MEASURING SNOW DEPTHS BY AERIAL PHOTOGRAMMETRY

Evaluation and Recommendations [1]

By

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Introduction

Aerial photography is the accepted tool for observing large areas of land simultaneously. Aerial photogrammetry--the science and art of deriving reliable measurements from aerial photography--is an even more valuable use by which quantitative data and maps displaying this information about land surfaces can be generated. Aerial photogrammetry has been successfully used to measure snow depths at several thousand points in a 100-acre study basin in southwestern Idaho. The research demonstrates that photogrammetry is a practical method for quantitatively analyzing the patterns of snow accumulation and melt in large areas of extremely variable snow distribution.

Photogrammetric measurement of snow depths bears the same relation to field measurement as topographic maps made from aerial photos do to maps derived from plane table surveys. In a plane table survey, selected points are measured with high accuracy and the terrain between points is interpolated. On the other hand, in a photogrammetric survey the entire terrain surface may be scanned and the elevation for any point plotted without interpolation. Such elevations are determined with less accuracy than a plane table survey, but the photogrammetric map as a whole is more detailed and informative.

Similarly, a field measurement of snow depth at a particular point is more accurate than a corresponding single measurement obtained by photogrammetry. However, from the ensemble of photogrammetric depths a more detailed representation of the snow distribution is available, either as digitized data or as a map, than can be obtained from any practical number of field measurements.

Photogrammetric maps of snow depths cannot yet be made with the accuracy of good photogrammetric maps of ground surfaces. In fact, some surveyors have contended that they cannot be made at all. The purpose of this paper is to discuss the reliability and usefulness of photogrammetric snow surveys.

Frequent reference to the stereo model will be made in this paper; therefore, it is desirable to define the term now. When aerial photographs are to be used for stereoscopic viewing, successive photographs are taken that overlap each other 60 percent. Each of any two overlapping photographs provides a view of a common area from a slightly different angle. The three-diminsional image of the common area created by simultaneously viewing the two photographs in a stereoscope is called the stereo model. (Figure 1).

Experimental Area

The Northwest Watershed Research Center [3] established the upper Reynolds Creek Experimental Watershed as an outdoor laboratory for hydrologic investigations in 1960 (Robins, Kelly, and Hamon, 1965). The watershed is located in the Owyhee Mountains in southwestern Idaho. Snow research is carried on in a selected study basin in the higher reaches of the watershed. Elevations in the study basin range from 6600 to 7000 feet. The

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topography is characterized by north- and northwest-trending ridges with gently inclined windward slopes and steep north- and east-facing lee slopes.

Predominant vegetation is sagebrush, with scattered stands of Douglas-fir and quaking aspen. Midwinter snow distribution is extremely variable, ranging from less than half a foot to more than 20 feet within 100-foot distances.

Measuring Snow Depths By Photogrammetry

Initial Field Testing. In the first set of experiments conducted in 1964, using aerial photographs at a scale of 1:6000, a single model was set up in the plotter 4/ and snow depths were measured photogrammetrically at 2200 grid intersections over an area of 90 acres. In the field, this would be equivalent to measuring snow depths at every intersection of a 50-foot grid. The first step was to establish several vertical and horizontal control points in the study area before the snow season and mark them clearly for identification from the air. In the plotter, aerial photographs of the area were adjusted to the control points and the resulting stereo model was superimposed on a scaled 50-foot grid. Ground elevations were measured photogrammetrically at the 2200 grid intersections.

After snow accumulation began, aerial photographs of the snow-covered area were taken. In the plotter, the stereo model of these aerial photos were horizontally adjusted to the same control points. The vertical control for the model was established by adding the ground elevation and the measured snow depth at each vertical control point obtained with a snow tube on the same day the aerial photographs were taken. After the snow model was horizontally and vertically adjusted in the plotter, snow surface elevations were measured photogrammetrically at the same 2200 grid intersections at which ground elevations had been previously determined.

