UPGRADING INTERFEROMETRIC MODELS OF EUROPEAN TIDEWATER GLACIERS WITH ALTIMETRY DATA

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ABSTRACT

This paper proposes an original concept for the complementary use of satellite interferometry and altimetry aimed at generating, geocoding and mosaicking equivalent morphological and rheological models of large European tidewater glaciers (TWGs). Basic methodological aspects and potential glaciological applications, including glacier change detection, ice-divide and ice-coast height measurements, determination of glacier horizontal velocities and ice flux estimation at seaward glacier margins will be discussed. Several new value-added products derived from ERS-1/2 SAR images (1995-1996) and ICESat–GLAS altimetric transects (2003) representing the present state of the largest ice caps and outlet TWGs in the Barents Sea region will be demonstrated.

1 INTRODUCTION

Tidewater glaciers are among the most varied objects on the solid earth's surface as a result of climatic change and enhanced oceanic forcing. In the European Arctic Sector, calving TWGs shrink by an average of several hundred meters each year, and publications periodically announce drastic changes in the position of tidewater glacier termini in the high-latitudinal archipelagos of Spitsbergen, Franz Josef Land and Novaya Zemlya, cf. [1, 2, 3]. Previous studies of European TWGs tended to be of a local rather than regional character, however, and the analysis of relationships between processes at glacier tops and fronts was not always possible even with remote sensing data. Very little is known at the present time about general modes and driving mechanisms of glacier changes in the region, and overall estimations of glacier regime at macro-level resulting from spatial extrapolations to the continental scale remain very inaccurate. Repeat-pass SAR interferometry (INSAR) providing large terrestrial coverage and high sensitivity to glacier motion / changes offers a unique opportunity to study the dynamics, mass-flux variations and mass-balance characteristics of the largest European TWGs on a synoptic basis [4, 3]. However, rapid elevation changes, the lack of reliable ground control and ambiguous interpretation of glacier interferograms pose a serious obstacle to precise morphological and rheological modelling of large TWGs solely from INSAR data.

The combination of satellite radar interferometry and altimetry offers a particularly potent solution to the geometric modelling of large maritime glacier complexes in the case of insufficient quality of elevation control data [3]. The present paper reports on preliminary results achieved in the SIGMA CryoSat AO project No. 2611, which is aimed at integral estimations of the TWG regime in the European Arctic. The underlying concept of the project is to compensate the lack of basic, especially vertical, control with satellite altimetry, both radar and lidar, and to apply

a) single-pass altimetry data to reliably interpret, geocode and update single SAR interferometric models, and adjust INSAR blocks;
b) multi-pass and multi-source altimetry data to reference, calibrate and interpret differential INSAR models,

thus upgrading the information content and enhancing the accuracy, completeness, durability, and versatility of both existing and future glacier interferometric models. The study is considered as a preparatory stage for the upcoming research associated with the launch and operation of the ESA CryoSat mission and scientific initiatives devoted to the International Polar Year 2007-08. Our paper deals with joint processing of the ERS-1/2 SAR interferograms and ICESat–GLAS altimetric transects obtained over large European TWGs in the cold seasons of 1995-1996 and 2003. The main test sites comprise several large outlet TWGs belonging to the Main Ice Sheet in north Novaya Zemlya, Austfonna Ice Dome in Svalbard and Tyndall Ice Cap in Franz Josef Land.

2 GEOGRAPHIC OUTLINE OF THE STUDY AREA

Analysis of contemporary topographic maps and national glacier inventories shows that some 1000 tidewater TWGs extending into the sea exist in the European Arctic, with some of these producing icebergs. Our approximate cartometric estimations show that the present total area of European TWGs makes up 30,000 km², and average size of a "typical" maritime drainage basin is about 30 km². The largest clusters of tidewater glaciers exist in the Franz Josef Land (733 TWGs) and Svalbard (211 TWGs) archipelagos. Novaya Zemlya hosts only 41 TWGs, and 6 TWGs persist at Jan Mayen Island, the latter is regarded as the southernmost location of European TWGs [3]. Most European TWGs terminate in the Barents Sea.

