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This paper includes a literature review of the methodologies invoked to surmount difficulties inherent with aerial photograph mensuration. The synopsis of early achievements is followed by a more intensive examination of experimental studies of the last decade, particularly the work on controlled scale photography.

This report on the pursuit of unbiased photo volume estimates culminates with a discussion of recent trials using the techniques of analytical stereoscopy. A Carto AP190 analytical stereoplotter linked to an IBM AT personal computer was used for precision camera orientation reconstruction at the moment of exposure, thereby removing many sources of bias. A trial photo cruise of a mature stand of Douglas-fir in Oregon's Coast Range indicates that it is possible, when using these mathematical solutions of parallax, to determine gross volumes to within five percent of ground-verified estimations.

OVERCOMING THE OBSTACLES OF EFFECTIVE PHOTOGRAMMETRIC MENSURATION

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Finally let me acknowledge a source of inspiration. How extraordinary it is to witness a true love of learning. Captured in the soul of a child, comes a wisdom far beyond her sense of being. This thesis is lovingly dedicated to this spirit, with the wish it remains an unbridled quest throughout her life. To Krimson McKnight, God's speed.

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OVERCOMING THE OBSTACLES
TO EFFECTIVE PHOTOGRAMMETRIC MENSURATION

INTRODUCTION

Advances in photogrammetric techniques applied to forestry have been rapid in recent years. In particular the advent of low-cost analytical stereoscopy has brought these skills to a new realm of accuracy and precision into the land manager's office. The conceptual fundamentals of this science are presented here with a report on applications of the Carto AP190 analytical stereoplotter in research conducted at Oregon State University.

This paper is also a literature review. There are many problems associated with taking measurements from photographs, and historically, many attempts to overcome them. For the sake of focus, emphasis is placed on forestry applications of photo mensuration . Innovative methods and techniques are appraised according to their accuracy or contribution to efficiency.

Recent work has concentrated in two areas: overcoming obstacles through double sampling which corrects for bias by correlating photo features with those measured in the field, or by exercising controlled-scale procedures so that unbiased measurement can be taken directly off the photos. As to the former, stand stratification by aerial photos has been combined with double sampling and fixed, variable, and proportional probability plot theory. Controlled-scale photography can be accomplished by either establishing a fixed airbase, or through the acquisition of precise altitude and camera tilt information. A brief survey of the accomplishments obtained with laser altimeters is included.

Analytical stereoplotters represent the state of the art in measurement accuracy, realizing some long-set goals of photogrammetrists. There has been a long held adage recently re-stated by Avery (1985) that photo interpretation is meant "to compliment, improve or reduce field work rather than to replace it." Now, with newly introduced instruments such as Carto's AP190, it is possible to make more accurate measurements with photos than all but the most exacting field procedures. This type of equipment will play a key role in the acquisition and interpretation of data in forestry's future.

In a policy statement (Tuchmann, 1989), the Society of American Foresters (SAF) said, "the quality of public policies and programs depends upon realistically understanding the capabilities of different lands and forest types. Advances in the inventory of forest resources and surveying their capabilities is necessary to undertake responsible forest management. SAF supports policy that promotes resource inventory and the means to interpret survey information."

Multiple resource inventory databases are combined with computerized cartography in geographic information systems (GIS). It is beyond the scope of this paper to evaluate the capacities of GIS, but these powerful programs are greatly enhanced by the digital data yielded by modern analytical plotters. This link to GIS is considered of primary importance. But modern plotters can stand alone, allowing the routine completion of tasks heretofore rarely performed. In forest engineering there are numerous new uses involving road planning, profile mapping, and skyline load analysis. Forest science projects concerning snag distributions, wildlife habitat indexing, and temporal succession analysis have also been assisted with these techniques. Other applications, perhaps in ecological modeling of forest stand connectivity, pathological assessment, or geologic references to soil movement and mass wasting seem apparent and obvious to the initiated.

This paper also reviews a photo cruise procedure developed for the AP190. The discussion centers about the creation of algorithms and procedures which enable the digital data to be interpreted. Results of early trials conducted by the F520 class are presented and analyzed. There is also a section in which the instrument itself is described, and one which gives an overview of the analytical solution.

Before a specific problem statement is made concerning photo mensuration, it is appropriate in this introduction to review the two types of aerial photo volume tables (PVT's) in use. They represent two distinctive paths to the mensurationist's bottom line of determining volumes, and from there, computing value. It's essential to realize that either method depends on adequately designing the sampling procedure.

Tree photo volume tables (TPVT's) provide calculated volumes of individual trees from equations using the predictor variables of total height, visible crown diameter, and sometimes percent crown closure. This approach also yields stand and stock tables, showing by diameter class, the numbers of trees per acre and the volume per acre. These statistics are only obtainable from photographs by carrying out these procedures. The biggest dilemmas of the individual tree approach is the usual requirement of large-scale photography (1:4000 or larger), and knowledge of precise scale control.

Stand photo volume tables (SPVT's) are much more frequently used because of their comparative ease of use. They only provide volume on a per acre basis but simply require an estimate of mean stand height and percent crown closure. Stand PVT's are better adapted to 1:12,000 resource photography (Paine, 1983). They do not offer the information breakdown by diameter class available from tree PVT's.

With this foundation, the problems surrounding photo mensuration can be thoroughly discussed.

PROBLEM STATEMENT

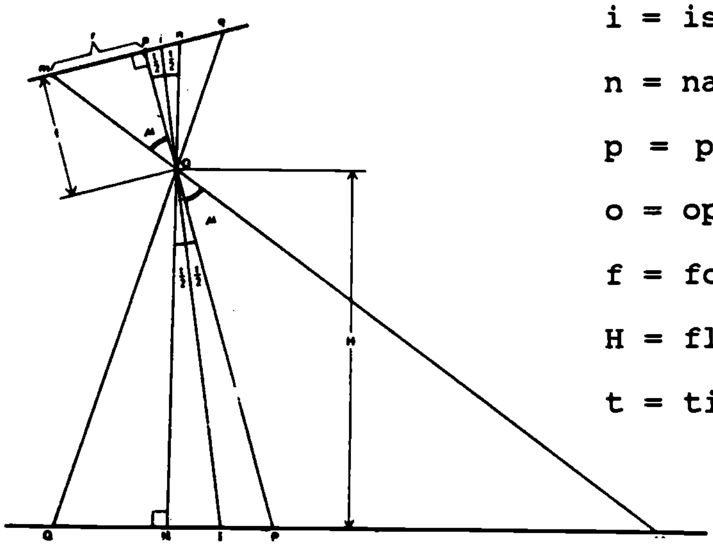
Despite the large amount of information that can be gained from photo mensuration, these money saving techniques have not seen widespread acceptance by the forestry community. A portion of the problem is due to ignorance and inexperience in this admittedly esoteric profession. We can assume however, the lack of comprehensive training will be quickly overcome once the incentives are clearly understood (Paine, 1983).

The other difficulties can be conveniently grouped into three subcategories: bias in estimates, interpretive errors, and data insufficiency. These will each be examined. But it is also important to acknowledge what won't be considered in this paper. The principal exclusion is the effect of distortion. Distortion arises from defects, such as lens aberration, image motion or film shrinkage, resulting in a perspective change and a shift of the image. The study and removal of distortion is a science of its own, and can not be adequately addressed in a brief manner. Readers interested in the analytical detection of geometric asymmetry are referred to Hakkarainen and Rosenburch (1982). These authors demonstrated how aerial camera lenses are among the best optical products available today, with errors of just a few microns over the entire format. Let it suffice, for our purposes, to consider the problems associated with distortion as largely solved.

Bias in Estimates

Bias refers to systematic errors usually caused by faulty techniques or, less commonly, by instrument error. In this section there will be a specific examination of bias arising from (1) the failure to consider camera tilt and (2) the affects of imprecise knowledge of scale. Subsequent sections will deal with other sources of bias including tree-top displacement and photo interpreter error.

Camera tilt Tilt displacement occurs whenever the camera station is not perfectly horizontal. The principal point, corresponding to the ground point depicted at the center of the focal plane, and the nadir, the point directly below the camera station will no longer coincide as they do on vertical photographs.



i = isocenter

n = nadir

p = principal point

o = optical center

f = focal length

H = flying height

t = tilt angle

Fig 1. Geometric analysis of a tilted photograph
(adapted from: Lo, 1976)

The point midway between the principal point and the nadir is the isocenter, and it is from here that tilt displacement radiates. Tilt causes images to appear radially displaced toward the isocenter on the upper half of the photo, and radially away on the bottom half. These image displacements can be explained in terms of changes in photo scale.

By this diagram, when the angle of tilt, t, is a known value, then:

the scale at the isocenter is $$\frac{io}{oI} = \frac{f}{H}$$

at the principal point $$\frac{po}{oP} = \frac{f * \cos(t)}{H}$$

and at the nadir $$\frac{no}{oN} = \frac{f}{H * \cos(t)}$$

Since tilt affects photo scale it unquestionably biases crown diameter (CD) measurements, but less obviously, it is also a source of bias in total height (TH) measurement as well. Tilt along the flight line biases the differential parallax measurement and is especially serious when the amount and/or direction of tilt is different on each photo of the stereoscopic pair. Also, it is more serious for long focal length lenses than short ones (Pope, 1957).

Precise scale information Bias can also result from not knowing the precise scale at the plot location, the severity depending on which type of photo volume table is being used.

depending on which type of photo volume table is being used. Because stand PVT's utilize percent crown closure (%CC), they accurately provide volume estimates on a per unit basis regardless of plot size. Errors in determining photo scale do not create a bias due to incorrect plot size. However, there is a bias in volumes because of incorrect determinations of the mean stand height and crown diameter.

