Canadian Large-Scale Aerial Photographic Systems (LSP)

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ABSTRACT: This paper reviews Canadian approaches for acquiring and processing large scale aerial photographs (LSP). Developments in Canada show that large scale aerial photographs (LSP) can be used as a sampling tool and so reduce the need for expensive and slow ground surveys in forest inventories. The use of LSP is a two-step process involving photo acquisition and analysis, with both steps requiring specialized equipment and techniques to ensure efficient recording, extraction, and processing of data. Canadians have pioneered two different photographic approaches and tested various measurement-interpretation systems. One photographic approach uses twin-vertical 70-mm cameras mounted on a fixed air base; the other uses single-camera, timed-interval photography with a radar or laser altimeter and in-flight recording of tilt. The major systems for photo analysis use analytical stereo digitizers and computers to extract and process data.

INTRODUCTION

CANADA IS A LARGE COUNTRY that has 22 percent of its 9.9 million km² classified as inventoried, productive forest land (Bonner, 1982). As management of these forests in intensified, so are the demands for timely, cost-effective methods for monitoring forest conditions. Large-scale aerial photography (LSP) (1:200 to 1:3000 scale) is a tool that has been developed to improve the efficiency of forest sampling in forest inventories. A distinguishing characterisitic of such photos is the provision of ground-quality measurements from aerial sampling independent of ground control.

Over the past 20 years various authors have published progressive accounts of developments in LSP equipment and methods, including Kippen and Sayn-Wittgenstein (1964), Lyons (1967), Edwards and Waelti (1972), Aldred and Sayn-Wittgenstein (1972), Bonner and Aldred (1974), Aldred and Lowe (1978), Williams (1978), Bradatsch (1980), MacLeod (1981), Hegyi and Quenet (1984), Hall *et al.* (1984), and others. The purpose of this paper is to summarize the current state of developments, drawing upon information compiled for a recent national review (Spencer, 1984).

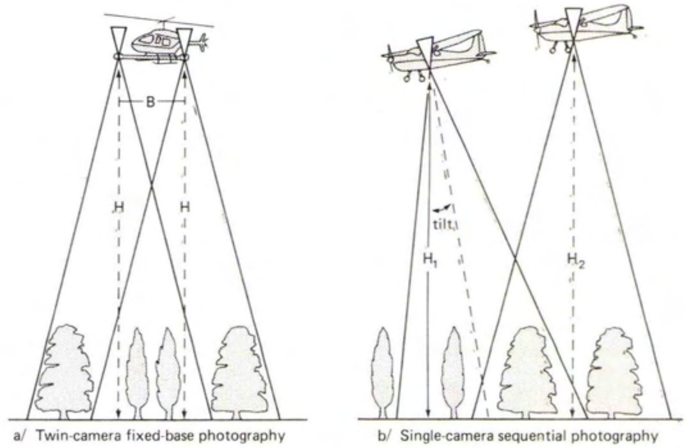

FIG. 1. Methods of large-scale aerial photography. (a) Twin-camera fixed-base photography. (b) Single-camera sequential photography.

METHODS OF ACQUIRING LARGE-SCALE PHOTOGRAPHS

Two different approaches have been developed in Canada for obtaining LSP: twin-camera fixed-based systems (Figure 1a) and single-camera sequential systems with and without a radar or laser altimeter and a tilt recorder (Figure 1b). Large format cameras are generally not well suited for such very large scales because of limitations with camera cycling rates, image motion, and higher costs. Consequently small format cameras, in particular 70-mm cameras, are common. The twin-camera fixed-based system and single camera sequential system use different methods for photo scaling and photo orientation for measurement purposes. Different designs are also used according to choice of aircraft, camera mountings, airbase orientation, and application (Figure 2). The two basic systems are described in the following sections.

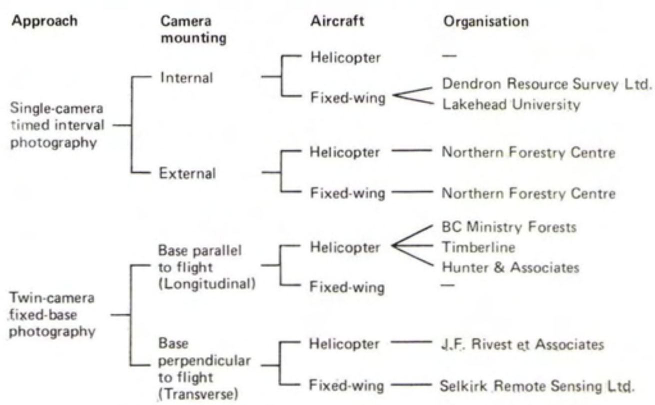

FIG. 2. Alternative systems for LSP in Canada.

