An Investigation of the 3 Km Motion Anomaly on Fountain Glacier Using SAR Interferometry and Ground Penetrating Radar

K. Whitehead, B. Moorman, and P. Wainstein
Department of Geography, University of Calgary, 2500 University Drive NW, Calgary, Alberta, Canada

ABSTRACT
During an interferometric study of glacier velocities on Fountain Glacier, an anomalous fringe pattern was noticed on an ascending-pass interferogram from February 2009. Field investigations using ground penetrating radar revealed a series of unusual reflections at the base of the glacier. These were interpreted as being due to a body of subglacial water immediately down glacier from the visible anomaly. The detection of this water body is a consequence of the sensitivity of the interferometric technique, and also of a particularly favourable imaging geometry.

RÉSUMÉ
Au cours d'une étude interférométrique sur les vélocités glaciaires du glacier Fountain, un diagramme de franges anormal a été observé sur un interférogramme datant de février 2009. Des recherches ont été effectuées sur les causes possibles de cette anomalie et suggèrent que celle-ci était probablement due à l'expression en surface de processus hydrologiques proglaciaires. En utilisant un géoradar lors de recherches sur le terrain, une grande nappe d'eau proglaciaire a été découverte et une claire anomalie laisse croire que cette nappe se situe immédiatement en aval du glacier. La détection de cette nappe d'eau a été possible grâce à la sensibilité de la technique d'interférométrie ainsi qu'à une géométrie d'imagerie particulièrement favorable.

1 INTRODUCTION

In a 2009 study, "Whitehead et al. (2009)" used a series of interferograms generated from ascending and descending-pass TerraSAR-X images to establish seasonal velocity patterns for Fountain Glacier on Bylot Island. Down-glacier velocities were calculated from paired ascending and descending-pass interferograms.

The interferograms showed generally similar characteristic fringe patterns. However an interferogram created from ascending-pass imagery acquired on the 5^{th} and the 16^{th} of February 2009 appeared strikingly different, having a series of concentric fringes defining a roughly circular pattern in a region located about three kilometres up glacier from the terminus.

The objective of the study described in this paper was to investigate the particular circumstances which caused this anomaly to appear on the early February interferogram, and also to determine why this feature showed up so prominently on the ascending-pass interferogram, but was not readily apparent on the descending-pass interferogram acquired over almost the same time period. This involved looking at the conditions relating to the acquisition and processing of this interferogram, as well as carrying out field investigations using ground-penetrating radar (GPR), in order to determine how this feature related to environmental variables such as the basal hydrology of the glacier and the interaction between the glacier and the underlying permafrost layer.

2 STUDY AREA

Bylot Island (Figure 1a) is situated in Canada's Northern Archipelago. The island is heavily glaciated and has a central ice cap roughly 4,500 km^2 in extent, which occupies the interior Byam Martin mountain range. A series of valley glaciers radiate out from this ice cap and flow towards the coast.

Climatically Bylot Island can be classified as being an arctic desert, with the region around Fountain Glacier typically receiving less than 200 mm of precipitation, and with winter snowpack thicknesses reaching a maximum of 80 cm "(Moorman 2003)". The island is located in the zone of continuous permafrost and has an average air temperature of -15°C "(Moorman 2003; Irvine-Fynn et al. 2006)".

Fountain Glacier (Figure 1b) is a relatively small valley glacier, which lies to the South of the main ice cap. It is approximately 15 km long and 1.2 km wide close to the terminus.

There is a good deal of geophysical and hydro-geological evidence to suggest that Fountain Glacier is polythermal in nature, comprising a core of warm wet ice covered by a layer of colder drier ice. The glacier has a large associated proglacial icing which occupies the proglacial flood plain to the east of its snout. This feature depends on liquid subglacial storage for its regeneration. The polythermal nature of the glacier and the presence of the proglacial icing are both a consequence of the underlying permafrost layer, which ensures that marginal regions of the glacier remain frozen to the glacier bed year round.

