Suivi des glaciers de montagne par imagerie radar satellitaire

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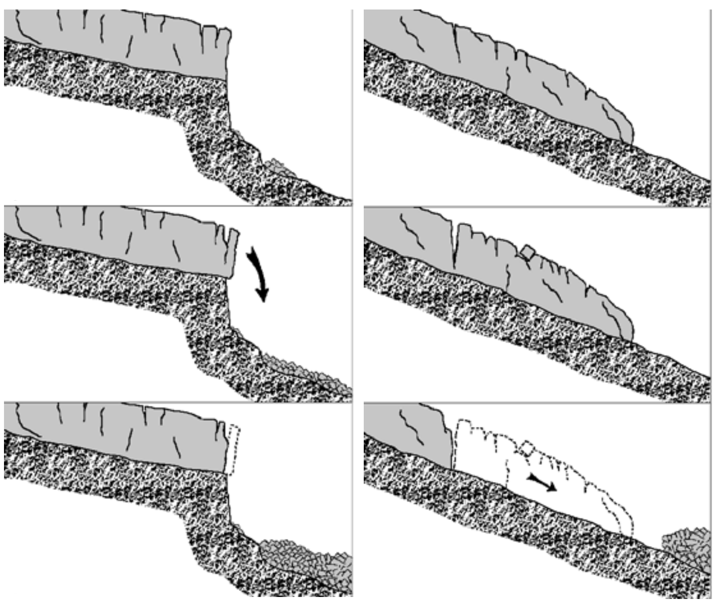
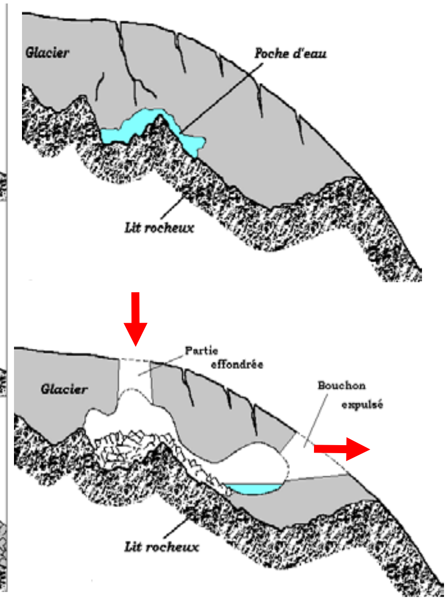
With contributions from : J.-M. Nicolas (Télécom P.), M. Gay and G. Vasile (GIPSA), Y. Yan, R. Fallourd, A. Dehecq and M. Jauvin (LISTIC), and project partners from :

- MEGATOR (ACI MD 2004-2007) : http://www.megator.fr
- EFIDIR (ANR MDCO 2008-2012) : http://efidir.poleterresolide.fr/

Why monitoring temperate glaciers?

- Economical issues
  - water resources, tourism activity
- Environmental issues
  - local impact of global change
- Risk assessment
  - seracs, crevasses, water accumulation...



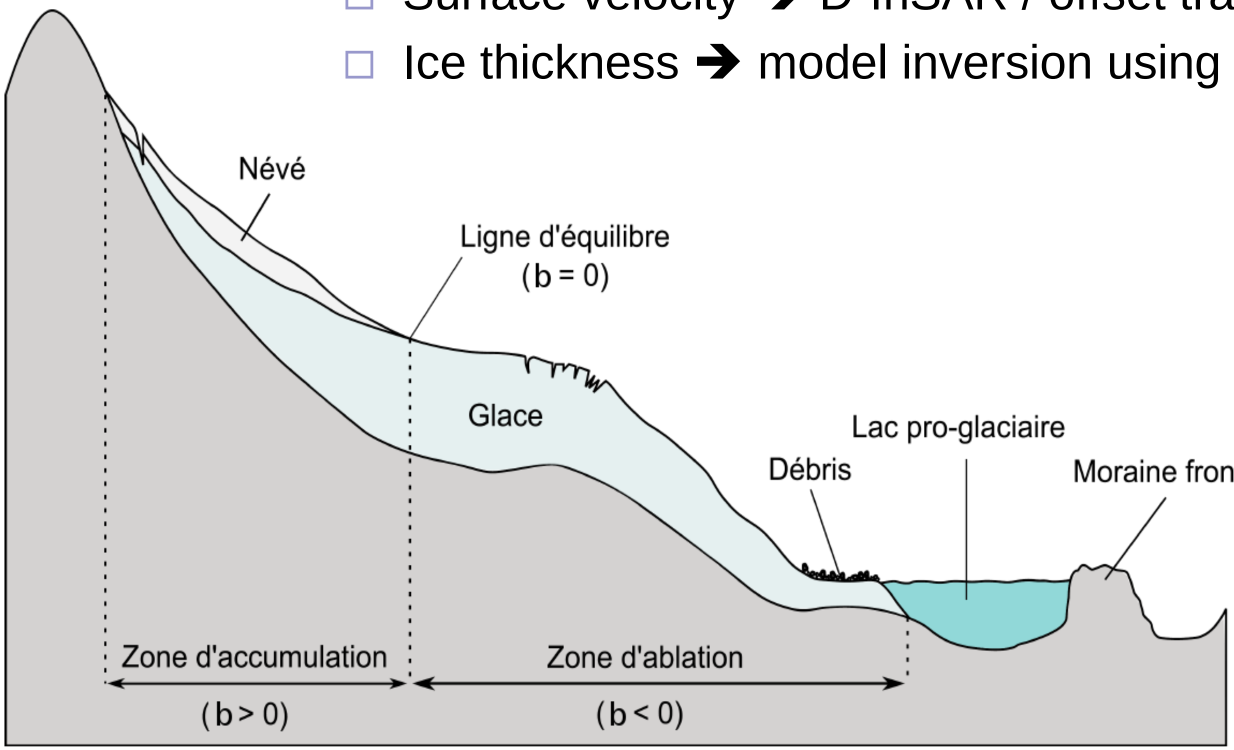



© : Musée alpin de Chamonix
1860


Photo : Sylvain Coutterand
2008

SAR contribution for glaciology

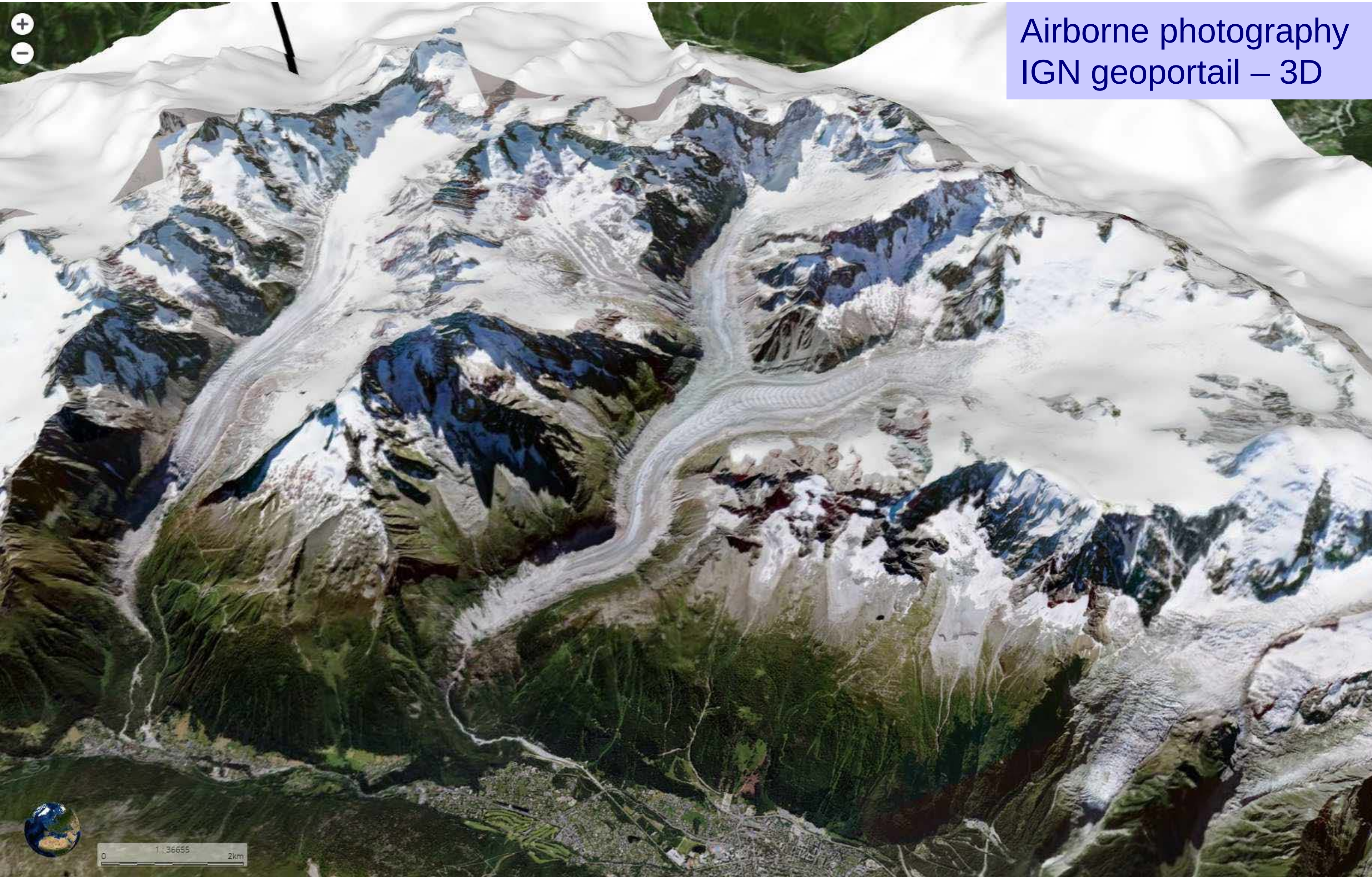
- Physical parameters to observe
  - Front position ➔ HR data segmentation / change detection
  - Surface state ➔ PolSAR data
  - Elevation variations / mass balance ➔ InSAR, TanDEM-X
  - Surface velocity ➔ D-InSAR / offset tracking
  - Ice thickness ➔ model inversion using velocity



