The Use of Ground-Based Photogrammetry and SAR Interferometry to Characterize the Surface Motion of an Arctic Glacier

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ABSTRACT
Measurements of surface displacement made using GPS, SAR interferometry, and ground-based photogrammetry were compared for a number of targets located close to the terminus of a polythermal arctic glacier. The results showed that average measurements for the winter period made using GPS and SAR interferometry agreed well at most locations. Horizontal and vertical photogrammetric measurements were more variable, reflecting a greater sensitivity to seasonal flow variations. This study shows how the combination of these different measurement techniques is naturally complementary for studies of glacial dynamics.

RÉSUMÉ
Des données de déplacement de surface prises à l'aide de GPS, d'interférométrie SAR et de photogrammétrie de surface ont été comparées parmi un certain nombre de lieux ciblés localisés à proximité du terminus d'un glacier subpolaire de l'Arctique. Les résultats ont démontré que, pour la période hivernale, les données moyennes obtenus par GPS et interférométrie SAR étaient semblables pour la plupart des sites. Toutefois, les mesures photogrammétriques horizontales et verticales variaient davantage, ce qui reflète leur plus grande sensibilité aux variations saisonnières de l'écoulement. Cette étude démontre comment la combinaison de ces différentes techniques d'échantillonnage de données permet d'obtenir de l'information appariée lors d'études sur la dynamique glaciaire.

1 INTRODUCTION

The general dynamics of glaciers and icecaps are complex due to the interaction of a number of processes which affect the behaviour of ice. The dynamics of polythermal arctic glaciers are particularly complex as a result of the heterogeneous distribution of warm and cold ice within the glacier, and because they have a distinctly thermally sensitive subglacial and englacial hydrology. Unlike temperate glaciers, which have little interaction with permafrost conditions, the ice flow dynamic patterns of polythermal glaciers are affected by the presence of frozen glacial margins. These promote the accumulation of subglacial water, while at the same time they act to retard basal sliding through longitudinal and lateral stress coupling.

To fully characterize a glacier's surface dynamics it is necessary to measure flow patterns throughout the course of a year, or better still over a period of several years. Ideally measurements should cover the whole surface of the glacier and be made on a near daily basis, in order to capture rapid changes in surface motion. There is however no single way of obtaining such measurements. In-situ field surveys offer the possibility of making high accuracy point measurements on a daily or even hourly basis, but only for a few discrete points on the glacier surface. Remote sensing, on the other hand, allows measurements to be made across the entire surface of the glacier, but only allows a limited number of measurements to be made in a year.

The ideal measurement system would combine the spatial coverage obtained by remote sensing with the temporal coverage provided by in-situ measurements. This paper describes how this may be achieved by using a combined approach, in which spatial estimates of displacement across the entire glacier surface are obtained using SAR interferometry (InSAR), while in-situ discrete measurements are obtained using ground-based photogrammetry. While this methodology is still being developed, initial results are promising, and suggest that this approach has the potential to provide reliable and consistent measurements of glacial flow throughout the year. In addition to estimates of down-glacier velocity, this methodology also offers the advantage of allowing quantifications of surface elevation to be made on a daily basis, thus providing information about the 3D motion of the ice surface which can subsequently be related to variations in the englacial and subglacial environment.

2 STUDY AREA

The study described in this paper focuses on the terminus region of Fountain Glacier, a relatively small polythermal glacier, which is located on Bylot Island in the eastern Canadian Arctic (Figure 1a). Bylot Island is roughly 180 km by 100 km in extent and is situated to the north of Baffin Island. The study area has an average temperature of -15°C and is situated in the zone of continuous permafrost "(Irvine-Fynn et al. 2006)". The average annual precipitation is less than 200 mm, with a maximum of 80 cm of snow falling in the winter near the terminus of Fountain glacier "(Moorman 2005)". The interior is dominated by the Byam Martin Mountain range which is covered by an icefield 4,500 km^2 in extent. Valley glaciers radiate out in all directions from this central icefield towards the coast.

