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Measuring Alpine Snow Depths by Digital Photogrammetry
Part 1. Conjugate Point Identification

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ABSTRACT

In this study, we examine the use of softcopy (digital) photogrammetry as a method of measuring the spatial distribution of snow depths, with the assumption that snow depth contributes most of the spatial variance associated with snow water equivalence in alpine basins. The primary obstacle with which we were confronted was the ability to determine the parallax of conjugate points in an aerial stereopair using automated pattern matching techniques. Snow is often considered to be one of the most difficult surfaces for pattern matching algorithms. We have found, however, that sufficient snow surface texture exists in our alpine study area on Niwot Ridge to enable successful automated pattern matching in many locations. This sets the stage for using softcopy photogrammetry to measure the spatial distribution of snow depth in alpine basins, thus is an important step forward in our use of distributed-parameter hydrologic models in snowmelt-dominated alpine basins.

INTRODUCTION

In alpine basins of the Colorado Front Range, snow depth is often the most spatially variable characteristic of the snowpack. Snow depth may range from zero in places where severe wind scouring occurs, to several meters in areas receiving deposition of wind-transported snow. Other snowpack characteristics, such as density, are assumed to be somewhat constrained within estimable limits. Therefore, obtaining improved estimates of the spatial distribution of snow depth in alpine basins should in turn allow improved estimates of the magnitude and spatial distribution of snow water equivalence (SWE) of basin snowpacks. Such improved estimates would have many important implications, but the present objective is to improve our ability to initialize distributed-parameter hydrologic models with spatially-distributed hydrologic inputs for specific alpine basins in the Colorado Front Range.

The National Park Service and Colorado State University are presently examining potential responses of hydrologic and aquatic ecosystems to climate change at several scales in Rocky Mountain National Park (RMNP) in north central Colorado. The centerpiece of this investigation is a combined data and simulation system, RHESSys (Regional HydroEcological Simulation System) that combines a set of remote sensing/GIS techniques with integrated ecological and distributed parameter hydrologic models in order to simulate flux and storage processes in a watershed (Band *et al.*, 1992). At present, initialization of such models requires many simplistic assumptions about the quantity of water stored as snow within a basin. The problem of initializing distributed-parameter hydrologic models in snowmelt-dominated areas such as the Colorado Rockies severely constrains our ability to model mountain hydrologic systems.

To address this problem, a remote sensing solution is considered necessary. Difficult winter access to the more remote alpine areas of RMNP severely limits the field measurement of the spatial heterogeneity of alpine snowpacks. Unfortunately, no suitable remote sensing technique has been developed for measuring SWE in alpine regions at appropriate spatial scales. In this study, therefore, we decided to examine softcopy (digital) aerial photogrammetry as a method of measuring the spatial distribution of snow depths in alpine areas of RMNP, with the assumption that snow depth contributes most of the spatial variance of SWE in these areas.

Softcopy photogrammetry uses automated pattern matching to make measurements of surface elevations; developers of softcopy photogrammetric software have indicated that cross-correlation pattern matching algorithms would not work on snow (Jordan, 1992, pers. comm.; Yang, 1992, pers. comm.). Indeed, we have not yet successfully measured snow depths using this technique. However, we have had some success with the automated pattern matching on alpine snow surfaces. This paper discusses our experiences with automated pattern matching on alpine snow surfaces, and relates them to the task of using softcopy photogrammetry to measure alpine snow depth.

BACKGROUND

The use of photogrammetry to measure snow depth in mountainous regions is not a new idea. Smith *et al.* (1967) reported on successful photogrammetric mensuration of snow depths in southwestern Idaho. The method they described involves the photogrammetric determination of the elevations of a surface, as is done routinely for topographic mapping. In this case, however, two surfaces were measured: first the snow-free terrain, and later the snow that had accumulated upon that terrain. The depth of the snowpack was determined by taking the difference.

The results were quite successful, yielding a standard deviation for point measurements of 21 cm, and a standard error of less than 1 cm for all measurements in their study area. The primary difficulty the authors encountered was obtaining photogrammetric measurements of the snow surface. However, they determined a solution and clearly outlined procedures required to perform the task. It is surprising that although the authors noted the potential significance such measurements could have on the understanding of snow dynamics, the technique was never widely adopted. This may be due in part to laborious procedures inherent to manual photogrammetry.