The seaward margins of European TWGs are mostly precipitous and rise 5 to 100 m above sea level (Fig.1, a). The information about the heights of maritime glacier faces given in existing topographic maps and hydrographic charts is, however, extremely scarce, obsolete and inaccurate. Frontal parts of TWGs are subject to rapid changes due to the impact of melting, marine abrasion and calving. The current retreat of TWG fronts dL and rapid disintegration of thinner glacier margins lead to a corresponding increase of the subaerial part of the glacier face, thus raising actual ice coast heights h_a (Fig.1, b). Previous field observations and remote sensing surveys in the Barents Sea region revealed that most TWG fronts have risen 10 to 40 m above sea level in the past 20 to 50 years [3]. This fact does not contradict the general lowering of glacier surfaces in the ablation area dh as a result of increased melting and, probably, accelerated ice flow at seaward glacier margins.

On the other hand, the comparison of ICESat altimetric transects with the hypsometric profiles reconstructed from existing topographic maps corroborated significant positive height changes up to 30 – 60 m in the accumulation areas of test TWGs. Most test glaciers have steepened their sides. Fig. 2, for example, represents typical hypsometric profiles derived from topographic maps and ICESat altimetry data, which demonstrate different stages in the evolution of large TWGs in north Novaya Zemlya (a), Franz Josef Land (b) and Svalbard (c, d). The reliable data on diurnal, seasonal and interannual changes in glacier motion are available only for few European TWGs, and the general influence of ice-flow variations on the elevation and slope of TWG margins still remains uncertain.

a) 

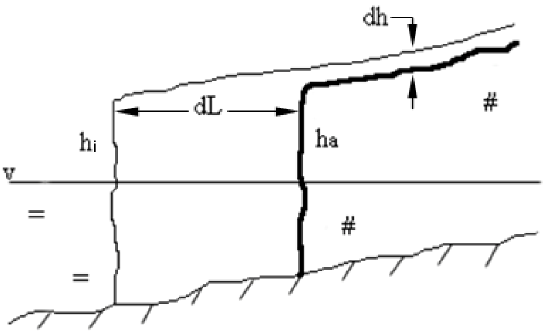
b) 

Fig.1. Seaward margin of Rykachova TWG, north Novaya Zemlya: a) terrestrial photograph (2001); b) present (thick) and former (thin) longitudinal profiles derived from ICESat data (2003) and Russian topographic map (1952 /1971)

3 DATA SET INSPECTION

14 repeat-pass ERS-1/2-INSAR tandem pairs with suitable spatial baselines of 20 to 150 meters taken in the period of XI / 1995 – III / 1996 under steady, cold and cloudless weather conditions were selected for modelling and studying the behaviour of the largest TWGs in the Barents Sea region. Precision orbital data records were available for interferometric processing of each INSAR pair. Most glacier interferograms were obtained during neap tides (the first or third quarter of the moon). All SAR interferograms show a high mean coherence value of 0.7 over steady tracts of land ice, irrespective of the test site. The lowest mean coherence value of 0.47 was observed in the areas subjected to rapid motion and local meteorological effects, e.g. snow drift, melting, hoarfrost etc.

No ground control data was available for precise geometric processing of INSAR data. We therefore used 210 altimetric transects of the study glaciers obtained by the ICESat-GLAS lidar sensor under similar weather conditions in March, October and November 2003. Multitemporal ICESat tracks intersect each other at a latitude-dependent angle building a specific rhomboidal net that covers the whole study region. At the latitude of Austfonna, the available track spacing is about 10 km. 70-m footprints are spaced at 170 m, thus providing regularly and densely distributed control data [5]. Preliminary tests of positional and elevation accuracy were performed prior to joint geometric processing of INSAR and altimetry data.

