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IMAGE-BASED DENDROMETRY SYSTEM FOR STANDING TREES

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ABSTRACT

A new photogrammetric image-based dendrometry system called TreeD is particularly suited for measuring stem features on individual standing trees. There are two phases in the application of the system. In phase one, stereo digital images are taken of the sample trees and seven field parameters associated with that particular image/object environment are measured. In phase two, the parameters are used to register the images in a computer where they can be viewed stereoscopically. The dimensions of any feature visible on the tree stem can then be measured, and the position of the feature located in three-dimensional space.

Validation of the system was carried out using images of a radio mast of known dimensions; results showed that for heights less than 20 m, characteristics such as stem diameters, branch diameters, internodal distances, and (implicitly) stem sweep can be measured to an accuracy of ±1 cm. Absolute height measurements were measured to an accuracy of better than 10 cm.

The system can provide essential information for stem and log characterisation in pre-harvest assessment. It also provides a useful image archive of all sample trees and data capture points and is routinely being used in research trials to improve understanding of stem quality.

Keywords: TreeD; dendrometry; photogrammetry; forest mensuration;

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INTRODUCTION

There has long been an interest in improving the accuracy and precision of estimates of upper diameters on standing trees, along with those parameters that determine log quality and grade, without the necessity to climb the tree. This is especially important where there is a wide difference in value between different log grades, and variability in the proportion of those log grades between harvest areas. The results from research trials may be greatly enhanced when upper stem characteristics are measured, not estimated. Although parameters such as stem diameter, branch sizes and their frequencies, and the distance between branch nodes (internodal distance) can be readily measured close to the ground, instruments that measure the whole stem are either expensive or less accurate than desired. There are few instruments that can position the stem in three-dimensional space to obtain estimates of stem curvature or sweep. Clark *et al*. (2000) reviewed past research on dendrometers, listing the various tests of accuracy of handheld instruments, including the use of laser instruments such as the Criterion*. Recently, scanning LIDAR devices have been developed (for example, the “Tree Attribute Profiler”, GeoSmart Systems, Auckland, New Zealand) that can scan the whole profile of the standing stem to provide most if not all of the desired parameters. However, these are tripod mounted and relatively expensive — an order of magnitude dearer than handheld instruments such as the Criterion.

TreeD is a digital image-based dendrometric system that originated from its analogue-based counterpart (Firth *et al*. 2000) and has been developed to operational status to provide accurate dimensional and positional measurements of the branches, whorls, and stem of standing trees (including sweep and three-dimensional position). By utilising a digital camera to obtain a pair of images separated by a horizontal distance of around 1 m, a workable solution has been obtained to the inaccuracies caused by tree-sway in wind, differences in skill levels of observers, and adverse conditions of terrain and undergrowth. Most measurements are made in an office environment, and there is the added advantage of provision of a permanent record of the tree and data capture points.

This paper describes the photogrammetric principles involved in solving the problem of obtaining photogrammetric control points for a tree, the subsequent field measurements required, image acquisition procedures, and the implementation of the system.

PREVIOUS WORK

The feasibility of measuring tree stem dimensions from terrestrial photographs has been assessed since the 1960s (Shelbourne & Namkoong 1965). The ease of

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capturing the image with a handheld (usually non-metric) 35 mm camera prompted the approach, but the complexity of accurate data reduction frustrated the effort, and has continued to do so. These complexities generally fall into two categories: firstly, the difficulty of implementing the traditional photogrammetric procedures — interior and exterior orientation (Wolf 1983) — including the need for control points, and secondly, the need to attend to the precision of photo-measurements with an appreciation for camera focal length, frame size, and the image distortions that result from the lens designs — both in the camera and in an enlarger if used — and the lack of film flatness in a normal off-the-shelf (non-metric) camera (Fryer *et al*. 1990). Still, in the late 1990s the new digital cameras and 3D laser scanners renewed the interest in remote-sensing terrestrial techniques for tree measurements (Clark *et al*. 1998, 2000; Nourozi 1995; Weezhuizen *et al*.1997).

