CONTROLLED INTERFEROMETRIC MODELS OF GLACIER CHANGES IN SOUTH SVALBARD

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ABSTRACT An original approach to geocoding and interpreting glacier interferograms with altimetric and photogrammetric constraints was designed and tested. New results demonstrating considerable glacier changes in South Svalbard were obtained through the joint analysis of ERS-1/2-SAR interferograms, ICESat-GLAS altimetry data and ASTER-VNIR imagery obtained over study glaciers in 1995/96, 2003 and 2004, respectively. Sörkapp Land might become a separate island with a total land area of 1270 km² due to complete disintegration of Hornbreen and Hambergbreen by 2020.

INTRODUCTION

Synthetic aperture radar interferometry (INSAR) is regarded as a highly informative remote sensing method for detecting glacier changes and studying glacier mechanics. INSAR determinations are, however, relative in character and, analogously to stereometric techniques, they necessitate precise ground control or fixed references for positioning and correlating interferometric features. Precipitous glacier faces, rapid changes and the lack of adequate reference models pose essential difficulties in geocoding of glacier interferograms and distinguishing between the impacts of ice surface topography and surface displacement on the interferometric phase [1].

The present paper reports on the main outcomes of the INTEGRAL (EC FP6) and SIGMA (ESA AO No.2611) research projects devoted to enhanced interferometric modelling of glacier dynamics without or independently of the use of surveyed control points. The underlying concept of the research is to compensate for the lack of reliable basic control in extensive glacial areas with precise altimetry and photogrammetric data. The study area comprises the Sör-Spitsbergen National Park in south Svalbard, Norwegian Arctic with a total land area of approx. 4,500 km². The basic test site of smaller size covers the system of Hornbreen and Hambergbreen tidewater glaciers (H-H) situated in the southernmost part of the Svalbard archipelago (Fig. 1). Up-to-date topographic maps and digital elevation models of these glaciers are either nonexistent or of limited quality and coverage. The geometric constraints needed for the precise interferometric modelling of the study glaciers were thus derived from spaceborne ICESat-GLAS altimetric transects and ASTER-VNIR imagery.

The paper describes basic principles and glaciological applications of the joint geometric processing of ERS-1/2-SAR interferograms, ICESat-GLAS altimetry data and ASTER-VNIR imagery obtained over study glaciers in 1995/96, 2003 and 2004, respectively. Special emphasis is placed on

- methodological aspects of merging interferometric, altimetric and photogrammetric spaceborne data,
- estimation of interferometric phase distortions and phase offsets,
- determining glacier heights at specific target points between altimetric transects,
- parametric geocoding of INSAR models,
- studying related effects, such as data disparity, both spatial and temporal, meteorological and tidal phenomena,
- detecting, mapping, measuring, interpreting, verifying, and forecasting glacier changes in linear, areal, volumetric and fluxometric terms at local, regional and continental (synoptic) scales.

6 multitemporal ERS-1/2-SAR tandem pairs of the H-H test site were processed and precise interferometric models of the study glaciers were generated and tested using the proposed technology referred to as *controlled* interferometric modelling. The study revealed drastic shrinkage of tidewater glaciers in south Svalbard during the observation period of 1900-2004. Glacier changes and related processes were represented in the form of controlled interferometric composites, satellite image maps and animated graphics. Our tests proved the high elevation accuracy of controlled interferometric composites, and typical height errors were estimated as being nearly 5 times smaller than those in standard INSAR products. The results obtained were compared with the outcomes from photogrammetric, radio-echo sounding, ground-penetrating radar and dGPS terrestrial surveys performed by Russian, Norwegian, British and Finnish investigators in the 1900s, 1970/80s and 2000s. Further ground-control surveys, reference observations and map content reviews will be carried out during our field campaign in 2006.

GATHERING OF CARTOGRAPHIC MATERIALS

Major spatial information about glacier changes in Svalbard is obtained by comparing historical maps with later surveys and modern remote sensing data. The first topographic map series and early outline map sheets of the study glaciers were published and republished at scales ranging from 1:84 000 to 1:380 000 after the 1899-1901 Russian-Swedish expedition to Svalbard, which was devoted to the precise measurement of the arc of a meridian. The arc triangulation network extending from the southern tip of the main landmass of Spitsbergen through Storfjorden and Hinlopenstretet to the northernmost point of the Svalbard archipelago at Rossöya was established using precise astronomic observations and tachymetric surveys. The relative error in measuring the length of 6 to 21 km long base lines varied between 1:360 000 and 1:170 000 [2]. The positional accuracy of the 1:200 000 topographic maps based on this basic control was estimated at ± 100 m by A.Pälli et al., who compared old Russian maps with modern cartographic products. The map vertical accuracy for steady points was given as ± 25 m [3].

