Photogrammetric Technique for Measuring Bole Straightness [1/]

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INTRODUCTION

Workers in various fields of forestry require precision in quantifying bole straightness. In wood property studies, attention is paid to the relationship between bole morphology, the development of reaction wood, and the resulting effects on wood structure and lumber and pulp properties. In tree improvement programs, bole straightness is therefore recognized as an especially important characteristic.

Bole characteristics are hard to assess using subjective indices where stand conditions, age, and height of stem vary. It is not difficult to subjectively reject stems which are not straight, or are leaning, but for precise studies such as for progeny and provenance assessments, some means of quantitative measurement of bole morphology is necessary.

Methods used in the past can be broadly divided into two types: the subjective rating method, where a tree is rated as good, fair or poor (1, 2, or 3), and the method where the assessor actually measures the deviations of the stem from straightness. The former has been widely used in the grading of select trees, and in comparing progenies, while fewer people have gone to the greater labor involved by the second /e.g. Perry (1960), Shelbourne (1963), Goddard and Strickland (1964.g. The techniques used by these authors were crude and imprecise.

The most important aspects of bole straightness from a practical point of view are the degree to which a 'stem deviates from straightness and from the vertical. With the technique described here, these attributes are measured on two photographs of the tree taken at right angles.

Geometrical and Statistical Basis of the Technique.

A tree can be considered to be a continuous distribution of points in space formed by the assumed pith (loci of mid-diameter points up the tree). If the points delineated by the pith in three dimensions are projected onto two vertical planes at right angles to one another, two right angle graphs may be plotted (Figure 1) with height up the stem as the abscissa and the horizontal distance of the pith from a vertical line as the ordinate. The abscissa is arranged to be vertical and is situated at any convenient distance from the tree for the two planes (A and B).

Three different models can then be fitted to these two projections of the stem in the A and B planes, by the normal statistical procedures of linear and curvilinear least squares regression. The models are: (1) A vertical straight axis (passing through the mean A and B for the A and B projections respectively; see Figure 1). (2) A straight linear regression axis. This fits a straight line to the points described by the stem in the tree's direction of lean so that the sum of squared deviations from a straight line is minimal. (3) A curved axis. The easiest curve to fit is the quadratic which gives a simple "parabolic" curve.

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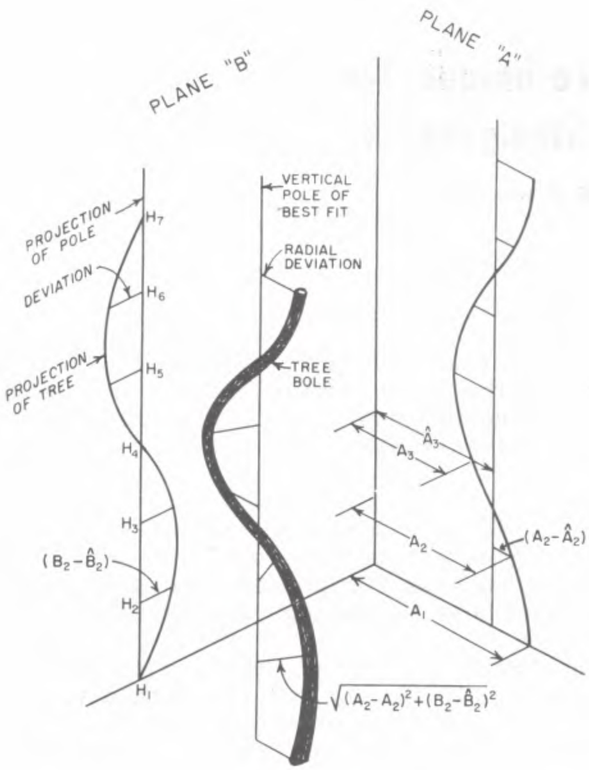

Figure 1 -- Projection of tree bole onto two vertical planes (at right angles). A vertical model is being fitted.

