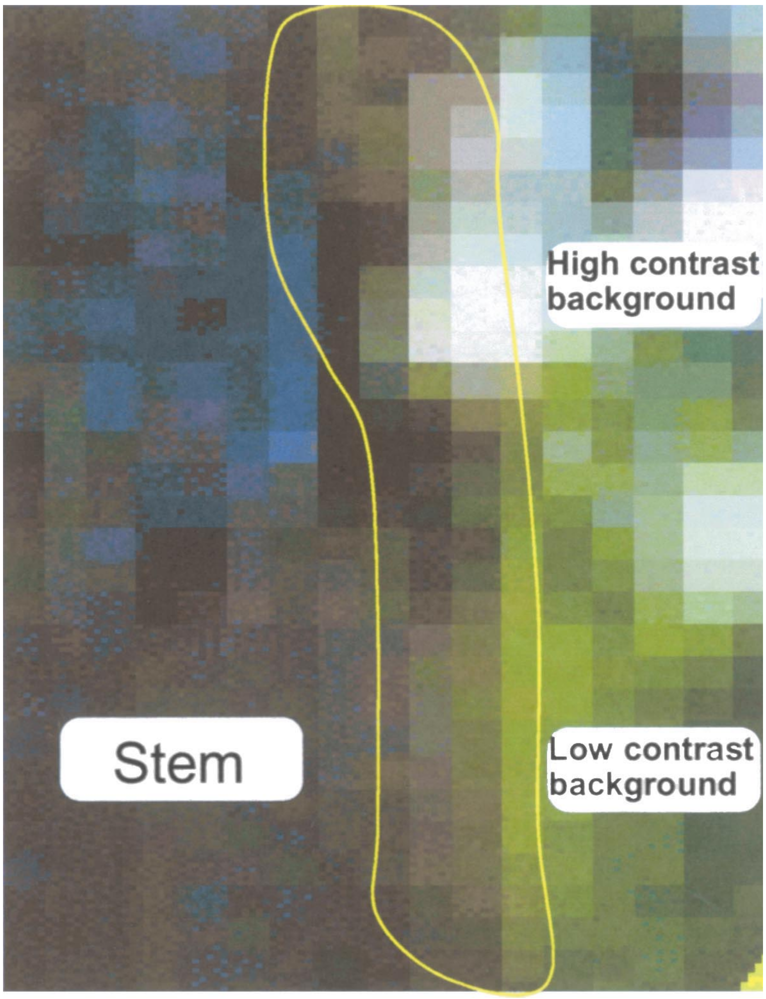

Fig. 2. Magnified portion of image showing the edge of a stem shifted by differing background spectral properties. The outlined region represents the indiscrete region containing the edge of the stem.

edge, the question remains whether to select the background pixel or the stem pixel coordinates, since no subpixel interpolation was performed. To offset any overlap problem an attempt was made to select towards the stem on one edge and away from the stem on the other. Often a larger 'window' (increased area coverage) had to be used to incorporate contextual information to help infer point placement.

Finally, error can result from improper analytical methods. There may be more efficient or better ways to perform the diameter calculations. Inputs such as the row value for the base point B_0 could be changed to an image coordinate value to correct for angular error from the point to the lens center and to the stem axis rather than the parallel tangent. Alternate methods for diameter calculation could be applied as well as recognizing that a stem cross-section can only be referred to as a closed convex region rather than a circle or an ellipse (Brickell, 1970). There is also the issue of rounding error, especially given the minute angle measurements. Double precision (15 significant digits) data types were used for the storage and calculations of floating point values. Given the other possible sources of error this should be minimal.

5.2. Camera related errors

Interior orientation and the precision of the CCD are sources of error introduced by the camera. Interior orientation is a term that describes the 'parameters that model the passage of light rays through the lens and onto the image plane' (Fryer, 1989). Lens distortion, image plane deformation, and the orientation of the CCD array to the focal point are included in this definition.

Lens distortions are caused by aberrations in the manufacture of the lens that refract light in a manner not predicted. Usually lens distortions are broken down into radial and tangential components. These components are assumed to be systematic and can be corrected for, though this was not done in this study. Radial lens distortion is often significant near the edges of an image.

Image plane deformation would occur if any of the CCD elements were out of alignment. This would likely only have a limited effect at a certain location (row and column) in the image, and should be inconsequential.

Lastly the CCD array itself could be tilted or misaligned in relation to an axial ray coming directly through the center of the lens. Ideally this ray should pass through the principle point on the image plane. This could perhaps explain some of the negative bias in the upper stem heights resulting from the correlation of these heights with image space location. Considering the small size of the CCD array and the short focal length a small amount of tilt could have substantial effects. An added complication is that the non-metric nature of the camera may cause this effect to be random rather than systematic, making corrections impossible.