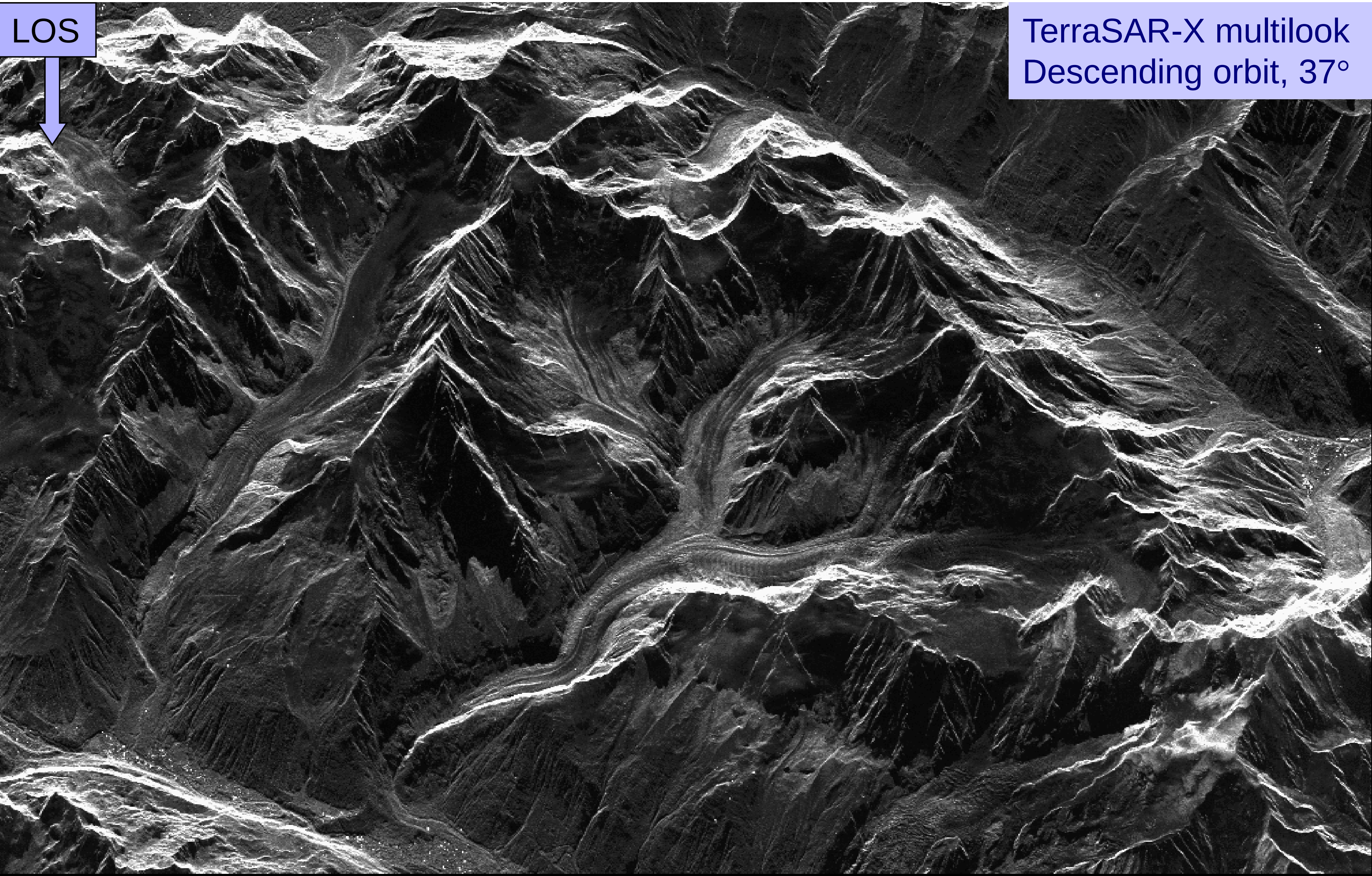
[Gardelle 2012]

Chamonix Mont-Blanc test-site

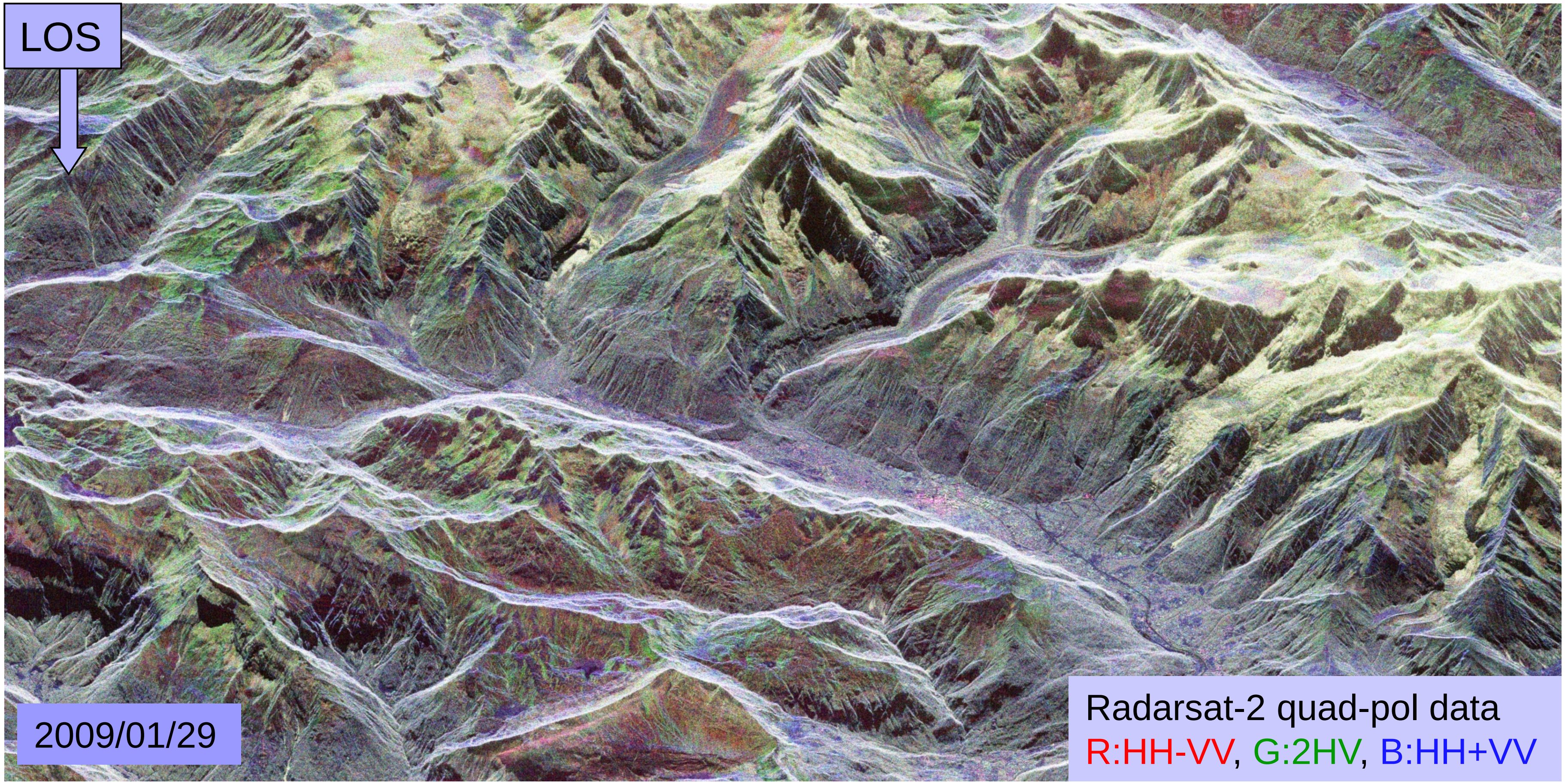
Airborne photography
IGN geoportail – 3D



