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***Abstract*—Temperate glaciers are an indicator of the local effects of global climate change. For economical and security reasons in the surrounding areas, the monitoring of those geophysical objects is being a necessity. SAR data are expected to provide dense measurements of physical parameters which are necessary to detect significant changes and to constrain glacier flow models. In this paper, five descending one-day ERS-1/2 tandem interferometric data pairs from July 1995 to April 1996 are studied in the Chamonix Mont-Blanc area (French Alps). This multi-temporal interferogram series is used to analyse the coherence levels and fringe patterns over nine glaciers. Moreover, when the coherence is sufficient, Differential SAR Interferometry (D-InSAR) processing are applicable to derive a three-dimensional (3-D) velocity fields. An expert knowledge and a ten years measurements analysis of glacier flow are used to fix the line of sight (LOS) displacement offset. Finally, an analysis of the wrapped phase difference between interferograms is exposed to detect the presence of residual topographic fringes and to characterize the surface flow field evolution.**

I. Introduction

Temperate glaciers are an indicator of the local effects of global climate change. For economical and security reasons in the surrounding areas, the monitoring of those geophysical objects is being a necessity. Compared to sparse terrestrial ground measurements, Synthetic Aperture Radar (SAR) allows regular acquisitions on mountainous areas. SAR data are expected to provide dense measurements of physical parameters which are necessary to detect significant changes and to constrain glacier flow models. For example, InSAR techniques can be applied to measure glacier surface flow fields which can reach several decimeters per day in the French Alps. Spaceborne data from ERS-1/2 tandem mission have been successfully used to derive velocity fields [1], mainly during the cold season because of the strong temporal decorrelation in summer [2].

In the first part of this paper, five descending one-day ERS-1/2 tandem interferometric data pairs from July 1995 to April 1996 are studied in the Chamonix Mont-Blanc area (French Alps). This multi-temporal interferogram series is used to analyse the coherence levels and fringe patterns over nine glaciers. Like coherence is a criteria of interferometric processing performance, an analysis of multi-date coherence in glaciers and non-glaciers areas is exposed. A survey concerning the altitude influence on coherence preservation is achieved.

Next, when the coherence is sufficient, Differential Interferometry SAR processing is applicable to derive a 3-D velocity field. However, several difficulties have to be overcame. Due to the high topography, most of the Chamonix Valley glaciers are visible only on descending pass. Since, one pass interferometric phase provides the 3-D surface displacement projected on the SAR line of sight axis, only one velocity component is available. Moreover the phase unwrapping step provides over each glaciers a displacement field with an unknown offset. An expert knowledge and a ten years measurements analysis of glacier flow allow the detection of areas where the velocity is stationary during different seasons. Annual in-situ measurements are taken into account to fix this LOS displacement offset. A displacement profile is shown and a comparison with differential GPS measurements is exposed.

Finally, an analysis of the wrapped phase difference between interferograms is proposed. A method based on a comparison of the fringes with the perpendicular baseline is described. It determines if residual topographic fringes are correctly removed or not in the interferogrmas. Therefore, Digital Terrain Model (DTM) errors can be retrieved by this analysis.

TABLE I
ORTHOGONAL BASELINE AND ALTITUDE OF AMBIGUITY

interferogram date	$B_\perp$ (m)	e_a (m)
95.07.09/95.07.10	52	162
95.10.22/95.10.23	-107	80
95.12.31/96.01.01	208	41
96.03.10/96.03.11	9	960
96.04.14/96.04.15	93	93

TABLE II
PERCENTAGE OF PIXELS HAVING A COHERENCE ≥ 0.5

date of acquisition	glacier name		non glacier areas
	Mer de Glace Leschaux	Argentière	
July 95	5.33	0.70	38.65
October 95	27.75	37.17	39.28
December 95	2.45	1.49	7.34
March 96	35.05	44.94	32.20
April 96	1.37	34.90	9.41

Furthermore, when topographic fringes are correctly removed, a comparison of multi-date interferometric phases allows a characterization of surface flow field evolution.

