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Using ground-based laser scanning to monitor surface change on the Rolleston Glacier, New Zealand

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Abstract

Ground-based laser scanning is investigated as a tool for use in glacier observations. Repeat scans, a month apart, enabled changes in the spatial distribution of glacier surface elevation to be established. Ninety-five percent of the glacier area subject to repeat scans lowered by between 0.3 m and 2.0 m, with a mean of 1.3 m. The measurements provide a baseline to determine the long-term mass balance of the Rolleston Glacier.

Laser scanning proved especially useful in crevassed areas, and for steep or dangerous regions the ground-based laser scanner is seen as the only means of obtaining surface position data. However, the size and weight of the equipment, combined with the complexity of the data processing, currently prevents the technology from immediately being widely used in glaciological field work. As these limitations are reduced, the application of ground-based laser scanning to glaciology will become increasingly common. For regions of icefalls and calving faces, the ground-based laser scanner presents a means of obtaining quantitative data that has been unavailable before now. This will expand current observations beyond limited, safe, easily accessible areas to the full spectrum of glacier surfaces.

Keywords

Ground-based laser scanning, glaciers, glaciology, ablation, melt, LIDAR, terrestrial laser scanning, surveying.

Introduction

Glaciers are a major component of the hydrology of many catchments throughout the world (World Glacier Monitoring Service, 1989) including New Zealand (Chinn, 2001). A common approach to monitoring glacial processes is through measurements of accumulation (snow and ice build up) and ablation (snow and ice melt) (Kaser *et al.*, 2003); these approaches have frequently been applied in New Zealand (e.g., Anderson *et al.*, 2006; Anderton and Chinn, 1978; Bishop and Forsyth, 1988; Chinn, 1994; Gunn, 1964; Kirkbride, 1995; Purdie *et al.*, 2008; Ruddell, 1995; Smart *et al.*, 2000; Thompson and Kells, 1973).

A standard method to measure glacier melt has been the use of ablation stakes (Østrem and Brugman, 1991; Paterson, 1994). An ablation stake is usually a pole of wood or hollow plastic placed in a hole drilled into the glacier. Over time, the increased length of pole exposed above the ice surface provides a measure of glacier melt. The advantages of the system are its simplicity and low cost; the disadvantages are the high labour input, leading to generally poor spatial and temporal coverage, and the difficulty in monitoring hazardous regions such as steep slopes or crevassed areas. Automatic ablation measurements may be obtained with the use of pressure difference sensing systems (e.g., Bøggild *et al.*, 2004) or sonic distance ranging systems (e.g., Campbell Scientific Inc., 2008). While these methods provide an improved temporal record, they are still spatially limited and do not overcome the problem of monitoring inaccessible areas. Repeat surface surveys enable surface elevation changes to be determined. While not directly comparable to ablation observations, surface surveys are frequently used to derive ablation estimates. Such surveys, utilising GPS (e.g., Hagen *et al.*, 1999) or tacheometry (e.g., Hochstein *et al.*, 1995), provide better spatial coverage than point observations, but they are still limited by access. Remote sensing methods, generally operated from air or space craft, can overcome the access limitations of these methods, potentially providing full spatial coverage. These systems include photogrammetry, LiDAR (Light Detection And Ranging) (e.g., Baltsavias *et al.*, 2001) or radar (radio detection and ranging). The primary disadvantages of these systems are higher costs, and poor coverage of glacial regions oblique to the sensing platform (e.g., vertical cliffs).

With advances in technology, new instruments are continually being made available that have the potential to overcome the limitations of current observation methods in glaciology. Prior to the adoption of these new technologies, however, their value in improving efficiency or understanding must be assessed. One such technology is the ground-based laser scanner.

