Capabilities of L-band SAR data for arctic glacier motion estimation

Tazio Strozzi[1], Andreas Wiesmann[1], Aleksey Sharov[2], Alexei Kouraev[3], Urs Wegmüller[1] and Charles Werner[1]

[1] Gamma Remote Sensing, Worbstrasse 225, 3073 Gümligen, Switzerland
http://www.gamma-rs.ch, e-mail: strozzi@gamma-rs.ch
[2] Joanneum Research, Wastiangasse 6, 8010 Graz, Austria
[3] Laboratoire d'etudes en geophysique et oceanographie spatiale (LEGOS), Observatoire Midi-Pyrenees (OMP), Avenue Edouard Belin 18, 31401 Toulouse cedex 9, France

Abstract — L-band SAR interferometry and offset tracking were applied for the estimation of arctic glacier motion over Franz Josef Land, Novaya Zemlya and Svalbard using SAR data acquired by the JERS-1 satellite with 44 days time interval. Our SAR interferometric results indicate a generally good coherence with well preserved fringes over the slow moving glaciers. Decorrelation is mainly observed along outlet glacier margins with excessive strain rates. On the other hand, the effects on the interferometric coherence of snow and ice melting, snow accumulation or wind drift, and volume decorrelation because of microwave penetration in the dry snow cover and ice are limited. Offset tracking applied to pairs of SLC images highlights the displacement of the fastest moving glaciers around the ice caps. However, azimuth streaks, possibly related to auroral zone ionospheric disturbances, were detected.

Keywords: SAR interferometry, glacier motion, offset tracking, L-band SAR, ionosphere.

I. Introduction

Glaciers and ice sheets are sensitive indicators of climate fluctuations. The effects of climate warming are for instance evident in the continuous retreat of glaciers. More specifically, changes in climate and in the energy fluxes at the earth's surface (temperature, precipitation) are directly affecting accumulation and melt along the surface of glaciers, and have therefore an effect on spatio-temporal changes of the mass balance. Monitoring of ice sheet and glacier flow rates is also important in climate change studies, with accelerated motion indicating decreasing ice masses due to global warming. Recently, satellite SAR data have made it possible to derive ice surface velocity fields without the expense of in-situ measurements by means of interferometry and offset tracking.

Most of the SAR interferometry or offset-tracking studies considered data from the ERS-1/2 and RADARSAT-1 satellites at C-band (5.7 cm wavelength λ) with 1, 3 or 24 days acquisition time intervals [1-3]. A limited number of glacier flows studies were performed at L-band (λ = 24.3 cm), C-band (λ = 5.7 cm) and X-band (λ = 3.1 cm) with acquisitions of the SIR-C/X-SAR during a flight of the Space Shuttle Endeavour in October 1994 [4-6]. The experience with L-band SAR data with longer acquisition time intervals is however limited [7-8], in spite of the huge amount of SAR data collected by the JERS-1 SAR mission between 1992 and 1998 at λ = 23.5 cm and HH polarization.

As already demonstrated for the monitoring of land subsidence [9], landslides [10] and active rock glaciers [11], L-band SAR interferometry has the capability of complementing the existing applications based on C-band data, because its larger wavelength is more appropriate for mapping large displacements. Furthermore, the greater penetration of the radar signals into the snow and firn at L-band than at C-band [12] should result in a reduced decorrelation. The focus of this contribution is on the potential and limitations of L-band SAR interferometry and offset tracking for the estimation of arctic glacier motion. SAR data acquired by the JERS-1 satellite over Franz Josef Land, Novaya Zemlya and Svalbard are analyzed.

II. SAR Data

The JERS SAR mission [13] was operated between 1992 and 1998 collecting a huge amount of SAR data at L-band. JERS SAR data are archived both at Japan Aerospace Exploration Agency (JAXA) and at the European Space Research Institute (ESRIN), where there are more than 100,000 JERS SAR frames over Europe acquired at the Tromsø and Fucino ground stations. For this study 8 winter JERS SAR scenes covering Svalbard, Franz Josef Land and Novaya Zemlya were exploited (see Figure 1). The images were taken under favourable weather conditions and were selected in order to compute 4 interferograms with acquisition time intervals of 44 days and short baselines. The JERS SAR data were obtained from the ESRIN archive as long stripes Level-0 raw data. The raw data of complete orbits were then processed to full resolution Single-Look Complex (SLC) images over the islands of interest.

III. SAR Interferometry

Interferometric processing of the JERS SAR pairs was done to 6 azimuth and 2 range looks with common-band filtering after co-registration of the SLC images. The baseline was first estimated from the orbit data and subsequently refined based on the fringe rate in range and azimuth directions. Our SAR interferometric results indicate a very good coherence in all the cases, with well preserved fringes over the slow moving glaciers.