In the first phase of our research (Firth *et al*. 2000), we used a common 35 mm film camera (Nikon F90X, fitted with a 28 mm focal length lens); however, we were particularly attentive to lens distortions, signs of film unflatness, camera frame dimensions, and precise measurements captured with an analytical photogrammetric plotter while viewing images stereoscopically. The traditional photogrammetric interior and exterior orientations were implemented (with some simplifying assumptions), and the collinearity equations were used to transform between the image and tree dimensions. Our purpose was to study and establish accuracies, and our results were encouraging (Brownlie, Firth, & Carson unpubl. data).

Others have investigated the use of digital cameras for the close-range measurement of tree dimensions (Dean 2003; Gaffrey *et al*. 2001; Clark 2001) with mixed success. The camera calibration issues differ somewhat (Matsuoka *et al*. 2003), but the TreeD system described below employs an SLR, full-frame, digital camera, fitted with a calibrated 35 mm focal length lens.

Using a digital camera and a PC-based digital stereo viewing platform, rather than a film camera with an analytical stereoplotter, offers significant cost savings in terms of materials, ease of use, and the time required to process and analyse the images.

THEORY

Theoretical Basis of TreeD Measurements

During the early stages of the TreeD development (Firth *et al*. 2000) we decided to adhere to the mature set of concepts and developments available in the field of photogrammetry, the technology commonly employed to develop object coordinates — on a map or, in this study, tree dimensions — from measurements on an image or set of images as, for example, captured by our camera. Two of the authors (Firth and Carson) are photogrammetrists, familiar with this technology and therefore aware of the technical concerns involved and of the mathematical tools that the field has provided over its century-long period of development. Adhering closely to this mature technology, the problem was to determine the “correct geometry”; the result could then be validated by testing that geometry.

Generally, the mathematical description utilised in TreeD algorithms is based on the familiar photogrammetric concept of the space resection of a single photograph by collinearity (Wolf 1983). This method utilises the collinearity equations, through the coordinates of image points and related and known control points on the object (in our study, known points near the tree), to establish the relationship between all other image and object points. The technique (explained well by Wolf (1983) and in most other photogrammetry textbooks) provides an “exterior orientation”, described by the location of the camera and the angular orientation of it with respect to the coordinate system that locates the object features.

A space resection solution is generally implemented through a minimum of three, well-distributed, control points and the related image coordinates. We do employ the space resection technique; however, we simplify our need for control points by taking advantage of the fact that we are carefully photographing a near-vertical tree and we are satisfied to collect coordinates in an arbitrary, tree-based, coordinate system.

In essence, with data on the length of a vertical pole hanging in each photo and the angle relating the camera perspective point (P) and the transponder (T), measured up or down from the horizontal, we have enough information to determine the relationship between the transponder and the camera perspective point in an object coordinate system near the tree and, in fact, with an origin at the base of the tree: the distance H down from the transponder — placed at breast height, on the face of the tree, by convention. The pole length, as it is to be hanging freely and therefore vertically, is used to establish the horizontal distance between the camera and the pole. A “measurement plane” in this coordinate system is required as well and this is described below.

There is a simple geometric relationship (Fig. 1) between the pole, the transponder, the horizontal, the camera perspective point, and the camera focal length (exaggerated somewhat). It is clear that, given the angle θ and the distance D (both measured with a hypsometer), the orientation of the camera ω can be established. Further, if the offset of the pole from the transponder location PL is known as well as the pole length, the horizontal distance to the transponder can be computed and compared to the measured D to ensure that the scaling between the pole tip image points and the pole length is correct. These simple metrics — the angle to the transponder and the length of a free-hanging pole — are enough to establish the (Y,Z) coordinates of the camera perspective point. In addition, the length D establishes an extra measurement that is useful for checking the orientation.