The ground-based laser scanner is a tripod-mounted device that calculates the spatial position of a surface by measuring the travel time of a laser pulse from the scanner to the ice surface and back to the scanner, and through the angle of the laser beam with respect to the scanner. Through incremental changes in the direction of the laser, the position of the viewable surface relative to the scanner (i.e., in scanner coordinates) is built up. Location and orientation of the scanner position in a geographic coordinate system (measured through differential GPS) then allows the scanned surface position coordinates to be oriented in that same geographic coordinate system. This ensures separate scans can be related, either to increase the spatial coverage or to assess changes over time.

Ground-based laser scanners have been used in a limited number of glacier studies around the world. The Gößnitzkees, a glacier in Austria, has been scanned on several occasions since 2000, demonstrating that the scans can be used to detect changes at different time scales, to quantify the effect of debris on glacier melt, and to determine the importance of supraglacial meltwater streams to glacial melt (Kellerer-Pirklbauer *et al.*, 2005). On the Pasterze Glacier, also in Austria, Avian and Bauer (2005; 2006) found that a ground-based laser scanner provided a higher quality and lower priced digital elevation model than was obtainable from airborne laser scanning or photogrammetric methods. The ground-based scans allowed variations of surface lowering to be attributed to variations in debris cover, shadowing, flow speed and sub-glacial cavity collapse. Another interesting glaciological application was the use of a high resolution ground-based laser survey to characterise surface roughness in order to automatically classify crevassed regions in airborne LiDAR glacier elevation data of the Hintereisferner (Kodde *et al.*, 2007). In the Himalaya, ground-based laser scanning has been used to monitor changes of the Lobuche and Changri Nup glacial fronts (Gelmini *et al.*, 2005). The logistics and expense of the system, compared to airborne methods, were seen as a distinct advantage, especially where only a small area was to be monitored. Temporal changes in the glacial boundary of the ice-contact Miage Lake in Italy have also been investigated using ground-based laser scanning technology (Conforti *et al.*, 2005; Tamburini *et al.*, 2005; Tamburini *et al.*, 2007). There the inaccessibility and vertical orientation of the calving ice cliff made ground-based laser scanning the best available solution to carry out the survey. In the Dry Valleys of East Antarctica, ground-based laser scans of the terminal faces of the Upper Victoria and Suess glaciers have been made for comparison to photogrammetric surveys carried out in the 1980s (I-Site, 2005).

In a related field, ground-based laser scanning has been used for measuring snow surface elevation in Davos, Switzerland, and was found to be safer, quicker and more accurate than probing, and more rapid and with better spatial resolution than tacheometry (Prokop *et al.*, 2008). The ability to scan a snow slope remotely was seen as a distinct advantage of the ground-based laser scanner for assessing snow build up and melt on an avalanche-prone site in the Wattener Lizum in Austria, although the inability to scan during snow storms was seen as a limitation (Jörg *et al.*, 2006). Rock glaciers have also been monitored using ground-based laser scanners, for example the Hinteres Langtalkar rock glacier in Austria (Bauer and Paar, 2003). On this rock glacier the steepness of the surface slope reduced the accuracy of airborne monitoring and favoured a ground-based approach, while the remote sensing of the hazardous terrain by the laser was seen as a distinct advantage over GPS or tacheometric survey techniques.

The objective of this study was to trial the use of a ground-based laser scanner to monitor surface elevation change on the Rolleston Glacier, New Zealand, and assess the limitations and advantages of the technology.

Study area

The Rolleston Glacier (Fig. 1) is a small (0.15 km^2) glacier located at 42.89°S, 171.53°E within the Southern Hemisphere westerly wind belt. The glacier is just 50 km east of the Tasman Sea, ensuring moist maritime conditions. The mountains of the Southern Alps extend 30 km to the west, causing orographic uplift of the predominant westerly winds. The glacier is near the central axis of the mountain chain, with the main divide of the Southern Alps just 2 km to the east. The glacier itself lies on the southeast slopes of the 1967 m high Mt Philistine, which has no higher mountain barrier to the west. The glacier elevation ranges from 1720 m to 1860 m, 600 m above the adjacent valley floor.