Chamonix Mont-Blanc test-site



Chamonix Mont-Blanc test-site



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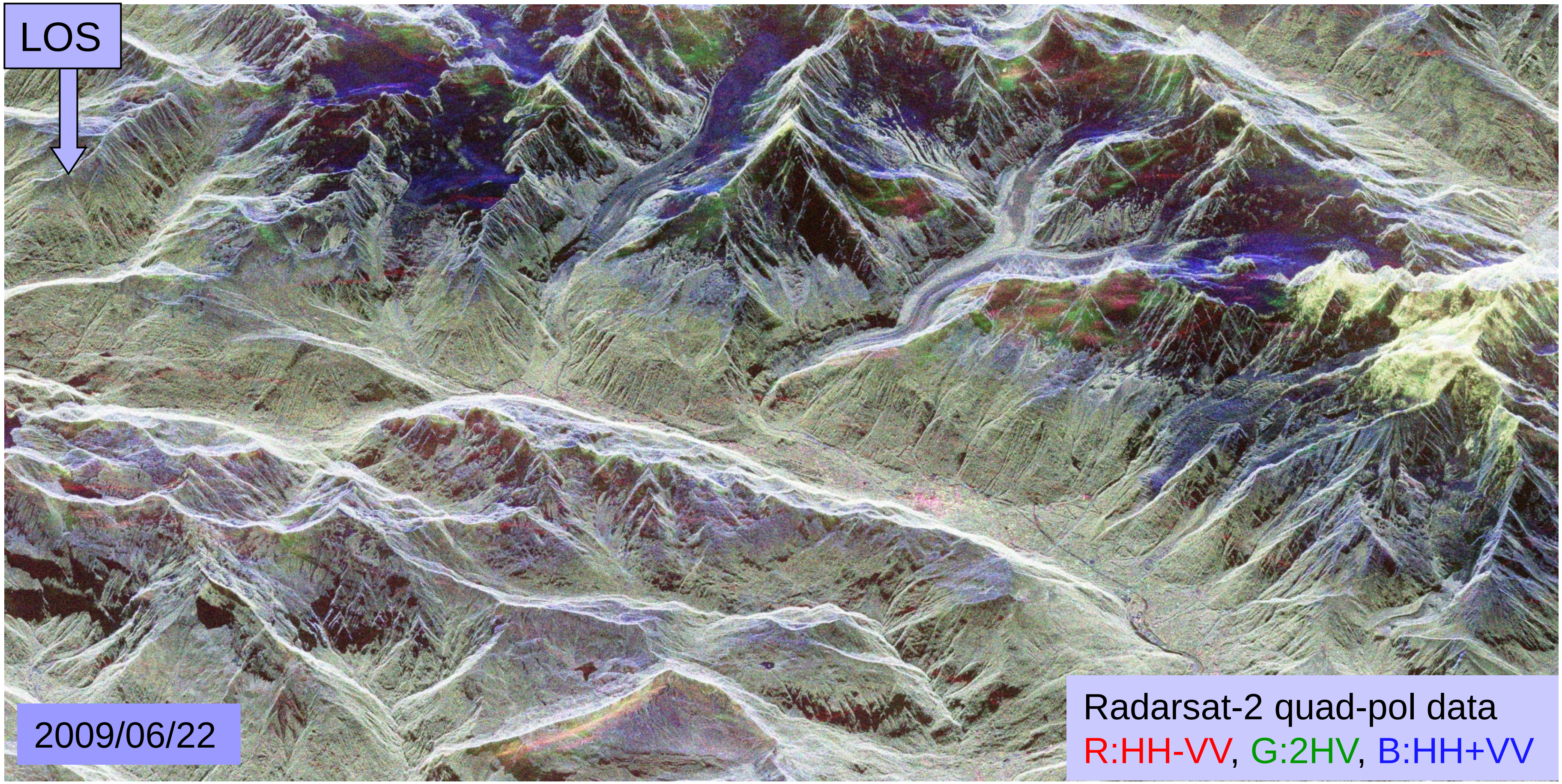
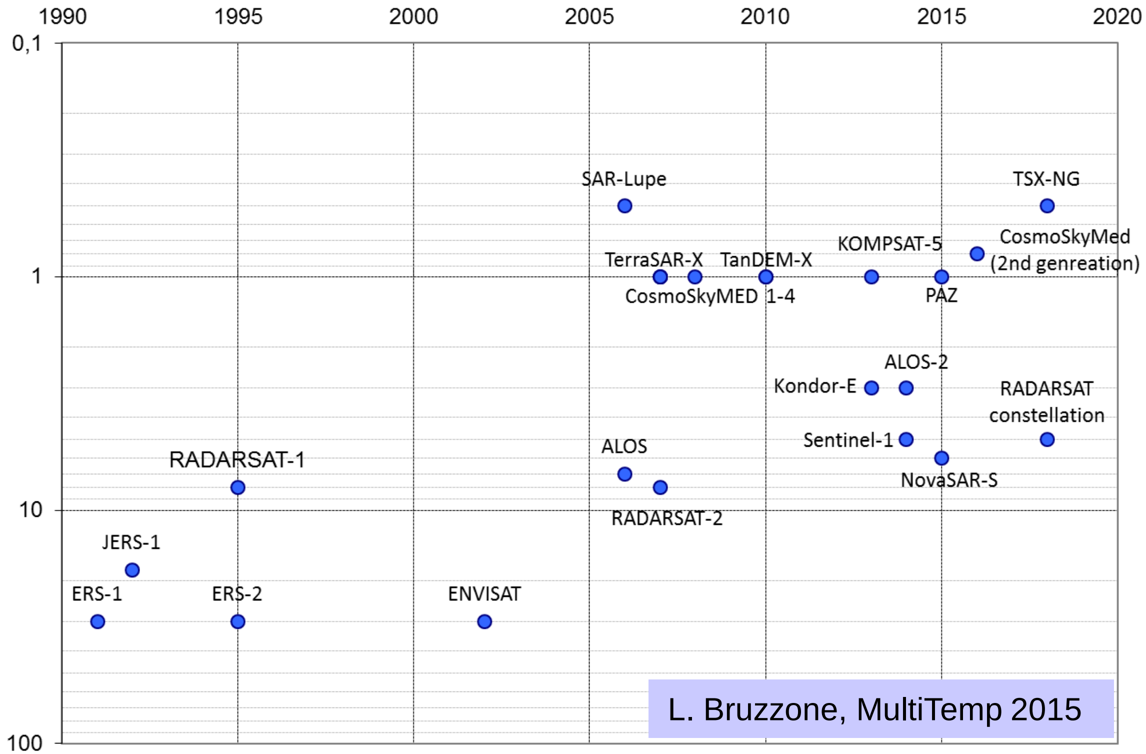


3 generations of SAR satellites



- 90-2015 1st generation
  - ERS-1/2, ENVISAT:
    C band, ~20m, 35 days
  - JERS: L band, 20m
  - Radarsat-1: C band, ~10m
- 2005-2014 2nd generation
  - ALOS: L band, 10m, quad-pol, 46 days
  - TerraSAR-X (DLR): X band, ~1m, dual-pol, 11 days
  - Radarsat-2 (CSA): C band, ~3m, quad-pol, 24 days
  - COSMO-SkyMed (ASI): X band, ~1m, 4 satellites => 4 days

- High Resolution
- Polarimetry

- 2015-2025 3rd generation
  - Sentinel-1 A/B: C band, ~5x15m, dual-pol, 12->6 days, **systematic, FREE ACCESS**
  - …

Overview

1. Surface displacement by differential interferometry
    - Potential and limits
    - Processing steps
    - Results from ERS tandem data
2. 2D/3D surface displacement by offset tracking
    - Potential and limits
    - Processing steps
    - Results from TerraSAR-X stripmap images
3. Surface elevation by SAR interferometry
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    - Results from TanDEM-X data
4. How about Sentinel-1?
5. Perspectives

Interferometric data

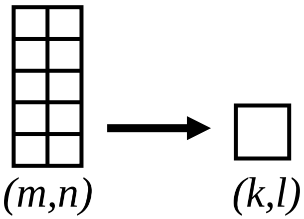
- 2 SLC images:

$$u_1(m,n) = \rho_1(m,n)e^{i\phi_1(m,n)}$$
$$u_2(m,n) = \rho_2(m,n)e^{i\phi_2(m,n)}$$

