SATELLITE HYDROGRAPHIC MONITORING ALONG THE RUSSIAN ARCTIC COAST

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ABSTRACT

Two original alternative techniques have been offered for the precise modelling of ice shores and the ice-motion estimation for large outlet glaciers in the Western Russian Arctic using tide-coordinated ERS-1/2-INSAR data. Speed and simplicity of implementation are important features of the proposed techniques, which make use of single interferograms and do not require additionally the topographic reference model. One method is based on the interferometric measurement of the coast-ice translation caused by the glacier flow; other approach consists in analysing gradient images of single interferograms. The results obtained by different techniques were in good correspondence and it has been concluded that both methodological variants can provide comparable accuracies.

1. INTRODUCTION

Synthetic aperture radar (SAR) image data and derived products have proven to be a valuable source of information for monitoring studies in the Arctic. The use of spaceborne SAR imagery in arctic research has increased in recent years following the introduction of satellite radar interferometry (INSAR), which became a *cause celebre* in sciential circles. While several good examples have already been shown of INSAR spatial modelling in the Arctic (Kwok & Fahnestock 1996, Fatland & Lingle 1998, Guneriussen et al. 1999), there is still some doubt among Russian researchers as to the performance of this generally promising technique (Malyavskiy, personal communication 1998). Successful applications of ERS-1/2-INSAR products for coastal monitoring, tidewater glacier studies, and coastal zone management in different regions have been reported, e.g. in (Dowdeswell et al. 1999), but, to our knowledge, the subject of using INSAR data for natural explorations in coastal zones of the Russian Arctic Sector has never been treated by other investigators.

Socio-economic justification for such explorations is ensured due to the immense significance of regular and safe merchant shipping along the Northern Sea Route for the industrial development and reactivation of trade in the region and improvement of living conditions of the local human population. The Northern Sea Route (or Northeast Passage) **-** a maritime communication between the Atlantic and Pacific oceans along the northern coast of the Eurasian continent - is one of Russia's most important waterways, which depends on icebreaking fleet and provides reliable year-round transportation of goods between marine Arctic harbours and port facilities in estuaries of Russian northern rivers.

Trustworthy contemporary hydrographic data, e.g. on coastal changes, distribution of sea ice in coastal waters, iceberg influx, tidal effects, currents etc., are needed for a careful administration of this transport system and conducting long-term economic projects in this remote region. Satellite radar remote sensing that do not require clear sky or daylight is capable of providing such information over vast arctic territories on the periodic basis at both regional and local scale. Our initial tests using spaceborne repeat-pass interferometric data for topographic modelling of glaciers and shorelines in the Franz Josef Land archipelago, Russian Arctic were encouraging as a whole and attested to the feasibility of applying the INSAR method to the detailed hydrographic studies and coastal change detection in the Arctic (Sharov 1998, Raggam & Sharov 1999).

This paper reports on the first stage of the AMETHYST research project aiming to evaluate and utilise the full potential of satellite interferometry for the purposes of coastal hydrographic monitoring in the Western Russian Arctic (WeRA). The acronym AMETHYST originates from "Assessment and Monitoring of Environmental Trends regarding Hydrographic Situation in the WeRA". The polar idea of our project is to demonstrate the utility of INSAR data to operational users in the Russian Federation, and the final goal is to support natural exploration, maritime operations and environmental protection in the extreme North of Russia with reliable up-to-date hydrographic information in the form of a regional coastal reference database (RECORD). At this stage, main emphasis has been put on methodological aspects, and major attention was paid to the following specific objectives:

- designing and testing new methodological variants using ERS-1/2-INSAR data for the reliable spatial modelling of coastal tracts of land and detection of ice-shore changes in the Russian Arctic;
- optimisation of available algorithms for the glacier motion estimation and variational analysis of ice velocities using differential interferometry (DINSAR);
- accuracy analysis and investigation of modelling errors; demonstrations of INSAR/DINSAR practical applications to coastal hydrographic monitoring in the Russian Arctic.

Specific science questions related to main trends in ocean-land interactions will be considered as well, especially with reference to their impact on the natural exploration and socio-economic activity in the study region. Essential bathymetric studies are without the scope of this research. Seven ERS-1/2-INSAR tandem image pairs taken over the Franz Josef Land archipelago (FJL) in autumn and winter 1995 have been selected for our detailed methodological tests and practical demonstrations / illustrations. Image processing had been accomplished using the ADOBE 5.0, ENVI 3.0 and RSG 3.21 software packages. At the moment of writing this paper, we had no results of investigations from other regions in the WeRA.

2. GEOGRAPHIC DEFINITIONS AND UNKNOWNS

The general and specific objectives pursued in the present research are devoted to satellite monitoring of hydrographic changes along Russian Arctic coasts and the subject of our research is related with spatial relationships and functional interdependencies between principal components of the Arctic coastal hydrographic system including such elements as land, glacier and sea ice, inland water basins and the sea (Figure 1). In the Franz Josef Land archipelago, each island represents a typical example of such system and, thus, falls entirely in the category of coastal hydrography. In this context, it is worth to note that all previous extensive terrestrial surveys in FJL including third-order triangulation and levelling, erection of geodetic and navigational signals, establishment of benchmarks and tide-gauge observations were performed in 1954-1960 by the No.10 expedition of the Hydrographic enterprise of St.- Petersburg.