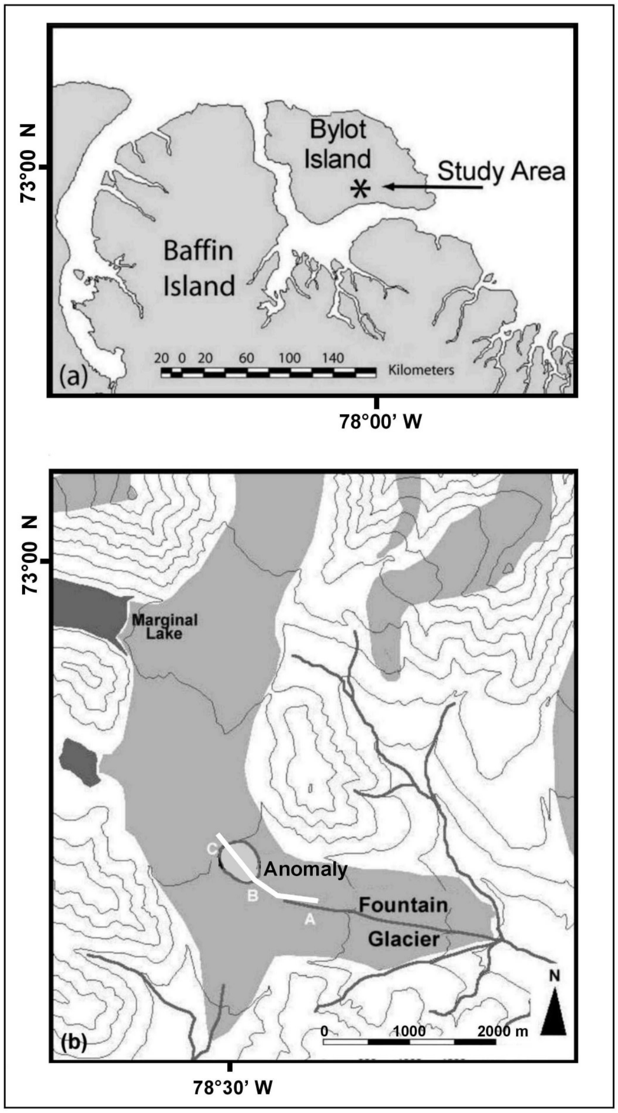

Figure 1(a) Location of the study area, and (b) location of the anomaly on Fountain Glacier. The line ABC shows the location of the GPR profile obtained in the summer of 2009

It has been observed that the icing follows an annual cycle of regeneration and erosion, with the accretion of ice happening throughout the winter and its partial erosion occurring during the short arctic summer, as a result of thermal and hydraulic erosion of glacial melt waters. "Wainstein et al. (2008)" suggested that the icing's seasonal regeneration cycle provides evidence that a supply of liquid water is present year round beneath Fountain Glacier. It has been suggested this water owes its existence both to the glacier's polythermal character and to the supply of water from a large marginal lake that connects Fountain and Akteneaq Glacier, as well as water originating from a series of smaller marginal lakes.

There is additional evidence to suggest that Fountain Glacier has a highly active hydrology. In the early 1990s the glacier had a gently sloping terminus. However, during the mid 1990s a terminal collapse feature began developing, as the roof of a large subglacial cavern collapsed. It is believed that this cavern was originally eroded by subglacial water flow, which annually reoccupied the same hydraulic routing. Since the first collapse feature was observed, several other terminal and marginal collapse features have developed. These features have subsequently expanded as a result of ice erosion by subglacial flow, accelerated glacier retreat, and undercutting of the glacier terminus by marginal streams. The present day terminus comprises a vertical cliff face, which has been measured to be roughly 35 m high in some places.

Fountain Glacier is unusual in terms of its shape. The top two thirds of the glacier is oriented roughly in a north / south direction. However the bottom third of the glacier turns through 90° and ends up oriented roughly west / east. This rotation of the glacier has important implications for interferometric analysis, since it means that both ascending and descending satellite tracks are parallel with glacier flow at different points on the glacier. Where the satellite track and the direction of the glacier flow are aligned it is not possible to make accurate measurements of ice velocity, since interferometry only provides a measure of the distance towards or away from the satellite in the look direction, which is at 90° to the satellite track.

3 BACKGROUND

3.1 SAR Interferometry

SAR interferometry (InSAR) is a well established technique for measuring the surface velocities of glaciers. Numerous studies have been carried out in Antarctica, Greenland, and for valley glaciers throughout the world. Interferometry has been used to study the dynamics of polythermal glaciers in the Arctic on a number of occasions. "Gudmundsson et al. (2002)" used a combination of InSAR and other ice displacement data to produce 3D maps of surface motion at the Gjálp eruption site in Iceland, while "Burgess et al. (2005)" used InSAR in a comprehensive study of the flow dynamics of the Devon Ice Cap. As long as it is possible to obtain good coherence between the images forming the interferogram, highly accurate estimates of glacier surface velocity can be obtained.