II. MULTI-TEMPORAL COHERENCE ANALYSIS

Five descending one-day ERS-1/2 tandem interferometric pairs from July 1995 to April 1996 are processed with the Repeat Orbit Interferometry Package (ROI-PAC) software from the Jet Propulsion Laboratory (JPL). This processor takes the precise orbits from the Delft University, the Netherlands, into account to remove the orbital fringes [3]. Moreover, a DTM is used by ROI-PAC software to estimate the topographic fringe component and remove it from the interferogram. After the ROI-PAC topographic and orbital fringe removal, an adaptive neighborhood filter has been applied to re-estimate the interferometric phase and coherence [4].

A. *Multi-date coherence analysis*

To investigate the potential of ERS-1/2 tandem interferometry all along the year, an analysis of the interferometric coherence from July 1995 to April 1996 is proposed.

Among the five interferometric couples shown in Fig.1, the highest coherence is observed in March 1996. Indeed, almost 45% of the Argentière glacier has a coherence greater than 0.5 (see table II). The couple of March has the smallest perpendicular baseline ($B_\perp = 9m$) (see table I). Moreover, the interferograms acquired in winter show a better coherence than those acquired in the other seasons. Compared to March, the 31 Dec.95/1 Jan.96 interferogram shows a loss of coherence. This loss is observed on glacier (2%) and non glacier (7%) areas. The large perpendicular baseline ($B_\perp = 208m$) causes a significant volume decorrelation, especially in the valley forested areas. In warmer seasons (October and April), the coherence is preserved only on the upper parts of the glaciers. Indeed, for low altitudes, the higher temperature leads to a relevant change of the glacier surface state and causes a loss

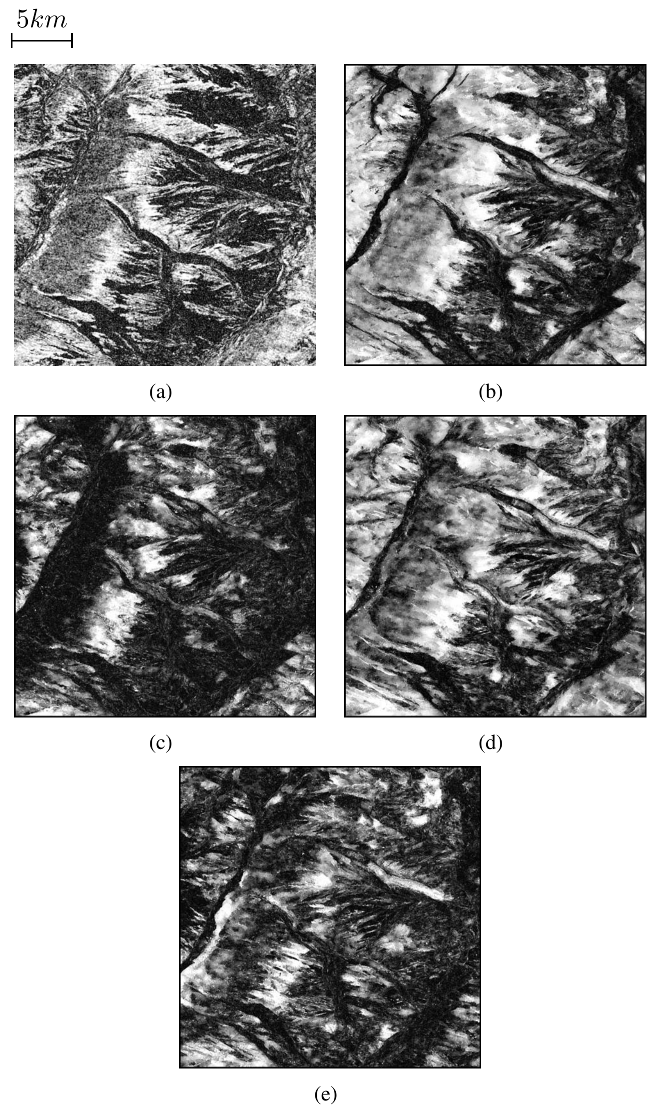
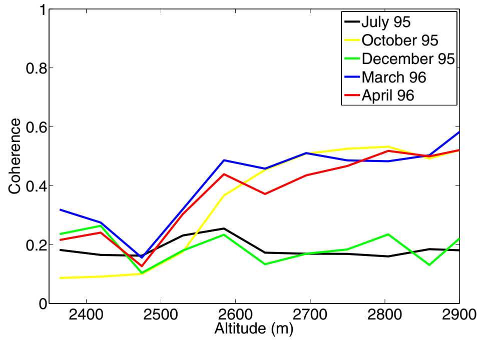