To compare photogrammetric depths with actual field measurements, 31 randomly located points were established prior to the aerial photography. At the time the photographs for the ground elevations were taken, these points were marked for identification on the photographs and located on the model base grid. In subsequent photographs of snow cover, these points were not marked in the field; their location was determined entirely from the base grid in the model and the snow depth at each point was determined photogrammetrically. The field measurements of the snow depth at these points, made on the same day the aerial photographs were taken, provided the comparative data for the evaluation.

A computer program was written to compute snow depths at each intersection by subtracting the ground elevation from the snow elevation. These elevations were manually transcribed on adding machine tapes, but automatic equipment for entering the data on punched cards is almost a necessity. Not only does manual transcription take too long, but there is a possibility of errors. In several instances there were obvious errors of 100 feet. These mistakes are easy to detect, but smaller transcription errors are not. Several automatic devices are now on the market for reduction of photogrammetric measurements to digital form, and their use should be specified.

Analysis of the depth measurements from the initial field tests showed a consistent bias in the photogrammetric measurements--the average photogrammetric snow depth was about 0.5 foot greater than the average measured depth (Figure 2a). The bias was suspected to have been caused by inadequate surveyed vertical control. The standard deviation of a point measurement error was about 0.7 foot (Cooper, 1965); that is, after correcting for the bias, about two-thirds of a collection of photogrammetric measurements could be expected to fall within plus or minus 0.7 foot of the actual measured mean depth. This variation is apparently consistent and independent of snow depth; measurement of deep and shallow snow alike is subject to the same standard deviation (Cooper, 1965).

Evaluation Program. Following the initial field testing, an evaluation program was conducted in 1966 to examine further the bias of the photogrammetric determinations that had appeared in the earlier tests and to examine the standard deviation of the point

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4/ Our comments in this paper refer to the Kelsh plotter, Model 5030. Mention of specific manufactured products is in the interest of clarity and in no way implies endorsement of these products by the Agricultural Research Service, USDA.

measurements.

Inadequate model control was suspected as a possible source of the bias in the initial test. It was also reasoned that a logical way to decrease the point photogrammetric measurement errors would be to increase the scale ratio of the aerial photography. Consequently, the evaluation program was repeated in a different area with a scale of 1:3000. A 100-acre area adjacent to the first area was covered by five models with five control points per model. A scaled 25-foot base grid was established in the plotter and elevations were measured photogrammetrically at 7000 grid intersections.

The ground models were set up and elevations were read and automatically digitized in punchcards; the snow surface elevations were likewise read and digitized automatically. Such a procedure eliminates the transcription errors encountered when the readings are manually punched on tapes. Snow depths were calculated by computer.

As before, points were randomly located in the study area. At the selected 36 points, photogrammetric depths and field measurements were compared. The data from the 1:3000 evaluation program show that the photogrammetric measurements were unbiased (Figures 2b and 3b). However, the standard deviation of the point measurement errors remained at 0.7 foot. This suggested that the reading errors may be less sensitive to photo scale than we originally anticipated. Furthermore, reevaluation of the data from all 2200 points in the initial survey (1964) indicated that the bias at the smaller photo scale was less than had appeared at first (Figure 3a). A modified statistical method (reduced major axis regression) was used to reevaluate the initial field test results.

Precision of Mean Depth Measurements

Our evaluation of the photogrammetric measurements of samples of individual points substantiates that snow depths can be accurately and quite reliably measured using aerial photography.

The significant advantage of this method is that the information obtained is a collective property of all the included points. Another advantage is simply the extremely large number of points digitized.

The appropriate statistic to evaluate the precision of photogrammetric measurements of mean snow depth over an area is the standard error of the mean of all the points rather than the standard deviation associated with individual points. Since the standard error is simply the standard deviation divided by the square root of the total number of points, the more points at which photogrammetric measurements are taken, the smaller the resulting standard error of estimate.

