DIGITAL PHOTOGRAMMETRIC DETERMINATION OF ALPINE SNOWPACK DISTRIBUTION FOR HYDROLOGIC MODELING

Donald W. Cline

ABSTRACT

This paper discusses progress in the use of digital photogrammetry for producing two products: 1) orthophotos, from which maps of snow-covered area (SCA) can be produced, and 2) maps of the spatial distribution of snow depth, determined by subtracting a snow-free DEM from a snow-covered DEM. SCA is commonly used by snow hydrologists for modeling and other purposes. When aerial photography is used as a source for SCA, it is important that the photography is first ortho-rectified. In this paper, it is shown how digital photogrammetry can be used to produce orthophotos on a desktop computer, using ground control obtained from maps and a digital elevation model (DEM). The digital photogrammetric determination of snow depth has proved to be a much more difficult task, and results so far have been unsuccessful. Strict requirements for ground control accuracy appear to be the major constraint for this method. A brief overview of digital photogrammetry is provided, followed by a discussion of testing results from Sky Pond, an alpine basin in Rocky Mountain National Park, Colorado.

INTRODUCTION

Photogrammetry is principally concerned with retrieving geometric and physical properties of objects in photographs; commonly the photographs are assumed to be vertically oriented and the objects in question are terrain features or the topography itself (*i.e.* surface elevations). Aerial photographs and photogrammetry are frequently used to determine the spatial distribution of snow cover. In mountainous regions, photogrammetric procedures are generally necessary to correct geometric distortions in the photography caused mainly by topographic relief. The resulting orthophotos are routinely used to calculate snow-covered area (SCA) for use in hydrologic models, such as the Snowmelt Runoff Model (Martinec, Rango, and Major, 1983). For research, but not operational purposes, conventional photogrammetry has been used to determine the spatial distribution of snow depth by subtracting a snow-free elevation surface from a snow-covered elevation surface (Smith, Cooper, and Chapman, 1967).

Traditionally, photogrammetry has required the use of specialized optical systems and laborious human interaction to generate orthophotos or to reconstruct surface elevations. These traditional methods may be referred to as projective photogrammetry, in that the geometric relationship between light rays, the camera, and the surface is mechanically recreated in photo-optical instruments such as analog or analytical stereoplotters. Trained photogrammetrists are ordinarily required to operate such instruments, and the large expense of the instruments themselves has generally restricted their use to larger production-oriented service bureaus or mapping agencies. In the past, most snow hydrologists requiring photogrammetric products would require such services.

A rapidly developing stage of photogrammetry is digital photogrammetry, in which the effects of the specialized optics used in conventional mechanical instruments are calculated digitally within a computer. Aerial photographs are captured in a digital format, and the physical photo/optical measurements of projective photogrammetry are replaced in large part by computation using a desktop computer. One aim of digital photogrammetry is full automation (Zheng, 1993); while digital photogrammetry is not (yet) fully automated, the need for a fully trained photogrammetrist is obviated by the elimination of the photo-optical instrumentation. This creates an opportunity for researchers in other fields, such as snow hydrology, to perform their own photogrammetry at a potentially much reduced cost.

Digital photogrammetry is still very much in a developmental stage; most recent advancements relate to implementing the well-understood mathematics of photogrammetry in an automated

---

Department of Geography, University of Colorado, Boulder, CO 80309

environment, *i.e.* making the machine do what we can already do using manual (photo-optical) methods. Digital photogrammetric software is now widely available, as the development of most basic functions is complete. In an on-going study of snowmelt and runoff in two small Colorado Front Range basins, I elected to explore the utility of digital photogrammetry 1) for orthophoto production to determine SCA, and 2) for determining the spatial distribution of snow depth within the basins.

In this paper, I discuss my experiences gained to date with digital photogrammetry pertaining to these two snow distribution characteristics. First, a brief overview of digital photogrammetry is provided. The focus here is on general aspects which should be relevant regardless of the specific software used. Then, results of testing digital photogrammetry for determining snowpack distribution in Sky Pond, Rocky Mountain National Park will be discussed.