New methods for digital photogrammetric processing, often referred to as "softcopy" photogrammetry have become available in recent years. These methods utilize digitally scanned aerial photography; all the photogrammetric calculations may be performed very quickly using a desktop computer. Given the importance of snow depth as a hydrologic parameter and the newly available digital photogrammetric equipment, it seems appropriate to examine the viability of digital photogrammetric methods for spatially-distributed measurement of snow depth.

SOFTCOPY PHOTOGRAMMETRY AND SNOW

As with conventional photogrammetry using analog or analytical stereoplotters, softcopy photogrammetry uses aerial stereopairs. Stereopairs are simply vertical photographs taken from an aircraft at two locations along a flightpath so that an area on the ground is viewed from two different angles. The different viewing angles (differential parallax) provide a means to reconstruct the elevation of points on the ground if the three-dimensional coordinates of a few points on the ground are well known. Conventional photogrammetric methods require specialized optical systems and laborious human interaction to reconstruct surface elevations. With softcopy methods, the photographs are digitally scanned and entered into a computer. The effects of the specialized optics used in conventional methods are calculated digitally within the computer. With relatively little user interaction, digital surface models of the terrain can be developed very quickly, representing an extremely dense network of potentially thousands of point measurements of elevation. In general, photogrammetric measurement of surface elevations is much more efficient than field techniques if many point measurements are required. The recent availability of desktop softcopy photogrammetric technology offers a significant capability to researchers without access or the time to operate expensive photo-optical systems.

Softcopy photogrammetry is based on the automated identification of conjugate points in a stereopair, and the measurement of the differential parallax between them. A common method of automated identification of conjugate points is cross-correlation analysis of the pixel gray values in a reference window and a corresponding searching window, referred to hereafter as pattern matching. Ordinarily, this is an extremely robust technique; distinct patterns with adequate contrast result in high correlation coefficients in the pattern matching, and subsequently allow accurate determination of the differential parallax and thus the elevation of a particular point. Snow surfaces recorded on aerial photography are considered to be an extremely problematic case for automated pattern matching methods, however, as they are thought to lack distinct patterns with adequate contrast (Greenfeld, 1991).

Characteristics of Snow on Aerial Film

Smith *et al.* (1967) faced a very similar problem: in a manual photogrammetric environment, a photogrammetrist must be able to visually identify corresponding points on a snow surface in two photos of an aerial stereopair. The human ability to visually identify patterns is extremely powerful, but on normally exposed aerial photographs, snow surfaces tend to be saturated, appearing white with few identifiable features and little or no contrast. Smith *et al.* established a protocol enabling a photo interpreter to successfully perform this task: 1) select a time for acquisition of aerial photography when snow surface texture has developed, 2) use low solar illumination angles to emphasize surface texture, and 3) expose and develop the film specifically to emphasize tone differences in the snow-covered portions of the photographs. These guidelines do not address the reflective properties of snow as much as they address taking advantage of shadows caused by texture of the snow surface. Alpine snow surfaces frequently exhibit significant texture such as sastrugi, drifts, and ablation hollows. Low sun angles enhance these features, making identification of surface features possible if the film is exposed to avoid saturation in the snow-covered areas. In rugged terrain, however, low solar incidence angles frequently cannot be achieved at all places in one photograph because solar illumination angles vary according to topography. Thus some locations have extremely low incidence angles that enhance surface texture, while other locations have extremely high incidence angles that minimize the appearance of surface texture.

How do the reflective properties of snow influence the appearance of an alpine snow surface in an aerial stereopair? Most aerial films are sensitive to the wavelengths from 0.25 μm to 0.70 μm; infrared films extend this sensitivity to around 0.9 μm (Kodak, 1992). Snow cover is highly reflective at all these wavelengths. The major exception to this is in shallow snow, where the reflectance may be altered considerably by the substrate (Dozier, Schneider, and McGinnis, 1981; Nolin, Dozier, and Davis, 1990). Contaminants in the optically-active layer of the snowpack also can have a significant impact on reflectance throughout this spectral region (Dozier, 1990). The bidirectional reflectance properties of snow undoubtedly cause differences in snow surface appearance between each photo of a stereopair. Anisotropic reflectance characteristics of snow in the visible wavelengths result in a strong directional component to the reflected rays at about 60° azimuth (Kuhn, 1985). Snow surface texture itself affects the magnitude and direction of bidirectional reflectance. Since two exposure stations (comprising the stereopair) are necessary to determine surface elevations, the viewing geometry changes from one photograph to the next while the solar geometry remains approximately the same. Apparent brightness differences in the snow surface appearance of conjugate locations in a stereopair are probably due in large part to the bidirectional reflectance properties of the snow, however these expected effects on the appearance of snow in aerial photography have not been adequately quantified.

