A Large-Scale Aerial Photographic Technique for Measuring Tree Heights on Long-Term Forest Installations

Practical Paper

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Abstract

Tree height is both one of the most important and most expensive measurements to collect in the periodic reassessment of older genetic test sites, growth and yield plots, and other long-term forest installations.

The methodology described here provides a feasible alternative to the conventional clinometer and tape technology. The system uses large-scale aerial photographs (LSP) with permanent ground control points.

Test results indicate that, by the second assessment in installations containing 456 trees or more, the cumulative cost of LSP-measured tree heights will be less, and be as accurate as and more precise than clinometer-measured heights. By the 10th assessment in installations containing 3000 trees or more, the LSP system can offer 80 percent cumulative savings over the clinometer and tape method.

Introduction

Long-term forest genetic tests and growth and yield studies require accurate determination of individual tree performance in terms of height, diameter, volume, crown area, and other attributes. During the early development of a forest stand, heights can be measured quickly and accurately with the use of a ruler, a simple graduated pole, or a telescopic height pole. Beyond the reach of the height pole, however, the most commonly used technique with clinometer and measuring tape becomes cumbersome and expensive[1] for doing 100 percent remeasurement of heights. For example, a partial survey in the British Columbia Ministry of Forests' Research Branch indicates that by 1999 the number of trees requiring height measurement exceeding 15 m will increase from 43,000 to 152,000 per year.[2] Assuming a conservative $4.00[3] average cost per tree, this means that the yearly height measuring costs would jump from $172,000 to $608,000 by 1999, thus likely becoming financially prohibitive. To avoid the high cost of tree height measurement in older installations, researchers are often forced to reduce the number of trees they wish to measure, or revert to some other indirect, less expensive (and usually less accurate) technique.

Previous trials indicate that tree heights measured from large-scale photographs (LSP) — given adequate control over systematic errors — can be at least as accurate as, if not superior to, the field measurement of standing trees (Lyons, 1966; Nielsen *et al.*, 1979; Titus and Morgan, 1985; New Zealand Forest Research Institute, 1989). With recent advances in aerial cameras, films, and instrumentation (Thorpe, 1993), and the rapid evolution of desk-top computing, photogrammetric applications are becoming more reliable and cost-effective. Expensive analog plotters are being replaced with much lower priced, highly accurate analytical units, capable of faster, more reliable photogrammetric restitution than their predecessors (Valentine, 1987; Warner, 1988; New Zealand Forest Research Institute, 1989; Reutebuch and Firth, 1992).

Given the large number of trees projected for height measurement in British Columbia, and some of the developments mentioned above, the objective of this study was to test the accuracy and feasibility of LSP-measured heights compared to that of commonly used clinometer and tape method, in repeated measurement applications.

The technique described in this paper offers increased reliability of height measurements, coupled with simplicity and economy for monitoring applications.

Materials and Methods

A description of the methodology using commonly available equipment is provided below. Currently developing technologies such as the global positioning system (GPS) (Curry and Schuckman, 1993) and softcopy photogrammetry (Gagnon *et al.*, 1990; Klaver and Walker, 1992; Gagnon *et al.*, 1993) were purposely not used, as their limited availability and initial high cost could turn potential users away from applying the proposed method. In the future, however, these technologies will more than likely replace some of the ground control measurement methods, photo techniques, and plotting equipment mentioned here.

[1] Estimates received from B.C. Ministry of Forests professionals in 1993 and 1994 ranged from $0.93 to $10.00 per tree, with an average estimated cost close to $6.00.

[2] Personal communciations with C. Ying, J. Woods, B. Jaquish, M. Carlson, J. Pollack, F. van Thienen, D. Wallden, F. Sheran, B. D'Anjou, T. Newsome, and L. de Montigny, B.C. Ministry of Forests, Research Branch, 1993-1994.

[3] All costs in Canadian currency.

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TABLE 1. DESCRIPTIVE STATISTICS OF TRUE-HEIGHT[1] SAMPLE TREES AND OF DIFFERENCES BETWEEN THE MEASURED AND TRUE HEIGHTS FOR GROUND AND LSP TECHNIQUES.