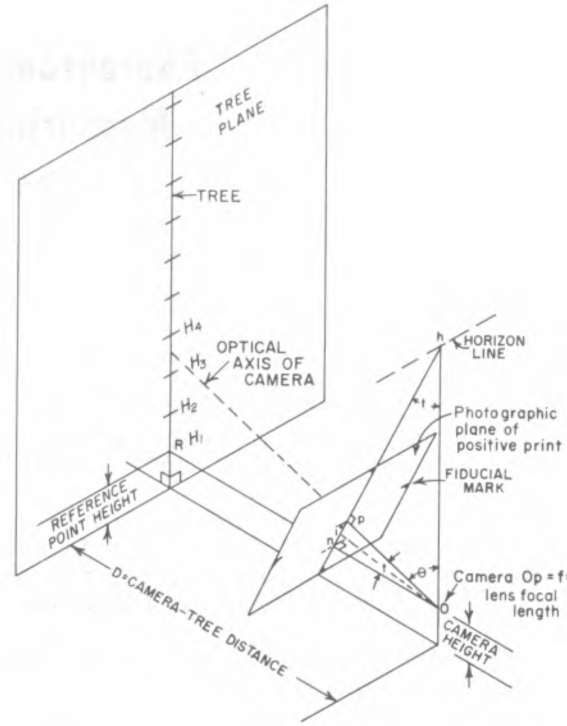

Figure 2 -- The oblique tree photograph.

After fitting•these three models to the projections of the bole in the A and B planes, it is possible to compute the deviations of the location of the tree pith (as projected on that particular plane A or B) from the theoretical position of the model (vertical, leaning straight, or curved). In practice we can photographically measure Al, A_2, ... A_n and B1, B_2, ... B_n (Figure 1), and statistically calculate the expected positions of models as $\hat{A}_1, \hat{A}_2$, .. $\hat{A}_n$ and $\hat{B}_1, \hat{B}_2$, ... $\hat{B}_n$ The differences in each projection of the stem, $A_1 - A_1$, and $B_1 - \hat{B}_1$ etc., give the individual deviations from the model. Because the A and B planes are at right angles to each other, the square root of the sum of the squared deviations sq. root of $(A_1 - A_1)^2 + (B_1 - B_1)^2$ is the actual radial deviation of the stem from the model "axis," at that height position. By the same procedure, the radial deviations of the stem from the three models can all be calculated. These can be presented as the sum of each deviation squared (sum of squares) or as the mean square of deviations from model.

A computer program has been written to obtain the following parameters of bole straightness:

1. Angle of lean. This is the angle made by the linear regression axis to the vertical and is calculated as:

   tangent angle of lean = sq. root of $b^2_A + b^2_B$

   where b_A is the coefficient of the regression line in the A plane and b_B is the same for the B plane.

2. Sum of squared radial deviations from the vertical straight axis passing through the mean A and B; i.e., total sum of squares, which is a measure of non-straightne'ss and non-perpendicularity. The ideal tree, straight and vertical, would have a sum of zero.

3. Sum of squared radial deviations from the linear regression axis. This represents the deviations remaining after lean has been accounted for, and can be called non-straightness. It would be zero in the straight but leaning tree. It includes deviations caused by the curvilinearity or sweep as well as crooks (see below).

