RECENT VARIATIONS OF LARSEN ICE SHELF, ANTARCTIC PENINSULA, OBSERVED BY ENVISAT

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ABSTRACT

Areal changes of Larsen Ice Shelf, Antarctic Peninsula, and the response of the outlet glaciers after the ice shelf disintegration events in 1995 and 2002 are investigated using ERS SAR and Envisat ASAR data up to July 2004. After a decrease of 8050 km^2 between January 1995 and March 2002, the ice shelf section Larsen B decreased by another 830 km² in the last two years. In addition, 215 km² of grounded ice were lost at the major outlet glaciers of former Larsen A and B, contributing to sea level rise. Motion fields of glaciers above Larsen A and Larsen B were analysed by means of ASAR data from 2004 using amplitude correlation and compared with 1995 and 1999 InSAR motion maps of the ERS tandem mission. Similar to the rapid response of glaciers above Larsen A, significant acceleration of the large tributary glaciers of Larsen B was observed soon after the disintegration of the ice shelf. ERS SAR and ASAR data are also used for mapping the catchment basins and flow field of Larsen C, the large southern ice shelf section.

1. INTRODUCTION

Larsen Ice Shelf on the east coast of the Antarctic Peninsula has undergone significant retreat during the last decades as an effect of significant warming in the region, culminating in two spectacular disintegration events in 1995 and 2002 [1] [2]. Detailed observations of ice retreat have been possible since 1992 by means of ERS SAR, and since 2002 by means of Envisat ASAR and MERIS. Of particular interest in connection with this retreat are the processes leading to rapid disintegration events, as well as the impact of ice shelf retreat on grounded ice that contributes to sea level rise. The first evidence on acceleration of outlet glaciers after ice-shelf break-up was presented by H. Rott for the glaciers above the previous Larsen A and Prince Gustav Channel ice shelves, based on analysis of ERS tandem data from 1995 and 1999 [3]. New data, provided by Envisat ASAR, enabled us to study also the retreat and acceleration of glaciers after the disintegration of Larsen B in 2002. In addition, we also investigate the flow behaviour of the ice shelf and tributary glaciers of Larsen C, to obtain baseline information for possible future changes if the climate signal spreads further south.

2. AREAL CHANGES OF THE NORTHERN LARSEN ICE SHELF

Since 1962/63 areal changes of the northern Larsen Ice Shelf (Fig. 1) can be analysed based on satellite images (Fig. 2). The first images were panchromatic satellite photographs from the U.S. intelligence satellite program. In the 1970s and 1980s a few Landsat images were available. Since 1991 ERS has provided a better data base, because optical sensors often fail due to frequent cloudiness in the region. However, ERS images have only been available on a campaign basis, when the O'Higgins station was operated. Since 2002 Envisat has provided new observational dimensions, because of on board storage and SAR beam steering capabilities.

Major changes in ice shelf area occurred in 1995 when Larsen A collapsed completely within a few days [1], the ice shelf in Prince Gustav Channel disintegrated, and a big tabular iceberg broke away from Larsen B. In 2002 the northern part of Larsen B collapsed after a period of steady retreat since 1995 [2] [4] [5]. The ice shelf area decreased from 11512 km² in January 1995 to 3463 km² in March 2002. In Tab. 1 the area changes of Larsen B since 1995 are tabulated, with the recent data based on Envisat ASAR images. Between 18 March 2002 and 13 February 2004, 830 km² of floating ice calved into the sea. The last event (34 km²) took place near Cape Fairweather in January/February 2004. Also grounded ice is affected by ice shelf disintegration.

The outlet glaciers of the peninsula retreated and accelerated soon after the collapse of Larsen A [3]. Similar rapid response to the disappearance of buttressing ice shelves is now observed at the glaciers above former Larsen B, with significant retreat of grounded ice starting soon after the disintegration of the ice shelf. ERS SAR and Envisat ASAR data enabled us to analyse the retreat of grounded ice after disintegration of Larsen A and northern Larsen B with great detail up to July 2004 (Tab. 2). The area of grounded ice lost after January 1995 up to July 2004 at the main

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tributaries of the northern Larsen Ice Shelf amounted to 215 km².

At the northernmost section, Sjögren and Boydell (S-B) glaciers were completely separated from each other in February/March 2002. On the other hand, no changes could be detected since 1995 for the front of the main glacier nourishing the Larsen Inlet indicating that it has already found its new equilibrium which may be an effect of its steeper topography. Dinsmoor, Bombardier and Edgeworth glaciers (D-B-E), the northern outlet glaciers to Larsen A, advanced slightly between 2003 and 2004 after major retreat. Drygalski Glacier, the main outlet glacier to previous Larsen A, showed little change for 2 years, after major retreat and acceleration before 2002 [3].