Extensive triangulation and field surveying by Norwegians began in 1907 and continued well into the 1930s, thus providing the control for topographic mapping. The main topographic map series was photogrammetrically compiled at 1:100 000 scale from the airborne oblique stereoscopic photographs obtained in 1936. There also exist a series of 14 map sheets published in 1949 at 1:50 000 scale covering south Spitsbergen and a few sheets at 1:10 000. We gathered several updated 1:100 000 map sheets compiled from the air photographs taken in 1966, 1977 and 1990. Our experimental data set also included 2 sheets (B4 and B5) from the series of 14 thematic maps showing different types of coasts in Svalbard published at 1:200 000 scale by R.Ödegard, K.Högward, J.Sollid et al. in the early 1990s. Smaller-scale coverage is provided by the topographic map sheet (Blad 1) published at 1:250 000 scale by the Norwegian Polar Institute in 1996. This map sheet shows the position of tidewater glacier fronts for both 1936 and 1990. The hydrographic chart No. 3137 issued by the British Hydrographic Service in 2003 was also at our disposal. This 1:750 000 scale chart is based on information from Norwegian and Russian government charts showing water depths along the fronts of tidewater glaciers in the southern part of the archipelago. We generated several digital elevation models (DEMs) with 50 m posting and ± 50 m uncertainty in glacier elevations from those maps (Fig 1, b).

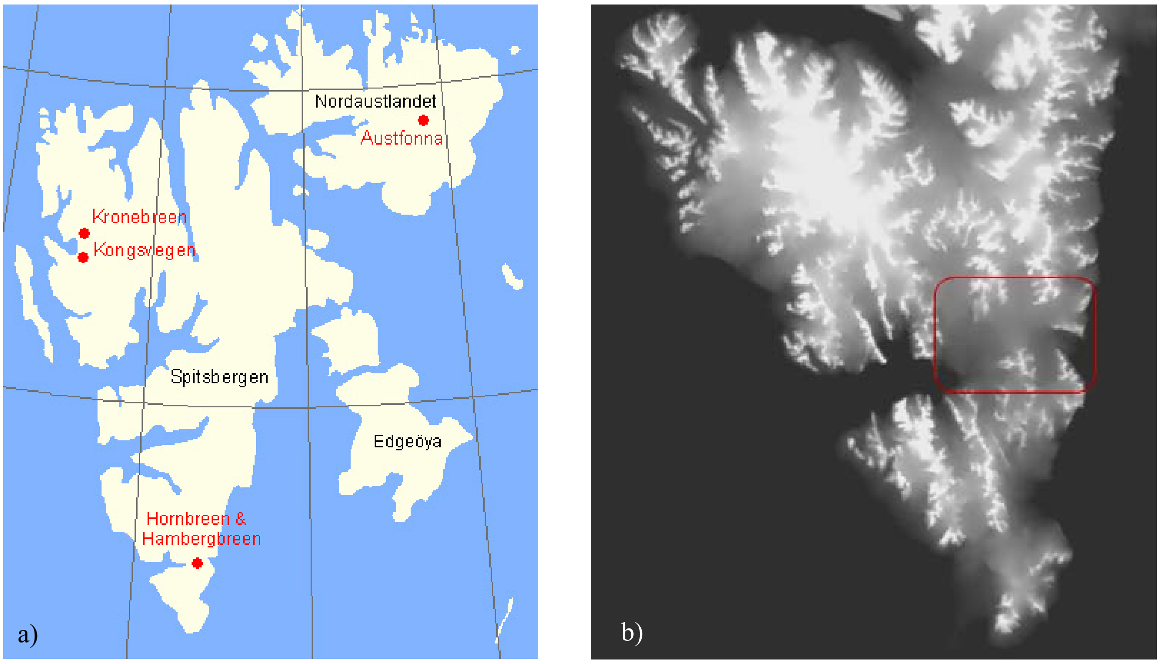


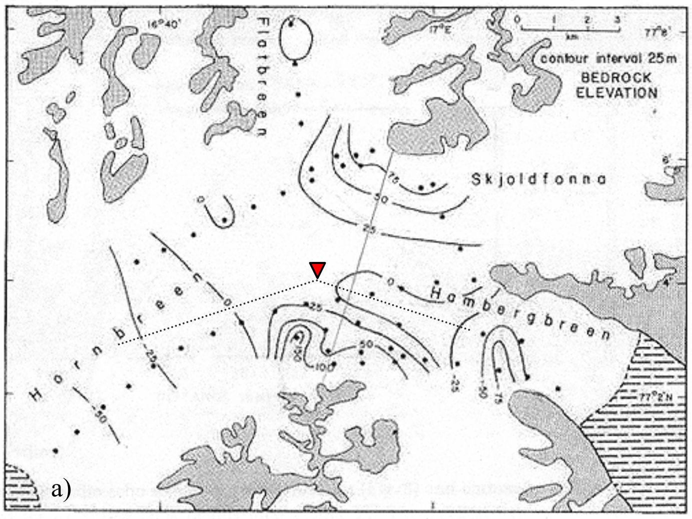
Fig. 1. INTEGRAL study glaciers in Svalbard (marked in red, a);
DEM of South Spitsbergen (1936) with the H-H test site (marked in red, b)