Though the consequences of some of these camera parameters are unknown, the precision issue has a definite effect. Precision of pentaprism calipers is regulated by the gradations on the instrument. In a similar way, the precision of rangefinder dendrometers is constrained by the precision of angular measurement. This also is the case with the camera. Thus, overall precision is directly related to object space

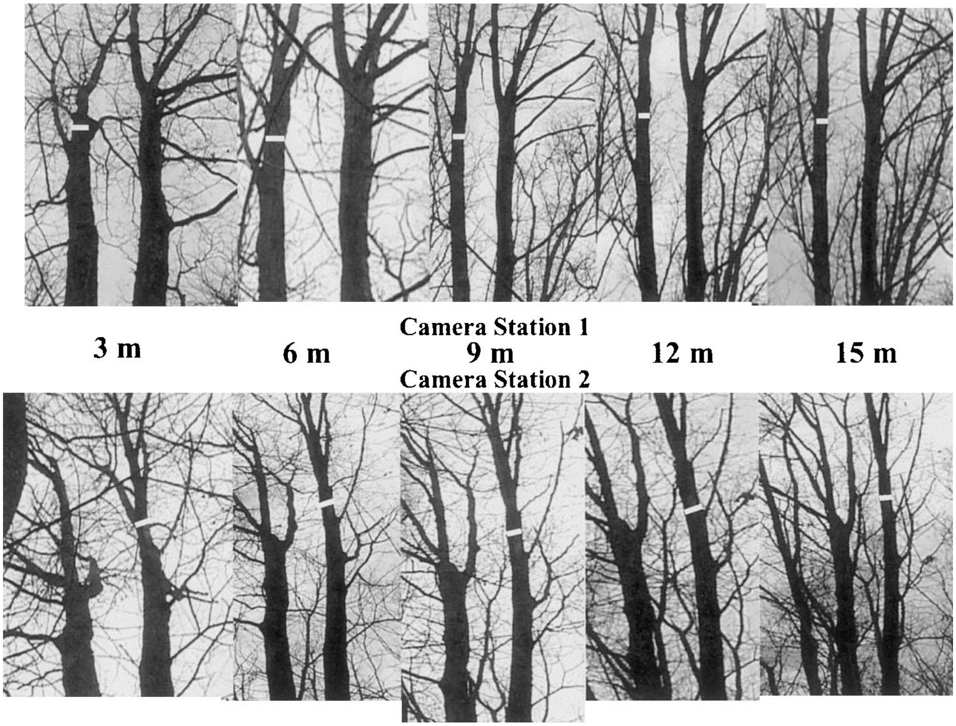

Fig. 3. Location of points for a given diameter at various distances from two diametrical directions. The locations are consistent within each direction but not between directions.

distance to the camera from the measurement points on the stem. This partially explains increased variance at upper stem heights and, theoretically, with increased distances to the tree; although lean effects overshadowed the precision issue with the methods used in this study.

5.3. Mislocation error

Unlike similar studies which tested the capabilities of an instrument rather than the reliability of a total method, the heights of the diameters were not marked but were determined by the camera system and the conventional system (after felling) independently. While not the best way to make comparisons to other methods, it provides more realistic expectations of actual performance. The hypsometric component of a dendrometer is an extremely important factor for its usefulness. Fig. 3 shows the location of a diameter measurement at different distances for two opposing camera stations. The location of the diameters is fairly consistent by direction, but differs between diametrically opposed camera stations. Using the branch as a marker it is apparent that the points measured from the camera station direction are higher on the stem than the points measured from the diametrical direction. This is primarily a result of tree lean, which is not accounted for using the methods set forth and used in this study. Measurement of inclination angle and camera factors can also contribute to this mislocation, but to a lesser extent.

It should also be noted that both stem portions in each frame of Fig. 3 are of the same stem. This poses problems with the method presented in this paper. If the camera station orientations are orthogonal to the fork as in Fig. 4, overlap, as well as lean, becomes a problem when attempting to distinguish the edge points.

Within the selected height plane there are two other mislocation problems. One is the difference in the line of sight around the stem axis between the camera station

Fig. 4. Perpendicular view of same stem shown in Fig. 3 depicting the problems inherent in determining edge points on a forked stem.

