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Multi-pass interferometry for studies of glacier dynamics

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Abstract

This paper presents recent results from the ESA Tandem Announcement of Opportunity study 'An Investigation of the Utility of ERS SAR Data for Studies of Glacier Dynamics.' The study is conducted by the Danish Center for Remote Sensing in collaboration with the Danish Polar Center.
A key element in the study is multi-baseline repeat track interferometry (RTI), which potentially can be used to measure both velocities and the micro topography of glaciers. A primary test site has been established on the Storstrømmen Glacier in North-East Greenland. Tandem ERS data acquired in August - December 1995 covering the glacier have been investigated. DCRS has acquired complementary airborne RTI data over the glacier in August of 1994 and RTI as well as single-pass interferometry (XTI) data in August of 1995. In-situ measurements including repeated positioning of poles as well as deployments of corner reflectors were performed by the Danish Polar Center.

Keywords: SAR, Interferometry, Glacier, ERS, EMISAR

Introduction

This article describes work performed in connection with the ERS Announcement of Opportunity study 'An investigation of the utility of ERS SAR data for studies of glaciers dynamics.' The focus is on glaciers in north-east Greenland which are important as the dynamics and mass balance of glaciers in that region is not well understood. Recent studies indicates that the major outlet glacier Storstrømmen has a surge like behavior with a 70 years period (Reeh, *et al*., 1994), and thus extrapolations of observations performed within a short period of time should be interpreted with care as the natural variability of the extend and thickness of some glaciers might be large. Also the mass balance of the north-eastern region of Greenland has great interest as 20 km3/y of ice cannot be accounted for in present models. Possible explanations are that the ice-sheet is growing thicker, or the ice is removed by some unmodelled drain such as melting at bottom of large floating glaciers, (Reeh, 1993).

The AO study augments on-going experiments with the airborne polarimetric and interferometric EMISAR, (Christensen *et. al.* , 1996), (Madsen *et. al.*, 1996), operated by the Danish Center for Remote Sensing (DCRS) and intensive field work in north east Greenland conducted by the Danish Polar Center (DPC) and the Alfred Wegener Institute. Questions addressed includes

Can multi-baseline interferometric SAR data provide useful measurements of glacier dynamics?
Can satellite SAR data (interferometric or not) be utilized to spatially and temporally interpolate results from localized studies involving high resolution airborne SAR and extensive ground truth programmes?

This paper describes the on-going work at Storstrømmen, recent results from the decomposition of ERS tandem interferograms into displacement and topography, and discuss the limitations of the products generated with interferometric techniques.

Experiments on Storstrømmen

The Danish Polar Center in collaboration with the Alfred Wegener Institute has performed field work on Storstrømmen in the field seasons 1989ñ1995, (Reeh *et al*., 1994). The work included collection of surface velocity and height data by repeated GPS positioning of stakes. Mean velocities during time periods spanning from 2 to 30 years have also been measured by surveys of lake ridges. Between 700 and 1000 m a.s.l. a large number of lakes are located in stationary surface depressions. Each year a ridge is formed, and thus the velocity can be estimated by measuring the distance between the ridges. Velocities and ice margins have also been derived from aerial photographs taken in 1963 and 1978. In all seasons meteorological data were collected.

In 1994 and 1995 DCRS acquired EMISAR radar data from a 10 km (NS) by 30 km (EW) test field on the lower part of the glacier. In 1994 Cband repeat track interferometric (RTI) and Cband polarimetric data were collected on a one day mission. In 1995 Lband RTI data, Cband topographic across track interferometric (XTI) data and Lband polarimetric data were acquired on two consecutive days. Compared to the one day mission in 1994 where the maximum temporal baseline achieved was on the order of two hours, the one day baseline of the 1995 data greatly enhance the chance of getting useful velocities from the RTI data.

In 1994 corner reflectors were deployed by DPC. Two on the bedrock to the West of Storstrømmen on Dronning Louise Land and two on the semi-nunatak near the Eastern ice margin. The positions of the reflectors, serving as reference points for the radar observations, were surveyed by GPS in 1994 as well as in 1995.

Other data such as surface elevations along profiles collected in collaboration with the Greenland Ice Core Programme (GRIP) are also available.