When tree PVT's are used there is a bias involved both with plot size and tree size, but they are somewhat compensating. In an example adapted from Paine (1983), assume one-acre plots are to be measured on 1:1100, large scale photographs. It is later determined that actually, the correct scale at plot center is 1:1000. The resultant 10 percent negative bias in plot diameter represents a -17.3 percent bias in volume, just due to incorrect plot size. Individual tree measurements, CD and TH, are also assumed to be larger than they actually are. Depending on which TPVT is being used, and how it was developed, this may more than compensate the bias introduced from plot size error. In final judgment, it is reported that SPVT's are more subject to bias due to photo scale error than TPVT's.

In a closely related matter, topographic displacement also can lead to bias if its effects are not taken into account. Scale, of course, varies with the distance between the terrain and the focal plane. Even when the average elevation of a sloped area is the same as that of the nadir, errors in area calculations can exceed 25 percent (Paine, 1981).

Interpretive Errors and Data Insufficiency

Another source of bias emanates from the interpreter's inability to accurately quantify the measured components of the photo cruise. Most of these problems are due to either obstruction of the object due to shadow or overhanging vegetation, or problems with poor resolution on the photo itself.

Height measurements are difficult in dense stands where the ground level can not be seen, and must be estimated. At the other end of the tree, the total top may not resolve if the crown is long and narrowly tapered.

Similarly, the CD measurement may be challenging to accurately determine. In dense stands with a closed canopy, it is not always easy to isolate the boundaries of individual crowns. Since they are typically measured with a dot scale, there is also the problem of matching uncircular crowns to their proper size class. Additionally, when the tree is far from the principal point, the problem associated with not viewing the crown vertically must also be accounted for.

Smaller trees, not as large as the co-dominants in the canopy, are often missed in tree counts simply because they can't be seen. Tree counts may also be incorrect from treetop displacement. On photographs, all objects including trees, appear to lean away from the photo's center. Depending on which side of the plot is being examined, and its relation to the nadir, trees may be wrongly identified as either in or out of the plot. As discussed before, differences in scale between ground level and canopy height also contribute to this bias, increasing as flying height decreases (i.e. scale increases).

Other problems, including species identification and wide-spread pathogenic assessment have been successfully overcome with the proficient combination of scale and film format, such as large-scale color infrared diapositives (Murtha, 1983). For the most part however, it is not possible to determine defect or log grading on individual trees, and there is little information for stand age, growth rate, or site index.

It is the purpose of this paper to demonstrate how modern applications of analytical photogrammetry overcomes many of these problems. What follows is a brief accounting of the interesting history leading to the development of these techniques. This literature review will outline early advances in photogrammetry, discuss evolving photomensuration technique and its accuracy, and traces the technology progress leading to modern stereoplotters.

EARLY CHRONOLOGY

Aerial photography was first used in a forestry application in 1887 by a young German forester (Spurr, 1954). Given the arduous task of creating a stand map, he was first to consider using photography in connection with a balloon capable of lifting him high enough to view the entire area with his camera. He regarded the results as "magnificent." The pictures were clear and sharp, and interpretation of the photograph's tones and textures permitted stand type classification. But a most important failing appeared; the scale was indeterminable, not to mention the fact that it varied at differing points on the photo. Until the photo geometry was considered, these images could not be used for mapping. Actually, some ten years earlier another German, named Meydenbauer, published a paper on the subject, and coined the term photogrammetry (Ghoush 1988).

Despite the bright start, real interest wasn't generated in aerial surveying until after WW I. The first major use of the airplane in forest stand mapping occurred in 1919, by the Canadian forester, Ellwood Wilson (1920). By 1924, the forestry board of the Ontario government had mapped 22 million acres of forest land, principally using oblique photographs. It was not until 1929 that improvements in both cameras and aircraft permitted true vertical photography. Then another Canadian, H. E. Seely, began his forest surveys in which areas were measured by planimeter, tree heights were estimated from shadows, and stand volumes were estimated using crude aerial stand volume tables.

Meanwhile in Germany, Professor R. Hugershoff directed students at the forestry research institute at Tharandt to test and evaluate principles of photographic measurements for timber volume estimates. These tests established the effectiveness of parallax measurements of tree height, direct photo measurement of crown diameter, and the feasibility of developing volume tables based on these parameters. Despite good results, the photo scales were so large, and the photographic equipment was so expensive, that little practical application was found. The findings did however, lay the basis for many present-day techniques and practices.

Interest in photographic forest surveys got off to a slow start in the United States. It wasn't until the thirties that results of careful tests of species identification (Ryker, 1933), and timber cruising utility (Foster, 1934) were assessed here. Robert Burwell (1942) wrote on the importance of aerial photos in fire detection and suppression work. He also states, when woodland owners "realize that the forester has pictures of their property close at hand, they tend to be more restrained in their actions."

In 1940, a notably powerful new use for aerial photos was found by the consulting firm of Mason and Bruce, while working in the redwood forests of northern California. They were apparently the first to stratify stand classes with aerial photos (Spurr, 1945). In a paper by Trobitz (1950) concerning old-growth Douglas-fir near Shelton, Washington, the significance of photo stratification for the optimization of the cruise sampling scheme was again asserted. He reported that, by reducing within stand variation, stratification can lower sampling errors by as much as 40 percent compared to using the same number of plots in an unstratified design. This important concept provides the basis for varying sampling density according to the variation within the strata and the accuracy desired. Other parameters such as allocated budget, strata value, and fluctuating costs per plot for different stand types can be substituted or combined with the precision standard.

At the close of WW II, foresters who had served in the military using aerial photography to gather intelligence, were ready to put their experience to work in the woods. At the Harvard Forest, the first aerial photo volume tables for use in this country were created by Stephen Spurr. He also developed a series of short courses on photo mensuration, and by 1948 had written the first textbook on aerial photographs in forestry. Another center of interest was in California. Forest Service personnel, including the colleagues of Karl Moessner (1951), authored early interpretive guides for timber cruising. In Oregon, Robert Pope (1950) was developing both the individual tree and mean stand photo volume tables for Douglas-fir. A method of adapting standard local volume tables for aerial photo use was later presented by Dilworth (1956).

Naturally, a significant amount of work has been conducted since the mid-fifties. Recent studies, of the last decade or so, have been concentrated in large photo scale projects; these are reported in a separate section. But first, let's examine the accuracy of fundamental operations.

ACCURACY OF BASIC PHOTO-MENSURATION TECHNIQUES

Measurement error, an accepted fact in forest photogrammetry, is dependent on several factors. Besides the quality of photography and skill of the interpreter, it is also dependent on the quality of equipment and techniques employed to complete the tasks. The following review examines early photo-mensuration technique and quantifies the measurement errors associated with these practices. It is discussed in the context of the two measurement types. Direct measurements from the photograph only have errors associated with sufficient sampling and accuracy. Indirect measures are obtained through regression estimation and include the additional variation resulting from imperfect correlations (Paine 1981).

Errors in total height and crown measurement are of particular importance because most aerial photo volume tables use these two variables as predictors. Emphasizing the importance of this relationship with volume, a separate section discusses the creation of volume tables, and the verification of their accuracy.

Direct Measurements

Heights This is the most critical piece of information needed to determine the volume in a tract of timber, but it's often one of the most difficult to obtain. Virtually all modern methods of determining heights are based on measuring parallax difference as first espoused by Dr. Hugershoff. Two popular early methods for measuring parallax were the Harvard wedge and the Abram's height finder, a type of parallax bar. These techniques were compared in a report by Worley and Landis (1954). They found that interpreters using the "floating dot principal" of the parallax bar underestimated the actual heights of large and medium conifers. Those interpreters with the parallax wedge also underestimated heights, but to a lesser extent. It was judged that the sloping lines formed by the wedge gave a better reference for judging the tree top than the single image of the fused dots. The report concluded with correction factors for these systematic errors, escalating the measured heights of tall trees by as much as 25 percent when the height finder was used. Sammi (1953) also found that errors in parallax measurement increased with increasing total height. He graphed the standard deviations of ten repeated measurements, over the mean parallax difference on 48 different trees on both positive transparencies and semi-matte prints (960 measurements). While he did conclude that the diapositives were superior to the prints for this purpose, he also found that on both formats, standard deviations increased at about a ten percent rate as differential parallax increased. He admitted that this seemed to him counter-intuitive because tall, mature trees acquire flattened tops which should be able to be measured with greater consistency than younger trees with spired crowns. A plausible explanation was offered by Paine (1965) suggesting that the effect was due to unrectified tilt causing parallax error in direct proportion to tree height.

There have been many studies which have sought ways to reduce the error associated with parallax determination. Increased resolution (Sammi, 1953), differing photo scales (Pope, 1957) and magnification (Bernstein, 1958). With the exception of Sammi who found that the diapositives resulted in a two to four percent advantage over the prints, these studies did not improve methodologies. The limiting factor seems to be the skill of the interpreter. Even the best eyes are not able to detect differences smaller than about 0.001 of an inch. Consequently, equipment or materials that are of higher quality than this are not fundamentally more precise.

Other causes of incorrect height observations are due to errors in photo scale determination, tip and tilt, or false parallax. Correct photo scale at the point of interest, is a fundamental requirement to any measurement. But it's important to recognize the impediment of obtaining precise scale information without reconstructing the geometry of exposure, and using a device such as a stereoplotter. Any tip along the line of flight will result in an erroneous measure of the parallax base. This dilemma of uncorrected tip and tilt is of more particular concern with large-scale work obtained through long focal length lens. While a tilt of three degrees causes errors as much as nine percent with a six inch lens, the error increases to nearly 35 percent with a 24 inch lens (Pope, 1957).