An interferogram is generated by multiplying the phase component of one scene by the complex conjugate of a second scene. The resulting interferogram gives a measure of the phase difference between the two scenes. This phase difference may arise because of topography, or because of surface displacement.

When measuring surface displacement, the topographic influence needs to be removed. This is achieved by generating a synthetic, topographic-only interferogram from an existing digital elevation model (DEM). When this synthetic interferogram is subtracted from the original interferogram, the resulting product reflects only phase changes due to surface displacement.

The interferogram which is produced consists of a series of interference fringes. Each fringe gives a highly accurate measure of the relative phase within a single wave cycle. However to get an absolute measure of phase it is necessary to sequentially add the fringes to build up a continuous surface. This process is known as phase unwrapping. An unwrapped interferogram can be used to estimate displacement in the radar line of sight direction over the period between the acquisition of the two scenes.

3.2 Obtaining Velocity Estimates

In order to obtain estimates of down-glacier velocity, it is necessary to project the line of sight displacement obtained from the interferogram into the flow direction of the glacier. In cases where both the direction of glacier flow and the surface slope of the glacier are known, displacement and hence down-glacier velocity can be estimated from a single interferogram using the following formula "(Cumming and Zhang 2000)":

$$|D| = \frac{|R|}{|\sin\mu\cos\theta + \sin\gamma\cos\mu\sin\theta|} \quad [1]$$

Where R = line of sight motion, μ = glacier surface slope, θ = incidence angle, and γ = angle between the satellite track and the glacier flow direction.

.

If the glacier's flow direction is not accurately known, a second interferogram from a second look direction may be used to derive this direction. In this case it is normal to use interferograms obtained from ascending and descending passes "(Cumming and Zhang 2000)". While this procedure still does not give sufficient information to fully determine the full three dimensional velocity vector for the glacier, an assumption is normally made that the flow direction is parallel to the surface. In practice this means that it is assumed that no change will occur in the surface height of the glacier, other than through normal down-glacier motion. The glacier flow direction can now be found, as it is the value at which the projected displacements obtained from ascending and descending-pass interferograms are equal.

3.2.1 TerraSAR-X

TerraSAR-X is a high-resolution radar satellite, which has an orbital repeat period of only 11 days. The satellite carries an X-band radar, which has a 3 cm wavelength. Launched in 2007, the satellite is capable of acquiring images at ground resolutions of up to 1 m. "Whitehead et al. (2009)" used a combination of 1m high-resolution spotlight, 1.5 m spotlight, and 3 m stripmap imagery in their 2009 study.

4 METHODOLOGY

The study by "Whitehead et al. (2009)" used a series of ascending-pass and descending-pass TerraSAR-X interferograms to obtain velocity estimates for Fountain Glacier. Glacier flow was assumed to be parallel to the surface in each case and the flow direction was calculated by finding the direction which gave the closest agreement between ascending and descending-pass displacements. The median flow direction from the different matched ascending and descending-pass sets of interferograms was then adopted for each point on the glacier surface. The full methodology is described in "Whitehead et al. (2009)". As part of this study, a series of centre line profiles were produced.

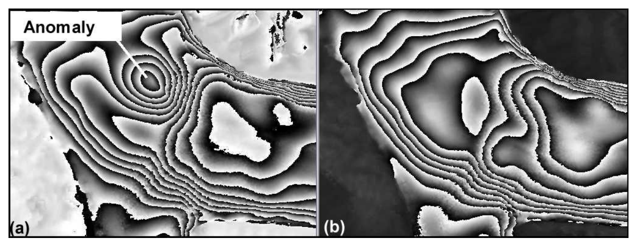

Figure 2: Back to back interferograms from February 2009. The interferogram on the left was produced from images acquired on the 5th and the 16th of February 2009 and shows the anomaly. The interferogram on the right was produced from images acquired on the 16th and 27th of February 2009 and shows the typical fringe pattern observed on all other ascending-pass interferograms