Importance of interferometric measurements of topography and velocity of glaciers

Topography and velocities can potentially be derived from multi pass interferometric SAR, (Massonnet *et. al.*, 1993), (Goldstein *et. al*., 1993), (Kwok and Fahnestock, 1996). On a point by point basis, the accuracy of field measurements is generally much better than the corresponding interferometric SAR measurement. However, the interferometric measurement has a lot of advantages, the most important being:

Imaging capability, - providing spatial measurements on a dense regular net.
Global availability, - since satellites usually covers most of the Earth. This makes regional or even global studies feasible.
Temporal availability, - as the measurements are usually repeated within a short time interval (days to months). However, the life time of a satellite is short (some years), but occasionally a series of similar satellites is launched.

The imaging capability enables studies not possible solely with the sparse amount of insitu measurements usually available. Valuable input for further studies is a DEM and a velocity map, enabling a direct modeling of the dynamics and mass balance of a glacier. It is important to note that for glaciers and icesheets a velocity map is an unavoidable product when generating a DEM, since glaciers in general is moving or deforming. The required accuracy of DEMís for different applications is summarized by Zebker *et. al.* (1994).

Recent results from ERS Tandem Data

We have presently received five descending ERS tandem data sets covering the glacier Storstrømmen from ESA. Two pairs from late October and early December 1995, with good coherence and favorable spatial baselines, were selected for further investigation. The data cover a 100 km by 200 km region around Storstrømmen as two frames were merged before processing. The basic processing includes:

- CEOS header reading.
- Cleaning (missing lines, SWST changes etc.) and merging of raw data.
- Doppler estimation.
- Processing to single look complex imagery, (common reference line).
- Estimation of interferometric baseline by cross correlation of small image patches.
- Interferogram formation and multi-looking.
- Unwrapping.

At present a simple decomposition procedure is utilized. First the baseline in each interferogram is tuned separately using tie-points. Secondly the phase is decomposed into displacement and topography. The displacement is converted from a slant range displacement to an equivalent horizontal velocity towards the radar, see figure 1. In figure 2, the corresponding topography map is shown. Note that both images are in slant range projection and have been spatially averaged in order to ease the electronically publishing. Note that north is up to the left and that the satellites were flying down the right side of the figures as they are shown here.

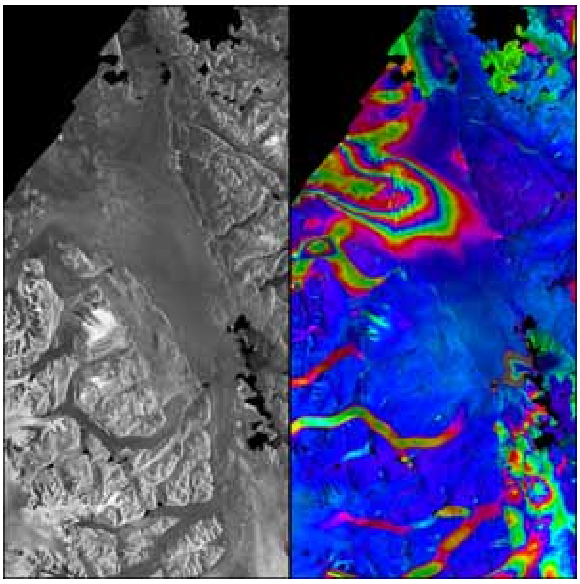

Figure 1. Equivalent horizontal velocity towards the radar of Storstrømmen, NorthEast Greenland (right) magnitude image (left). One color cycle is 100 m/y, blue is 0 m/y, red is +30 m/y, green +60 m/y etc. Data: ERS1/2.SAR.RAW. Acquired: 951028 - 951203. Processed: 960906. Track: 382. Frame: 2025+2043. Number of looks: 20.

