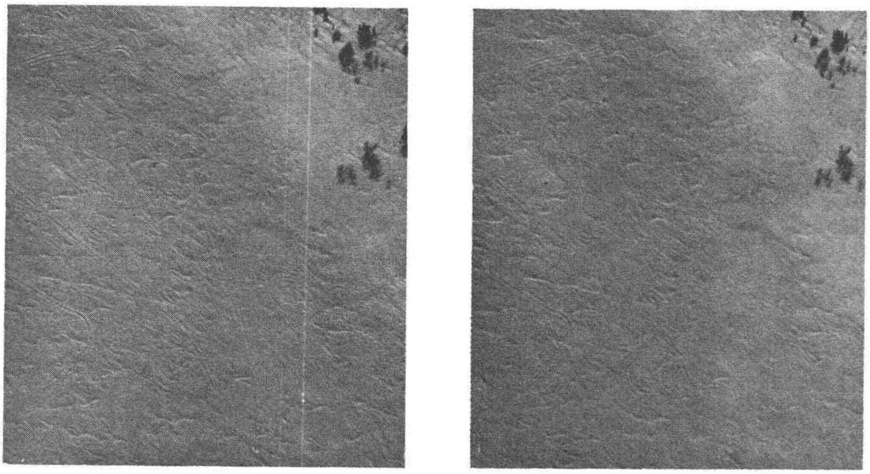

FRONTISPIECE. Stereogram at scale of 1:2400, showing typical snow conditions. Black cross at upper left marks a control station.

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Snow Cover Measurement†

Photogrammetric techniques constitute a practical means for determining the volume of snow in mountain areas and the water subsequently available for stream flow

(*Abstract on next page*)

INTRODUCTION

MOST MOUNTAIN STREAMS in temperate regions owe their origin chiefly to the melting of snow. Preseason forecasts of the expected discharge of snow-fed streams and analysis of the processes by which snow is translated into runoff, both require knowledge of the quantity and distribution of water stored in the snowpack as the season progresses. The great variability of snow depth and rates of melt in mountain areas makes this information extremely difficult to obtain.

Experiments in the Owyhee Mountains of southwestern Idaho have shown that the depth of snow at a point and its volume on an area can be estimated photogrammetrically with considerable accuracy. Point measurements can be used to study patterns of snow distribution. Snow volumes determined by photogrammetry can be multiplied by average snow density to estimate the quantity of water stored in the snowpack.

The use of photogrammetry to measure snow and ice is not new. Zingg (1954) produced a map of snow distribution in a mountainous area of southern Germany by a technique much like that described in this paper. Both aerial and terrestrial photogrammetry have been used to plot movement of glaciers and changes in their volume (Blachut, 1960; Konecny, 1964). Apparently there have been no critical evaluations of the accuracy of photogrammetric measurements of snow cover, however.

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ABSTRACT: *Snow depths can be determined photogrammetrically by subtracting ground elevations at the intersections of a half-inch map grid from snow surface elevations at the same points. Tests in southwestern Idaho have shown that elevations are no more difficult to read accurately on snow than on bare ground. Photogrammetric snow depths consistently exceed measured depths by 0.5 to 1.0 foot, but it should be possible to reduce or eliminate this bias. The calculated standard deviation of snow depths is 0.78 foot at a photo scale of 1:6000. This is within the accepted range of photogrammetric accuracy. Photogrammetry is a practical means of determining the volume of snow on an area, or its depth at a point in relation to land form and solar radiation.*

THE PHOTOGRAMMETRIC TECHNIQUE

Snow depth is measured by subtracting photogrammetrically determined ground surface elevations from similar elevations of snow-covered sample points. The base elevations are obtained when the area is free of snow. The necessary horizontal and vertical control stations are monumented with tall poles so they can be easily relocated when covered with snow. At specified intervals during the winter, the area is reflown after premarking the control stations with black paper laid on the snow. Snow depth at each control station is measured at time of flight.

A grid with squares of proper size is laid on the projection table of a stereo plotter, and ground elevations are read at each grid intersection. Attachments are available to record elevations directly on punched cards or magnetic tape without intermediate steps, or they can be manually transcribed. If a half-inch grid is used, the output from a normal stereo model is a deck of some 2,200 cards, each specifying the elevation and grid coordinates of a point.