DIGITAL PHOTOGRAMMETRY: A BRIEF OVERVIEW

For the present purpose, digital photogrammetry can be conveniently divided into four procedural steps. First, aerial photos must be acquired in a digital format. The basic concepts of film type, photo scale, ground coverage, etc. still apply, but there is an added consideration of how the photos will be captured digitally. The second step is aerotriangulation, determining the orientation of the camera relative to the ground for each photo of a stereopair. Third is the production of orthophotography, the correction of inherently distorted photography to an orthographic projection. Last is the generation of surfaces by computation of the $x,y,$ and z coordinates of a relatively large number of unknown points. This overview cannot be exhaustive in nature; it is intended to provide only an introduction to digital photogrammetry, and to provide some indication of what is required in order to use it.

Digital Photo Acquisition Considerations

The principal characteristic of digital photogrammetry is that the aerial photos are digital, *i.e.* a matrix of brightness values. In most cases, this requires that a photo negative, diapositive, or print must be electronically scanned. Digital-recording aerial cameras exist, but are not yet commonly used. All common aerial film types (panchromatic, color, color-infrared) are suitable for digital photogrammetry, although only one band is necessary for the photogrammetric calculations. Scanning panchromatic photography produces a single-band file, while color scanning produces a three-band file (red, green, and blue). For color photogrammetry, one of the bands is used to determine the necessary corrections, which are then applied to all three bands.

Scanning may be performed using any of a number of available desktop scanners with suitable format size (the standard aerial format is 230 mm x 230 mm). Either transparencies (black-and-white negatives and color diapositives) or prints may be scanned, however transparencies offer improved resolution over prints. Resolution ultimately governs the accuracy of the photogrammetry, so both the resolution of the photos and the resolving power of the scanner are important considerations in the digitization process.

Much of photogrammetry is concerned with the measurement of horizontal distances on a photo, such as the measurement of parallax or the position of image points. In digital photogrammetry, the measurement precision for a digital image is one pixel. As image resolution increases, the precision, and ultimately the accuracy of the photogrammetry improves. For example, the error of height determination is given by the equation (Light *et al.*, 1980)

$$\Delta H = \frac{(H/f)}{(B/H)} \Delta Px \qquad \textbf{(1)}$$

where ΔH = error of height determination

H = altitude of camera

f = focal length

B = distance between exposure stations

ΔPx = measurement error.

For a standard 152 mm lens and 60% overlap, the base-to-height ratio is approximately 0.6. Equation 1 then reduces to

$$\Delta H = \frac{P}{0.6} \tag{2}$$

where P = Pixel Dimension in ground units.

However, the gain in accuracy with higher resolution results in rapidly increasing data volume as the pixel size is decreased for a given ground area coverage (Table 1).

Scanning resolution (R) is easily related to the resulting pixel dimension in ground units (G) using the scale factor (S) (the denominator of the representative fraction) of the photography:

$$G = \frac{S * R}{10^6} \tag{3}$$

where R is in micrometers and G is in meters. The dimension of one edge of a pixel for different scanning resolutions and photo scales is given in Table 2, together with the ground area covered by a 230 mm x 230 mm photo at each scale. It is evident that a given pixel resolution is obtainable from many combinations of scanning resolution and photo scale. The higher cost of larger scale photography for a given ground area coverage as well as the increased data volume as scanning resolution increases are additional factors to be considered in the digital photo acquisition process.

Table One. *File sizes resulting from scanning standard 230 mm x 230 mm photo at common resolutions.*

Scanning Resolution	Approx. Equivalent	File Size for 230 mm x 230 mm Photo
80 μm	300 dpi	8.26 Mb
60 μm	400 dpi	14.69 Mb
40 μm	600 dpi	33.06 Mb
20 μm	1200 dpi	130 Mb

Aerotriangulation

For both digital orthophoto production and for surface generation, aerotriangulation is necessary to establish the position and orientation of the camera when each photo of a stereopair was exposed. The two viewing angles of a ground point enabled by a stereopair provide the geometry necessary to calculate the position of the point, once the orientations of the camera are known. Each point that appears on a photo can be considered a record of a light ray which traveled from the surface, through the focal point of the camera/lens system, and exposed a grain on the photographic film. The photo as a whole, then, is a record of a bundle of such rays, and a bundle of rays becomes the basic unit of photogrammetry. Each light ray in the bundle may be described mathematically as a function of a) the

Table Two. *Pixel dimensions in ground units as a function of photo scale and scanning resolution. Also shown is the ground coverage associated with each photo scale.*