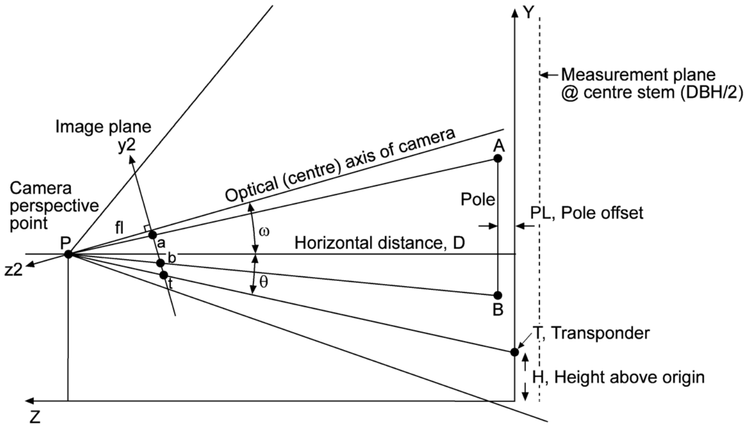

FIG. 1–The TreeD camera-to-tree geometry

Of course, even though every attempt is made to capture images in such a way that the geometry of Fig. 1 is replicated, there will be deviations — offsets in the image x-coordinate and what is called kappa rotation about the camera optical axis. Typical values are shown in the hypothetical image plane shown in Fig. 2a. It is clear that this image was captured with both kappa rotation from the vertical axis of the pole (established as free-hanging) and the transponder that was offset from the y-z plane of the camera. We account for this eventuality in two steps. First, we compute the kappa rotation necessary to align the "vertical pole" with an image-coordinate system that is aligned properly. The result is shown in the new (x2, y2)

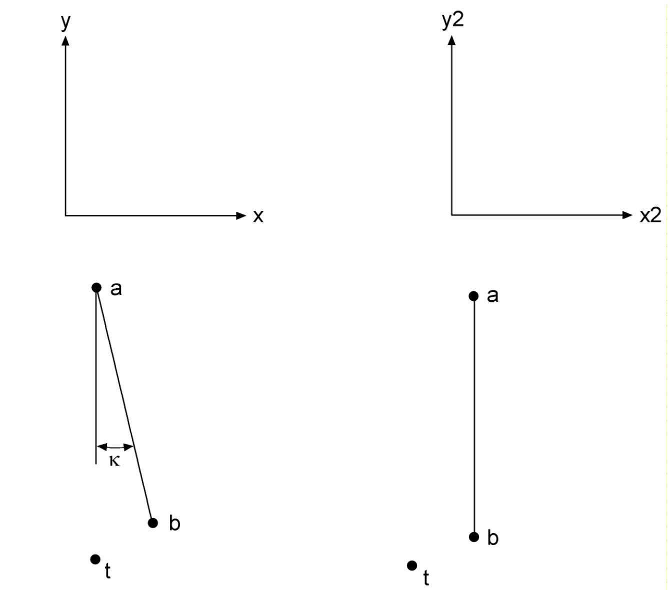

FIG. 2a–Before alignment FIG. 2b–After alignment

coordinate frame of Fig. 2b. In this frame the general offset of the transponder image is easily computed.

The second simplifying step is based upon our freedom at this point to choose the orientation of the tree-based object-coordinate system. Generally, we chose to have the Y-axis aligned with the vertical tree, the Z-axis horizontal and aligned from the tree towards the camera, and the coordinate system origin fixed a given distance below the transponder (H). The X-axis is directed in the right-handed orthogonal sense to the right, but there is a choice as to the precise direction. We chose to allow this object coordinate system to rotate about the Y-axis such that "the x2-axis of the kappa-clear image plane (Fig. 2b) and the object X-axis are parallel". In other words, the angles in the rotation matrix between the camera image-coordinates and our assumed object-coordinate system will have a small directly computed kappa, a phi rotation of zero, and a relatively large omega that can be determined from the geometric relationship between the transponder and its image location on the image plane.

In summary, our single photo data collection system depends upon the collinearity equations to relate the object coordinates to image coordinates. The (X,Y,Z) of the perspective point and the (omega, phi, kappa) of the image plane, after an assumption of phi=0, are established through the simple geometry related to the location of the transponder in the image, the measured angle down to its actual location, and the horizontal distance between the transponder and camera as established by the pole length. Once all is established, any object coordinate in the measurement plane can be computed from its image coordinates, where the measurement plane is specified from a tree lean and offset specification with respect to the coordinates of the base of the tree and the orientation of the Y-axis, which is, by definition, vertical. In the event that a stem is three-dimensionally swept it is necessary to capture a TreeD image at 90° to the primary location camera axis (known as a "secondary" location and recorded as out to the left or right of the "primary" location). The centre line of the tree stem is digitised on the secondary location (left) image and the TreeD program computes a swept measurement plane, based on the sweep datafile, which is used for the associated primary analysis.