All ICESat altimetric transects were first co-registered to existing topographic maps at 1:200,000 and 1:500,000 scales. Subsequently, ICESat ellipsoid heights were transformed to geoid heights and compared with those given in cartographic documents through a dozen arbitrary check points situated in flat ice-free areas, such as beaches, plateaus, etc. The root mean square difference between altimetric and cartographic heights was given as ± 0.7 m. Careful inspection of multitemporal transects taken over large ice caps proved high repeatability of altimetric observations in cross-over areas. The r.m.s. difference between altimetric heights measured with a time gap of 3 days in fall 2003 was evaluated as being less than 0.3 m. A high spatial homogeneousness of altimetric heights was also observed over areas of fast sea ice. In addition, several frozen lakes situated at different elevations ranging from 10 to 255 m were selected for additional accuracy checks of lidar data. Surprisingly, the spatial distribution of altimetric heights determined over the lakes was much more irregular and the height variance exceeded 3 meters, which was explained by the influence of "mixed pixels".

Our tests nevertheless proved the high elevation accuracy of ICESat GLA06 (L1B) data, and typical height errors were estimated as being 10 to 20 times smaller than those in standard INSAR products. Hence, it was concluded that the lidar altimetry data can be applied as an alternative control to precise geocoding of glacier interferograms. The fact that the altimetric control is younger than the imagery to be processed suits well for modelling both current and projected conditions. In real data processing, we assumed a spatially homogeneous distribution of glacier elevation changes during the 7-year interval between interferometric and altimetric surveys, and supposed that the residual cumulative influence of ablation-accumulation processes on height measurements did not exceed several meters. Significant positional changes dL at calving glacier fronts were detected and measured from the altimetric transects overlaid on INSAR products. For example, we recognised that the seaward margins of Bråsvellbreen at Austfonna Ice Dome with a height of 44 m a.s.l. have retreated 350 - 500 m in the course of the past 7 years.

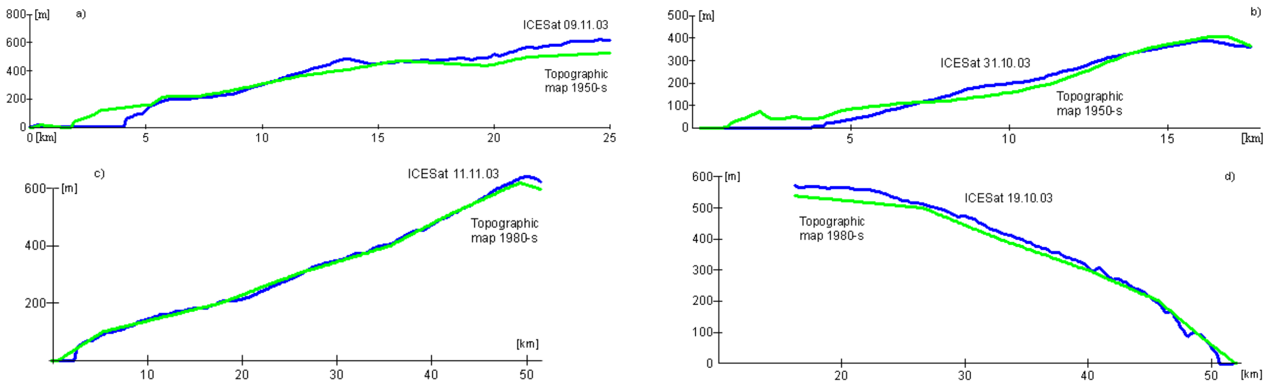


Fig.2. Hypsometric profiles of Petersen (a), Renown (b), Bråsvellbreen (c) and Schweigaardbreen (d) TWGs from topographic maps (green) and ICESat altimetry data (blue)

4 ABSOLUTE ORIENTATION OF GLACIER INTERFEROGRAMS WITH ALTIMETRY DATA

The procedure of absolute orientation of SAR interferograms involves the following basic steps:

1) co-registering altimetry data with standard interferograms ("compilation & identification of control points");
2) determining and removing phase or/and height offsets, height ambiguity control & spatial baseline refinement ("levelling, scaling, adjustment");
3) geocoding and mosaicking of INSAR models ("orientation to available control").