Fig. 1. ERS-1/2 tandem interferograms over the Mer de Glace - Leschaux and Argentière glaciers area (1024×1024 pixels). Coherence filtered by amplitude driven adaptive neighborhood. (a) 9/10 Jul.95, (b) 22/23 Oct.95, (c) 31 Dec.95/1 Jan.96, (d) 10/11 Mar.96, (e) 14/15 Apr.96

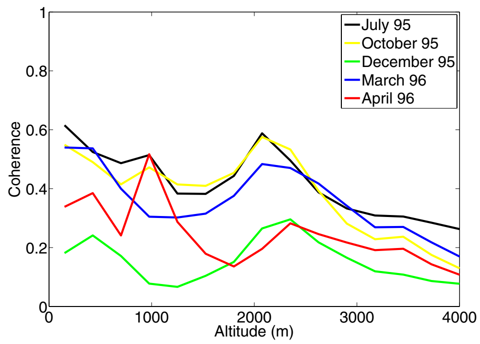
of the interferometric coherence. For the same reason, during the hot season, coherence is not preserved on the whole surface of the nine observed glaciers.

B. *Influence of altitude on the interferometric coherence*

In April 1996, coherence is preserved only on the upper part of the Argentière glacier. 35% of the pixels have a coherence greater than 0.5, whereas on the Mer de Glace/Leschaux glacier, only 1% of the pixels preserve the coherence. As the altitude is higher on the top of Argentière glacier than on the Mer de Glace/Leschaux glacier, coherence preservation may be dependent on glacier elevation. To investigate this relation, a Digital Terrain Model (DTM) has been used to build a mask of visibility. This mask determines which regions are not visible (foldover, shadow) on the ERS-1/2 images. Then the transformation from ground geometry to the SAR slant



(a)



(b)

Fig. 2. Influence of altitude on multi-date ERS-1/2 tandem interferometric coherence. (a) on the Argentière glacier, (b) on non glacier areas

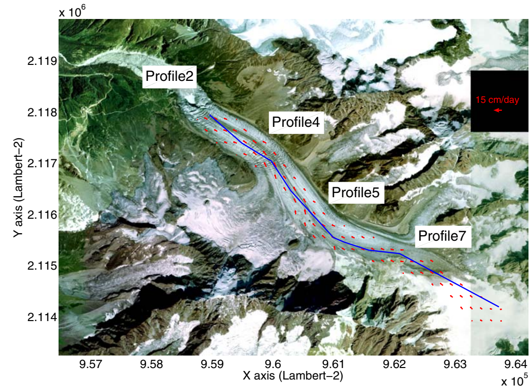
range geometry is coded in a look up table which is used to convert the mask of visibility and resample the DTM in slant range. Only the visible regions are taken into account in the plot of the coherence as a function of altitude. Fig.2 shows the average coherence as a function of the altitude on the Argentière glacier (Fig.2(a)) and on non glacier areas (figure 2(b)).

A low coherence can be observed in December 1995 (green line) due to the large baseline of this interferometric pair. Although coherence is well preserved on July 1995 (black line) on non glaciers areas, on the Argentière glacier, the significant change of the glacier surface state in summer does not allow a coherence preservation. Note that in October 1995, March and April 1996, coherence increases with altitude on the Argentière glacier. The higher the glacier is, the more coherence is preserved. This relation cannot be established on non glacier areas because coherence varies a lot, with a strong effect of the slope on high altitudes areas.