The climate is dominated by the prevailing westerlies of the southern hemisphere mid-latitudes, leading to high average annual precipitation, as measured at nearby gauge sites, of 5076 mm at Otira and 4468 mm at Arthurs Pass for the 1971 to 2000 period (NIWA, 2008). The mean annual temperature at 1770 m is 0.5°C, derived by applying a vertical temperature lapse rate to long-term temperature measurements at Otira and Arthurs Pass. The coldest mean monthly temperature of –5.1°C occurs in July, and the warmest, 5.8°C, occurs in February. A lapse rate of 0.0069°C m^{-1} was used, as it results in the least difference in the values derived from the Otira and Arthurs Pass records. An

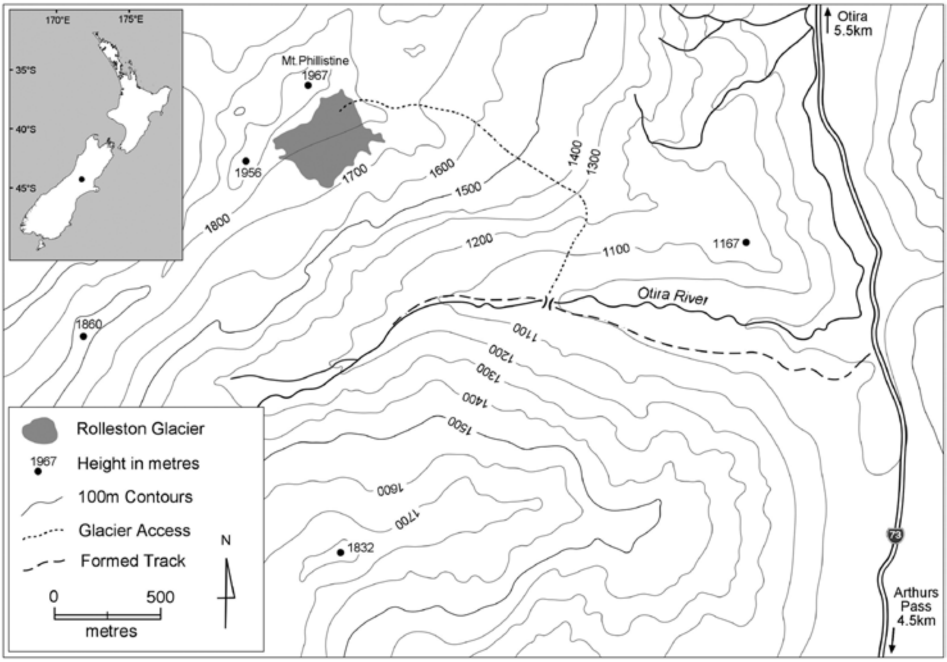

Figure 1 – Rolleston Glacier: map showing glacier location and topography.

estimate of the long-term equilibrium line altitude (ELA), based on an accumulation area ratio (AAR) of 0.66 of the total glacier area, is given as 1769 m by Willsman *et al.* (2008). For the 29 observations taken over the last 30 years, the end of summer snowline has been the same elevation as the long-term ELA for one year, above the long-term ELA for 12 years and below it for 16 years (Willsman *et al.*, 2008), with no statistically significant rising or lowering trend. These observations indicate that over the last thirty years the glacier has been in a general state of equilibrium, but with strong year-to-year variability of mass inputs.

The upper glacier is a gently sloping snow field surrounded by steep rock faces. Down glacier, the surface increases in gradient to the ablation region, which is incised with crevasses and melt channels. The terminus of the glacier is on a small rock shelf. Except for a few steep slopes in the upper region adjacent to the surrounding cliffs, and some severely crevassed zones in the ablation area, the majority of the glacier may be accessed on foot. The glacier was selected for the trial because of its proximity to Christchurch, enabling travel and fieldwork to be carried out in a single day.