The snow surface model is set up in the plotter just as was the ground base. The control elevations are the surveyed elevations of the premarked stations plus the measured snow depth at the time of photography. A grid, oriented like the original, is laid down and the snow surface is read at each grid intersection. The output is again a deck of punched cards, each giving the snow surface elevation and the grid coordinates of a point.

The computer program used for analysis of the data was derived from one originally developed for photogrammetric estimation of earthwork quantities in open-pit mining. The computer subtracts the ground elevation from the corresponding snow surface elevation at each grid intersection, and averages the result to give the mean depth of snow and its volume on the entire area. For more detailed analysis of the relation of snow depth to land form and exposure to solar radiation, the computer can be programmed to deliver a cross-section along any specified grid line.

FIELD TESTS

Preliminary tests of photogrammetric snow measurement were made in February, 1962, on the Reynolds Creek Experimental Watershed in southwestern Idaho. The study area, 5 miles northwest of the abandoned mining town of Silver City, ranges in elevation from 6,700 to 7,000 feet. Midwinter snow depth varies from less than a foot to about 20 feet. Vegetation in the sample area is predominantly open sagebrush about 2 feet high, with a few aspen and Douglas fir trees up to 60 feet high and willow clumps 15 feet high.

The first test was made at a photo scale of 1:12,000. A unit within the larger block was flown at a scale of 1:2,400. Results were encouraging. A map made from the larger scale photography shows the distribution of snow in relation to topography (Figure 1). Prevailing winter winds in southwestern Idaho are from the southwest, so the southwest slopes are blown nearly free of snow while deep drifts build up in sheltered areas facing to the north and east. Snow depth in the 16-acre mapped area ranged from a few inches to more than 14 feet.

The 1962 results indicated that the 1:12,000 photo scale was too small, and the 1:2,400 scale was too large. A more detailed test in the winter of 1963–64 was therefore based entirely on 1:6,000 photography.

An area 3,000 feet by 1,800 feet was laid out to include the widest range of slopes and snow conditions that could be incorporated in a single stereo model. The base photography was flown in October, 1962. Photographs with snow on the ground were taken on

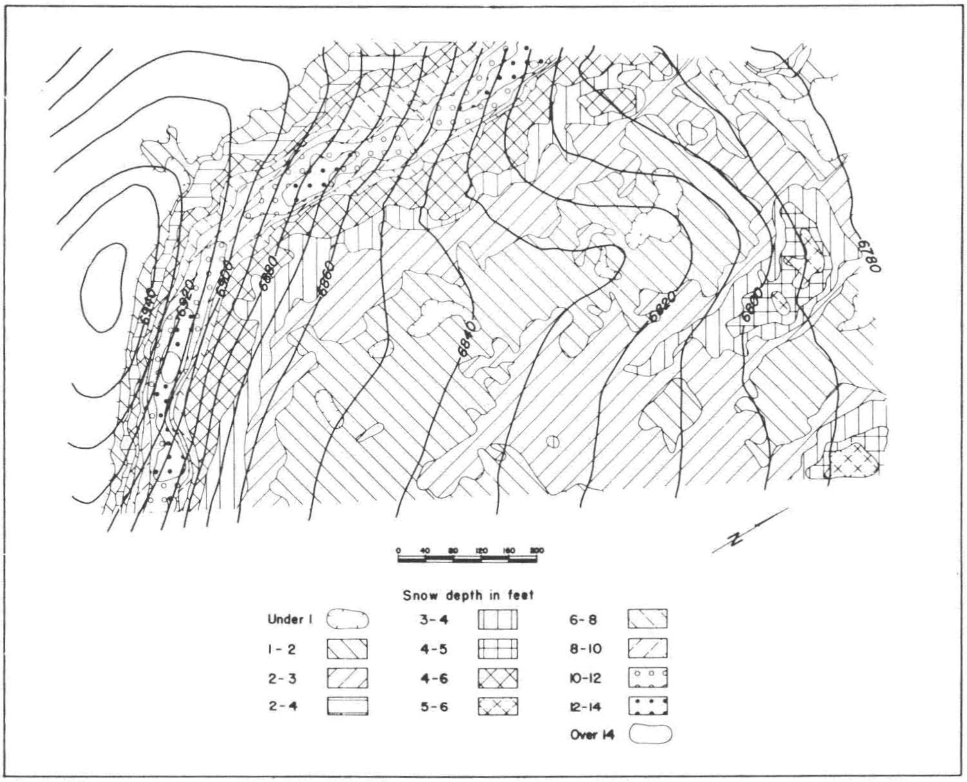

FIG. 1. Map showing distribution of snow on a 16-acre area in the Reynolds Creek Watershed, Owyhee Mountains, Idaho. Prepared from aerial photographs made on February 26, 1962.