4. The sum of squared radial deviations from the quadratic curved axis. This represents

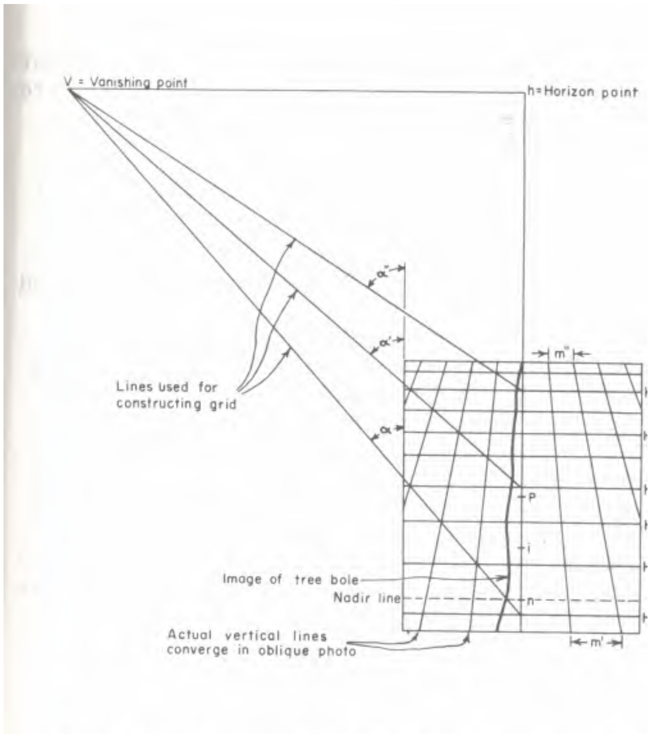

Figure 3 -- Perspective grid with tree bole photograph

the deviations from a curved axis and corresponds to residual crook. Where there is no curvilinearity, this quantity will be the same as No. 3.

5. The additional sum of squares due to fitting the quadratic curve. This measures the extent to which the curved axis removes extra variation not accounted for by the linear regression, and as such is a direct measure of the acuteness of the curve or the incidence of sweep. The ratio of this quantity to No. 3 above represents the goodness of fit of the quadratic curve to the tree, or the proportion of the deviations from a linear regression accounted for by the quadratic curve. A high ratio would indicate that most of the deviations from linear regression are due to curvilinearity or sweep, and that crook is not important. A low ratio indicates the converse.

All the above measures of bole straightness may be expressed as sums of squared deviations, as mean squares or as standard errors. In practice, mean squares are used for comparison.

As deviations from model at each measurement point are printed out by the computer, the position of any large deviations can be located. Variation of these deviations about their mean is measured by the mean square of variation of deviations.

METHODS

There are several ways of recording the projections of the stem in two planes, but photography is the most direct and simplest. Trees must be photographed with the optical axis of the camera tilted, causing vertical lines to appear to converge on the photograph. Also, there are changes in scale with increasing height up the tree. The geometry of the oblique photograph has been fully worked out for the oblique aerial photograph and the notation of Tewinkel (1951) has been drawn on heavily for this.

The practical procedures for photography, perspective grid construction and making measurements on projected photographs together with the computer program for the analysis and also a more complete treatment of the statistical basis of the method and the photogrammetric aspects will be described in a separate publication.

The geometry of the oblique photograph of a tree is shown.in Figure 2. Provided three characteristics of the oblique photograph are known, namely angle of tilt, t; tree to camera distance, D; and lens focal length, f, a perspective grid can be constructed. The photograph is then projected onto the grid (see Figure 3) and measurements of Ai and Bi distances are made and appropriate scales can be calculated for each height position so that actual Ai and Bi distances can be computed.

The perspective grid enables measurements of Ai and Bi to be made from the stem to a given vertical line, and horizontal lines are so spaced as to be located at equal height intervals up the tree.

In practice the photographs are projected onto a screen with a magnification of x 20 and a photographic scale of from 0.03 to 0.05 at 40 feet from the tree. A suitable perspective grid is superimposed on the screen and measurements of Ai and Bi (mid diameter point on stem to a given vertical line) are made there.

EQUIPMENT

A 35 mm single lens reflex camera (Pentax S.1.) with a 28 mm ultra wide angle lens has proved satisfactory for taking photographs in wild and plantation stands of southern pines of varying ages. The main problem is to get sufficiently far from the tree to include the whole of it in the photo, while being close enough to get a more or less unobstructed view.

Figure 4 -- Camera and clinometer.

The camera must be fitted with properly adjusted fiducial marks which produce images on the photograph to enable delineation of the principal line and principal point.

A Tiltall tripod Model 4602 is suitable. A special L-shaped attachment must be constructed into which the base of the camera fits snugly and which can be clamped between camera and tripod head by the tripod screw. On this L-shaped attachment a spirit level and Suunto Clinometer should be mounted (see Figure 4). The mounting must be done precisely so that, with the spirit level set, the long sides of the negative are exactly vertical. Leveling the camera and thus the photo in the horizontal plane enables the edges of the photo to be used as a vertical reference from which to measure angle of lean. The angle of tilt is set on the Suunto by adjusting the camera's tilt appropriately and the Clinometer reads zero degrees when the camera's optical axis is horizontal.