False parallax is created by object movement between the exposures. Wind, parallel to the flight line may create this effect by blowing tree tops. Little can be done about this, or the problem of obscured tree bases. The suggestion of moving short distances along a perceived contour to an open measuring point has little relevancy in a mature stand of coastal Douglas-fir. Better penetration may be possible at the same photo scale by increasing flying height and focal length simultaneously. While the crowns of most merchantable trees will not be obscured, the tops of narrowly tapering trees may not resolve at smaller scales. Errors of this type are systematic and therefore correctable.

Visible crown diameters In the construction of aerial PVT's many authors have used crown diameter (CD) as one of the independent variables. The actual correlation and its associated error will be considered in a later section; but here we look specifically at the CD measurement. It, along with height, is the only other parameter of the regression which can be measured directly from the photo.

Crown diameters taken from aerial photographs are not comparable with measurements taken from the ground. Only that portion of the crown which is visible from above, can be measured on the photograph, thus leading some authors (Dilworth 1956, Paine 1981 and others) to use the term "visible crown diameter" or "VCD". Because of intermingling branches among adjacent trees and problems with resolving narrow limbs, the photo-measured CD is often smaller than that determined on the ground. Despite this, the photo measured CD is likely to be more highly correlated to volume because it provides an evaluation of functional growing space, and it exhibits a smaller standard deviation than the ground measurement (Paine, 1981).

Most commonly, the measurement is performed with some form of optically variable micrometer, either a diverging line or dot-type wedge. Since the dot obscures the crown under measurement, it's reasoned that the diverging line wedge is superior. To help reduce errors due to irregularly shaped crowns, Dilworth (1956) used the mean of minimum and maximum crown diameters. He reviewed many works which collectively conclude that at a 1:20000 scale, CD's can be accurately grouped into 5 foot size classes, while at 1:12000 this can be improved to 2 or 3 foot classes.

Degree of stocking The percent of stocking is of primary importance in calculating stand volumes. It is not always used with tree PVT's, because of the strong correlation between CD and the tree's diameter at breast height, DBH. But with stand PVT's it must be determined by either a tree count per acre or by estimating the percent crown cover.

Tree counts can be made with considerable accuracy in open stands. But the numbers of trees alone, without regard to size, may have little or no correlation with true stand density. An index, which accounts for average DBH would make the statistic more useful. As reported in Paine (1981), his experiments have yielded crown counts as much as 19.3 percent low, but because these trees were much smaller than the average, they accounted for only 2.3 percent of the total volume.

Estimating percent crown closure (%CC) is not limited by the necessity of open grown stands, and is thus much better suited to the conditions common on the westside of the Cascades. Although estimating crown closure is far more easily done on photos than on the ground, the process is not as straightforward as it might seem. There are three common approaches to the problem: empirical ratio determination by dot-grid or digitizer (Null, 1969), visual guides such as crown-density stereograms (Moessner, 1949), or by ocular estimation techniques. While the empirical approach provides objective results, the procedures can be tedious. Stereograms have proved useful as training aides when developed for the specific vegetation type being analyzed, but prove unwieldy for everyday use (Wintenberger and Larson, 1988).

Ocular estimation of crown cover is probably the most common method, and has most likely occurred since foresters first began using aerial photographs. In Pope (1961), he formalized a method called "tree-cramming", standardizing the process. One source of bias which remains, even when using this procedure, is due to shadow. The tree's shadow may cover a much larger area than the actual crown and contrast much better with the background than the tree itself. Hence, correct classification of two-storied stands, with shade tolerant species underneath, may be impossible (Wintenberger and Larson, 1988).

Areas In places were timber tracts are unsurveyed, photo interpretation is often relied upon for acreage determination. The various methods historically invoked to accomplish this include the weight apportionment method, dot count, and planimeter.

Weight apportionment involves cutting the photograph. Each stand or stratum in the tract is individually weighed and compared to the sum as a ratio of the total acreage. The obvious disadvantage to this method, regardless of its inherent inprecision, is that total acreage must be known beforehand.

The dot count method is perhaps the most widely used process to estimate areas (Paine, 1981). By superimposing a transparent grid, a total number of dots is tallied for each type class. Each count can be compared to the total in a way similar to the apportionment method, or the area can be calculated directly, given a knowledge of scale. The shortcoming here, is the tiresome, mind-numbing task of counting all the dots.

The planimeter is an instrument specially designed for measuring areas, and simply involves tracing the stylus around the boundaries of the tract. Dials on the planimeter allow the direct reading of area in square inches or centimeters of the photo, which then must be converted to ground acreage by an appropiate unit conversion.

Earlier, in the problem statement, the serious consequence of not accounting for topographic displacement was discussed. Radial-line triangulation was one early way of eliminating this problem, and allowed the portrayal of true planimetric positions of objects. This process is predicated on the theory of radial displacement; though the exact location of an object may not be readily determined from a vertical photo, it is certain that it lies somewhere on a line which is projected from the principal point through and beyond the object's apparent location. By tying together a network of photos, control points are defined by the intersection of these radial lines. The operations of resection and intersection, which identify true locations, are described as cumbersome and tedious, but with the aide of hand template overlays, transfer to a map base can be inexpensively accomplished. Radial-line triangulation does not remove the affects of tilt, errors in the location of the principal point, or problems with differential film shrinkage (Paine, 1981).

Stereoplotters are able to reconstruct the geometry of the focal plane at the moment of exposure, and therefore completely remove the effects of these problems. Further, they are capable of precise stereoscopy and orthographic projection. Early stereoplotters were handicapped by their tremendous cost and the requirement of highly trained specialists. Besides that, they were slow. This combination of attributes confined their use in civilian practice to general cartography or high priority engineering projects. A detailed examination of the theory and application of modern stereoplotters is the subject of an entire section later in this paper.

Indirect Measurements

Indirect measurements are determined by correlating observable features to those which can not be directly measured. Measurements of this type include DBH, site index, growth and age, and volumes.

Paine (1965) reports that significant correlations between crown diameter and DBH have been recognized as far back as 1834, with the first statistical relationship developed in 1928. Many studies in the 40's and 50's indicated that the addition of total height improved the correlation, and that non-linear techniques may better document conditions at the extreme ends of the model.

Site index, a benchmark of ecological quality, is based on the height of the dominant stand at an arbitrary age, usually 100 years. In ponderosa pine country the correlation relating TH, CD, and %CC to site index was, $r = 0.886$ (Paine, 1965). The literature review did not reveal established relationships for Douglas-fir cover types. Heuristic approaches have used physiographic features to model site, but the correlation explained less than a third of the variation (Choate, 1961).

Limited material exists on the relationships between growth and age to measurable features on photos. No studies were found from the western U.S. While this is easily understood for individual photo sorties, it is surprising that a sequence of photos over time haven't been evaluated, with the relationship established temporally.

Construction of Aerial Photo Volume Tables

Another example of indirect measurement are the volumes arrived through the use of PVT's. One procedure, as described by Pope (1962), consists of defining significant variables and using multiple regression techniques to define interactions and the variables' form. Testing for homogeneity among residuals is stressed, with a report of one model showing variance in taller stands over 150 times that of the variance in shorter stands.

Pope's prelimenary study included the correlation of volume to eight independent variables. For predicting board foot volumes he found the best single variable to be the interactive term, TH^2*CD, having a squared correlation coefficient (R^2) of 80.8 percent. The best combination of all eight variables had a slightly better R^2 value, 84.7 percent. But just two variables, TH and %CC, explained 84.3 percent of the regressive relationship, and were selected in the final form of the equation. Paine (1981) obtained a higher R^2 value, 86.9 percent, with the addition of CD as the third variable.

Volumes have also been determined without the knowledge of height. A single-variable tarif access system, using CD, was devised by Hitchcock (1974), for the ponderosa pine stands of northern Arizona. His squared correlation coefficient (R^2) was a remarkable 98.5 percent. Later in this paper, a proposal to apply the tarif system to Douglas-fir photo cruises (McCadden, 1985) will be thoroughly examined.

EARLY AERIAL SURVEYING AND CARTOGRAPHY

The basics of aerial surveying is the translation of the perspective image recorded on the photograph to a planimetric or topographic map. Much of the pioneering research in this field was conducted by the German forest photogrammetrist, Dr. Hugershoff. He developed a precision mapping device, the Aerocartograph, in the early 1920s. The theory involved is still used, in part, as the basis for more modern optical projection plotters. One example, the Zeiss stereoplanigraph, is idealized in the schematic below. This was one of the most versatile instruments of its type ever produced, and was available from the early 1930s to the mid-70s, with only four design modifications.

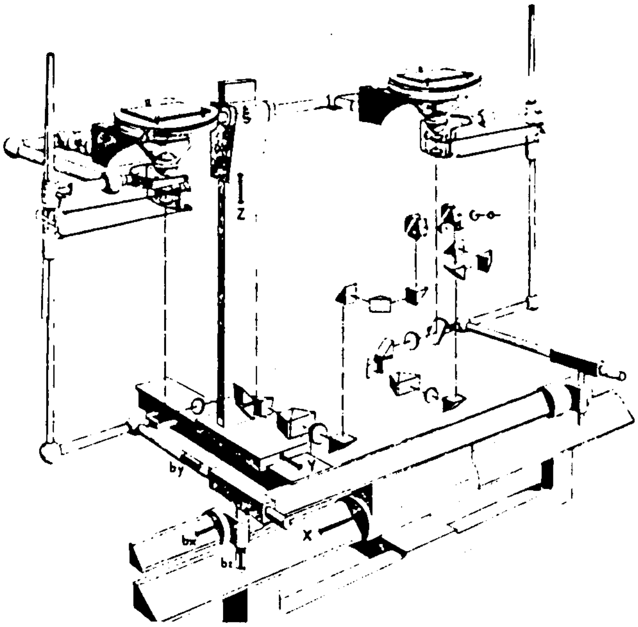


Fig. 2 Zeiss Stereoplanigraph Universal Instrument

(Reproduced from: Burnside, 1985)

Here optical projectors accept standard size diapositives and illuminate them with low voltage lamps. At any particular pointing, the light is brought into focus by telescoping optics, a series of right angle lenses and an adjustable mirror. A small black dot in the center of each mirror forms the floating mark.