	True height						Measured - true height differences			
	No. of trees	Mean (m)	Min. (m)	Max. (m)	SD (m)	Scale	No. of obs.	Bias (m)	SD (m)	MSE (m^2)
GROUND TECHNIQUES										
Laser-felled[2]	11	14.33	10.60	18.00	1.98	—	43	−0.13	0.18	0.049
Suunto-felled[3]	11	14.33	10.60	18.00	1.98	—	41	−0.40	0.53	0.441
Clinometer-felled[4]	51	14.49	7.40	21.80	2.91	—	51	0.02	0.70	0.490
Clinometer-felled[5]	180	N/A[6]	N/A	N/A	N/A	—	180	−0.12	0.86	0.754
Clinometer-felled[7]	502	16.26	7.60	22.00	2.44	—	502	0.08	0.95	0.909
Suunto & tan-felled[8]	794	24.35	5.46	59.07	10.42	—	794	0.23	1.16	1.399
Laser-true height[9]	71	17.78	3.38	29.87	6.52	—	11	0.09	1.22	1.546
Abney-felled[10]	394	25.28	8.50	40.80	5.54	—	394	0.17	1.32	1.771
Suunto-true height[11]	71	17.78	3.38	29.87	6.52	—	65	0.15	1.56	2.456
LSP MEASUREMENTS, DUNCAN, HELICOPTER, 70 MM CAMERA										
Boom[12], whorl[13]-height pole	115	7.41	2.14	11.02	1.61	1:800	96	0.06	0.29	0.088
Boom, tip[14]-height pole	115	7.41	2.14	11.02	1.61	1:800	95	0.04	0.44	0.195
Time[15], whorl-height pole	115	7.41	2.14	11.02	1.61	1:1000	133	−0.27	0.28	0.151
Time[16], whorl-height pole	115	7.41	2.14	11.02	1.61	1:1200	166	−0.21	0.34	0.160
LSP MEASUREMENTS, PRINCE GEORGE, FIXED WING, 9- BY 9-INCH CAMERA										
Visible[17], tip-height pole	44	8.84	4.88	11.48	1.33	1:1200	84	0.10	0.48	0.240
All, tip-height pole[18]	44	8.84	4.88	11.48	1.33	1:1200	76	0.05	0.59	0.351
All[19], tip-height pole	44	8.84	4.88	11.48	1.33	1:1200	133	0.18	0.63	0.429
Not clear[20], tip-height pole	44	8.84	4.88	11.48	1.33	1:1200	49	0.41	0.80	0.808

[1]Felled, or climbed tape-measured length of a tree, or measured standing with a height pole.
[2]F. van Thienen, unpublished report, 1993.
[3]F. van Thienen, unpublished report, 1993.
[4]Hall *et al.*, 1993.
[5]Nielsen *et al.*, 1979
[6]Information not available.
[7]Titus and Morgan, 1985.
[8]Larsen *et al.*, 1987.
[9]Williams, 1993. Observer 6 only.
[10]Lyons, 1966.
[11]Williams, 1993. Observer 6 only.
[12]Fixed-base, boom photography. Stereocord G2 plotter.
[13]Measured at whorl below tip.
[14]Measured at the tip of the tree. Stereocord G2 plotter.
[15]Time-interval photography. AP190 plotter.
[16]Time-interval photography. AP190 plotter.
[17]Tips coded as "visible." AP190 plotter.
[18]All codes included. Stereocord G2 plotter.
[19]All codes included. AP190 plotter.
[20]Tips coded as "not clear." AP190 plotter.

LSP Tests

During the course of this research project, several test flights were taken using a variety of aircraft and cameras.

The first flight was in 1992 over a Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) progeny test site at Duncan, B.C. with helicopter-mounted, 70-mm twin camera system (Hasselblad electric camera, 100-mm focal length lens), originally developed by the Ministry of Forests (Lyons, 1966) and later modified by Timberline Ltd. of Vancouver, B.C. (M. Mastine, pers. comm., 1992). In these tests, both "boom" photography (simultaneous exposures taken by the front and rear cameras) and time-interval photography (overlapping images of one of the cameras) were tried at several scales (1:800, 1:1000, 1:1200, 1:1500, 1:3000, 1:5000) using Agfa Avichrome 200 film. However, due to the small area coverage at the required large scales, the 70-mm approach was judged to be impractical for this application and was discontinued. The test results, nevertheless, were useful to demonstrate the accuracy of the system (Table 1), as the photogrammetric process we used was identical to the single camera techniques with ground control.

