Exegesis of Interferometric and Altimetric Observations in South Spitsbergen

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The present paper is based on the main outcomes of the INTEGRAL (EC FP6) and SIGMA (ESA AO No.2611) research projects devoted to enhanced modelling of glacier mechanics and studying the regime and changes of large European tidewater glaciers from satellite interferometry and altimetry. Synthetic aperture radar interferometry (INSAR) is regarded as a highly informative remote sensing method for glacier studies. Still, the exegesis [from Greek *exegeisthai* - to explain, interpret] or critical interpretation of the spaceborne interferograms taken over labile glacial environments is by no means straightforward and necessitates additional constraints and precise topographic reference models. 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.

The underlying concept of the research is to facilitate the geometric processing of interferometric data and to compensate for the lack of reliable reference models in extensive glacial areas with precise altimetric and photogrammetric data, yet without or independently of the use of surveyed control points. 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, a) and characterized with high rate of spatial changes. The character and causes of these changes are not fully understood at present. Up-to-date topographic maps and digital elevation models of the test site 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.

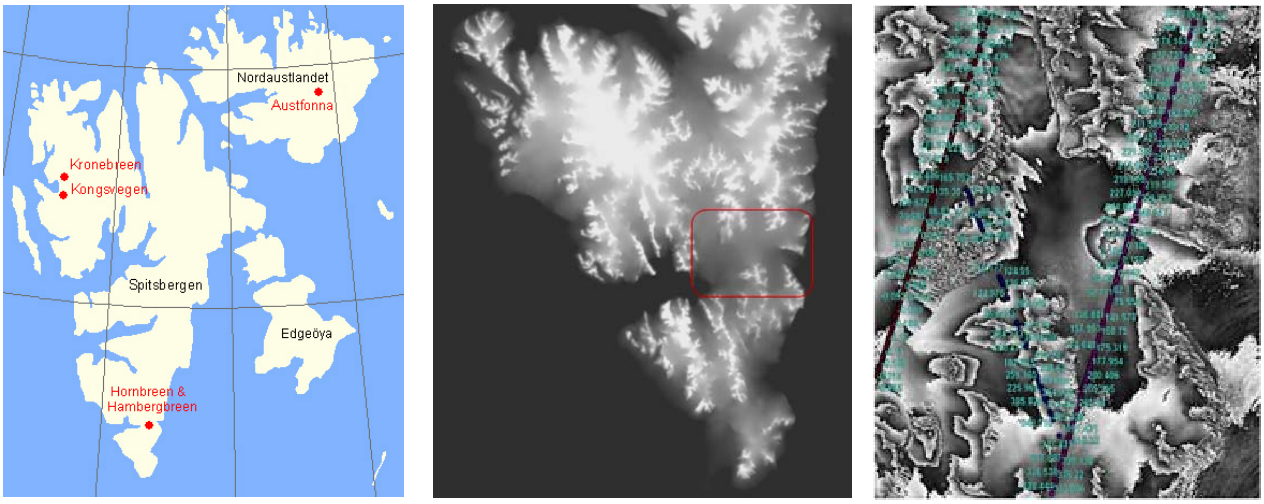

Figure 1. H-H test site in a small-scale map of Svalbard (a), in raster DEM of South Spitsbergen (1936, b), and in INSARAL composite (1996-2003, c)

The Hornbreen-Hambergbreen system is composed of two relatively thin and flat grounded tidewater glaciers flowing in opposite directions, terminating and calving in deep waters of 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 bridge” exceeded 35 km in 1900 and was still about 25 km in 1936. 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. 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. 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 ground penetrating radar surveys performed by Finnish colleagues in the year 2000 after the airborne radio-echo soundings done by

Russian and British explorers in 1980-s could neither verify nor negate the hypothesis about the presence of a sub-glacial strait between Torell and Sörkapp lands, which was first expressed 30 years ago by V.Koryakin.

Surprising is that tides in south Svalbard, which can reach 1.5 m (Fig. 2) and might essentially influence ice-loss processes in marginal parts of tidewater glaciers, had not been taken into account in previous studies. We therefore tried to apply tide-coordinated INSAR data to determining the modes of ice motion, deformation and destruction in the ice-bridge area, which becomes thinner and narrower with time. 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 so as to provide short spatial baselines within the range of 0 – 100 m (Table 1). The INSAR data was processed in a standard way using the RSG 4.6 in-house software package. The amplitude of astronomical tides at Longyearbyen was determined for the times of INSAR data acquisition using the tidal prediction service provided by the University of Oslo (Fig. 2). 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.