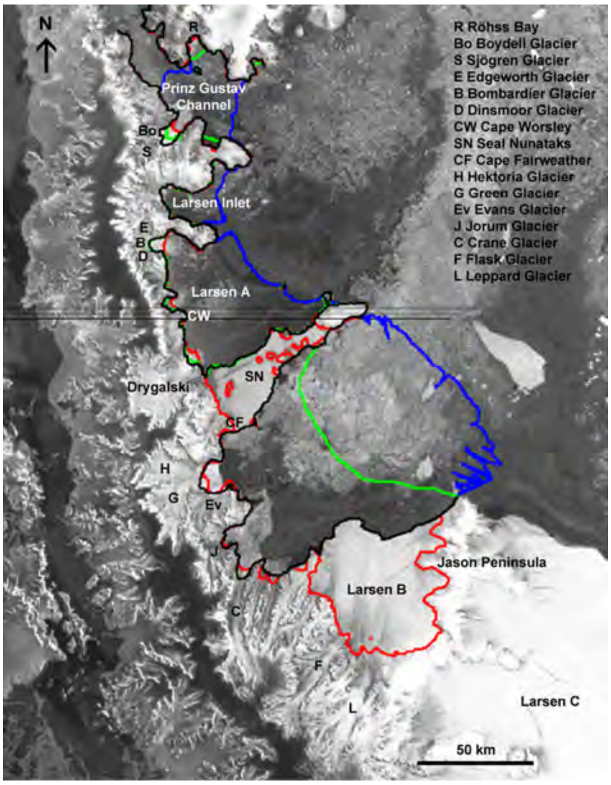

Fig. 1. Envisat ASAR wide swath image of 1 September 2003, showing the area of the northern Larsen Ice Shelf. Blue/green/black line: ice edge in March 1986/October 2000/June-July 2004. The grounding line (red) is derived by ERS SAR interferometry, for sections which disintegrated before October 1995 from the ice edge; © ESA, 2003.

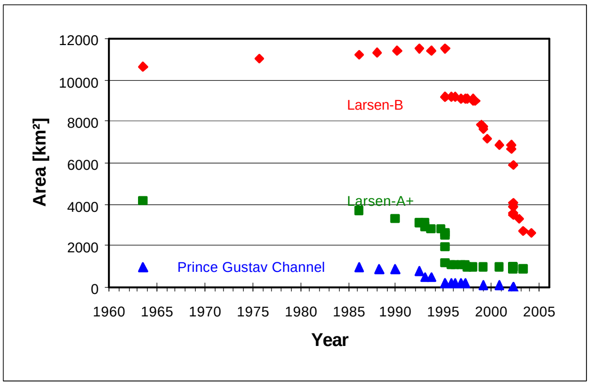

Fig. 2. Areal changes for three ice shelf sections of the northern Larsen ice shelf with time derived by satellite images. Larsen-A+ contains also the ice shelf area around the Seal Nunataks and in Larsen Inlet.

Tab. 1. Area of Larsen-B ice shelf for several dates between 1995 and 2004.

Year	Day	Area [km²]	Satellite, Sensor
1995	25 Jan.	11512	ERS, SAR
	30 Jan.	9192	ERS, SAR
1998	25 Apr.	9022	Radarsat, SAR
	18 Nov.	7829	Radarsat, SAR
1999	5 Aug.	7198	Radarsat, SAR
2000	6 Okt.	6831	ERS, SAR
2001	12 Dez.	6829	ERS, ATSR
2002	4 Feb.	6664	ERS, ATSR
	24/27/28 Feb.	5942	ERS, SAR
	5 Mar.	4052	Terra, MODIS
	6 Mar.	3887	ERS, SAR
	7 Mar.	3551	Terra, MODIS
	18 Mar.	3463	Envisat, ASAR
	3 Nov.	3327	Envisat, ASAR
2003	19 Mar.	2678	Envisat, ASAR
	23 Apr.	2667	Envisat, ASAR
2004	13 Feb.	2633	Envisat, ASAR

Tab. 2. Loss of grounded ice at selected former tributaries of northern Larsen Ice Shelf.