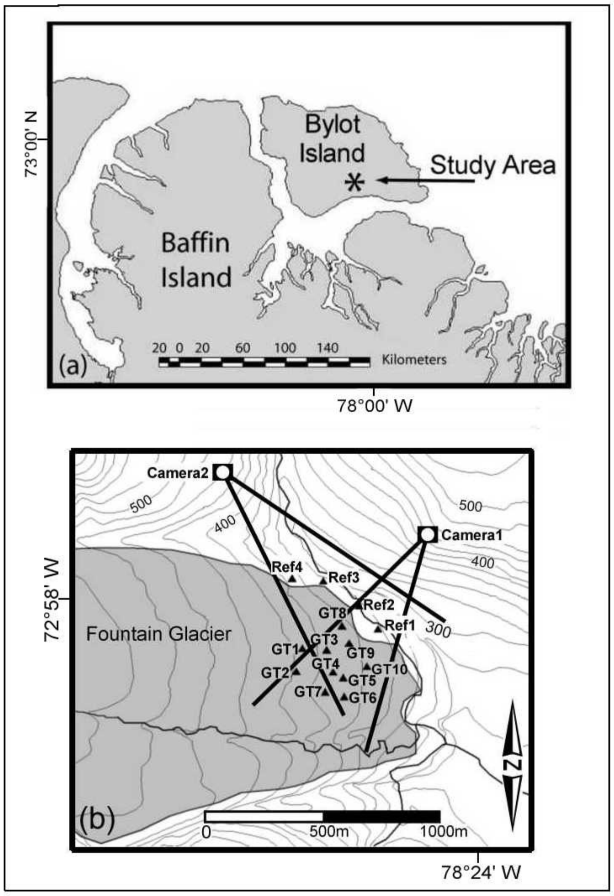

Figure 1(a) Location of Bylot Island north of Baffin Island, Nunavut and (b) the terminus region of Fountain Glacier showing the spatial distribution of cameras and targets. Targets (GT1 to GT10) are located on the surface of Fountain Glacier whereas reference points (Ref1 to Ref4) were placed within the marginal proglacial area.

Fountain Glacier (Figure 1(b)) is designated as B26 by the "Glacier Atlas of Canada (Inland Waters Branch 1969)". Ground-penetrating radar surveys have suggested that it is polythermal in nature, consisting of a core of temperate ice surrounded by cold dry ice "(Wainstein et al. 2008)". It is believed that most of the other glaciers on Bylot Island are also polythermal in nature.

Fountain Glacier has a catchment area of 72 km^2. Because of its high inertia, the glacier has shown little sign of retreat until recently "(Wainstein et al. 2008)". The main process driving the current retreat of appears to be mass-wasting. The glacier terminates in a 30 m high cliff face which was measured by "Wainstein et al. (2008)" to have retreated at an average of 10 m per year between 1995 and 2001, mostly through ice calving. Comparison between recent TerraSAR-X images and a Landsat ETM image obtained in 2001 shows that the average rate of retreat increased to 17 m per annum between 2001 and 2008. Field observations made in June and August 2008 showed the calving face to be extremely active, and it is hypothesised that the rate of retreat is continuing to increase. Though mass-wasting appears to be the dominant process, thinning is also occurring. "Wainstein et al. (2008)" calculated thinning rates of approximately 1 m per annum over the lower glacier between 1982 and 2007.

Fountain glacier has an active subglacial hydrology. In the last 20 years the terminus region has changed in character from having a gently sloping profile to the previously-mentioned vertical face. This is believed to have been the result of the collapse of several subglacial caverns, which were seasonally occupied by water. The development of these collapse features combined with fluvial undercutting from marginal streams has lead to the development of the current rapidly retreating vertical face. Developing an understanding of the hydrological and dynamic processes which caused the observed changes to the terminus is therefore of key importance in predicting the future behaviour of the glacier.

3 BACKGROUND

The successful implementation of the proposed approach depends on the integration of two different measurement technologies; SAR interferometry and ground-based photogrammetry, which respectively provide continuous and discrete point data.