TWIN-CAMERA FIXED-BASE SYSTEMS

Early developments of this system for Canadian forestry (Lyons, 1961, 1964, 1966, 1967) were based on recommendations from the USA (Avery, 1958, 1959). The method uses two identical, synchronized cameras mounted a set distance apart with their principal axis parallel (Figure 1a). Stereopairs are obtained by simultaneously exposing the two cameras, thereby providing a

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means for determining photo scale based on the ratio of photo base over actual air base (i.e., camera separation). The relationship between this scale and focal length of the cameras then provides a simple method for determining flying height that does not require ground control.

The fixed-base method provides stereopairs of photographs of known relative orientation and freezes dynamic scenes, such as tree crowns swaying in the wind. A disadvantage of the method, however, is that the fixed base controls the amount of overlap at each scale, thereby affecting differential parallax, and, consequently, the accuracy of photo height-measurement (i.e., less stereo effect at smaller scales because of reduction in the base to flying height ratio).

There are now eleven fixed-base systems in Canada (Spencer, 1984): nine of a helicopter boom system (Figure 3) in the direction of flight, one of a helicopter-boom system (Figure 4) perpendicular to the direction of flight, and one that is a transverse wing-tip system on a fixed-wing aircraft (Figure 5). Seven of these systems are government owned and four are in the private sector. Major components of each system are summarized in Table 1.*

FIG. 3. Longitudinal fixed-base photo system, Timberline Ltd., Vancouver, B.C.

FIG. 4. Transverse fixed-base helicopter photo system, J.F. Rivest et Assoc., P.Q.

* The exclusion of certain private companies and manufactured products does not imply rejection nor does the mention of other companies or products imply endorsement by the authors.

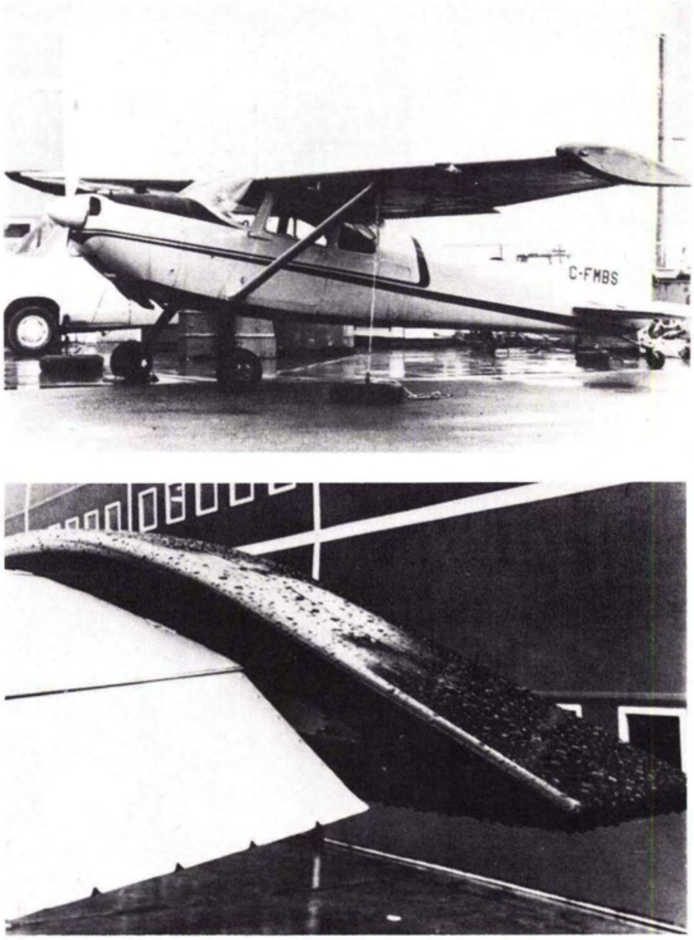

FIG. 5. Wing-tip system, Selkirk Remote Sensing Ltd., Richmond, B.C.

Canadian results (Rivest, 1980) confirm those reported from Germany (Rhody, 1977) and Australia (Spencer, 1979), where it was found that transverse orientation of the air base with respect to the flight direction minimized problems attributable to poor camera synchronization. This is because lateral movement of the aircraft is nearly zero under favorable operating conditions. Any time lag in exposure of the two cameras therefore does not change the effective length of the air base. This contrasts with longitudinal orientation of the air base, where a time lag between exposures changes the effective length of the air base. For example, exposure of the front camera before the rear camera causes a shortening of the effective air base and vice versa. In the absence of ground control, there is no way of determining from the photographs whether either of these problems has occurred. Therefore, the accuracy of results cannot be guaranteed but, by using a synchronization monitor, it is possible to assess the photogrammetric quality.