The standard error of the average snow depth obtained in the photogrammetric models was about 0.02 foot--small enough to be ignored entirely. Inaccuracies in photogrammetric measurement of average snow depth over a large area can be expected to arise almost entirely from overall errors or bias in reading the model. Therefore, providing that horizontal and vertical controls are adequate and snow surfaces are read by experienced professional operators, quite shallow snow depths averaging even less than 0.5 foot can be measured with satisfactory precision.

Discussion

One obvious feature limiting the usefulness of aerial photogrammetry is that it is not possible to estimate water content directly from a photogrammetric map--all that such a map shows is the distribution of snow depths. Depth information alone, however, can be highly useful.

Photogrammetric measurements of snow depth are useful as a research tool in helping to untangle some of the complex influences of topography, vegetation, and solar radiation on snow accumulation and melt in mountain areas. More detail is available than can be obtained from any practical sequence of ground measurements.

Suggestions have been made that it should be possible to make fast and inexpensive operational snow surveys for forecast purposes by means of synoptic radar observations from conventional aircraft or from satellites. Development of this technique will require extensive ground calibration. Photogrammetric surveys of the snow depth over selected calibration targets will probably prove indispensable to assessment of the feasibility and reliability of radar snow measurements.

Watershed management personnel of the USDA, Forest Service, are installing snow fences along the Continental Divide near Independence Pass, Colorado, designed to increase the size of winter drifts, thereby delaying snowmelt and increasing the late summer runoff. They are testing photogrammetric surveys as a method to evaluate the accumulation of snow behind these fences during the winter, which would be an extremely laborious task if done from ground measurements alone.

So far only point measurements at grid intersections have been evaluated. This scheme permits analysis of many more depth values than would be practical from a field survey, but these are still interval measurements and considerable information about the transitions from point to point is lost. Contour maps of snow surfaces can easily be made from the photogrammetrist's point of view--more easily than point measurements. Newly available data processing equipment permits reducing contour maps to digital form at the time the contours are traced, and statistical techniques being developed at The University of Michigan and elsewhere will yield data from comparisons of contour maps that have not been previously obtainable.

Recommendations

In general terms, the reliability of measurements from vertical aerial photography depends on the flying height above the surface and the focal length of the camera lens. Together they determine the scale ratio of the aerial photography and consequently the mapping scale. The focal length by itself determines the vertical exaggeration in the stereo image and also the topographic displacement. The following relation:

$$\text{Scale ratio} = \frac{\text{Distance on photograph}}{\text{Distance on ground}} = \frac{\text{Focal length of lens}}{\text{Flying height above ground}}$$

is useful when comparing different scales.

Photo Scale and Map Scale. Any particular flying height-lens combination determines (1) the area covered in a particular model, (2) the maximum allowable vertical ground relief in the area covered by the model, and (3) the scale of the finished map. With 1:6000 aerial photography, the size of the area covered by one model is about 1800 by 3000 feet; for 1:3000 photography, the size of the area covered by one model is about 900 by 1500 feet. The optimum relief 5/ allowable within one model is usually figured as plus or minus 10 percent of the flying height. With extensions on the plotter, the maximum relief is nearly twice the optimum, but the optical system of the plotter is then being used near its limit. The scale of the finished map is five times the scale of the aerial photography. 5/ Various photogrammetric relations for two different scale ratios taken with a 6-inch lens are shown as follows:

Photographic Scale Ratio	Map Scale	Flying Height Above Surface	Optimum Relief Per Model
1:6000	1 inch = 100 feet	3000 feet	600 feet
1:3000	1 inch = 50 feet	1500 feet	300 feet

The choice of scale ratio is somewhat arbitrary at lower to middle elevations but should be a consideration at higher elevations where the flying height for a given scale would require the use of oxygen equipment. Photography with scale ratios smaller than 1:6000 were not evaluated; however, for topographic mapping it is known that spot elevation accuracy is larger than one foot for scales of 1:12000 or 1:15840.