In October 1992, a second flight was taken over a lodgepole pine (*Pinus contorta* Dougl. ex Loud.) provenance test-site, 10 km south of Prince George, B.C. This time a 9- by 9-inch format aerial camera without forward motion compensation (FMC), a 6-inch focal length lens and a fixed-wing aircraft were used. Unfortunately, air turbulence and the use of slow exposures resulted in poor photo quality. This combined with the large radial displacement caused by the 6-inch lens, made tree images very difficult to view at large scales. In the spring of 1993, both sites were re-flown by a different contractor with a 9- by 9-inch format camera and a 12-inch focal length lens, but without FMC. Again, due to image motion caused by turbulence and possibly high aircraft speed, most of the resulting photos did not provide sufficiently clear images to accurately measure tree tips.

The last tests were flown in the spring of 1994 by Hauts-Monts Inc. of Beauport, Quebec. This time, the contractor used a slow-flying aircraft, a Zeiss RMK A 30/23 camera with FMC, and a 12-inch focal length lens. The film specified in the contract was a Kodak 2443 infrared positive film, but sample exposures of other emulsions, in combination with a 0.3-mm and a 0.7-mm shim, were also tried at the Duncan test site. Among the tests done with this equipment, the Kodak 2443 film images taken at Prince George were found to be the most suitable for measurements and are presented in Table 1.

Description of the Method

The methodology described in this paper uses large scale 9-by 9-inch photographs and permanently established, visible ground control. The system requires a one-time ground-measured elevation difference between the ground control and each tree base, thereby determining the vertical coordinate of the base. By knowing the tree base coordinate, the need for "seeing" and placing the stereoplotter's measuring dot on the ground near the base is eliminated. Also, the repeated measurement of each tree base in succeeding assessments — a common practice in most ground and aerial photo approaches — becomes unnecessary. Figure 1 provides a schematic illustration of the system.

Before photographs are taken, permanent targets (i.e.,

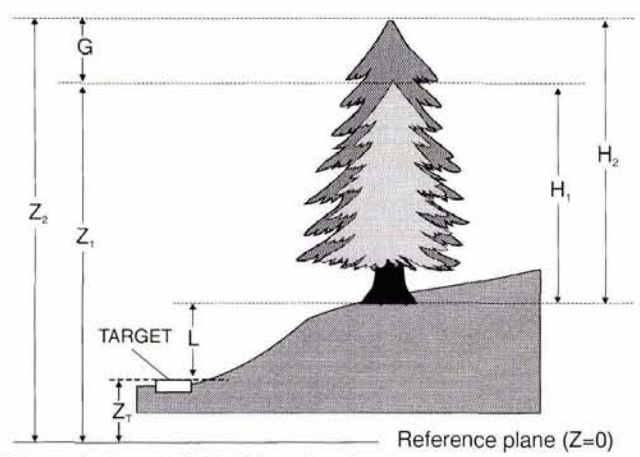

Figure 1. Tree height determination from successive photo measurements using permanent ground targets.

ground control points) are placed in suitable openings (see suitability specifications below) throughout and surrounding the installation. After the area has been photographed, those targets visible on the photos are surveyed in order to define their position with an *X*, *Y*, and *Z* coordinate. The next step is to tie each tree base into the vertical component of the coordinate system. This is best done by measuring the elevation difference between the targets and nearby trees (L) and adding it to the vertical coordinate of the target (Z_T) from which the level difference has been taken. Because the target coordinates provide the numerical values for absolute orientation of the stereoscopic model, measurements from the photos will be in the same coordinate system as the tree bases. Thus, the total height of a tree at the time of the first photography (H_1) is obtained by subtracting the tree base coordinate (Z_T+L) from the photo-measured tree tip (Z_1). Periodic growth is determined by rephotographing the site at a later date, using the same permanent targets for photo orientation and remeasuring tree tips (Z_2). The difference between the two photo measurements (Z_2-Z_1) is the periodic height growth (G). Total height at remeasurement time (H_2) is obtained by subtracting the tree base coordinate (Z_T+L) from Z_2.