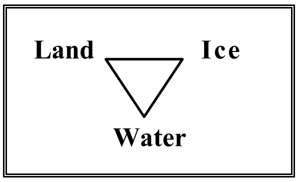

Figure 1. Arctic coastal hydrographic system (central part of FJL)

Coastal hydrography refers to a scientific discipline dealing with mapping of seashores and studying the properties of coastal waters with special reference to their use by man (Geographic Encyclopaedic Dictionary 1988). *Coastal hydrographic monitoring* is accordingly defined as a systematic hydrographic survey of a concrete coastal area, portions of the shore or separate water bodies ashore aimed at the detection, analysis, forecast and documentary description of actual and potential hydrographic changes. In general, a *hydrographic survey* consists of two operations: determining the horizontal co-ordinates of points on the surface of the body of water (position fixing) and determining the water's depth at those points. However, limited possibilities of radar remote sensing usually do not allow for the direct investigation of submarine objects even in shoal areas. In this research, shorelines and their changes were the only hydrographic features studied in detail. Some related phenomena providing ancillary information indicative of changes in coastlines, such as glacier ice motion, distribution of fast sea ice, wave action, tides and other effects accessible for radar observations are of interest as well.

In FJL, the total length of seashores makes up 4,460 km and the ice shore extends over 2,650 km, which is 59,4% of the total coastline. Calving fronts of outlet glaciers stretch for 1570 km, so that more than half of the ice shore is represented as uncertain coastline (by dashed lines) in contemporary maps (Atlas of the Arctic 1985). Cliffed rocky shores and gently sloping sand-clayey coasts are dominant among ice-free shorelines. Both, ice shores and sand-clayey coastlines are presently undergoing significant spatial changes due to the impact of sun, wind and water.

The largest coastal changes, amounting to several kilometres across the shore, have been recorded at fronts of several outlet glaciers (Kloster & Spring 1993, Sharov 1998). The most drastic retreat of ice shores caused by marine abrasion and calving was detected to be 2-4 km at Rough Bay in the southern part of Hall Island. While most outlet glaciers in FJL show rapid withdrawal of their frontier parts during the past decades, several largest tidewater glaciers, e.g. Impetuous, Eastern, Karo et al., have advanced offshore by several hundreds of meters and more. Even in summer, the upper surface of large outlet glaciers is largely covered by snow and is quite homogeneous excepting heavily crevassed zones at the front part of some fast moving tongues (Figure 1).

The number of large icebergs in surrounding seawaters is not constant and varies from year to year, thus, reflecting the glacier-ice flow instability, which is scarcely studied. There are extremely few data on the ice flow velocities and thickness of insular ice masses (Grosswald et al. 1973). In interior parts of large ice caps, the glacier motion was published to be less than 1 cm/day. Ice velocities of outlet glaciers were previously determined at several islands, e.g. Hooker, Hayes and Rudolph islands, as being 10 - 40 cm/day, but practically nothing is known about glacier velocities and their variations in other parts of the archipelago. The lack of reliable knowledge on glacial dynamics renders change interpretation extremely difficult and the character of the ice-shore evolution in FJL is not fully understood at present.

All sandy shores in FJL are composed of permanently frozen ground, and some portions of them rest on the subsurface ice layers. The largest deposit of fossil ice is revealed on Hall Island in the south-eastern part of FJL (Atlas of the Arctic 1985). The thickness of upper layer of frozen sediments that were deposited on the ice surface is not large here. Our field observations at Lake Cape showed that it does not exceed several meters. Such coasts are subjected to spatial changes because of the eustatic sea-level rise, wave action, fluvial sedimentation, thawing permafrost and melting of fossil ice. The rate of freeze-thaw disintegration and marine erosion of such shores increases due to the current climate warming in the Arctic. Many islands are known throughout the Russian Arctic, e.g. Dashka, Diomid and Mostakh, Semyonovskiy and Vasil'evskiy islands etc., which have become much smaller or even totally disappeared because of marine erosion. It was reported that coast recession is in progress on 30% of the Barents Sea coastline and the rate of coastal erosion reaches 5-6 m/year at lower altitudes (Bird 1984).

A plentiful supply of sediment from disintegrated shores raises the sea bottom just offshore. This effect was proven by crew of the Dal'nie Zelentsy research vessel, which grounded on unknown bank close to Lake Cape with the real depth of 5 meters instead of 8 m given in navigational charts (Korsun, personal communication 1994). At this cape we detected photogrammetrically the coast retreat of 80 – 100 m having occurred in the course of the past 45 years. This is the only fact known to us about present rates of coast recession in FJL.

Several counteractive processes operate simultaneously in this region, namely the eustatic rise of the sea level, regional glacio-isostatic uplift as well as swaying tectonic movements, which are typical of a litospheric platform, and possibly seismic impacts. The evaluation of the relative intensity of these processes is technically difficult and, still, there is no sole point of view on the origin and typical rates of current vertical movements in the archipelago. Numerous marine terraces or so-called raised beaches spreading along the coast of FJL are considered important indicators of ancient shorelines and of relative sea-level changes in the region. A number of indirect studies have been made that attempt to interpret coastal changes in FJL by comparing the heights of marine terraces with the radiocarbon ages of the organic rests (bones, timbers, molluscan fauna) sampled on the surface of those terraces (Grosswald et al. 1973, Forman et al. 1995). These studies led to the conclusion that the earth's crust in that area had been subjected to geologically recent uplifts, although the terrace spectra, even of adjacent islands, sometimes were beyond correlation (Sharov 1997). The contemporary rate of uplift specified in different publications varies from 1-2 mm/year (Forman et al. 1996) to 3-4 mm/year (Matishov 1993).