Methods

The glacier surface was scanned using a Trimble GX 3D scanner. This has a range of 350 m for a 90% reflective surface, a 12 sec horizontal and 14 sec vertical scanner position accuracy, and a scan spot size of 12 mm at 200 m. The standard deviation of position accuracy, for a 4 point average on a perpendicular surface, is 6.5 mm at 200 m (Trimble, 2007). The scanner operates with a laser at a 532 nm wavelength, while also recording surface colour. Two scanning campaigns were undertaken in the late summer of 2008 (13th March and 14th April), spanning a period of time considered long enough to detect an observable change in glacier surface elevation. Logistics limited the time available for scanning during each campaign to four hours on a single day. Because of the limited time, priority was given to scanning areas of the ablation zone of the glacier where changes in surface topography were most likely to be observable.

For each scan, the scan site was surveyed using differential GPS, corrected to a GPS base station set up for the campaign on a nearby mountain spur. A pre-scan of the viewable glacier was then made. This provided an opportunity to manually limit the scan window to the glacier areas and prevented time being wasted scanning large areas of rock adjacent to the glacier that were of no interest to the survey. The full scan of the in-view glacier area was then made.

All laser angle and distance values are automatically converted in the scanner processor to positional coordinates in the instrument coordinate system for later processing. Each recorded position was taken as an average of four scanned points to reduce the positional error derived from the limitations of the scanning position mechanics. Lastly, before moving to a new scan site, the next scanner position was scanned. This provided a means of linking the separate scans in scanner space. This process was then completed at the next scan site, where the scan sites were selected to maximise the view of the glacier and provide overlap with other scans.

Post-processing of the scans involved combining the separate scans into a single coordinate space, and reprojecting this into geographic coordinates using the differentially corrected GPS coordinates from each scan site. The output from each campaign was the geographic coordinates, laser intensity, and colour value for each scanned point.

Surface elevation changes between the two campaigns was assessed through a simple differencing of the interpolated surface. A difference map for the scanned glacier was prepared to show the spatial variability of surface lowering across the glacier.

The surface lowering (Δz) in the ablation zone of a glacier is the result of melt (b_n), emergence velocity (w_s), and vertical shift of the sloping ice surface (angle α) under horizontal flow (u_s) (Hooke, 2005):

$$\Delta z = b_n + w_s - u_s \tan \alpha \qquad (1)$$

In a steady-state glacier, the annually-averaged melt rate in the ablation zone equals the sum of the emergence velocity and the flow-derived elevation change. Over a year under these conditions, no surface elevation change would be observed. During the ablation season, the glacier is not in a steady state. An ablation stake, flowing with the glacier, measures ice melt only, whereas a laser scanner, in a fixed coordinate system, measures the sum of the surface melt and the flow-derived vertical change. As no flow observations were taken, the ablation cannot be directly derived, though the total surface elevation change may be considered a lower bound to ablation.

During the first campaign, a radiation-shielded temperature sensor (HOBO S-THB-M00x) was mounted 1.5 m above the surface on an aluminium pole inserted into a hole drilled into the glacier at the lower boundary of the névé. The attached logger collected 15-minute averaged temperature data. The sensor was removed at the end of the second measurement campaign. This temperature record, and the lower bound of ablation (i.e., the surface lowering), has been used to determine a minimum melt per degree of temperature above 0°C per day (the degree day factor) required to enable modelling of melt (Hock, 2003). This was then compared to values obtained elsewhere in New Zealand and for other glaciers globally.

Two ablation stakes were drilled into the glacier to a depth of 2 m during the first scan campaign, and were retrieved during the second campaign. A GPS surface survey was carried out during each campaign by walking across the glacier surface in a pseudo grid whilst carrying a logging GPS.

Subjective evaluations of the laser scanning compared to the ablation stakes and the GPS survey were made. The criteria for assessing the usefulness of the laser scanning system included the ease of use, the quality of the observations, the spatial coverage, the data processing effort and any limitations. Consideration was then given to specific glaciological applications for which the scanning would be of most value.