Mission Planning

The planning process for an LSP application should begin with an assessment of the feasibility of the operation. Indications are that small, dispersed areas may not be suitable for the LSP approach because initial costs may prove to be too high for a feasible operation. Preliminary estimates suggest that 400 to 500 height measurements will justify the photographic approach (see discussion of costs below, under "Results and Discussion"). Naturally, accessibility, efficient scheduling of flights and manpower, or the introduction of alternative, inexpensive technologies may reduce costs considerably.

Determination of Scale

Once the decision has been made to photograph an area, the planner must decide on the photo scale sufficient for detecting the object of measurement on the photos (i.e., tree tip, or last whorl of branches). Given the required scale, the size of the area, and overlap (60 percent forward and 30 percent side), the flying contractor then has sufficient information to calculate the number of flight lines and time intervals between exposures to cover the installation.

For our tests, Caylor's (1989) approach for scale determination was adopted. This resulted, for the detection of the Douglas-fir leader (estimated to be 4 cm in diameter), in a scale of 1:690 and, for the lodgepole pine leader (estimated to be 8 cm in diameter), in a scale of 1:1380. However, it was impractical for a fixed-wing aircraft to attain a 1:690 scale image, partly because of safety reasons, and partly because of other technical difficulties encountered at low flying heights (such as using a small aperture to ensure the necessary depth of field and still maintaining a fast exposure time and inadequate recycle time for the FMC compensation mechanism). Thus, in addition to the Douglas-fir tree tip, we decided to test the use of the last whorl of branches just below the tip (see "Determination of Tree Height" below), and to reduce the required scale to 1:1000.

Target Layout

The next step in the planning process is to find a sufficient number of suitable openings to accommodate long-term target locations for photogrammetric control. As a general guideline, a 90- by 160-m area (i.e., the portion of gross overlap of a pair of 1:1000 scale photographs that is actually used in photogrammetric procedures) must have four or more (Moffitt and Mikhail, 1980, p. 360; Slama, 1980, p. 393) visible control points (targets), located in openings, such as a road, rock outcrop, landing, windfall area, or creek bed. The targets should be well distributed close to the periphery, with one or two in the center part of the stereoscopic model. Adjoining models will require at least two additional openings because they usually share two or three points within the overlap areas.

The maximum distance between targets along the flight line should be equal to, or less than, the distance between successive exposures, and the maximum distance between targets normal to the flight line should be equal to, or less than, the distance between adjacent flight lines. These values can either be calculated beforehand by the planner, or obtained from the flying contractor, who must calculate these values for the photographic mission in any case.

To provide a good choice, we recommend locating targets at less than the maximum distance referred above. The final selection can always be made after the completion of the photography.

The size of the required opening can be either visually estimated or calculated using simple relationships. One convenient way to determine the size of opening is to calculate the maximum angles along and normal to the planned flight line that will allow a stereoscopic view of a target until the end of the monitoring cycle. In an existing stand, suitability of an opening can be determined by standing at the proposed target position and measuring the angles to the expected top edge of the opening along and normal to the planned flight line. If either of the angle measurements is larger than the maximum angle calculated, the opening will not be large enough to provide a clear view of the target in the stereo model. In a new plantation, opening size can be determined from the projected height of the stand at the last assessment. That estimate then can be used to calculate the required distance from the plantation edge to the proposed target location.

A lack of suitable openings, however, may not always be prohibitive for undertaking a photographic mission. Techniques such as "bridging" control points (Reutebuch and Shea, 1988) or aerial triangulation can usually resolve the problem. To apply the bridging process, the area is flown twice, one at high and another at low altitude. The high level photos are intended to capture a sufficient number of ground control points to orient these smaller-scale photos, after which easily identifiable image points are digitized and their *X*, *Y*, *Z* coordinates are assigned to the same image points on the lower level photos, to be used as control points.

