Determination of glacier velocities on King George Island (Antarctica) by DInSAR

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ABSTRACT

The Antarctic Peninsula is a region very sensitive to climate change. To estimate the climatic impact on glaciers several parameters like the velocity field have to be known. Radar interferometry is a feasible method in such remote areas. The available ERS tandem pairs with reasonable baselines have been processed for King George Island, but only 5 out of 17 showed enough coherence. Only one of them could in the end be processed to a complete velocity field of the island with movement rates of up to 120m per year. External elevation data was necessary for the chosen processing approach. Validation with DGPS measurements from several field campaigns shows good agreement with the interferometric derived velocities.

1 INTRODUCTION

The Antarctic Peninsula has been identified as a region of ongoing considerable changes in the glacial and climatic system. The disintegration of the Larsen-A and –B ice shelves in the late 1990's on the East coast [1],[2],[3],[4] as well as of Wordie Ice Shelf in the late 1980's on the West coast of the peninsula [5] have certainly demonstrated this in a most spectacular way. Surging and enforced mass loss after the break-up and destabilisation have been identified by ground measurements [6] as well as by remote sensing [7]. Recent studies have also compiled comprehensive databases on glacier frontal positions and resulting glacier retreat for the entire Antarctic Peninsula [8],[9]. They show that retreat is not only restricted to the large ice shelves but a common phenomenon in this region, although some advance was also recorded. The few available glacier mass balance measurements indicate negative tendencies during the recent years [10],[11]. This signal from the cryosphere is further supported by significant positive surface air temperature trends observed at various coastal stations on the peninsula [12],[13]. A maximum of about 2K in 50 years is reported from Faraday-Vernadsky station at 65.15°S/64.17°W. The observed changes in the precipitation pattern are attributed to changes in the atmospheric circulation system affecting the climate and variables and components of glacier mass balance. Vaughan [14] has stressed the negative role of Antarctic Peninsula and the West Antarctic ice sheet and that their prognostic mass deficit will jointly with the Greenland ice sheet counterbalance the positive mass gain of the East Antarctic ice sheet.

King George Island is located on the northern tip of the Antarctic Peninsula and experiences maritime climate conditions, which are generally considered highly sensitive to climate change. Previous studies have determined considerable glacier retreat since the 1950's [15],[16],[17], but stopped in the 1990's although these have been the warmest years recorded. Significant positive trends of monthly surface air temperatures have been determined for the summer term and annual record [13]. Other studies have focussed on specific components of the glacier mass balance and surface energy exchange [18],[19],[20],[21], but no long-term records exist. Using a simple ice dynamic model Knap et. al. [22] came to the conclusion that the ice cap of King George Island is highly sensitive to further temperature increase. However, their analysis was considerable restricted by the available input data. Meanwhile, further glaciological data sets with spatial coverage have been acquired, but ice velocities are still a missing component for ice dynamic modelling.

Differential radar interferometry (DInSAR) has already demonstrated its potential to acquire surface ice velocity fields in various regions. However, applications on the Antarctic Peninsula and in particular on the maritime South Shetland Island group are still rather scarce. One major reason are certainly the unfavorable climate conditions in the West Wind Zone of the southern hemisphere causing continuous surface changes and melt also during winter. The focus of this study is the extraction of a surface ice velocity field for the King George Island ice cap in an area of rapidly changing surface conditions. Data of the ERS-1/2 tandem mission as well as an external digital elevation model (DEM) compiled from heterogeneous sources have been combined. The InSAR results are validated against DGPS displacement measurements at stakes obtained during comprehensive field surveys.

2 STUDY AREA

With about 1,250 km², King George Island (62.1S/ 58.4W) is the largest of the South Shetland Islands (Fig. 1) and about 93% of the island is ice covered [15]. It reaches its highest elevation with 705 m at one of the ice domes.

Previous glaciological studies have shown that most parts of the King George Island ice cap can be regarded as temperate e.g. [23],[24],[25]. The glacial system is characterized by several large outlet glaciers draining the ice cap to the south and a comparable smoothed topography with ice masses calving to the sea in the northern coast. Only few, mainly smaller glaciers terminate on land.
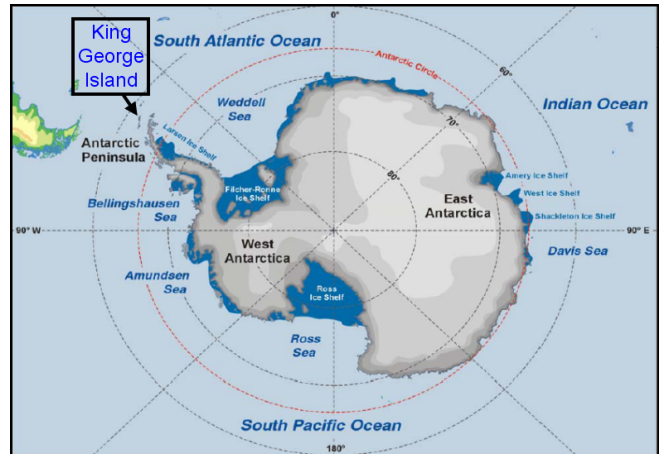