Registration, Hermitien product

$$u_1(m,n).u_2^*(m,n) = \rho_1(m,n).\rho_2(m,n).e^{i(\phi_1-\phi_2)}$$

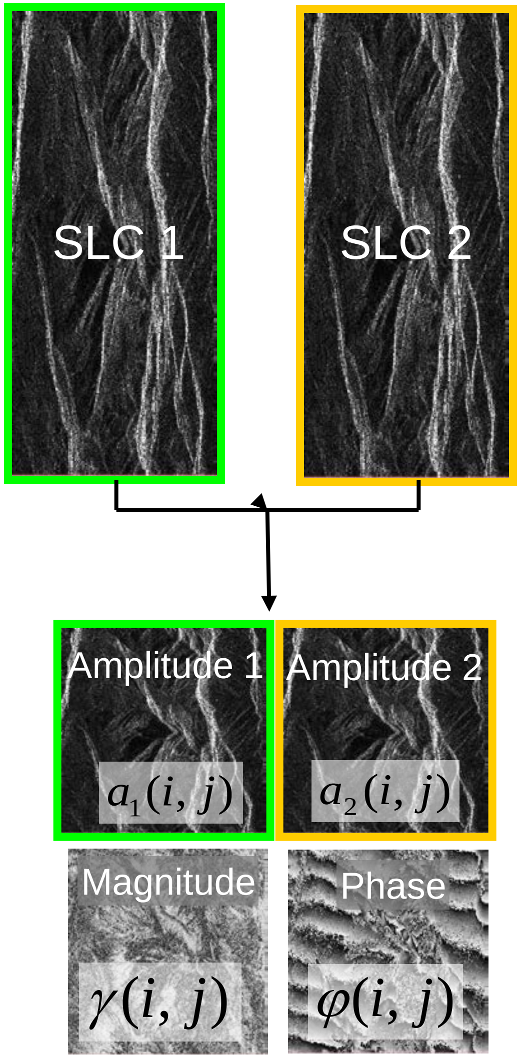
- Initial complex multi-looking



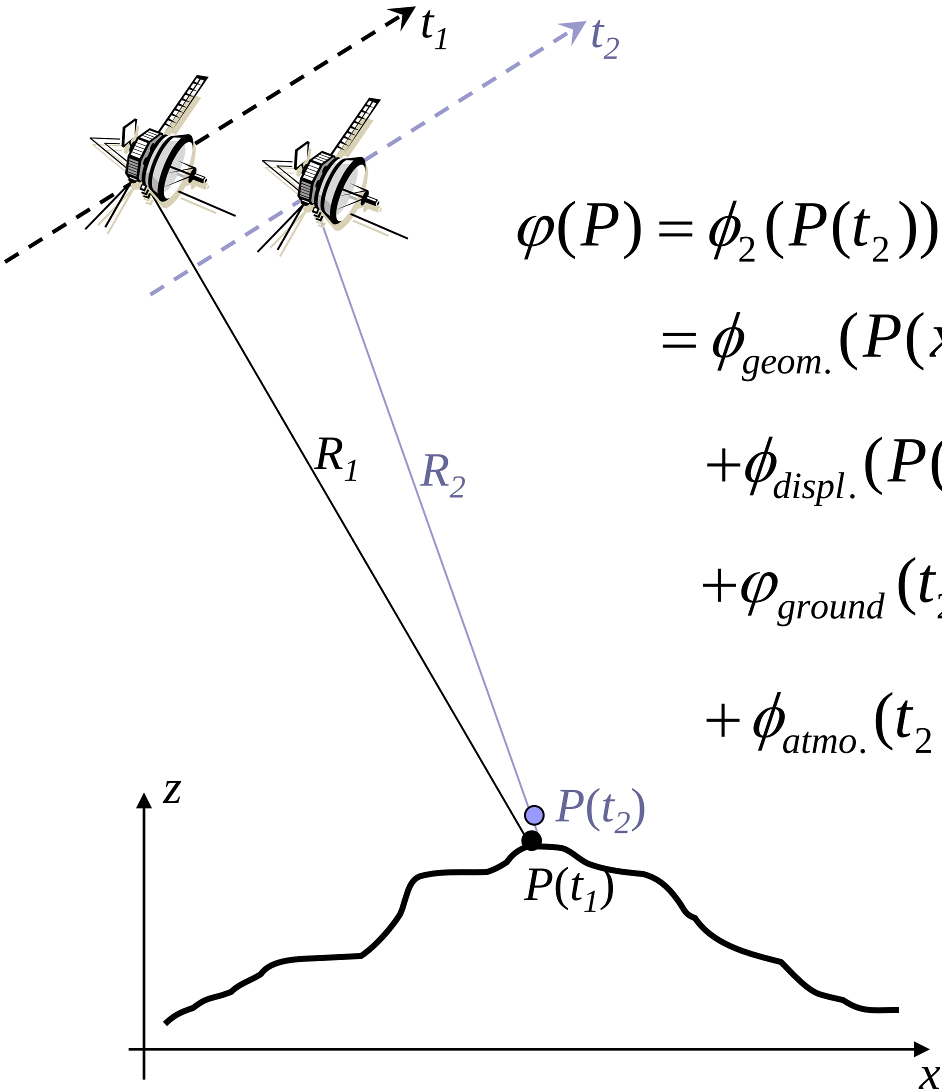
$$\gamma(k,l)e^{i\phi(k,l)} = \frac{\sum_{(m,n)} u_1(m,n).u_2^*(m,n)e^{-i\phi(m,n)_{known}}}{\sqrt{\sum_{(m,n)} |u_1(m,n)|^2 \cdot \sum_{(m,n)} |u_2(m,n)|^2}}$$

COHERENCE

INTERFEROGRAM



Interferometric phase



$$\varphi(P) = \phi_2(P(t_2)) - \phi_1(P(t_1)) = \frac{4\pi}{\lambda}(R_2 - R_1) + ...$$

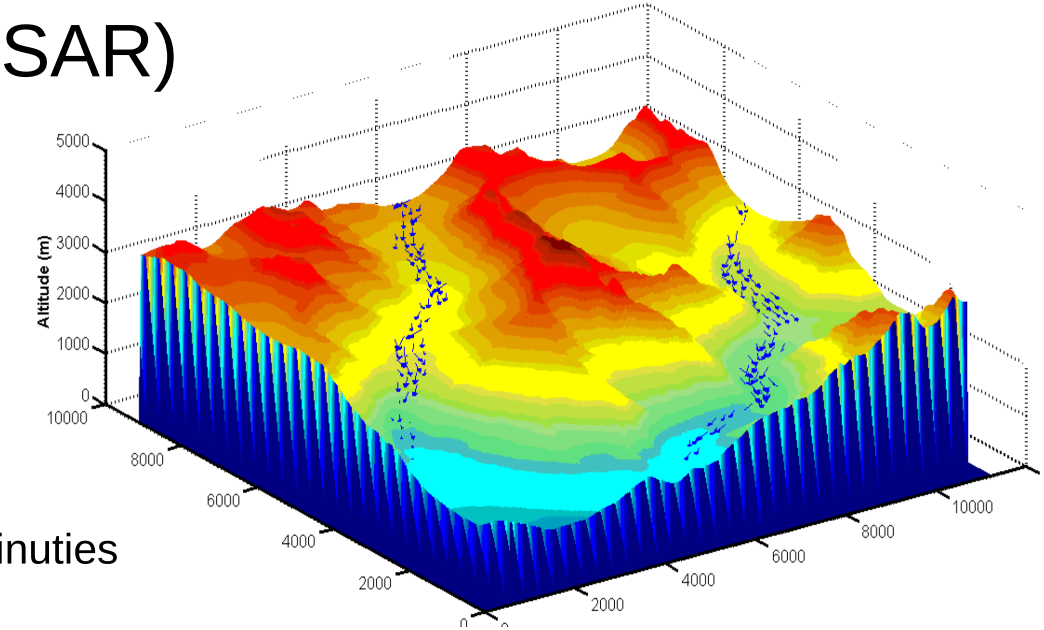
$$= \phi_{geom.}(P(x,z))$$ ⇒ Digital Elevation Model (DEM)

$$+\phi_{displ.}(P(t_2) - P(t_1))$$ ⇒ Displacement field

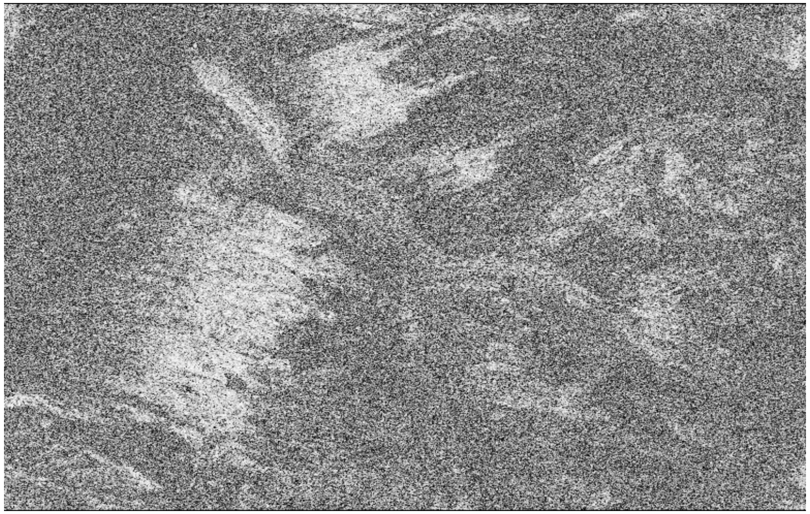
$$+\varphi_{ground}(t_2) - \varphi_{ground}(t_1)$$ ⇒ Decorrelation