Meanwhile, regression analysis of the data recorded during 1976-1991 at tide-gauge stations in Murmansk and Polyarnoe (Annual data...1971-1994) shows that the mean annual level of the southern Barents Sea rose for 10 cm in 16 years, i.e. 6.25 mm/year (Figure 2). Besides, our previous photogrammetric works and topographic-geodetic measurements performed at Lake Cape in 1994-1995 have clearly shown that this tract of land *subsided* for 70 cm in the past 40 years with respect to the mean level of the Barents Sea. Sandbars and wide tidal flats along the coast also indicate the downward movement of the land in this area. A large area of open water with broken ice floes has been recently discovered in an icy isthmus connecting Lake Cape to the main Hall Island (Sharov 1997). Field observations in June 1999 revealed the salinity of water and the occurrence of superficial current in this "opening" (marked with black arrow in Fig. 3), while other parts of coastal waters were totally covered with sea ice. Further thematic studies are needed in order to reliably interpret and classify all coastal changes in the area.

Lake Cape with the total area of 65 km² and the old geodetic pyramid established in the 1950-s on its tip (≈ 8 m a.s.l., Fig. 3, d), was chosen as the key site for our present methodological experiments. An area comprising the whole Hall Island with surrounding islands, such as Wilczek Land (western coast), Berghaus, Hayes, Komsomol'skie, McClintock (eastern part) and Newcomb islands was selected for regional experiments. It is 55 x 55 km² in size, i.e. totally within the single frame (No. 1953) of the ERS-1/2-SAR imagery. Several fragments from topographic maps and satellite imagery representing the study area and showing the location of the key site are given in Figure 3 a, b, d.

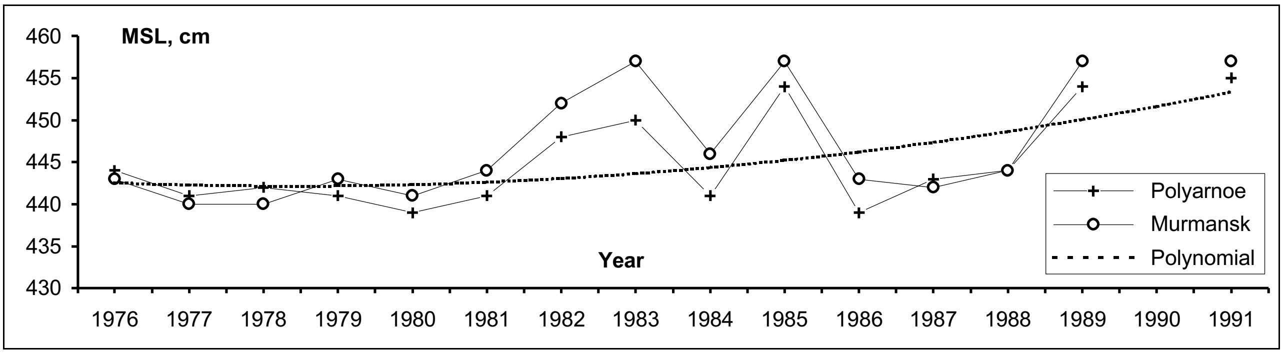

Figure 2. Annual changes of the Barents Sea level

3. METHODOLOGICAL SETTING

ALMAZ-1, the first civilian Russian satellite carrying high-resolution SAR was designed without polar interferometry in mind and did not pass over the High Arctic due to the restricted orbital inclination of 72°. The applicability of the INSAR data originated from other missions, such as RADARSAT-1-SAR (repeat cycle of 24 days, orbital inclination of 98.6°), JERS-1-SAR (44 days, 97.7°) or recent SRTM-SAR mission on board of the Space Shuttle orbiter Endeavour (single-pass, 57°), is also limited because of long repeat pass intervals or/and restricted orbital inclination. Thus, spaceborne high-resolution INSAR data over the whole Russian Arctic territory are provided solely by the ERS-1/2-SAR polar-orbiting missions (repeat pass interval of 1, 3 and more days, orbital inclination of 98.5°).

Although astonishing elevation accuracies of interferometric glacier modelling on the order of several meters have been reported (Joughin et al. 1996), further experiments have shown that those figures were too optimistic, and moderate estimates of typically 20 m for repeat-pass ERS-1/2-SAR interferometry and 10 m for single-pass SRTM-X-SAR interferometry were newly published (DLR 2000). Nevertheless, the presently achieved accuracy of polar interferometry is believed to be far away from the theoretically established limit. In this context, methodological imperfections in interferometric data processing are the principal causes for inaccuracies, which could and should be corrected before anything else.

In our case, one of the least perfected technological operations in INSAR data analysis is that of distinguishing between the impacts of glacier topography and ice motion on the interferometric phase. This procedure is essential to both, accurate topographic modelling of the glacier surface and measuring the velocity of glacial flow. Traditionally it is based on differencing between the original interferogram I_1 and the reference interferogram of the same area I_2, which, in ideal case, doesn't contain the phase term related to the ice motion and then is called topography-only interferogram I_{topo}.

