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Monitoring of Belvedere Glacier using a wide angle GB-SAR interferometer

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ABSTRACT

Belvedere Glacier, east face of the Mount Rosa, has experienced drastic changes in flow regime and morphology in the last years. Within the activities of the GALAHAD project funded by the European Commission, a ground-based SAR (GB-SAR) interferometer was employed on this glacier. Although based on the ground, the sensor works with the same principles as satellite radar interferometry measuring the deformation field of the illuminated surface. It was used for the first time on this glacier in 2004 and a new survey, here reported, was arranged last summer (2007). During this latter survey, the radar antenna moved around a vertical axis in order to illuminate a larger part of the glacier. It provided deformation maps of a wider part of the glacier every half an hour almost continually for 1 month. Finally, a procedure for building a digital elevation model (DEM) of the glacier was developed and the obtained DEM was compared with an available topographic map dated July 2005. Large differences in the ice surface height appear from the comparison confirming the overall reduction of the ice mass.

1. Introduction

The recent history of Belvedere Glacier is characterized by rapid and extraordinary movements, which were supposed to be related to global climate warming (Tamburini and Mortara, 2005). Due to this extraordinary activity, it has been object of many researches over the last years and it is still under surveillance by the local authorities.

GB-SAR interferometers work with the same principles of satellite SAR interferometry. They are sensors able to measure surface motion continuously under almost all weather conditions and, so far, they have been mainly used to monitor landslides (Antonello et al., 2004) and for topographic mapping (Noferini et al., 2007).

In the framework of the GALAHAD project aimed at developing and testing remote sensing techniques for natural hazard mitigation, two GB-SAR surveys were arranged at Belvedere Glacier, in summer 2006, reported in Mecatti et al. (2007), and in summer 2007, which is the matter of this paper.

Before GALAHAD, satellite radar interferometry had been already widely applied to mapping glacier velocities (Goldstein et al., 1993). However, very little experience was available for GB-SAR: a GB-SAR interferometer working at C band was installed near the main body of Belvedere glacier in 2004 for checking its feasibility of continuously monitoring the glacier (Luzi et al., 2007). GB-SAR could provide continuous observations of critical glacier parameters, like the surface velocity, working from remote thus making the installation and servicing safe for the operator.

With respect to the previous surveys, in summer 2007, images were collected at two different looking angles about 30° apart, in order to widen the illuminated area to nearly all the valley. GB-SAR produced both surface velocity and topographic maps of the valley. Section 3.1 of this paper deals with the superficial deformation maps that were produced at a rate of about two per hour almost all August long. GB-SAR actually measured only the ice velocity along slant range. Thanks to the chosen viewing position, the greater part of the motion was retrieved. In Section 3.2, instead, the phase model exploited for DEM generation is discussed. With respect to motion detection, the phase model for topography takes into account the acquisition geometry that is varied on purpose. To do that the antenna was lifted along a vertical bar fixed to the GB-SAR rail. Wide images from different heights above the horizontal rail were collected. Because of the motion of the glacier during the time needed for collecting the images (some hours), the phase model had to take into account at the same time movements, atmospheric contribution and viewing geometry. Final results from this processing are both the range velocity and the elevation map. The latter was compared with an available DEM dated July 2005 in order to point out eventual morphological difference as time lapsed.

2. The GB-SAR survey

The GB-SAR survey described in this paper was carried out on August 2007, in the framework of the GALAHAD project (www.galahad.eu).