Glacier/ Region	Area [km²] 1995 - 1999	Area [km²] 1999 – May 03	Area [km²] 2003 – July 04
Röhss Bay	-	+ 8	-
S-B Gl.	+ 24	+ 30	-
D-B-E Gl.	+ 34	+ 5	- 4
Gl. n. CW	-	+ 23	-
Drygalski Gl.	+ 24	+ 8	-
H-G-Ev Gl.	-	+ 57	- 16
Crane Gl.	-	+ 3	+ 19

3. VELOCITY CHANGES AND RETREAT OF DINSMOOR-BOMBARDIER-EDGEWORTH GLACIERS

The main ice inflow to Larsen A was through Drygalski Glacier (984 km^2) and Dinsmoor, Bombardier and Edgeworth glaciers (D-B-E) with a grounded basin of 681 km² in 1995. Between October 1995 and January 1999 / November 2002 an area of 34 / 39 km² was lost at D-B-E, and the front retreated from the original grounding by 6.5 / 7.3 km (Fig. 3).

By means of ERS SAR interferometry a velocity of 2.9 m/d was derived in the centre of the 6 km wide front of D-B-E glaciers in austral spring 1995. At the central flowline 2 km above the 1999 ice front the velocity accelerated from 1.5 m/d in 1995 to 6 m/d in 1999. For the year 2004 a velocity of 1.8 m/d at the ice front of 2004 was derived by means of amplitude correlation (Fig. 4).

Amplitude correlation [6] measures the displacement of conservative surface patterns such as crevasses, rifts, surface undulations, and melt features. The many small icebergs in front of the glacier termini are well traceable as long as they are stuck in fast ice (Fig. 4 and Fig. 5). The temporal baseline (we used 35 days for the Larsen Ice Shelf glaciers) for measuring surface displacement by non-coherent techniques depends on the magnitude of ice motion and on the stability of surface features. Better results can be achieved for winter images due to better stability of the patterns. In summer the features may change rapidly due to melt, and amplitude correlation is often not applicable. The size of the template window depends on the ground resolution of a pixel and should be chosen in a way that the typical wavelength of surface features fits into the window. For the outlet glaciers investigated in this study an optimal template window size of about 2000 m by 2000 m was found. The error due to non-perfect co-registration of the images corresponds to +/- 0.03 m/d for the 35 day interval.

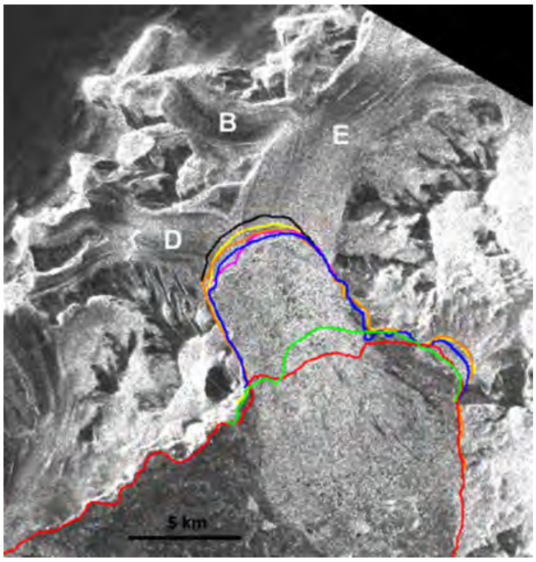

Fig. 3. ASAR IMS amplitude image, tr152, fr4941, IS2 HH, from 2 July 2004 showing ice front positions of Dinsmoor (D), Bombardier (B) and Edgeworth (E) glaciers (red = grounding line estimated from the ice edge in 1995, shortly after the ice shelf collapse, green = 01-11-1996, blue = 31-01-1999, yellow = 24-02-2002, black = 03-11-2002, orange = 04-04-2003, magenta = 13-02-2004.