Another alternative to having a sufficient number of natural openings is to create artificial ones — a situation which may arise in existing dense stands, or in new plantations. In these cases, however, consideration should be given to the additional clearing costs and the potentially unwanted effects of artificial openings.

A convenient way to establish the control points is to use 90- to 120-cm long metal rods, driven into the ground and marked with a surveyor's tape. Then the targets can simply be placed over the rods before the flight and removed afterwards, if so desired. Our targets were made from white corrugated plastic (two 10- by 122-cm strips arranged perpendicular to each other), which proved to be durable enough to withstand west coast weather conditions for several months.

Target Survey

After the establishment of the control points (targets), an accurate traverse survey is required to register their *X*, *Y*, and *Z* coordinates. This is preferably done after the photography, when the target selection has been finalized but may be done at any convenient time before. During the survey, the targets must be in place to ensure consistency between the elevation readings of the photo and the ground measurements. Survey results are usually submitted in a map form, together with a list of the easting (*X*), northing (*Y*), and elevation (*Z*) values of all control points. These coordinates are subsequently used in the photo orientation process, described below under "Photo Measurements."

Tree Base Leveling

The measurement of the tree base elevations is a relatively low-cost, one-time operation, best done with an engineering level and standard leveling techniques. Because this measurement is not affected by tree growth, it can be carried out at any convenient time after stand establishment. To ensure consistency between the determination of "breast height" and tree base elevation measurements, the 1.3-m mark on the leveling rod should be aligned with the 1.3-m diameter reference height, usually painted on each tree in permanent forest installations.

Photography

One of the first specifications in assigning a photographic mission is a suitable window for flying. Because forest installations are usually measured during the dormant season, a knowledge of the length of the dormant period for the area and tree species in question is essential. In the northern temperate forests, the dormant period usually begins around mid-August and lasts until early May the following year. This relatively long period allows the flight contractor to plan for fall flights and, if necessary, rephotograph some of the areas in the spring before the next growing season begins.

Another important consideration is that the flying contractor understand and adhere to the photographic requirements of this application. To increase the probability of success, the specific requirements for LSP tree-height measurement should be stated, of which the most important are

- If it is available, use a self-leveling mount for the camera (Caylor, 1989);
- Use a 9- by 9-inch frame aerial camera with a 12-inch focal length lens, preferably with an *f*/4 or greater aperture capability, equipped with FMC;
- To reduce out-of-focus problems at scales close to 1:1000, consider using a 0.3-mm shim for this application. If a 0.3-mm shim is not available, ensure that the maximum aperture is not greater than *f*/5.6;[4]
- Use 1/300 second or faster exposure times (Caylor, 1989) to reduce the image movement caused by tip, tilt, and crab of the aircraft;
- Ensure that the flying speed is slow enough to allow the FMC mechanism to recycle within the time frame available for obtaining the required forward overlap, usually 60 percent (e.g., for 1:1000-scale photography and a 2.5-second FMC recycle time, the flying speed must be 131 km/h or less);
- Fly only when winds are calm (less than 6 km/h);
- Outline the area accurately, because a small deviation in the desired flight path at large scales may result in inadequate coverage and rule out any opportunity to re-fly specific areas under similar conditions; and
- Use the light-meter reading applicable to the top part of the canopy, because most measurements will be taken there. Target visibility is usually assured by its open location and high-contrast composition.

The choice of film, although very important, is not something we can confidently recommend. In most instances in our tests, the image quality was either influenced by unfavorable weather conditions, or by various compromises made during the flight, causing image motion or out-of-focus problems on the photos. The films that showed the least amount of image motion and/or image blur, and on which the test measurements were made (Table 1), were color positive films — Agfa Avichrome 200 and the Kodak 2443 color infrared used in the 70-mm and 9- by 9-inch cameras, respectively.

The image motion referred to above was caused by the movement of the tree branches (wind sway), turbulence (uncorrectable by the FMC), or both. Thus, flying in calm weather conditions appears to be a key factor in obtaining good image quality. If any turbulence is present, either fast exposures must be used (1/400 second or faster) or the mission should be postponed.

Although these requirements may appear limiting to successful photographic missions, they are not prohibitive. The long dormant season mentioned above should provide sufficient opportunities for meeting all constraints. One approach to completing a photo mission is to prepare the test sites for a fall flight. If suitable conditions do not occur in the fall, another opportunity will more than likely arise during the following spring.