Pattern Matching

The standard to which automated pattern matching is often compared is the human visual system (Greenfeld, 1991). Not surprisingly, then, the pattern matching methods employed by the human visual system have often been used as a model for the development of automated techniques. Given a point in the left image of a stereopair, an automated technique must initially determine the approximate location of the conjugate point in the right image, then progressively refine the determination of this position. The specific approach used to accomplish this varies between softcopy photogrammetric software. In this study, the software ERDAS Digital Ortho™ is used; only the pattern matching methods related to this software are discussed here.

A hierarchical searching method is used to "focus in" on matching points in the fashion of an image pyramid. First, each original full-resolution image is degraded to coarser resolutions, with each level of increased coarsening containing information of lower and lower spatial frequencies. Three to four levels of spatial frequency are used in the pyramid. The lowest spatial frequency, or coarsest resolution contains only the most basic image information, *i.e.* major features in the original image. The highest spatial frequency is the original image at full resolution. Initial matches are identified in the coarsest image first; these matches are transferred to the next level to serve as approximate searching limits for the next searching level. As this proceeds, the search for a particular conjugate point in the right image is progressively narrowed until it is determined to lie within a particular matrix of pixels, called a search window, in the original full resolution image. Once this search window has been identified, the conjugate

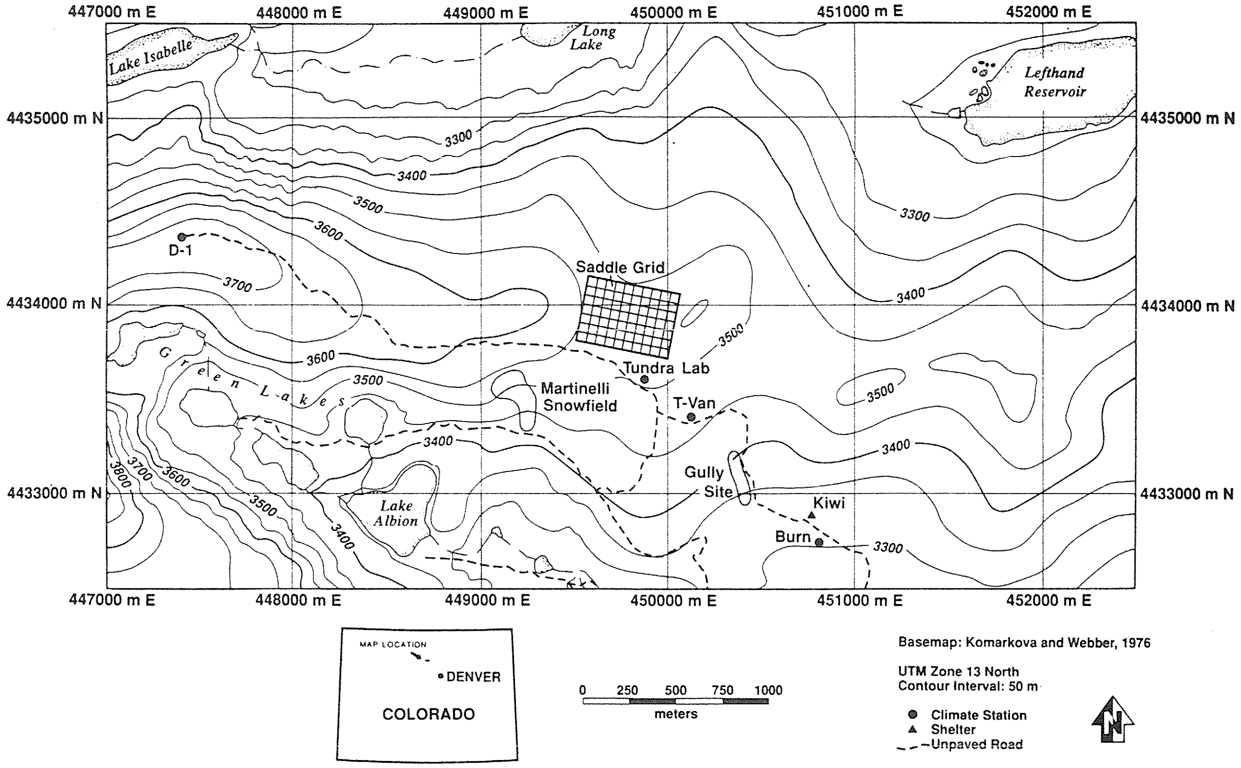

Figure 1. *Map showing Niwot Ridge study area. Photogrammetric testing was performed in the Saddle Grid area.*