3.1 SAR Interferometry

SAR interferometry measures the phase difference between two radar images, taken several days apart. An interferogram is generated by multiplying the phase component of the first image by the complex conjugate of the second image. The resulting interferogram consists of a series of fringes, each of which represents a complete phase cycle at the radar wavelength. Such an interferogram is typically used to measure either topography or surface displacement.

Where surface displacement is desired, the interferogram must first be flattened by removing the topographic phase component. This is normally done by using a Digital Elevation Model (DEM) to generate a synthetic interferogram, and subtracting this from the original interferogram. The differenced interferogram now represents the effect of surface displacement over the time period between the acquisition of the two source images. This interferogram is then unwrapped by sequentially adding the fringes in order to give a continuous measurement of phase, which may then be used to determine the distance moved in the radar line of sight direction. A comprehensive description of the theory behind SAR interferometry is given by "Rosen et al. (2000)".

SAR interferometry has been used extensively in the study of glacial motion patterns in many different environments, with a number of studies using the technique to measure the motion of polythermal glaciers in arctic environments, e.g. "(Gudmundsson et al. 2002; Burgess et al. 2005)". However the main problem in deriving glacier velocities in this way is that InSAR only gives displacements in the radar line of sight direction. In order to derive down-glacier velocity, it is necessary to project the line of sight displacement into the down-glacier direction. This requires knowledge of both the glacier flow direction and surface slope. Where flow direction is unknown, a second interferogram with a different look direction may be used. Most commonly ascending and descending-pass interferograms are used in this way. If glacier flow is assumed to be parallel to the surface it is then possible to calculate down-glacier velocity, e.g. "(Joughin et al. 1998; Cumming and Zhang 2000)".

3.1.1 TerraSAR-X

Interferograms were generated using imagery from the TerraSAR-X satellite. This is an X band (3 cm wavelength) radar satellite, launched in June 2007. This satellite has an 11 day orbital repeat period and is capable of acquiring imagery in a number of different modes. TerraSAR-X Spotlight imagery with an approximate resolution of 1.5 m was mainly used in the current study, although Stripmap imagery with a ground resolution of 3 m, and high resolution Spotlight imagery with a ground resolution of 1 m were also used to generate interferograms.

3.2 Ground-based photogrammetry

Ground-based photogrammetry has been used in a number of glacial studies, e.g. "(Harrison et al. 1992; Brecher and Thompson 1993)", though few studies to date have made use of fully automated time-lapse imagery. Photogrammetric measurements can be used to derive highly accurate motion estimates for specific points on the glacier surface. If the camera is calibrated, so that the geometric relationship between the image sensor and the camera lens is known, then the principle of collinearity can be used to define a ray of light linking a point in 3D object space, the perspective centre of the camera lens, and the point's representation on the camera's image plane. By intersecting such rays from two or more cameras, the position of the point in 3D object space can be defined.

The exterior orientation of the camera defines its position and orientation in 3D object space. A camera has six exterior orientation parameters, its X, Y, and Z coordinates in object space, and three rotations ω, φ, and κ, which define rotations around the camera's x, y, and z axes respectively. Exterior orientation parameters are often established using a process known as single photo resection. If the positions of at least three ground control points are known in object space, and their corresponding photo coordinates are also known, then the principle of collinearity can be used to uniquely define the position and orientation of the camera in object space. In cases such as the current study, where the camera position is already known, the rotation parameters can be established using only two ground control points.

4 METHODOLOGY

4.1 SAR Interferometry (InSAR)

A series of ascending and descending-pass TerraSAR-X images were acquired over a one year period between May 2008 and May 2009. These were processed interferometically and estimates of down-glacier velocity and flow direction were obtained from the paired ascending and descending-pass interferograms, using the methodology described by "Vachon et al. (1996)" and "Cumming and Zhang (2000)". A more detailed description of this work is given in "Whitehead et al. (2009)".

Velocity estimates were derived for May 2008, October 2008, February 2009, and May 2009. These were also used to obtain an estimate of median winter velocity. Because none of the acquisitions occurred over the short arctic summer, when basal sliding would be expected to contribute more significantly to the overall motion of the lower glacier, it is believed that the average winter velocity may significantly underestimate the overall annual motion of the glacier surface. Velocities were derived for a 100 m grid of points across the glacier surface, and also for the glacier centre line.