Results

The first scan was carried out on 13 March 2008. Six people were required to transport the ground-based laser, the GPS base station, GPS rover, the survey tripods (two for the scanning, one for the base station) and equipment batteries. An example of the scanner setup at the base of the Rolleston Glacier is shown in Figure 2.

Access to and from the glacier took several hours, limiting the available time for scanning on the glacier itself. Three laser scans of the lower region of the glacier, and two of the upper glacier were carried out. An individual scan took just 5 minutes, though the full setup and scan from each position took 30 minutes. An additional 10 to 15 minutes were required to move the equipment between scanning locations. Figure 3 shows a 3D representation of the output of the scans. It can be seen that a large part of the middle section of the glacier was not scanned, as it was not within view of the scanning positions used. It was estimated that a further four scans would have allowed most of the glacier surface to be covered. Figure 3 provides an indication of the level of detail obtained, with the pattern of crevasses clearly evident. While not shown in the figure, the ability to discern the colour of the surface at each scan point ensured that glacier and rock could be clearly delineated. The weather during the scan was calm with a light mist. The mist did not affect the ability to carry out the measurements, as the loss of intensity of the reflected pulse was insignificant. On the flat upper glacier, despite the low incidence angle of the laser beam, the returning pulse intensity was still sufficient to determine the surface location.

Figure 2 – Scanner setup at the base of the Rolleston Glacier during the first scanning campaign.

The second scan was carried out on 14 April 2008. Less time was available on this date because of reduced daylight hours. As a result, only three scans along the terminus of the glacier could be carried out. Figure 3-b shows a 3D view of the second scan.

During the day prior to this second survey, a light fall of snow occurred. This prevented the clear distinction between rock and glacier that was possible with the scans from the previous campaign.

Each scan was converted to a 5 m resolution elevation model, where each grid cell value was an average of the scan point elevations of the scan points within that grid cell. Differencing these elevation models provided the surface elevation change that had occurred over the intervening 32 days (Fig. 4). Over the common area of the two campaign scans, an average of 1.27 m of surface lowering was observed. Ninety-five percent of the surface lowering was within the range 0.3 m to