4.1 Co-registering altimetry data with standard INSAR products

All data points (with known geodetic co-ordinates x, y, z) within the ICESat tracks were co-registered to corresponding interferometric models using a straightforward and rigorous transformation and the ERS-SAR sensor model implemented in the RSG 4.6 in-house software. The transformation accounts for precision state vectors and zero-Doppler processing of INSAR data and is sometimes referred to as radar coding. The results of co-registration are represented in the form of INSAR composite products. An original INSAR composite image of the northern part of the Main Ice Sheet in Novaya Zemlya consisting of an amplitude image (inland) and fringe image (offshore) with several altimetric transects overlaid is given in Fig. 3. Digits 1 through 5 denote Inostrantseva, Pavlova, Vera, Bunge and Petersen tidewater glaciers, respectively. The altimetric profile AB is shown in Fig. 2, a. In such composite products, every height spot within each altimetric transect is given corresponding interferometric phase and coherence values.

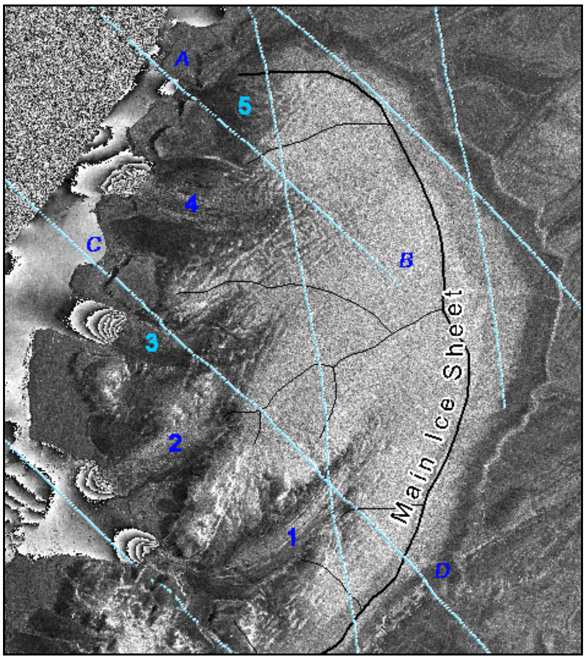


Fig. 3. INSAR composite product showing active outlet TWGs and major ice divides of Main Ice Sheet in north Novaya Zemlya with altimetric transects (cyan) overlaid.

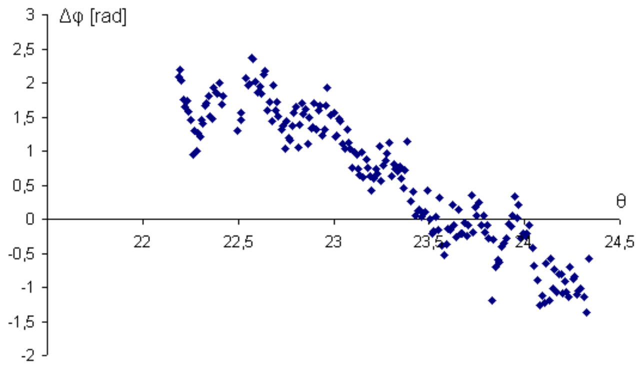


Fig. 4. Typical distribution of phase offset values in SAR range direction

The co-registration accuracy was estimated through 21 check points situated in ice-free areas, such as coastlines, ravines, rivers, escarps, rocks etc., which could be reliably identified on both INSAR image products and altimetry transects. The positional error was characterised by an r.m.s. value of ± 1.2 pixel.