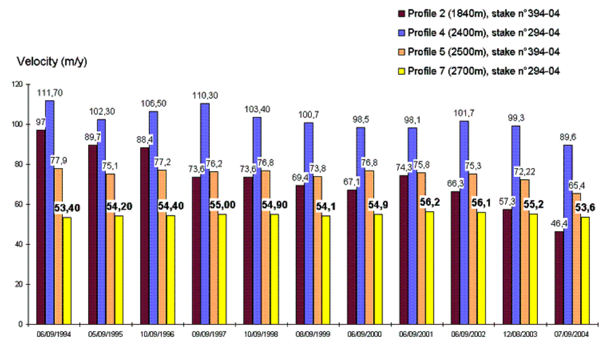
III. 3-D SURFACE DISPLACEMENT

When the coherence is sufficient, glacier displacement can be monitored by Differential SAR Interferometry processing. Three-dimensional (3-D) velocity fields can be derived with ERS 1-day interferograms from October 1995 to April 1996 on most of the glaciers of the studied area.

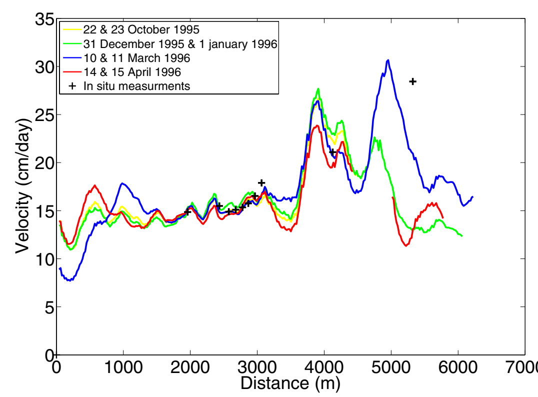
The phase unwrapping step provides over each glaciers a displacement field with an unknown offset. To fix this constant,



(a)



(b)



(c)

Fig. 3. Analysis of Argentière glacier displacement: (a) Displacement velocity field (red arrows), location of the annual measurements presented in Fig. 3(b)) and position of the longitudinal profile (blue line) presented in Fig. 3(c) , (b) Comparison of annual displacement from 1994 to 2004 at 4 altitudes, (c) Longitudinal velocity profile from the upper part (2900m asl) up to profile 4 (2300m asl)

a common technique is to find a part of the glacier where the displacement is assume to be zero. Unfortunately, such assumption cannot be done on the Argentière glacier due to the quite steep slope.

An expert knowledge and a ten year measurement analysis of glacier flow allow the detection of areas where the velocity is stationary during different seasons. Fig.3(b) shows the annual displacement of the Argentière glacier from 1994 to 2004 at 4 altitudes. Note that at 2700m above sea level (asl) (profile7 on Fig.3(a)) the displacement is the same every year. Moreover an expert knowledge confirms that the displacement in this part of the glacier is stationary during different seasons. Consequently, an annual in situ measurements at 2700m asl can be used to fix the one-day LOS displacement offset.

Since, one pass interferometric phase provides the 3-D surface displacement flow projected on the SAR LOS axis, only one velocity component is available. Thus, two common assumptions are made to retrieve the 3-D surface displacement flow [5]:

- a flow parallel to the glacier surface.
- a flow in the direction of maximum averaged downhill slope.

Fig.3(c) shows a longitudinal displacement profile on the Argentière glacier. The first cross is the only point used to fix the LOS offset. Note that near the reference point, the 1-day displacement is stationary. There isn't much variation on the displacement profile from October 1995 to April 1996. Annual in-situ measurements are in good agreements with the displacements obtained by interferometry. On the bottom of the Argentère glacier, the 1-day displacement varies more with the date of acquisition. The fluctuations between March and April 1996 velocities seems to confirm that the hypothesis of a stationary area would not be valid in the lower part of this glacier.