	Scanning Resolution (μm)				Ground Coverage
Photo Scale	80	60	40	20	
1:1500	0.12 m	0.09 m	0.06 m	0.03 m	345 m x 345 m
1:3000	0.24 m	0.18 m	0.12 m	0.06 m	690 m x 690 m
1:6000	0.48 m	0.36 m	0.24 m	0.12 m	1380 m x 1380 m
1:12000	0.96 m	0.72 m	0.48 m	0.24 m	2760 m x 2760 m
1:24000	1.92 m	1.44 m	0.96 m	0.48 m	5520 m x 5520 m

position of the ray's origin point on the ground, b) the position of the camera's focal point at the time of exposure in the ground reference system, c) the orientation of the camera, and d) the perspective geometry (distortion characteristics) of the camera. The perspective geometry of the camera is ordinarily determined by laboratory calibration. Once it, and the position of three or more points on the ground appearing in the photograph are known, the position of the camera in space and its orientation can be determined. Once these are known, the coordinates of any point on the ground within the stereo overlap area can be computed as the point of intersection of two light rays (Wong, 1980). Aerotriangulation consists of four orientations: 1) interior, 2) exterior, 3) relative, and 4) absolute.

Interior Orientation. The interior orientation is the perspective geometry of the camera, and consists of the precise focal length of the lens, the center of the image area (principal point), and all distortion characteristics of the camera/lens system (Wong, 1980). Since coordinates of points on the ground are determined by the positions of those points in the photos, any camera/lens distortion that might affect the location of image points must be accounted for.

Exterior Orientation. The exterior orientation is the position of the exposure center of the camera and the direction of the optical axis of the camera in relation to the ground (Wong, 1980). The camera position is determined in the three-dimensional ground coordinate system. The direction of the camera's optical axis is defined by the three rotation angles tilt (ω), swing (ϕ), and azimuth (κ). The precise coordinates of a minimum of three ground control points appearing in a photo are required to solve the exterior orientation. Poorly known points result in errors in the exterior orientation solution, which can result in poor determination of unknown point coordinates later on.

Relative Orientation. Once the exterior orientation of each photo in a stereopair is known, the relative position and orientation of each of the photos in relation to the other must be determined so that corresponding pairs of rays from the two photos intersect in space (Wong, 1980). There are five unknowns in the coplanarity equation used in the relative orientation, therefore if a minimum of five pairs of rays intersect, then the relative orientation is solved and all pairs of rays in the two bundles of rays will intersect as well. Therefore, five accurate ground control points in the overlap area of the stereopair are required to determine the intersection for relative orientation. A greater number of ground control points allows for improved estimation of the relative orientation using least squares methods.

Absolute Orientation. Finally, the orientation parameters are used to transform the stereo model from the image system to the ground reference system. The transformation includes a scale adjustment, the three parameters of the exposure center, and the three rotation angles.

Determining Coordinates of Unknown Points. Once the absolute orientation parameters are determined, three-dimensional coordinates in the ground reference system can be computed for any unknown point by calculating the intersection point of a pair of rays. This is the basis for generating DEMs photogrammetrically. To reiterate, the accuracy of coordinates determined through this process depends on how accurately the orientation parameters have been determined, which in turn is a function of the accuracy of ground control points used in the triangulation.

Orthophotography

The central projection of an uncorrected aerial photograph results in the positions of objects on the ground being displaced from their correct positions in photographs. Both rugged relief and tilt in the camera/lens system accentuate this displacement. As well, photo scale changes with elevation above and below some datum plane of the photography, with the result that area measurements on a photo become a function of position on the photo. These effects are illustrated in Figure 1. These undesirable properties can be nearly eliminated by ortho-rectification. The resulting orthophoto is thus suitable for area calculations and other spatial analysis. Digital orthophotos can be easily registered to GIS databases for analysis, hydrologic model inputs, etc. It should be noted that although the *goals* of ortho-rectification are the same as for rectification of satellite imagery, the rectification procedures are necessarily different due to the effects of relief displacement on aerial photography.

Ortho-rectification requires the same relative orientation parameters as described above, although less accurate ground control can usually be tolerated for horizontal positioning than is required for vertical positioning. For many purposes, ground control for orthophoto production can be determined from topographic maps, DLG data, or other published sources. In digital orthophoto production, the $x,y,$ and z ground coordinates of each image pixel must be known, and are determined using the orientation parameters and a digital elevation model (DEM).

