Glacier velocity determined by ERS-tandem data
- A case study of the Antarctic Peninsula -

S. Wunderle¹ & J. Schmidt²

¹Institut für Physische Geographie, Universität Freiburg, Werderring 4, D-79085 Freiburg
swun@ipg.uni-freiburg.de

²Institut für Navigation, Universität Stuttgart, Keplerstr. 11, D-70174 Stuttgart
juergen.schmidt@nav.uni-stuttgart.de

ABSTRACT

The technique of interferometry is a powerful tool to obtain information of remote areas (i.e. the Antarctic Peninsula) which could not be extracted from SAR intensity or optical remote sensing imagery. Especially the derivation of digital terrain models (DTM’s) and velocity fields of glaciers are of great interest because ground truth campaigns are very expensive. To derive velocity fields the topographic information has to be eliminated from the interferogram because the phase difference contains both, the information on glacial movement and the effect of topography. Due to the high dynamic of meteorological parameters on the Antarctic Peninsula the coherence between master and slave data is often lost. Different DTM’s were used to overcome this problem. Afterwards the part of the phase difference which is caused by the glacier velocity was obtained.

We used two single look complex SAR images, acquired during the tandem phase of ERS-1/2 on Oct. 15./16, 1995. During this time the surface changes due to melting of the snow cover are negligible. Only on small parts of the scene we had problems with decorrelation and therefore no phase difference was calculated for this areas. In subsequent steps the reference phase of the earth ellipsoid (WGS 84), of the DTM extracted from the Antarctic Digital Database and of a DTM derived from aerial photographs was removed. The remaining motion fringes were converted to flow velocity for a given direction. We extracted the flow lines of McClary and Northeast Glacier from aerial photographs and Landsat-TM imagery and projected the velocity to the flow lines. The result is in good agreement with ground measurements. The result shows the importance of high quality DTMs for further studies of glacial flow on the Antarctic Peninsula.

1. INTRODUCTION

During the last decades significant changes of ice shelf extension were discovered in the vicinity of the Antarctic Peninsula (Vaughan 1996, Doake 1991, Skvarca 1993). Changes of glacier extension and glacier thickness could be also detected on the South Shetland Islands and the Marguerite Bay area (Corbera 1993, Wunderle 1996).

The reason for the disappearance of Wordie Ice Shelf and the northern Larsen Ice Shelf might be a slight increase of air and sea temperature. King (1994) shows an increase of 0.02°C/year during the last 40 years. With mean annual air temperatures of -2.2°C on the South Shetland Islands and -5.3°C at Marguerite Bay. Further warming will considerably increase melt events during the summer season. Therefore it is expected that any further increase of mean annual air temperature will affect the mass balance of small glaciers on the Antarctic Peninsula due to strong melt events. In order to study the behaviour and the response of glacier systems it is necessary to analyze the flow dynamic.

The flow velocity could be obtained from SAR-single look complex data which were analyzed by the technique of interferometry. The main difficulty for extracting the flow velocity of a glacier is that the phase difference contains the information of the earth ellipsoid, the local topography as well as the flow velocity. Therefore the calculation of the glacier velocity requires a method to eliminate the effect of topography. We used two different DTM’s which were obtained from the Antarctic Digital Database (ADD) and from aerial photographs. The ADD-DTM was derived from 250m equi-distance contour lines using ARC/INFO. The DTM could now be used for the whole Antarctic Peninsula with a pixel size of 30x30m². The high precision DTM (HP-DTM) with an accuracy of 10m was obtained from aerial photographs. Both were used to remove the phase information caused by topography. The accuracy of the remaining phase derived by means of the ADD-DTM was poor. Therefore, we used only the HP-DTM for further computations. The flow velocity was calculated for a given flow direction. For this purpose we determined the flow lines from aerial photographs and Landsat-TM imagery. This paper shows the dominant effect of topography in rough terrain on the phase difference and, as a result, the flow velocity of Northeast glacier, Marguerite Bay.

2. TEST AREA

McClary and Northeast glaciers, both situated in the vicinity of central Marguerite Bay, show distinct responses to the recorded changes in temperature (and possibly in precipitation). Therefore these glaciers are interesting test sites. As changes in the meteorologic conditions are similar for both glaciers, we may presume
that the distinct response of the glaciers is due to the differences of the extension of the catchments. In fact, the catchment of Northeast glacier extends only to the plateau, whereas the catchment of McClary glacier is restricted to the coastal zone. Additionally, McClary glacier owns different flow directions. So far the flow velocities have been delimited very roughly by means of GPS measurements. Field data samples yielded flow velocities of 60 to 120 m/year. Yearly accumulation rates vary between 40 and 60 cm with the snow cover melting down completely in lower areas of Northeast and McClary glaciers. With an annual mean of -5.3°C, a slight increase of temperature can result in a displacement of boundary lines separating areas of different snow types. The distribution and seasonal variation of areas of wet, percolation, and dry snow (Paterson, 1994) within the test area can be monitored on a distance of up to 20 km using SAR-PRI imagery.