Photo Measurements

The application presented here requires access to an analytical plotter. In this project, a Carto Instruments AP190 analytical plotter and software, and a converted MS DOS-compatible Zeiss Stereocord G2 with ISM's Systemap software, were used.[5] The choice of plotters was based simply on availability, except for one instance at the Prince George site, where measurements were repeated with the Stereocord G2 to test instrument performance.

The photogrammetric process usually begins with the camera calibration records and the control point coordinates being entered into the designated computer files. An overlapping photo pair is then placed on the viewing platforms for which interior, relative, and absolute orientations are performed, usually guided by the photogrammetric software. The software also provides an analytical solution of the rectification, accompanied by an output of residuals for all three orthogonal axes.

Following the orientation process, the measurement of

[4]Personal communication with David Skea, Minerva Research Ltd., Victoria, B.C., July 1993. The determination of a suitable *f*-stop for a required hyperfocal distance is described in Moffitt and Mikhail (1980).

[5]ISM is International SysteMap Corp., Vancouver, B.C., Canada.

individual trees can begin. In the case of planted research test sites, the location of the installation and of the individual trees within is a relatively simple matter of visual identification (the latter usually aided by a plantation stem map).

Test sites in natural stands can be slightly more complicated to locate because these installations usually have no easily recognizable distinguishing features. However, if the plot center *X* and *Y* coordinates are included in the ground survey, it is a simple matter to guide the floating point mark to these points. Similarly, the plot center may be found if the distance, slope, and azimuth are known from a photo-identifiable point (Reutebuch and Firth, 1992). Once the plot center is available, the position of each tree thought to be inside the plot can be closely approximated by recording its tip. A ground-generated stem map can then be visually matched with the photo stem map, and the trees inside the plot identified. If a ground stem map is not available, identification of the trees inside the plot can be left until the next field maintenance, and those outside the plot can be eliminated.

The measurement of a tree tip on a stereo model consists of placing the plotter's floating point mark first alongside (to determine appropriate height), then onto the top of the leader and pressing the "record" button to store its *X*, *Y*, and *Z* coordinates onto the measurement file. Depending on the type of software used, the location of the tree tip is also registered on the screen, with an option to be plotted later.

Once the trees inside the plot are identified and the coordinates are electronically stored, their positions and identities can be retrieved and used again at remeasurement time.

Determination of Tree Height

The total height of a tree may be defined as the distance between the tree base (such as the estimated point of germination) and the tip of the leader. In a pure plantation of a thin-branched species (such as Douglas-fir), where the tree tip is difficult to see on a photograph, the tree height for a given year may be obtained by measuring the distance between the tree base and the last whorl of branches below the leader, one growing season later. Using the last whorl usually eliminates the difficulty of positioning the floating point dot on the leader tip. In mixed stands, however, the "last whorl" approach is not recommended, because the whorl heights will not be based on the same year's leader growth as the tip-measured heights. Nevertheless, adherence to the LSP requirements specified above will more than likely produce acceptable quality photos for the measurement of tips in all species, without the need for any compromise.

Thus, in most installations, the tree height is simply obtained by subtracting the ground-measured *Z* coordinate of the tree base from the photo-measured *Z* coordinate of the tip. The measurement error due to leaning trees with this method is similar to that accepted in conventional ground-measuring techniques. If, however, in addition to the base *Z* coordinate, the *X* and *Y* coordinates are also available (i.e., from a ground-measured stem map or an early photo measurement), most photogrammetric software will calculate the distance between the two points, providing the length of the tree regardless of lean.

Accuracy Tests

To test photo measurement accuracy, the height of the last whorl and tip on 115 trees at Duncan and on 44 trees at Prince George were measured with a telescopic height pole. These height-pole measurements were accepted as "true" measurements for the LSP tests, although we recognize that they are not free of errors either.[6] At Duncan, only those trees located at the northern part of the test site were photo-measured. With the aid of an existing stem map, height-trees were visually identified on a stereo model and measured with either the AP190 or the Stereocord G2 two or three times, following a predetermined measuring sequence.