4.2 Ground-based Photogrammetry

Two automated camera stations were set up to view the region of the glacier terminus in a highly convergent configuration. The camera stations each consisted of a Canon Digital Rebel XTi camera with a 50 mm fixed zoom lens. The cameras were sealed in a rugged enclosure designed by Harbortronics. Each camera was powered by a solar array, backed up by twin batteries, and was controlled using a DigiSnap time-lapse controller. The cameras were set up on high ridges, overlooking the northern side of the terminus of Fountain Glacier. The time-lapse controller was programmed so that each camera would acquire one image per day, close to the local noon time.

Ten targets were set up on the surface of the glacier, in the region which was visible from both cameras. The targets consisted of 60 cm diameter red circles, set against a white background. In addition four reference targets were set up on the moraine next to the glacier, with two of these targets in the field of view of each camera. The location of the cameras and targets are shown in Figure 1b. A complete real time kinematic (RTK) GPS survey of both the camera station and target positions was carried out on August the 20th 2008. The cameras and targets were subsequently left to acquire imagery through the winter, with the images being retrieved in June 2009. A follow up RTK GPS survey was carried out of all target positions on the 20th of June 2009, 305 days after the initial survey.

Analysis of the imagery revealed that Camera 1 had acquired useful imagery until the 10th of November, after which time snow had obscured the view of the reference targets. Camera 2 acquired images up to the 17th of October, when the camera station was covered by snow. This meant there was a 59 day period for which imagery was available from both cameras.

The exterior orientations of both cameras were computed by carrying out single photo resections using the images acquired on August the 20th, the date when all target positions were measured and could therefore be used as ground control points. For images acquired after this date, it was assumed that the targets on the glacier had moved, and could therefore not be used in the single photo resection process. In this case an iterative adjustment was made of the rotation elements, with the camera positions being held fixed. This was done by using the known camera positions and the positions of the two reference targets visible from each camera. This process was repeated for all photos obtained over the eight weeks where both cameras were working. A detailed description of this workflow, applied to the nearby proglacial icing, is provided by “Whitehead et al. (2010)”. Using this technique allowed a full set of exterior orientation parameters to be derived for each image.

The 3D positions of the targets on the glacier were then calculated by space intersection. Using the principle of collinearity allows a ray of light to be back projected from a point on the camera image plane, through the perspective centre of the camera lens and into 3D object space. Where the rays from both cameras intersect, the point location in 3D object space is defined. Using this technique allowed the daily positions of seven of the glacier targets to be calculated over the 59 day period for which photos were available. It was found that targets 1, 2, and 7 were not visible from camera station 2, so these were omitted from the analysis.

Horizontal displacements were calculated for each of the seven targets using three different methods. GPS displacements were calculated for the period of 305 days between measurements and these were adjusted to give estimates of average daily displacement. Estimates of horizontal displacement were also calculated using both SAR interferometry and photogrammetry. To facilitate comparison, the displacements obtained from InSAR were converted to horizontal displacements by multiplying them by the cosine of the glacier surface slope in the region of the target. The surface slope was obtained from a high resolution digital elevation model (DEM), generated interferometically using TerraSAR-X images.

Photogrammetric measurements were also used to investigate variations in surface height at each target over the 59 day measurement period. In order to measure this, it was necessary to correct for down-glacier motion, since each target was constantly getting lower as it moved down glacier. This correction was calculated by multiplying the horizontal distance travelled from the starting point by the tangent of the surface slope in the vicinity of the target. Figure 3 shows changes in surface elevation for all seven targets.

5 RESULTS

A comparison of motion estimates derived using each of these three techniques is shown in Tables 1 and 2, and in Figure 2. The daily measurements obtained by intersection from the two cameras were subject to positional errors. These resulted from inaccuracies in determining the exterior orientation parameters, and from measurement errors when estimating the position of each target on the photos. While clearly a simplification, the horizontal motion was assumed to be linear over the 59 day period. A regression line was therefore fitted to the observed points in order to characterize motion over this motion over this time (see Figure 2).