Mathematics Used to Establish the Stereo Viewing

Even though our digital data collection depends only on the single primary (left) image, it is imperative for the system to offer a stereo view to aid visually in the interpretation of details on the tree. To provide this, the operator steps about 1 m to the right (by convention) and takes a second image, attempting to replicate the geometry of the primary (left) image. This pair of images will form the stereo pair.

If we were, again, to adhere to photogrammetric methods for forming a stereo image, this would require a proper "relative orientation", a procedure that requires a collection of considerable image data. However, based upon the unique geometric relationship between our image and tree (described above), and the fact that we don't expect to take stereo-based measurements (recall that only the stereo view is important), we decided to pursue another route — photogrammetric in principle, but simpler than a full orientation.

We have implemented a stereo view, composed by relating the left and right images through a three-dimensional coordinate transformation (Wolf 1983) based upon the set of four y-parallax-free data points taken at the transponder, the pole tips, and an arbitrary fourth point on the stem of the tree near the top of the images. (Note: the first three points are available in the space resection of the tree in the independent orientation of each image — the left and the right.)

The operator prepares for the stereo view by orienting both the left and the right images as if they were independent. However, the two image perspective points — generally in the X-direction — are separated by only approximately 1 m, so usually the same transponder, pole, and tree description data are used to determine the space resection solution of both single images. Our special orientation solution for each single image provides a unique object-coordinate system, namely, a solution that directs the object X-axis such that the image phi-rotation is zero (*see* previous section on TreeD mathematics). Therefore, the two images are linked with the same control points, but they are each related to an individual and slightly different object coordinate system. Yet, since each image must provide the same values at the four points, the parameters of the three-dimensional transformation between these object coordinate systems are determined based upon a least-squares match at these points — a photogrammetric procedure generally called a seven-parameter transformation between two three-dimensional coordinate systems.

In order to establish a parallax-free stereo image in our viewing system, the analytical system must provide right image coordinates that match a given set of left image coordinates. For the algorithm to function, it requires the operator to move the measurement cursor to a point in the left image, generally to interpret a feature. This left image coordinate provides an (XYZ) object coordinate in the left image system. This (XYZ)-left-image object coordinate is related to an (XYZ)-right-image object coordinate that can be computed through the three-dimensional transformation. In turn, this right image object coordinate provides an image coordinate used to position the right image and form a parallax-free stereo view on the monitor.

The computational procedure is not expected to work well outside the line of the control points — namely, the transponder, pole tips, and fourth point near the tree top. However, it has been observed to work well along this line that generally coincides with the area of interest in TreeD procedure.

TreeD IMPLEMENTATION

Acquiring Images

The TreeD application process begins with locating the sample tree and determining the most appropriate position from which the stem of the tree can be imaged. The available light (not looking directly into the sun), the lean and /or sweep of the tree (operator should stand at right angles to any lean or sweep), and the visibility of the features up the stem should all be taken into consideration when making this selection. It is also preferable for the camera position to be above the level of the base of the tree. This imaging position is referred to as the primary location. Any vegetation or branch material obscuring the visibility of the stem or the "line of sight" to the tree base is cleared or topped. If the tree has sweep in two planes, a further imaging position (the secondary location) must be found at approximately 90° to the primary location.

A surveyor's pole (fully extended to 4.4 m in length) is hung on the tree (facing the camera position) to provide a measure of verticality and for validating the system's geometry. A transponder is attached to the tree at or about breast height where it is targeted using a Vertex hypsometer (Haglof Inc., Langsele, Sweden) to measure the distance from the camera to the tree and the camera to transponder angle (θ). The position of the transponder also defines the origin of the object coordinate system. The origin, by convention, is generally 1.4 m below the transponder.

An oblique stereo pair of images, separated by about 1 m, is taken of the sample tree with a full frame (36×24 mm, 14 megapixel CMOS sensor) digital camera. The camera is hand-held because using a tripod in the forest is impractical and time-consuming for this type of work. Suitable ISO settings are selected to ensure that shutter speeds slower than 1/60th second are avoided. For the left image, the centre line of the grid in the camera viewfinder is aligned with the hanging pole. For the right image, the centre line is aligned approximately 1 m to the right of the pole.