3. INTERFEROMETRY

Figure 2 shows a small section of our test area. This ERS-1 SAR intensity image was recorded at O'Higgins on 15 October 1995. It covers an area of approximately 30x50 km² of the northern Marguerite Bay area. During that time of year, most of the ocean's surface is still covered with ice. Dry snow cover within the percolation zone appears as bright areas on the image. The reason being the large number of ice lenses embedded in the snow resulting in higher radar reflectivity. An absence of ice lenses and a presence of smaller size snow grains explains the low reflectivity in areas of dry snow on the Antarctic Peninsula (Wunderle, 1995). This phenomenon is depicted as a darker area in the upper right hand corner of the image. The rectangle drawn in black delineates the subsection of the image to be discussed in the course of this paper. The area covers both McClary and Northeast glaciers separated by the Butson Ridge. The Argentine base San Martin is located in front of the ice cliff.

Fig. 2: ERS-1 SAR intensity image of northern Marguerite Bay. The black rectangle shows Northeast glacier (lower right corner) and McClary glacier (middle of the subset).

To calculate the phase difference two ERS-1/2 scenes from the tandem phase were used in order to keep temporal decorrelation at a minimum. The baseline was 113 m. The scenes were recorded at O'Higgins on 15 and 16 October 1995.

Clear fringes can be seen on the phase difference image in the area of McClary and Northeast glaciers. Based on the WGS 84 the effect of the Earth's curvature has already been eliminated. The phase difference now consists of only topographical effects and the fields of movement of both glaciers.
Fig. 3: Phase difference from SAR images aquired on Oct. 15 (ERS-1) and Oct. 16 (ERS-2), 1995. The glaciers with their relatively flat surface gradually rise towards the plateau. McClary glacier lies approximately 200 m higher than Northeast glacier. Behind Butson Ridge a small glacier flows towards Northeast glacier.

3.1 Integration of Digital Terrain Models

In order to georeference both DTMs ground control points were selected from the DTM that had been derived from aerial photography. Further GCPs located on the coast and on selected nunataks were taken from topographic maps.

Fig. 4: Digital terrain model of McClary and Northeast Glaciers estimated from aerial photographs (© IfAG Frankfurt). The accuracy of the DTM is approximately 10m.

Fig. 5: Digital terrain model of McClary and Northeast Glaciers estimated from Antarctic Digital Database (ADD). The accuracy of the DTM is approximately 40m. Determining GCPs both on the DTMs and on the slant range imagery proved to be extremely time-consuming. The two DTMs were converted to Lambert Conformal Conic (LCC) Projection using the Earth ellipsoid WGS 84.

3.2 Calculation of a ground range synthetic interferogram

Using orbit information of both ERS-SLC datasets as well as a set of ground control points the baseline for both DTMs was determined. These parameters are later used for calculating the phase information.

Fig. 6: Synthetic Interferogram in ground range derived from the aerial photography DTM
The two synthetic interferograms differ considerably from each other, which is a result of a deviation of elevation data. In the interferogram derived from the ADD-DTM the smooth interpolation between contour lines, which does not account for slight changes in elevation, can clearly be seen.

In the following step the interferograms were regridded to obtain an even grid when doing the ground-range-to-slanl-range conversion. Converting the data into slant range format is necessary before the phase information of the synthetic interferogram can be eliminated from that of the real interferogram. With a phase wrapping procedure the resulting phases were then transformed into fringes. The main part of topography was removed (fig. 8 and 9). The deviation between both results can be attributed to the height difference of the DTMs. The data set presented in fig. 8 now serves as a starting point for the calculation of the flow velocity using the remaining part of the phase values.

3.3 Derivation of glacier flow velocity by means of interferometry

Subsequently to phase-unwrapping areas without sufficient coherence and backscatter intensity were mapped. Afterwards the areas were masked out. In addition, we masked the mountains where flow velocity is zero. The determination of the glacier velocity by means of interferometry requires a defined flow direction (Cumming, 1997), because we used only the phase information in range. The resolution in azimuth is to coarse for the small test site. An alternative could be to combine ascending and desending pairs of ERS data but for this area additional pairs are not available.