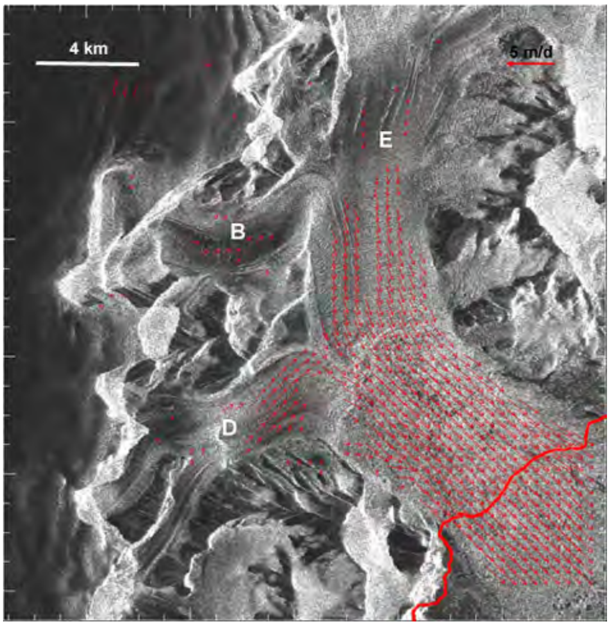

Fig. 4. Motion field of D-B-E glaciers derived from the ASAR IMS image pair of 28 May 2004 and 2 July 2004 by means of amplitude correlation (red line = grounding line), superimposed to ASAR amplitude image of 2 July 2004.

4. ACCELERATION OF HECTORIA-GREEN-EVANS GLACIERS

The motion field of Hektoria, Green and Evans glaciers (H-G-E), with a grounded area of 1583 km² before the ice shelf collapse, one of the largest tributary glaciers of Larsen B, was mapped by means of amplitude correlation (Fig. 5) with 2004 ASAR data. The H-G-E glaciers showed major retreat behind the grounding line in summer 2003 after the collapse, and have been advancing slightly since April 2003.

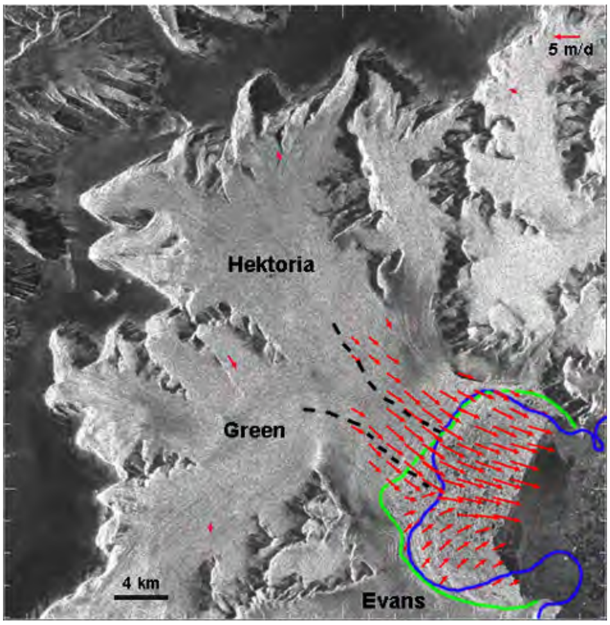

Fig. 5. Motion field of H-G-E glaciers derived from the ASAR IMS image pair, tr424, fr4941, IS2 HH, of 12 May 2004 and 16 June 2004 by means of amplitude correlation (blue line = grounding line, green line = ice front, black lines = flowlines of Green and Hektoria glaciers shown in Fig.6), superimposed to ASAR amplitude image of 12 May 2004.

A comparison of the velocities of Hektoria and Green glaciers in 1995, derived by ERS SAR interferometry, and the velocities in 2004 show significant acceleration of flow after the collapse of Larsen B (Fig. 6). In 1995 maximum velocities of 0.9 m/d for Green Glacier and 0.8 m/d for Hektoria Glacier with only small changes upstream along the flowline were observed. In 2004 maximum velocities of 6 m/d for Hektoria Glacier and 5 m/d for Green Glacier, decreasing with distance from the glacier front, were derived.

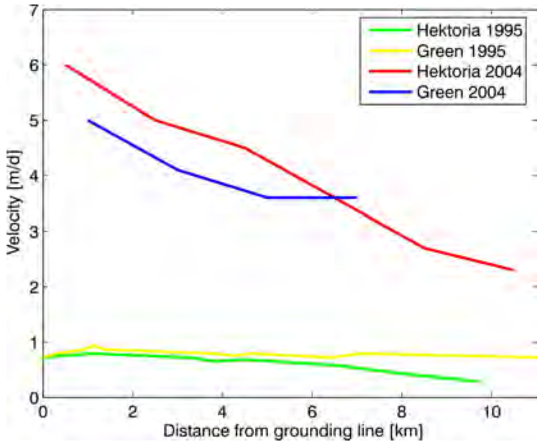

Fig. 6. Magnitude of the velocity vector along the central flowlines of Hektoria and Green Glaciers derived from ERS interferometric pair of 31 October - 1 November 1995 and ASAR amplitude correlation pair of 12 May - 16 June 2004.

