The use of a reflectorless scanning total station for non-invasive measurements of snowpack and glacial ice volumes

1Duane, W.J., 1Pepin, N., 2Chowanski, K and 3Hardy, D.R.

1Department of Geography, University of Portsmouth, UK,
2Mountain Research Station, University of Colorado,
3Department of Geosciences, University of Massachusetts
Introduction

The measurement of snow and ice volumes has seen a number of methodologies applied with differing degrees of success. These range from low-tech ‘pole-in-hole’ approaches, through ground-based sonar instrumentation and on to space-based platforms using radar. As with all measuring systems each method can have both its advantages and disadvantages. By their very nature these features generally exist in harsh environments and so can prove to be difficult to capture. Accurate manual surveys can be extremely costly in terms of human resources and can also lead to disturbance of the surface especially on freshly fallen snow.

With the advent of reflectorless total station technology it has now become possible to obtain accurate elevations from either snow or ice without disturbing the surface. In essence, a form of remote sensing. Because these total stations also work with motorised axes, it becomes possible to set the instrument to scan at preset intervals to produce a grid of points that, from their elevation values, can produce a digital elevation model. Using scans repeated at different time intervals it becomes relatively simple to derive quantifiable surface change.

Field Measurements

The current maximum operable range is approximately 200 metres, (reflecting off a 50% Kodak grey), although with more reflective surfaces this distance can be greater. Thinner atmospheres at higher altitude will also increase the effective range of the instrument.

Areas to be scanned and suitable resolutions are determined by balancing a number of factors. These can include time available, battery life and the accuracy required to produce meaningful results for the study. Once these have been determined instrument position(s) can be considered. More than one instrument set up can be considered by tying all positions into the same spatial referencing system. This is usually achieved by locating one station from another using standard traverse survey techniques. However, by coordinating three fixed targets from one position, further instruments positions can be located and orientated using resection methods. This is extremely useful if instrument positions are not inter-visible or if instrument position markers are not expected to survive between scans. Fixed targets are also useful in that they offer the opportunity to check consistency between scans and hence provide accuracies.
Irregularly shaped polygons, defining the scan boundaries, can be created utilise a 'point and shoot' method through the telescope. Finally resolution, (grid interval), in the horizontal and vertical axes can be entered. Given the number of points required and a scanning speed of approximately 600 points per hour it is possible to estimate the amount of time required. Quoted accuracy for the instrument in distance are given as 3mm ± 3ppm while the beam has a divergence of 4cm per 100m. The significance of the latter means that the reflected signal does not emanate from a single point, but from an area which increases in size with distance from the instrument. This can influence results, particularly when scanning surfaces with extremely local high relief.

Figure 1. Total station in operation scanning a snow surface in Colorado.

Figure 1 shows a typical arrangement of the total station in use on Niwot Ridge, Colorado, scanning a snow surface in an alpine meadow. Data can be exported in ASCII format as X, Y and Z coordinates for subsequent use in relevant software.

Post-Processing
Once the data has been collected in the field it is possible to create surfaces from the raw data. A number of interpolation algorithms are available which will affect the shape of the surface. For regular terrain features, typical of snow surfaces, asymmetric kriging usually works well. This is demonstrated in Figure 2 where the blue dots indicate the position of the raw data points and the resultant surface using a kriging algorithm is displayed. Surfaces change can be obtained by taking scans of the same surface at different times and simply subtracting one from the other. However this can give misleading results as elevation change is, itself, a function of the slope angle.
This is demonstrated in Figure 3 where, for equivalent rates of material loss, the two different slope angles give different results when purely taking vertical change into account. To obtain values of material loss it becomes necessary to apply the cosine of the slope angle to obtain slope-normal change. From these values of slope normal change, further analysis is possible to examine the different rates of change over the model relative to other variables. These can be terrain feature such as rates of slope or plan curvature within the model or external variables.
Two examples are presented here to demonstrate differing uses of the system. The first examines the role of wind velocity in patterns of snow depths on Niwot Ridge, Colorado while the second presents the role of this methodology in studying ice cliff retreat on the Northern Icefield on Mt. Kilimanjaro, Tanzania.

**Niwot Ridge, Colorado**

Snow pack amounts are extremely important in determining water resources. These amounts can be conditioned by three natural processes; precipitation, redistribution and ablation. This study focuses on the aeolian redistribution of snow, by examining the patterns of both snow and wind velocities within a forest clearing in a sub-alpine environment over a number of days. The aim is to explore how closely snow depths are related to wind speeds. Key questions are to determine the strength of any relationship and additionally, to explore how much the build up of snow affects the wind patterns such that it feeds back into the snow surface. It is expected that wind speeds will increase in the clearer areas while decreasing in, and in the lee of, the forested areas. These velocities should be reflected in the depths of snow where higher wind speeds will induce scouring and therefore thinner snow coverage.

Anemometers locations were distributed across the snow surface and correlated with a control anemometer to determine wind ratio patterns over the surface. Simultaneously, scans were taken at daily intervals to derive snow depths. Figures 4, 5 and 6 show the field site at 11,000 feet, (3,350m) during the 2003 winter. Figure 4 shows the control flux tower and a large snow drift, where scouring by wind through a gap in the trees has produced a large difference in snow depth.

**Figures 4, 5 and 6.** Two views and a map of the field site. The red circles in Figure 6 indicate anemometer locations, blue squares are control points and the green triangles show trees. The flux tower can be seen to the left in Figure 4 and the observation tower is the wooden platform seen semi-buried in Figure 5.
By combining a summer survey of ground elevations with scans of winter snow surfaces it was possible to obtain snow depths across the clearing. Such a combination can be seen in Figure 7 showing an exploded view of the variation of snow depth over the ground for one scan in March 2003. Total and spatially distributed snow volumes can be calculated for all scans giving change over time and space.