4.2 Determining and removing phase and height offsets

In standard repeat-pass SAR interferograms of large TWGs, the interferometric phase is essentially distorted due to the influence of technical imperfections and processing inaccuracies related to sensor noise, orbital data uncertainties, atmospheric path delays, radar penetration into dry snow, interferometric decorrelation, etc. The interferometric phase distortion can be represented as a superposition of random phase noise and systematic phase offset. The influence of rapidly varying random errors can be practically eliminated or neglected by selecting the glacier areas characterised by high coherence of the interferometric signal. The influence of systematic phase offsets may reach a significant level even within highly coherent areas and must first be removed from INSAR products.

In most cases, the phase offset function $\Delta\varphi(x, y)$ is periodic and anisotropic. Fig. 4, for example, shows the typical empirical distribution of phase offset values versus look angle θ. Global restoration of the whole function $\Delta\varphi(x,y)$ from its single realisations 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. Two possible flow charts showing the sequence of the principal stages of this procedure are given in Fig. 5. The methodological variant shown in Fig. 5, a) involves mostly operations in the space domain and applies inverse phase-to-height transformations, while that in Fig.5, b) involves operations in the phase domain (shaded boxes) applying both direct height-to-phase and inverse transformations. In both cases, the reference point P_0 with known altimetric height and the target point P_1 with unknown height are selected in order to provide the locally highest coherence values. The local phase offset and height offset values are correspondingly determined as

$$\Delta\varphi_1 \cong \Delta\varphi_0 = \varphi_{a0} - \varphi_{i0} \quad \text{and} \quad \Delta h_1 \cong \Delta h_0 = h_{a0} - h_{i0}, \qquad (1)$$

where subscripts 1 and 0 specify target and reference points; *a* (altimetry) and *i* (interferometry) denote the actual and initial state of variables, respectively. Both algorithmic variants aim at determining and controlling the target height h_{a1}. Optionally, height ambiguity control and spatial baseline refinement can be performed, e.g. by comparing the height interval between two altimetric spots located at opposite edges of the same interferometric fringe and the height ambiguity value calculated from orbital geometry data. At glacier tops, the higher rate of interferometric fringes in comparison with that expected from orbital geometry might serve as a sensitive indicator of slow vertical motions, e.g. due to firn densification.

4.3 Geocoding and mosaicking of INSAR models

ICESat data points and several additional control points derived from existing topographic maps and clearly identified in INSAR amplitude images were used for the generation of coarse digital elevation models (DEMs) covering each test site. The Delaunay-based bi-linear interpolation was applied to estimating height values between points with known heights. The resultant DEMs served as a basis for the image-to-map transformation and for the generation of INSAR orthoimages using bi-linear resampling of SAR interferograms. Three overlapping INSAR orthoimages taken over Austfonna Ice Dome on 7/8.11, 10/11.12 and 16/17.12.1995 were assembled in semi-controlled mosaic providing a continuous representation of the large portion of Nordaustlandet, Svalbard, with a total land area of approx. 14,000 km^2. The image mosaic served as a basic layer for the output image map of Austfonna Ice Dome represented in the UTM projection (Zone 35, WGS 84) at 1:500,000 scale. A small-size copy of the image map is given in Fig. 6.