IV. Analysis of the wrapped phase difference between differential interferograms

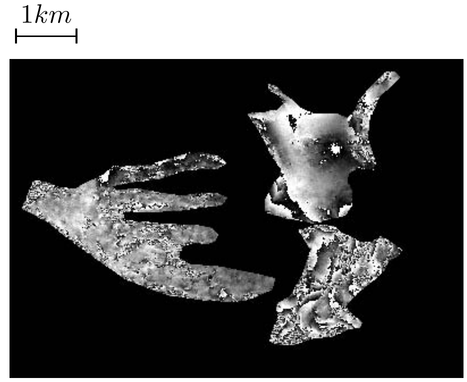
In this section, a study of the temporal variation of D-InSAR displacement fields is proposed. This analysis was achieved to determine if all non-displacement fringes are removed from the interferograms. If Φ_i and Φ_j denote two one-day interferograms acquired at date $(i, i+1)$ and $(j, j+1)$ respectively. The wrapped phase difference between interferograms $\Delta\Phi_{i-j}$ is defined as:

$$\Delta\Phi_{i-j} = [\Phi_i - \Phi_j] \text{ modulo } 2\pi \tag{1}$$

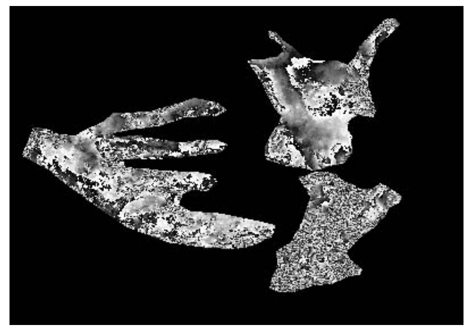
The two main sources of possible residual fringes in $\Delta\Phi_{i-j}$ are topographic fringes and atmospheric perturbations. First, an algorithm is proposed to detect the presence of residual fringes in $\Delta\Phi_{i-j}$. Next, a comparison of fringes pattern is achieved to determine if atmospheric fringes can be neglected. Finally, if non-displacement (topographic, tropospheric, ...) fringes are correctly removed or negligible in each one-day interferogram phase, $\Delta\Phi_{i-j}$ allows a characterization of surface flow field evolution.

A. Residual topographic fringes

Fig.4 shows the wrapped phase difference between interferograms on the Tour, Trient and Saleina glaciers at three dates. Residual fringes can be observed on the Trient glacier situated on the North East of the image. If all non-displacement fringes are removed from the interferograms, it means that the Trient glacier displacement is not stationary all along the year. The



(a)



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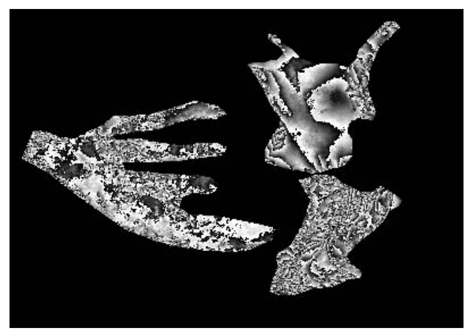

(c)

Fig. 4. Wrapped phase difference between interferograms on the Tour, Trient and Saleina glaciers: (a) $\Delta\Phi_{April-March}$, (b) $\Delta\Phi_{April-December}$, (c) $\Delta\Phi_{April-October}$

displacement changes a lot from October to April. In order to see if these fringes correspond to displacement variation or residual fringes, we propose to make a comparison between the residual fringes observed on the Trient glacier and the perpendicular baseline differences.

Let Φ^i_{topo} be the interferometric terms at date i corresponding to topographic fringes, ie: fringes due to height variation Δz over the studied area. Φ^i_{topo} can be expressed as a function of the orthogonal baseline at date i ($B^i_\perp$) by the following equation as:

$$\Phi^i_{topo} = \frac{4\pi}{\lambda} \frac{B^i_\perp}{R_1 \sin\theta} \Delta z = \frac{2\pi}{e^i_a} \Delta z \tag{2}$$

with the altitude of ambiguity defined as:

$$e_a^i = \frac{\lambda}{2}\frac{R_1 \sin\theta}{B_\perp^i} \quad (3)$$

Next, the equivalent orthogonal baseline $\Delta B_\perp^{ij}$ can be defined as the difference of the two orthogonal baseline at dates i and j. Similarly, the equivalent altitude of ambiguity Δe_a^{ij} can be defined by Eq. (5):

$$\Delta B_\perp^{ij} = B_\perp^i - B_\perp^j \quad (4)$$

$$\Delta e_a^{ij} = \frac{\lambda}{2}\frac{R_1 \sin\theta}{B_\perp^i - B_\perp^j} = \frac{1}{\frac{1}{e_a^i} - \frac{1}{e_a^j}} \quad (5)$$