Since movement is an inherent quality of any glacier, it is very problematic to find out the reliable reference model among original interferograms. Reference interferogram could be synthesised from available topographic maps. However, the accuracy of traditional stereoplotting in accumulation zones at large ice caps usually do not meet standard demands and vertical inaccuracies up to 15 meters are typical of contemporary topographic maps in FJL (Sharov 1998). Alternatively it was shown that, when the velocity field does not change with time, two original interferograms with *equal* temporal baselines can be differenced to cancel ice motion and, thus, obtain a topography-only interferogram (Joughin et al. 1996, Raggam & Sharov 1999).

Further, the subtraction of the resultant topography-only interferogram from one of original interferograms has been offered in (Kwok & Fahnestock 1996, Fatland & Lingle 1998) in order to extract the translation phase and to estimate the ice motion. Careful judgement on the correctness of such a procedure is beyond the scope of our paper, and we only like to present the general scheme of this approach, which can be given as

$$\begin{cases} I_1 - I_2 = I_{topo}, \ \mathit{if} \ V_1 = V_2 \, , \ T_1 = T_2 \, ; \\ I_2 - I_{topo} = I_{motion} \end{cases} \tag{1}$$

and leads to the paradoxal situation that appears as follows

$$\begin{cases} I_{motion} = I_2 - (I_1 - I_2) \overset{?}{\longleftrightarrow} 2I_2 - I_1 \\ \mathit{or\ even} \ \ I_{motion} = I_1 - (I_1 - I_2) \overset{?}{\longleftrightarrow} I_2 \, . \end{cases} \tag{2}$$

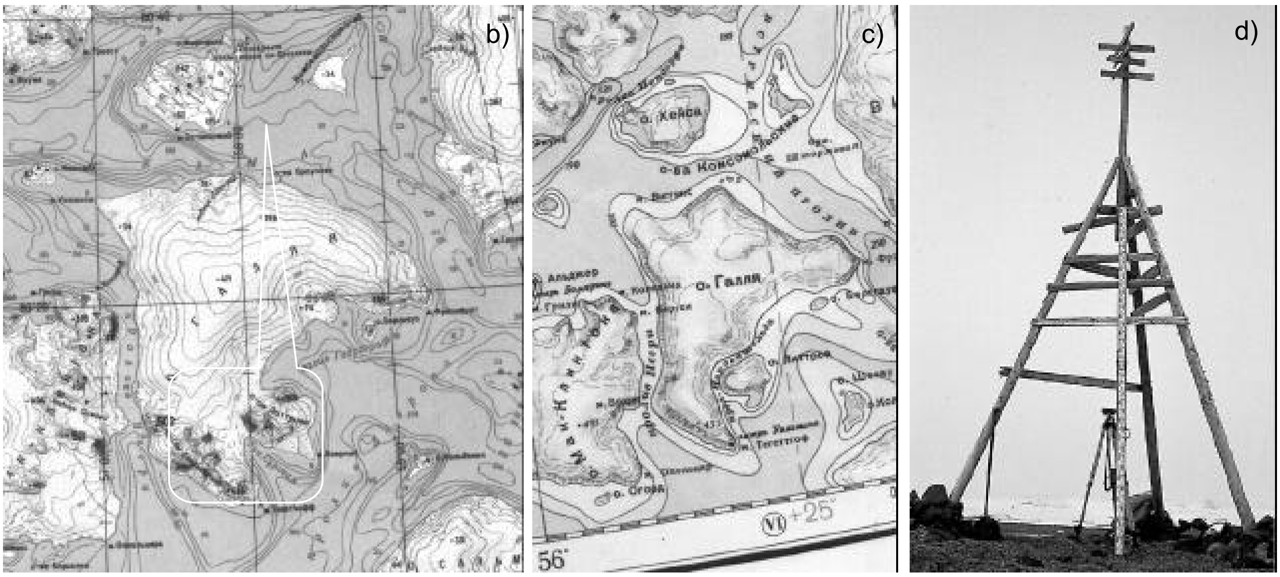

Figure 3. KATE-200 spaceborne photograph (a) and Russian topographic maps issued in 1971 (b) and 1944 (c) showing outlines of the study area and of the key site (in white frame); 45-year old geodetic pyramid at Lake Cape (d)

Phase anomalies, e.g. concentric fringe patterns or “bull-eyes”, are frequently observed in the I_{motion} differential interferograms generated in such a manner. Therefore, it was concluded that, in some cases, the constant-velocity assumption is not valid, i.e.

$V_1 \neq V_2$ (Fatland & Lingle 1998). Another explanation can be given of the is due to the fact that original interferograms are usually unwrapped and scaled before the combination in order to equalise spatial baselines and corresponding topographic phase terms (Kwok & Fahnestock 1996). In general, such scaling virtually violates the equality of temporal baselines, i.e. $T_1 \neq T_2$, which brings about additional difficulties in DINSAR data analysis (Kenyi et al. 1999). It should be reminded here that the rate of motion fringes does not depend on the spatial baseline, but only on the temporal baseline.

The combinatorial approach offered in (Raggam & Sharov 1999) provides a more flexible solution to DINSAR data processing in the Arctic that permits the contradiction between desirable temporal and spatial baselines of original interferograms to be resolved. The combination of interferograms is performed without previous phase unwrapping either before or after the "flat terrain phase" (FTP) correction is performed. This reduces the number of necessary operations and decreases the interferometric phase distortion caused by processing imperfections. In many cases, such an approach leads to the generation of a single-fringe interferogram of the glacier surface and, thus, lessens the perplexity of phase unwrapping.