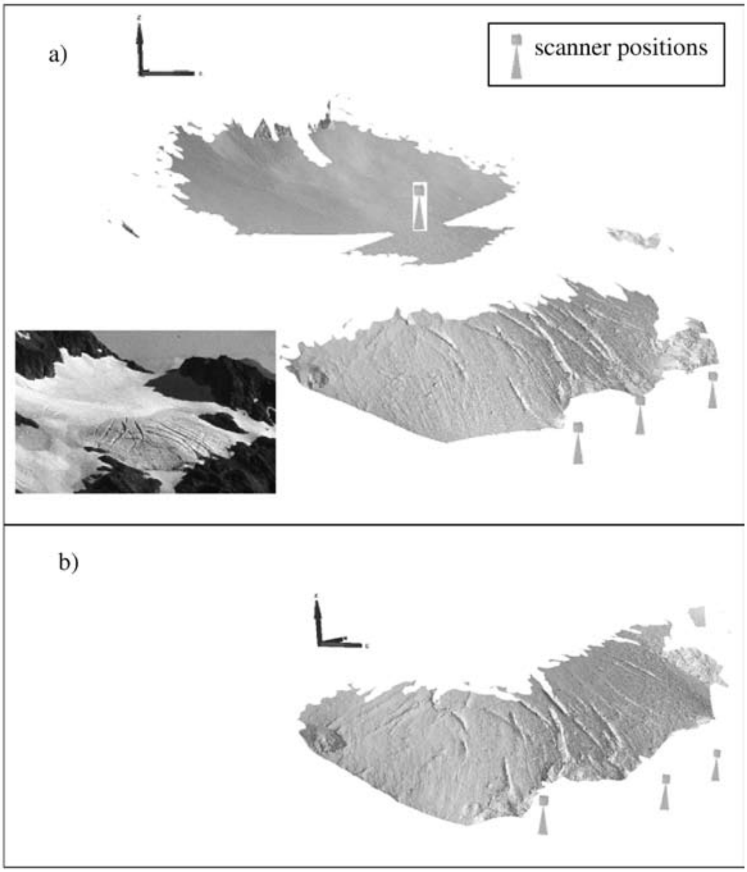

Figure 3 – 3D representation of: a) the first scan, taken on 13 March 2008; b) the second scan, taken on the 14 April. Inset, oblique aerial photograph taken on 14 March 2008 (Willsman and Chinn, 2008).

2.0 m. The surface lowering varied spatially, with no change observed over gravel near the terminus of the glacier and the two small rock outcrops to the side of the glacier (seen as black in Figure 4). On the glacier itself, the least surface lowering occurred on higher elevation, lower angle areas. A difference in surface lowering according to aspect is also apparent, with less surface lowering to the south compared to the east, which may be attributed to variations in insolation affecting melt rates. The largest surface lowering was observed near the terminus of the glacier and near crevasses. These areas are very steep, so that the vertical component of any surface melt is considerable. A histogram of the surface lowering is shown in Figure 5.

The accuracy of the scan points is derived from the mechanical positional accuracy of the scanner, the angle of incidence of the laser beam with the surface, the distance to the surface, and the GPS positional accuracy of the scanner. The scanner's mechanical position accuracy is specified by the manufacturer, enabling a position coordinate accuracy, relative to the scanner, to be calculated. To further reduce the errors through averaging, each point was scanned four times. The worst-case situation for the scans carried out (a distant surface with a 5° angle of incidence) was for a vertical accuracy of less than 3 cm, with a horizontal resolution of 140 cm at 200 m. When differencing scans, this error increases through the need to spatially average scan points. From the observations on the rock outcrop to the right of the glacier, the 2 m resolution difference image returned values from −0.3 to

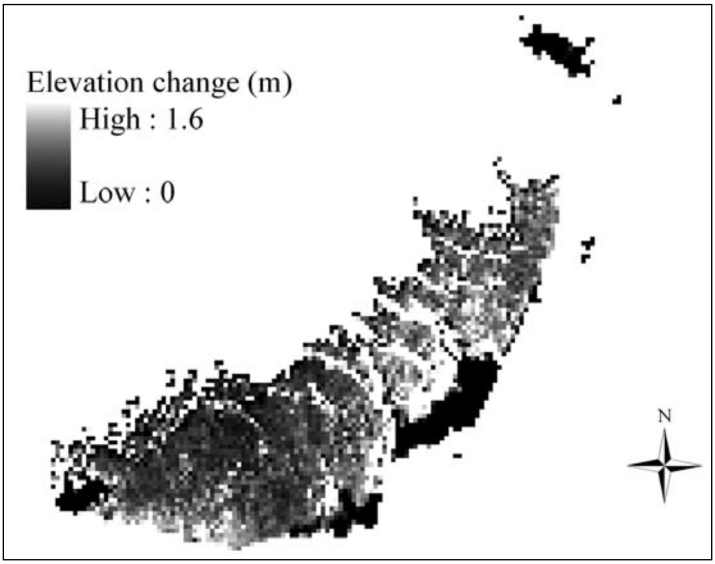

Figure 4 – Vertical difference in surface elevation between 14 April and 13 March 2008 for that part of the glacier that was scanned on both occasions.