January 27, April 8, May 12, and May 20, 1964. On the first two dates almost all of the sample area was snow covered. On May 12 the snow had melted from about two-thirds of the area; on May 20 only about one-fourth still had snow. All photographs were made with a Park Precision Aerial Camera equipped with a 153.63 mm. Metrogon lens.

Elevations were determined on a Kelsh plotter by experienced personnel of Aerial Mapping Co., Boise, Idaho. With the five-power enlargement of the Kelsh plotter, the mapping scale was 1:1,200. Half-inch grid squares were used, corresponding at this scale to a ground distance of 50 feet between readings. Elevation data were entered manually on adding machine tapes, from whence they were transcribed to punched cards.

The snow was fresh but wind-sculptured on the first two dates. New snow had fallen two or three days previously. The strong winds prevalent in this area had formed many small irregularities in the surface (Frontispiece). Snow melt was well advanced at the time of the last two sets of photographs. The snow was dirty, and its reflectivity was relatively low.

EVALUATION PROGRAM

The precision, accuracy, and systematic error of the photogrammetric technique were evaluated through statistical comparisons of field and photogrammetric measurements at 31 randomly located stations. All three of these elements must be considered in the assessment of any measurement process (Eisenhart, 1963).

Systematic error, or bias, is the extent to which a process measures something other than that which was intended. It is the difference between the mean value of a substantial number of measurements and the true value of the quantity being measured. The precision of a measurement process is determined by the degree of mutual agreement among repeated independent measurements of a single quantity made under specified conditions. Accuracy refers to the degree of coincidence of such measurements with the true value of the quantity concerned.

Accuracy thus had to do with closeness to the truth; precision only with closeness together.

The precision (or more correctly the imprecision) of a measurement process is ordinarily expressed by its standard deviation. Unfortunately, there is no analogous comprehensive measure of accuracy. To characterize the accuracy of a measurement process it is necessary to specify its precision and to place credible bounds on its systematic error or bias (Eisenhart, 1963).

The sample points used in the evaluation of photogrammetric measurements were premarked before the ground surface was photographed, and were plotted on the base grid when the original stereo model was set up. The location of the points bore no relation to the arbitrary plotting grid. The sample points were not premarked when the snow photographs were made. Their position in respect to the snow was established entirely from their marked location on the base grid. Their accuracy of relocation thus depended upon proper orientation of the base grid, just as did the accuracy with which the grid intersections fell at the same point in each model.

The apparent elevations of the ground and the snow at each of the 31 sample points were read independently by three experienced plotter operators. Each observer's estimate of snow depth at every point was then computed by subtracting his estimate of ground elevation from his estimate of snow elevation. These photogrammetrically determined snow depths were compared with field measurements of snow depth at the same points, made on the day the area was photographed.

There were at least two weaknesses in this experimental design, one of which could not have been foreseen. In the first place, each stereo model was set up by one operator, and the same setup was used by the other two observers. It would have been better if each observer set up his own model and levelled it to the designated control elevations. In the second place, the same three observers were not used throughout. One of the operators who read the ground surface and the January 27 snow model was not available when the last three sets of snow photographs were analyzed. A different operator therefore had to be used.

Relative Variability of Ground and Snow Measurements

Experienced photogrammetrists are accustomed to working with a variety of cover conditions, but snow is outside their usual experience. Because of its high reflectivity and lack of surface features, it might be expected that it would be more difficult to make accurate elevation readings on snow than on bare ground. Analysis of variance of the three sets of measurements at the 31 sample points was used to test this assumption. Deviations from the mean of all the elevation observations without snow on the ground and with the January 27 snow cover were partitioned to show the contributions of initial elevation differences among the sampling stations, elevation differences due to presence or absence of snow on the two dates, observational differences among the three observers, and the interactions of these components (Table 1).