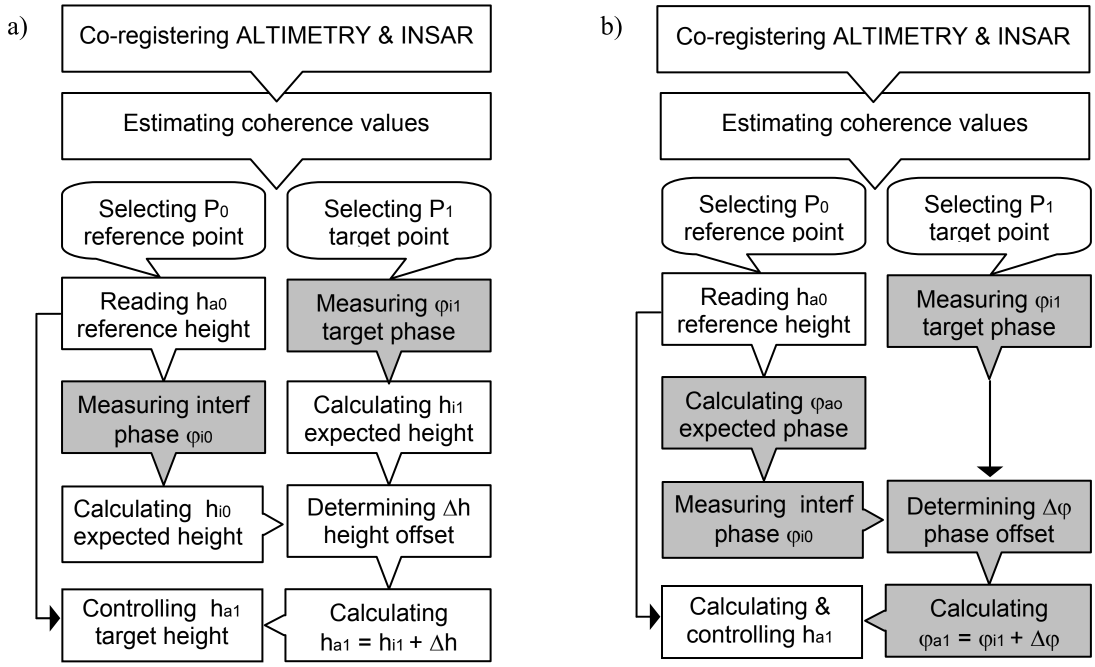


Fig. 5. Two principal flowcharts of the proposed technique with most operations performed in space domain (a); phase domain (b)

5 EXTRACTING GLACIER TOPOKINETIC QUANTITIES FROM GEOCODED INSAR PRODUCTS

Joint interpretation of geocoded fringe images and altimetric transects allowed the location of ice-flow divides to be determined and topographic heights of main ice divides, ice coasts and specific locations on the glacier surface to be precisely measured. The top height of the Austfonna Ice Dome was determined as 797.1 m, which is 7 meters higher than the value reported in [1]. The influence of snow accumulation in fall 2003 must, however, be taken into consideration. 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.

Frontal glacier velocities were measured from *single* geocoded SAR interferograms by using two alternative techniques. The original *fringe tracking* technique is based on tracing the reference interferometric fringe, which runs along steady ice coasts and protracts inland in outlets flowing away from the sensor, with subsequent counting of interferometric fringes enclosed between the reference fringe and the outlet glacier front (Fig. 7, a). Known heights of ice coasts are used as a topographic reference for precise measurement of the real number of motion fringes. For the sake of illustration, a small fragment from the fringe image representing the Outlet Basin No. 3 at Austfonna Ice Dome with the ICESat transect and several height spots overlaid is given in Fig. 7, a). The transferential technique of measuring frontal glacier velocities described in [3] is based on analysing the horizontal shift of the coastal sea ice forced by glacial flow. The velocity values obtained for study glaciers in Franz Josef Land and north Novaya Zemlya have already been published in [3]. Frontal velocities of several TWGs in Nordaustlandet for the cold season of 1995-1996 are given in Table 1.