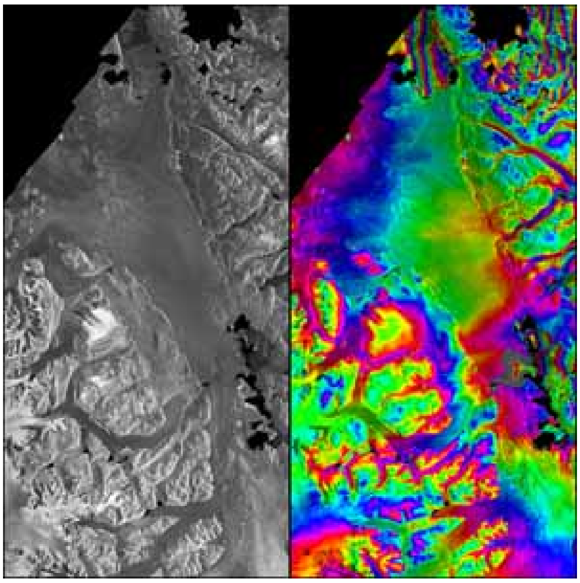

Figure 2. Surface height of Storstrømmen, NorthEast Greenland (right), magnitude image (left). One color cycle is 1000 m, red is 0, green is +300 m, blue +600 m etc. Data: ERS1/2.SAR.RAW. Acquired: 951028 - 951203. Processed: 960906. Track: 382. Frame: 2025+2043. Number of looks: 20.

The accuracy of the velocity map shown in Figure 1 is easily evaluated, as rocks are present throughout the image. The worst case velocity error is 10 m/y of which at most half can be linked to residual topography. The remaining uncertainty seems to be caused by some low frequency undulations of the phase in one of the interferograms. Those undulations corresponds to 0.5 cm variation in the path length which might be caused by changes in the delay in the troposphere.

In the upper right corner of the velocity map some regular shaped artifacts are seen in the mountains. Those are caused by unwrapping errors. Fortunately unwrapping errors are most unlikely to appear on the ice (at least in areas with good coherence). On the other hand unwrapping errors also cause errors in the topographic products. In areas with steep mountains, those errors will require operator interaction to be identified and corrected.

The quality of the topographic map is not sufficient for most applications. The reason is the short spatial baselines of approximately 20 m and 2 m. This implies that baseline uncertainties and path length changes due to tropospheric delays scale the errors to much more than with a baseline of some hundreds of meters optimal for topographic mapping.

A second reason for the large uncertainties in the topographic data is the quality of the tie-points. A major limitation with the present method is the identification of tie-points on a map. The exact horizontal position of stationary points (mountains) is difficult to identify in the interferograms and since the mountains typically are steep, this translates into a height error on the tie-point.

A possible improvement is to enhance the tie-pointing method, or probably better, to develop software for utilization of the coarse DEMís available for the area. On-going work is also to utilize the Precision Orbit Data (PRC) from the D-PAF. This will ease the generation of interferograms as the processor (originally developed for airborne SAR) allows focusing of the raw data to a common reference line. This will also simplify the geocoding since the PRC data are in a common earth body fixed reference system.

Limitations on ERS Interferometry

Space borne SAR interferometry is a promising technique, that has already proven useful for generation of input to models of glacier dynamics. However, some limitations apply depending on the application. In the following the most important limitations are addressed.

Temporal decorrelation and phase unwrapping

As reported in virtually all previous work on satellite interferometry, temporal decorrelation pose a significant problem as it corrupts the phase measurement and eventually prevents phase unwrapping. For arctic regions the most likely causes are surface melting when the temperature exceeds 0 C, and changes in the surface caused by precipitation. The five tandem pairs analyzed in this study have exhibited correlations reaching from zero to nearly one, see table 1.

Date	Track	Bper[m]	Corr.ñIce	Corr.ñRock	Orbits [E1/E2]
July 31, 1995	110	-14	0.20-0.50	0.95	21140/01467
Sep. 4, 1995	110	55	0.40-0.70	0.95	21641/01968
Sep. 24, 1995	382	-112	0.10-0.60	0.85	21913/02240
Oct. 29, 1995	382	-21	0.90	0.95	22414/02741
Dec. 3, 1995	382	1	0.65-0.95	0.70-0.95	22915/03242

Table 1. Baselines and correlations for processed images. Baselines are estimated from the data. Correlations are typical values. All data sets are 1-day repeat ERS-1/2 tandem pairs, frame 2025+2043 (100 km x 200 km).

We have only been able to unwrap a reasonable large area in two (Oct. and Dec.) of those five interferograms.

The solution to the decorrelation problem seems to be to avoid data from periods with significant surface melting, and to acquire/process more than one data set of each area of interest, in order to maximize the chance of getting data from a period without excessive precipitation (or other processes changing the surface such as strong winds).