A "projection table" (see Figure 5) was devised so that a 150 watt Wollensak projector with film strip attachment projected an image enlarged twenty times, onto a mirror and through a plate glass table top onto a translucent acetate sheet on which was plotted the perspective grid. The projector was modified to take a Kodak Luxtra projection lens with short (50 mm) focal length, but this arrangement was not ideal. Better but more expensive projection equipment is on the market.

EVALUATION OF THE METHOD

Two series of tests were made of the photogrammetric method to evaluate its accuracy and to gain experience in interpreting the different measures of bole straightness.

The first test was made on a wire helix of 2.2 inches in diameter and with five full rotations in five feet of total length. This model was set up in four different configurations: vertical, leaning at an angle of 5° from the vertical, vertical but curved, and leaping but curved. Two pairs of photos were taken of each model, and measurements of A^i and B distances were made at intervals corresponding to three-inch intervals on the wire model.

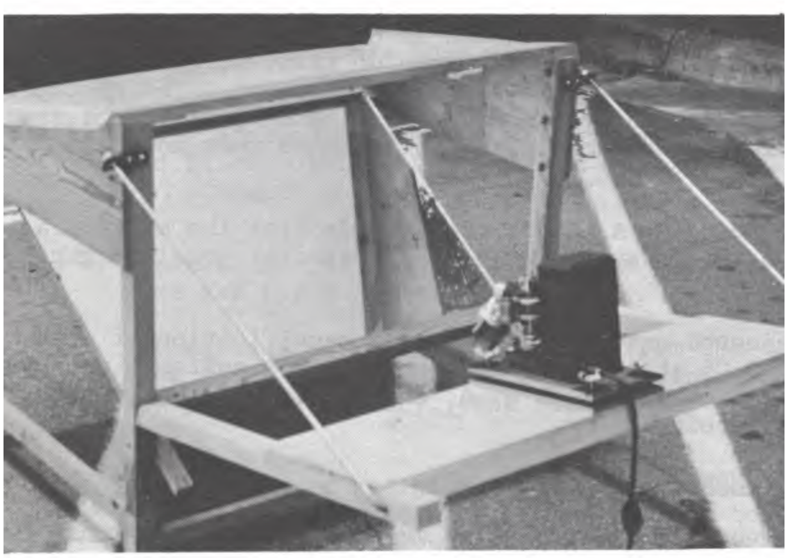

Figure 5 -- Projection table.

Repeatabilities and coefficients of variation are shown below for each measure of bole straightness:

$$R = \frac{\hat{\sigma}^2_B}{\hat{\sigma}^2_B + \hat{\sigma}^2_W} \quad \text{and C . V.} = \hat{\sigma}^2_W / \text{mean.}$$

	Repeatability (%)	Coefficient of Variation (%)
Angle of lean	98.4	10.1
Non-straightness	98.8	5.3
Sweep	99.7	6.1
Sweep ratio	99.7	8.5
Crook	56.7	7.2

The value of 56.7 for repeatability for crook can be explained by the fact that the same helix, bent in different configurations, was used for each model.

The size of the different measures and the separation between measures for different models was exactly as would be expected from a knowledge of the models' configurations. For example, Models 1 and 2 showed very slight sweep, while Models 3 and 4 showed a mean square for sweep about thirty times greater; crook showed no significant differences between the different models. Angles of lean were as expected, ± 1/2 degree. The size of the mean deviation from the best curve fitted was 1.1 to 1.2 inches in all cases corresponding closely to the actual radius of the helix of 1.1 inches as constructed.

The second test was made on a collection of eight plantation-grown trees, all aged 11 years and with heights of 55-60 feet. Three were selected for extremes of bole characteristics, while the remainder were a random sample, and of intermediate straightness. Three pairs of photos were taken of each tree and Ai and Bi distances were measured at intervals corresponding to two feet on the tree. (Normally only one pair of photos would be taken of each tree.) Repeatabilities and coefficients of variation are shown below for each measure of bole straightness.