Table 1: Comparison between GPS, photogrammetric, and InSAR derived horizontal displacements at each target. Displacements shown are in mm per day. Columns 5 and 6 show the percentage differences between photo and GPS measurements and between InSAR and GPS measurements respectively

	GPS (mm)	**Photo (mm)**	**InSAR (mm)**	**Photo / GPS**	**InSAR / GPS**
GT3	7.08	4.37	11.57	61.7 %	163.4 %
GT4	12.79	10.49	14.12	82.0 %	110.4 %
GT5	12.91	12.49	13.45	96.7 %	104.2 %
GT6	15.26	17.06	15.37	111.8 %	100.7 %
GT8	8.1	5.67	8.08	70.0 %	99.8 %
GT9	8.97	5.99	10.11	66.8 %	112.7 %
GT10	9.72	10.33	10.50	106.3%	108.0%

Table 2: Comparison between GPS and photogrammetry-derived motion directions for each target in degrees

	GPS	Photo	Photo - GPS
GT3	87.6°	83.3°	- 4.3º
GT4	95.8°	119.8°	24.0º
GT5	94.6°	121.2°	26.6º
GT6	98.7°	126.1°	27.4º
GT8	76.8°	48.9°	- 27.9º
GT9	76.2°	72.9°	- 3.3º
GT10	89.4°	109.4°	20.0º

The displacements derived using the three methods show variations at each of the targets. In general the best agreement is seen between GPS measurements and the median winter flow measurements derived from TerraSAR-X. Both of these measurements represent average conditions over the autumn, winter, and spring. Because these measurements are aggregated, short term and seasonal variations in surface velocity are smoothed out. The TerraSAR-X measurements are also spatially averaged, having been derived from a 100 m grid of sample points. While this technique yields representative results across the surface of the glacier, it does not account for local variations. The effect of such variations can be clearly seen at target GT3, where the derived velocities from InSAR, GPS, and photogrammetry vary significantly.

The photogrammetric measurements showed greater variation. These measurements represented the motion over the specific 59 day period between the 20th of August and the 17th of October. When these are compared with the GPS measurements, it can be seen that there are significant differences, especially at targets GT3, GT8, and GT9. It is believed that these differences are a consequence of seasonal variations in glacier flow. If the GPS measurements are assumed to be the reference against which the other measurements can be compared, then it can be seen that targets on the northern side of the glacier, such as GT3, GT4, GT8, and GT9, moved a smaller distance than the GPS average over the 59 day period. Targets GT5, GT6, and GT10, which lay closer to the centre line of the glacier, showed less difference between photogrammetric and GPS measurements over the same time period.