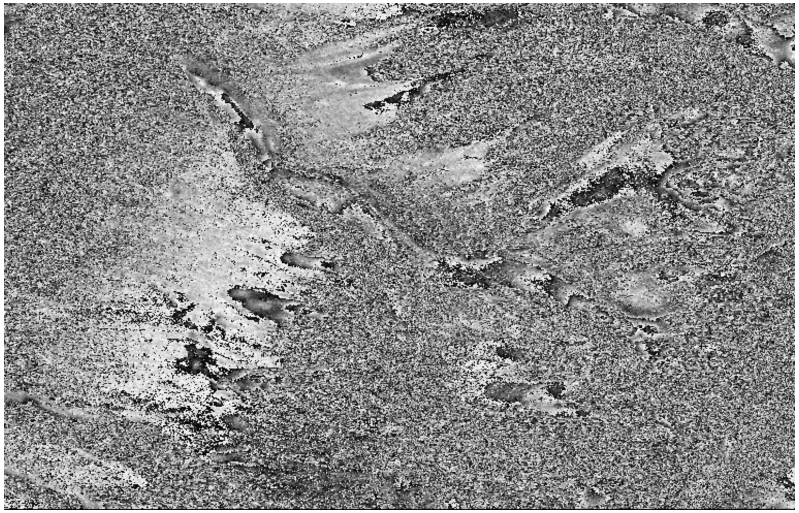
$$+\phi_{atmo.}(t_2) - \phi_{atmo.}(t_1)$$ ⇒ Atmospheric perturbations

Interferometric data (InSAR)



- Potential
  - InSAR: topography
  - D-InSAR: displacement
- Limits
  - Temporal/baseline decorrelation
  - Aliasing
  - Phase unwrapping: noise, discontinuties
  - Atmospheric perturbations

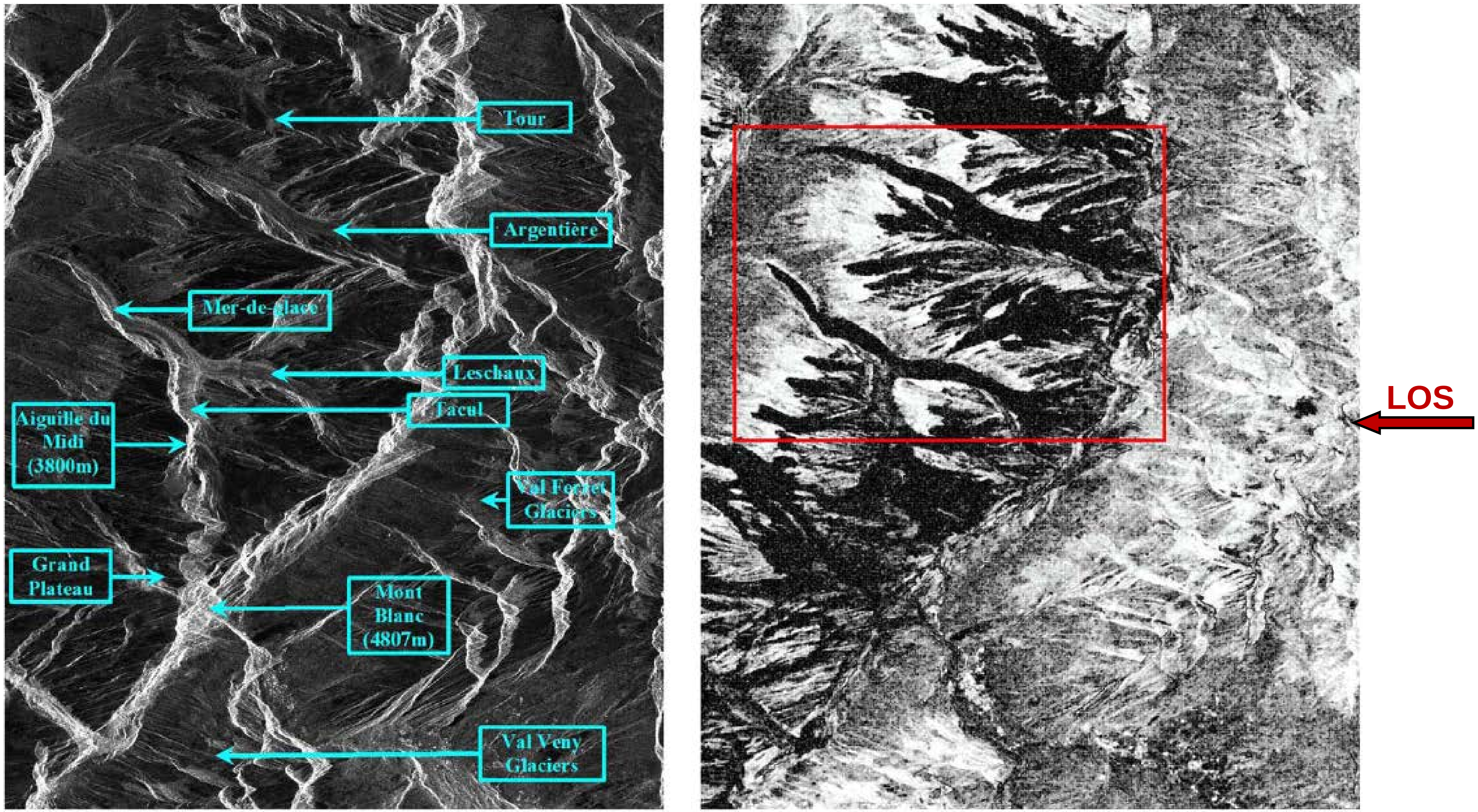




ERS 1/2, 95/12/31-96/01/01, Mont-Blanc area

Coherence limitation, ERS

- ERS data, C band, Res~20m



ERS-1, 3-day pair, summer 1991, Chamonix Mont-Blanc

Noise and phase unwrapping limitation

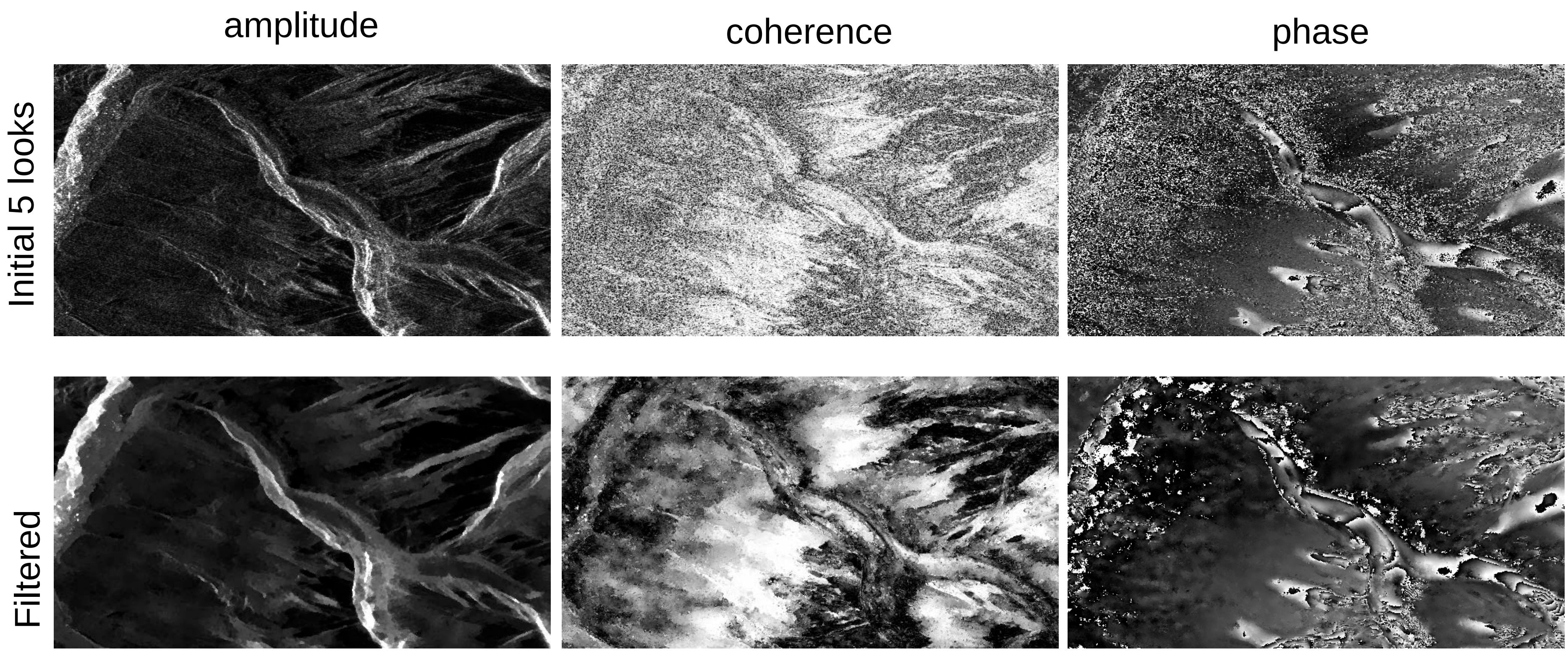
Estimation of the 2D local frequency (phase gradient): (f_x, f_y)

- Analytic signal $$e^{i\phi} = e^{i\phi_d} e^{i\phi_n}$$
- 1st order model $$\phi_d(m,n) = \phi_d(k,l) + 2\pi[(m-k)\cdot f_x + (n-l)\cdot f_y]$$