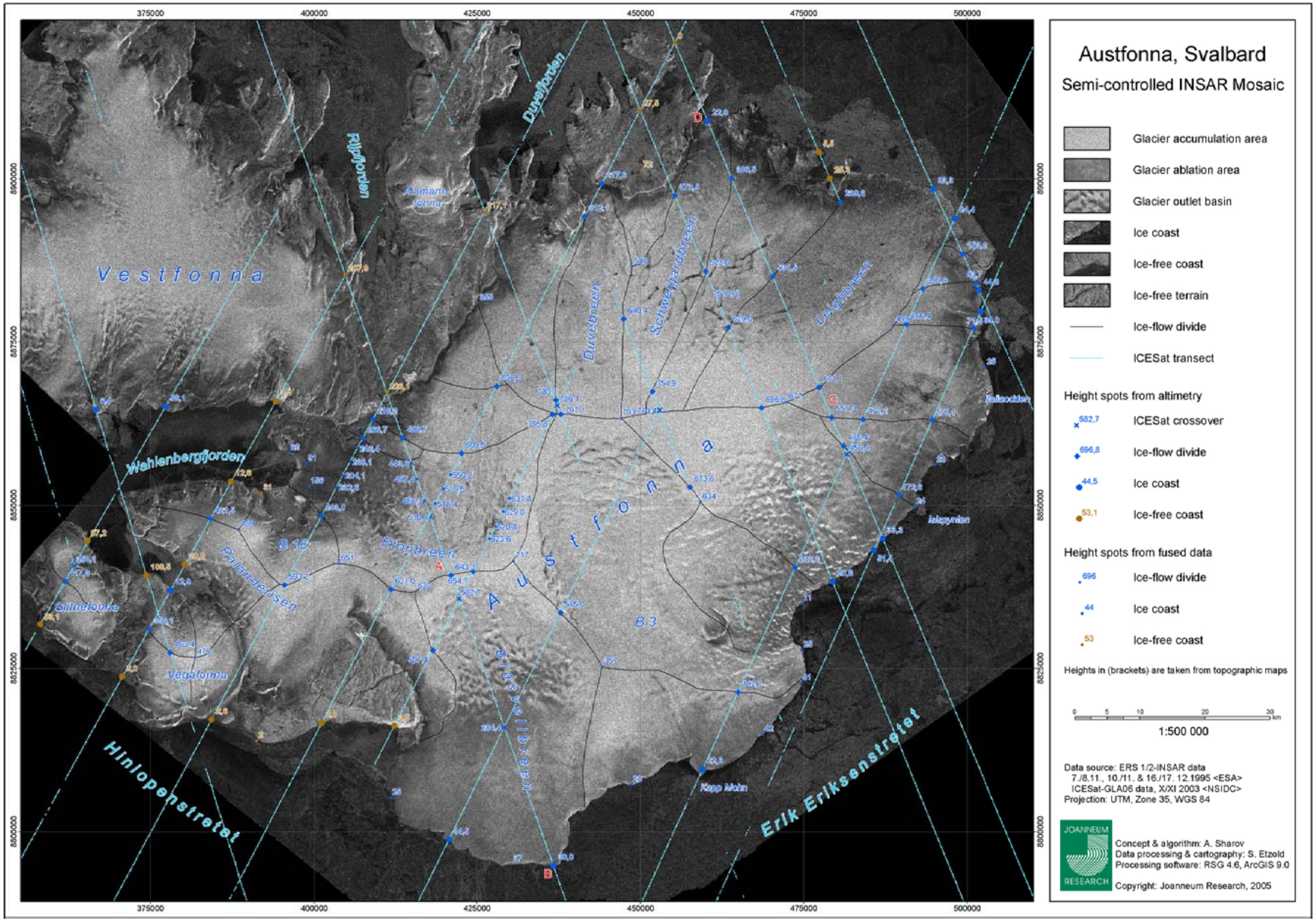


Fig. 6. Small-size copy of the INSAR image map of Austfonna Ice Dome 1:500,000

The present heights of ice coasts and INSAR velocity values were applied to the quantitative analysis of the annual ice discharge through outlet glacier fronts, which can be approximately estimated as

$$\Phi \approx \rho \cdot L \cdot (\overline{h} + \overline{\tau}) \cdot \overline{V} \,, \qquad (2)$$

where $\rho \simeq 0.9$ t/m³ is the ice density, L is the length of the calving glacier face, $\overline{V}$ is the average annual velocity (approx. half the maximum INSAR velocity); $\overline{h}$ is the average value of the ice coast height and $\overline{\tau}$ is the average thickness of the submerged part of a glacier, which is supposed to be equal to the water depth given in the 1:600,000 hydrographic chart published by the Norwegian Hydrographic Service in 2002. The resultant approximate values of annual ice flux through the fronts of Basins Nos. 3 and 18 on Austfonna Ice Dome are estimated at 63.3 and 34.2 Mt/a respectively.