5. RETREAT OF CRANE GLACIER

The areal changes of Crane glacier, one of the main tributary glaciers of the former Larsen B, were investigated by several ASAR images between April 2003 and July 2004. A pronounced retreat of the glacier of about 5 km inland the previous grounding line was observed from December 2003 until July 2004 (Fig. 7). The total loss of grounded area amounts to about 22 km².

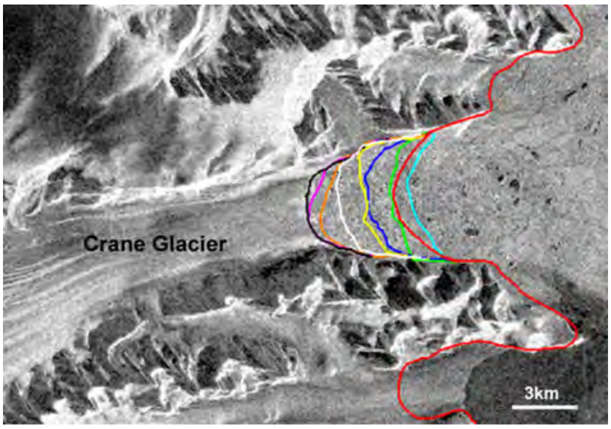

Fig. 7. ASAR IMS image, tr424, fr4959, IS2 HH, from 21 July 2004 showing ice front positions of Crane glacier (cyan = 23-04-2003, green = 24-12-2003, blue = 28-01-2004, yellow = 03-03-2004, white = 07-04-2004, orange = 12-05-2004, pink = 16-06-2004, black =21-07-2004). The grounding line (red) is derived by ERS SAR interferometry.

6. MAPPING OF CATCHMENT BASINS AND ICE EDGE OF LARSEN C

In contrast to the northern Larsen Ice Shelf no major changes of the ice front position of Larsen C (Fig. 8) were observed in the last 15 years. The last big calving events took place between 1975 and 1986-89 when two large icebergs calved off [7]. The catchments and ice flow of Larsen C and the glaciers have not been mapped in detail so far. ERS SAR and ASAR enable us to study the characteristics of these ice masses in detail.

The catchment basins of Larsen C (Fig. 8 and Tab. 3), here named after the inlet the glaciers are draining to, were determined by using a digital elevation model [8] and various optical and SAR images. The grounded area amounts to about 27000 km² and the floating area between Jason Peninsula and Hearst Island covers about 55000 km². This results in a ratio of grounded to floating area of 0.49. The mean ice thickness of Larsen C is about 350 m [9].

The floating ice can be traced back to major inlets. Each of them is nourished by one up to 10 glaciers which are usually rather steep and narrow, draining from the high plateau of the Antarctic Peninsula mountain ridge into the ice shelf. The largest catchment basin is Mobil Oil Inlet with a grounded area of 5475 km².

In the northern part of the ice shelf east of Churchill Peninsula and along Jason Peninsula large rifts can be seen, and on the line Kenyon Peninsula – Gipps Ice Rice the ice shelf is heavily crevassed. These rifts are also clearly visible in the interferometric data. We will pay particular attention to these disturbed zones on the ice shelf, to identify early signs of dynamic instability and ice retreat which might happen if the climatic warming signal spreads further south.

The interferogram of Larsen C (Fig. 9) shows velocities up to 500 m/a in the middle of the ice front. Discontinuities between the tracks are due to orbit errors and different tidal motions. The processing of velocity maps of the ice shelf and its tributary glaciers is in progress.

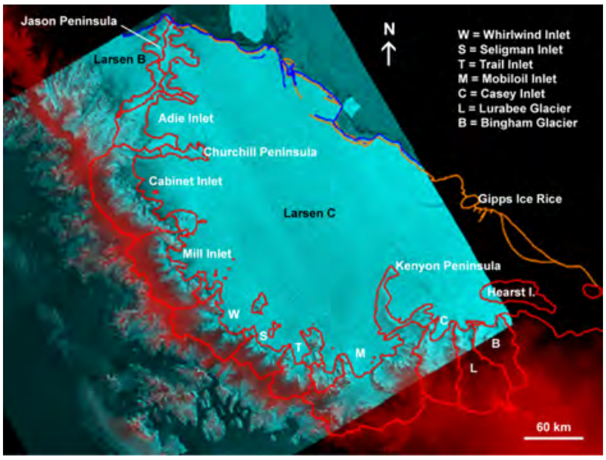

Fig. 8. ASAR WSM image from 6 May 2004 superimposed to a digital elevation model (DEM) (blue = ice front 6 May 2004, orange = ice front 22 March 2000 derived from a MODIS image) showing the Larsen Ice Shelf C and its catchment basins (red line). The grounding lines are derived by means of ERS SAR interferometry; © ESA, 2004.