GLACIOLOGICAL PECULIARITIES OF THE TEST SITE

The Hornbreen-Hambergbreen system is situated in the mid-eastern part of Sör-Spitsbergen National Park at approx. 77° N latitude. It is composed of two relatively thin and flat grounded tidewater glaciers flowing in opposite directions, terminating and calving in Hornsund in the west and Hambergbukta in the east, and forming a relatively narrow ice isthmus, which connects Sörkapp Land with the main island of Spitsbergen. According to available topographic maps the width of the ice isthmus exceeded 35 km in 1900 and was still about 25 km in 1936. In the maps of the 1900s, the area of level ice formed by Hornbreen and Hambergbreen reached its highest elevation at 280 m a.s.l. and was called Mendeleev Plain. For the year 1980 the total glacier area of the H-H system was estimated at approx. 320 (179 + 144) km² and the total ice volume was given as 62 km³ [4]. No regular mass-balance measurements have been performed in the H-H study area. It is only known that the equilibrium line altitude varies from 250 m in the west (Hornbreen) to 220 m in the east (Hambergbreen). Hambergbreen surged in about 1890 and 1960. The study area is characterised by "unfavourable" geophysical conditions of glacier existence and, presently, both glaciers are in a retreating phase.

Ice surface elevation does not exceed 220 m a.s.l. over the most part of the elongate glacier-covered valley between Hornsund and Hambergbukta, although glacier maximum heights attain 600 m at the flanks. The vague ice divide separating Hornbreen from Hambergbreen is dissected by two nearly parallel melt-water channels flowing eastwards 2 km apart from each other. Both streams begin and terminate within the ice isthmus and do not reach the glacier margin. There are no nunataks at the H-H ice divide and there is strong evidence that the glacier bed lies below sea level in this area. The idea about the presence of a sub-glacial strait between Torell and Sörkapp lands was first expressed 30 years ago by V.Koryakin, who studied historical maps, geomorphologic and bathymetric indicators [5]. The airborne radio-echo soundings performed over the low-lying part of the H-H system by Russian and British explorers 25 years ago could neither verify nor negate the hypothesis due to the sparse coverage of the area by flight tracks, the absence of bottom returns over heavily crevassed areas and inaccurate referencing [6, 7]. The conclusion that *"no deep trough exists here"* made in [7] remains ambiguous. We nonetheless represent the cartographic sketch from that publication showing the bedrock elevation in the H-H area for the sake of comparison (Fig. 2, a).

Ground-penetrating radar (GPR) surveys performed at the test site by Finnish colleagues in April 2000 revealed that *"beneath the lower glacier centre lines and near the snouts, both the beds are below the sea level"* [3]. The GPR surveys showed that Hornbreen and Hambergbreen were not frozen to their bed, the latter lay at – 25 to +25 m a.s.l. Positive heights of the bedrock were detected over a relatively small part of the study area, which was located north of Ostrogradskifjella. Fig 2, b) represents several profiles showing the glacier surface elevation in 1900, 1936 and 2000 (3 upper profiles) and the bedrock topography with a maximum elevation of approx. 25 m a.s.l. (lower profile). The approximate location of the GPR profile is shown with a dotted line in Fig 2, a). The turn in the profile is marked with a red triangle. The maximum ice thickness of approximately 200 m was detected in the upper part of Hornbreen. In the area of the H-H ice divide the ice thickness was given as approx. 160-180 m. Heavily crevassed areas could not be accessed with snowmobiles. The bed elevation error was given as ± 5 m and the vertical accuracy of the surface elevation measured with DGPS in 2000 was estimated at ± 1.5 m. Finally, the conclusion was drawn that *"the low-lying glaciated valley filled by Hornbreen and Hambergbreen is likely to become a* ***partially inundated*** *ice-free isthmus in the relatively near future"* [3].