In order to maintain the highest image resolution and to provide maximum image processing flexibility, the camera is programmed to capture the images in RAW format (image file size is typically 16 Mb).

Generally, for TreeD applications, it is necessary to obtain a view of the tree stem up to a maximum height of 20 m. To achieve this "coverage" the optimum distance from the tree to the camera, on level ground, should be about 15 m (with 28 mm lens fitted) to 20 m (35 mm lens) when using a full frame camera in portrait orientation. The true focal length and radial distortion characteristics of the lens must be known in order to provide measurements with sufficient accuracy.

Six field parameters need to be measured from the camera position associated with the left image of each stereo pair. These parameters (and the accuracy with which they should be measured) are:

(1) The horizontal distance from the camera (i.e., from the nodal point in the lens) to the tree (i.e., the transponder) (±5 cm).

(2) The height of the transponder above the ground (±2 cm).

(3) The angle down (or up) to the transponder with respect to the camera location (< 0.5°).

(4) The horizontal offset of the suspended height pole, with respect to the position of the transponder, in the camera axis (±1 cm).

(5) The tree lean toward or away from the camera (±0.5°).

(6) The diameter of the tree at the transponder height. This is measured with a calliper oriented with its arms pointing towards the camera position (±1 cm).

The length of the extended height pole must also be known and recorded (±1 mm).

Technically the same six field parameters also need to be measured for the right image but it is acceptable to default to the left image parameters provided the values are not substantially different (the normal separation of approximately 1 m between camera stations does allow the left image parameters to be used).

Stereo Viewing

Although the stem features on some trees can often be seen with adequate clarity on a single image, a significant improvement in visual interpretation and hence measurement reliability can be gained by viewing the trees stereoscopically.

TreeD is designed to input a stereo pair of image files (in JPG format) and to display them in a Windows environment for 3D viewing. This process uses a CRT computer monitor, to which a Monitor ZScreen 2000i® bezel (Stereographics Corporation, San Rafael, CA, USA) has been attached, for displaying the stereogram. A built-in controller unit activates the bezel in synchrony with the signal provided by the graphics card, in such a way that the left and right components of the stereogram are circular polarised in opposite directions. When the resulting display is viewed through eyewear of polarising filters, the left eye sees only the left image and right eye sees only the right image. The interpreter can then view a full colour 3D image of the tree. A further requirement for 3D viewing is that the PC is equipped with a stereo-ready dual-monitor graphics card.

Program TreeD Operation

There are two options available for analysing the images of a tree. If the stem is straight, leaning, or exhibiting sweep in one plane only, the images taken from the primary position will be sufficient to describe the three-dimensional shape of the tree by a procedure known as a primary analysis. If the tree stem exhibits sweep in two planes, for optimum accuracy a secondary analysis should be carried out and followed by a primary analysis. The secondary analysis involves measuring the sweep in one plane. The TreeD software uses these sweep data to modify the measurement plane utilised in the primary analysis.

After the appropriate project files are set up, the primary analysis implements the interior orientation of the left image, using a camera file containing the pre-determined constants of lens focal length, radial distortion parameters, and frame size.

An exterior orientation must be carried out to implement the space resection solution. This geometry enables the coordinates of an object measured on the image (i.e., a pixel row and column) to be transformed to real-world coordinates (X, Y, and Z, in metres) at the tree. The process involves digitising three control points on the image — the transponder and the bottom and top of the free-hanging height pole. The exterior orientation is completed by processing the coordinates of the digitised control points and the values of the six parameters measured in the field for that image.

Stereo viewing is recommended and requires the inner and exterior orientation procedure to be carried out also for the right image of the stereo pair, using the appropriate field parameters. It requires a fourth, well-defined but arbitrarily placed, point near the top of the tree to be digitised in both the left and the right image. This provides another y-parallax-free point, which ultimately ensures stereo viewing all the way up the tree stem.

The result is a stereo image on the CRT monitor fitted with the bezel and a mosaic of windows on the second monitor. The mosaic has three components — (a) the full image of the tree, (b) an enlargement of the part of the stem to be digitised, and (c) a table listing the points that have already been digitised.

System Check on Accuracy

The top and bottom of the height pole are digitised during the exterior orientation procedure for the purpose of establishing verticality in the measurement plane. Although the distance to the transponder is recorded, in addition to the six field parameters, it is not used directly for the exterior orientation, but to validate the image scale.