Application:

- Coherence and phase filtering
  ➔ compensation of the local slope in the averaging window to respect the “local stationarity” hypothesis [Vasile-08]
- Phase unwrapping
  ➔ integration of the phase gradient

Coherence and Phase filtering - results



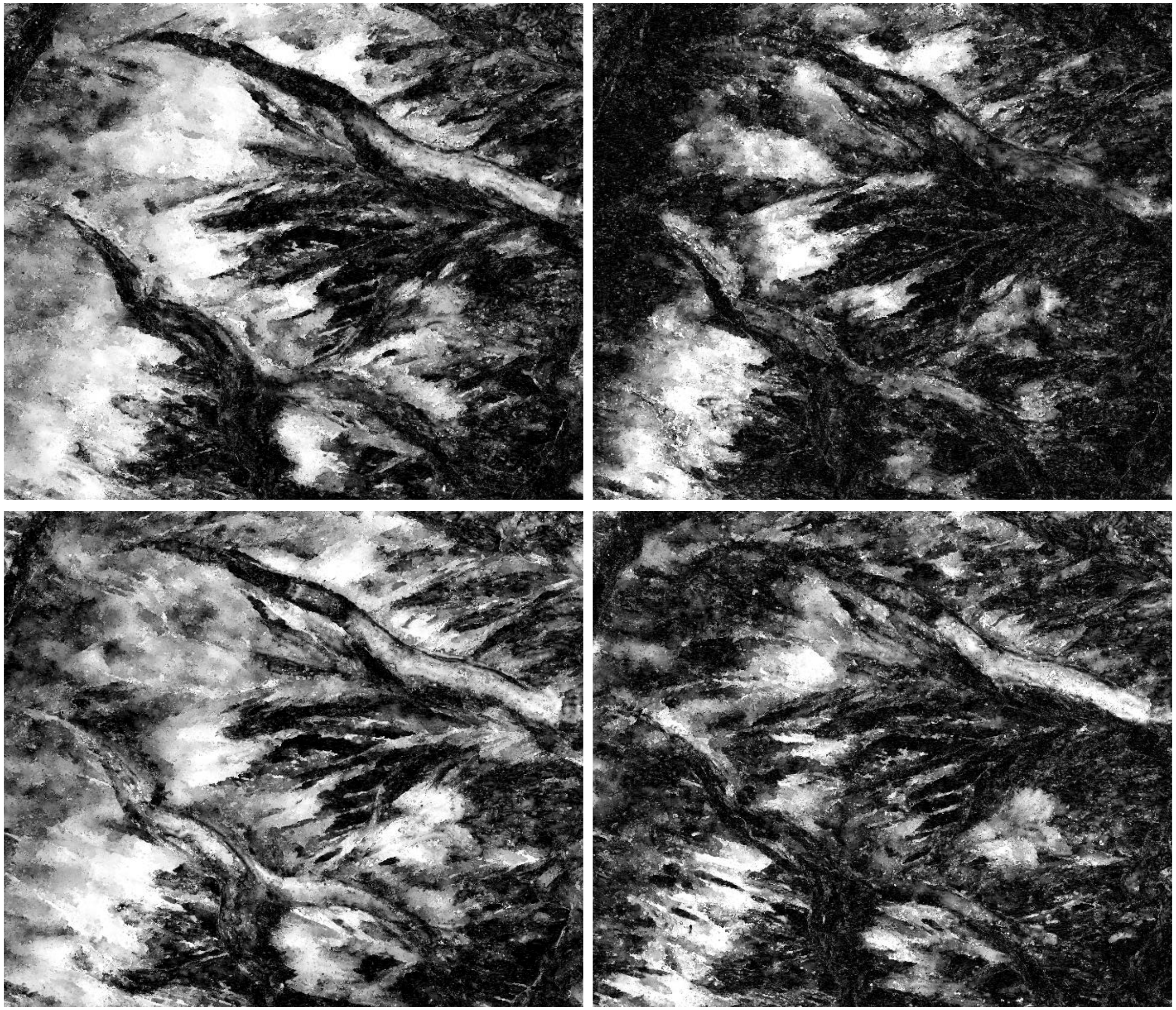
ERS, Mer-de-Glace glacier [660 × 360 pixels]

ERS, D-InSAR over Alpine glaciers

LOS

22 / 23 oct 95
$b^{\perp}$ = -107 m

31 déc 95 /
1 jan 96
$b^{\perp}$ = 208 m



10 / 11 mar 96
$b^{\perp}$ = 9 m

14 / 15 avr 96
$b^{\perp}$ = 93 m

ERS-tandem, autumn/winter/spring 95-96, Chamonix Mont-Blanc

ERS, D-InSAR over Alpine glaciers

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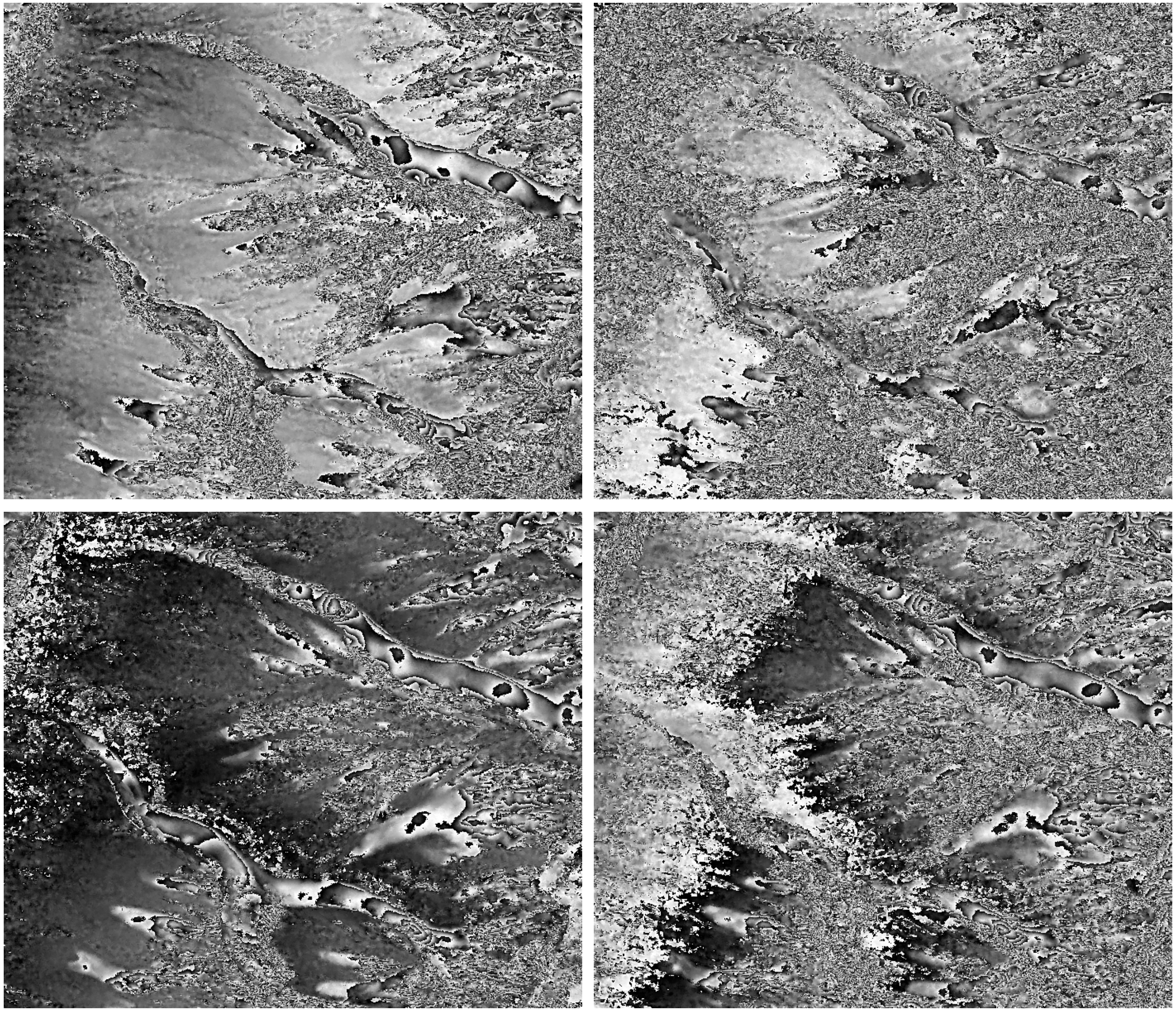