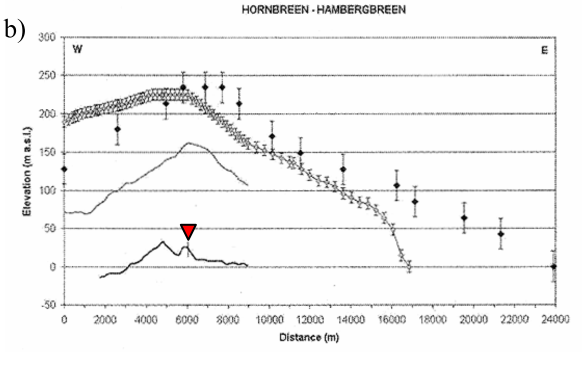


Fig. 2. H-H bedrock elevation derived from airborne radio-echo soundings (a, from [7]) and GPR surveys (b, lower graph, from [3])

This conclusion is also somewhat equivocal and we may say that the character and causes of glacier changes in the H-H test site are not fully understood at present. In south Svalbard, tides (semidiurnal at the western coast and irregular semidiurnal along the eastern coast) can reach 1.5 meters (Fig. 3) and might essentially influence ice-loss processes in marginal parts of tidewater glaciers. Low atmospheric pressure and storm surges cause water levels to rise, while the majority of arctic surveyors prefer high atmospheric pressure and good weather conditions resulting in significantly lower water levels. Tidal effects had in any case to be taken into account, which had not been done in previous studies. We therefore tried to apply tide-coordinated interferometric SAR (INSAR) data to determining the modes of ice motion, deformation and destruction in the "ice-bridge" area, which becomes thinner and narrower with time.

INSAR MODELS OF THE TEST SITE

7 spaceborne repeat-pass ERS-1/2-SAR interferometric tandem pairs taken in 1995 - 1997 at 1-day intervals under steady cold weather conditions were selected for studying the behaviour of large tidewater glaciers in south Svalbard. The INSAR image pairs were selected so as to provide short spatial baselines within the range of 0 – 40 m and to avoid unstable weather with high winds, heavy clouds, precipitation and melting at the glacier surface. The INSAR data was processed in a standard way using the RSG 4.6 in-house software package. Nearly all interferograms showed quite high visibility of fringes with a typical mean coherence value of 0.68. The lowest mean coherence value of about 0.47 was observed in an interferogram with a very short spatial baseline taken in the warm season. The main parameters of the INSAR pairs available are specified in Table 1.

The amplitude of astronomical tides was determined for the times of INSAR data acquisition using the tidal prediction service provided by the University of Oslo (http://www.math.uio.no/tidepred/index.shtml?language=eng). Some typical graphs showing the sea level variations at Longyearbyen, which is approx. 130 km from the test site, versus Norwegian normal time (UTC + 1 hour) are given in Fig. 3. The INSAR image data obtained in March and April 1996 shows an extensive area of fast sea ice attached to tidewater glacier faces and along glacier-free coasts. This feature was used for the regional estimation of tidal effects and indirect interpretation of tide-induced glacier ice motion. The analysis revealed that daily differences in water level did not exceed several decimetres (Table 1) at the times of the INSAR surveys, i.e. about 12:00 (descending orbits) or 21:00 (ascending orbits) NNT.

Table 1. List of ERS-1/2 INSAR pairs for south Svalbard

Satellite	Date Acquired	Orbit	Frame	Normal baseline, m	Tide / Atm. pressure, mb
E1/ E2	30.05.95 / 31.05.95	20251 / 0578, D	2025	- 3	● 20 cm diff / H
E1/ E2	23.10.95 / 24.10.95	22346 / 02673, D	2043	+ 33	● 5 cm diff / H
E1/ E2	07.12.95 / 08.12.95	22985 / 03312, D	2025	+ 29	○ 10 cm diff / H
E1/ E2	10.12.95 / 11.12.95	23028 / 03355, D	2025	+ 17	☾ 15 cm diff / 1005 > 1000
E1/ E2	05.03.96 / 06.03.96	24259 / 04586, D	2025	+ 169	○ 10 cm diff / H
E1/ E2	09.04.96 / 10.04.96	24760 / 05087, D	2025	- 39	☾ 1 cm diff / H > 1000
E1/ E2	17.12.97 / 18.12.97	33597 / 13924, A	1557	-108	☾ 25 cm diff / H