Surface (DEM) Generation

As discussed above, the orientation parameters may be used to determine the three-dimensional ground coordinates of points located within the stereo overlap area of a stereopair. If the coordinates of a sufficiently large number of points can be determined in this manner, the points can then be used to interpolate a regular grid of elevation values for a DEM. Assuming the orientation parameters have been determined accurately, the largest remaining problem is to locate conjugate points, *i.e.* the same point on the ground in both photos of a stereopair. Several automated methods are employed to perform this task; generally they involve automated pattern matching techniques. Details of pattern matching for snowpack surfaces have been discussed elsewhere (Cline, 1993). The degree of interpolation required depends on the density of intersected points.

Recalling Equation 2, the accuracy of snow depth distributions determined by subtracting two DEMs is dependent in large part by the pixel size chosen. However, it should also be clear that errors in determining orientation parameters will carry forward to the determination of point coordinates used in interpolating each DEM used in the subtraction. For their digital photogrammetry software, ERDAS™ suggests that ground control points be accurate to within 0.1 to 0.5 the pixel dimension to ensure accurate aerotriangulation. If reasonably accurate snow depth measurements are to be made (*eg.* ±0.5 m, or ±0.25 m for each DEM), pixel sizes on the order of 15 cm are required on theoretical grounds, and ground control points must be accurate to within ≈ 7 cm. These are obviously significant constraints on this approach to snow depth measurement.

RESULTS FROM SKY POND, ROCKY MOUNTAIN NATIONAL PARK

Background

Sky Pond is a glacierized sub-watershed of Loch Vale, in Colorado's Rocky Mountain National Park. The Continental Divide forms the western boundary of this small 2 km^2 alpine basin; elevations range from 3180 m to 4040 m. Avalanche risks within the basin are typically high during the late winter and early spring, severely limiting the number of locations where field measurements of snow depth may be safely made. Deep snow accumulates in the basin, much of it drifting in from a long windswept fetch