An example for Duvebreen in Austfonna (Svalbard) is presented in Figure 2. Decorrelation is mainly observed over the areas with excessive strain rates, in particular along the margins of the glacier. On the other hand, the effects on the interferometric coherence of snow and ice melting, snow accumulation or wind drift, and volume decorrelation because of microwave penetration in the dry snow cover and ice are limited.

A band of phase decorellation can be observed to the south of Duvebreen. Analysis of the offsets between the two SAR images in slant-range and azimuth direction (see Figure 3) shows a strong azimuth offset in this area, possibly related to auroral zone ionospheric disturbances [14]. Ionospheric streaks on the azimuth offset maps are not rare even in the case of C-band SAR mapping in polar regions, but L-band SAR data is much more sensitive to ionospheric conditions along the SAR swath path. After consideration of the offset fields in resampling of the two SLC images, the interferogram is no more decorrelated in this region.

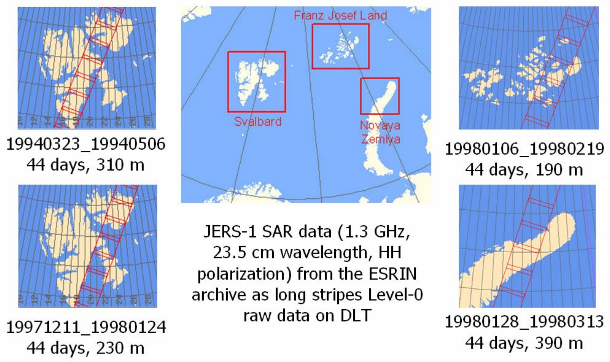

Figure 1. JERS SAR data considered in this study with indication of acquisition dates, time interval and perpendicular baseline.

IV. Offset Tracking

A. Method

With offset tracking the registration offsets of two SAR images in both slant-range (i.e. in the line-of-sight of the satellite) and azimuth (i.e. along the orbit of the satellite) directions are generated and used to estimate the displacement of glaciers [15,16]. The estimated offsets are unambiguous values which means that there is no need for phase unwrapping, one of the most critical steps in SAR interferometry. In this study the offset fields are generated with a normalized cross-correlation of image patches of detected real-valued SAR intensity images. The location of the peak of the two-dimensional cross-correlation function yields the image offset. The successful estimation of the local image offsets depends on the presence of nearly identical features in the two SAR images at the scale of the employed patches. For the JERS SAR interferograms considered in this study coherence is retained. Therefore the speckle pattern of the two images is correlated and tracking with small image patches can be performed to remarkable accuracy. In order to increase the estimation accuracy, oversampling rates are applied to the image patches and a two-dimensional regression fit to model the correlation function around the peak is determined with interpolation. Coarse information on the slant-range and azimuth offsets is used to guide the search of the cross-correlation maximum.

The image offsets in the slant-range and azimuth directions are related to the different satellite orbit configurations of the two SAR images, the displacement occurring between the acquisition time interval of the image pair, and ionospheric effects. The estimation of glacier motion requires the separation of these effects. The orbital offsets are determined by fitting a bilinear polynomial function to offset fields computed globally from the SAR images assuming no displacement for most parts of the image. Ionospheric streaks on the azimuth offset maps are high-pass filtered along the range direction.

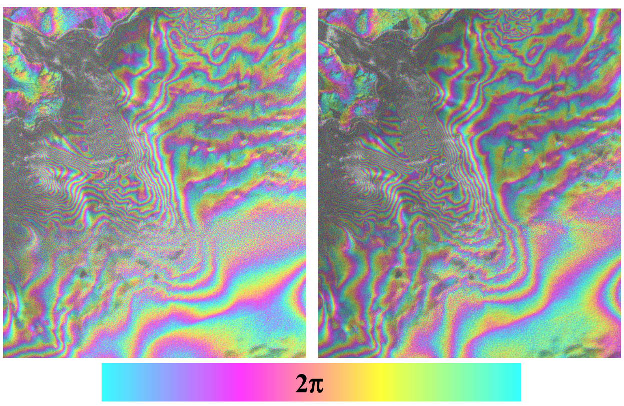

Figure 2. JERS interferogram of December 11, 1997 and January 24, 1998 in SAR geometry for Duvebreen (Austfonna, Svalbard). Image to the left was obtained with standard SLC co-registration. Image to the right was achieved after consideration of the offset fields in resampling of the two SLC images. Image width is ~30 km.