Surveyed Control Points. Surveyed control is the most important requirement for precise photogrammetric measurement. Third-order accuracy must be strictly adhered to for

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5/ This varies slightly with other than Kelsh plotters.

horizontal control. Vertical control should be accurate to less than one-tenth of the minimum prescribed contour interval for the particular map scale. Minimum control required five points per stereo model, all of which must have vertical control; three of the five must also have horizontal control (Figure 4).

Control Point Targets. Horizontal and vertical controls are permanently marked with brass caps. The target is usually a 90-degree cross intersecting over the control point. White paper, cloth, or plastic is often used for ground control; the width and length depends on the photo scale. A total length of 6 feet and a width of 4 inches are sufficient for 1:3000 photography. If the scale is halved to 1:6000, the dimensions of the target should be doubled.

Marking control points after snow has begun to accumulate requires that the vertical projection of the ground control point be easily located. This was accomplished by driving fence posts at the control points or erecting poles in locations where snow accumulation is higher than the fence posts. Black crosses, marked with boards of the dimensions indicated above, were used to locate the control points on the snow.

There are disadvantages to posts and poles since they must be marked for visibility from the air before each flight. Also, snow movement bends poles and displaces the top of the pole from the vertical projection of the control point. Consideration has been given to using towers or stands with control points marked on platforms which would serve as a datum for both ground and snow surface model setups. If the proper platform could be designed, this would eliminate revisiting and premarking the area before each flight. Some designs are to be tested during the winter of 1967-68.

Snow Surface Elevations. Difficulties in accurately reading snow surface elevations arise from three independent sources: (1) film exposure and processing, (2) snow surface texture, and (3) light contrasts in the immediate area of the point being read.

It cannot be emphasized too strongly that film must be exposed and developed specifically to emphasize tone differences. Snow in properly exposed and developed pictures appears gray or dirty, not white and sparkling. In snow, tone, or the range of shades between black and white, results from albedo differences of the surface ice or snow and from shadows created by the microrelief of sun cups and wind sculpturing.

The texture or roughness of the snow surface is a critical feature determining the success of photogrammetric snow measurements. Newly fallen snow is very flat and does not acquire satisfactory texture until differential melting or wind sculpturing has occurred. Photogrammetric snow surveys should be postponed until a surface texture has developed.

Contrast, or the degree of difference between tones, varies from low, as between similar tones, to high, as between light grays and black. The greater the contrast, the greater the ease of reading elevations in the immediate vicinity of the contrast. The shadows from scattered trees and shrubs produce the highest contrast on snow surfaces, which enhances reading ability. A mosaic of shadows and light makes for excellent surface readings, Obviously, depths cannot be determined in large areas of complete shadow coverage.

It is worth repeating that the photogrammetric measurement was done by professional, experienced photogrammetrists. The science of drawing reliable information from a white surface depends also on the art of using any subliminal information available on tone, contrast, texture, slope, etc.--this comes only by experience.

Digitizing Elevations. Automatic digitizing of elevations is strongly recommended to prevent transcription errors. In addition, X and Y grid coordinates should be specified for readings to ensure that the correct ground elevations are subtracted from the snow elevations at precisely the same point. Not only does the coordinate system reduce errors, it generates the data in a form that can be easily handled on a computer for such problems as fitting surfaces, plotting cross sections, etc.

Conclusions

Measuring snow depths by aerial photogrammetry has been demonstrated to be a practical technique for obtaining detailed information on the distribution of snow in areas of