Fig. 1. Location of King George Island.

3 DATABASE

3.1 Satellite data

ERS 1/2 data acquisitions on the Antarctic Peninsula are limited to the operation of the DLR receiving station in O'Higgins. A total of 17 tandem pairs over King George Island have been evaluated with InSAR techniques. The images were taken under spring (October/November) and summer (January-March) conditions. Data was ordered as raw scenes and subsequently processed as explained in section 4 Methodology.

Tab. 1. InSAR processed ERS tandem pairs (no. denotes the number of the interferogram)

no.	acquisition date	track	frame	path	coverage	sufficient coherence	perpendicular baseline
1	1995-10-15/16	195	4887	descending	complete	+	-157m
2	1995-10-23/24	304	5913	ascending	complete	+	88m
3	1995-10-26/27	347	5913	ascending	western part	+	83m
4	1995-10-31/11-01	424	4887	descending	complete	-	31m
5	1995-11-08/09	32	5913	ascending	eastern part	+	85m
6	1995-11-11/12	75	5913	ascending	complete	-	-122m
7	1996-01-17/18	32	5913	ascending	eastern part	-	63m
8	1996-01-28/29	195	4887	descending	complete	-	89m
9	1996-02-05/06	304	5913	ascending	complete	-	195m
10	1996-02-08/09	347	5913	ascending	western part	-	173m
11	1996-02-21/22	32	5913	ascending	eastern part	-	147m
12	1996-03-03/04	195	4887	descending	complete	-	228m
13	1996-03-11/12	304	5913	ascending	complete	-	71m
14	1996-03-14/15	347	5913	ascending	western part	-	44m
15	1996-03-22/23	467	4887	descending	western part	-	93m
16	1997-03-12/13	32	5913	ascending	eastern part	+	9m
17	1999-11-09/10	424	4887	descending	complete	-	164m

3.2 Digital elevation model

An external DEM was available for the DInSAR computations. As topographic data is scarce in Antarctica, the DEM was composed using various information layers from maps and kinematic DGPS surveys. For the central part of the ice cap high-precision kinematic DGPS profiles with a 1km spacing where available. A DEM with 50m cell size was interpolated using the topogrid function under ArcInfo. This function is particularly suited for the generation of hydrologically correct DEMs using heterogeneous input data from point and line coverages. In case of overlapping information priority was given to the layer of highest precision. A detailed description of the DEM compilation is given in [26].

3.3 DGPS glacier velocities

During summer field campaigns repeat static DGPS measurements were performed at about 60 pre-defined locations. For the measurements 3-4m long aluminium tubes where drilled into the firn and ice. The GPS antenna was mounted on

top of the stakes using an adapter so that the antenna could be exactly positioned for the repeat measurements. The receivers were deployed to the start and end of the 6-week field surveys (1997/98, 1999/2000 and 2004/05) enabling the determination of movement rates in an interval of 3-4 weeks. The precision of the static repeat DGPS measurements was about 1 to 2 cm. The 2D velocity vectors were computed from the difference of the positions at the two measurement dates; values range between 0 cm/d to 20 cm/d in the beginning of the major outlet glaciers. After the field survey, the stakes were de-installed due to environmental reasons. At points measured in 1997/98 and 2004/05 the DGPS velocities do not show inter-annual variations. However, as both field campaigns only cover summer conditions where considerable melt water is present, no knowledge about seasonal variation of the glacier velocities is available. This is important as suitable tandem scenes only cover winter situations.

4 METHODOLOGY

4.1 General remarks
Decorrelation represents one of the main limits to operate interferometry in these regions. High weather instability determine strong changes in the ice and snow surface structure and consequently abrupt changes in ice backscattering characteristic occur even with one day temporal baseline acquisitions (melting, snow transport). Even the time of acquisition play an important role; descending orbits acquired during the day show generally lower coherence than ascending acquisitions that are acquired overnight. A possible explanation is related to the partial melting of the ice surface that is more relevant during the day. In total 34 ERS scenes were processed from raw data to interferograms, but only few showed enough coherence to support further integration in the complete processing chain.