Figure 7. An exploded view of the snow field showing the thickness of snow overlying the ground.

Wind speeds were taken across the clearing at a constant height of 0.5 metres above the surface. As there were insufficient anemometers to obtain simultaneous readings at all stations a ratio method was devised to refer all speeds to a control instrument. Using this method, wind ratio values less than 1 indicate wind speeds less than at the control while wind ratios of greater than 1 show wind speeds greater than at the control. Numerous wind speed observations were averaged at each location (>100).

Figures 8 and 9 below show the relationships between snow depth change and wind ratios during a period of snow accumulation and a period of snow depletion respectively. Wind speeds ratios are derived solely using observations recorded when the control wind speed was greater than 1 m/s because at lower wind speeds the ratios become both numerically unstable and temporally inconsistent. The relationship is strong during the accretion stage, windy areas seeing much less accretion than sheltered locations. However, during the depletion stage the relationships are weak, possibly because radiative processes become more important than wind in controlling ablation at this location in spring.
Figures 8 and 9. Scatterplots of change in snow depth over time against wind ratios. Figure 8 is over a period of four days of falling snow and Figure 9 is over a period of seven days with no precipitation. The purple dots correspond to the anemometer locations and the blue points represent the interpolated points.

Even during the accretion period there is much scatter about the regression line. Figure 10 maps the pattern of residuals across the snow field. Of particular interest are the areas of large residuals in the bottom left hand corner of the figure. Relationships between the shape of the snow surface itself (i.e. aspect, concavity and convexity) and these residuals may suggest modification of the wind/accretion relationship by the snow topography through feedback mechanisms. This requires further investigation.

Figure 10. Residuals from the accumulation regression line shown in Figure 8

Further work aims to expand the database, so that wind ratio patterns under different wind directions and speeds can be examined (at present there is not enough data to allow this). In this way the influence of changing synoptic conditions on the pattern of snow distribution can be examined, in particular the demarcation of areas sensitive to changes in frequencies of wind directions.
Northern Icefield, Mt. Kilimanjaro, Tanzania

As part of a large NSF-funded project into examining climate forcing of tropical glacial ice retreat, a method of measuring retreat of ice cliffs was required. The glacial retreat on these high altitude glaciers is of mounting concern amongst climatologists, although understanding of the direct cause of the retreat is still incomplete. Instrumentation has been, and continues to be, installed on the Northern Icefield. Currently an automatic weather station and other equipment are recording data, particularly focusing on energy budgets at 19,000 feet, (5,800m). While these are monitoring the input processes, the response can be seen as the glacial ice mass budget. Although recordings of accumulation and ablation on horizontal and near-horizontal ice surfaces are being taken using pole measurements, there are few measurements along the ice cliff boundary. Given that these ice cliffs rise approximately 30 metres above the ground, any direct measurement would be extremely difficult, if not hazardous, to obtain. The use of the reflectorless total station allows for a large number of points to be measured at all points along the ice cliff.

The first set of observations using the total station were taken in September, 2004. Considering the extent of the ice cliffs, approximately 500 metres in length, only sample areas could be observed. As can be seen from Figures 11 and 12 there was the general form of the cliff but also, within this, many other smaller scale, ice-cliff morphological features. To capture both broad scale and small scale changes a number of scans were obtained at different resolutions.

Figures 11 and 12. Total station in operation on two sections of the ice cliff on the Northern Icefield, Mt. Kilimanjaro.
The first scan was designed to capture a major section of the ice cliff, (approximately 100 metres in length). To capture as much detail as possible within a reasonable time frame the cliff was scanned with a horizontal resolution of 2 metres and a vertical resolution of 1 metre. Due to intermittent cloud the scan was completed in two parts and successfully combined to produce a scan of 1362 points. The derived grid to produce the surface seen in Figure 13 was defined with a 0.5 metre interval in X and Y with an isotropic kriging interpolation. In addition, breaklines were surveyed to define the top and bottom edges of the cliff and were included in the interpolation algorithm. Further dummy points were added to produce reasonable representation of the near-horizontal surfaces above and below the ice cliff.

Further scans were taken to highlight specific morphological features. One example, shown here on the right, looks at the rill-like features on a section. As opposed to the first general scan, this scan captures the vertically-aligned ridges and gullies. To obtain this the horizontal resolution (0.3m) was less than the vertical resolution (0.6m). This resulted in a total of 2,184 data points which were then used to create a grid with a 0.1 metre interval in both X and Y.
Figure 14. Comparison of the vertical section between the original scan (left) and the more detailed scan (right).

Figure 14 shows a visual comparison between the surfaces from the general scan (left) and the more detailed scan (right). As can be seen the the latter defines the detail much more clearly and can be used to investigate the behaviour of specific features.

Additionally, any glacial retreat can be compared against terrain variables to determine if any relationships are present. Figures 15 and 16 show frequency distributions of slope angle and aspect over the section seen in Figure 14. So, from these examples, when a second scan has been obtained, it is possible to establish if retreat is greater on steeper slopes or preferred orientations. This can be extended to include lower versus higher cliff sections and planate versus curved faces in both horizontal and vertical. In all, this approach will increase the understanding of ice-cliff mass responses to intense radiation balances at different scales and over different morphologies.
Figures 15 and 16. Frequency distributions of terrain variables, slope angle and aspect for a section of the ice cliff.