The phase shift of 360° represents only 2.8 cm of line-of-sight component of displacement between two surface points in 24 hours. Thus, to calculate the surface velocity we need the projection of this component. Five main flow lines with additional branches were determined on McClary and Northeast Glacier. The flow lines were extracted from aerial photographs which were used to generate the HP-DTM and from one Landsat-TM imagery, recorded on March, 16, 1986.
Fig. 10: Geocoded intensity image of McClary and Northeast glacier, dated 15th of October with the determined flow lines. Flow line 4 starts at The Amphitheatre on the Plateau of the Antarctic Peninsula and ends at the ice cliff of Marguerite Bay between Base San Martin and Stonington Island.

Fig. 11: Phase values caused by glacier velocity with flow lines (1 - 5) and 50m-contour lines. For further calculations we used the profil of flow line 4.

Along the altitudinal profil of flow line 4 we projected the displacement in flow direction parallel to the glacier surface.

Fig. 12: Altitudinal profile of flow line 4 which starts at the Amphitheatre on the Plateau of the Antarctic Peninsula and ends at the ice cliff of Marguerite Bay.

Figure 12 shows the altitudinal profile of flow line 4 with a continous descent from The Amphitheatre to the ice cliff. The flow line only once cuts a small depression approximately at index 380.

Fig. 13: Glacier velocity at flow line 4 (North-east Glacier). The diagramm of the surface flow velocity reflects the complex topography of this area.

The glacier starts with a velocity of approx. 125 m/year near The Amphitheatre and decelerates to 50 m/year at index 100. At this location the glacier widens out. The ice input from two small glaciers (flowline 3 and 5A) are less than expected because the glacier velocity slows down. Further downstream the glacier accelerates to a velocity of approx. 125 m/year caused by a narrowing of the glacier bed (index 200). The second minimum of the flow velocity occurs at index 300 because the glacier widens out (see flow line 5B). At the lower parts of Northeast Glacier the input of the small glacier (flow line 5B) accelerates and the velocity is approx. 110 m/year. The third minima was localized at index 500. The flow velocity is approx. 10 m/year caused by the divergence of the ice and a ridge in the glacier bed which acts as a barrier to the glacier. This subglacial ridge was postulated from visual interpretation of the Landsat-TM imagery and the aerial photographs.

See plate II at end of volume
3.4 Ground truth measurements

During the austral summer 1993/94 we marked some position on McClary and Northeast Glacier with ablation stakes. The positions were determined by trigonometric measurements and GPS. Every year the measurements were repeated and visualized in fig. 15. The measurement points x2, y1-y6 are located on the lower part of McClary Glacier, the stakes A13, A15 and A17 were installed on Northeast Glacier. The vector A17 is almost parallel to flow line 4 which was extracted from aerial photographs and Landsat-TM imagery. The flow vectors represent the flow direction and velocity. The velocity differs between 8m/year for x2 and 70m/year for A17. The measurements were done during the campaigns 93/94 and 94/95.

Fig. 15: Flow vectors determined by ground measurements for lower parts of McClary (x2, y1 - y6) and Northeast Glacier (A13, A15, A17). The measurements were done during the field survey 1993/94 and 1994/95.

The field measurements show a good agreement with the results derived from interferometry. The deviations are caused by errors in the trigonometric method due to few reference points and by the time differences of the measurements. The ground measurements represent a mean of one year in contrast to the ERS-1/2 remote sensing data which were acquired during 24 hours.

4. FINAL COMMENTS AND OUTLOOK

Particularly in maritime Antarctic regions the limits of interferometry become obvious. Highly dynamic atmospheric conditions lead to snow cover fluctuations which in turn result in large scale decorrelation between two or more SLC images. Not only does a slight deviation of the snow cover's liquid water content cause significant changes in the intensity of the reflected radar signal, it also shifts the dominating backscatter levels within the snow cover itself. However, to determine velocity fields eliminating topographic information from the interferograms is essential. This requires the integration of DTMs created with traditional methods. Using ARC/INFO a DTM for the entire Antarctic Peninsula was created from the contour lines of the Antarctic Digital Database (ADD). Further processing was done on a subsection of Marguerite Bay in order to investigate the general applicability of the method to the exploration of radar data. Moreover, in comparison with a DTM derived from aerial photographs the size of the error could be assessed. It became obvious that, particularly in areas of small scale relief, differences between both DTMs occur that have to be accounted for in further data exploration. Especially in the case of slow moving glaciers the remaining error within the phase information will result in inaccurate flow vectors. Relative to the topographic phase information the phase information resulting from the glacier's velocity is small. Existing DTMs should be improved for maritime Antarctica, particularly for areas of the Antarctic Peninsula, in order to be able to determine the flow dynamics of selected glaciers on a large scale.

The derivation of glacier flow velocities on small glaciers by means of interferometry requires a high precision DTM. The availability of such a DTM allows to calculate the flow velocity in areas where no ground measurements exist. This new information could be helpful for further investigations on the Antarctic Peninsula.

5. ACKNOWLEDGMENT

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