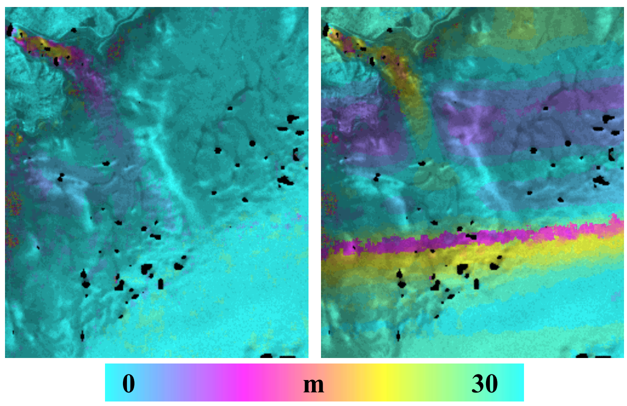

Figure 3. Offset fields in slant-range (left) and azimuth (right) direction computed from the JERS SAR images of December 11, 1997 and January 24, 1998 for Duvebreen (Austfonna, Svalbard). Look direction (descending mode) is from the right, incidence angle is ~35°, and the perpendicular baseline is 230 m.

B. Results

Offset tracking was first applied to the two pairs of SAR images covering Duvebreen. For presentation and interpretation, slant-range and azimuth displacements were combined to provide a 2-dimensional ground displacement field and the maps were terrain corrected geocoded using an external Digital Elevation Model (DEM). The results of Figure 4 highlight the displacement of the glacier, even if azimuth streaks are still visible.

Offset tracking was subsequently applied to the pairs of JERS SAR images covering Franz Josef Land and Novaya Zemlya. For these image pairs the azimuth streaks are very limited. The results of Figures 5 for Wilczek Land, Hall and La-Ronciere islands in Franz Josef Land are in the original SAR geometry and show the displacement of the fastest moving glaciers. These results suggest that after 44 days the speckle at L-band is retained. The velocity map for Novaya Zemlya is superimposed to a glacier map derived from Landsat imagery (ca. 1990) and a schematic map of outlet glaciers from the catalogue of URSS glaciers of 1977 [17]. In Figure 6 it can be observed that for certain areas the boundaries of outlet glaciers from the catalogue do not correspond to the regions of significant ice displacement from JERS SAR data. Thus, offset tracking could significantly improve the mapping of glaciers.

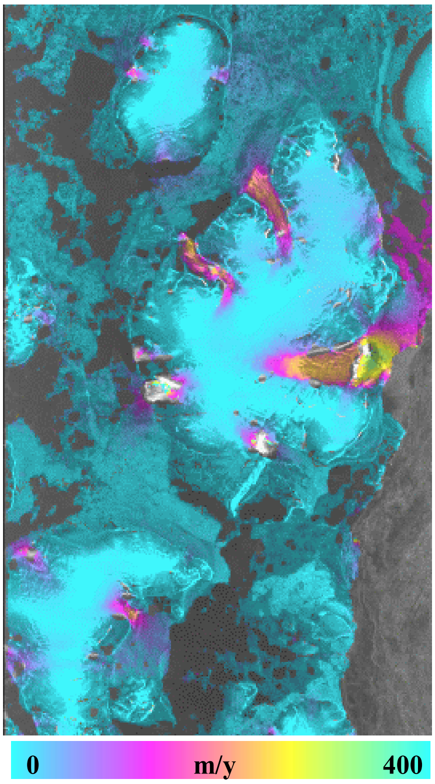

Figure 5. Horizontal displacement for Franz Josef Land from JERS offset tracking between SAR images of January 6 and February 19, 1998 with a perpendicular baseline of 190 m. Image width is ~80 km.

C. Error analysis

Error analysis is essential to demonstrate the applicability of offset tracking to surface movement. In a first part, the error analysis discusses the transformation of the pixel registration accuracy into displacement accuracy. Then, the expected accuracy of JERS offset tracking is assessed in stable zones and by comparison with ERS SAR interferometry.

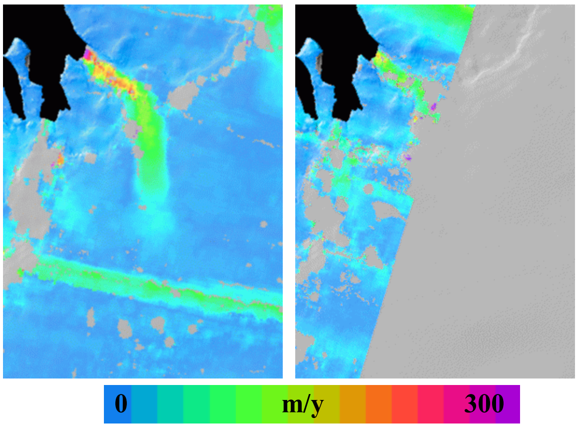

Figure 4. Horizontal displacement for Duvebreen (Austfonna, Svalbard) from JERS offset tracking between SAR images of December 11, 1997 and Januray 24, 1998 (left) and March 23 and May 6, 1994 (right).