Table I. Analysis of Variance, Ground Surface Elevations and January 27 Snow Surface Elevations

Component	*Degrees of Freedom*	*Mean Square*
Stations	30	28746.27**
Snow cover present or absent	1	569.27**
Interaction: Stations × Snow Cover	30	6.87**
Observers	2	0.60 N.S.
Interaction: Observers × Snow Cover	2	0.30 N.S.
Residual variance		
Snow observations	60	0.31
Ground observations	60	0.23

** Significant at one percent probability level.
N.S. Not statistically significant.

The first two of these components are environmental effects which must be removed before differences among observers can be properly evaluated. Since the sampling stations extended over an elevation range of 270 feet, and since average elevation of all the points was 3.5 feet higher with snow on the ground than when the surface was bare, these components were, as expected, statistically highly significant. So was the interaction between them, showing that the snow was deeper at some points than at others.

Of more interest are the components involving the three observers. There was no statistically significant difference in the overall average elevations, including both snow and ground readings, measured by the three observers. In other words, although there were differences among the three in reported elevations at a single point, these differences

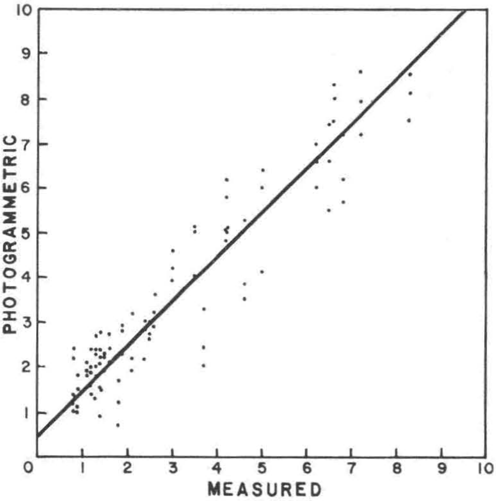

FIG. 2. Relation of photogrammetric snow depth to measured depth on January 27, 1964. All depths in feet.

were neglibible when averaged out over all 31 points.

Likewise, there was no significant interaction between observers and cover. There was no evident tendency for one operator to measure either ground or snow elevations markedly differently than did the others.

Finally, although the unaccounted for residual variation among measurements was slightly greater for the snow observations than for the ground, the difference was not statistically significant. The standard deviation, the range around the true elevation within which 68 per cent of all measurements are expected to fall, was 0.48 foot for the ground measurements and 0.56 foot for the snow measurements.

These results suggest that there is no material difference in the ability of experienced plotter operators to obtain consistent results whether they are working with snow or bare ground. A similar analysis of the April 8 snow measurements yielded essentially the same results and led to the same conclusions.

Reliability of Photogrammetric Measurements

When photogrammetrically determined snow depths were plotted against measured depths, they fell nearly along a straight line (Figure 2). Regression methods were used to test the fit of these points to the line.

Thirty-one sample points had snow on January 27 and April 8. By May 12 the snow had melted away from all but 12 points, and on May 20 so few points still had snow that a comparison was not worthwhile.

Determination of the photogrammetric snow depths on January 27 was straightforward, because the same three observers read both the ground surface and the snow surface elevations. A new man had to be used for one of the readings on the later dates, though, and there was no initial ground reading with which his snow elevation measurements could be compared. It was therefore necessary to use the mean of the ground elevations determined by the three original observers as the new operator's base elevation. This procedure introduced some unavoidable bias.

The observations were entered in regression equations of the form

$$y = a + bx \tag{1}$$

where y is photogrammetrically determined snow depth, x is measured depth, and a and b are constants. The hypotheses to be tested are that the regression coefficient b is not significantly different from 1.00, and that the constant term a is not significantly different from zero. If these assumptions are true, photogrammetric depths are on the average equal to measured depths.

The primary analysis involved the data from January 27 and April 8, when all the sample points were snow covered. There were 186 paired observations of photogrammetric and measured depths—31 for each of 3 observers on each of 2 dates. Covariance analysis was used to compare the differences in the constants a and b among observers and between dates.

There was no significant difference among the regression coefficients calculated for the separate sets of observations, or between the regression coefficients calculated from the pooled observations on each of the two dates. Furthermore, none of the regression coefficients was significantly different from 1.00.