Adaptation of the twin-camera concept to fixed-wing aircraft offers the potential advantages of a longer air base, lower operating costs, and greater flying range (Williams, 1978). Conversely, it suffers disadvantages due to the adverse effect of higher aircraft speeds on image motion, as well as the lower maneuverability and reduced ground visibility with fixed-wing aircraft. The system may also suffer from instability due to wing flexing, but Williams (Pers. Commun., 1984) indicates that this can be reduced by using aerodynamic camera pods and mechanical compensation to the camera mounts although not to the extent that is needed for rigorous photogrammetry.

TABLE 1 TWIN-CAMERA FIXED-BASE PHOTOGRAPHIC SYSTEMS.

Characteristics	B.C.* Ministry of Forests	J.F. Rivest et Assoc. (Quebec)	Selkirk Remote Sensing Ltd. (Vancouver)
Base orientation	Longitudinal	Transverse	Transverse
Aircraft	Bell Jetranger 206B	Bell G-47 piston	Cessna 180
Airbase (m)	6.1	9.11	11.3
Camera	Hasselblad MK70	Hasselblad MK70	Vinten 492
Lens f (mm)	100, 60	100	76, 152, 300
f stop	3.5, 5.6	3.5	2, 2.8, 3.5
max. shutter speed (sec)	1/500	1/500	1/500 - 1/3000
Preferred flying heights above canopy (m)	130 or 100	100	250
B/H ratio	Varies with *H*	Varies with *H*	Varies with *H*
@ 1:1000	1:16	1:11	1:250
@ 1:1200	1:20	1:13	1:16
Photo scales	1:200-1:1500	1:1000	1:800-1:3300
Flying height control	Barometric altimeter & judgement	Bonzer radar	Barometric altimeter & judgement
Overlap %	Varies with *H*	Varies with *H*	Varies with *H*
@ 1:1000	89	84	80
@ 1:1200	91	86	83
Special navigational aids	None** Tree flagging double sample plots	None	None

*Timberline Ltd. (Vancouver) and Hunter & Assoc. (Toronto) operate identical systems except for addition of a synchronization meter.
**Hunter and Associates use a video recorder for postflight tracking and sample point location.

TIMED-INTERVAL LSP SYSTEMS

This method uses sequential photographs from a single camera to obtain stereo coverage through forward overlap of the photos. Scale can be determined from ground reference points, a foliage-penetrating radar, (Aldred and Hall, 1975) or a rapid pulse laser altimeter that provides for discrimination between canopy and ground signals (A.H. Aldred, Pers. Commun., 1984). Relative orientation of stereophotographs is usually determined from direct measurement of camera tilts, although it can also be done photogrammetrically when the photo-base-to-flying-height ratio is large enough (Williams, 1978).

There are five single-camera timed-interval LSP systems being used in Canada for ongoing forestry programs (Table 2), but measurement of tilt, together with accurate determination of flying height by laser altimeter make the system operated by Dendron Resource Surveys Ltd the only 70-mm system that currently meets all requirements for rigorous photogrammetry (Figure 6). Because of the importance of tilt as a source of measurement error, it must either be eliminated or measured and accounted for in order to obtain consistently accurate photo-measurements. Four organizations use Vinten 70-mm cameras; the fifth (Letourneau, 1982) uses a Zeiss RMK 23-cm survey camera. The camera system of the Northern Forestry Centre (NoFC) of the Canadian Forestry Service uses a rigid camera mount with preflight adjustment in an external pod designed for a helicopter (Figure 7) or fixed-wing aircraft (Hall, 1984); the others all use internal mounts, usually in fixed-wing aircraft with in-flight adjustments for tip, tilt, and swing.

Due to the special problems of navigation and flight recording with LSP, increasing attention is being given to the use of microprocessor camera controls and flight recording devices, plus simultaneous broad-coverage tracking imagery at smaller scales using cameras or video. For example, NoFC has been using a menu-driven, microcomputer-based camera control system since 1985.

LSP MEASUREMENT SYSTEMS

Equipment developed for LSP measurements exhibits innovation and variety in terms of capabilities, cost, and speed of operation (Spencer, 1984). The simplest systems for measuring height consist of a stereoscope and parallax bar with encoder for semiautomated recording of measurements. These include a modified Abrams 2x/4x lens stereoscope and bar developed by Canadian International Paper Inc. (CIP) in Quebec and an Alan Gordon Enterprises parallax bar with mirror stereoscope and digitizing tablet adapted by Associated Resource Managers Ltd. in British Columbia.