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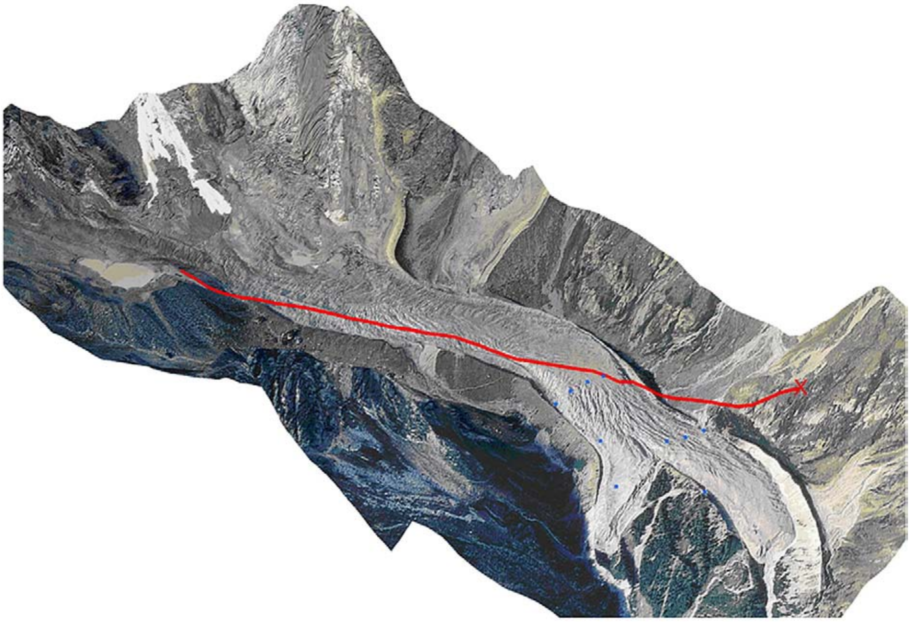

Fig. 1. Orthographic picture of Belvedere Glacier with the radar line of sight highlighted. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

A GB-SAR generally operates in the same manner as satellite and airborne sensors but, working at smaller scale, it is more easily manageable. In order to synthesise the antenna aperture, the GB-SAR antenna moves on a linear horizontal rail, about 2 m long, fixed to the ground. The maximum range for the radar is typically about 3 km.

In the present case, the sensor was positioned on the left flank of the glacier's valley, just above the moraine, at 2000 m a.s.l. Fig. 1 shows an orthographic view of the glacier: the SAR position and the line of sight are highlighted red. From that position the most of the glacier motion comes along the radar look direction maximizing the measurement sensitivity. Due to the absence of electricity, an alternative power supply, consisting of solar panels, wind and hydro generators, was built. The instrumentation with the observed area in the background is shown in Fig. 2.

The GB-SAR worked almost continuatively gathering about two images per hour for all the month of August. Being a debris covered glacier, the most of the radar signal was backscattered by surface layers hence information refers only to this part of the glacier. The working parameters are summarized in Table 1. The used antenna illuminates within a 30° aperture cone essentially. This means that at a 1 km distance the width of the illuminated area would be about 500 m which is only a limited part of the valley. In order to widen the illuminated area, the GB-SAR antenna switched on two positions about 30° apart around a vertical axis and from each position gathered a single look image. The images from different antenna position were processed separately. The results shown here were obtained by combining the results from the two processing chains. The final radar images cover only 26% of the total area of the glacier because of many shadow areas where there is no information (see Fig. 3). Anyway

Fig. 2. The radar instrumentation and part of the power supply.

Table 1
Measurement parameters used for the campaigns.

Polarization	VV
Central frequency	5.01 GHz
Bandwidth	10 MHz
Number of transmitted frequencies	801
SAR scansion length	1.95 m
SAR scansion point number	101
Single image acquisition time	22 min

about 80% of the imaged area shows a high degree of coherence (>0.8) and can be interferometrically processed.

3. Phase model

In this work two different phase models were used: the first, which is more typical in GB-SAR applications, was used for motion detection and the second for generating DEM of the illuminated part of the valley. As far as motion detection is concerned, the GB-SAR gathered images from the same position. By comparing subsequent images to form an interferogram, surface movements of the glacier along the radar line of sight (LOS) could be directly retrieved without any knowledge about the topography. Actually, this inversion was complicated by the presence of a phase term due to the propagation through the atmosphere: this point is discussed here after in Section 3.1. Instead, for generating DEM the phase model has to take into account both glacier movements and changes in the radar illumination geometry as well as the atmospheric component. The used model is the same as in Noferini et al. (2007) with the addition of a phase term due to the motion of the glacier as discussed in Section 3.2.

3.1. Motion detection

By using images taken from the same position, the interferograms are directly related to the LOS motion. In the current measurement geometry, depicted in Fig. 4, the LOS motion was mostly related to the horizontal component of the superficial ice flow vector. Before retrieving motion from the interferograms, the atmospheric term has to be taken into account.