There was a significant difference between the constant terms a in the regression equations for the two dates. It was 0.5 on January 27 and 1.0 on April 8. Considering the two dates separately, there was no significant difference in the value of this term among the three observers on January 27, but there was on April 8. The observations of the new operator averaged 0.4 foot lower than those of the other two observers. However, since it was known in advance that a bias was being introduced by the use of the new man, too much meaning cannot be ascribed to this result.

The correlation coefficient (r) between photogrammetric and measured snow depth was 0.95, meaning that about 90 per cent (r^2) of the variance of the observations was accounted for by regression.

The results of the May 12 observations were not nearly so satisfactory. The calculated regression coefficient was significantly different from 1.00, and the regression equation accounted for only 56 per cent of the variance. The model was accordingly set up again and the 12 points read again by the three observers. No obvious difficulties were noted in setting up the model that might have been responsible for the poor initial readings. Nevertheless, with the new setup the regression equation accounted for 71 per cent of the variance, a 26 per cent gain in efficiency. On both setups one point consistently appeared about 4 feet lower than field measurements would indicate. This point lay in a deep snowbank and was marked by a pole which was bent by shifting snow.

It is likely that the field measurements were as much in error as the photogrammetric. In any case, when this point was discarded and the regression recalculated from the second setup, the results fell closely into line with those of the previous dates. The adjustments that were made to attain this result biased the data too strongly for the May 12 observations to be included in the overall calculation. Because of the small number of points available on this date and because of other possible sources of error, not too much significance can be attached to the poor results of the May 12 observations.

Errors of Point Measurement

The consistent upward bias of the photogrammetric depths as compared with the field measurements, ranging from 0.5 to 1.0 foot on the three dates, is an apparent systematic error. It could arise in several ways. There is a recognized tendency for plotter operators to read high on light-colored surfaces and low on dark. All the measured snow points were substantially lighter than the surfaces encountered in normal practice.

The premarks used to level the model, on the other hand, were black paper crosses. Although the paper was only 7 inches wide, the operator who set up the model centered his floating dot at the center of the cross rather than on the adjacent snow surface. This had not been anticipated by the Agricultural Research Service field crews who handled the ground control. We assumed that the plotter operator would level to the snow surface immediately beside the premarks. Because of absorption of solar radiation by the black paper, the premarks in some cases sank 0.2 foot or more below the level of the surrounding snow. This depression was not measured. The fact that the premarks actually were slightly below the snow surface, coupled with the likelihood that the operator read the dark crosses even lower than they really were, could have produced a systematic error. Possible ways to eliminate this error are considered later.

There is also a random error resulting from the cumulative effect of minor mistakes in reading the elevations of the ground and snow surfaces. This can be estimated from the results of the regression analysis.

The standard deviation of the photogrammetric measurements, as calculated from the regression equations for January 27 and April 8, is 0.78 foot. If there were no general or systematic difference between the means of the photogrammetric depths and the measured depths, 68 per cent of all photogrammetrically determined depths would fall within 0.78 foot of the true value. Simple calculations based on Student's t distribution indicate that 90 per cent of all photogrammetric depths would be within 1.3 feet of the true value, and 50 per cent within 0.5 foot. The standard deviation of the less satisfactory May 12 measurements was about 1.0 foot.

The precision and accuracy of photogrammetric measurements are apparently independent of snow depth. Neither the variability nor the systematic error increased as the snow became deeper (Figure 2). The statistical comparisons of photogrammetric with field depths assume that the field depths were fixed values measured without error. Obviously this was not true. This introduces complications in precise statistical interpretation, but does not alter the general conclusions.

The variability of photogrammetric observations is put in better perspective when compared with the variability of snow depths determined by actual field sampling. Snow depth and water content at Reynold Creek are routinely measured throughout the winter at 60 random sampling points, including all those used in the analysis reported here. On March 26, 1964, three depth measurements were made at the 45 stations that had at least 1 foot of snow. These measurements, made with a standard snow sampling tube, were spaced no more than 2 feet apart.

Analysis of variance showed that the standard deviation of the depth measurements at a single point was about 0.14 foot. A similar analysis of data from another area several miles away showed the standard deviation of field measurements to be 0.16 foot. This is roughly one-fifth that of the photogrammetric measurements.