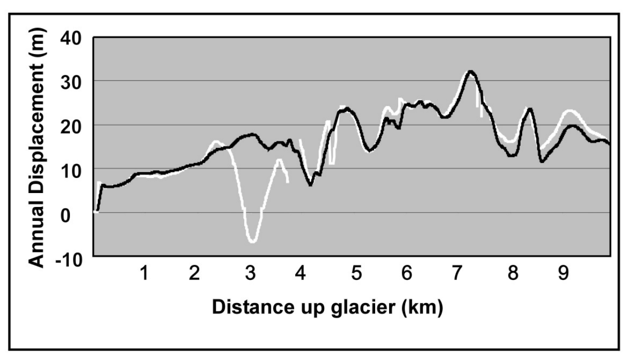

Figure 3: Centre line profile obtained from the Feb 5 -16 interferogram showing the anomaly in white compared with average down glacier displacement in black "(Whitehead et al. 2009)". Note the apparent negative displacement at 3000 m from the terminus

To assess the contribution of vertical surface motion, an assumption was made that the down-glacier motion over this period could be represented by the average down-glacier motion computed by “Whitehead et al. (2009)”. An estimate of 15 ma^{-1} was therefore used to represent the down-glacier velocity in the vicinity of the anomaly. Equation [1] was then used to calculate what this down-glacier displacement would represent when it was reprojected into the radar line of sight direction at the location of the centre of the anomaly. This estimated displacement was then subtracted from the observed line of sight displacement, with the difference being assumed to represent the effect of vertical motion on the line of sight displacement.

The vertical displacement of the glacier surface could now be found from:

$$V_{disp} = LOS_{disp} / \cos\theta \qquad [2]$$

Where θ is the incidence angle, which in this case was 29.28°

4.1 Field survey

In June of 2009, a ground penetrating radar (GPR) survey was carried out over the area of the anomaly, using a Pulse Ekko Pro GPR system. It had been hoped to run a series of GPR lines across the whole area. In the event however technical problems limited the survey to a single longitudinal line, passing through the centre of the anomaly (line ABC in Figure 1b). The GPR survey was carried out using twin 50 MHz antennae in parallel broadside configuration. This frequency allowed penetration to the bed of the glacier, which was about 200 m deep in the region of the anomaly.

5 RESULTS

The anomaly observed on the early February interferogram is shown in Figure 2(a). It can be seen that it comprises roughly four fringes and is approximately circular in shape, with a length of roughly 750 m in the down-glacier direction. The centre line profile for this period shows the line of sight displacement measured across the anomaly projected into the down-glacier direction, using the surface parallel flow assumption (Figure 3). At 3 km from the terminus it can be seen that the down-glacier displacement drops to below zero, suggesting the glacier was flowing in reverse at this point. It is much more likely that the fringe pattern observed represents vertical motion of the glacier surface which has been wrongly projected as a consequence of the adoption of the surface parallel flow assumption.

5.1 Interferogram analysis

When the predicted down-glacier velocity of 15 ma^{-1} was reprojected into the radar line of sight direction it gave a displacement of -9 cm over the 11 day orbital period. The TerraSAR-X radar operates at X band, which has a wavelength of 3 cm. This displacement therefore represents approximately three interference fringes.

The vertical surface displacement could now be estimated for the region of the anomaly. The actual measured value for line of sight displacement in the centre of the anomaly was +2.4 cm, which meant that the change in elevation represented a displacement of 11.4 cm in the line of sight direction, corresponding to 3.8 interference fringes. This agrees well with the four fringes which can be observed on Figure 2. After correcting for the incidence angle, the vertical motion of the glacier surface was found to be approximately 13 cm upwards, at the centre of the anomaly. This motion occurred over the 11 day period between the 5th and the 16th of February.