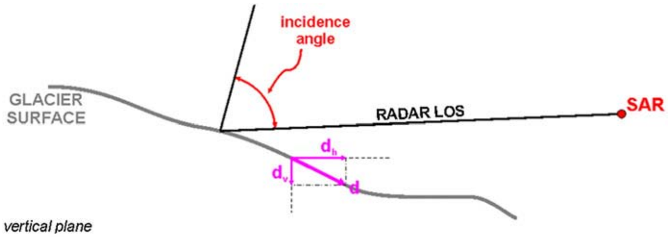

Fig. 4. Measurement geometry. GB-SAR is mostly sensible to the horizontal component $\mathbf{d}_h$ of the ice flow vector **d**.

Although the distances are within a few kilometers, the weather conditions still affect the propagation of the radar signal noticeably and their variability with time causes unwanted phase patterns on the interferograms that must be distinguished from real motion (Noferini et al., 2007; Pipia et al., 2006). The atmospheric effect depending on the propagation is more severe at further distances. In this work, it was modeled as a ramp although turbulent phenomena cannot be generally neglected. The ramp was estimated according to the phases measured on a set of points that are known to be steady in the time of interest, and then removed from the interferograms (Mecatti et al., 2007).

During the last summer some images were seriously compromised by the weather conditions, especially in case of heavy rainfalls. Because the ice velocity was so fast that phase ambiguities could occur if not immediately subsequent images are compared, many separate data set consisting of subsequent good images were analyzed only. Within each data set, images were compared two by two. After atmospheric term removal, the displacement occurred between them was retrieved. The final displacement is the sum of these partial displacements. An example of the final displacement map relative to a 31 h long data set recorded on the 15th August is shown in Fig. 5.

The radar sensor was able to properly detect the central moving area of the glacier, (light blue and yellow) measuring displacement

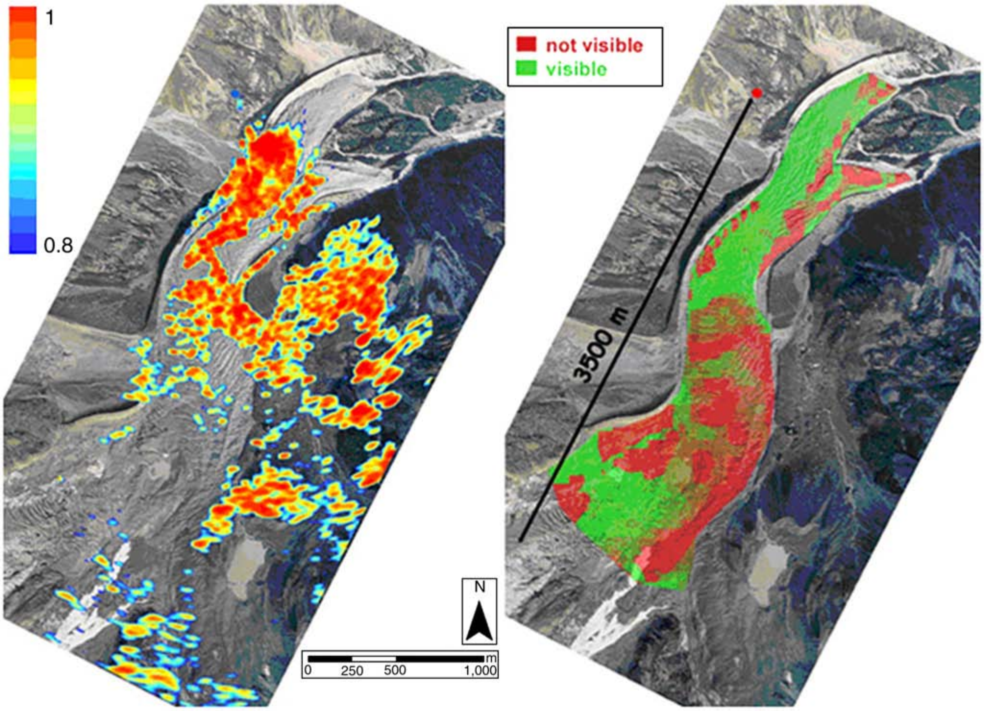

Fig. 3. Coherence map, on the left, and the area above the glacier effectively illuminated by the radar, on the right.