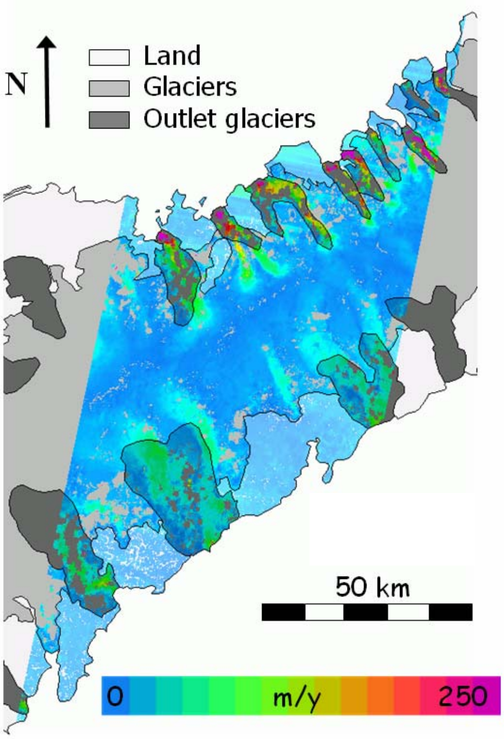

Figure 6. Horizontal displacement for Novaya Zemlya from JERS offset tracking between SAR images of January 28 and March 13, 1998 with a perpendicular baseline of 390 m.

If JERS SAR data with acquisition time intervals of 44 days are considered, typical slant-range and azimuth offset estimation errors computed with window sizes of 64x256 pixels are on the order of 1/5th of a pixel. The resulting precision of displacement for JERS SAR data processed to a slant-range pixel spacing of 8.778 m and to an azimuth pixel spacing of 4.428 m assuming flowing on a horizontal plain is therefore on the order of 3.2 m, i.e. 26 m/year.

The magnitude of the errors in the flow rate can be assessed by the apparent displacement of rock areas. After masking areas of ice and water, mean displacement values for JERS data where strong azimuth shift modulations were detected and filtered to a certain degree were 1.14±1.85 m or 9±15 m/year. Mean displacement values for 44 days JERS data where azimuth shift modulations are very limited were 1.17±0.52 m, i.e. 10±4 m/year.

JERS offset-tracking records of surface ice velocity are compared to ERS SAR interferometry results along the approximate main flow line of Duvebreen in Figure 7. The ERS SAR interferometry records indicate an increase of ice velocity from 1994 to 1996, but seasonal variations may also account for this. The JERS offset-tracking results in 1998 are similar to the SAR interferometry outcomes of 1996. In particular between 10 and 25 km there is a very good correspondence, with differences within ±10 m/year. Strong azimuth streaks are observed in the JERS results between 0 and 10 km, where differences with ERS SAR interferometry results are larger than ±10 m/year. The JERS SAR images of 1994 are covering only the front of Duvebreen, where measured surface ice velocities are smaller than in 1998 and comparable with the SAR interferometry rates of 1994. However, at the front of the glaciers large variations of ice velocities are observed.

In conclusion, our precision analysis, investigations and experience suggest that for the application of offset tracking using JERS SAR data with 44 days acquisition time interval expected errors are about 20 m/year after filtering of azimuth streaks. Further efforts to identify and minimize ionospheric electron density fluctuations on SAR and INSAR processing techniques are reported in [18].

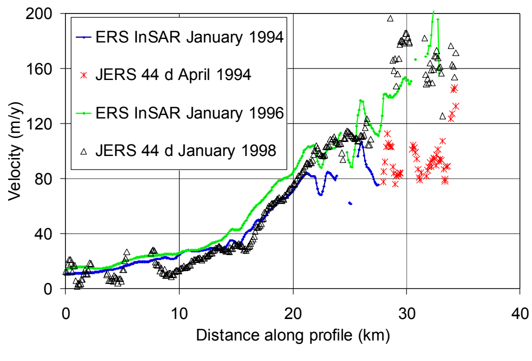

Figure 7. Comparison between ice surface velocities along the approximate main flow line of Duvebreen from ERS SAR interferometry in January 1994 and January 1996 and JERS offset tracking in April 1994 and January 1998.

V. Conclusions

SAR data acquired by the JERS-1 satellite between 1994 and 1998 over Franz Josef Land, Novaya Zemlya and Svalbard were investigated for glacier motion studies using interferometry and offset tracking. The JERS results presented here, obtained using SAR data acquired by a satellite operated until 1998, are significant in expectation of data from the PALSAR sensor onboard the Japanese ALOS mission launched in early 2006.

VI. Acknowledgements

Work supported by the FP6 EC INTEGRAL project (Contract No. SST3-CT-2003-502845) with Swiss contribution under BBW Nr. 03.0049. JERS SAR data courtesy C1P.2611 (SIGMA, P.I. A.Sharov). DEM of Nordaustlandet © NPI.

VII. References

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