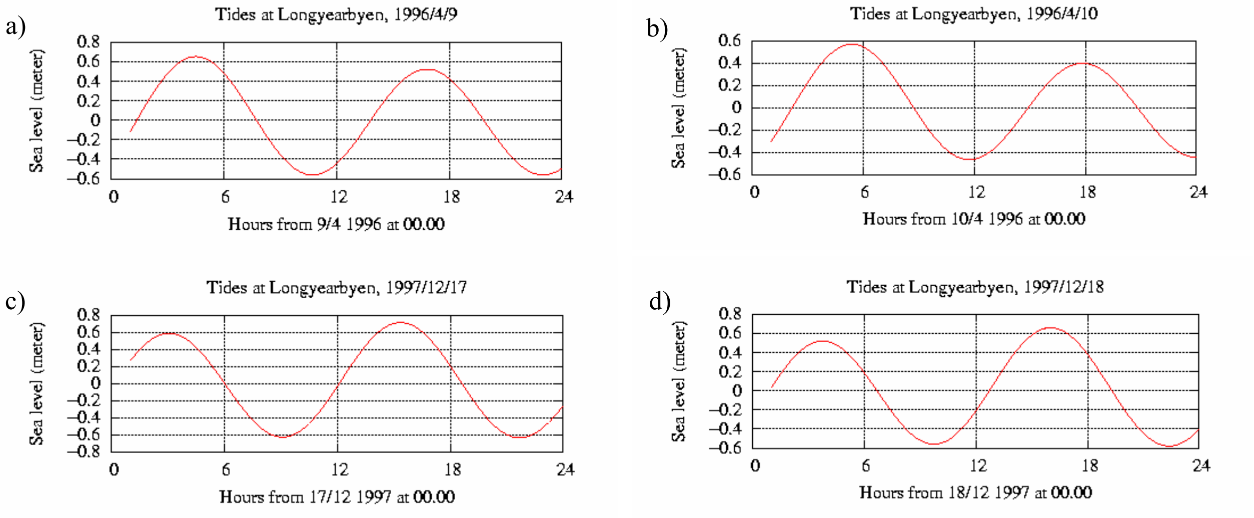


Fig. 3. Predicted tides for the instants of INSAR surveys: 09/10.04.96 (a / b) and 17/18.12.97 (c / d)

Fig. 4 represents typical fragments from multitemporal ERS-1/2-SAR interferograms showing the H-H “ice bridge” at small (≤ 5 cm, a), medium (≤ 15 cm, b) and large (> 15 cm, c) differences in water level. The comparative analysis of multitemporal interferometric products revealed very interesting motion features that increase in length and number with water level difference. In the case of high water level and large level differences, these features join together to form a lambda-shaped stripe that spans the Hornsund Fjord and Hambergbukta (Fig. 4, b and c). The general origin of these features is believed to be related primarily to the vertical displacement of the ice surface forced by tidal motions because of available analogies in the interpretation of interferometric pictures of other ice bridges such as those in Nordenskjold Fjord in Franz Josef Land and Matusevitch Ice Shelf in Severnaya Zemlya.

Several fringe images were draped over the most up-to-date DEM thus providing an interesting, albeit imprecise perspective on the study glaciers and facilitating the interpretation of phase discontinuities and relevant phenomena, such as tidal effects. Preliminary measurements in geocoded INSAR amplitude images showed that the width of the ice isthmus decreased from 14.4 km in 1990 to 10.2 km in 1996. INSAR amplitude and phase-gradient images of 1996 showed an increase in surface roughness and ice deformation in marginal parts of the “ice bridge” (Fig. 7). Hence, we expected to see their continued destruction in the nearest future.

The hypothesis about faster changes of stressed areas at glacier margins has recently been proved. The ASTER-VNIR optical image taken on August 7, 2004 showed that large frontal parts of both Hornbreen and Hambergbreen glaciers had disintegrated, and the ice bridge width had decreased from 10.2 to 8.8 km. Only broken sea ice and icebergs can be seen offshore Ostrogradskifjella, which turned into Cape Ostrogradski. Sikorabreen, formerly a tributary of Hambergbreen, had become a separate tidewater glacier. Several orthorectified ASTER images were assembled in a semi-controlled image mosaic, which was successfully applied to the verification of our hypothesis in the whole study area of Sör-Spitsbergen National Park. It was confirmed that the high glacier strain rates manifested in our phase-gradient images reliably indicated both glacier retreat and advance, the latter was detected at the front of Mendeleevbreen, which had advanced about 400 m from its position of 1990.