point is identified using linear regression. A 5 x 5 matrix of 25 pixel gray values centered on a point in the left image serves as the dependent variable. This left image matrix is incrementally centered on each pixel of the right image search window, and the 5 x 5 neighborhood around each of these pixels becomes the independent variable. The right image pixel whose 5 x 5 neighborhood of gray values has the highest correlation coefficient with the 5 x 5 left image neighborhood is determined to be the matching pixel. The size of the search window must be specified according to the maximum amount of relief displacement expected within the image, *i.e.* the search window must be larger than the expected number of pixels of parallax, otherwise searching may not occur at sufficient distances from the expected position to locate the conjugate point. This seems to have significant consequences for pattern matching on snow surfaces in rugged alpine terrain, as discussed below.

METHODOLOGY

Study Area

The site selected for initial testing and calibration of the softcopy photogrammetry is the Saddle of Niwot Ridge, in the Colorado Front Range about 18 km south of RMNP (Figure 1). This site is the focus of the Niwot Long Term Ecological Research (NWTLTER) program. As part of this program, snow depths are measured routinely at 50 m intervals in a 500 m x 350 m regular grid on the Saddle (see Walker, *et al.*, this proceedings). The site is on alpine tundra, experiences regular wind redistribution of snow during winter (creating snow surface texture), receives considerable snow accumulation, and contains a variety of slopes and aspects. This relatively small alpine area, therefore, is likely to produce a wide range of geometric and radiometric distortions expected to occur in aerial photographs of alpine snow surfaces. It is by no means complete in this manner; for example, it contains no steep incised couloirs or valley walls, which are often found in alpine basins. However, the dense network of snow depth measurements taken in the Saddle by the NWTLTER provide a convenient means to verify photogrammetric results.

Data Acquisition

Stereo panchromatic aerial photographs were taken of the Saddle area on May 10, 1993. The photographs were acquired at scales of 1:12,000 and 1:6000. At either scale, the snow-covered portion of the Saddle area is located in the overlap of one stereopair, and therefore can be modeled using a single model. This acquisition date is within a few days of what we considered to be the peak accumulation of the 1992 - 1993 snow season. In the days prior to the flight, a hard crust had formed on the snow surface, with considerable sastrugi and other textural features present. However, the roughness height of these features was only on the order of a few centimeters. Larger scale surface patterns were also present; these patterns consisted of elongated strips aligned roughly parallel to the fall line of the slope. The strips tend to be a few meters wide and several tens of meters in length, and appear to be produced by melting at the snow surface. Redistribution of a very light snowfall during the two days prior to photo acquisition resulted in the presence of very reflective fresh snow in some shallow catchment areas in the Saddle.

The film used for this experiment was Kodak 2405, a standard panchromatic aerial mapping film. It is sensitive to wavelengths from 0.25 μm to 0.7 μm. Following guidelines proposed by Smith *et al.* (1967), the film was exposed specifically to improve tonal contrast in snow covered areas by reducing the metered exposure approximately 1.5 stops. The contrast in the resulting photos was enhanced slightly during the subsequent scanning process. The accuracy of softcopy photogrammetric elevation measurements depends largely on the pixel size, which is controlled by scanning resolution. For initial testing purposes, the 1:12,000 photos were scanned with a nominal ground pixel size of 0.75 m. The expected vertical accuracy associated with this pixel size (from theoretical computation) is 1.25 m. Snow depths in the Saddle range from zero to seven or eight meters, thus this level of accuracy is adequate for the present purpose, which is primarily to establish whether automated pattern matching can be performed successfully on alpine snow surfaces. Several three-dimensional ground control points necessary for aerial triangulation were surveyed the previous fall using high-resolution differential GPS and laser ranging techniques.