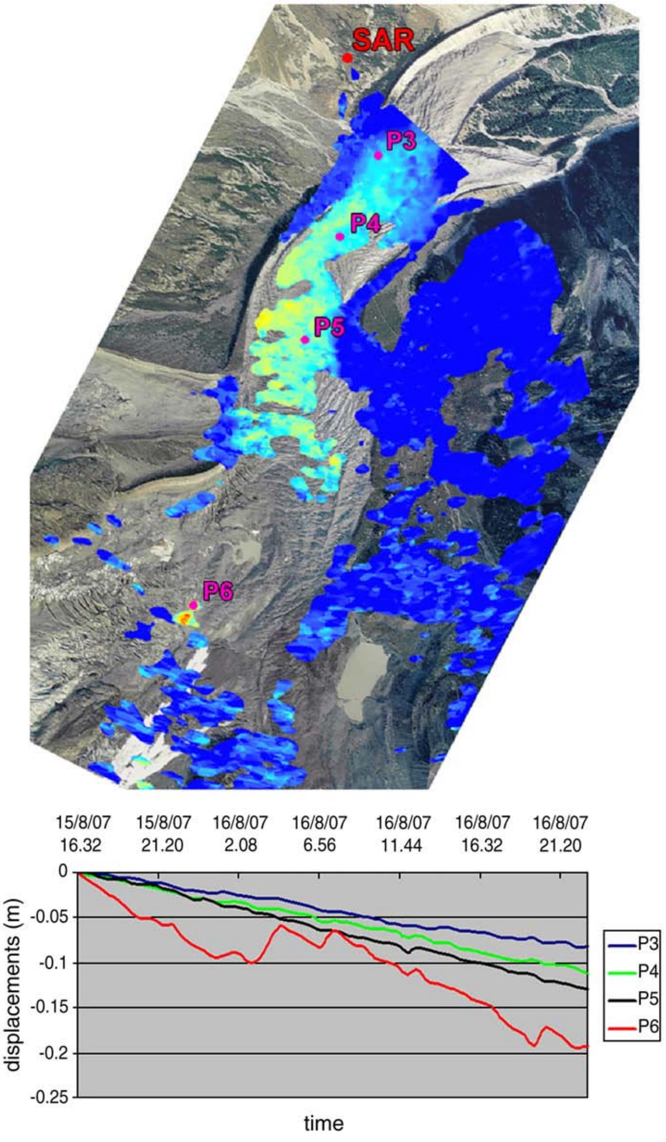

Fig. 5. Displacement map relative to a 31 h long observation recorded on the 15th August. At the bottom is the displacement with time of 4 points highlighted on the map.

rates up to 10 cm/day. The displacement of some pixels highlighted on the map was also reported on the plot at the bottom of the figure. Considering the looking geometry, the displacement LOS component of point P5 is surely larger than that of point P3, no meaningful differences appear along the main glacier's flow that seems to move firmly at a practically constant rate. Point P6 is located in a fast moving area where, as it can be seen from the plot, some phase cycle was lost.

3.2. DEM

A set of images taken with different acquisition geometries was gathered at the beginning of September 2007 with the aim at generating an elevation map of the illuminated area. Actually, the radar antenna was lifted at different heights on a vertical bar fixed to the antenna rail. Images from 7 different heights ranging from 0 cm up to 25 cm above the horizontal rail were collected over a period of about 6 h. A couple of images were collected from each height with the antenna 30° apart around the vertical axis. In the process the images from the same angle but from different height were analyzed separately and finally combined to form a wider elevation map.

The main problem in comparison with previous applications was that while images were collected the illuminated scene was changing because of the motion of the glacier. A new phase model was used for taking into account at the same time LOS movements, atmospheric term and acquisition geometry. In the model the glacier is supposed to move at a constant speed and the atmospheric term is a ramp with range as before. Considering the interferogram between images separated by a time interval t_k and a baseline B_k, the phase of a pixel at range r from the radar, is (Noferini et al., 2007):