	Repeatability	Coefficient of Variation
Angle of Lean	94.8	23.0
Non-straightness	99.5	12.8
Sweep	99.0	21.0
Sweep ratio	86.7	16.9
Crook	95.7	23.3

In general for all characteristics the size of confidence intervals was such that the stems picked as extremes showed wide separation and the remainder tended to show significant differences between certain groups though not between members of the same group. However, grouping of trees was not the same for every characteristic.

Coefficients of variation were about twice those for the wire models, mainly because the trees were much larger than the models and were photographed at a 40 angle of tilt under field conditions. However, repeatabilities were still high, giving confidence in the utility of the method.

DISCUSSION

The photogrammetric technique appears sufficiently reliable to provide a practicable means of measuring deviations of trees from the simple mathematical models used, i.e straight vertical, straight leaning and curved. Estimates of deviations from these models form an effective means o.f quantifying bole morphology. In addition to providing estimates of the angle of lean, non-straightness, sweep, and crook of the tree, the technique allows examination of the size of the individual deviations of the stem at successive height intervals.

Under reasonably favorable stand conditions, the field procedure requires only about ten minutes per tree by a technician and assistant; the time for measurement in the laboratory is approximately the same. Transfer of measurements from data sheets to IBM cards and subsequent computer time is insignificant on a single tree basis. Total time required is probably comparable to that required for other wood property measurements such as specific gravity and fiber length. Investment in equipment is not great, particularly since the three major items, single lens reflex camera, wide angle lens, and projector will have many other uses.

In addition to model fitting, errors in the technique occur at three main stages: photography, projection, and measurement.

The basic faults of the technique lie in the failure of the main assumption that the tree plane is vertical. Differences in tree-measurement-point to camera distances from those calculated on the basis of tilt and perpendicular tree to camera distance will result, and hence errors in the actual photographic scale at each H_i point will occur.

The photographic scale depends on tree to camera distance and focal length of the lens, as well as the tilt angle. Thus, the smaller the scale, the greater will be a given absolute measurement error, and so the smaller the tree to camera distance (and the smaller the tilt angle), the more accurate the measurements will be. A partial solution might be to photograph only the lower part of the bole that contains--or will eventually contain--the greatest and most valuable part of the merchantable volume. Thus it would be possible to assess progenies no later than when they had reached a height below which the bulk of the merchantable volume would be contained at maturity. An additional advantage of an assessment at a young age would be that the true configuration of the bole would be obtained before differential diameter growth obscured much of the tree's crook, as always happens as a tree ages.

Additional errors in scale can result from imprecise alignment of the camera; camera tilt angle must be the same as the tilt angle used for computing the perspective grid dimensions. Errors in leveling the camera cause errors in measurement of lean angle.

Any scale errors cause incorrect measurement of the deviation values and incorrect location of the vertical sampling points. Thus the "A" projected deviation is measured at a different height than the "B". The result is considerable error in line fitting and the location of the stem, with errors in its deviations from the model.

Measurement accuracy on the projected photograph was from ± 1/50 to ± 1/100th inch using a clear plastic rule; this means an error of from 0.2 to 0.7 inches at scales 0.03 to 0.05 used in the tree photographs.

LITERATURE CITED

Goddard, R. E. and R. K. Strickland. 1964. Crooked stem form in loblolly pine. Silv. Gen. 13(3):155-157.

Perry, T. 0., 1960• The inheritance of crooked stem form in loblolly pine (*Pinus taeda* L.) J. For. 58(12):943-947.

Shelbourne, C. J. A., 1963. Growth rates, stem form and branching characteristics of five provenances of P. *Khasya* grown under plantation conditions in N. Rhodesia. Comm. For. Rev. 42(4), No. 114:334-346.

Tewinkel, G. C., 1951. Basic Mathematics of Photogrammetry. Chap. VI. Manual of Photogrammetry. Second Edition. American Society of Photogrammetry, Washington.