The program displays a computed pole length based on the measured distance to the transponder (i.e., as calculated using the geometry of the measurement model). If the difference between the two numbers is greater than about 0.005 m, then a check should be made to ensure that the field parameters were entered correctly. If the check suggests that no obvious errors have been made, the option exists to adjust the horizontal distance and re-run the model until the calculated pole length is equal to the actual pole length.

Digitising Stem Features

Digitising takes place in the digitising window (Fig. 3) using the mouse to point-and-click and scroll up and down the stem. The image is first optimised using the zoom, brightness, and contrast buttons then the appropriate data collection option is selected. The measurement cursor is dynamically linked to the cursor in the stereo view window. Panning and zooming in the digitising window invoke a similar response in the stereo view window. This greatly facilitates the interpretation process.

Once a feature has been digitised, an associated graphic icon appears on the digitising image and also on the full-tree image. The resultant image data file of recorded points contains all image and object coordinates, and computed object dimensions, and can be accessed and viewed via the drop-down menus.

FIG. 3–The digitising window. This example shows the bottom of the height pole and the transponder digitised.

VALIDATION

Validating the accuracy of the TreeD system using a tree stem can be problematic. This is because a bole has a highly irregular taper and is commonly swept, its cross section is rarely a perfect circle, and attempting to define the precise location of the top and bottom of the whorls can be subjective. In addition, the tree usually needs to be felled (destructively sampled) in order to get a reasonable estimate of these parameters. For these reasons it was decided to determine the accuracy of the TreeD system using the regular, clearly defined structure of a radio mast* (Fig. 4).

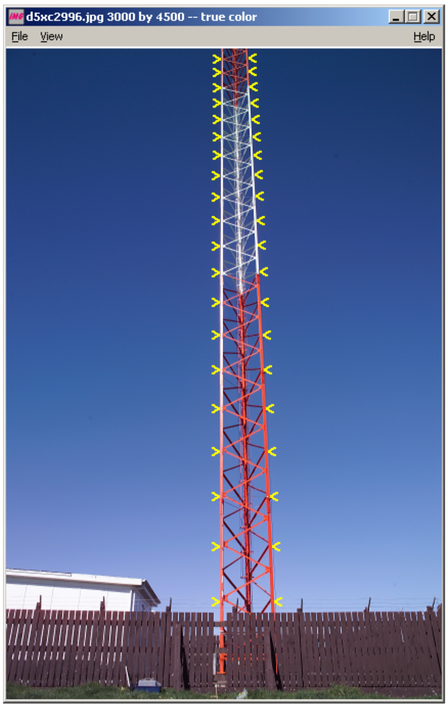

FIG. 4–An image of the radio mast showing the location of some of the points used to assess the accuracy of TreeD.

The transponder was secured to the face of one of the support legs of the radio mast. This ensured that all the cross brace structures that were to be measured, on the near face of the mast, were then in the "measurement plane". The extended height pole was attached (free to hang) to the same support leg, just above the transponder.

Images of the mast were then taken at a distance of 15 m, with the camera in "portrait" orientation, using both a 28 mm and a 35 mm focal length lens. This distance was chosen in order to ensure coverage of the lower 20 m of the mast in all the images.

The locations of the mast width measurement points are designated with graphic icons in Fig. 4. The results obtained from a range of measurements made on the mast are given in Table 1. The heights of the cross braces were taken to represent the

* This mast differs from that used to test the accuracy of the analogue predecessor of TreeD (Firth 2000).

TABLE 1–Accuracy of measurements made on images of the radio mast taken at a distance of 15 m using two lenses.

Mast section height (m)	Difference from actual dimension							
	Height of cross braces (cm)		Spacing of cross braces (cm)		Mast leg width (cm)		Cross brace depth (cm)	
	Lens focal length		Lens focal length		Lens focal length		Lens focal length	
	28 mm	35 mm	28 mm	35 mm	28 mm	35 mm	28 mm	35 mm
0–<10	–1	0	–1	0	–0.3	–0.4	+0.3	+0.2
10–<15	–3	–4	–1	–2	–0.1	–0.1	+0.9	+0.3
15–<20	–6	–8	–2	–3	–0.5	–0.4	+0.5	+0.1
20–<25	–11	nc*	–2	nc	–0.2	nc	+0.3	nc
25–<30	–15	nc	nc	nc	–0.5	nc	+0.8	nc

* nc = no coverage, due to reduced field of view

heights up a tree, the spacing of the cross braces represented internode length, the mast leg width represented stem diameter, and the cross brace depth represented branch diameter. In order to reduce the possible effects of interpreter error, the data presented are the mean of three sets of measurements.