Comparison with Conventional Mapping

The precision of the snow measurements compares favorably with that of conventional photogrammetry. Of 12 mapping projects accepted by the California Division of Highways and analyzed by Funk (1958), 4 had standard deviations greater than 0.78 foot. The standard deviations of the 8 remaining mappings ranged from 0.72 to 0.52 foot. All 12 of these projects were mapped at a scale of 1 inch to 50 feet, twice that used in the snow study. Standard deviations of measurements at the scale used in the California work would normally be smaller than at the 1 inch to 100 foot scale used in the snow surveys.

Snow measurements are differences between two photogrammetric measurements, each with its own error. The standard deviation of such a compound measurement is given by

$$s_c = \sqrt{s_1^2 + s_2^2} \qquad (2)$$

were s_1 and s_2 are the standard deviations of the two sets of determinations. It is thus apparent that the standard deviation of snow measurements is necessarily greater than that of ground measurements alone made under identical conditions. This puts the relatively low standard deviation of the snow measurements in an even more favorable light.

The systematic error or bias of the snow measurements was substantially greater than that of the highway maps studied by Funk. The bias of the 12 highway maps ranged from -0.40 to $+0.62$ foot, with the majority no more than 0.10 foot from the correct value.

Accuracy of Volume Determinations

If statistical limits are to be assigned to snow volume estimates, it is necessary to assume that the variance of grid intersection measurements is the same as the variance of the measurements at the 31 random sample points. There is no objective evidence for this except that the measurements at the grid intersections were made in the same way as at the sample points.

It is also necessary to assume that usable statistics can be computed from grid data. To conform fully with the requirements of statistical theory, measured points must be randomly spaced. However, usable statistics have commonly been derived from grid sampling designs in forest inventory and in other applications. Provided there is no regular pattern of environmental factors, as there might be in a corn field planted in rows, there is no fatal objection to a grid design. Admitting certain theoretical difficulties, it seems legitimate to apply conventional statistics to the estimation of snow volume from a photogrammetric grid.

The standard error of a mean is $s/\sqrt{n}$ where s is the standard deviation and n is the number of observations used to compute the mean. There were 2,376 photogrammetric measurements at grid intersections in the Reynolds Creek study, and, as stated above, the standard deviation of the sample measurements was 0.78 foot. Therefore, the standard error of the mean snow depth is 0.016 foot, negligible for practical purposes. To this error must be added the systematic error resulting from the failure of the mean of all the photogrammetric sample measurements to equal the mean of the field measurements. This bias ranged from 0.5 to 1.0 foot on the three sampling dates.

Snow volume is computed by multiplying the area of the sample by mean snow depth. The area is a fixed value, so the error of the volume estimate depends entirely on the error in mean depth. This error is principally the systematic error that consistently makes snow depths appear too great. Because of the large number of photogrammetric measurements used to compute the mean, random variation around this systematic error is too small to be of any practical consequence.

The systematic error of a measurement process ordinarily has both constant and variable components (Eisenhart, 1963). Some of these are of known and some are of unknown origin. Constant errors of know origin can, in principle at least, be identified and accounted for. Others must be estimated on the basis of theory or of repeated measurements made under similar conditions. As Eisenhart (1963) has pointed out, it is rarely possible to apply statistical probability values to the magnitude of systematic errors. The most that can usually be done is to place credible bounds on the likely error.

Some of the sources of bias in photogrammetric snow measurements have already been discussed. It seems likely that with improved ground control and other refinements, the systematic error can be held to well under 0.5 foot.

Problems and Reduction of Errors

If an area is to be repeatedly photographed for research purposes or for year-to-year estimates of snow cover, permanent control stations should be erected above the snow. These might consist of level wooden platforms about 12 feet on a side, mounted on sturdy wooden poles set well into the ground below the frost line. To the extent permitted by spacing requrements in the photogrammetric model, the platforms should be on windy sites where they will largely be swept clean. Crosses painted on the platforms would serve to level the model in the plotter. The platforms would need to be shovelled clean for midwinter photography, but solar heating would do the job during the melt season. The other plausible type of permanent ground control, a slanting pole with evenly spaced horizontal crossarms that become progressively covered or uncovered by snow, is probably less practical because of drifting and radiation melt.