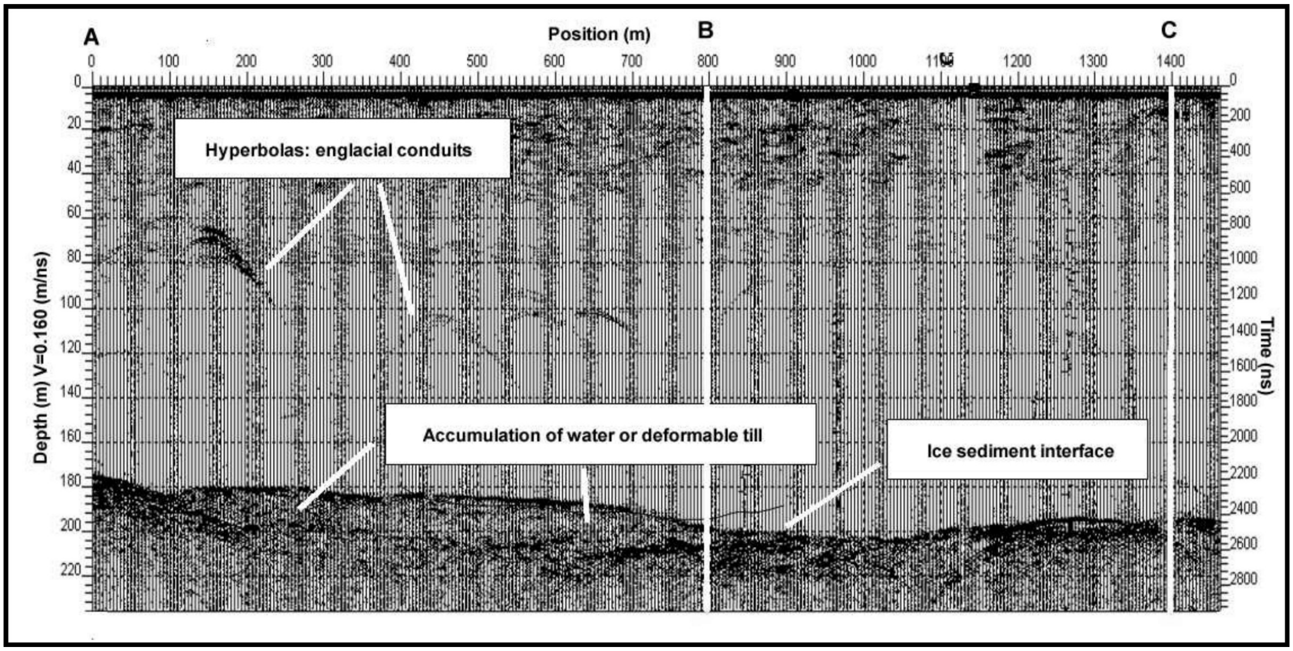

Figure 4: Annotated GPR trace showing the reflections at the glacier bed which were interpreted as being from a body of subglacial water or saturated till. The location of points A, B, and C can be seen on Figure 1b.

5.2 GPR survey

The interpreted GPR trace is shown in Figure 4. Analysis of the GPR trace revealed the presence of a double horizon at the base of the glacier which was interpreted as being caused by a large body of water or saturated glacial till. By recalculating to account for the different speed of propagation through water, this layer was estimated to be roughly 6 m deep. Its down-glacier length was about 750 m, roughly the same as the surface expression of the anomaly. However the water layer was located down glacier from the anomaly, between A and B on the GPR trace, whereas the anomaly occurred between B and C (see Figure 1b).

6 DISCUSSION AND CONCLUSIONS

It is interesting to note that in this case the contribution to line of sight displacement from down-glacier motion was comparatively small, and secondly that such a small change in surface elevation could have produced such a prominent fringe pattern on the interferogram. The reason that the down-glacier motion had such a small effect on the measured line of sight displacement is to do with the direction of the glacier flow. In the region of the anomaly, the satellite track and the glacier flow direction were only 14° different. This meant that relatively high values of down-glacier velocity were represented by displacements of only a few centimetres, when projected into the line of sight direction.

The prominence of the anomaly is also a consequence of the projection geometry. Because the line of sight displacement due to down-glacier motion was so small at this point, the change in the surface height showed up disproportionately. Had this amount of uplift occurred on other parts of the glacier where the flow direction and the satellite track were more widely separated it is likely that the signal would have been masked by variations in the down-glacier displacement. By way of contrast, the region of the anomaly is considerably less apparent on the descending-pass interferogram covering the same time period. In this case the angle between the satellite track and the glacier flow direction is much greater, so down-glacier motion produces a much larger displacement in the line of sight direction, effectively masking small variations in surface elevation.

The discovery of what is believed to be a body of water or saturated till beneath the surface of Fountain Glacier provides important clues regarding the subglacial hydrology of Fountain Glacier. It is believed that the subglacial system is fed by multiple sources of water including meltwater and inflow from marginal lakes, especially the large lake between Fountain and Akteneaq Glaciers, located a further three kilometres up glacier. The fact that the glacier surface was observed to be rising over a large area suggests that a substantial amount of water was flowing into the subglacial environment and collecting in cavities beneath the glacier at the time. This supports the idea, suggested by “Moorman (2003)” and “Wainstein et al. (2008)” that there is a continuous flow of water between the marginal lakes and the glacier terminus year round.