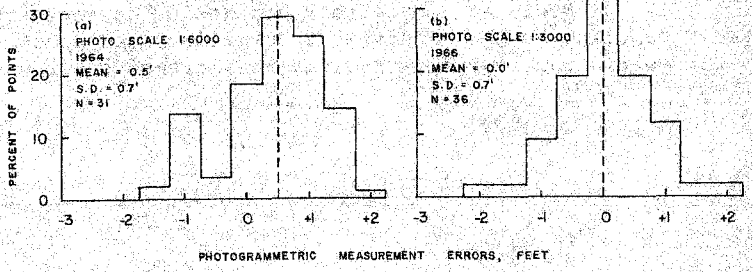

FIG.2. PERCENTAGE DISTRIBUTION OF PHOTOGRAMMETRIC SNOW DEPTH MEASUREMENT ERRORS

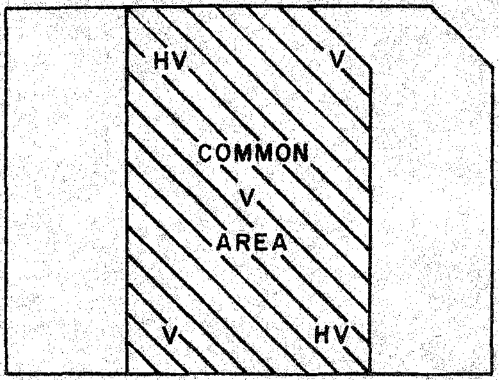

FIG.1. EXAMPLE OF THE STEREO MODEL (CROSSHATCHED AREA) OF THE COMMON AREA OF TWO ADJACENT AERIAL PHOTOS

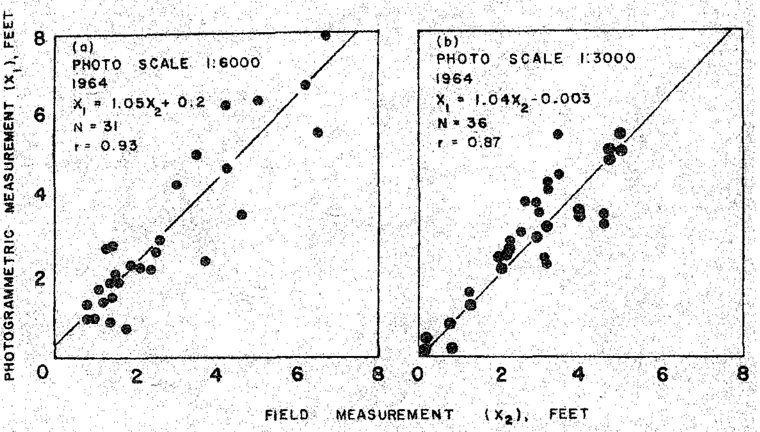

FIG.3. COMPARISON OF PHOTOGRAMMETRIC AND FIELD MEASUREMENT OF SNOW DEPTHS

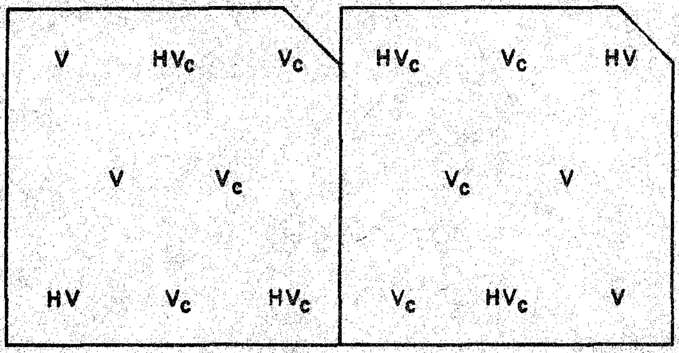

FIG.4. LOCATION OF SURVEYED VERTICAL (V) AND HORIZONTAL (H) CONTROL POINTS ON TWO ADJACENT PHOTOS. SUBSCRIPT c DENOTES POINTS COMMON TO THE STEREO MODEL. (SEE FIG.1.).

complex relief and for determining mean snow depth in such areas with high precision.

With the required surveyed controls, minimum errors for point elevation determinations on snow surfaces can be obtained by professional photogrammetrists under specific qualities of film exposure and development, snow surface texture, and light contrast.

Newly available data processing equipment and computing techniques permit efficient handling of the generated information. The application of such techniques to photogrammetric snow surveys promises to increase their usefulness substantially in the future.

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