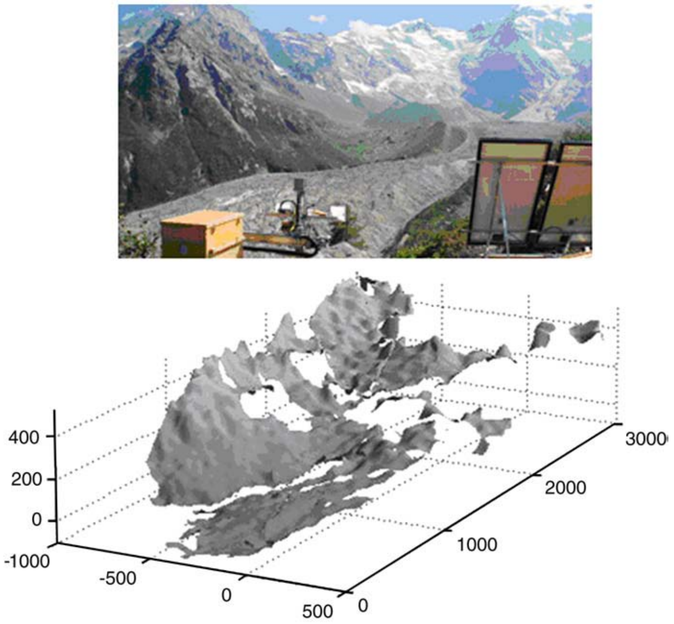

Fig. 6. The obtained DEM and the picture of the corresponding area.

$$\varphi_k = a_k + b_k r + c_k r^2 + \frac{4\pi}{\lambda}\left(v \cdot t_k + B_k \cdot \frac{z}{r}\right) \tag{1}$$

where a_k, b_k and c_k describe the phase ramp due to the atmospheric term, z is the elevation and v is the LOS velocity of the pixel.

Final results from the interferometric data processing are both the LOS elevation map and the velocity map. In Fig. 6 the obtained DEM is shown in comparison with an optical picture. In Fig. 7 the colors represent the obtained velocity. Note that velocity close to the radar (0,0,0) changes sign because motion is now departing from the radar and not approaching as

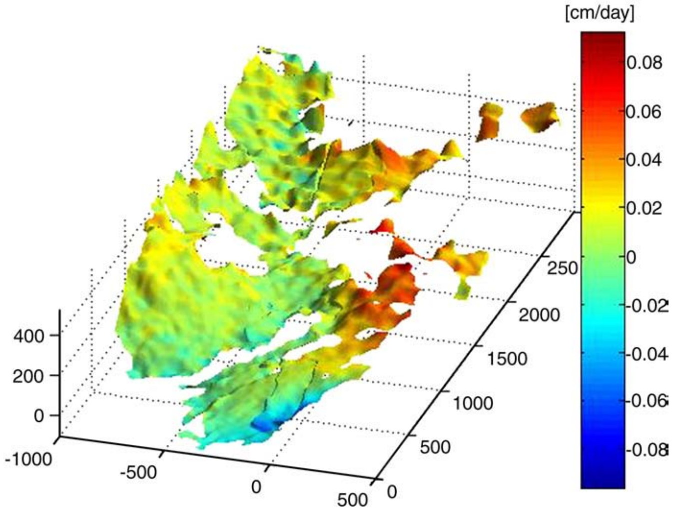

Fig. 7. The obtained DEM with colors representing the obtained LOS velocity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