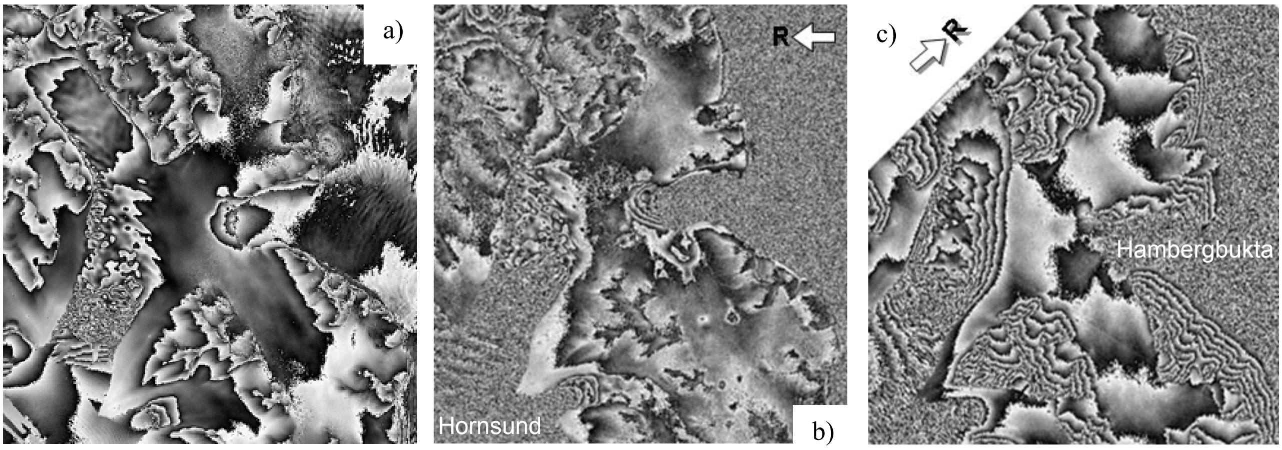


Fig. 4. H-H icy isthmus in the multitemporal interferograms taken under small (09/10.04.96, a), medium (07/08.12.95, b) and large (17/18.12.97, c) differences in water level

INSARAL MODELS OF THE TEST SITE

Our glacier interferometric and elevation models were further upgraded with laser altimetry data obtained by the ICESat satellite in March, October and November 2003. First all data points with known geodetic co-ordinates x, y, z were co-registered to corresponding maps and SAR interferograms using a straightforward transformation, precise orbits and the ERS-SAR sensor model implemented in the RSG software. The co-registration error was characterised by an r.m.s. value of ±1.2 pixel and the r.m.s. difference between cartographic and altimetric heights of steady targets was given as ± 0.7 m. The results of co-registration were represented in the form of INSARAL composite products so that every height spot within each altimetric transect is given corresponding interferometric phase and coherence values (Fig. 5, a).

Such a combination allows interferometric phase distortions to be reliably estimated and phase offsets to be removed over homogeneous glacier surfaces. In most cases, the phase offset function $\Delta\varphi\ (x, y)$ is periodic and anisotropic, as shown in Fig. 5, b), and its global restoration from single realisations (along altimetric transects) is computationally complicated. We thus decided to determine phase offsets locally assuming a monotonous and slowly varying character of the search function within the selected region, i.e.

$$\Delta\varphi_1 \cong k \cdot \Delta\varphi_0 = k \cdot \left(\varphi_{a0} - \varphi_{i0}\right), \tag{1}$$

where subscripts 1 and 0 specify target and reference points, *a* (altimetry) and *i* (interferometry) denote the actual and initial state of variables, respectively, and *k* is the regression coefficient. All reference points with known altimetric heights and target points with unknown heights were selected so as to provide the locally highest coherence values and to reduce random phase errors. The resultant phase offsets were averaged and subtracted from the original phase values. Then the actual glacier heights at specific target points between altimetric transects were determined and controlled using the stepwise algorithm proposed in [8, 9]. This provided the basis for determining the present height of tidewater glacier fronts above sea level. ICESat data points, target points with known heights and several additional control points derived from existing topographic maps and clearly identified in INSAR amplitude images were further used for upgrading available DEMs of the study area and geocoding INSAR models. In geocoded INSAR products, all foreshortening effects at precipitous ice coasts can be accounted for, thus allowing precise ice-coast change detection in SAR multitemporal data sets.

The accuracy of controlled interferometric composites was checked by two independent experts, who measured the heights of identical target points using different reference points. Typical elevation discrepancies along maritime glacier faces and main ice divides did not exceed ± 5 m, meaning that they were almost 5 times smaller than those in standard INSAR products. The absolute accuracy of spaceborne determinations has yet to be verified during dGPS surveys and field observations, which are planned for spring 2006. Until now, however, the terrestrial coverage of the southern Svalbard by the ICESat transects remains rather sparse, which brings about essential difficulties for radar coding over the whole study area with relatively rough topography.