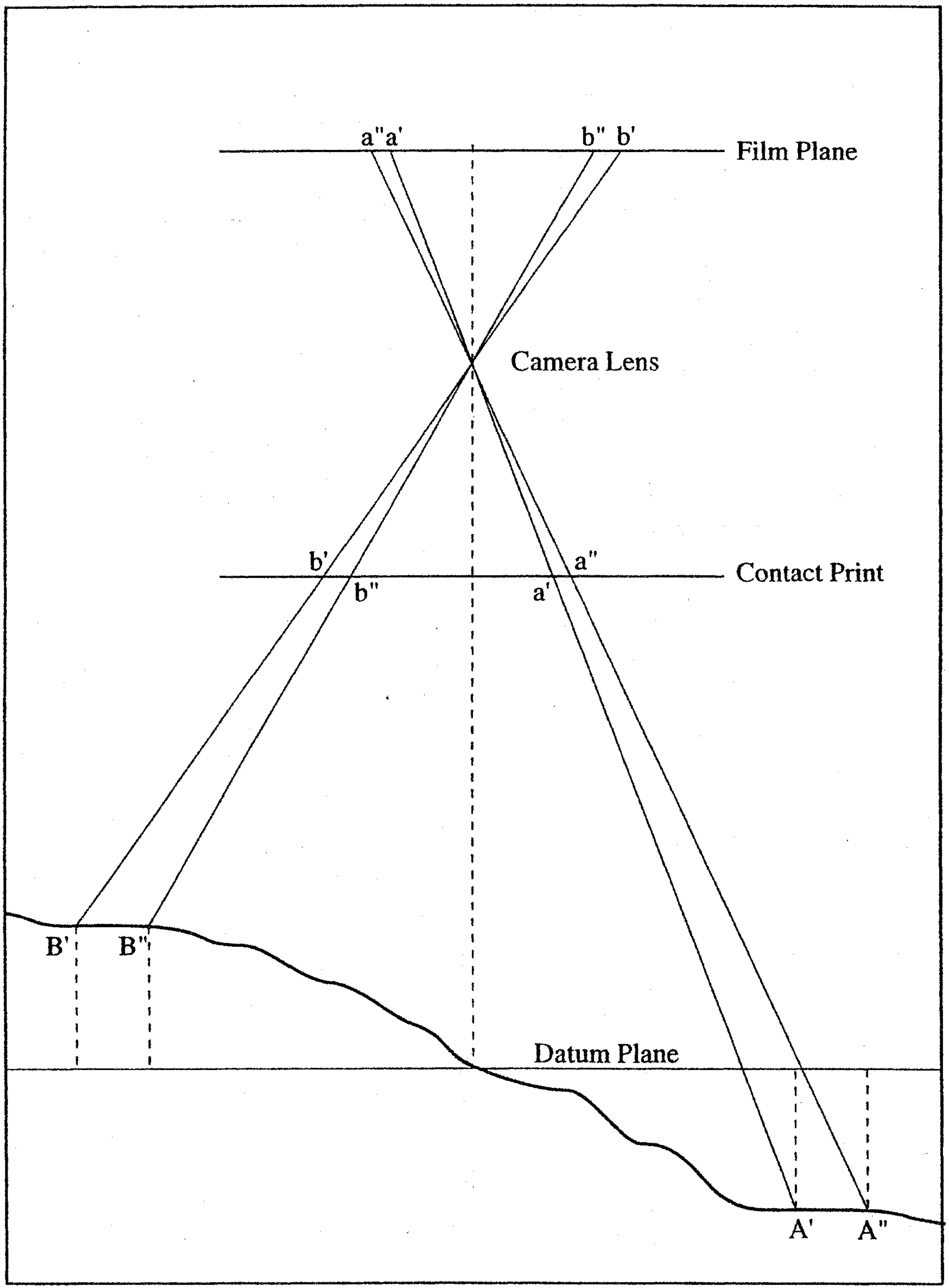

Figure 1. *Effects of topographic relief on scale and position of objects in aerial photography. The distances A'-A" and B'-B" are equal on the ground, but on the photo a'-a" is less than b'-b". The object a'-a" is displaced inward toward the center of the photo, while the object b'-b" is displaced outward away from the center. Ortho-rectification removes both of these effects from the photography.*

west of the Divide. As part of a larger project involving the entire Loch Vale watershed and a second watershed to the south, initial tests of the digital photogrammetry were performed at Sky Pond to assess its utility for determining snowpack distribution characteristics.

Aerial Photo Acquisition and Digitization

Panchromatic aerial photos at 1:12000 scale were flown over Loch Vale near the time of peak accumulation (May 10) 1993, and again at minimum accumulation on October 4, 1993. At this scale, one stereopair from each flight was sufficient to provide stereo coverage of Sky Pond. The photo negatives were scanned at 25 µm resolution to produce a pixel size of 30 cm x 30 cm in ground units. On the basis of Equation 2 above, this pixel size is required to produce an expected error in heighting accuracy of 0.5 m for each DEM, thus allowing an overall depth measurement error of ±1.0 m. At this resolution, each photograph (four total) required approximately 85 Mb of disk storage on the computer.

Digital Photogrammetry

The software used in this experiment was ERDAS™ Digital Ortho. The photogrammetry was performed on a Sun Sparc 10, operating at 125 mips.

Triangulation. Using a total station, a network of fourteen ground control points with accuracy of approximately 10 cm were surveyed within the Loch Vale watershed. Eight of these were located within the Sky Pond overlap area. To avoid burial by snow, the points were placed in locations that were expected to be scoured free of snow by wind during the winter. All points were marked with either a three- or four-panel array, each panel being approximately 1.5 m x 0.5 m in size. Although care was taken in the selection of location and marking of points to ensure good visibility, it was in fact very difficult to identify the precise location of the surveyed points in the digital images acquired at peak accumulation. While the ground was generally snow-free in the vicinity of the markers, small pockets of snow in the lee of rocks, etc. generated substantial uncertainty when identifying ground control locations for the aerotriangulation procedures. As well, placing points by design in some of the windiest locations of the basin resulted in the loss of some panels, again making precise identification of the control point difficult.

Pattern Matching and Intersection. For DEM generation, the ERDAS software uses a hierarchical pattern matching procedure, whereby a relatively coarsely spaced grid of conjugate points is matched first, then those points are used as vertices for a more dense grid in between, followed by an even more dense grid at the third matching level. A DEM can be interpolated from any of the three levels; accordingly the degree of interpolation required to produce the DEM decreases as the point density increases. The software allows manually editing of individual points at each matching level to ensure that conjugate points are identified correctly.

In this experiment, every point in the first and second level grids was matched automatically, but then edited manually to verify that conjugate points had been identified correctly. The second level grid contained 680 points for the May photos and 500 points for the October photos. The third level grid was matched automatically, producing over 161,000 points for the May photos and over 198,000 points for the October photos. The extremely high density of this grid precluded manually editing. The spacing of this grid of matched points corresponded to approximately five meters on the ground. For each date, all of the points were intersected to determine their x,y, and z coordinates. From this array of points, a 5 m x 5 m DEM was generated in effect not by interpolation, but essentially by sampling one intersected point per DEM grid cell. This high density approach was chosen to avoid uncertainty due to interpolation, and is not necessarily required or recommended for typical applications.