It is interesting to note that the body of water or saturated till was found down glacier of where the anomaly appeared. Why this is the case is unclear. It is possible that there was a build up of water pressure backing up from the existing body of subglacial water or saturated till, which may have been due to a constriction in the subglacial system further down the glacier. At some stage separation pressure could have been exceeded, causing the glacier to separate from its bed upstream of this feature, and resulting in the observed rise in surface elevation.

This case study shows both the advantages and disadvantages of using SAR interferometry to determine glacial surface velocities. On the plus side, the sensitivity of this technique allows extremely small horizontal and vertical displacements to be measured. No other satellite remote sensing technique is available which would detect a surface rise of 13 cm over an 11 day period, and over such a small area.

On the negative side, the fact that the full 3D velocity vector for the glacier cannot be derived from two interferograms means that it was necessary to adopt certain limiting assumptions. The assumption of surface parallel flow is particularly restrictive, since it interprets all motion as occurring in the down-glacier direction. Any vertical motion of the surface, other than that due to forward motion of the glacier, is therefore wrongly interpreted. The example discussed in this paper illustrated an extreme case of this effect, where vertical motion of only a few centimetres could actually be interpreted as a reversal in the glacier flow direction.

Particular caution is required when applying SAR interferometry to slow-moving polythermal glaciers, such as Fountain Glacier. While InSAR allows highly accurate estimates to be made of flow rates, the slow rates of flow mean that even small amounts of vertical motion can have a much larger effect on the apparent down-glacier velocity than would be seen on faster moving temperate glaciers. Glaciers which are hydrologically active are also more likely to be subject to changing surface elevations, so the surface parallel flow assumption may not be appropriate under such circumstances.

The ideal configuration would be to have three interferograms with significantly different look directions. At arctic latitudes a very strong angular configuration can be achieved if a left-looking interferogram is included, in addition to the more common ascending and descending-pass right-looking interferograms. Under these conditions the full 3D motion vector of the glacier can be determined without any prior assumptions of surface parallel flow or surface slope. Incorporation of a third, left-looking interferogram is a focus for future studies linking the surface dynamics and the subglacial hydrology of Fountain Glacier.

ACKNOWLEDGEMENTS

This work was supported by grants and in-kind contributions from the Polar Continental Shelf Program, the National Scientific Training Program (NSTP), the National Science Research Council (NSERC), and Alberta Ingenuity. Logistical support was provided by Parks Canada.

REFERENCES

Burgess, D. O., Sharp, M. J., Mair, D. W. F., Dowdeswell, J. A. and Benham, T. J. 2005. Flow dynamics and iceberg calving rates of Devon Ice Cap, Nunavut, Canada. *Journal of Glaciology.* Vol 51(173): 219-230.

Cumming, I. and Zhang, J. 2000. Measuring the 3-D Flow of the Lowell Glacier with InSAR. *FRINGE'99: Advancing ERS SAR Interferometry from Applications towards Operations*, Liege, Belgium

Gudmundsson, S., Gudmundsson, M. T., Björnssson, H., Sigmundsson, F., Rott, H. and Carstensen, J. M. 2002. Three-Dimensional Glacier Surface Motion Maps at the Gjálp Eruption Site, Iceland, Inferred from Combining InSAR and Other Ice-Displacement Data. *Annals of Glaciology.* Vol 34: pp.315-322

Irvine-Fynn, T. D. L., Moorman, B. J., Williams, J. L. M. and Walter, F. S. A. 2006. Seasonal Changes in Ground-Penetrating Radar Signature Observed at a Polythermal Glacier, Bylot Island, Canada. *Earth Surface Processes. Landforms.* Vol 31: pp.892-909.

Moorman, B. (2003). Glacier-permafrost hydrology interaction, Bylot Island, Canada. *Permafrost: 8th International Conference*. Zurich, Switzerland: pp.783 - 788.

Wainstein, P., Moorman, B. and Whitehead, K. 2008. Importance of Glacier - Permafrost Interactions in the Preservation of a Proglacial Icing: Fountain Glacier, Bylot Island, Canada. *Ninth International Conference on Permafrost*. Fairbanks, Alaska. 2: pp.1881-1886

Whitehead, K., Moorman, B. and Wainstein, P. 2009. Determination of Variations in Glacier Surface Movements through High Resolution Interferometry; Bylot Island, Canada. *IGARSS 09*. Cape Town, South Africa: pp.II-230 - II-233