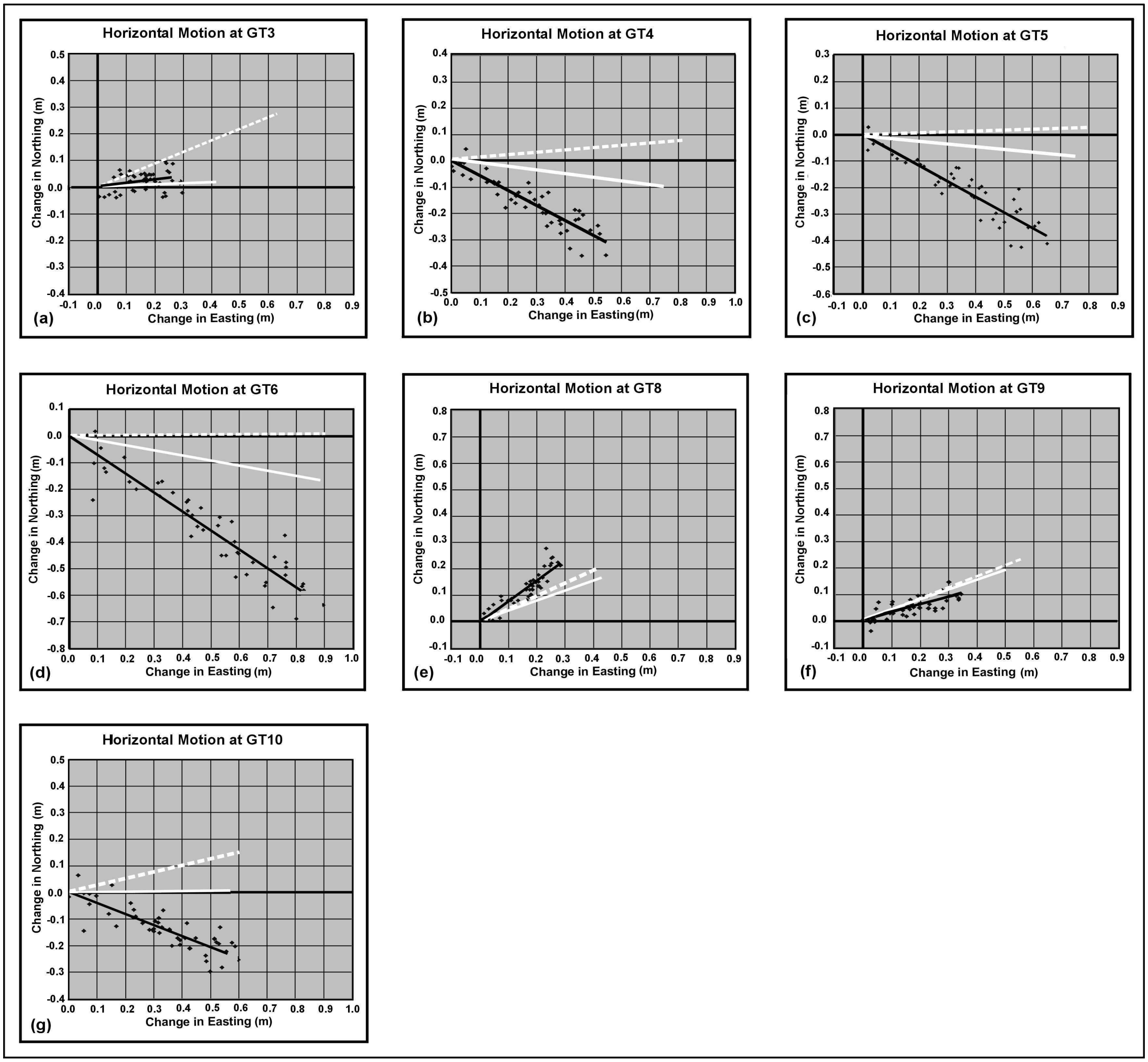

Figure 2: Measurement of horizontal displacement over 59 days. The black dots represent individual photogrammetric measurements, with the black line being fitted by regression. The continuous white line represents measurements derived by GPS, whereas the dashed white line represents average displacements derived from SAR interferometry.