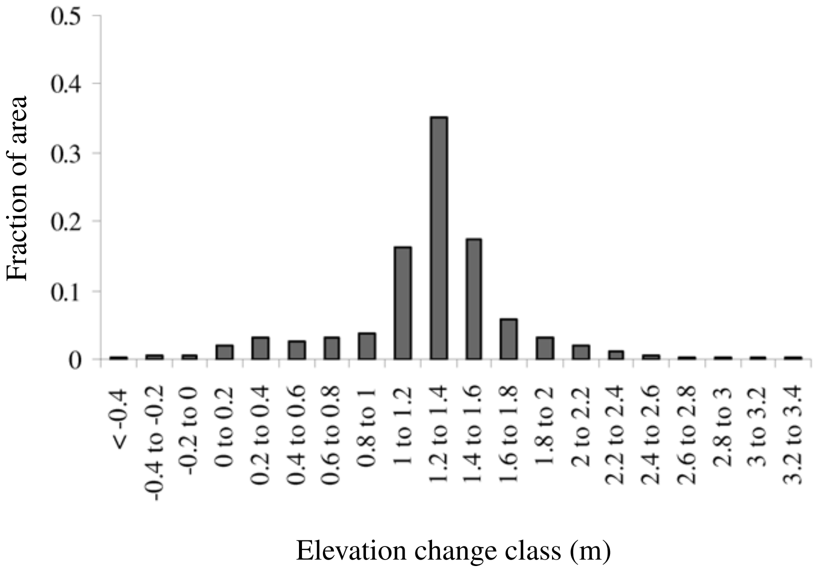

Figure 5 – Frequency distribution of elevation change between 14 April and 13 March 2008 for that part of the glacier that was scanned on both occasions.

+0.3 m, providing an error estimate for that resolution.

Assuming an ice density of 900 kg m^{-3} (Paterson, 1994), the elevation change of 1.27 m represents a minimum melt of 1.13 m water equivalent (w.e.). The observed temperature leads to a minimum degree day melt factor of 6.9 mm (w.e.) $°C^{-1}$ day^{-1}. This compares to the mean values of 7.1 mm (w.e.) $°C^{-1}$ day^{-1} found for an ice surface on the Franz Josef Glacier (Anderson, 2004) and 7.4 mm (w.e.) $°C^{-1}$ day^{-1} found for an ice surface on the Tasman Glacier (Kirkbride, 1995) and is comparable to values found in other regions throughout the world (Hock, 2003).

The two ablation stakes were placed in 2 m deep holes at the top and bottom of the ablation zone during the first survey. Both ablation stakes had melted out by the second survey, suggesting a minimum of 2 m of melt. This would indicate that a large component of the > 2 m of surface lowering that was observed in some regions of the lower glacier was a result of melt. However, such surface lowering was not observed in the upper ablation zone where the upper stake melted out. The upper stake may have fallen out prior to melting out, perhaps following the encroachment of a nearby crevasse. Such an eventuality may also have occurred for the lower stake, thereby preventing a definitive comparison between the laser-derived surface lowering and the minimum melt estimates derived from the ablation stakes.

The GPS surface surveys covered the entire glacier at a spatial resolution of 5 m along track and 20 m between tracks, with a vertical accuracy of 50 cm, accounting for GPS accuracy and antennae height variations as the surveyor moved across the glacier surface. In several areas of the glacier near rock faces, the positional accuracy of the GPS was lower because of poor satellite coverage. Differential correction of these surface surveys against the base station was not possible because the reception of the GPS carrier signal was too intermittent. Differencing the two GPS surveys leads to a vertical error of 1 m. This high vertical error prevented a meaningful GPS-derived difference surface from being obtained. Table 1 provides a summary of the various survey techniques with regard to coverage, accuracy, expense, and effort.

Table 1 – Comparison of glacier surface change survey methods.