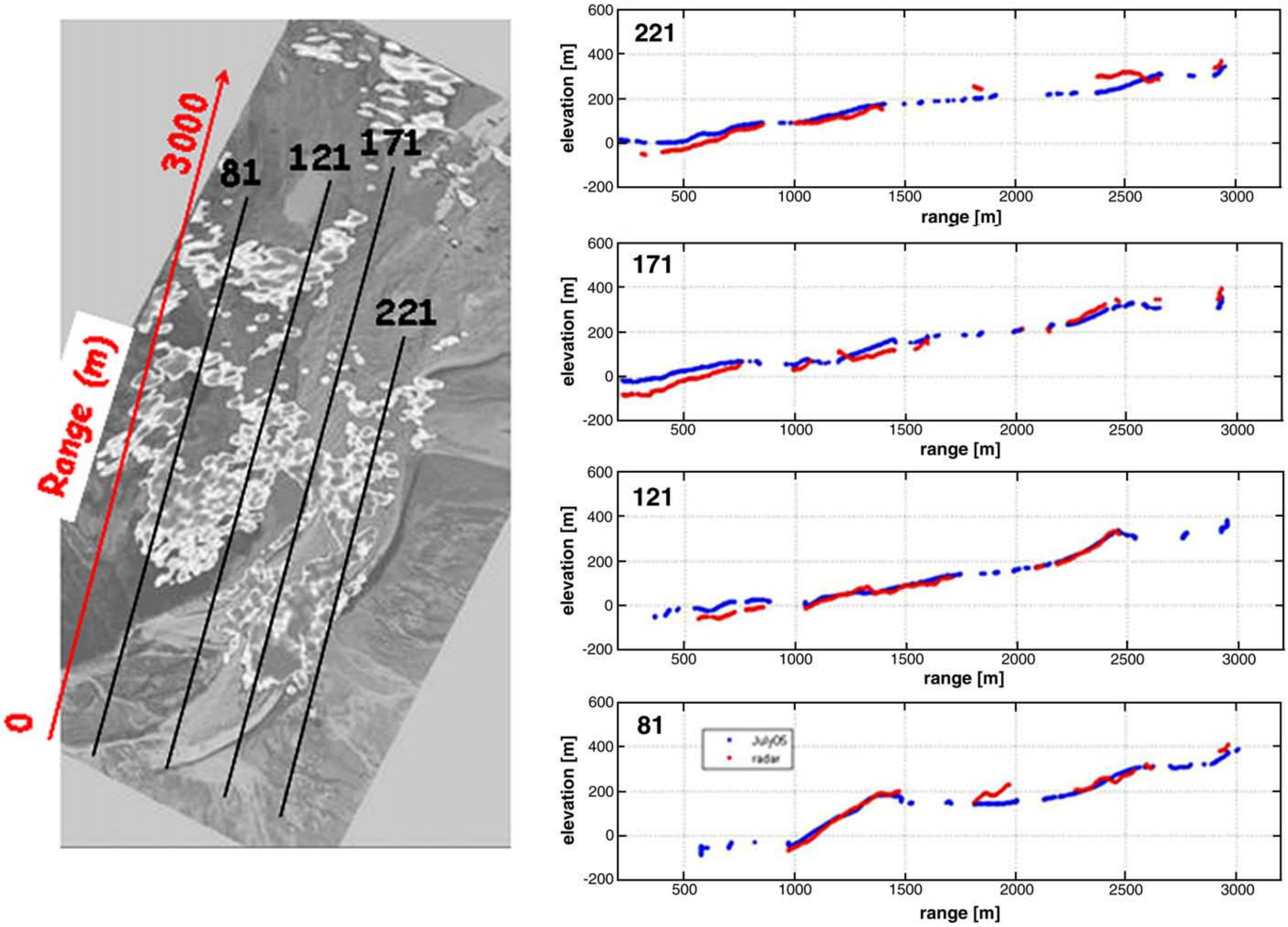

Fig. 8. The radar elevation map and some plots showing both the radar (red) and July 05 (blue) elevations taken along the lines traced on the map, versus range. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

for the upper part of the glacier. The map appears a little noisy, especially far from the radar. In particular, as far as velocity estimation is concerned, dealing with very small phase terms in comparison with those due to the elevation, velocity can be more strongly affected by a not well compensated atmospheric effect.

Although the DEM errors could be very large (more than 10 m), the DEM obtained by the radar was compared with an available DEM dated July 2005 with the aim at finding out information about the ice volume variation. The results are shown in Fig. 8. Many lines were traced on the radar elevation map and the corresponding elevations from both radar and July 05 map were plotted together for comparison purposes. Radar information over the glacier is available only within the first 2 km from the radar. Relative to these ranges all the plots, except '81', which doesn't cross the main body of the glacier, agree in highlighting a reduction of ice volume: the elevations observed by the radar are dozens of meters lower than those reported on July 05 map.

4. Conclusions

Ground-based SAR sensors can be easily arranged in almost all the environments. They can work continuously over a long time providing real time widespread information with centimetric accuracy without the need for a physical survey. Glacier monitoring can benefit from all these appreciable advantages largely.

In the present work a ground-based interferometer has been employed at Belvedere Glacier to detect motion and provide an up-to-date digital elevation model. In this work, the possibility of exploiting information from GB-SAR data for ice flow dynamics monitoring (displacement maps over time) and for assessing about ice volume variations (DEMs) was discussed.

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