Nevertheless, the combinatorial technique can not cope with the shortcomings inherent in traditional differential approach that are due to different weather conditions, physical changes of the glacier surface and variable penetration of radio waves into dry snow at instants *1* and *2*. In the past studies carried out in 1999 - 2000, we tried to overcome these methodological difficulties. The most recent and specific INSAR experiments, which resulted in several alternative and creative ideas on the precise modelling of ice shores and the ice-motion estimation without combining two different original interferograms, will be described in the next chapters.

4. SPECIFIC INSAR EXPERIMENTS IN FJL

To demonstrate the utility of INSAR data the following methodological examples using multi-look ERS-1/2-SAR interferograms were chosen:

- indirect estimation of the outlet-glacier motion in the solitary interferograms obtained over FJL in the cold season,
- generation and interpretation of INSAR gradient images,
- comparative analysis of results and accuracy control.

4.1 Ice-motion interpretation in single interferograms

There is a close interrelation between the state and dynamics of outlet glaciers on the one hand and sea-ice conditions in the FJL straits on the other. Fast coast ice covering all straits of the archipelago for most of the year locally undergoes the powerful action caused by moving body of an outlet glacier. Although the velocity of glacier-ice motion decreases in the cold season, any outlet glacier continues to move in winter and, thus, pushes coast ice away from the shore. In our test area, the thickness of sea ice attains usually 60 to 80 cm, but remains thin (20-40 cm) in the middle of Austrian and Markham sounds (Matishov 1993). Both, the resistance of sea ice to the glacier motion and the deformation of sea ice floes can be considered as negligible. Therefore, in the vicinity of the glacier snout and under calm weather conditions, the local horizontal velocity of the sea-ice motion (offshore) can be considered to be equal to the frontal velocity of gently sloping tongues of outlet glaciers.

Vast plane floes of one-year-old coast ice with very small elevation above the sea level represent an ideal surface for the interferometric analysis of both little horizontal and vertical hydrographic motions. Practically, there is no need in topographic reference in this case, and we decided to try the glacier motion estimation in single interferograms. So, we have acquired several ERS-1/2-INSAR image pairs obtained over the study area in the winter season with temporal span of 1 day (9/10 and 18/19 October, and 17/18 December 1995) under calm and cold weather with a relatively high atmospheric pressure and few clouds. All image pairs were subjected to standard interferometric processing including the FTP correction. Figure 4 represents some results of this processing.

The comparative interpretation of INSAR data shows the increasing concentration of fast sea ice in the FJL straits from insignificant in I_1 to intermediate in I_2 and full coverage in I_3. In I_2, coast ice floes, e.g. that marked with an arrow in Rough Bay, are not yet constrained and supported by shores from opposite sides and, thus, undergo swaying movements due to the wave action and tidal effects. The dates of 18/19 October and 17/18 December 1995 correspond to the nearly equal moon phase of 0.55/0.59 and 0.58/0.62 respectively (the third quarter). Therefore, it can be supposed that there were no strong tidal effects in FJL at those dates. In this context, we can speak about *tide-coordinated* INSAR data.

The I_1 image pair was taken when the moon phase was 0.94, i.e. several days after new moon (0.25 corresponds to full moon), and significant tides up to 30 cm might not be excluded. The I_1 interferogram represents some additional fringes in the flat marginal area of "ice bridges" between Hall Island and Littrow peninsula. We assume that these fringes are due to the local vertical movement caused by tidal effects. In different parts of ice bridges, the value of vertical displacement equals to 20 cm.

Very interesting motion features called "outflows" are to be observed offshore at fronts of active outlet glaciers in the I_3 fringe image. The direct influence of heavy winds, currents, melting, wave action on the local state of sea ice can be excluded, and the origin of outflows is believed to be related with the glacial flow. Our hypothesis seems to be true also because of the inverse interferometric contrast in opposite outflows, which is due to the direction of ice motion toward or away from the sensor. Each fringe in the outflow can be converted to a horizontal surface velocity in the range direction as

$$V_{ha} = \frac{\lambda}{2t \cdot \sin\theta}, \tag{3}$$

where $\lambda = 5.66$ cm is the wavelength, θ - incidence angle and $t = 1$ day is the temporal baseline of the interferogram.