4.2 Raw processing
Every tandem pair was processed with the same average Doppler centroid frequency (Dcf) to account for the relative azimuth spectral shift. When combining ERS-1 and ERS-2 data sets the Doppler centroid frequencies of the corresponding scenes could be moderately different; e.g. interferogram 2 from Tab. 1, further noted as IF(2), with Dcf of 339Hz (ERS-1) / 86 Hz (ERS-2). All scenes were amended with precision state vectors from Delft University with an accuracy of about 5cm to improve automatic baseline estimation [27].

4.3 Interferometric processing
From every processed single-look complex image (SLC) pair an interferogram was created. It has to be mentioned that the study area of King Gorge Island only covers about 1/8 of a typical ERS full scene and mainly consists not of a continuous coherent area, but is divided into several disconnected parts. This makes precise baseline estimations in general difficult.
The SLCs were first coregistered with subpixel accuracy. Due to the rather uniform appearance of the central ice cap without pronounced land marks, manual adjustment was necessary to select the reliable positions of offsets on which the polynomial transformation was based. In coastal areas many points were found with high correlation peaks (SNR) but incorrect offsets. The interferograms were multilooked with 1x5 or 2x10 (for low coherence areas) pixel windows. Adaptive filtering for smoothing was applied. To remove the flat earth component the baseline has to be estimated. This could be done automatically by using the precise orbit information or the fringe rate or manually by setting Ground Control Points (GCP) with known height information. For this work the baseline was automatically derived, because the available DEM was not precise enough to give sufficient accurate elevation values. Furthermore the complete Island is covered nearly by glaciers what makes it even more inaccurate to use GCPs located on the glacier, because this GCPs have phase values that consist not only of the topographic phase, which is needed for baseline estimation, but also of a velocity based phase. Ice free areas without a velocity component are mainly at the rim of the island, but here the terrain and surface conditions changes very rapid.
Thus the baseline was estimated on the orbit parameters and the fringe rate. For the use of the fringe rate a flat terrain is needed and again there should be no movements merged with the topographic information. This is not feasible for King George Island. As approximation a relatively flat area with low glacier velocities was chosen. This baseline was combined with a baseline estimation derived from the orbit information. The result for a small area not covered by glaciers show no significant phase trend after flat earth removal.
Phase unwrapping was done with the Minimum Cost Flow Algorithm [28]. Therefore a mask based on local coherence and a validity mask to guide the phase unwrapping process was manually created for robust unwrapping.

4.4 Differential interferometry
To generate the differential interferogram a 2-pass approach was chosen. For this proceeding a Digital Elevation Model (DEM) is needed to eliminate the topographic induced phase values, thus leaving only velocity information in the interferogram present. The external DEM mentioned in section 3.2. Digital elevation model was used therefore. The coregistration of the DEM and the interferogramm was done by calculating a radar intensity image based only on the backscatter of the DEM. This synthetic radar image was coregistered to the intensity master image. An interferogramm based on the DEM was created with phase information from topography only. This synthetic interferogram and the real

radar interferogram were least square fitted to eliminate a bias due to insufficient baseline estimation. At the end the topographic phase information was subtracted from the interferogram to leave only the velocity information present. A small area in the West of KGI not covered by glaciers was used to estimate the phase value for non-motion, which was then subtracted. The result was geocoded to UTM coordinates.

4.5 Velocity extraction
As DInSAR of either ascending or descending orbits provides only velocities in the line of sight of the radar sensor, further input information is necessary to derive a 2D-vector. This additional movement information could be taken from a flow vector derived from radar intensity or optical imagery, or from an external DEM under the assumption that the glacier flows along the steepest slope. In this work the normal vector at every position of the available DEM (section 3.2 Digital elevation model) is calculated and the phase difference is projected to the corresponding direction [29].

4.6 Specific processing remarks
In total 17 interferograms were generated of which 12 have not sufficient coherence (see table1). IF(2) showed the best result and is the main input of this work. IF(3) which has the best overall coherence of all interferograms could not be used, because baseline estimation by orbit parameters showed significant bias in non glacier areas and for proper baseline estimation via fringe rates the coherent areas were to small (only a small part of western King George Island is imaged).

Double differencing [30] of IF(2) and IF(3) could have been tested although the interferograms were from different tracks. But the circumstance, that both have nearly identical perpendicular baselines of about 85m makes this not reasonable.

