DETERMINATION OF VARIATIONS IN GLACIER SURFACE MOVEMENTS THROUGH HIGH RESOLUTION INTERFEROMETRY; BYLOT ISLAND, CANADA

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ABSTRACT

Interferograms were generated from 10 TerraSAR-X image pairs, with the objective of obtaining estimates of winter surface motion for a slow-moving polythermal arctic glacier. Flow directions were computed using both ascending and descending-pass interferograms for each period, with the median value being adopted as the final direction. The weighted average flow was computed, with weighting based on the inverse of the difference between the ascending and descending-pass displacement estimates for each date. This study uses multiple interferograms with different imaging geometries to provide estimates of down-glacier flow. The methodology adopted minimizes the effects of glacier / satellite track alignment and those resulting from vertical motion of the glacier surface. Current velocities were compared with flow estimates derived from a 1992 ERS-1 image pair. The velocities were similar over most of the glacier, but current velocities were found to be 30% to 50% lower on the lower glacier.

1. INTRODUCTION

Repeat-pass SAR interferometry is a well-established technique for measuring glacier surface velocities. Numerous examples exist of this technique being used to measure and quantify glacial surface dynamics in Greenland and Antarctica, e.g. Joughin et al. [1], Rignot & Kanagaratnam [2]. In the Canadian Arctic Burgess et al. [3] used a combination of SAR interferometry and speckle tracking to determine the dynamics of the Devon Island icecap. Sjogren et al. [4] compared coherence measurements over an area which included a number of glaciers on Bylot Island.

InSAR has also been used to study valley glaciers Vachon et al. [5] used five ERS-1 / ERS-2 image pairs from the winter of 1995 / 1996 to determine winter flow rates for the Athabasca and Saskatchewan glaciers. Cumming and Zhang [6] analyzed flow patterns for the Lowell glacier, using both ascending and descending-pass ERS Tandem image pairs.

To date there have been relatively few studies which have used InSAR to study the surface dynamics of small arctic valley glaciers. With its high spatial resolution and 11 day repeat period TerraSAR-X is well suited to this task. The main objective of this study was to use SAR interferometry (InSAR) to determine the average winter flow rates for Fountain Glacier, on southern Bylot Island. Estimated winter flow will be used as a baseline for future studies of motion anomalies.

2. STUDY AREA

Bylot Island is roughly 180 km by 100 km in extent and is situated to the north of Baffin Island (figure 1a). It has an average temperature of -15° C. 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 [7]. The interior is dominated by the Byam Martin Mountain range, which is covered by an icefield 4,500 km² in extent. Valley glaciers radiate out in all directions from this central icefield towards the coast.

This study focuses on Fountain Glacier which is officially designated as B26 in the Glacier Atlas of Canada [8]. This glacier is believed to be polythermal in nature [9]. It is approximately 15 km long and has a catchment area of 72 km². In the last 15 years Fountain Glacier has entered a phase of rapid retreat [9], which is being driven by mass-
wasting. In recent years the terminus of the glacier has developed into a vertical cliff face, which is up to 30 m high in some areas. This face was measured by Wainstein et al. [9], who estimated that it had retreated at an average 10 m per year between 1995 and 2001.

Subglacial hydrological processes are believed to play an important part in the seasonal dynamics of Fountain Glacier. The glacier has an associated proglacial icing, which regenerates throughout the winter. Wainstein et al. [9] suggested that the annual regeneration of this feature provides evidence that a substantial quantity of liquid water is present at the base of the glacier, even in the winter months.

3. METHODOLOGY

Ten interferometric pairs of TerraSAR-X images were available, with stripmap mode images for May 2008, high-resolution spotlight mode images for October 2008, and spotlight mode images covering February 2009, and May 2009. Matching ascending and descending-pass image pairs were available for every acquisition period. In addition, an ERS-1 image pair from March of 1992 was available. With the exception of the October pair which only covered the lower glacier, the image pairs covered most of the glacier, other than the accumulation zone.

Digital contours were available from 1982. However significant changes have occurred on the glacier margins in recent years, so it was necessary to construct a detailed DEM reflecting current conditions. This was done using a variation of the differential interferometry (DInSAR) technique. Two back to back descending-pass interferometric pairs were available for February 2009. These had significantly different baselines, and hence significantly different sensitivities to topography. It was assumed that no change had occurred in glacier motion between the two interferograms, and the two interferograms were therefore subtracted in order to eliminate the effects of motion. The resulting difference interferogram was then used to generate a DEM. While the slow-moving margins were well represented by this DEM, some areas in the centre of the glacier showed major differences in motion between the two interferograms, which were likely due to vertical motion of the surface. These sections were replaced by sections of a DEM generated from the 1982 contours.

Motion interferograms were produced from each of the 10 interferometric pairs. These were unwrapped and flattened, and the topographic phase component was removed using the composite DEM. They were then calibrated to obtain line-of-sight displacements and orthorectified. The provisional direction of glacier flow was estimated by tracing the lines of visible flow stripes on the glacier surface, using an orthorectified amplitude image. Down-glacier slope was also computed, averaged over a 500m distance along the direction of the flow stripes.

If the direction of glacier flow is accurately known, and flow is assumed to be parallel to the surface, then down-glacier displacement can be computed from single-pass line-of-sight displacements using the following formula [6]:

$$|D| = \frac{|R|}{\sin \mu \cos \theta + \sin \gamma \cos \mu \sin \theta}$$ (1)

Where $R = \text{line-of-sight motion}$, $\mu = \text{glacier surface slope}$, $\theta = \text{incidence angle}$, and $\gamma = \text{angle between the satellite track and the glacier flow direction}$.