Operational forest inventories involving hundreds or thousands of large-scale sampling photographs require better, but more expensive, instruments with built-in facilities for parallax measurement, tilt adjustment, and the automated recording and processing of coordinate data. These requirements have led to the development of customized systems based on Helava's analytical plotter concept developed at the National Research Council of Canada (Friedman *et al.*, 1980). Analytical plotters use mathematics and computers to solve the relationships between photographic image coordinates in two dimensions and ground coordinates in three dimensions. They are therefore mechanically simpler and more compact than analog plotters and can readily accommodate the effects of different focal lengths, film formats, lens distortions, and shrinkage. Their major advantages are that they provide straightforward, semiautomated procedures for relative orientation and recording of digital data. They also allow the operator to read, record, and store ground or other coordinates and to recall data at any stage with the computer.

The Zeiss Stereocord (Figure 8) is a portable analytical plotter that was developed from the Stereotope as a direct result of LSP research in the Canadian Forestry Service (Brun, 1972) and is the most popular instrument. It has been driven by a programmable Hewlett-Packard (HP) 9825 calculator with tape cartridge, but alternatives are available in the more modern and powerful microcomputers such as the HP 9826. Manuals prepared by specific users such as the British Columbia Ministry of Forests and Lands (1981) describe its use for forest measurements.

An alternative to the Stereocord is a modified Zeiss Jena Interpretoskop (Figure 9) (Hall, 1984). Its modifications involve installation of *x*, *y*, and *z* encoders with 20-micrometre resolu-

TABLE 2. SINGLE-CAMERA TIMED-INTERVAL LSP SYSTEMS*.

Characteristics	Dendron Resource Surveys Ltd. (Ottawa)	OCRS** (Toronto)	Hautmont Inc. (Quebec)	NoFC*** (Edmonton)	Lakehead University (Thunder Bay)
Aircraft	Piper Aztec, or Bell 206 B Jetranger****	Piper Navajo Chieften	Apache	Bell 206 B Jetranger or Cessna 185	Cessna 172
Groundspeed (km/hr)	125-160,60-120	300-400	120+	60-120+	110-120
Camera	Vinten 70mm	Vinten 70mm	Zeiss RMK 230mm	Vinten 70mm	Vinten 70mm
Lens f mm	300	300	300	281	300
f stop	4.0	4.0	5.6	4.8	4.0
Shutter speed (sec)	1/1000 or 1/1500	1/500 or 1/1000	1/1000	1/1000 or 1/2000	1/1000
Image motion (micrometres)	10-44	variable	33+	8-33	6-7
Mount location	Internal	Internal	Internal	External pod	Internal
Tip/tilt adjustments	yes	yes	yes	no, planned	yes
Drift adjustment	no	yes	yes	no	yes
Tilt recorder	yes	no**	no	no, planned	no
Altimeter	Lidar laser	NRC radar	NRC radar	Honeywell radar	no
Normal flying ht(m)	300-400	variable	300	300	1500
B/H ratio @ 1:1000	1:13-1:15	variable	1:3	1:14-1:18	1:13
@ 1:1200	1:13-1:15	-	-	1:14-1:18	-
Photo-scale*	1:1000-1:1200	variable	1:1000	1:1000	1:5000
Flying height control	Laser	Radar	Radar	Radar	Barometric
Normal overlap (%)	60-65	-	60	65-70	60
Special navigational aids	no	Global nav., Nav-sight and Video	Nav-sight	Black-and-white video	Nav-sight
Tracking camera	Vinten 70mm/f=40mm	Video	Hasselblad 70mm/f=50mm	Vinten 70mm/f=77mm	Vinten 70mm/f=80mm

*Specifications used to obtain photography for tree measurements, except for OCRS which currently is not using LSP for tree measurements.
**Tilt-recording capability discontinued at Ontario Centre for Remote Sensing (OCRS)
***An adapted RC10 mount is also available at Northern Forestry Centre (NoFC) for use in a twin-engine Aztec aircraft.
****Not currently being used, but can be fitted.
Footnote-Flying height can be varied with each of the above systems to obtain different scales for other specific purposes but helicopter systems given advantages of slower ground speeds for larger scales (e.g. 1:500).

tion plus an electronic interface for a HP 9825, 9826, or 9816 computer. Software being developed for the system at NoFC will provide capabilities similar to packages available for the Stereocord.

At Laval University, a modified photo-carriage from a Stereotope is combined with a Baush and Lomb Zoom 95 stereoscope, a Wild Tri-axis locator, and *x, y, z* encoders reading the 0.01 mm to provide yet another strong measurement capability (G. Ladouceur, Pers. Commun., 1984). This system is coupled to an HP 9845 microcomputer and uses software developed in-house for photo orientation and measurement.