Because the primary interest in these tests was to establish the predictive accuracy of photo measurements in comparison to that of the "true" height pole measurements, a Statistical Analysis System (SAS[7]) template program (Gribko and Wiant, 1992) was used to compute bias, standard deviation, confidence, prediction, and tolerance intervals at p = 95 percent for both the absolute and percent differences between the two quantities.

For comparative purposes, test-of-accuracy results of commonly used ground techniques were also collected (Table 1). However, because the raw data for some of the ground measurement techniques were not reported and the accuracy tests could not be carried out on them, the presentation of statistics in the table was reduced to show the number of observations ("No. obs."), the bias, and the standard deviation (SD) available in all tests. Furthermore, because the measurement data originate from different sources and represent a variety of stand conditions (see "True height" statistics in Table 1), a tabular presentation of the results was considered more appropriate than a statistical test. To aid comparison, the mean square error (MSE) — calculated as the sum of the bias squared and the variance (Cochran, 1977) — was used as a criterion to compare the different measurement techniques.

Results and Discussion

As can be seen in Table 1, most ground height measurements (with the exception of van Thienen's laser tests) have larger MSE than do the LSP measurements. Among the LSP tests, the 70-mm boom photographs taken at a 1:800 scale and the measurements made at the last whorl produced the lowest MSE (0.088). Tip measurements on the same trees were slightly less precise, resulting in a higher MSE (0.195). For the time-interval tests, made at scales 1:1000 and 1:1200, only the whorl measurements were included in the table, as the tips were unsuitable for accurate height determination.

In the table, under LSP measurements for 1994 fixed-wing flights at Prince George, only the tip measurements are shown, as the lodgepole pine tree tips were large enough to position the measuring dot on them, thus eliminating the need for measuring the whorls. Here the AP190 measurements are coded into two visibility classes: "visible" and "not clear." The frequency of these codes helped us in judging the quality of the photographs and the reliability of measurements. As shown, the measurements coded "visible" have a lower MSE than either the combined (coded "all") or the "not clear" group, and are as accurate (bias) and more precise (SD) than those shown for clinometer and tape techniques. This result also implies that the LSP technique could produce improved measurement reliability if it were combined with a real-time error checking routine.

At the Prince George site, a subsample of the 44 height-trees was remeasured (76 observations) with the Stereocord G2 analytical plotter. The results indicate repeatability using different instrumentation.

It must be noted that all the photo measurements included in the table are raw, unedited data, presented without modification, even when the resulting height estimates were obviously unrealistic.

Additional explanation is required regarding the validity of comparing the limited height-range photo sample, taken at Duncan and Prince George, with ground tests covering a

[6]Tests comparing operational vs. check measurements of plantations showed acceptable accuracy and precision (i.e., 1 to 3-cm bias, 7 to 10-cm root-mean-square error) for height-pole measured heights.

[7]SAS is a registered trademark of SAS Institute, Inc.

wider range of heights (see "true" height statistics in Table 1). In a strict statistical sense, the question of validity is justified given the lack of wider-ranging data for the LSP tests. However, one need only refer to basic photogrammetry to see that height measurement errors at a given flying height will decrease with increased heights of objects. Thus, the system should work as well (or even better) for tall trees as for short ones, especially when tree-base photo measurements will not be needed. The opposite is true with ground measurement techniques. To obtain the most accurate results with the hand-held clinometer, the distance from the observer to the tree should be approximately equal to the height of the tree (Andrews, 1936). This also means that the observer must be farther away from a tall tree than from a short one. Assuming the same angle measurement error for both, the resulting absolute error in the height estimate will be larger for a tall tree than for a shorter one.

Costs

Estimates based on the actual costs of ground measurement contracts and on the estimated costs of operational photo missions[8] indicate that by the second assessment, in installations containing 456 trees or more, the cumulative cost per tree for the proposed LSP measurement will be less than for clinometer and tape measured heights (Figure 2).

Installations containing 1300 trees or more will cost half as much to measure by the second assessment with the LSP approach than with the clinometer and tape approach. For installations containing 3000 trees or more, the LSP system may, by the 10th assessment, offer 80 percent cumulative savings over conventional ground techniques.