10 / 11 mar 96
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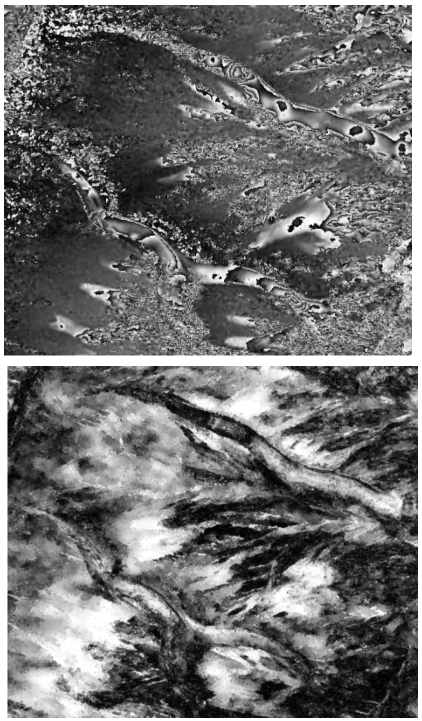
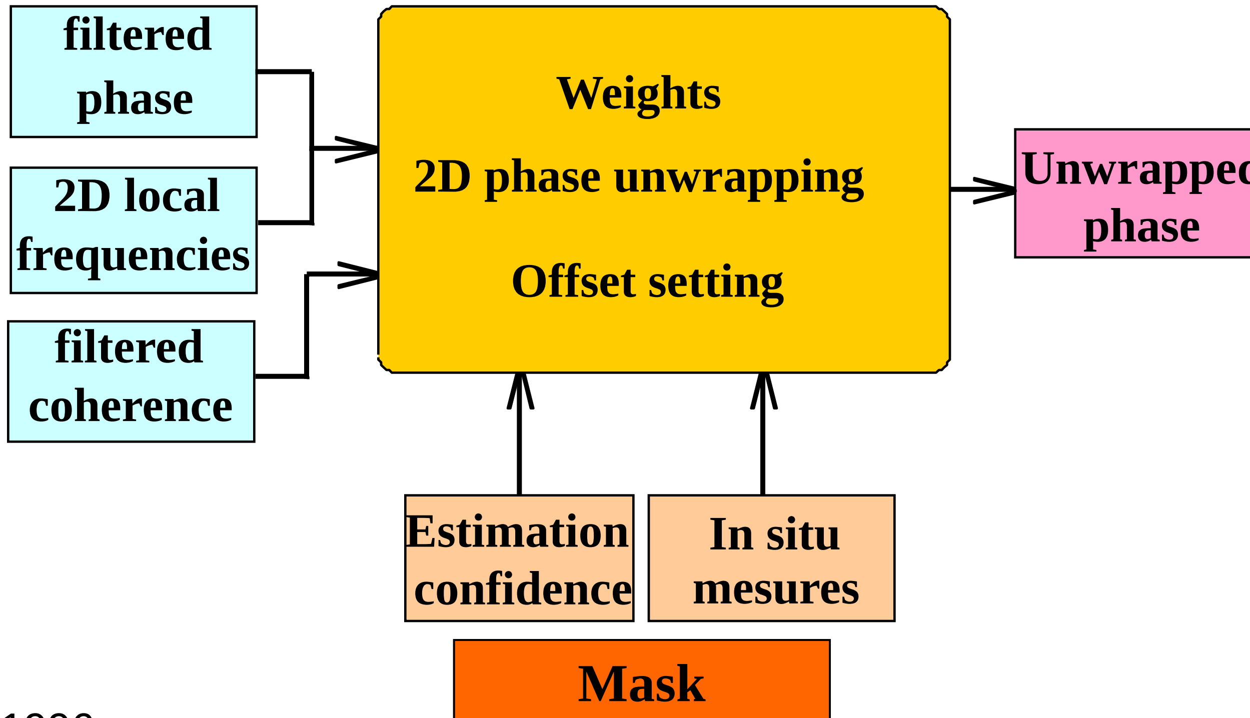
ERS-tandem, autumn/winter/spring 95-96, Chamonix Mont-Blanc

Weighted Least Square Phase Unwrapping



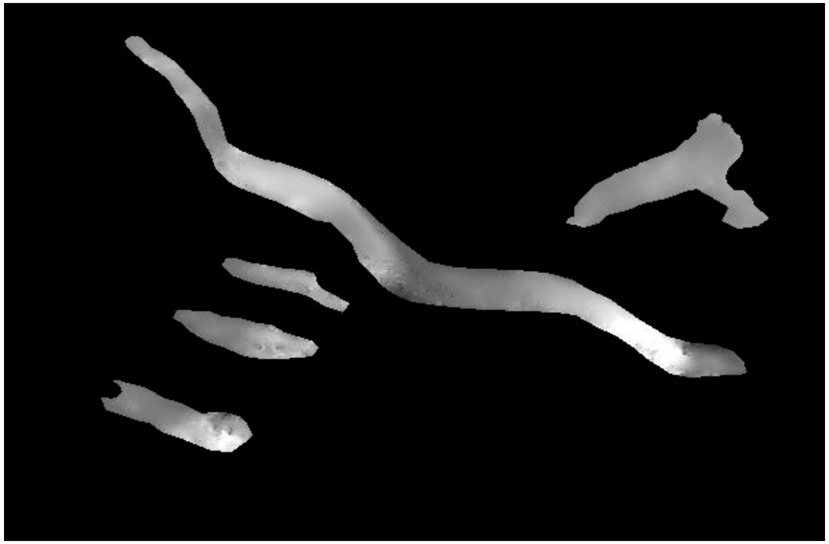
TANDEM ERS, 10/11-March-1996
Chamonix Mont-Blanc



D-InSAR phase unwrapping result

- Mer-de-glace glacier, ERS Tandem, weighted least-square phase unwrapping [Ghiglia and Romero, JOSA, 1994]

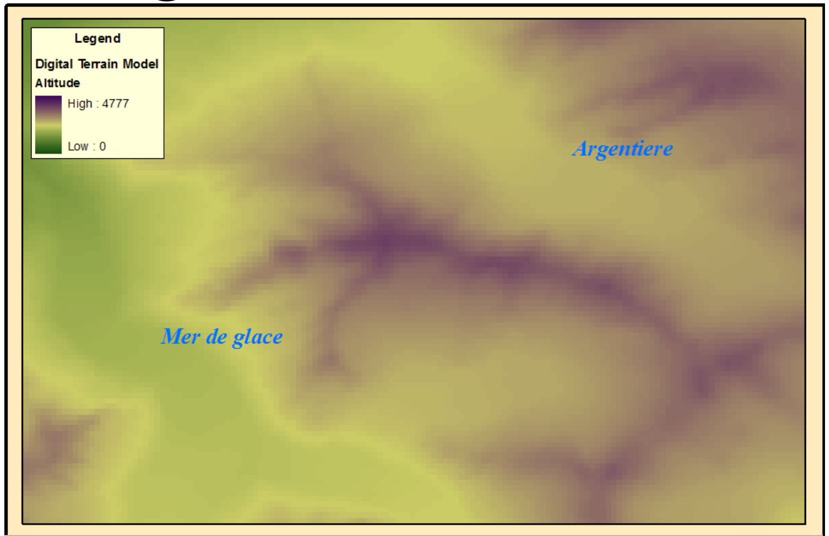
Filtered phase

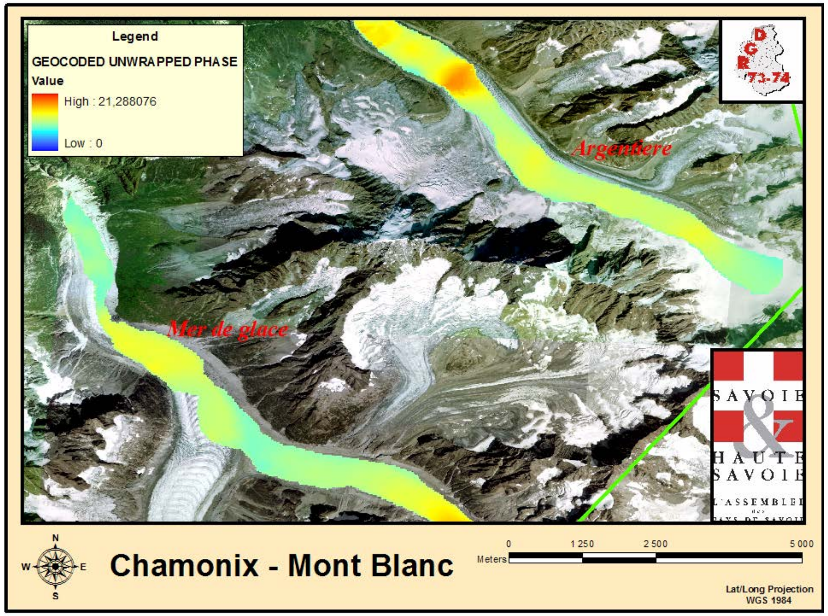


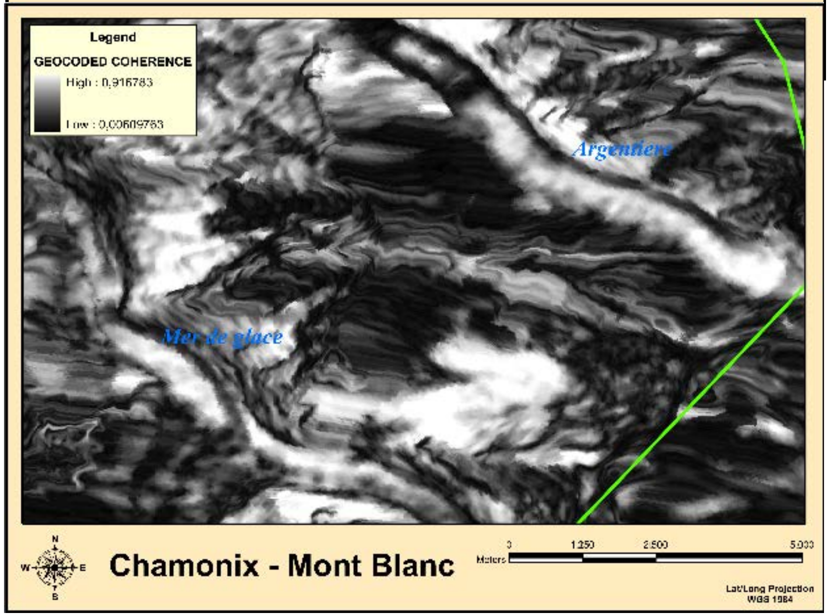
Unwrapped phase

ERS, D-InSAR over Alpine glaciers [Trouvé-07]