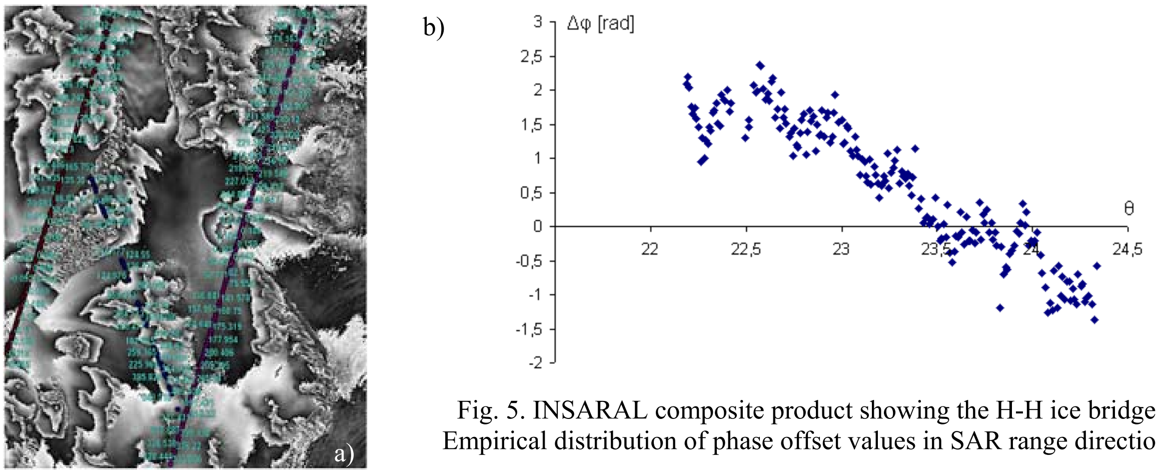


Fig. 5. INSARAL composite product showing the H-H ice bridge (a). Empirical distribution of phase offset values in SAR range direction (b).

QUANTITATIVE ESTIMATION AND REPRESENTATION OF GLACIER CHANGES

The comparison of ICESat altimetric transects with the hypsometric profiles derived from existing topographic maps corroborated the significant (up to 100 m) lowering of the glacier surface in the study area. The H-H ice-bridge elevation decreased by even 130 meters and the surface roughness of the ice isthmus increased drastically over the past years (Fig. 6). The sides of Hornbreen and Sykorabreen have steepened. The H-H ice-bridge withdrawal was animated using all available multitemporal models. The calculations revealed an almost linear decrease of the ice-bridge width over time, and it was concluded that, under current environmental conditions, the H-H ice isthmus will disappear by 2020. The present width of the more or less steady (unstressed) part of the ice bridge at the narrowest point was estimated at approx. 2.1 km.

Both horizontal and vertical glacier changes were legibly represented in the form of satellite image maps covering the whole Sör-Spitsbergen National Park at 1:300 000 scale. The resultant maps and the animation can be accessed at http://dib.joanneum.at/integral/ (cd results). A small-size copy of one image map is given in Fig. 7. Our practical work confirmed that it was much more convenient and, therefore, expedient to perform integral planimetric measurements of glacier changes in linear and areal terms over the whole study region from precise cartographic products than from separate raw images. The approximate thickness of the submerged part of glacier faces needed for the estimation of glacier changes in volumetric terms was determined from the available hydrographic chart and previous publications. Quantitative integral estimations of glacier changes in the study area are given in Table 2. The resultant values of glacier changes correlate well with previous estimations made by other explorers [4, 5, 6] and show that, in the past decades, the rate of land-ice-loss processes in south Svalbard have not changed significantly.

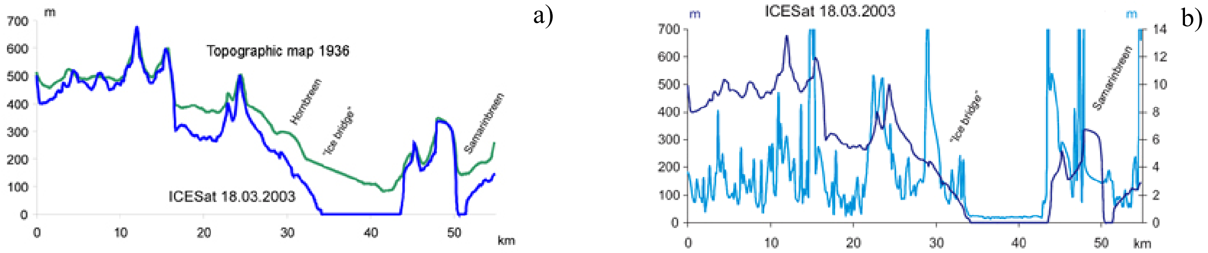


Fig. 6. Glacier changes in the H-H test site: a) hypsometric profiles from topographic maps (green) and ICESat altimetry data (blue); b) ICESat roughness (cyan) and ICESat elevation (blue)

Table 2. Quantitative estimations of glacier changes in south Svalbard

Parameter	Period	Change	Note
Ice coast length	1936 - 2004	+ 24.1 ± 0.5 km (+ 23 %)	Due to irregular outlines of calving glacier faces
Glacier area	1900 – 1936	- 210 ± 1 km^2 (- 5.6 %)	-
Glacier area	1936 – 2004	- 351.5 ± 0.5 km^2 (- 9.7 %)	-
Average ice thickness	1900 - 1976	- 41.6 m	-
Average ice thickness	1936 – 2004	- 65 m	-
Ice volume	1900 – 1936	- 79.2 km^3 (- 10.9 %)	Total ice loss
Ice volume	1936 – 2004	ca. – 100 km^3 (- 15.5 %)	Total ice loss
Ice volume	1936 – 2004	- 28.12 km^3	Ice loss due to marginal disintegration
Ice wastage	1936 – 2004	0.0025 km^3/(a km)	Extrapolated from local estimates

CONCLUSIONS

A combination of satellite interferometry and altimetry was used for generating, geocoding and interpreting rheological and morphological models of large tidewater glaciers in south Svalbard, measuring heights of ice divides and ice coasts, detecting, measuring and interpreting glacier changes in linear, areal and volumetric terms, and estimating ice wastage at seaward glacier margins. Apart from measuring glacier heights, our approach mitigates some local problems related with interferometric phase unwrapping at ice cliffs and provides high accuracy of geocoding and change detection at glacier fronts and tops.