Tab. 3. Catchment basins of Larsen C ice shelf and tributary glaciers.

Name	Area [km²]	Mean Height a.s.l. [m]
Adie Inlet	1436	318
Cabinet Inlet	3467	873
Mill Inlet	2606	1163
Whirlwind Inlet	1880	977
Seligman Inlet	972	874
Trail Inlet	1068	1040
Solberg Inlet	515	961
Mobil Oil Inlet	5475	997
Casey Inlet	2095	1193
Lurabee (L) Glacier	2372	1397
Bingham (B) Glacier	1506	997
Kenyon Peninsula	965	247
Joerg Peninsula	442	460
Tonkin Island	52	101
Francis Island	133	210
Betw. W and S Inlet	88	329
At Mamelon Point	306	531
Cole Penisula	338	227
Stanley Island	8	188
Churchill Peninsula	356	127
Jason Peninsula	882	194
Between L and B	29	717
Nunatak 1	10	43
Gipps Ice Rice	124	10

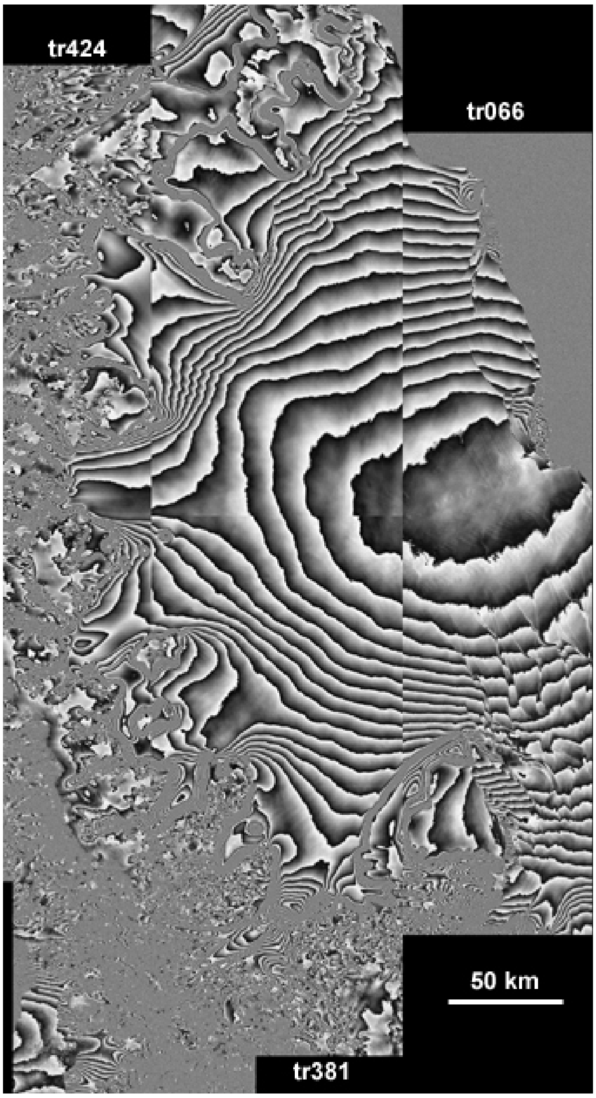

Fig. 9. ERS Tandem interferogram of Larsen C composed of track 424 (31 October – 1 November 1995), track 381 (28 – 29 October 1995) and track 066 (10 – 11 November 1995).

7. CONCLUSION

ERS SAR and Envisat ASAR provided a unique time series to observe and analyse the retreat and collapse of the northern sections of Larsen Ice Shelf at the Antarctic Peninsula. In this paper new observational results for the ice shelf and glaciers are presented based on ASAR data up to July 2004. The observed major retreat of grounded ice and the rapid acceleration of the glaciers after the collapse of Larsen B Ice Shelf in 2002 are particularly exciting. These observations confirm the previous findings after the Larsen A collapse that ice shelves have an important impact on the stability of grounded ice [3]. Ice export increased rapidly after the glaciers started to calve directly into the ocean. We plan to continue analysing these data and follow the future developments, using archived and future SAR data, complemented by altimetric data of the coming Cryosat mission.

8. ACKNOWLEDGEMENTS

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