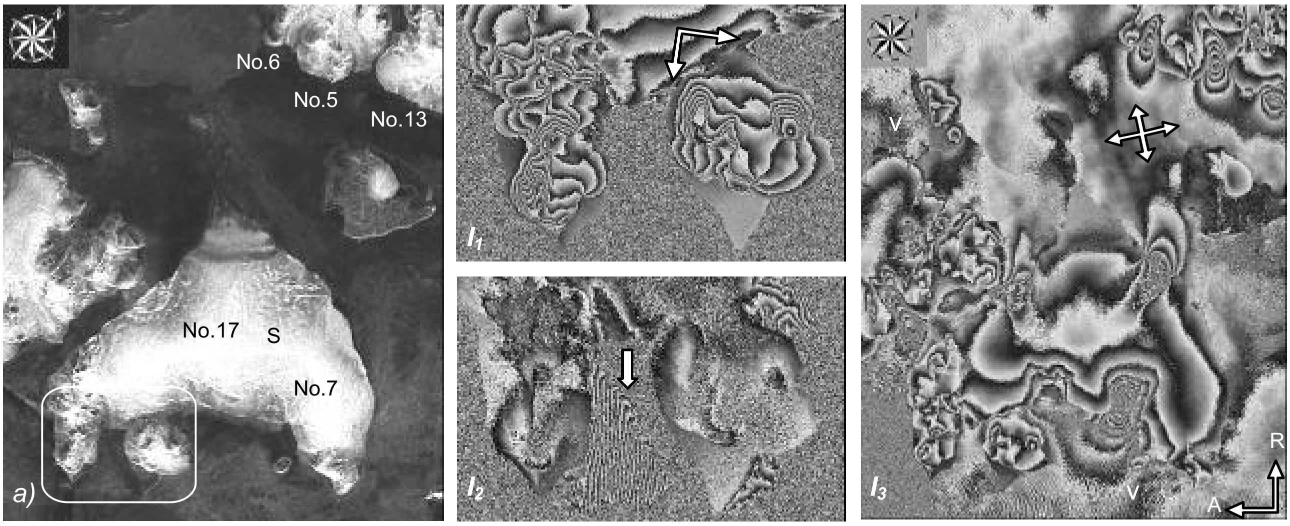

Figure 4. Amplitude image of 17/18 December 1995 showing the study area (*a*) and three different interferograms depicting the ice motion: I_1 - 9/10 October ($B_\perp = 129$ m) , I_2 - 18/19 October ($B_\perp = 18$ m) and I_3 - 17/18 December 1995 ($B_\perp = -43$ m)

The orientation of the most outlet glaciers in the study area coincides with the SAR-range direction and their daily velocities were directly determined as given in the next Table. According to our knowledge the velocities of those glaciers are determined for the first time in the history of explorations in FJL. Nevertheless, these results are in a good correspondence with the velocities of 14 – 41 cm/day obtained by other investigators during field measurements in other seasons and other parts of the archipelago (Grosswald et al. 1973).

Table 1. Daily velocities of several outlet glaciers (names are given in accordance with the Catalogue of Glaciers in FJL, 1965)

ISLAND	GLACIER	VELOCITY, cm/day	DATE
Champ	Outlet glaciers No. 5 and 6	32.6 and 21.7	17/18 December 1995
Hall	Sonklar Outlet Glacier, glacier No. 7 and glacier No. 17	30.2 , 47.4 and 18.9	17/18 December 1995
Salisbury	Eastern Outlet Glacier and outlet glacier No. 13	18.1 and 34.8	17/18 December 1995
Wilczek Land	Renown Outlet Glacier, outlet glacier No. 9	27.9 – 30.2, 36.2	18/19 October 1995

4.2 Generation and interpretation of gradient images

An original methodological stratagem has been offered for discriminating between topographic and motion fringes in single interferograms obtained over FJL in warmer seasons. This processing artifice is based on the fact that the INSAR scheme is much more sensitive to glacier displacements than to the relief of the glacier surface. Due to the relatively flat topography of ice caps and rather high velocities of glacial flow along the outlet channels, the rate of motion fringes in the interferential picture is usually much higher than that of topographic fringes. Thus, topographic fringes can be associated with low-frequency components, while motion fringes can be related with high-frequency information in the interferogram.

At simplest, discriminating between low and high-frequency components in the interferogram can be achieved in the spatial (image) domain by a differentiation process, which emphasises the high-frequency components and partly or completely attenuates low-frequency information. The most commonly used method of differentiation in single-image processing applications is the gradient, which is typically approximated as follows (Gonzales & Wintz 1987)

$$G_+[f(x,y)] \cong |\, f(x,y) - f(x+1,y)| + |\, f(x,y) - f(x,y+1)|, \tag{4}$$

i.e. the value of the gradient is assumed to be proportional to the difference in grey level between adjacent pixels.

Our practical experiments with multi-look interferograms have confirmed that even *partial gradient*, i.e. the linear combination of an interferential picture with a translated version of the same interferogram given by

$$G_r[f(x,y)] \cong \left| f(x,y) - f(x, y+\delta_y) \right|, \tag{5}$$

where $0 < \delta_y \leq 5$ pixels - is the real number denoting the value of translation in the range direction, can be useful for the representation of glacier terrain and for the glacier-motion detection. Nevertheless, the best results were achieved with a *cross-gradient* using cross-differences as

$$G_\times[f(x,y)] \cong \left| f(x,y) - f(x+\delta_x, y+\delta_y) \right| + \left| f(x+\delta_x, y) - f(x, y+\delta_y) \right|, \tag{6}$$

which provides nearly complete removal of topographic fringes and preserves the secondary motion-fringes within the area of rapid glacial flow. The operations (5) and (6) can be applied to the processing of both multi-look and single-look interferograms either before or after the FTP correction is performed. Figure 5 shows several interferential pictures and *gradient images* illustrating this approach.

The resultant multi-look gradient image shown in Figure 5, b) resembles a single-fringe interferogram, which provides a realistic view of the terrain and can be unambiguously related to topographic height on a pixel-by-pixel basis. Therefore, it is sometimes referred to as *topogram*. In such a topogram nearly all outlet glaciers are reproduced with a particular wrinkled texture and thus can be reliably detected and delineated. Extensive landforms with the relief amplitude of 20 m and higher are also well detectable in such products. We could even recognise hummocky ice floes (marked with **V** in Figure 4, I_3) as well as marine terraces with the height of 10 m at best. Several huge crevasses at Hydrographers, Moscow and Vostock-1 ice domes with the width reaching up to 300 m were revealed in other topograms. The topogram is useful for the general overview of the terrain. The structural elements of the ground surface, e.g. highest positions, coastlines etc., primarily detected and measured in the resultant topogram can be used for the spatial baseline estimation and for the control of unwrapping errors (Brandstätter & Sharov 2000).