At Timberline Ltd. in Vancouver, a Ross SF 3 Stereocomparator (D. Jamieson, Pers. Commun., 1984) (Figure 10) is used. It is an instrument with a digitizing interface designed for close-range photogrammetry using prints or transparencies of up to 100-mm format. The instrument facilitates rapid orientation and measurement of photographs, and is coupled with an IBM-PC using software developed by Timberline.

FORESTRY APPLICATIONS OF LSP

A wide range of applications is possible, but most developmental work and efforts directed to applications have been concerned with estimating timber volumes (Spencer, 1984). Other research applications have included surveys of regeneration (Goba *et al* 1982; Hall, 1984), tree condition, logging residues (Kirby and Hall, 1979; Dendron, 1981), wood piles, forest fuels, range conditions, and stream conditions. In spite of interest and research over many years, the application of LSP as an operational tool is a fairly recent phenomenon. Consequently, the number of truly operational applications is still very small. A recent telephone survey of more than 90 intermediate and end-users (Price Waterhouse Assoc., 1984) identified three major causes for this low usage: the lack of awareness of LSP capabilities, the high costs for equipment and training, and skepticism about its accuracy and the role it would play among potential users.

Order-of-magnitude cost (authors) for a basic fixed-boom, twin-camera system is around C$60,000+, depending on options, whereas a single-camera sequential system with laser altimeter and tilt recorder would cost around $150,000+. Additional specialized aids for navigation and flight-recording can add considerably to these estimates. A suitable analytical stereodigitizer for photo-measurements costs around C$60,000+.

With increasing private-sector capabilities, however, end-users have three basic options for implementing LSP into a particular resource application (Hall *et al.*, 1984), namely

- contract the entire project;
- contract the photoacquisition but perform measurement-interpretation in-house, or through a combination of in-house and contract measurement-interpretation; and
- complete the entire project in-house

Regardless of the organizational arrangements, completing an LSP survey involves six steps, *viz*:

- establishing objectives and project planning;
- survey design;
- photo acquisition;
- field checking and measurements;
- photo measurement-interpretation; and
- compilation, analysis, and presentation of results

Investment into LSP technology becomes more attractive when it is viewed as a multiresource tool with wide-ranging potential

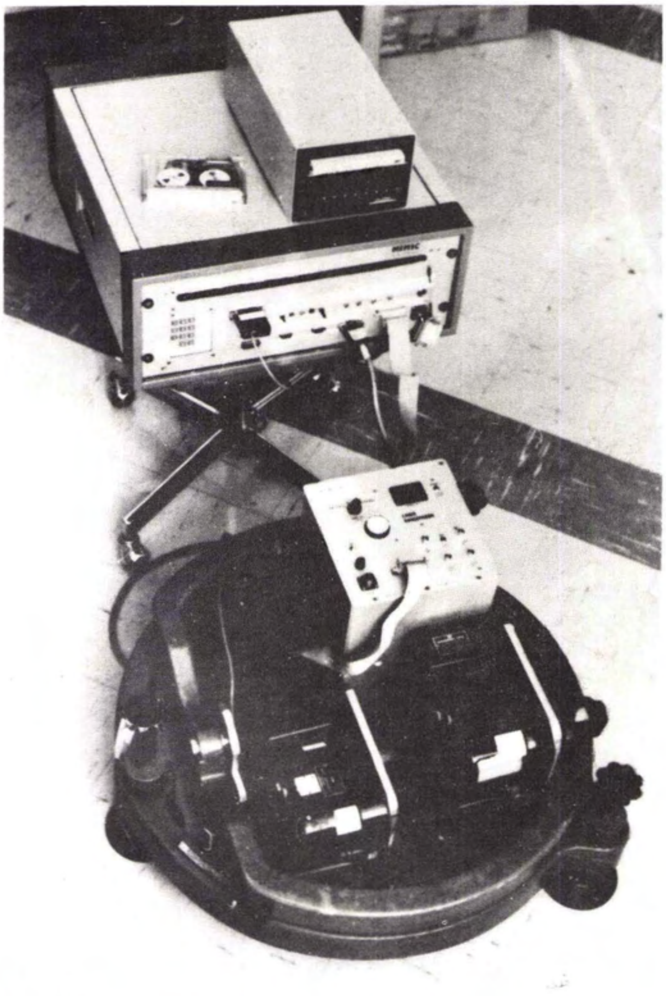

FIG. 6. Components of single-camera sequential system for rigorous photogrammetry, Dendron Resource Surveys Ltd., Ottawa, Ontario.

FIG. 7. Single-camera sequential system and tracking camera mounted in external camera pod, Northern Forestry Centre, Edmonton.

FIG. 8. Zeiss Stereocord photo-measurement system, Hunter and Assoc., Toronto, Ontario.