The actual dimensions of the radio mast were:

Spacing of the cross braces	243.7 cm
Mast leg width	15.2 cm
Cross brace depth	7.7 cm

RESULTS

The measurement error for the cross brace spacing increased gradually with height up the mast (Table 1), but they were all <5 cm for both the 28 mm and 35 mm lenses at all the heights assessed. The measurement error for the mast leg width was within ±1 cm for both lenses and at all the mast heights tested. The error in the cross brace depth measurements was also similar for both lenses at all tested heights and was less than ±1 cm.

Absolute height measurements were generally slightly under-estimated irrespective of the lens used. The 28 mm focal length lens appeared marginally more accurate than the 35 mm, while the latter was unable to provide heights above 20 m due to reduced field of view. The under-estimate increased with increasing measurement height. This result is to be expected as the further up the mast one moves, the lower the image resolution and the more accurate the parameters used to define the geometry of the space resection need to be. Irrespective of the lens used, absolute height up to 20 m can be measured to an accuracy of better than 10 cm.

In most instances where TreeD has been used to measure the features on a tree, the projects required that measurements be confined to the first 12 m of stem, i.e., to the first two log lengths. In these cases it is suggested that the following rounded figures would be typical of the accuracy that can be expected:

Stem heights	±5 cm
Internode lengths	±2 cm
Stem diameters	±1 cm
Branch diameter	±1 cm

These accuracy measures validate the concept and theory of the TreeD system, and these are the levels of accuracy that can be obtained in a forest situation, under optimal light conditions. However, when forest conditions are less than optimal, e.g., in very poor light situations, inferior image quality may increase the size of the errors.

CONCLUSIONS

TreeD is a digital image-based dendrometric system that has been developed to provide accurate dimensional and positional measurements of the branches, whorls, and stem of standing trees (including sweep and three-dimensional position). Stem diameters, branch diameters, internodal distances, and implicitly stem sweep can be measured to an accuracy of ±1 cm up to height 20 m. Absolute height measurements have been measured to an accuracy of better than 10 cm. The field equipment is lightweight, robust, and able to withstand the demanding physical conditions encountered in a forest environment.

It takes two to three people approximately 10 minutes (depending on the amount of site clearing required) to identify suitable camera locations, take the necessary images, and measure the six field parameters. A further 15 minutes are required by one person in the office to run program TreeD and take about 60 measurements per tree to produce a dataset of stem measurement coordinates and dimensions.

The TreeD system has been used successfully to image the lower 20 m of stems of individual sample trees in forest stands across New Zealand covering a wide range of stockings, pruning regimes, and undergrowth density. However, there are occasions when extremely steep sites can limit the number of camera-location options. Also, in higher stocked stands (>400 stems/ha) a camera that performs well at higher ISO settings is necessary because of the lower light levels encountered, particularly in the winter months with low sun angles.

TreeD has proved to be a useful research tool to characterise various aspects of standing trees and the system is also generic enough to be adapted for unique applications. Examples of applications include:

- Measurement of branching characteristics, such as cluster position, internode lengths and branch diameters (Grace & Brownlie in prep.)

- Stem form, for investigating the relationships between stem form and wood property variation (Grace *et al*. in prep.)
- Stem form (sweep and ovality) of logs prior to processing.

The TreeD program development has moved beyond the single-photo digitising which, as described, requires that a digitising object-plane be defined either as a swept curve taken from a secondary image or as a plane inclined at some measured angle. A developmental system (v4.0) now includes a full stereoscopic digitising capability. This option should allow the sweep data to be collected in stereo from the primary location. It should allow also for out-of-plane measurements to be made on branches or, more generally, in the tree crown. Comprehensive testing of the stereo digitising option will be carried out as part of an on-going development programme which will be reported on later.

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