Careful analysis of multitemporal amplitude, fringe and coherence images revealed that a quite large (up to 5 km²) seaward marginal part of Etonbreen Outlet in the western part of Austfonna undergoes vertical swaying motions with a maximum amplitude of approx. 8 cm caused by tidal effects (marked with arrow in Fig. 7, b). It is worth noting that the height of the tides in the Barents Sea region does not exceed 1.0 m under calm weather conditions. Hence the sea level recorded at the time of satellite surveys can be used as a datum plane for practical mapping of the study TWGs.

Table 1. Frontal velocities of tidewater glaciers in Nordaustlandet, Svalbard (cold season 1995 – 1996)

Glacier Name	INSAR velocity, cm/day	Date
Aldousbreen	39.1 – 26.3	14/15.01.96 – 30/31.03.96
Basin No. 3*	65.3	07/08.11.95
Basin No. 18*	76.8 – 60.2	10/11.12.95 – 24/25.03.96
Duvebreen*	56.2	16/17.12.95
Frazerbreen	84.3	30/31.03.96
Idunbreen	63.8	30/31.03.96
Nilsenbreen*	23.0	16/17.12.95
Palanderbreen	10.0 – 10.0 – 13.4	14/15.01 - 24/25.03 – 30/31.03.96
Rijpbreen	35.1	16/17.12.95
Sabinebreen	< 3.0	16/17.12.95
Schweigaardbreen*	59.1	16/17.12.95
S.Franklinbreen	9.7 – 20.2	16/17.12.95 - 30/31.03.96
N.Franklinbreen	13.5 – 3.8	16/17.12.95 - 30/31.03.96

*) outlet TWGs belonging to Austfonna Ice Dome.

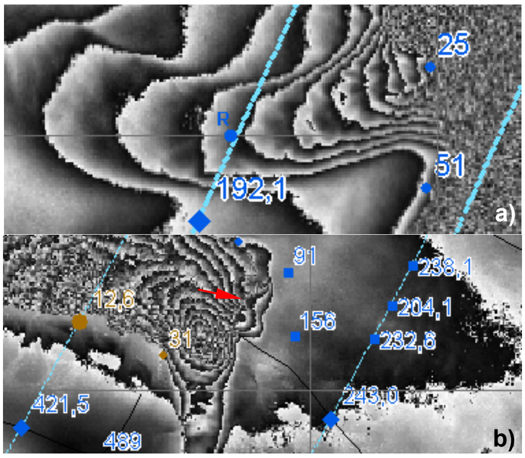


Fig. 7. Fringe images of Basin No.3 (a) and Etonbreen (b) used for motion measurement

CONCLUSIONS

The present methodological developments in precise geocoding and mosaicking of ERS-1/2-SAR tandem interferograms of large European glaciers provided by ESA using ICESat-GLAS altimetry data made available by NSIDC are believed to be both expedient and fruitful. Two alternative algorithms for the absolute orientation of glacier interferometric models were devised, tested and validated in different TWG environments. It has been demonstrated that the arbitrary height and velocity of each specific point on the glacier surface characterised by a high coherence value can be derived from single geocoded SAR interferograms without complex processing artifices such as phase unwrapping and differential interferometry. The large terrestrial coverage, high spatial resolution and vertical accuracy of our controlled composite products coupled with their astonishing sensitivity to glacier changes and motion are essential for synoptic studies of glacier regime in the European Arctic, which might lead to a better understanding of the evolution of TWGs and their dynamic response to climatic changes.

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