Baseline estimation

Even with multiple baseline interferometry the full set of baseline parameters can not be estimated directly from the data. The relative distances between the satellite tracks can in principle be estimated, but there is no mean for distinguishing a common mode rotation of the baseline angles from a tilt in the landscape.

In areas with mountains or other stationary features the remaining baseline parameters can be estimated by means of a DEM (available for most of Greenland) or by some other reference points for instance obtained with altimetry. If no tie-points are available it might be considered to utilize ascending and descending orbit data of the same area to remove the tilt as described by (Malliot, 1996).

Another uncertainty almost indistinguishable from baseline uncertainties is drift in the carrier. Massonet (1995) observed that a frequency drift caused several fringes in the azimuth direction over a few frames of ERS-1 data. This implies that not only the modulo 2*pi uncertainty from the phase unwrapping need to be estimated, but also the fractional value of the absolute phase.

Tropospheric effects

Path length changes caused by changes in the troposphere have previously been reported, (Goldstein, 1995:) and (Massonet, 1995). Such path length changes of up to some wavelengths create artifacts in the interferograms only distinguishable from real features if multiple interferograms from the same area are available. This implies that for generation of reliable products of unknown regions, multiple interferograms (and data acquisitions) are necessary.

In one of the two interferograms used above some artifacts are observed which we believe are due to tropospheric changes. A magnitude image, an interferogram and a correlation image of a window of the Oct. 29, 1995 data set are shown in figures 3, 4 and 5 respectively. The images cover approximately 40 km by 30 km of the lower part of Storstrømmen and Bistrup Bræ.

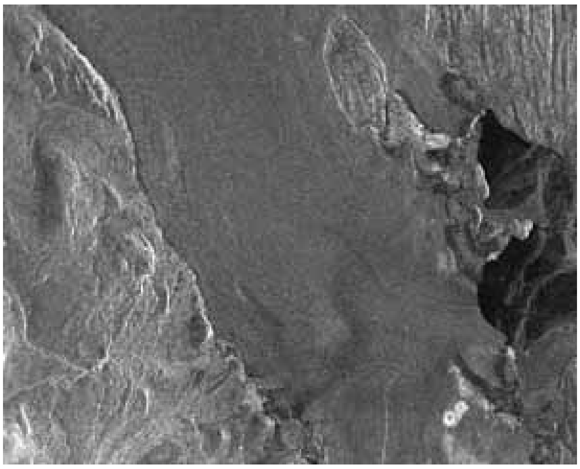

Figure 3. Magnitude of a 40 km by 30 km window in the Oct. 29, 1995 interferogram.

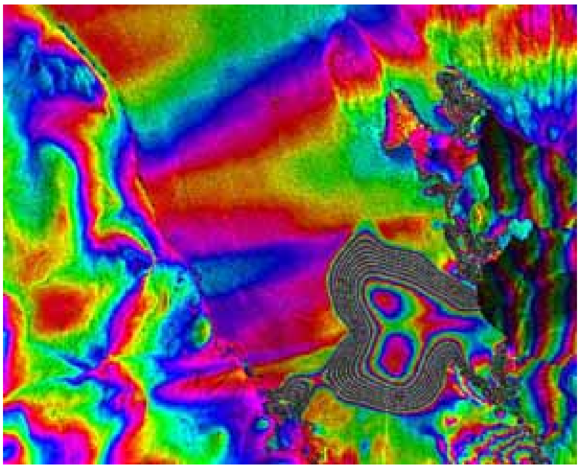

Figure 4. A 40 km by 30 km window in the Oct. 29, 1995 interferogram.

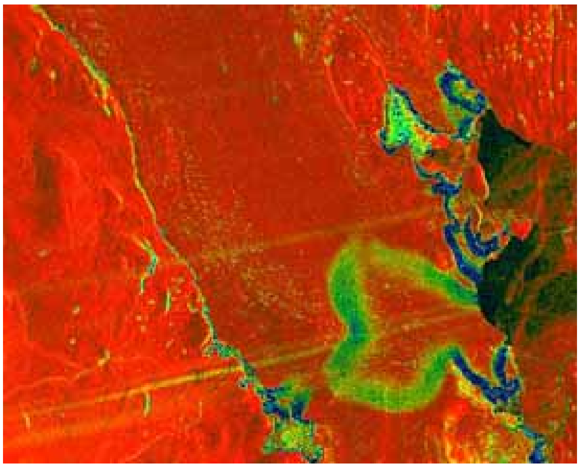

Figure 5. Coherence of a 40 km by 30 km window in the Oct. 29, 1995 interferogram.