The equivalent topographic terms $\Delta\Phi_{topo}^{ij}$ in the wrapped phase difference between interferograms at dates i and j can be expressed by:

$$\Delta\Phi_{topo}^{ij} = \frac{4\pi}{\lambda}\frac{|B_\perp^i - B_\perp^j|}{R_1 \sin\theta}\Delta z \quad (6)$$

$$= \frac{2\pi}{\Delta e_a^{ij}}\Delta z \quad (7)$$

Let $N_{ij}(X,Y)$ be the number of fringes observed on the interferogram difference $\Delta\Phi_{i-j}$ between two points X and Y and $\Delta z(X,Y)$ a height difference between X and Y. $N_{ij}(X,Y)$ is assumed to be positive if the fringe varies from the white to black color. The hypothesis that the observed residual fringes are linked to the topographic variations yields to:

$$\Delta\Phi_{topo}^{ij} = 2\pi N_{ij}(X,Y) \quad (8)$$

and by combining Eq. (7) and Eq. (8) to:

$$\Delta z(X,Y) = N_{ij}(X,Y)\Delta e_a^{ij} \quad (9)$$

This allows us to test this hypothesis by checking if the product $N_{ij}(X,Y)\Delta e_a^{ij}$ is constant over the different interferograms pairs (i,j).

$$N_{ij}(X,Y)\Delta e_a^{ij} = C^{te}(X,Y)\ \forall i,j \quad (10)$$

In this case the constant $C^{te}(X,Y)$ can be interpreted as a height difference $\Delta z(X,Y)$ which is not correctly removed in the D-InSAR processing and probably due to DTM errors. In other words, the equivalent altitude of ambiguity Δe_a^{ij} multiplied by the number of fringes observed is an indicator of the presence of residual topographic fringes.

The proposed method is applied on the four Tandem ERS-1/2 couples from October 1995 to April 1996. The following ERS parameters are used:

- R_1 = 790 km
- λ = 5.6 cm
- θ = 23°

Table III shows the equivalent orthogonal baseline and the equivalent altitude of ambiguity for the six different pairs of interferograms where coherence is preserved on glaciers. We can observe that the parameter $N\Delta e_a$ is unchanged for all the wrapped phase difference between interferograms on the Trient glacier. Therefore, according to Eq. (9) and results in table III, we can conclude that topographic fringes are not well removed on the Trient glacier probably because of the insufficient precision of the DTM on the Trient glacier which is located in Switzerland.

TABLE III
DETECTION OF RESIDUAL TOPOGRAPHIC FRINGES IN INTERFEROGRAMS

dates	Dec. Oct.	Mar. Dec.	Mar. Oct.	Apr. Mar.	Apr. Dec.	Apr. Oct.
$\Delta B_\perp$ (m)	315	-199	116	84	-115	200
Δe_a (m)	27	-43	74	103	-75	43
N	3	-2	1	< 1	-1	2
$N\Delta e_a$ (m)	81	86	74	< 103	75	86

B. Atmospheric perturbations

A second possible source of variation of D-InSAR fringe pattern is the presence of atmospheric perturbations. Fig.5 shows the wrapped phase difference between interferograms over the Mer de Glace - Leschaux and Argentière glaciers. As no residual fringe pattern are observable on the wrapped phase difference between interferograms, the studied glaciers are apparently not affected by global atmospheric changes [2]. Moreover, the glacier surfaces are rather small compared to a full ERS image and the path delay variation between due to saturation water vapor pressure less important with winter temperature (close or below 0 degree in this area). Accordingly, we can conclude that at first order, atmospheric perturbations are negligible compared to glacier displacement..

Once the topographic fringes are removed and atmospheric fringes neglected, $\Delta\Phi_{i-j}$ allows a characterization of surface flow field time evolution. Note that for two consecutive interferograms pair (April and March in Fig.5(a)), the wrapped phase difference is closed to zero and slightly increases with the time interval of the two interferograms (using March-December Fig.5(b) and March-October Fig.5(c) interferograms). Moreover, no residual fringes can be observed at the stationary area on Argentière glacier define on section III. It seems that at 2700m asl, the displacement is the same during the seasons.