Figure 5, c) represents the cross-gradient image obtained from the original interferogram of 3/4 September 1995 (I_4) without previous FTP correction. Topographic fringes are completely attenuated. Nevertheless, the system of secondary fringes can be seen within several glacier valleys, e.g. those of Simony Glacier and outlet glacier No.18 at McClintock Island (marked with **v**). The lateral parts of fast moving outlet glaciers characterised by very high rate of interferometric fringes could not be reliably reproduced in our multi-look gradient images due to the limited spatial resolution and aliasing effects. The visibility of secondary fringes depends on the glacier orientation and can be enhanced by manipulating the shift value separately in azimuth and range direction. The width of secondary fringes reaches 500 meters that can not be explained by the relief influence. Thus, these fringes were interpreted as motion fringes since we had no other reliable explanation at hand.

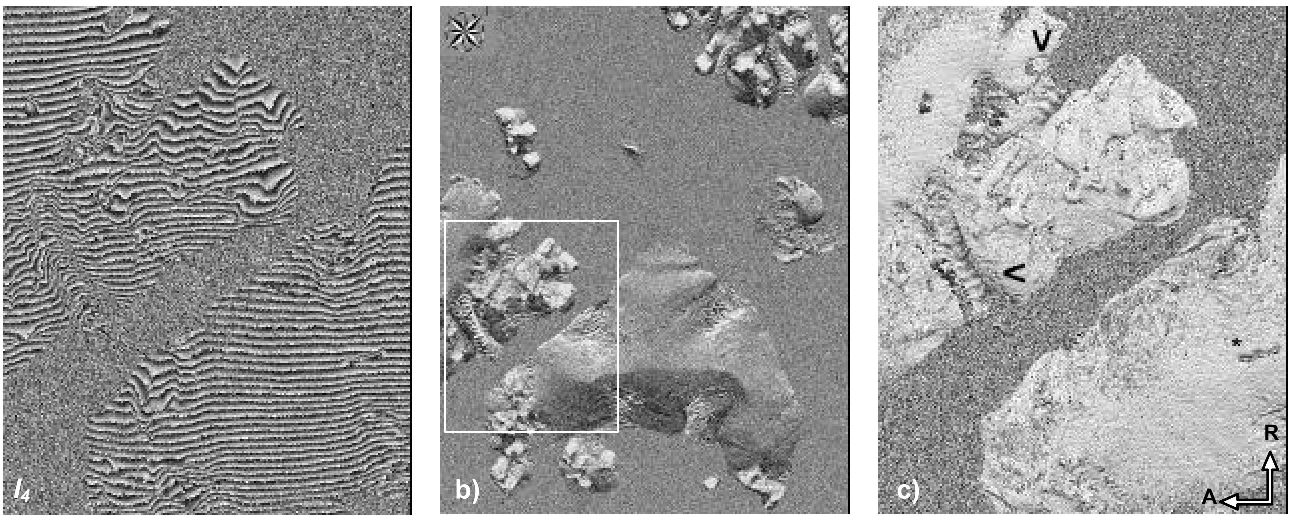

Figure 5. Fragments from the original interferogram of 3/4 September 1995 (I_4 , $B_\perp$ = - 50 m) and gradient images: partial gradient of the fringe image of 3/4 September 1995 (b); cross-gradient of the original interferogram of 3/4 September 1995 (c)

Simplified graphical example illustrating the technical origin of secondary motion-fringes is given in Figure 6. In this figure, topographic and motion fringes are represented as saw-functions of different frequency. The shift value δ determines the fringe contrast in the resultant gradient image; fringe contrast increases with the shift. However, δ might not be infinitely large because of intermodulation effects, which became dominant when $\delta_{x,y}$ exceeded the half of motion fringe. In our case,

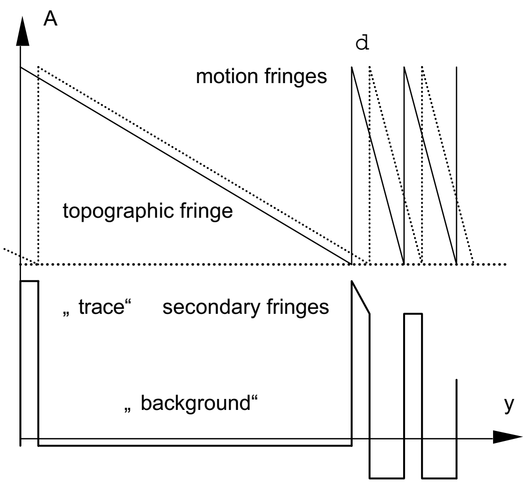

Figure 6. Graphical explanation on the origin of secondary fringes in the gradient image

the shift was determined empirically for each interferogram so that its value was much smaller than a typical width of topographic fringes and made up 10 to 50 % of the expected width of motion fringes. The rate of motion fringes remains unaltered, when the shift value δ is changed within these limits. If we assume no surface relief, the rate of secondary motion fringes is equal to that of original fringes. Narrow "traces" from the edges of fringes can be seen in our gradient images; their effect, however, is not so prominent as it was in the case of combinatorial DINSAR (Raggam & Sharov 1999).

The reliable algorithm for converting secondary motion fringes to the glacier-velocity field has yet to be developed, but, nevertheless, we think that the present methodological results could serve as an important aid to the INSAR data analysis. The proper linear combination of original interferograms always results in a new interferogram, which means that some stratagems of interferometric analysis could be directly applied to further processing of the gradient image. The concept of *phase shifting by translation* (Fleet et al. 1991) could provide valuable information essential to understanding the problem.