Results

Snow Depth. Viewed individually, both DEMs appeared generally satisfactory. However, the difference image representing snow depth indicated depths ranging between approximately ±100 meters. A spatial trend was clearly evident, with the largest positive values on the western side of the image, decreasing steadily to the largest negative values on the eastern side of the image. As a result, no significant relationship could be determined with a limited number of field samples of snow depth obtained at the time of the photo acquisition. These are preliminary results, in that the specific cause of the failure has not been determined. However the obvious tilt indicates that one or both of the stereomodels was not leveled properly during the aerotriangulation. This indicates a problem with the ground control, and could be a result of the uncertainty in identifying ground control points in images, and possibly an insufficient number of accurate ground control points.

Snow Covered Area. The tilt in one or both of the DEMs produced in this experiment indicated that the calculated orientation parameters were unsatisfactory for ortho-rectification purposes, and of course the spurious DEMs were unsuitable as well. Instead, orientation parameters were re-calculated using a large number of ground control points obtained from the USGS 1:24000 topographic map of the Sky Pond area, and the USGS 30 m DEM of the Sky Pond basin was used with these new orientation parameters for ortho-rectifying the photography. The results of this rectification appeared to be very successful. An interactive comparison of topographic features visible in the orthophoto with elevation values in the DEM indicated that the orthophoto was well-registered to the DEM. No quantitative accuracy assessment has been performed, however it appears that this relatively simple approach is adequate for producing reasonably accurate orthophotos.

DISCUSSION

It is clear that poor ground control, due either to the quality and/or number of point positions on the ground or to difficulty in identifying points in the photos, caused the initial testing of digital photogrammetry for snow depth measurements to fail. Similar problems have been noted previously by researchers attempting to measure snow depth using conventional photogrammetric techniques (Steinhoff and Barnes, 1976). Improved ground control, while difficult to obtain in mountainous terrain, will almost certainly be required before snow depths can be successfully measured using digital photogrammetry. To obtain heighting accuracy commensurate with typical alpine snowpacks, ground control must be accurate to within 10 cm. Markers must be large enough to identify, but small enough to permit accurate identification of the actual point. The small markers used in this experiment were difficult to identify in the photos, particularly when snow had accumulated between nearby rocks.

Much more testing of the digital photogrammetry is required before its utility for snow depth measurements can be definitively stated. The general approach seems to be satisfactory, but problems with ground control must be resolved. Accuracy of digital photogrammetric snow depth measurements cannot be assessed until reasonable DEMs can be produced. Further testing, focusing primarily on improving ground control, is planned.

The generation of orthophotos using a standard USGS 30 m DEM and ground control from a topographic map appears quite successful. The resulting orthophotos are by nature registered to the DEM, and suitable for immediate use in a GIS or hydrological model. Of the two snowpack distribution products examined in this study, SCA determined from digital orthophotos appears to have immediate utility.

REFERENCES

Cline, D., 1993. Measuring alpine snow depths by digital photogrammetry. Part 1: Conjugate point identification. *Proceedings of the Eastern Snow Conference, Quebec City, Quebec.* pp. 265-271

Light, D.L., *et al.*, 1980. Satellite photogrammetry. In *Manual of Photogrammetry.* Falls Church: American Society of Photogrammetry. pp. 883-977.

Martinec, J., Rango, A., and E. Major, 1983. *The SNowmelt-Runoff Model (SRM) User's Manual.* NASA Reference Publication 1100. 118 pp.

Smith, F.M., Cooper, C.F., and E.G. Chapman, 1967. Measuring snow depths by aerial photogrammetry. *Proceedings, 35th Western Snow Conference,* pp. 66-72.

Steinhoff, H.W., and A.H. Barnes, 1976. Determination of snow depth and water equivalent by remote sensing. *Completion Report A-019-COLO, Office of Water Research and Technology, US Dept. of Interior.* Fort Collins: Environmental Resources Center. 13 pp.

Wong, K.W., 1980. Basic mathematics of photogrammetry. In *Manual of Photogrammetry.* Falls Church: American Society of Photogrammetry. pp. 37-101.

Zheng, Y., 1993. Digital photogrammetric inversion: theory and application to surface reconstruction. *Photogrammetric Engineering and Remote Sensing,* Vol. 59, No. 4, pp. 489-498.