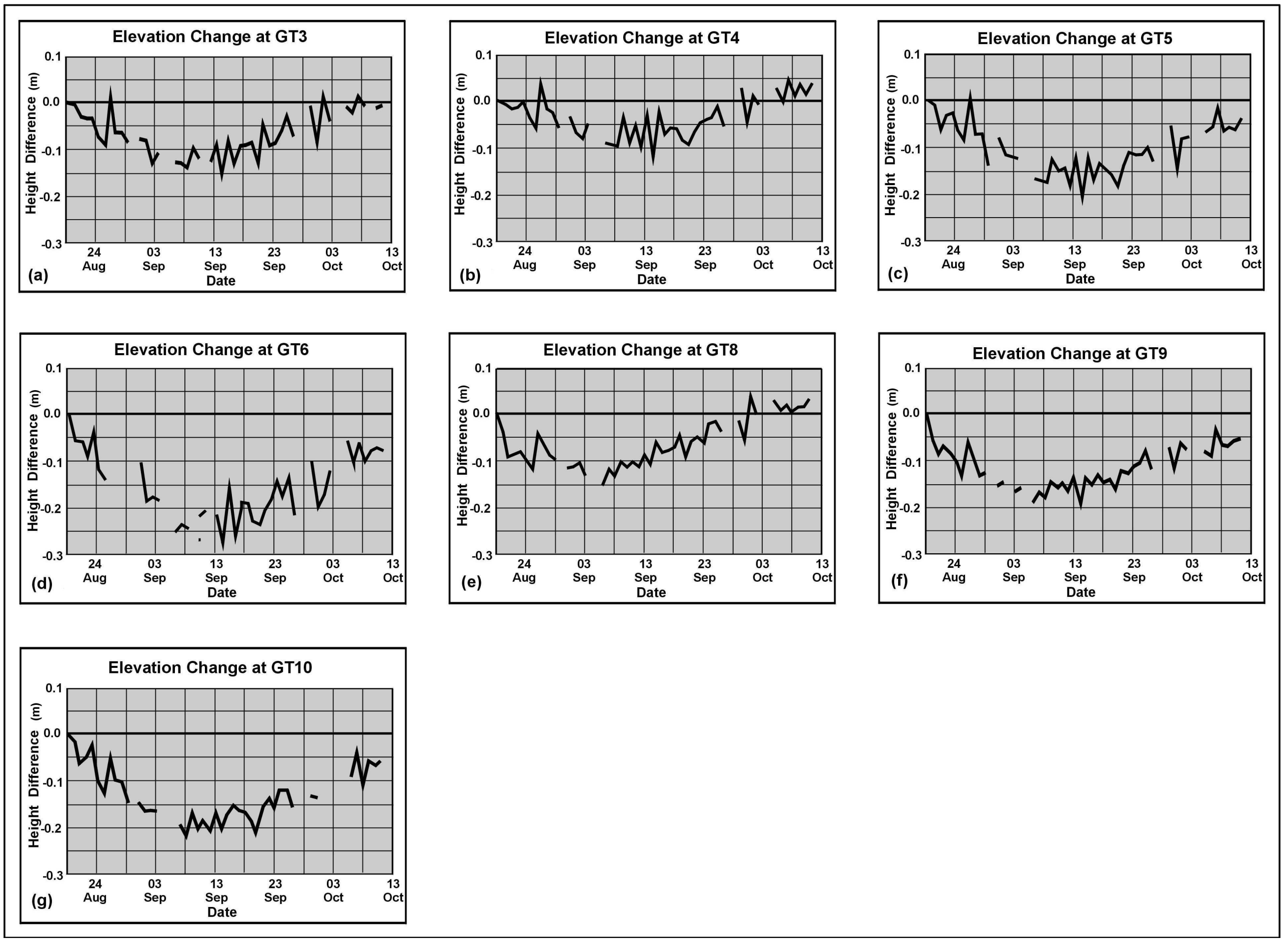

Figure 3: Vertical motion of the glacier surface over 59 days derived from photogrammetric measurements. The observations have been corrected to account for down-glacier motion.

Table 2 shows a comparison of the directions of glacier flow calculated using GPS and photogrammetry. The direction measurements computed from InSAR were averaged between points on a 100 m grid and as such are not included for consideration here, although they are shown on Figure 2. It can be seen that there appears to be a similar pattern, with GT3, GT8, and GT9 on the northern side of the glacier, all showing a rotation towards the northern edge of the glacier over the 59 day period. The targets situated closer to the centre of the glacier, such as GT6 and GT10 show a rotation towards the southern margins of the glacier.

The variations in surface height observed at each target are shown in Figure 3. It can be seen that each target shows a similar pattern. The height of the glacier surface dropped by 10 – 20 cm between the 20th of August and the 8th of September, followed by a similar rise in elevation which continued until the end of the measurement period on October the 17th. The last two points in the series showed a steep drop for all targets, however on investigation it was found that the rotation parameters derived for Camera 2 were incorrect for these dates. The elevation profiles are therefore only shown for the period up to the 13th of October. The magnitude of the drop in elevation and subsequent rise was greatest at GT6 and GT10. These targets were located closest to the centre of the glacier.

6 ANALYSIS AND DISCUSSION

The results of this study show how displacements obtained from SAR interferometry and ground-based photogrammetry are complementary. SAR interferometry gives wide spatial coverage, allowing accurate measurements of displacement to be made across the whole glacier surface, whereas ground-based photogrammetry allows detailed measurements of local surface motion to be made on a daily basis, as well as providing a measure of changing surface elevation. In this study the GPS measurements of the targets were assumed to provide an accurate baseline determination of average winter velocity. These values were used as the reference standard against which the InSAR and photogrammetric measurements could be compared.