Nevertheless, a precise characterization of the flow field evolution can be done only if topographic fringes are correctly removed from the interferograms and atmospheric fringes totally negligible. As topographic fringes are directly related with the altitude of the glacier and the glacier surface varies with time, a DEM at the date of acquisition should be used. Moreover, meteorological in situ measurements should be acquired at the date of the satellite acquisition to determine if interferograms are affected by tropospheric perturbations.

V. CONCLUSION

A multi-date ERS tandem interferogram analysis was carried out over glaciers and non glaciers areas in the Alps. This study shows when InSAR processings can be used to monitor temperate glaciers. A comparison of interferometric coherence preservation as a function of altitude was exposed. Thanks to the knowledge of a stable area over the Argentière glacier, a

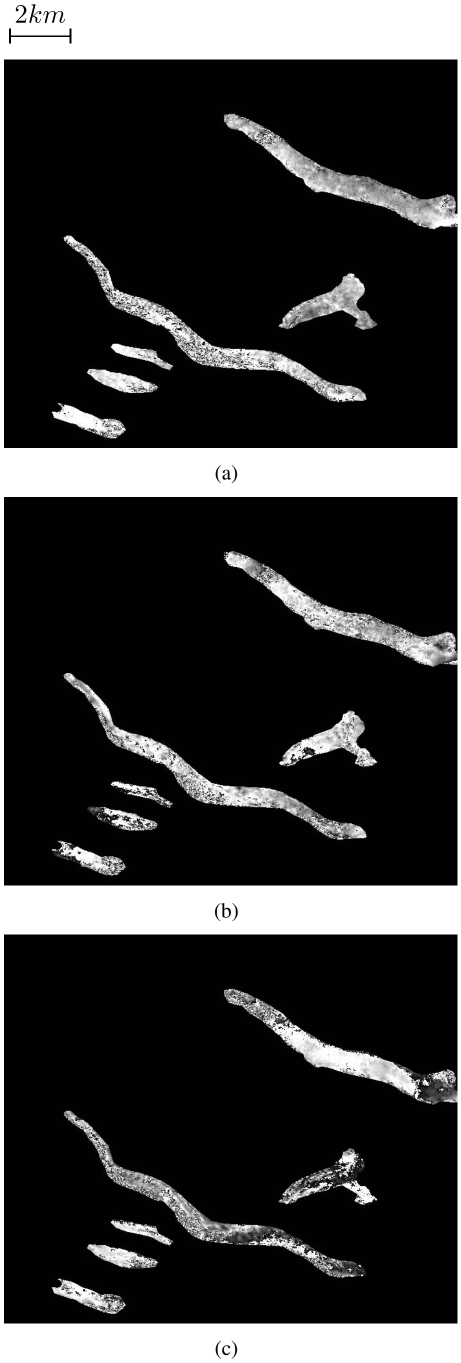

Fig. 5. ERS-1/2 wrapped phase difference between interferograms over the Mer de Glace - Leschaux and Argentière glaciers area. (a) $\Delta\Phi_{April-March}$, (b) $\Delta\Phi_{March-December}$, (c) $\Delta\Phi_{March-October}$

multi-temporal displacement field evolution was derived. A method based on the equivalent altitude of ambiguity was proposed to detect the presence of residual topographic fringes in wrapped phase difference between interferograms. Finally, a comparison of fringes was exposed to characterize the surface flow field evolution. Further works will deal with the use of a corner reflector and a continuous GPS (Global Positioning System) installed on the upper part of the Argentière glacier. The continuous GPS will provide one day displacement at the date of the SAR acquisition, which will be useful to fix precisely the SAR LOS offset. No more a priori knowledge (stationary area) will be necessary. Moreover, to exploit the phase difference between differential interferograms as an indicator of the velocity field evolution, the variation of atmospheric perturbations must be negligible compare to the variation of displacement. This observation cannot be done with the only information provided by ERS interferograms. The continuous GPS should allow us to remove the small atmospheric effects from the interferograms and to use the phase difference between interferograms to characterize the evolution of the displacement field.

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