IF (1) from a descending path would be very useful to extract a three-dimensional velocity vector by combining ascending and descending orbits [31]. Unfortunately the interferogram is divided in many areas with good coherence, but disconnected from each other. Consistent phase unwrapping is only possible for every region but not over the complete area. Thus differential interferometry is not possible and no determination of the absolute velocity would be possible, because no non-moving area is included in every unwrapped patch.

Furthermore, two interferograms IF(5)/IF(16) (latter one with good coherence) were available for the eastern part of King George Island, but the DGPS measurement area is not included and so the external DEM has low quality. These interferograms were not used because the velocity information could not be validated by DGPS measurements and the velocities even extracted from the single IF(16) with 9m perpendicular baseline need to be projected on the steepest slope for which no reliable DEM is available. Double differencing IF(5)/IF(16) to create a DEM was not feasible because areas of good coherence were not identical in both interferograms.
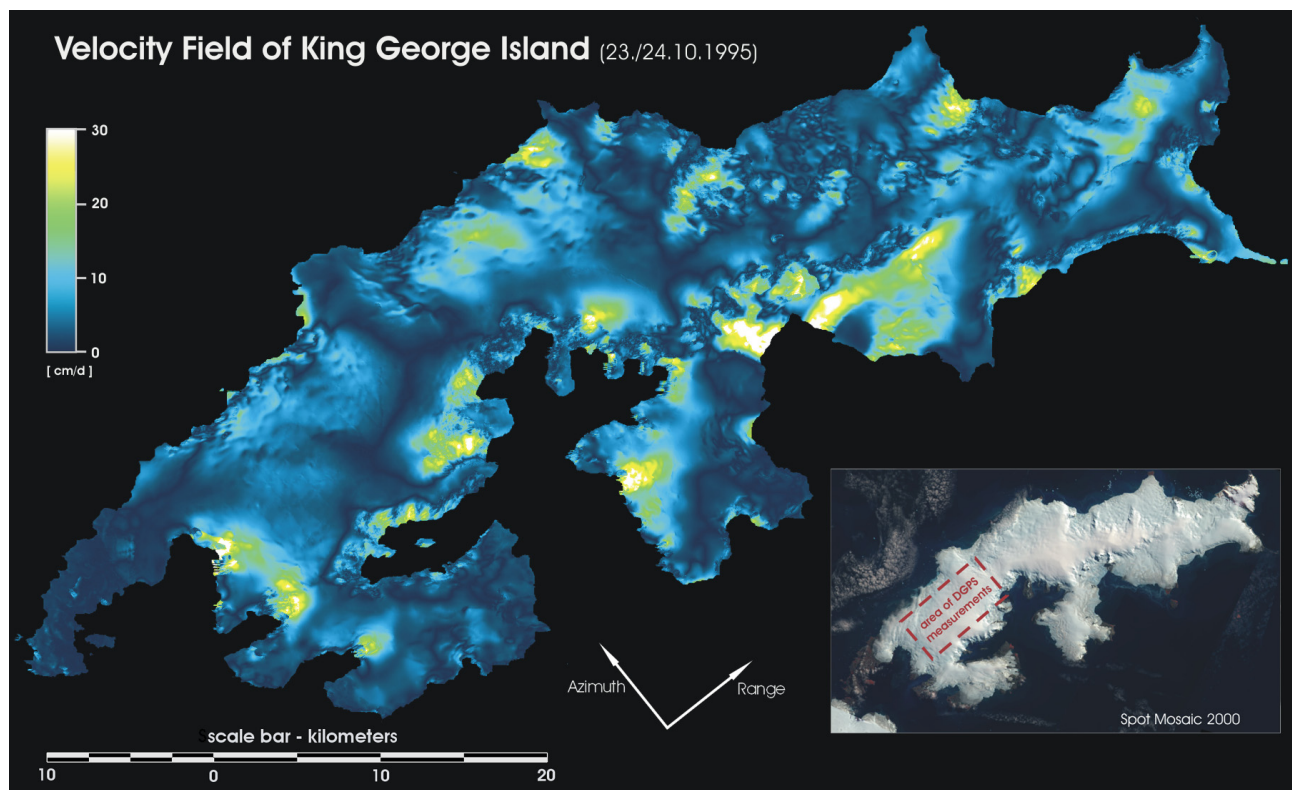

Fig. 2. DInSAR velocity field and optical Spot mosaic of King George Island (images are oriented north).