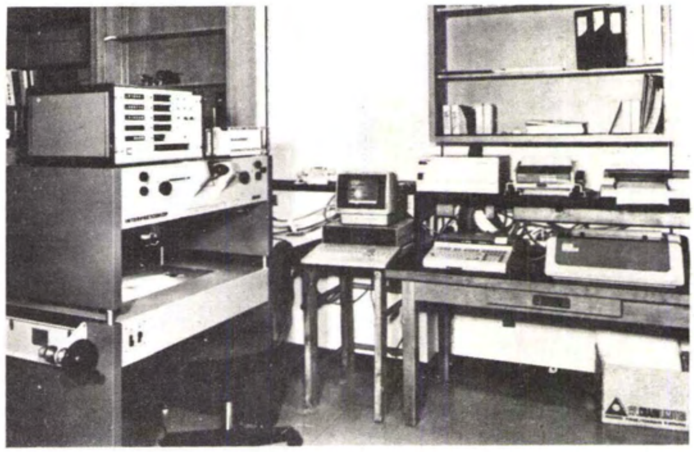

FIG. 9. Modified Zeiss Jena Interpretoskop photo-measurement system, Northern Forestry Centre, Edmonton, Alberta.

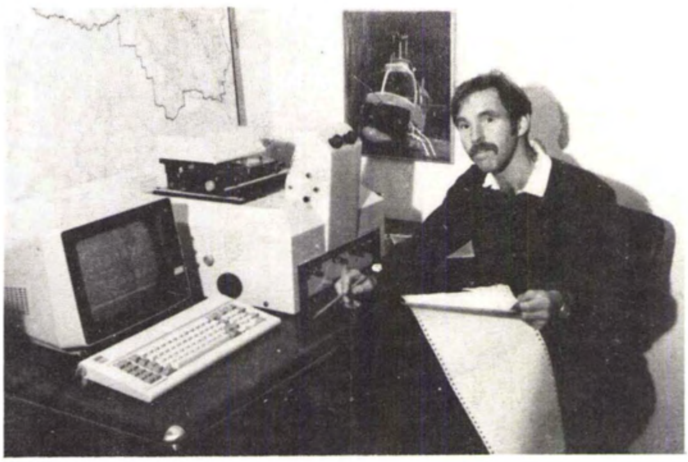

FIG. 10. Ross SF3 Stereo-comparator measurement system, Timberline Ltd., Vancouver, B.C.

applications. Therefore, attempts to rationalize its development for a single use, such as timber inventory, may be difficult and in fact unjustified when LSP can also be used for many other applications. The greatest cost in LSP acquisition is for mobilizing the equipment. Once an aircraft is equipped and deployed, however, the additional unit cost of photos for other applications, or over larger areas, is comparatively small. Economies of scale are, therefore, a major consideration with respect to overall cost-effectiveness. Its major advantages for forest surveys in Canada have been the ease and speed of surveying inaccessible areas, the provision of permanent records of ground conditions at particular times, and provision of the means to conduct major elements of forest surveys in a supervised comfortable office environment. Two applications — timber inventory and forest regeneration survey — are presented in greater detail to illustrate the use of LSP.

Timber Inventory

A major example of LSPapplication for forestry is Alberta's 1982-84 Phase 3 Provincial Inventory, a multistage sampling program piloted with the former Forest Management Institute and undertaken with assistance from the consulting firm Dendron Resource Surveys Ltd (B. Delaney, Pers. Comm., 1984). That inventory involved estimating timber volumes from photo-measurements of tree heights and crown areas on some 12,000 photo plots from 2800 line km of photography at about 1:1200 scale, sampling a total forest area of 155,000 km^2. The cost was estimated to be approximately 50 percent of a ground-only survey and the duration at about 25 percent, being 2.5 years instead of 10 years.

Volume estimates from this inventory were required for strategic planning relating to the allocation of timber rights in Forest Management Areas. Results showed that, with good control of scale and tilt, it was possible to determine mean tree heights on large-scale photo plots as accurately as by conventional ground methods (R. Nesby, Pers. Commun., 1984). Similar results were reported from British Columbia using a fixed-base system (Lyons, 1967).

It is suggested here that LSP techniques also have potential for intensive forest management, including monitoring of permanent sample plots where ground-measurement errors often mask periodic real changes. It is difficult to relocate plots with air photo techniques, but new navigation systems will help improve this method.

Application of LSP for timber inventories involves a combination of skills in photointerpretation and photogrammetry; the former is used to determine tree species, conditions, and locations and the latter to determine dimensions of trees, stands, and areas. Quantities available directly from LSP of suitable quality include area, tree height, crown dimension, stocking, and density. Derived values include stem diameter, and tree and stand volume.