In this case it was difficult to compare the data directly because the InSAR data was interpolated from a 100 m grid. This was due to processing constraints, since the final projected direction at each point had to be calculated iteratively. Recently implemented modifications to the vector projection algorithm should allow InSAR measurements to be processed on a per pixel basis, potentially giving spatial resolutions of better than 5 m after interferogram generation. Such a fine spatial resolution would provide a much better estimation of local conditions, and would likely provide displacement estimates at all targets similar to those obtained using GPS. In spite of being interpolated, the estimates of displacement obtained through InSAR generally agreed well with the GPS estimates. From Table 1, it can be seen that with the exception of GT3, GPS and InSAR estimates of displacement agree to within 15 %.

The timing of InSAR data collection also needs to be considered. In this case several interferograms were generated throughout the autumn, winter and spring, and median displacement values were calculated from them. If only a single interferogram were available then it may not provide representative displacement estimates over the whole winter, since it may reflect irregular horizontal and vertical motion of the glacier surface over the 11 day collection period. Another problem is that projection of InSAR derived displacements into the down-glacier direction requires an assumption to be made that glacier flow is parallel to the surface. This condition may often be violated on polythermal arctic glaciers, where trapped basal water can cause rapid variations in surface elevation to occur "(Whitehead et al. 2009)". If vertical motion is misinterpreted by assuming surface parallel flow, it can lead to substantial errors in measuring down-glacier displacement.

The measurements made using ground-based photogrammetry revealed considerably more information about the motion of each target than could be obtained from InSAR. Daily measurements of horizontal and vertical target positions were made, revealing a detailed pattern of horizontal and vertical motion over the measurement period.

The horizontal displacement at each target was compared with the average winter displacement derived from the GPS measurements. This revealed that the flow direction and magnitude over the 59 day measurement period was substantially different from the average wintertime values. The pattern of vertical motion may reflect changes in basal water pressure which occurred over the measurement period, or may be due to other factors, such as seasonal changes occurring in the terminus region. To obtain the average values calculated using the GPS measurements, there must have been a relative speed up of targets on the northern side of the glacier and slow down of those closer to the centre in the mid and late winter (see Table 1). This must also have been accompanied by a change in the glacier flow direction, with GPS measurements showing the flow at all targets to be almost directly down-glacier, as opposed to the photogrammetric measurements which showed flow directions rotated towards the northern and southern margins (see Table 2). This rotation may reflect a cessation of basal sliding in the autumn, with winter motion being dominated by ice creep.

The assumption that horizontal motion was linear over the 59 day measurement period is a simplification. Since the difference between the GPS and photogrammetric measurements showed that glacier flow direction changed over the winter, horizontal motion taken over the whole winter is obviously not linear. Nonetheless a linear regression line could be fitted successfully to the horizontal motion observed at each target over the 59 day measurement period. Typical standard errors were 5 cm or less, suggesting that this is a reasonable level of accuracy to expect for the photo analysis. In future the procedure used to derive photo orientations will be modified, with the glacier targets being used as additional tie points. This will greatly strengthen the orientation of each photo pair, reducing one potential source of error.

7 CONCLUSION

While the results presented here are preliminary they do show the potential of this approach for characterizing glacier surface flow. Having photographic data covering a longer time period would have been useful in establishing winter flow patterns, but in this case windblown snow obscured the view from Camera 2 in the middle of October. In the summer of 2009, both camera stations were rebuilt, with a view to obtaining imagery over a longer period in the following winter. It would also be desirable to obtain photo coverage for the summer, when basal sliding would be expected to contribute significantly to glacier surface motion. Interferometry is seldom possible at this time of year, since rapid decorrelation occurs between images.

Even allowing for these drawbacks, the results obtained so far suggest that this approach could provide a considerable amount of new information on the surface dynamics of glaciers, especially in remote areas where field time is necessarily limited.

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