5 RESULTS & DISCUSSION

From the available tandem pair from 23./24. October 1995 and the external DEM a 2D-velocity field [0-120m/y] for the ice cap could be generated. Fig. 2 displays the resulting glacier velocities in cm per day. The overall velocity pattern fits very well to the field observations as well as to the picture obtained during the field surveys and the SPOT mosaic (Fig. 2). The areas of high movement rates correspond very well with the main outlet glaciers of the ice cap. Ice divides can be identified clearly and agree to the lines previously derived from the DEM and SPOT mosaic. The InSAR velocities during winter conditions 1995 agree quite well to the field observations from summer 2004/05 (Fig. 3). On the other hand two main limitations from the available data are visible. First of all, the velocity field covers only the line of sight (LOS) vector of the SAR. This is a major drawback for areas where the main glacier flow vector is nearly perpendicular to the LOS vector (i.e. glaciers flowing SE-NW or vice versa). Whereas the error of the glacier velocity is considerably increasing or in the worst case not even captured at all. This is the case for areas on the central part of the island where reference data from the field campaigns exists (Fig. 2) or for smaller outlet glaciers.

A second limitation results from the fact that the data quality of the DEM is very pending on the input information and particular in the Eastern part of the island; the topographic information is 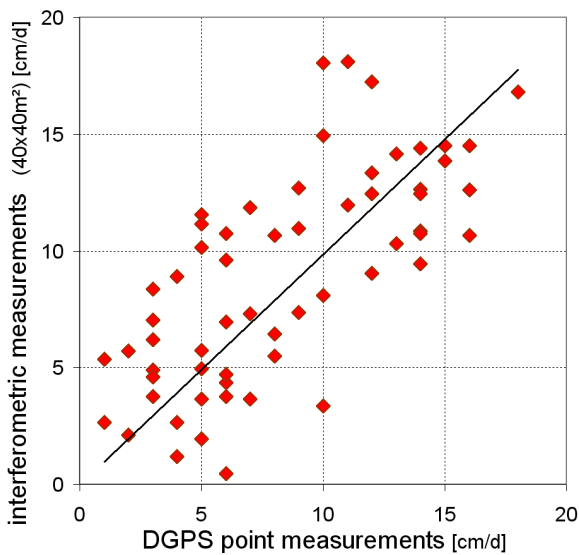not reliable. On the western part, either mobile DGPS measurements or a relatively good topographic map (scale 1:50000), based on a visual interpretation of aerial photographs, form the reference. Only at the glacier margins in the NW the database is inaccurate. The Eastern half of the DEM is based on contour lines from an early map from the 1960's; this information is not reliable. As a consequence, the complex topography and drainage pattern of the main island ridge and in the northern catchments are not captured in the DEM and hence introduce major errors in the velocity field. However, the velocities on the rather flat outlet glaciers to the South of the ridge are reasonable. The problem of data heterogeneity and inaccuracy is also pronounced on Krakow Icefield, a peninsula on the central southern side of the island. A third minor more local error can be attributed to the projection on the steepest slope. Small-scale topographic undulations are not captured by the present DEM, even not in the area where kinematic DGPS measurements are available (spacing 1km). This affects the computation of slope and aspect angle and hence also influences the projected velocities. The scatter of the InSAR and ground truth velocities in Fig. 3 can be partly attributed to this.

Fig. 3. Validation of DInSAR measurements by DGPS.

6 CONCLUSIONS & OUTLOOK

We have presented a DInSAR analysis over a glacier area with fast surface changes which hamper this technique. 17 ERS-1/2 tandem pairs have been processed. Limitations were encountered by decorrelation effects due to surface melt or wind drift as well as by lacking accurate external height information in several parts of the island. Nevertheless, a velocity field for King George Island could be generated with varying quality. In the area where reliable external measurements were available the validation shows very good results. The overall structure of the different glaciers on the island could be shown. The processing of a reliable interferogram with a different LOS (descending) would be very valuable to calculate a flow vector not only sensitive to a single direction, but also independent of the input of the external DEM. More of the coherent InSAR pairs could have been used if better reference for baseline estimation would have been available e.g. via corner reflectors – even if they would be transferable from actual scenes to the already acquired tandem pairs. Upcoming SAR missions (as e.g. ALOS PALSAR, TerraSAR-X) are expected to give no improvement to velocity field generation in this region as repeat cycles are even not nearly as short as for the existing ERS tandem pairs. Single-pass interferometry could provide valuable topographic information, however the present available tandem data will remain forming the baseline.

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