ACKNOWLEDGEMENTS

ERS-1/2-SAR data were provided by ESA, and ICESat-GLAS altimetry data were made available by NSIDC.

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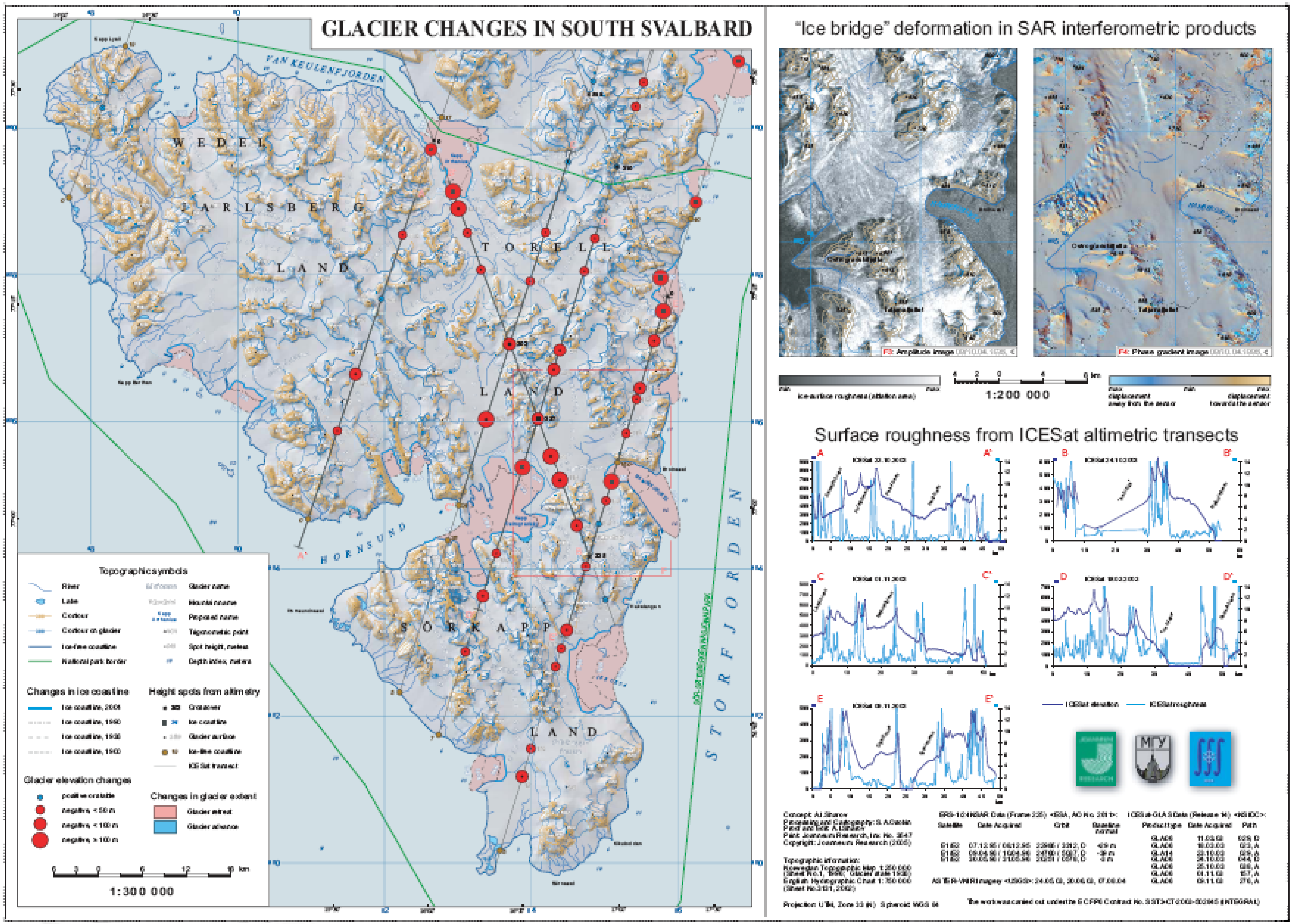

Fig. 7. Small-size map of glacier changes in Sör-Spitsbergen National Park 1:300 000 and H-H test area 1:200 000