A number of innovations have been developed to facilitate the measurement-interpretation process. These include the vertical projection of crown-centres onto the ground to determine whether trees are "in" or "out" of photo plots; algorithms to measure bole lengths of leaning trees; and the digitizing of several ground points within photo-plots to create a digital terrain model that is used as a reference for parallax measurements of tree tops to determine tree heights. Generally, timber inventories in coniferous forests have been quite successful, whereas greater difficulties are experienced in hardwoods because of their broader, more diffuse crowns that make measurement of heights and crown areas more difficult.

Volume estimates based on photo measurements imply the use of either aerial stand-volume equations or aerial tree-volume equations, the latter requiring photographs at scales large enough to show features of individual trees. Aerial tree-volume equations are mathematical expressions relating volumes with photo measurements, such as tree height and crown area. Two general approaches are used to develop such equations. The first approach uses stem volumes determined initially by accurate dendrometry of standing or felled sample trees. The second, frequently used, approach initially estimates tree diameters at breast height (DBH) from known relationships with photo measurements of crown width or crown area and sometimes stand density, and then uses these diameters to determine volumes from a volume table. The first more direct method is expensive to apply but it excludes volume table errors.

Early comparisons of different estimating models by Aldred and Sayn-Wittgenstein (1972) concluded that the best equations for estimating both DBH and tree volume (V) relied on the same independent variables, namely: height [h], height × (crown area)$^{1/2}$ [$h\ (CA)^{1/2}$], and (crown area)$^{1/2}$ [$(CA)^{1/2}$].

The form of the model is

$$\text{DBH(or } V) = a + bh + ch\,(CA)^{1/2} + d\,(CA)^{1/2}$$

where a, b, c, and d are constants derived empirically using least-squares regression.

Subsequent work based on wider analyses, including new types of equations, confirmed the value of h and CA, but the best equation had a different form (Table 3) (A.H. Aldred, Pers. Commun., 1984). A different model obtained in British Columbia (Bradatsch, 1980) uses natural logarithms in conjunction with tree height and crown width as the photo-measured variables (Table 3).

These models are, however, only two of a larger number of possibilities. Operationally, there is a cost incentive to exclude crown measurements unless they make useful contributions towards reducing residual errors. Consequently, a model developed for operational trials in Alberta was based on height alone (Aldred and Lowe, 1978), which was also the case for models developed in Quebec and the Yukon Territory (Table 3). Such differences in selection of variables and equation forms reflect regional differences in species characteristics and requirements for data collection and reporting. Tree height is the most important independent variable, and therefore measurement of height on aerial photographs has been the subject of many investigations (Allison, 1956; Collins, 1957; Pope, 1957; Johnson, 1958; Kippen and Sayn-Wittgenstein, 1964; Aldred, 1964; Aldred and Kippen, 1967; Lyons, 1961, 1964, 1966; Schut and Van Wijk, 1965; Gerrard 1969).

Forest Regeneration Survey

LSP is being used increasingly in conifer regeneration stocking surveys, with spring or fall photography usually giving the best discrimination between conifers and shrubs. Hardwood regeneration surveys, however, have generally not been as successful because leafless trees become transparent during spring or fall and summer photographs give stocking overestimates.

For this application 1:10,000 or larger-scale photos are usually used initially to stratify and map homogenous stocked and non-stocked areas as the basis for designing LSP flight lines and associated field work. LSP is then flown at scales up to 1:500, followed by two-stage and single-stage sampling strategies for stocking estimations. Clusters of photo plots are often used with separate stocking percentages being obtained for each selected stereopair. A subsample of photo plots is then double sampled in the field to obtain a regression to relate photo-stocking estimates with ground estimates. Hall (1984) reported a 5.6 percent difference between photo and ground stocking estimates when 1:500 scale photos and grid clusters of 25 sub-plots were used. Estimates varied, however, because of the difficulty of discriminating individuals within conifer clumps. Sampling intensity was usually higher with the photo method because of a greater number of plots per location (cluster), although usually there were fewer plot locations.