	Laser scanning	**Ablation Stake**	**GPS Survey**
Capital Expense	\$1500 – 4000 per day (lease)	<\$1 (purchase)	\$100s per day (lease)
Equipment weight	13 kg plus tripods and batteries	< 500 g	< 2 kg
Labour	2 people	1 person	1 person
Horizontal resolution	20 cm	n/a	20 m (max. track separation)
Vertical accuracy	+/– 3 cm	+/– 5 cm	+/– 50 cm
Data analysis/ post processing	Most	None	Considerable

Discussion

The amount and weight of the equipment required to generate the scans and survey the scan positions were at the limit of logistical feasibility without air support. The location of the glacier within a National Park prevented the use of helicopters without special permission. Transporting the equipment manually to the study site required a lot of personnel that would be difficult to justify in a commercial environment, especially given the scanning itself may be carried out reasonably efficiently with just two people. The range of the scanner was largely the determining factor in how much of the glacier surface could be scanned. It seems likely that with technological advancement, the size and weight of the equipment will be reduced, while the survey range of the available scanners will increase. Currently, the longest range a commercially available ground-based laser scanner can scan is 6 km. For the Rolleston Glacier, such a scanner would allow the full surface to be scanned from a single scan site. Compared to ablation stake measurements, the scanner provides a quantum leap forward in spatial coverage, which is seen as crucial for validating distributed physical glacier models. As in our case, with the melting out of our ablation stakes, the chosen positions of ablation stakes may not be representative for larger glacier areas. However, ablation stakes allow the surface melt to be measured along the glacier flow trajectory, while the scanner measures surface elevation changes in a fixed coordinate system. In order to derive surface melt, as opposed to surface elevation change, a combination of ablation stake and scanner observations may provide the optimum result. By scanning stake locations, glacier flow velocities may also be determined, so that surface elevation changes may be converted to glacier melt. At the same time, stake emergence observations provide an independent verification of the scan-derived glacier melt.

Compared to the GPS survey, the scanner had reduced coverage, but the coverage obtained was of a much higher resolution and accuracy. The general form of Rolleston Glacier's topography was of a gently sloping surface incised with crevasses in the ablation zone. For a general assessment of glacier-wide surface change, a spatial resolution of twenty metres, the maximum between-track distance obtained by the GPS survey, would be appropriate. The time required for glacier coverage doing a GPS survey was greater than that for the ground-based scanning, which is a function of the maximum scan distance of the scanner. Unfortunately, the vertical accuracy of the GPS survey (+/– 60 cm) means that only large changes in surface elevation could be observed. The GPS survey also required safe foot access and good satellite reception to generate a full survey. At scanning distances of >1 km, a scanner would be able to replicate a GPS survey in a shorter time, with better spatial resolution and much improved vertical accuracy, and it would not be limited by access or sky view.

The ground-based laser scanning system appears to provide a good solution for determining glacier surface elevation changes. The clear advantage of the system over all other technologies at present is in scanning steep and/or inaccessible regions of a glacier. Currently, there are very few assessments of crevasse, calving, ice cliff and ice fall zones of glaciers, and yet they can form large parts of a glacier system. An understanding of how ablation and accumulation measured on relatively flat areas relate to ablation and accumulation in these steep and broken regions is largely unknown. The use of ground-based scanners provides a mechanism to explore these zones, areas where traditional survey techniques can not be deployed.

Conclusion

A ground-based laser scanner has been trialled for use in observing changes in a glacier surface. The system provides very high accuracy and spatial resolution compared to ablation stakes or GPS surveys. The coverage is limited by the range of the laser and, in this instance (range 350 m), enabled a portion of the ablation area of a small (0.15 km^2) glacier to be surveyed within a four-hour period. Conversion of surface elevation change to ablation requires differentiation between the effects of melt and flow. This adds a level of complexity to the data processing and a requirement for additional flow data that is not necessary with direct ablation observations. The weight and volume of the equipment required was substantially greater than ablation stakes or GPS equipment, leading to logistical limitations. It is envisaged that the horizontal range of scanners will increase, while their price, weight and bulk will decrease with future advances in technology. This will make ground-based scanners an increasingly appealing option for glacier observations. Currently, the equipment is seen as the best solution for observation of steep, dangerous and inaccessible regions, areas under-represented in contemporary glaciological studies.

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