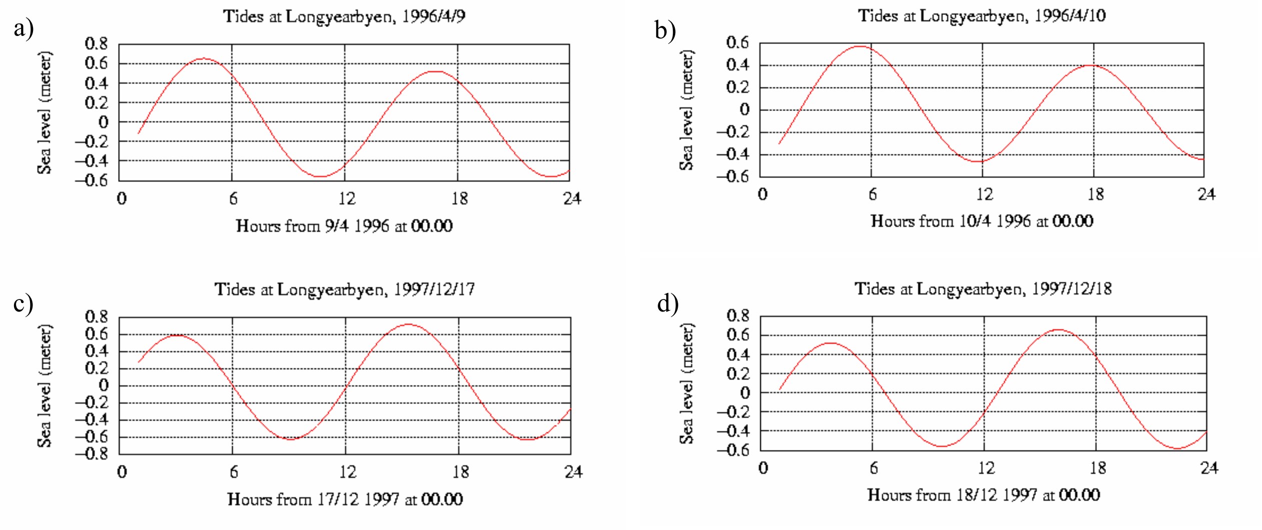

Figure 2. Predicted tides for the instants of INSAR surveys: 09/10.04.96 (a / b) and 17/18.12.97 (c / d)

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 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. 3, 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.

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. 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. 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. 4). 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. 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.

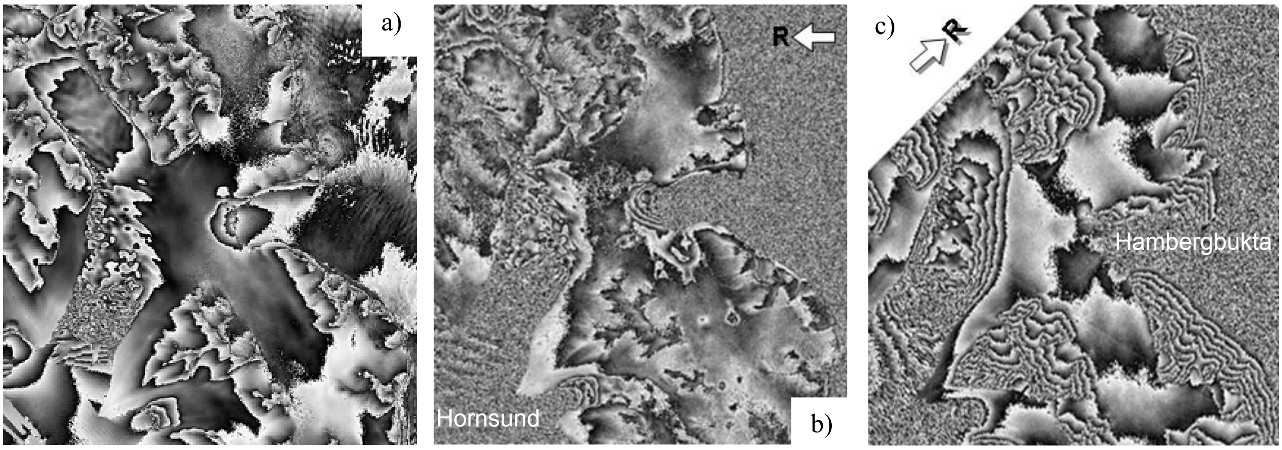

Figure 3. H-H ice bridge in the multitemporal interferograms taken under small (09/10.04.96, a), medium (07/08.12.95, b) and large (17/18.12.97, c) differences in water level