A phenomenon which we have not been able to explain is observed on the flat part of the glacier just south of the semi-nunatak. As the ambiguity height is approximately 500 m, the one fringe deep pattern cannot be caused by topography as the topographic changes on that part of the glacier are much smaller. Neither can it be due to motion as the pattern extends into the stationary mountains. Note also that the in-situ measurements in 1995 have shown that the actual glacier motion presently is a few meters per year.

In the same region of the image some streaks are observed in the correlation image. A closer examination of the streaks will show that they are not exactly aligned with the above mentioned phenomenon observed in the phase image. The cause of the streaks in the correlation image is presently not understood, and we do not even know whether they are caused by sensor effects or a geophysical phenomenon.

Ascending orbit data

Only the line of sight motion can be determined by interferometric measurements, thus descending orbit data alone can at most give a 1-D velocity measurement. The line of sight motion can simply be projected onto the glacier surface, taking the local slope (also available from multi-pass interferometry) into account. This approach will leave a minor bias (which can be modeled), as the velocity vectors in general points into the glacier in the accumulation zone and out of the glacier in the ablation zone. This is, however, a tiny effect.

An intrinsic limitation on interferometric measurements is that no information can be derived on the displacements parallel to the flight direction. In large parts of the central ice sheet the 2-D pattern might be modeled utilizing the local slope. However, the behavior of glaciers in the marginal zones is much more complicated. It is not a valid assumption that the flow direction can be derived from the direction of the local slope. As demonstrated on Storstrømmen it is neither valid to assume that the flow is stationary, as the glacier might grow thicker in some areas and thin in others. In general, mass-balance studies are difficult without a 2-D pattern, as it is impossible to extract bottom melting, runoff, ice build up etc. if the flow divergence is unknown.

Another important issue is validation of the developed models of ice dynamics. Multi pass interferometry from different angles giving 2-D velocity maps clearly has the potential for improving present modeling techniques.

An obvious solution is to acquire data from different track headings such as for instance descending and ascending orbits.

Tidal effects

A significant problem related to the extraction of the 2-D velocity pattern is that tidal uplift of the floating parts of glaciers corrupts the decomposition of the displacement into two horizontal components. Furthermore, the decomposition of the interferometric phase into displacement and topography is corrupted if the uplift is not exactly the same in the two interferograms.

An example of the effect of tidal uplift is shown on Figure 4, in the area with the dense fringe pattern. In the derived topography map on figure 2, this feature comes out with a height of 8000 m below sea level. Also note that the correlation drop significantly in the deformation zone, see Figure 5. In this image the problem is small, but other glaciers such as Nioghalvfjerds Bræ is floating over large areas.

There is no easy way to handle this problem with multi pass interferometry. Useful measurements might be extracted, but the uplift need to be modeled accurate and/or the observation must be acquired with the glacier in a near stationary position at high or low tide. Basicly the only reliable solution is to use a single pass interferometer either from an airplane or in the future from a satellite to generate the topographic component with a zero temporal baseline.

Discrimination

For regional studies a discrimination between glacier ice, shorefast ice, rock, lakes, etc. is of significant interest but automatic methods are much needed to do this job. In the winter images processed until now, different types of terrain exhibit similar backscatter and coherence. Solutions to this task might involve using interferograms from different times of the year, and/or using interferograms with a 35-day repeat or longer.

Conclusions

A displacement map has been generated for the glacier Storstrømmen in North-East Greenland from two descending pass ERS tandem interferograms. Only one component of the displacements has been extracted, but if ascending orbit data have sufficient coherence, a 2-D pattern can be generated. In combination with a data set with a larger spatial baseline which would enable the generation of a useful topographic map, this would allow us to solve for the 3-dimensional velocity vector. Only some of the ERS data sets exhibited sufficient correlation to allow phase unwrapping and in general it seems most desirable to acquire multiple data sets of each area to increase the chance of acquiring data with good correlation. Multiple data sets also allows for identification of artifacts caused by tropospheric path delays, and ease the delineation of different terrain classes.

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