At the present time, instruments using mechanical projection are by far the most popular. The solution using space rods was introduced in the 1950s, and has been one of the most successful restitution systems. Space rods physically represent the rays of light from the projection plane to the model point. These rods rotate about a mechanical point defined by the principal point of the photo. Any point can then be defined in model space as the intersection of the two rods. The Wild A8 Autograph, shown on the next page, featured freehand XY scanning and illuminated Z readings. It is typical of early models.

About twenty years ago, photo mensuration was attempted with an analog plotter, using the profile method (Smith, 1969). The primary product of the profile method are small scan strips across the model which, when plotted, yield ground profiles. Similarly, plots of the canopy profile can also be made. Comparing two such profiles was the subject of D.V. Smith's doctorate thesis. A Kelsh plotter (a modern optical system) was used remove the y-parallax from a model, thereby negating the affects of tilt. Then the plotter was used to construct the matched profiles. The area between the curves was measured and used to predict timber volumes. Significant correlation was found in the interesting trial, but less than 50% of the variation in Y, i.e. volume, was accounted for by the regression. Height measurements from the profiles were lower than the actual heights measured in the field. Poor resolution of the total top was suggested as the root of this bias. A recommendation was made to include another predictor variable, perhaps relative density, to improve the estimation of total volume.

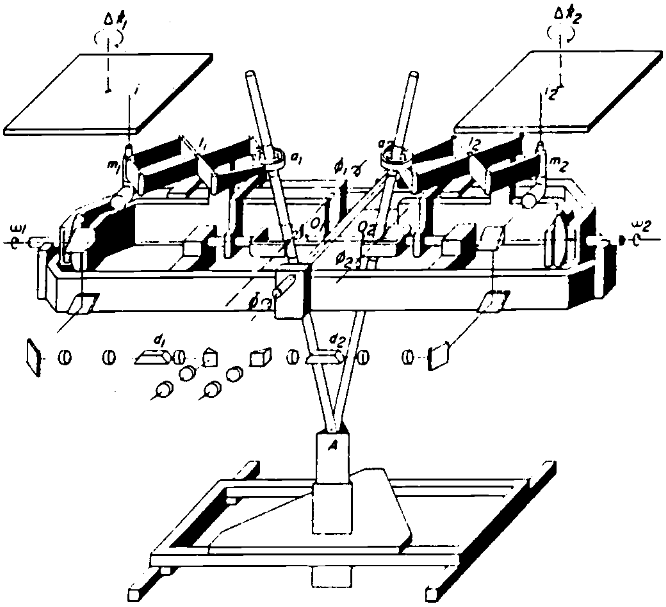


Fig. 3 Wild A8 Autograph Plotting Instrument

(Reproduced from: Burnside, 1985)

Interestingly, the mathematics for the analytical solution predate the mechanical answer found by Hugershoff. As far back as 1759, the subject of perspective geometry and space resection, was introduced by J. H. Lambert. But it was through a series of papers by Sebastian Finsterwalder, from 1899 to 1932, that the strong foundations for analytical photogrammetry were established. Many believe, had he possessed modern capabilities for extensive computations the course of the photogrammetry would have been quite different (Ghosh, 1988).

The British are generally credited with the creation of the first operational analytical stereoplotter in 1953, but the major thrust in advancement was made in the United States. Hellmut Schmid (1959) outlined principals based on the "Condition of Collinearity". His work was unique in the view of the application of least squares to his study of error propagation. He was also first to use the matrix notation, now standard in the practice.

The last two decades have witnessed tremendous growth in the development of machines which utilize the analytical approach to camera geometry reconstruction. Included are those which utilize "real-time" computerization, and all digital recording. The Carto AP190, which we will examine closely in a later section, is this type of system.

DOUBLE SAMPLING

Up to this point, there has been an examination of the problems and errors associated with photogrammetric mensuration; the attention is now turned to solutions.

There are two main approaches to the removal of these biases. One is to use a subsample of matched pairs of field and photo measured plot volumes and double sampling with regression to adjust all the photo plot volumes. This approach removes all the sources of bias in one operation, but it is expensive. Matched pairs of plots are expensive because of their widely scattered distribution and the extra time necessary to accurately locate the plots in the field. Also, a minimum of thirty matched pairs are required for statistical significance regardless of the size of the area inventoried. Thus, this method is only appropriate and cost effective for large areas (Paine, 1983).

The other approach is to remove the bias from each source independently. These procedures, undertaken primarily by the Canadians, require precise information on photo scale and tilt. Generally these methods can not yield log grade and defect estimations that are obtained through double sampling.

Colin MacLean (1972a) conducted one of the more thorough examinations into the values of double sampling with photo interpretation. In his study he asked three important questions:

1. Is double sampling a more efficient means of estimating total volume than simple field sampling when applied to extensive forest inventories in the Pacific Northwest?

2. Is stratification more effective when forest land is broken down into nine volume classes than when stratification is confined to two classes - forest and nonforest? If so, how much more?

3. How much more efficiently can total volume be estimated if optimum allocation instead of proportional allocation is used to distribute the field plots among the various photo strata?

The population included the twelve forested counties in the state of Washington. They were stratified by land use and volume class. The inventories were realistic in that the estimates of stratum size, variance and the plot cost data came from actual surveys. They were hypothetical in that the total number of field plots and their allocation among strata were manipulated to achieve the desired allocation and to equalize costs between paired double sampling and field plot designs. The number of plots assumed to have been field checked depended upon the method used to allocate the plots among strata. Where field checked plots were chosen in proportion to stratum area, they were assumed 1/16 the number of photo plots. When optimal allocation was used the ratio was assumed to be 24 photo plots to one field plot. Rather than calculating more efficient ratios for each county by either the proportional or optimum allocation formula, Forest Service experience was used for the reasonable division of work, thereby gaining an important source of costs and variance data.

The average costs of field plots, in 1972, were $114 in northwest Washington, and about $90 for central Washington. When the photo plots were stratified into nine levels, the average costs were $0.45 in northwest WA, and $0.25 in central WA. When broken into forest and non-forest strata only, the estimated cost per photo plot was thirty cents and fifteen cents respectively. The costs of photo interpretation include all salaries, supervision, and the costs of area familiarization trips for the interpreters, but not the actual costs of the photography as it was assumed to be borrowed material from the field offices.

The reported mean efficiency, a ratio of squared standard errors between the tested design and the field sample, has been weighted by county size. Note that by definition, the efficiency of the field plots equals 1.00.

	Inventory design		
		Nine strata	
	Two-strata	Proportional allocation	Optimum allocation
test area mean	1.26	1.96	2.11
high observations	1.58	2.99	4.06
low observations	1.06	1.45	1.46
mode	1.31	2.55	2.65

Efficiency standard: The ratio of squared standard errors (design SE^2/field SE^2)

Table 1 Efficiency of double sampling

(adapted from MacLean, 1972b)

A double sampling design with a relative efficiency of 2.00 would therefore be expected to be twice as precise (i.e., one-half the squared sampling error) as the field plot survey of equal costs. Put another way, a rating of 2.00 means that it would cost twice as much to obtain an estimate of equal precision from field plots alone.

MacLean has shown that double sampling, with stratification, has proven to be a design well suited to estimating total volume in the Pacific Northwest. As expected, the study showed the greatest advantage over simple field plot sampling in areas where residual patches of high volume old-growth timber are intermingled with low volume young growth and cutover lands. Areas where there is an absence of high volume stands result in generally low variance - nevertheless, even here double sampling provided estimates of total volume one and a half times better than the field inventory procedure.

Only about a quarter of the gain realized could be attributed to stratifying forest land from unproductive areas. Substantially more was found by stratifying into the nine volume classes. Although the design utilizing optimally allocated field plots had a nominally higher efficiency than the proportional allocation design, the advantage was quite small. In normal production situations, costs have to be predicted in advance of sampling and could be substantially in error. When this happens, a lower sampling efficiency is achieved, and anticipated gains may be erased.

MacLean also tested the relative efficiency of designs with the assumption that field surveys were also stratified into forested and non-forested units. Overall, that resulted in the gain in efficiency being dropped from about 2.00 to a 1.60 advantage. Unfortunately, no comparison was made in efficiency when the field plots were stratified into multiple levels.

This problem was revisited by MacLean (1981) nine years later, this time using small scale, black and white resource photography at 1:63000, reflecting a change in the techniques used by the Renewable Resource Evaluation Project at the Pacific Northwest Forest and Range Experiment Station. The thinking being that larger areas concentrated on fewer models would save money. On this occasion he did not evaluate the advantages of optimum over proportional allocation. Costs were updated to portray the 1981 economy.

Interestingly, the results were nearly identical to those found earlier at the larger scale; the efficiency ratio for double sampling with bi-level stratification was 1.21, and for the nine strata design, 2.01. The study did show that accurate volume estimations were obtainable from small-scale photos with double sampling, but that the costs of that accuracy was roughly the same as could be expected from medium scale formats. MacLean acknowledged that part of the reason for this success was the large range of plot volumes, and that even at small scales you can distinguish mature timber, from young second growth stands, and cutover regeneration plots.