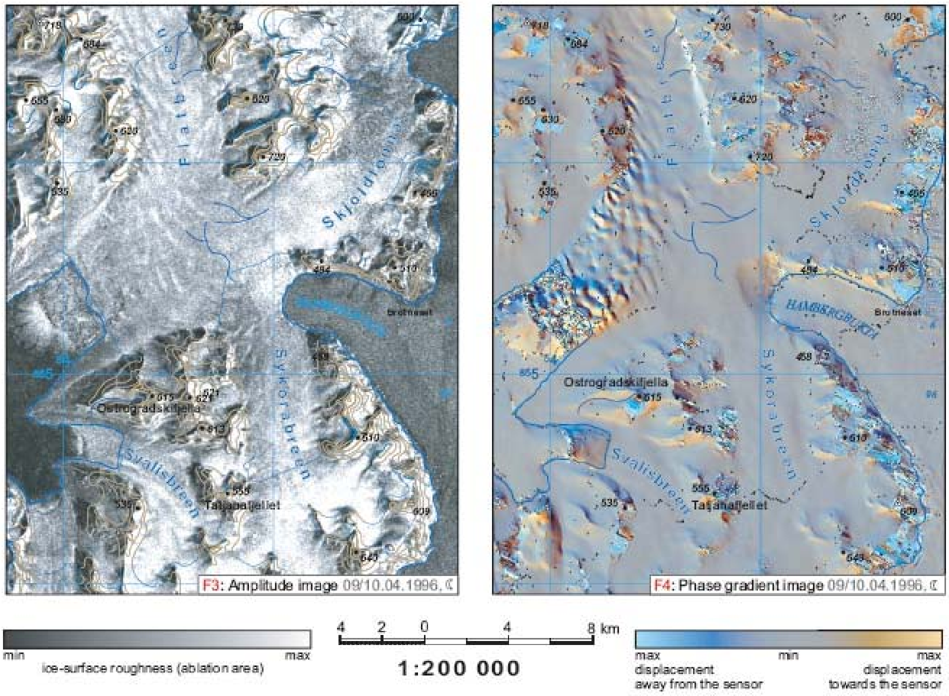

Figure 4. H-H ice bridge deformation in SAR interferometric products: amplitude (left) and phase gradient image (right)

Our glacier interferometric and elevation models were further upgraded with laser altimetry data obtained by the ICESat satellite in March, October and November 2003. 7 ICESat altimetric tracks were co-registered to corresponding maps, elevation models and SAR interferograms using a straightforward transformation, precise orbits and ERS-SAR sensor imaging model. 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. 1, c). Such a combination allows the actual glacier heights at specific target points between altimetric transects to be determined and controlled. This provided the basis for determining the present height of tidewater glacier fronts above sea level, upgrading available DEMs of the study area and measuring glacier elevation 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. 5). 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.

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). Quantitative integral estimations of glacier changes in the study area are given in Table 2. 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 available hydrographic charts and previous publications. The resultant values of glacier changes correlate well with previous estimations made by other explorers and show that, in the past decades, the rate of land-ice-loss processes in south Spitsbergen have not changed significantly.

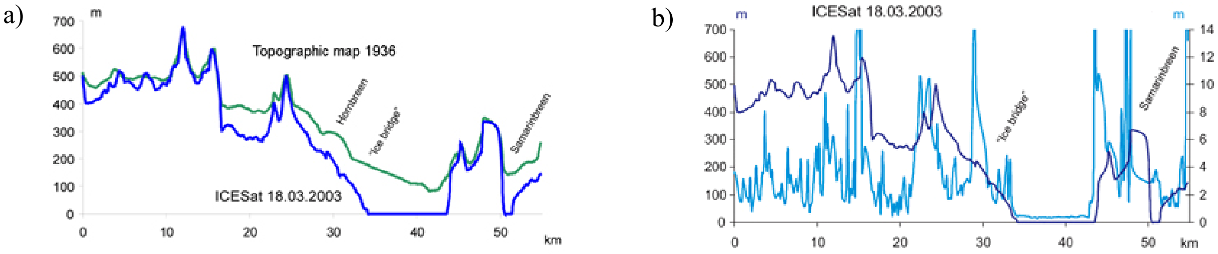

Figure 5. Glacier changes in the H-H test site: a) hypsometric profiles from topographic maps (green) and ICESat altimetry data (blue); b) ICESat roughness (cyan) and ICESat elevation (blue)

Table 2. Quantitative estimations of glacier changes in south Spitsbergen

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 km² (- 5.6 %)	-
Glacier area	1936 – 2004	- 351.5 ± 0.5 km² (- 9.7 %)	-
Average ice thickness	1900 - 1976	- 41.6 m	-
Average ice thickness	1936 – 2004	- 65 m	-
Ice volume	1900 – 1936	- 79.2 km³ (- 10.9 %)	Total ice loss
Ice volume	1936 – 2004	ca. – 100 km³ (- 15.5 %)	Total ice loss
Ice volume	1936 – 2004	- 28.12 km³	Ice loss due to marginal disintegration
Ice wastage	1936 – 2004	0.0025 km³/(a km)	Extrapolated from local estimates

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