Premarking on snow is not easy. The marking must be done immediately before the photographs are made, and close coordination between ground and flight crews is essential. If black paper premarks are allowed to remain too long in clear weather, heating by absorption of solar radiation causes them to sink into the snow. In snowy or windy weather they are soon obliterated.

Blachut (1960) concluded that if it is to be easily seen, a black target on a white background must be at least three times the size of a white target on a dark background. Our experience contradicts this. Black paper crosses of the same dimensions ordinarily used for white crosses on the ground proved satisfactory.

Flying in mountainous country in uncertain weather is hazardous, and flights often cannot be made when measurements are desired.

Snow surface conditions are important. Lack of surface definition may be critical if photographs are made immediately after a snowfall or if illumination conditions cause strong reflections (Blachut, 1960). Our experimental design called for one set of photographs to be made immediately after new snow had fallen, presumably the worst situation for accurate surface interpretation. Weather conditions did not permit this, however, and all photographs were taken after ripples and irregularities had been formed by the wind.

The spring ice glaze that results from daily thawing and nightly freezing is another probable unsatisfactory condition. One set of preliminary photos, in April, 1962, was made when this condition was well developed. Although no critical analysis was made, examination in the Kelsh plotter indicated no apparent difficulty in reading surface elevations.

Water Content Estimates from Photogrammetric Data

Water content of the snowpack is estimated by multiplying the photogrammetrically determined volume by average snow density. The latter is best obtained from field samples, although usable telemetering devices are being developed.

There are sampling and instrumental errors in both volume and density. The variance of the product of two terms each measured with error is greater than that of either alone. The total sampling error of a snow water content estimate is therefore dependent on the magnitude of the error of the volume estimate and of the density estimate.

It is likely that the sampling error of the photogrammetrically determined volume will be smaller than that of density determined from field samples. It has been shown that, with the large number of sampling points used in photogrammetric determinations, the standard error of volume estimate can be kept small.

Extensive field measurements over two seasons at Reynolds Creek demonstrate that, although mean snow density increases appreciably from early winter to late spring, the standard deviation of the density measurements on any particular date remains between 0.06 and 0.07 g/cc. The minimum standard error density that seems acceptable is about 0.02 g/cc. Application of the procedure suggested by Cochran (1956:501) for determining the size of sample necessary to hold sampling error within desired limits indicates that, with the observed variability among snow density measurements, between 35 and 50 field samples are required to estimate snow density with 95 per cent confidence that the computed density is within 0.02 g/cc of the true mean. This is close to the practical and economic limit for any one location.

Detailed study of snow density patterns may reveal measurable physical factors that can be used to stratify snow samples and reduce the variability of density estimates. In the meantime, it seems that density variations over an area will contribute substantially more to the uncertainty of photogrammetric estimates of snowpack water content than will snow volume errors.

Conclusions

Photogrammetric methods can provide a mass of detailed information about the distribution of snow that would be virtually impossible to obtain by field sampling. At a photo scale of 1:6,000, an area of about 90 acres can be incorporated in a single stereo model. The snow depth at more than 2,000 points, spaced 50 feet apart, can be sampled in such a model. The cost of field work to measure the actual depth of snow at all these points would be prohibitive.

In the tests reported here, photogrammetric snow depths were consistently 0.5 to 1.0 foot greater than measured depths. Better ground control and more careful attention to possible sources of error should reduce this bias.

There would still be a random variation of individual depth observations around the true value even if there were no overall bias. The standard deviation of the photogrammetric snow measurements, the variation from the true depth within which 68 per cent of all observations are expected to fall, is about 0.8 foot, compared with a standard deviation of about 0.15 foot for direct measurements in the field. A single photogrammetric measurement is thus less certain than a single direct field measurement, but this uncertainty is compensated for by the greater number of points that can be measured photogrammetrically.

Estimates of the total quantity of water stored in the snowpack are obtained by multiplying the volume of snow on the sample area by its density. The error of estimate includes the error in the photogrammetric volume and in the field density estimate. The second of these is apt to be the larger, at least when present methods, and is the limiting factor in the estimation of total stored water.

Photogrammetric measurement of snow cover requires expensive ground control and close coordination between ground and air crews, and may involve hazardous operations in bad weather. It is not a cost-cutting or labor-saving device. Its principal value is in providing information about the quantity and distribution of snow cover that cannot readily be obtained in any other way.

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