Double Sampling in Combination With Other Sampling Schemes

With the value of double sampling theory well established, researchers have turned to increasing efficiency by incorporating variable plot and probability proportional to prediction theory (3-P).

Paine (1965) incorporated variable plot techniques to his study on ponderosa pine. This solved the problems with bias in tree selection for fixed-plots, and saved some time as well. He found it worked well in open grown stands where large scale photos were available. This, of course, is a severe obstacle for most management units.

Three P sampling, the statistical concept of unequal probabilities, has also been applied to photo cruises. With selection being proportional to size, it allows more emphasis to be placed on larger, more valuable trees and stands. In a limited study (Rogers, 1972) 3-P sampling was applied to an aerial photo cruise of a 40 acre test tract of Douglas-fir. One problem with this thesis concerns the small sample size and the large proportion of the stand represented by each plot. That resulted in the number of selected "measure plots" to be lower than had been designed. The standard errors (gross volume) that Rogers reported varied with the different scales of photography being used, but ranged from 18.4 percent at 1:7000 to 48.7 percent at 1:12000. He claimed that interpretive errors and the too small sampling size were the cause of the disappointing results.

LARGE SCALE PHOTOGRAPHY

Because Canada has such large and inaccessible forests, they have been largely responsible for the development of large-scale aerial photography (LSP) to improve the sampling of forest inventories. After two decades work the techniques have become highly sophisticated. Their purpose is the acquisition of ground-quality measurements without the normal requirement of ground control. The extremely large photo scales, on the order of 1:500 to 1:1500 allow very close observation of ground phenomena.

It was quickly discovered that large format cameras were not suitable for LSP due to limitations with cycling rates and image motion. Consequently smaller formats, particularly 70-mm, were adapted. Another concern is the requirement for accurate flying height determination needed to calculate scale. What would be a negligible error at a flying height of 10,000 feet may be enormously significant at only 500 feet. Conventional altimeters were incapable of meeting accuracy standards at low altitude. Tilt is also magnified at large scales, necessitating the determination of this parameter as well.

In the search for alternatives, the Canadians established three solutions to the problem: an optical one using two cameras separated by a fixed airbase; a radar altimeter adapting existent equipment; and laser altimeters, which while theoretically best, were not commercially available at the time (Sayn-Wittgenstein, 1965). Later, in the United

States, LSP projects were attempted without sophisticated control (McCadden, 1985).

Fixed Airbase

Early developments of this system were based on using two identical, synchronized cameras, set a known distance apart with their principal axes parallel (Avery 1958). Simultaneous exposure of the cameras permits the determination of photo scale based on the ratio of the mean photo distance from principal point to conjugate principal point, and the known airbase between cameras. From this, and the relationship between height, scale and focal length, the precise flying height is easily determined without ground verification. An important element to Avery was that instantaneously produced photo pairs eliminates the problem of wind sway between photo frames. One disadvantage of the method is due to the reduction in the ratio between airbase and height. The reduced differential parallax results in a lessened stereo effect and a lowering of accuracy in height measurements (Spencer and Hall, 1988). Longer boom lengths would partially alleviate this, but the new boom would have to be thicker and heavier to provide the same rigidity. Regardless of this, Lyons (1966) used this procedure and reported obtaining tree heights within ± 4 foot standard deviation, a figure better than usually achieved by traditional field work. Further, no significant differences were found between ground and photo methods of predicting gross stand volume.

By the mid-eighties there were eleven fixed-based systems were being evaluated in Canada; nine on helicopters with booms mounted along the direction of flight, one helicopter system with the boom perpendicular to the flight line, and one using a common single engine aircraft, a Cessna 180, with the cameras mounted on the wingtips.

Tests have found that the transverse mounting of cameras minimizes problems attributable to poor camera synchronization. This is because the lateral movement of the aircraft is nearly zero, and a time lag between exposures does not result in a change in airbase. By contrast, if the boom is mounted longitudinally, a camera misfire results in a biased measure of the airbase (Spencer and Hall, 1988). As a tradeoff, transverse booms must be designed to handle aerodynamic problems and highly restrictive mounting configurations.

The adaptation of the twin-camera concept to fixed-wing aircraft offers potential advantages because of a longer airbase, lower operating costs, and greater flying range. To date however, the problems of motion effects from higher speeds and wing flexing have not been overcome.

Radar Altimeters and Tilt Indicators

This approach utilizes a single camera taking a sequence of photos, with scale determined accurately with a foliage penetrating radar. Radar altimeters were first adapted to these terrestrial studies by the Canadian Forest Management Institute, Ottawa, in the mid-60's. Altitude could be assessed within 20 feet in most canopy conditions regardless of flying height, but dense foliage was difficult to penetrate. Newer, more accurate lasers cannot penetrate foliage either, but their beam is narrow enough to go through gaps in the canopy.

For simple parallax height measurements to be valid, the photos must be substantially vertical. Because of the increasing detrimental effects of tilt on larger photo scale measurements, it was found that only those LSP systems that incorporated tilt indicators were found accurate enough to meet photogrammetric standards. If tilt is present, the degree must be known for corrections to be applied. LSP is highly susceptible to this defect, with Nielson (1974) showing that even a one degree uncorrected error could result in individual height errors as high as 12.8 percent. Overcoming this, the Ottawa group developed a gyroscopic indicator sensitive to tilt as small as a third of one degree.

Combination camera-altimeter-tiltmeter systems are expensive and designed primarily for inventory of large remote tracts where gathering ground data is costly. Studies in Alberta and the Yukon indicate that the system is only cost effective when the standard errors are required to be within twenty percent, and the survey areas require more than 100 plots (Befort, 1988).

Laser Altimeters

Aircraft laser data has been used successfully to estimate tree heights and canopy density to infer timber volumes (Nelson et al., 1987). Each pulse from the laser provides at least one, but often two or more ranging measurements, depending on the canopy characteristics. A time interval counter measures the elapsed time between the initial laser shot and the return signal(s). Accurate to 100 picoseconds (10^{-10} seconds), flying heights are known to approximately one-half inch. Fainter, secondary returns can be estimated to about a six inch level (Nelson et al., 1988). Laser estimates of canopy density were within 20 percent of actual measurements, 89 percent of the time, suggesting that they are as good as conventional photointerpretation. Though site specific variation is high, investigations have shown that stand volume estimations, using these predictor variables, are repeatable, yet consistently seven or eight percent low. This can be portrayed as systematic error and corrected. (Nelson, et al., 1987).

Uncontrolled LSP

An alternative to these very expensive operations was designed at Oregon State University by McCadden (1985). In the United States where access to forest tracts is generally much easier than Canada, it was felt that the large capital outlays required for controlled LSP could not be justified.

By not having control or a precise knowledge of photo scale, McCadden confronted three sources of bias. First, the photo measured tree heights would be biased. The key proposal to his thesis was the use of tarif tables, thereby eliminating the need for heights. Second, photo-measured crown area and crown diameter (CD) are biased, resulting in a biased prediction of stem diameter at breast height (DBH). Third, an incorrect photo scale has the consequence of a biased measurement of plot size leading to the possibility of large errors in tree frequency and volume per plot.

A compensating effect to this bias, as it relates to volume per plot, was explained through an examination of the photo scale reciprocal (PSR) equation, solving for ground distance (GD) and photo distance (Paine and McCadden, 1988).

$$PSR = GD/PD$$

For example, if the PSR used in a photo inventory is larger than the true PSR, then the crown diameter measurement (a ground distance) will be greater than it should be. Consequently, there's an overestimate of the tree's volume. At the same time, the assumed PSR would result in the plot radius, measured on the photo, to under-represent the expected ground distance, resulting in an underestimate of the number of trees per plot. An empirical test was created to evaluate the magnitude of adjustment when incorrect scales were assumed. The test data from his plots were recalculated with PSR's purposefully erroneous by ± five percent, and used to develop, once more, stand volume, and stand and stock tables.

The study incorporated the single camera approach to LSP, using a low cost fixed-wing aircraft. The photos were not rectified for the effects of tilt. Ground verified baselines were identified at both ends of each flight line for scale approximation. Tarif access information was gathered at the same time by the field crew.

Nearly 500 trees were used to determine the weighted nonlinear model $DBH = 0.4713\ (CD)^{1.18779}$, using the photo measured CD. This equation had an R^2 value of 0.90. Another correlation between crown area and basal area performed nearly as well. Volume could now be determined directly from the tarif table.

Scale adjustments had to be determined to correctly identify which trees fell within the plot boundary. Because tree bases are often obscured, the tree tip locations were chosen to determine the status of each candidate. By applying a derivation of the PSR equation, scale was calculated at the tree-top level.

$$PSR_t = \frac{H - h_t}{f}$$

Note how the PSR at the top of the tree is larger, if the focal length (f) is held constant. This is due to the subtraction of tree height, h_t, from the flying height, H. McCadden determined the value of h_t by inverse regression using DBH and volume. This involves an unquantifiable bias, from using DBH as both a dependent and independent variable, but it was judged slight compared to the scale differential.

The results of the study indicate that it is possible to obtain an accurate estimation of volume per acre without the use of specialized equipment. Stand volumes were estimated within 2.5 percent of field determined measures.

Stand and stock tables were of similar accuracy for DBH classes over 10.5 inches, but were significantly short on counts below this size. This was assumed to be due to small tops being indistinguishable in dense canopies. These intermediate to suppressed trees add little to the total volume of the stand.

Changing the photo scale by ± 5 percent was seen to cause errors in tree per acre (TPA) forecasts, but that the error from misinterpreting the volumes per tree overly compensated the effect.