OBSERVATIONS

Photo Characteristics

The 1.5 stop reduction in exposure was sufficient to cause non-snow-covered areas to appear dark gray or black in the photographs. It was necessary to limit the exposure reduction to this degree so that ground control points located on snow-free areas would remain visible in the final photographs. The amount of texture apparent in the snow-covered areas is variable, both in the Saddle area and in surrounding areas. For both the 1:6000 and 1:12000 scales, four features of the snow surface appear to contribute most of the visible snow surface texture. The first are the elongated strips noted above, thought to be produced by surface melting. These features appear slightly darker than the surrounding snow surface. Second, snow drifts in the lee of krummholz are a prominent source of visible texture near the forest-tundra ecotone; however, no drifts of this type occurred in the Saddle area,which is located above the forest-tundra ecotone. The third feature is the surface roughness of the snow, but it was not manifested in the manner expected. In general, the surface roughness of the snow was only a few centimeters in height; shadows caused by these minor features are too small to be seen in the photographs. However, freshly redistributed snow caught in the lee of these micro-relief features resulted in increased brightness in contrast to the surrounding snow surface, creating distinct patterns. The fourth feature is snow sloughs on steep slopes; again these do not occur in the saddle area, but occur frequently on steeper slopes of the surrounding terrain. In photographs obtained later in the melt season, krummholz snow drifts became a much less pronounced textural feature. The other three features became even more prominent.

Although snow surface texture was visible in many portions of the photographs, there were also many areas, including parts of the Saddle, in which no surface patterns could be discerned. These areas are most often on slopes oriented towards the sun, suggesting the importance of snow's bidirectional reflectance geometry for aerial photography.

Pattern Matching

The success of the automated pattern matching method used here may be judged by the correlation coefficients associated with each point, as well as by visual inspection of the position of matched points. To reiterate the matching operation, the matching pixel is determined from the matrix of 25 pixel gray values in the right image with the highest correlation coefficient when compared to a similar matrix in the left image. The searching area is confined to a search window, whose size is related to the amount of relief displacement expected in the scene. Good matches with high correlation coefficients can only be expected where both geometric and radiometric distortions are minimal between the source matrix and the search matrix. Because of natural geometric and radiometric distortions, good matches are often found with low correlation coefficients. The opposite is also true, as discussed below.

Initial attempts to identify conjugate points were made with a search window size reflecting the maximum amount of relief displacement expected in the study area. The early results were peculiar; in saturated areas, correlation coefficients were extremely low, as expected. However, in areas with visible surface texture, reasonably good correlation coefficients were frequently obtained although visual inspection indicated the match point was clearly incorrect.

The snow surface texture patterns were somewhat repetitive, but the shapes of individual pattern elements varied. It was thought that geometric distortions in the photography resulting from the rugged terrain might cause the neighborhood of pixels surrounding the correct match point to appear less like the conjugate pixel neighborhood than some other matrix nearby in the repetitive pattern. Therefore, the search window size was reduced to a minimum size to allow for just the amount of relief displacement expected in a small matching area. This change greatly improved the matches where patterns were visible. Correlation coefficients improved slightly but, more importantly, visual inspection of matched points indicated that correct matches had been more frequently identified by narrowing the focus of the search.

The pattern matching exercise produced approximately 11,000 matched points within a 40 ha area. The points were spaced 8 m apart, and most of them were located on snow covered areas. Based on a two-tailed t-test for n = 25, about 8000 of these points were significant at the 10% level. Of these, about 4000 were significant at the 1% level. Approximately 3000 points could not be matched with confidence; these points are interspersed among well-matched points throughout the study area.

CONCLUSIONS

Softcopy photogrammetry cannot be used to measure elevations of any surface if conjugate points in an aerial stereopair cannot be identified by automated methods. Although we are only in the preliminary stages of our work, we have found that we can perform this first crucial task with some success. Some areas in rugged terrain appear completely saturated in aerial photos because of the angles between the sun, the snow, and the camera. Since the viewing geometry changes for each photo, these saturated areas may be in different locations in a stereopair. Completely saturated areas offer no textural information for pattern matching, and thus surface elevation measurements cannot be made in these locations. Elsewhere, alpine snow surfaces have exhibited considerably more texture than expected, allowing successful pattern matching. We have proceeded from this stage and found that we can produce digital elevation models (DEM) of the snow surface in the Saddle area, although we have not yet assessed the accuracy of the models. The DEM simply contains empty holes where the snow surface was saturated in one or both photos of the stereopair.

The progress thus far is encouraging, and we are continuing our investigation of softcopy photogrammetry to measure alpine snow depths. Our experience has shown that a DEM covering 1 km^2 and containing elevations of 10,000 points can be produced in a couple of hours. Our priority is to assess the accuracy of the modeled snow surface elevations. We hope to find that accuracies on the order of those obtained by Smith *et al.* (1967) can be achieved using softcopy methods. Further study will include digital enhancement of snow surface texture to improve pattern matching. We will also begin testing these methods in the hydrologic study basins in Rocky Mountain National Park in the near future.

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