The above cost estimates assume 5 minutes ($6.31) per tree[9] and 84 heights per crew per day production for clinometer and tape measurements, and a very conservative 300 photo-height determinations per person per day.

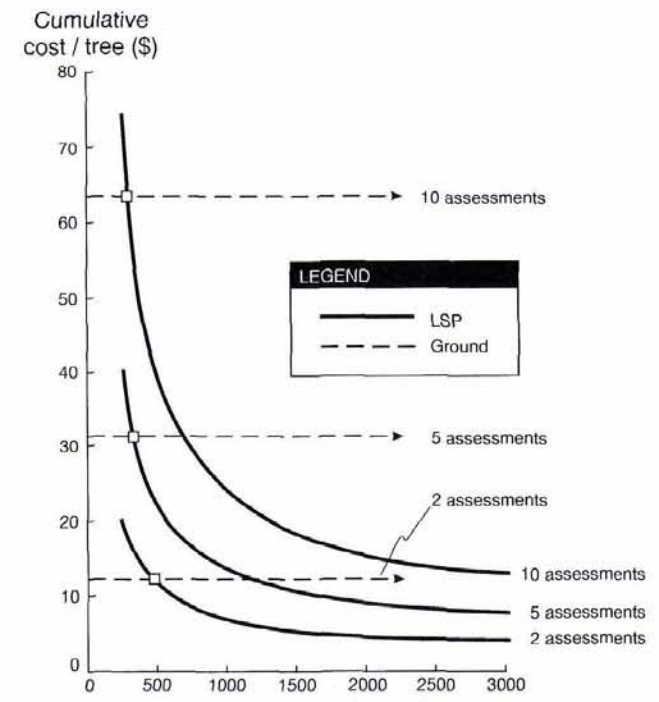

Figure 2. Cost per tree of two, five, and ten height assessments with clinometer and tape and with photo techniques.

Conclusions

The LSP technique has the potential to provide accurate and precise tree-height measurement data for long-term forest installations. However, our experience from these tests indicates that fixed-wing photography can produce consistent results only if extreme care is taken to observe all the requirements specified for photogrammetric tree-height measurement. These requirements depend partly on equipment (e.g., camera, film, FMC, shim, and slow-flying aircraft), but more importantly, on the expertise needed to recognize and select the appropriate attributes for the technique (e.g., wind, aircraft speed, accurate navigation, film selection, aperture/exposure determination, and film processing techniques).

Alternative technical solutions, such as a self-leveling, low-vibration, helicopter-mounted camera, could potentially remove most of the problems caused by the fixed-wing approach.

Thus, the emphasis in these tests is on the viability of the technique, rather than on the equipment used. With suitable equipment, responsible technical expertise, and a well-thought out computerized data screening program, photogrammetric tree-height measurement can become a useful, economically viable tool for forest geneticists and growth and yield specialists in the future.

[8]This estimate is based on one initial measurement and one remeasurement of an average test site, with 12 targets. Costs: target establishment and target survey: $1365.00; tree-base leveling: $1.77/tree; photography: $1530.00; and photo measurement: $0.57/tree.

[9]Personal communication with R. Hattie, B.C. Ministry of Forests, Research Branch; J. Braz, B.C. Ministry of Forests, Inventory Branch; F. Pendl and B. D'Anjou, B.C. Ministry of Forests, Vancouver Forest Region; Ralph White, White Woods R. Inc., Victoria, B.C., 1994.

Summary

The tree height measurement technique presented in this paper uses large scale, 9- by 9-inch format aerial photographs and permanent ground control points. The system requires a one-time elevation measurement of each tree base relative to the surveyed controls. This ground-determined base elevation provides a permanent vertical reference for the tree base measurement, which, if subtracted from a photo-measured tip elevation, gives the height of the tree at the time of photography. Tests show that this technique produces tree height measurements that are as accurate as and more precise than those obtained with the clinometer and tape method. Cost estimates indicate that, by the second assessment, the system becomes feasible (in comparison to clinometer and tape techniques) when the number of trees in a test area exceed 456. Larger savings are projected with an increased number of trees and with additional assessments.

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