Change % PSR	Change % TPA	Change % Vol
- 5.0	+ 10.1	- 2.4
+ 5.0	- 8.3	+ 3.3

(adapted from: Paine and McCadden, 1988)

Table 2. Volume error induced by incorrect scale

ANALYTICAL STEREOSCOPY

Another way of controlling the scale and tilt is with stereoplotting equipment, and the reconstruction of each exposure station's orientation about the three axis of tilt. Applying the "affine transformation" to photo coordinates and a designated planimetric system, allows orthographic measurements to be obtained.

Comparing Analog and Analytical Solutions

First, for the sake of comparison, let's review the concepts of orientation as it applies to optical analog plotters. In aerial photography, overlapping images are taken with a camera having "metric" qualities, i.e., the interior orientation is known by calibration. Relative and absolute orientation follows the mounting of the diapositive stereo-pair into projectors which have the same interior orientation as the camera. When the two projectors are brought to the same angular differences as the camera exposures had in flight, relative orientation is complete. This is done by removing the y-parallax (refer to figure 4 and the components of $\partial\kappa$, $\partial\phi$ and $\partial\omega$) at five or six "pass" points on the stereo model, and physically adjusting a projector's position. Absolute orientation of the model is accomplished by scaling and leveling until the plane defined by ground control points (at least 2 positional, and 3 elevational) coincides with the map projection.

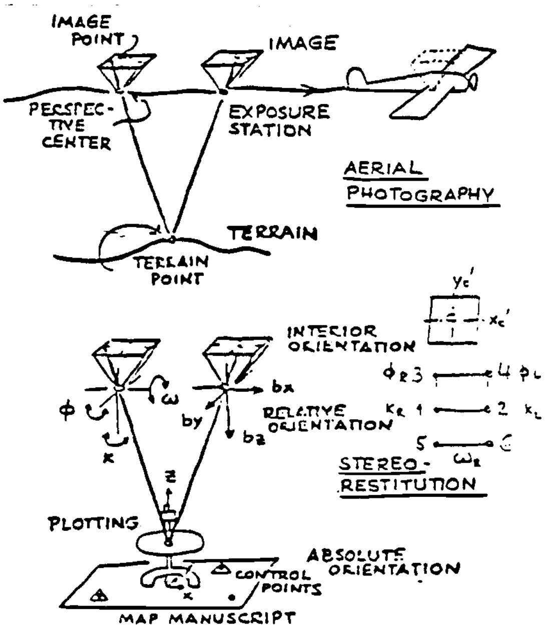


Fig. 4 Rotations about the camera station (illustration adapted from: Konecny, 1980)

Analog instruments are designed, either in an optical or mechanical manner, to reconstruct the processes of photographing the stereomodel. In optical systems the image is projected by a lens system onto a projection surface, which can be moved in x, y and z to measure the projected point. The second and more accurate analog instrument type are the mechanical projection systems in which mechanical space rods represent the image ray linking the photo point to the projection point (Konecny, 1980).

With the advent of computers in the 1950s, photogrammetrists rediscovered early analytical solutions from the turn of the century. One of these have been expressed as the "collinearity condition", and is used by most agencies using computerized methods (Ghoush, 1988).

The collinearity condition:

$$x' = -c * \frac{a_{11}(x - x_o) + a_{12}(y - y_o) + a_{13}(z - z_o)}{a_{31}(x - x_o) + a_{32}(y - y_o) + a_{33}(z - z_o)}$$

$$y' = -c * \frac{a_{21}(x - x_o) + a_{22}(y - y_o) + a_{23}(z - z_o)}{a_{31}(x - x_o) + a_{32}(y - y_o) + a_{33}(z - z_o)}$$

where,

$$\begin{bmatrix} a_{11}, & a_{12}, & a_{13} \\ a_{21}, & a_{22}, & a_{23} \\ a_{31}, & a_{32}, & a_{33} \end{bmatrix} = \begin{bmatrix} \cos\kappa\sin\phi & \sin\kappa\cos\omega - \cos\kappa\sin\phi\sin\omega & \sin\kappa\sin\omega - \cos\kappa\sin\phi\cos\omega \\ -\sin\kappa\cos\phi & \cos\kappa\cos\omega + \sin\kappa\sin\phi\sin\omega & \cos\kappa\sin\omega - \sin\kappa\sin\phi\cos\omega \\ -\sin\phi & -\cos\phi\sin\omega & \cos\phi\cos\omega \end{bmatrix}$$

and, x_o, y_o, z_o are the coordinates of the origin

What these two equations constitute, in parameter form, is the existence of a straight line linking image point, exposure station and object point in a ground coordinate system. The coefficients are a function of the camera's rotational elements, while interior orientation is expressed as a constant, c. When the location of some points used as control are known, these equations permit evaluation of their directional cosines, helping to determine the angular orientation of the photograph . What this means is anytime the orientation of the photographs is known, the corresponding image point Xi', Yi', may be calculated for any chosen ground point, Xi, Yi, Zi. This is precisely what an analog plotter does by the mechanical means of manipulating the space rods (Konecny, 1980).

The procedure for determining the orientation with an analytical stereoplotter is straightforward. The description that follows is specific to the Carto AP190, but would closely resemble other analytical systems. Interior orientation is matched by least squares fit, to the fiducial mark registration on the photo carriers. The computer now "knows" where the photos are on the carriage, and that they're flat and stable.

Next, a selection of well distributed objects, such as clearly visible stumps or small bushes are identified as the pass points for relative orientation. Parallax, in both x and y, is removed by driving the micrometers in order that the measurement dots are fused at the base of the object. Here least squares is used to explain redundant data collected to solve for the rotational parameters (with n-5 degrees of freedom). Now, despite only minimal involvement by the operator, the computer knows relative tilts at exposure.

Absolute orientation has also been reduced to "point and shoot" ease. A set of control points are selected over a model, in which the x and y, or z value of the chosen coordinate system is known. More often than not, choosing the State Plane Coordinate system, we digitally register these points from a referenced USGS 7 1/2 minute quad sheet, on a digitizing tablet. Optionally, control can be gained from oriented NHAP (National High Altitude Photography) material, and bridged down to the larger scale material

(Reutebuch and Shea, 1988). The affine transformation utilizes matrix algebra to rotate and scale the photo coordinates to the chosen projection. Now complete, the computer knows the precise scale at every location, and is ready for unbiased measurement and feature registration.

Advantages of Analytical Stereoscopy

There are many advantages to this computerized solution as compared to analog methods. Perhaps foremost of these is that the orientation parameters can be saved to disk, and then recalled if the model is to be reanalyzed. This has greatly increased the versatility of stereoplotters.

With analog systems, the meticulous and complex orientation corrections would take the better part of a day. Since the procedures were required to be followed each time the model was put into the projectors, most models were not re-used after initial measurements were recorded. The equipment was very specialized, expensive, and required highly trained technicians to operate it. Thus, the machines tended to be centrally located, far away from the operations office of the unit portrayed on the photos.

The advent of low-cost analytical plotters has now brought this technology directly into the land manager's office. Now anytime a stand is considered for a management activity, the disk-stored model can be called from computer memory, the images are mounted on the carriages, and after a five minute procedure to register the fiducial marks, it's ready for parallax-free observation.

And they are far more adaptable. Analog plotters were often limited by format type, focal length, and lens distortion. But since the camera geometry is calculated by the computer, analytical plotters are not so restricted. Another benefit of this reliance on mathematics is increased precision. Analog plotters are not able to exceed about ± 20 microns (μm, 10^{-6}m) at photo scale, where it is not impossible for analytical plotters to be within ± 2 μm (Freidman et al., 1980)

Another benefit is that computer programming is easily enhanced with ancillary capabilities through the addition of subroutines. Task specific programming such as p-line locations for road builders, and fixed-plot overlays for mensurationists demonstrate the new trend in applications.

THE CARTO AP190

Development

The focus of this paper will now be directed specifically to the Carto AP190 stereoplotter, and its application to ongoing work at the College of Forestry at Oregon State. The Carto instrument represents a breakthrough in analytical photogrammetry because it is one of the first to incorporate personal computers such as IBM's PC/AT, and thereby reduces purchase costs dramatically.

It's development in mid-1985 began when the Norwegian Research Council supported a project to evaluate methods that simplify digital map revision. The aim was to build an analytical stereoplotter based on a microcomputer that would allow real-time removal of both x and y parallax. The overriding objective was to reduce the costs of analytical photogrammetry (Carson, 1987). To do this, it was decided to sacrifice some advantages of the best quality plotters. Particularly, it was thought, the one to two micron accuracy wouldn't be needed for map revision projects. While these most accurate plotters can cost as much as $250,000, the Carto AP190, with current updates, sells for about $40,000.

An early investigation established that industrial ball-slide assemblies were suitable mechanical components for the basis of the 23cm x 23cm (equivalent to 9"x9") photography, to within ± 10 microns (Carson, 1985). The drive system for the movement of the right photo carrier, in the automated, real-time adjustment of parallax, is based upon two micrometers rotated by step motors capable of incremental movement of 2.5 microns.

Linear opto-electronic transducers encode major translations. The parallax adjustment encoder is a thumbwheel rotary encoder. A fourth encoder is included to be used for feature code input. The interface between encoders, step motors, controls and microcomputer is a Z80 microprocessor. The speed of the computational loop through the equations, is accomplished 30 times per second. All users have perceived the response of the system as immediate (Carson, 1986).

The optics for the mirror stereoscope were built by Cartographic Engineering, Ltd. of England, and include illuminated measuring dots, 50 microns in diameter, which are focusable in the photo plane. The fixed viewing system accommodates 4x, 6x, and 8x magnifiers. Like the encoders, the optical system must also meet the ± 10 micron limit set for the mechanical components. The stereoscope rests on a variable intensity light table for back illumination of diapositives.