4.3 Comparative analysis of results and accuracy control

As has been already mentioned, winter velocities of glacier motion in the study area are practically unknown. No physical measurements of the glacier motion have yet been achieved in the study area. Therefore, we had to compare the ice-motion velocities determined by different methods from different SAR data in order to verify the results obtained.

Careful comparison between the gradient images obtained from original interferograms of 17/18 December 1995 (I_3, $B_\perp$= - 43 m), 3/4 September 1995 (I_4, $B_\perp$ = - 50 m) and 8/9 October 1995 (I_5, $B_\perp$ = 129 m) has shown that, although the rate of secondary fringes decreases slightly in the winter image (I_3), it remains very similar in different interferograms in spite of quite different spatial baselines. This fact provides an additional evidence for the motion origin of the secondary fringes in gradient images. Alike, though not identical, motion features could be traced over all glaciers in different gradient images of the study area. Therefore, we have concluded on the resemblance of the general character of ice motion along large outlet glaciers in FJL in different seasons.

The methodological accuracy of our interferometric determinations was verified by comparing the winter interferogram I_3 with its cross-gradient image The comparison has revealed that the rate of secondary fringes ashore (Figure 5, c) more or less corresponds to the rate of motion fringes offshore (Figure 4, I_3). At 12 check-glaciers situated within the study area, the mean difference between the numbers of motion fringes ashore and offshore was estimated at - 0.5 and the rms. difference was given as ± 1.8, i.e. about 13 cm/day. Apart from methodological imperfections, this difference can be explained by different velocities in different parts of the glacier surface. These results seem to indicate that both methodological variants for the glacier-motion estimation in single interferograms can provide comparable accuracy.

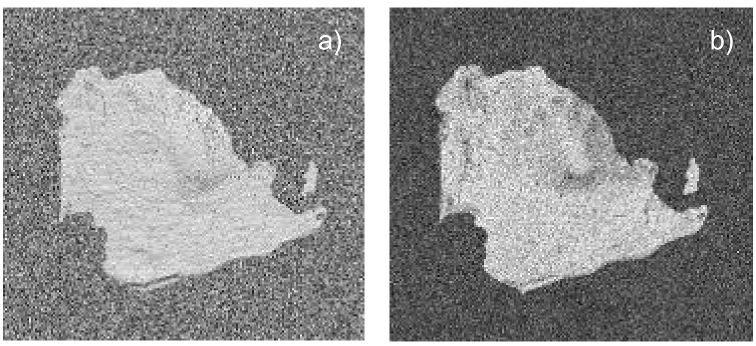

Figure 7. Cross-gradient (a) and coherency (b) images of Hayes Island

It would be also interesting to compare our results with the results obtained by the traditional DINSAR method making use of the reference interferogram synthesised from available topographic maps. The comparison with the coherency tracking technique offered in (Derauw 1999) is considered to be very expedient as well. We plan to carry out such experiments in the nearest future.

In gradient images, the shoreline even of small islets is well detectable (Fig. 7, a) and we think that, in some cases, the automatic delineation of coastlines can be performed with better accuracy than in coherency images (Figure 7, b), especially in the area of glacier fronts. Contemporary ground control data are needed for the absolute estimation of planimetric and tachometric accuracies of interferometric measurements in the dynamic glacial environment of Franz Josef Land. The best control could be obtained through the field surveys planned for the next summer 2001.

5. CONCLUSIONS

Two original alternative techniques have been offered for the precise modelling of ice shores and the glacier-motion estimation in the Western Russian Arctic using ERS-1/2-INSAR data. Speed and simplicity of implementation are important features of the proposed techniques, which make use of single SAR interferograms and do not require additionally the topographic reference model. Both techniques do not involve complex processing artifices in the Fourier domain.

Transferential approach to the glacier-motion estimation consists in measuring the translation of fast coast ice caused by the glacier flow. In this case, INSAR data have to be obtained in the cold period characterised by the smallest tidal effects, continuous cover of sea ice and negligible melting. Particular *differential* approach is based on analysing gradient images of single interferograms and can be applied to the interpretation of the interferograms obtained in different seasons.

In both cases the interferometric phase unwrapping and the co-registration of original interferograms being the most complex operations of INSAR data processing have been avoided. Thus, the influence of processing imperfections has been reduced. Spatial resolution of the original interferogram is preserved and even subtle detail of the shoreline is retained in the resultant topogram. Moreover, fewer additional *a priori* assumptions have to be made on the character of glacier motion and glacier topography. The results obtained by different techniques were in good correspondence and it has been concluded that both methodological variants for the glacier-motion estimation in single interferograms can provide comparable accuracies.

Still, we have no ready solution to the ice-motion estimation on glaciers, which are parallel to the satellite path. Both, very fast (more than 1000 cm/day) and slow (less than 1 cm/day) motions could not be reliably detected due to the limited temporal baseline of INSAR data, coherency-related phase noise and aliasing errors. Particular problems arise owing to the penetration of the radar signal into dry snow and mixed backscatter from snow and internal ice layers. Nevertheless, both stratagems are believed to be a very reasonable alternative to standard DINSAR techniques, which could provide a solid methodological foundation for the resultful work in the AMETHYST Project and for the other applications related with the INSAR data analysis.

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