Centre-line profiles were measured for each image pair. Estimates of down-glacier flow were then computed from equation (1) using the interpolated slope and direction. As suggested by Cumming and Zhang [6], directions were adjusted for each point on the centre-line profile to minimize the difference between ascending and descending-pass measurements on each date. The final direction at each point was taken as the median of all the computed flow directions, including the direction estimated from the flow stripes. This process was then repeated for a 100 m grid of points covering the whole glacier surface. To assess longer term changes in glacier flow, displacements were also computed using the 1992 ERS-1 image pair.

4. RESULTS AND DISCUSSION

The median centre-line profile shown in figure 2 shows winter velocities increasing from around 6 ma$^{-1}$ at the terminus, to around 32 ma$^{-1}$, 7.3 km up-glacier. The trend is generally linear, although there is some variation, particularly around the curved section of the glacier. The sharp spikes which can be seen in the individual profiles occur where the satellite track and the glacier flow directions are aligned, resulting in values for $\sin \gamma$ which are close to zero. The descending-pass image pairs were particularly affected by this, since the alignment of the top section of the glacier lies close to many of the descending satellite tracks. Adopting the median flow eliminated most of the errors caused by this alignment, as there was a variation of several degrees between the descending orbital tracks.

Images derived from the 100 m grid sampling are shown in figure 3. They generally show peak velocity occurring in roughly the same location on the upper glacier. Most of the images show a secondary maximum occurring about 3 km from the terminus. The variability of motion estimates is very high in this region, with back to back interferograms from February 2009 showing completely different motion patterns (see figure 2, at the 3000 m mark). This is believed to represent vertical motion of the glacier surface, which may be a response to underlying hydrological conditions. Wainstein et al [9] presented evidence that liquid water is present beneath Fountain Glacier throughout the winter, and plays an important part in the seasonal
regeneration of the associated proglacial icing. Future fieldwork will focus on this area with a view to testing this hypothesis.

To provide an estimate of the consistency of flow measurements over all dates, RMS deviations were calculated at each point using all TerraSAR-X down-glacier motion estimates (figure 4). The lower 3 km of the glacier was found to have the most consistent flow, with RMS deviations generally less than 1 m a\(^{-1}\). Similarly much of the upper glacier, including the fastest flowing section, showed relatively little variation between the different dates, with RMS deviations of around 3.5 m a\(^{-1}\). The largest variations in estimated down-glacier velocities occur in the middle third of the glacier, where RMS deviations were typically between 3 m a\(^{-1}\) and 8 m a\(^{-1}\). These variations are likely due to errors arising from the geometric alignment of the various satellite tracks with the glacier flow direction, but may also reflect real variations in horizontal and vertical velocity.

Using a weighted average is an effective way to reduce the effects of such motion variations. The influence of each measurement was determined from the inverse of the difference between the ascending and descending-pass motion estimates. Good agreement between ascending and descending-pass displacement is likely to indicate that the flow is being correctly projected in the down-glacier direction. The weighted average raster produced using this technique was compared to a median displacement raster, derived from all measurement dates. In most areas the agreement was better than 1 m a\(^{-1}\), with significant differences only occurring in a few isolated areas (figure 3).

Comparison of the ERS-1 derived motion estimates from March of 1992 with the TerraSAR-X weighted average image showed similar motion patterns over the upper glacier. The maximum velocity measured from the ERS-1 image pair occurred in the previously-discussed area of rapid motion 3 km from the terminus (figure 3). On the lower glacier, 1992 velocities were typically 30 to 50
percent higher than current velocities. It is believed that this reduction in the flow rate of the lower glacier is linked to the changes which have occurred at the terminus in recent years.

Derived flow estimates were compared with actual measurements of surface features on the glacier, using distances measured between features identified on May 2008 and May 2009 images. The number of features which could be reliably identified was limited by the effect of speckle. In total 27 points were finally identified (figure 4). The points on the upper glacier all agreed to within 1 pixel (5 m) with the estimated annual displacement from InSAR. On the middle and lower sections of the glacier, the picture was more complex. Several points agreed closely with the estimated annual displacement values. Five points showed flow rates that were between 10 ma^{-1} and 17 ma^{-1} higher than the estimated values, with the largest variations being seen on the outside of the curved section (figure 4). The results suggest that basal sliding may contribute significantly to the overall flow of parts of the middle and lower glacier. However the pattern is not straightforward, and because of the difficulty of reliably identifying features, as well as the in-built accuracy limitations of the measurement process, the results must be considered inconclusive at this stage.

5. CONCLUSIONS

This study shows that the high spatial resolution and 11-day repeat period of TerraSAR-X is particularly well suited for the study of the surface dynamics of slow-moving polar glaciers. The weighted averaging technique adopted meant that it was possible to minimize the effects of vertical motion and the effects resulting from alignment of the satellite track with the glacier flow direction. This allowed the average winter flow rate of the glacier to be estimated.

The variations in glacier flow between the different image pairs allowed areas with high variability to be identified. In particular, the section of the glacier which showed very high variability between back to back February interferograms is interesting. Comparisons between the weighted average image and the 1992 ERS-1 interferogram showed that velocities over the lower glacier have slowed significantly in recent years, which is believed to be related to changes which have occurred at the terminus.

Attempts to measure the overall annual flow of the glacier proved less successful, due to the difficulty of reliably identifying distinct features on the glacier surface. While the results were inconclusive, they did appear to suggest that basal sliding does contribute to overall motion, particularly for the middle and lower sections of the glacier.

6. REFERENCES