Equipment used in the measurement-interpretation process ranges from simple overlay grids and a pocket stereoscope to the more sophisticated computer-based stereo-digitizers (Figures 8, 9, and 10). In both cases the first steps are to determine the

TABLE 3. ESTIMATING DIAMETER AND VOLUME FROM LSP MEASUREMENTS

Organization	Species	Estimating Model	Source	Comment
British Columbia Ministry of Forests and Lands	Various including douglas fir, hemlock, red cedar, balsam fir.	$L_nV(\text{or}D) = b_0 + b_1(L_nh) + b_2(L_nCW)$	Bradatsch, 1980 Pers. Commun., 1984	Data from 6470 trees subdivided into species and inventory zones. Model is very poor for mature stands; best results with immature regrowth.
Timerline Ltd.				As above
Alberta Forest Service	White spruce, black spruce, balsam fir, larch, lodgepole pine, trembling aspen, balsam poplar, white birch.	$V = b_1h + b_2h^2 + b_3(e^{h/100} - 1)$ $D = b_1h + b_2h^2 + b_3[\sin h(h)]$	Aldred & Lowe, 1978	Data from 12 plots (number of trees not specified), supplemented with ground inventory data.
Alberta Forest Service	Three groups; spruce, pine, hardwood.	$V(\text{or } D) = b_1h^{b2}(CA)^{b3}$	Morgan, Pers. Commun., 1984	Developed from stem analysis of 350 trees covering species and size-class range in seven sampling regions then applied to approx. 12,000 photo plot sample of 155,000 km² for provincial Phase 3 inventory.
Quebec Forest Service	Black spruce, white spruce, balsam fir.	$D = f(h)$ - form unavailable	Letourneau, 1982 & Pers., Commun., 1984	Diameters from LSP; volumes from general volume table.
Laval University	as above	as above	Ladouceur, Pers., Commun., 1984	as above
CIP (Inc)	Black spruce, balsam fir, jack pine.	$D = b_0 + b_1h + b_2h^2$	Marcoux and Dumoulin, Pers., Commun., 1984	Diameters from LSP; volumes from general volume table. Separate regressions for different species each based on approx. 2000 trees.
Ministry of Natural Resources	Jack pine, black spruce, white spruce, poplar.	$D = b_0 + b_1h(CA)^{1/2}$	Mervart 1983	"Practical reasons" restricted photo study to diameter estimators; volumes from standard volume table. Compared regressions for different species and stands based on 2818 trees from 68 plots.
Forest Management Institute	White spruce, white pine, balsam fir, black spruce, hardwoods.	$V(\text{or } D = b_0 + b_1h + b_2h(CA)^{1/2} + b_3(CA)^{1/2}$	Aldred and Sayn-Wittgenstein, 1972	Six data sets of 383 trees.
Dendron Resource Surveys Ltd.	Spruce, jack pine, hardwoods.	$V(\text{or } D) = b_0h^{b1}(CA)^{b2}$	Aldred, Pers. Commun., 1984	Model is generally applicable, but relationship is stronger with younger stands. Source of data unavailable.
Yukon Lands and Forest Service	Spruce, lodgepole pine	$V(\text{or } D) = b_0h^{b1}$ $V(\text{or } D) = b_0 + b_1h + b_2h^2$	Bowlby, Pers. Commun., 1984	Data from approx. 100 felled trees.

V = volume, D = diameter at breast height, h = tree height, CW = crown width, CA = crown area, $b0,b1,b2,b3$ = constants, L_n = natural logarithm

scale of each stereopair and the most suitable overlay grid to represent a cluster of plots. Seedling detection varies with their height class, being greater than 75 percent for 30 to 60 cm seedlings, and greater than 95 percent for seedlings taller than 60 cm for experienced interpreters (Hall 1984).

Photo estimates of stocking are generally conservative compared to ground measures, but the regression developed from the double sample is used to adjust the photo figures. The costs of surveys using LSP for research purposes have ranged from C$15 to C$25 per hectare depending on the size of the survey area, the level of detail, and the precision required. It is expected costs would be reduced considerably in operational programs.

CONCLUSIONS

Application of large-scale photo methods for forest mensuration requires substantial investments in equipment and personnel training, with acquisition of necessary skills encompassing forest photointerpretation and mensuration and a good understanding of statistics, photography, and photogrammetry (Aldred and Lowe, 1978). Practice, however, as well as training and guidance is essential for maintenance of high-level skills. Volume and frequency of work must therefore be sufficient to provide for maintenance as well as development of skills.

In practical terms, the camera system to implement is a function of user applications and system availability. No system is perfect for all applications, and each has its own capabilities and limitations (Hall *et al.*, 1984).

Development of technology to apply LSP as an operational tool for forest sampling in Canada has been recent (around 1975 to 1980), in spite of interest and research extending over many years. Consequently, the number of truly operational applications is small, but the situation is complicated by lack of awareness of LSP capabilities, high costs for equipment and training (Hall *et al.*, 1984), and skepticism about its accuracy and roles.

With increasing demands for information coupled with increasing costs for ground surveys, it is suggested that LSP could fulfill a more important role in the future by reducing requirements for ground measurements and providing opportunities for new, quantitative and qualitative measures. LSP is, therefore, a potentially powerful tool that warrants more detailed consideration for forest planning and management.

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