Since the mechanical components of each instrument are unique in their manufacturing tolerances, calibration for each instrument is required. Kiser (1989) reports calibration data for the Oregon State unit, to be within ± 15 microns.

Field Tests

Early in 1987, the stereoplotter was tested in two field offices of the Tongass National Forest in southeast

Alaska (Reutebuch, 1987). Ideally, it was thought, the "user-friendly", menu-driven software would greatly increase the ease of operating the system, allowing local staff to take measurements directly after conducting a simple interior orientation. Reutebuch refutes the common belief that a lot of experience is needed to take reasonable measurements.

The training time needed to correctly perform these tasks was less than a day. In the Alaska workshops, 24 of 25 forestry staff were able to immediately digitize two points on 1:12000 photos to within eight feet of the correct ground measurement of 4,552 feet. Elevation measurements were correct to within a 20 foot contour after just a few minutes practice with the illuminated floating dot. After practicing two hours, all users who had regularly used a mirror telescope were measuring to within three feet of the actual coordinates unless the ground was obscured by vegetation.

In another field test, Reutebuch and Shea (1988) evaluated measurement accuracy from 1:2000 large scale photography. They wished to show that for many planning assignments, photo measurements were comparable to ground-surveyed data. Recognizing that obtaining adequate control for large scale photos is difficult because of their small effective area, this experiment also tested the concept of "bridging down" control from smaller scale images.

In a two step design, they first oriented a 1:32000 model with easily identifiable intersections, bridges, and spot elevation control. The State Plane coordinates (X,Y) were input from a USGS 7 1/2 minute quad sheet registered to a digitizing tablet. Twelve image points were then identified on this model that were also visible on the 1:12000 photography of the area. These points included road intersections, logs and stumps. Their coordinate values were determined from the stereoplotter, thereby transferring or "bridging" control to the larger scale. A least squares fit of the model to the twelve image points was performed. Horizontal and vertical residual errors, in feet, were 4.4 and 1.0 respectively, at ground scale. In similar fashion they identified several points on the 1:2000 photography whose coordinates could be measured from the intermediate 1:12000 model. This time residual errors of the absolute orientation were 0.5 feet horizontal, and 0.3 feet vertical.

Six distances were then measured in the field between pairs of easily distinguishable stumps with a steel tape and clinometer. Next, photo measurements were obtained. The results are shown in the table below.

Ground Distance (feet)	Photo Distance (feet)	Difference (feet)	Percent Difference
96.1	97.5	1.4	1.5
150.9	150.2	0.7	0.5
189.6	189.6	0.0	0.0
224.7	223.1	1.6	0.7
224.7	225.2	0.5	0.2
268.4	267.5	0.9	0.3

Table 3. Accuracy of bridging control

(adapted from Reutebuch and Shea, 1988)

The majority of this error can be attributed to the limited accuracy of the quad sheet. Well defined map points are generally plotted to within 1/50 inch of their correct position. On the 1:24000 map, this tolerance equals about 40 feet. For Reutebuch and Shea's study the control points averaged nearly 8000 feet apart, meaning the error is spread over a great distance. Accuracy would not be expected to exceed 0.5 percent.

For the Forest Service's planning activities, an accuracy of ten feet, ground scale, is generally considered adequate (Reutebuch, 1987). With the precision available from the Carto AP190, nearly all available resource photography can be used. The only practical limit to this is the human eye capacity to perceive differences, about 25 microns (Carson, 1985), suggesting even material exceeding 1:100000 could be used for planning. Readers interested in further documenting the precision of the AP190 are directed to Kiser (1989), who has recently completed exhaustive tests confirming the success of earlier trials.

Application Diversity

One exceptional attribute of analytical photogrammetry is the multitude of tasks that can be completed by either invoking subroutines or integrating other software. Carto's programming easily allows digitization of point, line, and polygon data with identifying feature codes. This format is ammendable, permitting adaptation to several GIS and surface modeling programs.

The AP190 can immediately report the horizontal or slope distance between any two points, or along any line. From any point on the photo, azimuths can be projected, while buffers, or corridors can be created along straight line segments. Further the AP190 can lay-out fixed circular plots of any radius, and project a true vertical cylinder above plot center.

Still being developed is a subroutine which models the location of alternative landing sites for a timber sale. It will permit the user to input a yarder's tower height, and then by analyzing the hillside's profile, identify areas where intermediate supports would be required to avoid drag and/or erosion problems.

The AP190 can produce output for the creation of either planimetric maps or three-dimensional profiles. The surface modeling package which Oregon State has purchased, has the trademark, Surfer. Besides a thorough array of graphical options, Surfer can compare models and compute volumetrics between them. This function may be found to be particularly useful in headwall stability studies.

The diagram below shows the linkages between the AP190 and various input and output devices.

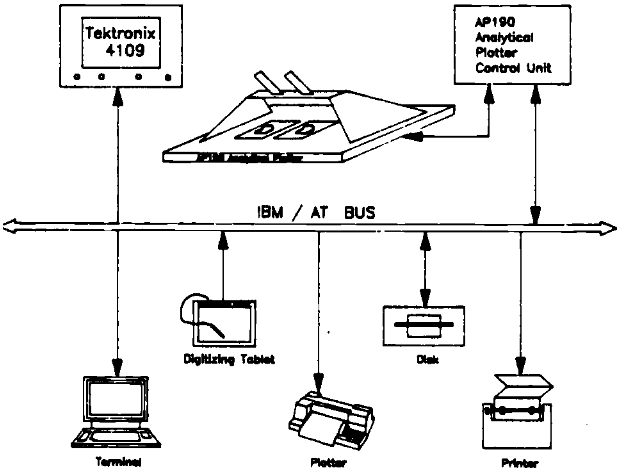


Fig. 5. AP190 - IBM/AT Configuration

TRIAL PHOTO CRUISE

Procedural Development

A test of the AP190's abilities, with particular regard to the estimation of timber volumes, was conducted at Oregon State University. It's important to note that this group effort by members of the graduate aerial photos course, F520, was not a formalized research project. It was particularly limited by time, with the course lasting just ten weeks. The author of this paper was a major contributor, but by no means sole contributor to the study. No attempt, prior to this date, has been made to report the results; and what follows should be considered preliminary coverage. Additional replications by qualified photo-mensurationists have been scheduled, but indeterminately delayed. These replications will provide a clearer view of the precision of the instrument and the variability among interpreters.

It was hypothesized that by using the stereoplotter and its six power magnification, high quality images taken at an intermediate photo scale could approach the accuracy of LSP projects, and thus eliminate the need for double sampling. Color-infrared diapositives of Oregon's Coast Range were borrowed from the Coastal Oregon Productivity Enhancement program (COPE) for this analysis. They were produced with a twelve inch lens at a 1:9000 scale. With this high quality resource photography, both the stand approach and the individual tree approach of determining volumes was evaluated.

Control was bridged down from NHAP, 1:58000, color-infrared prints obtained from the Environmental Remote Sensing Lab at OSU. An intermediate control was provided with the 1:18000 general resource photography for COPE. This two-step design is similar to Reutebuch and Shea's approach. The residual errors after calculation of absolute orientation for the 1:9000 model were 6 feet horizontal, and eight feet vertical. The chosen stand of mature Douglas-fir has an area, as determined by the AP190, of 52.7 acres.

The approach to the cruise itself has many parallels to Dilworth's 1956 research. We adapted his methods of utilizing standard volume tables, including the equation he developed correlating crown diameter to DBH. It was based on data from 1250 Douglas-fir trees, and was determined by the graphical multiple regression method; it was expressed as:

$$DBH = -3.9340 + 0.1128(TH) + 0.52929(VCD) + 0.000657(TH*VCD)$$

$P > .01$ for all coefficients
$R^2 = 0.979$
$SD = \pm 0.824''$

(adapted from table X, Dilworth, 1956)

Dilworth then processed these data with the standard volume table, Bulletin #201 (McArdle, 1949). Testing these relationships in well stocked stands, he determined from photos a volume of 618,030 b.f., compared to field volumes of 622,870 b.f. While within one percent of the actual volume, the standard deviation about the regression line was ±10.8 percent.

Our approach to the current research, based on computers, required the creation of an equation for volume, emulating the parameters of Bulletin 201, table XVI. Stepwise regression, performed by Statgraphics software, yielded the expression below. This relation was input to the APCRUISE program, a data base manager, developed by Sen Wang.

$$VOL = [\ 99.373 - 2.602*10^{-2}(TH^2) + 2.304*10^{-3}(DBH*TH^2) + 7.996*10^{-7}(DBH^2TH^2)\ ]$$

$P > .001$ for all coefficients
$R^2 = 0.996$
SD = ± 25.024 m.b.f.

The other goal of this study was to examine the potential for determining volume from SPVT's. This time, independent variables were mean stand height and percent crown cover. Since previous studies suggest that crown cover is commonly underestimated when occularly estimated, we additionally used a calculated value based on the ratio of the summed crown area of "in trees" over the total size of the plot, one-quarter acre. Determining the plot's average height is more tricky than it initially seems, requiring just a bit of intuition. The mathematical mean of all heights may not have the highest correlation to volume represented by the plot. A number of small trees could significantly skew the stand's average height, while actually contributing little or nothing to the total merchantable volume. Following Pope's (1962) precedent, only the estimated average size of dominants and co-dominants was recorded.