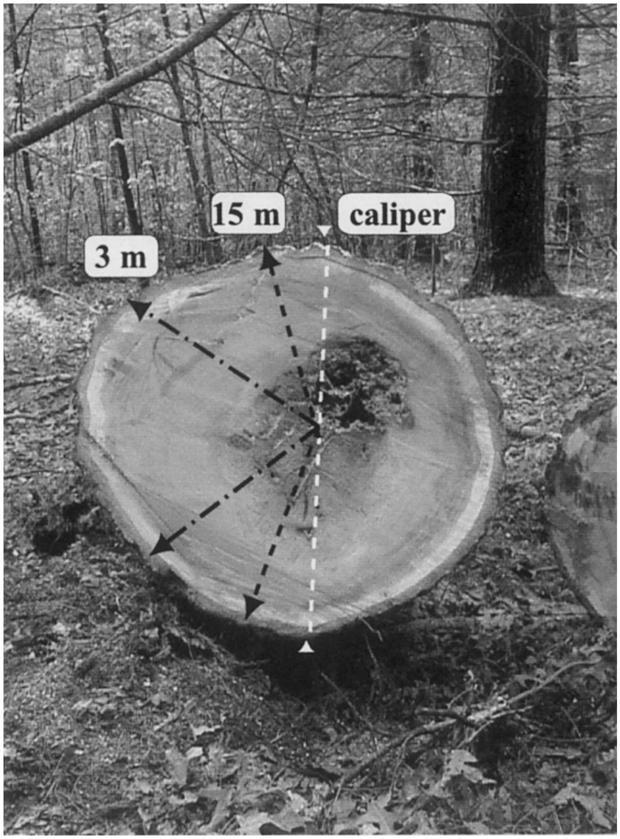

Fig. 5. Cross section at 1.5 m above ground indicating error caused by the observation of different points around a non-circular circumference.

and the direction measured by the calipers. The second problem is that of measuring points on the circumference that are farther from the caliper measured points with decreasing camera station distance (false diameters, Fig. 5.)

6. Conclusions

6.1. Data collection protocol

Only one data collection protocol was set forth in this paper. The user of this technique should use common sense in selecting focal length, distance from stem, inclination angle, image quality settings, etc. in order to meet their particular information needs. Focal length can be maximized to increase diameter measurement precision with a loss of areal coverage of the stem. Distance from the stem and inclination angle are related assuming that the camera and the stem are located on moderate terrain and that the camera is constrained in regard to elevation (within a couple of meters to the ground). It was found that increasing inclination angles did cause perspective problems in finding the desired measurement location and exacerbated tree lean effects. This is indicated by the significant difference in volume estimation at the 3 m distance. Too great a distance, though, results in loss of precision and a potential gain in image obscurity from objects in the forefront or background. A general rule of thumb is to set the camera distance equal height of the highest desired stem measurement.

The need for obtaining spectral information may also drive collection protocol. Here incident energy (light) is of major importance. Time of day, time of year, weather conditions, orientation, and camera settings are concerns for spectral sensitivity. Too little or too much light can reduce spectral contrast making an image useless for some analyses, such as defect detection, or in extreme cases even distinction of the stem from the background. Similar to a conventional camera, shutter speed and aperture can be adjusted to compensate for undesirable lighting. The digital camera does have the advantage of image viewing seconds after capture to assess image quality and make necessary adjustments.

6.2. Comparisons to results of other studies

The maximum anticipated error (of geometric mean diameters, $\alpha = 0.05$) for this camera,using the methods set forth in this paper, for heights from 1 to 5 m is 25 mm and around 40 mm for heights up to 20 m (Table 2). These results are inferior to the 7 mm results reported by Bell and Groman (1971). 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 the measurement precision varies from 0.84 to 1.6 cm. The accuracy to instrument precision ratio is about 3 which is consistent with most other instruments assuming 2.5 mm increments.

S.D.s are two to four times larger than most of the optical dendrometer studies previously mentioned. Two out of three times, volume estimates will be within 8% of those calculated using taped measurements. While not approaching the 4% reported by Grosenbaugh (1963) using the Barr and Stroud FP9, still an improvement over the 20–28% possible with applicable volume equations using only DBH and height. Caution should be used in making direct comparisons with single diameter studies given the different scale of data collected. Experimental conditions and ranges should also be contrasted.

6.3. Areas for further development

Operational implementation of this tool and procedure will require further research and development. Camera calibration should be performed in attempt to better describe lens distortions and interior orientation parameters. Digital clinometric and range finding devices can be incorporated into the camera to output the ancillary data into each image's header file. This will facilitate image processing to derive accurate three-dimensional measurements. Interpolation and focal length adjustments need to be examined to increase measurement precision. Further experimentation using marked diameters and compensation for stem axis deviation from datum should remedy the gross errors greater than twice the image precision. Comparisons should be made between different species (e.g. softwood, bottomland hardwood) and stand conditions (e.g. densities, leaf-on) as well as differing lighting conditions (e.g. overcast, full sun). Software improvements should be implemented for greater automation and increased informational functionality. The final development of this system will allow a user to image a stem and receive 'on-the-fly' information beyond diameter and volume; for instance, crown diameter, live crown ratio, form (e.g. sweep/crook), defect, etc., potentially changing the way data is collected in the forest.

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