The regressive relationship with volume Paine (1981) developed was selected:

$$\mathrm{VOL} = 3.05565 + 1.99 03 * 10^{-6} (\mathrm{TH}^2 * \%\mathrm{CC} * \mathrm{VCD})$$

$R^2 = 86.862\ \%$
$\mathrm{SD} = \pm\ 24.724$ m.b.f.

This equation has a slightly higher correlation coefficient, than Pope's. But unlike Pope's, the selected equation requires the input of average crown diameter; this parameter was automatically obtained from stereoplotter output.

Methodology

The sample size of nineteen plots was determined using a non-stratified, finite population formula (Eq. 4.5, Cochran, 1977). Plots were located throughout the stand according to a systematic grid. The adopted standard of accuracy for the digital recording of plot center was ± 0.5 feet of the suggested location. Since it had been previously decided to use quarter-acre plots, the plot radius of 58.876 feet was input into the computer, so that an audible signal would designate whenever the measurement dots move outside the plot's boundary. This enabled the "in trees" to be determined. Note that since the computer recalculates parallax at every point, and is constantly adjusting for changes in scale, no bias for selection is evident as had been without geometric reconstruction. Next, the interpreter drew a quick sketch of each plot for later referencing, and made an estimate of the percent crown closure.

The ensuing step was to digitize the crown perimeter of each tree, enabling the calculation of crown area and crown closure. Next we determined the tree's total height. Because of shadow and/or obstruction by other stems, the bases of all trees could not be seen. In these cases, an empirically assisted, best estimate of total height was substituted for measurement. When all trees had been recorded, the inter-preter assessed the stand's average stand height.

The database acquired digital information directly from the AP190, and used it to determine plot location, in trees, and crown area for each. Supplemental information, including tree height, average plot height, and estimated percent crown closure was manually entered into the database.

Field Cruise Report

An extensive ground cruise was designed to determine gross volumes with minimum standard error. Without a pre-cruise estimate of the stand's coefficient of variation, it was decided to use a conservative value and sample at a one plot per acre rate. These variable plots, measured with a Relaskop's 20 basal area factor gauge, consisted of full 360 degree sweeps to determine in trees. On every fourth plot, accurate measures of DBH and total height were recorded for each in tree; with the limitation that it was not necessary to measure more than ten trees on any given plot.

The great expense of this type of extensive cruising should be thoroughly considered. Even while acknowledging the error resulting in an over sampling, this job took three, two-man teams nearly ten hours to complete, including the four hours traveling time. This amounts to 60 man-hours!

Gross volumes were determined by applying an average volume / basal area ratio, V-BAR, to the basal area determined from the tree count plots. V-BAR was determined from each measure tree, treating each as a tarif tree and obtaining V-BAR from the designated table according to the tarif access system (Turnbull et al., 1980). The log rule used was Scribner, board feet, for 32' logs.

Results

The tables below, allow an easy comparison of the field cruise results with both approaches to the photo cruise. TPVT's can also be compared to the SPVT's that used both estimated (ECC%) and calculated percent crown closure (CCC%).

	Field Cruise	Tester #1	Tester #2
VBAR-TARIF	74959.09	-	-
TREE VOL TABLES	-	73031.53	83104.98
STANDARD ERROR %	5.24	2.12	1.92
STAND VOL TABLE (ECC%)	-	71790.00	75870.00
STANDARD ERROR %	-	8.42	7.25
STAND VOL TABLE (CCC%)	-	42300.00	62180.00
STANDARD ERROR %	-	10.06	7.41

Table 4. Field vs. APCRUISE volume statistics

As mentioned before, the primary benefit of the individual tree approach is that it permits the creation of a stand table. The data has been derived solely from the measured in trees on the sample plots. For field plots which had more than ten measure trees, the ratio of measure trees to total number of in trees was ascribed to the plot size constant.

STAND TABLE

(trees/acre)

DBH CLASS	Field Cruise	Tester #1	Tester #2
14"	8.78	0.42	0.00
16"	1.68	0.42	0.00
18"	5.31	3.16	0.00
20"	8.61	2.74	0.84
22"	1.78	7.16	2.74
24"	6.73	4.84	3.37
26"	6.36	7.37	6.32
28"	6.04	6.11	7.37
30"	5.73	5.47	7.37
32"	3.78	1.47	5.47
34"	2.60	1.05	4.63
36"	2.99	1.68	2.32
38"	1.49	1.26	0.84
40"+	4.94	0.84	0.84
TOTALS	66.82	43.99	42.11

Table 5. Field vs. APCRUISE stand table

Discussion

Procedures developed for the AP190 have succeeded in removing many sources of bias for the photo cruiser. Reconstruction of the photo geometry at the time of exposure allows the removal of all bias due to tilt and imprecise knowledge of scale. Photo mensurationists have long been capable of predicting accurate gross volumes per acre, but it has been difficult to determine total acrage exactly. This vital statistic is now determined without significant error.

Interpretive errors may have been reduced using Carto's stereoplotter, but they have not been eliminated. Height measurements are more precise because the interpreter can move the photo carriages slightly back and forth, clearly defining the horizontal plane at that elevation. To date, the problems associated with obscured tree bases have only been overcome through the use of laser altimeters that the Canadians have employed.

CD measurement continues to be a major source of error. From examination of the stocking table, it is conjectured that many small trees have been missed all together. Because of the concentration of photo measured trees between the 26" and 30" DBH classes, it seems reasonable to conclude that interpreters often over digitize the areas of small trees and under digitize the crowns of large trees. Two other explanations, in the form of indirect measurement error, could also account for the discrepancies. First, since double sampling was not used in this experiment, some variation is expected from differing sampling designs. Second, and more importantly, the regression relationship of CD to DBH was not developed for this specific stand, but for a broad region. The development of new relationships, enhanced by the incorporation of computerized statistical modeling, would seem to be the prudent way of quantifying this component of error.

The problems with data insufficiency have not been completely resolved. Though there was no empirical test of species identification in this stand, where virtually all merchantable timber was Douglas-fir; but it's clear that the practiced interpreter could easily accomplish this with these high quality transparencies and the six power magnification. Most importantly, log grading and defect deduction can still not be evaluated on photos. This remains the chief advantage of incorporating double sampling concepts.

Both interpreters that completed the test determined gross volumes within ± 3 percent of the field determined volumes using SPVT's and estimated %CC. The same approach, but using calculated %CC produced severe under estimations. Digitizing tree crowns is meticulous work, and the error associated with this operation is not firmly understood. Interpreters agree that smoother carriage movement would improve this delicate digitization. It is also probable that interpreters are better able to estimate CC by the "tree-cramming" method, intuitively including trees which may be missed in tree counts.

There is substantial differences between testers for volumes determined by TPVT's. It is surprising that tester # 2's results were slightly beyond a 10 percent overestimation in volume despite having the lowest number of trees per acre in the stand table. The revealing observation is that nearly all missed trees were the smallest in the stand, and therefore contributed little to total volume. Also, measured trees may each be slightly biased by interpreter systematic error. A much clearer picture of this phenomenon will be yielded with the completion of additional replications.

Summary

Low cost analytical stereoplotters, despite their recent introduction to industry, have already been confirmed tools of proven benefit. Larger corporations and public agencies that have GIS capability may soon find instruments like the AP190 an indispensable utility for updating their data.

The stereoplotter's most important function, from the viewpoint of the photogrammetrist, is the complete removal of bias resulting from camera tilt and inaccurate scale determination. "User-friendly" software, like Carto's, provides access to these benefits to virtually any regular user of aerial photography, without the requirement of extensive training in photogrammetry.

With the ability to recall models from computer memory, these precise techniques can be applied at all phases of management plan implementation. The importance to aerial surveying is stressed. Other applications for analytical stereoscopy are expanding rapidly, with new ideas being considered constantly. This author thinks it likely that natural resource research projects will most quickly adapt this methodology to provide temporal "snap-shots" of their study areas.

Industrial use, besides the GIS input, will probably advance primarily along engineering lines, including road design, logging applications, rock pit analysis and other volumetrics, and various hydrology projects. In time, this technology may be used as a resource to verify state forest practices compliance. The regulations concerning riparian buffer-strips could easily be monitored by the AP190.

In final analysis, the results of the photo cruise are mixed. The SPVT approach still seems superior to TPVT's for predicting volumes consistently. Easier methods of conducting stand level cruises already exist without the complexity of the stereoplotter. Individual tree methods are hampered by conditions common to the westside of Oregon. Open stands, in the intermountain region, are likely to have much better results, and should be evaluated.

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GLOSSARY

Affine transformation - Invoked to translate one coordinate system to another. Matrix algebra determines the parameters of rotation, scale differential and translational constants.

Analog - Represented by physical or mechanical means.

Analytical - Represented by mathematics, or broadly, by computer.

Diapositive - A positive transparency, analogous to "slides".

Mensuration - The art and science of taking measurements. To foresters, it implies measuring trees and stands.

Model - A stereographic pair, with completed orientation.

Orientation - The scaling, rotation and leveling of photographs to a ground coordinate system.

Orthographic projection - The simplest of all map projections, not accounting for earth curvature.

Parallax - Apparent displacement of an object, with respect to a reference system, caused by a shift in the observation point.

Pass point - A point whose position is known, intended for use in orientation.

Regression - A statistical procedure which correlates item(s) to a parameter of interest.

Standard deviation - A statistical term quantifying variation of individual observations about their mean.

Stereoscopy - The science that deals with the use of binocular vision for observing a pair of overlapping photographs.

Stereoplotters - A contraction of "stereoscopic plotter instrument"; an instrument for plotting a map or obtaining spatial solutions by observing stereoscopic models.

Tarif system - A series of local volume tables, one of which is appropriate for any given stand. Eliminates the need for many measurements once the tarif number is determined on a sub-sample of trees in the stand.