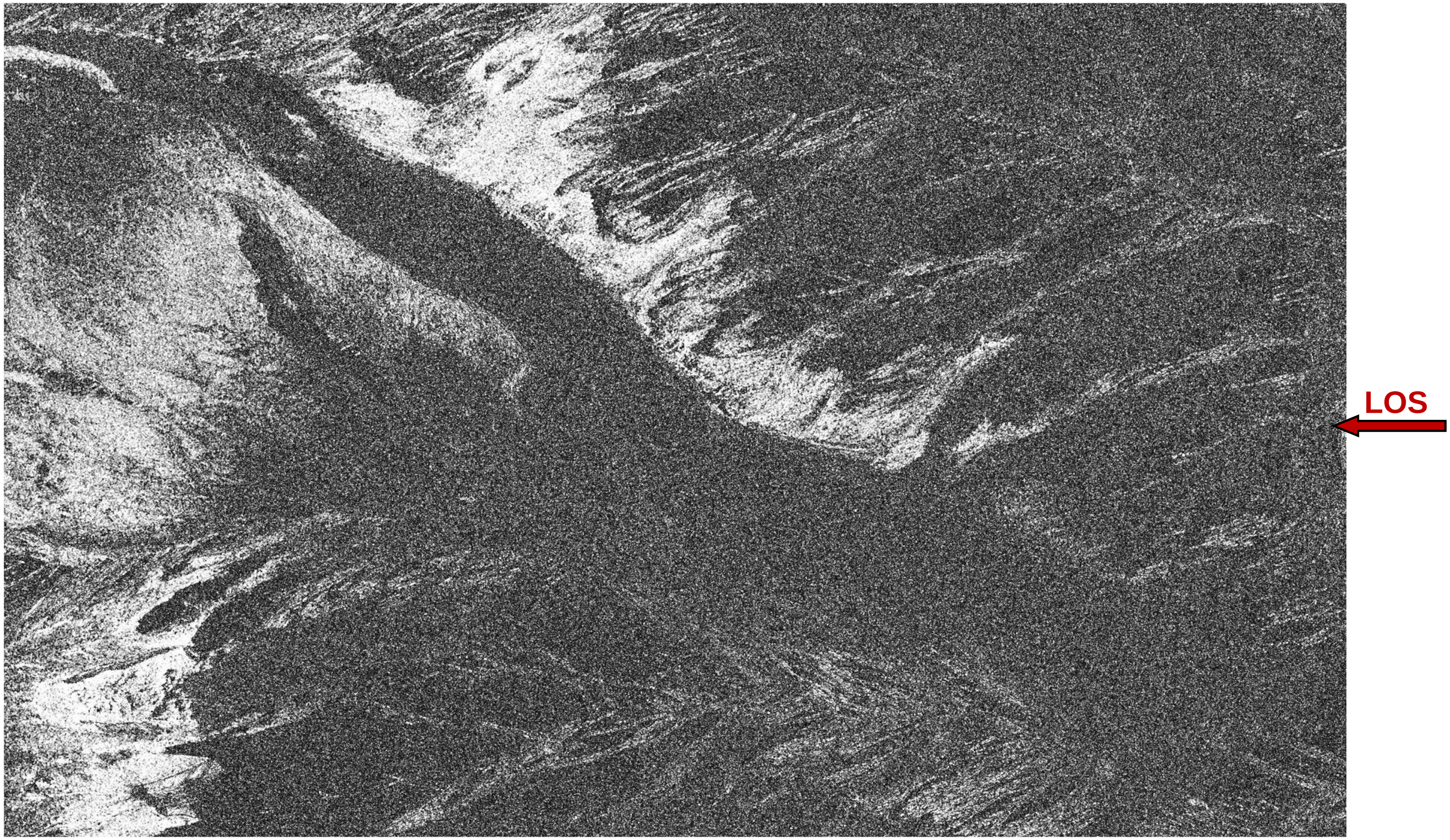
- Combined results:
  - InSAR: LOS displacement
  - GPS: unwrapping offset
  - DTM: ➔geocoding
    ➔flow direction





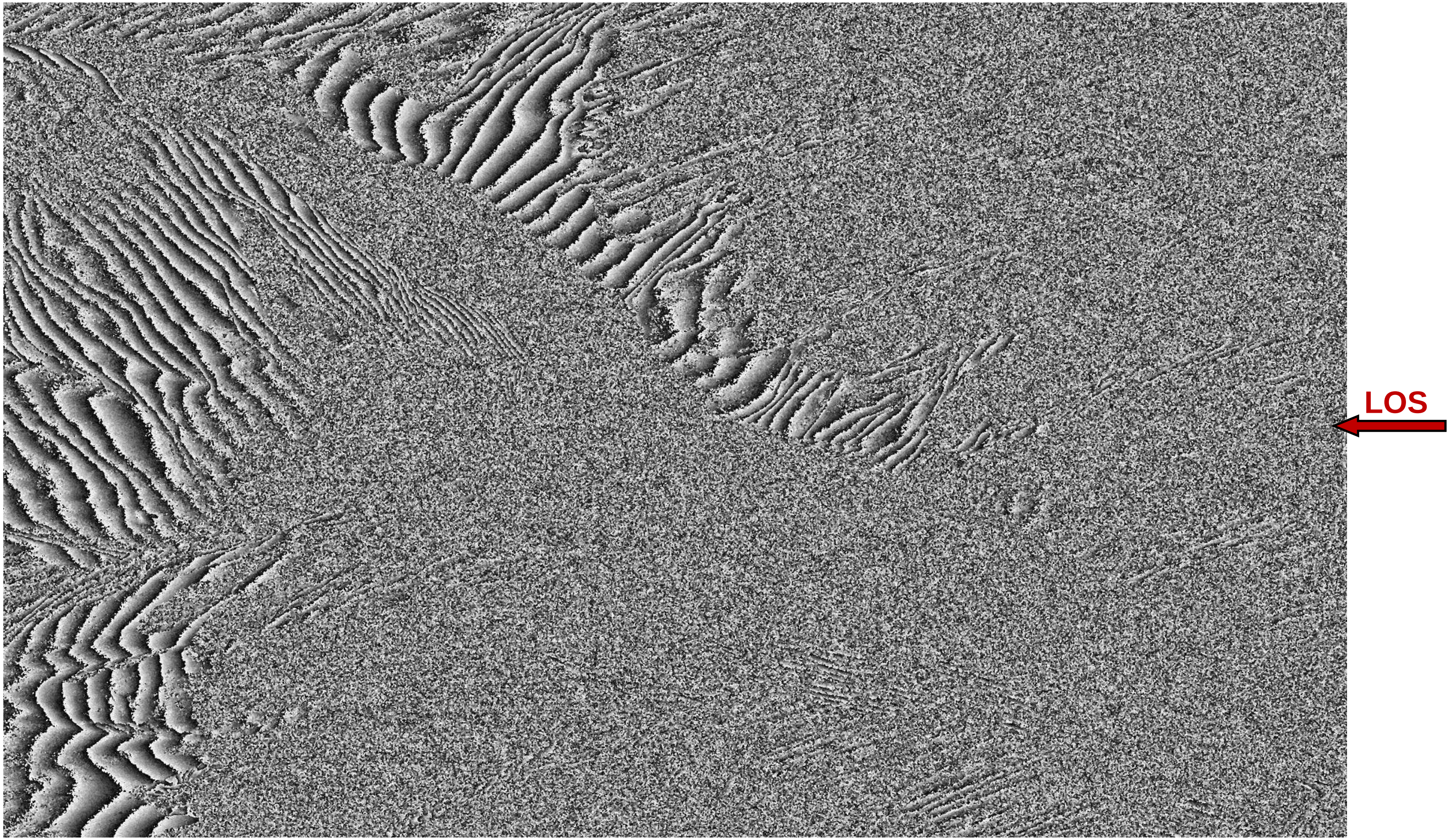


Coherence limitation, TerraSAR-X



11-day pair, Sept. 29 / Oct. 10 2008, Argentière glacier

Coherence limitation, TerraSAR-X



11-day pair, Sept. 29 / Oct. 10 2008, Argentière glacier

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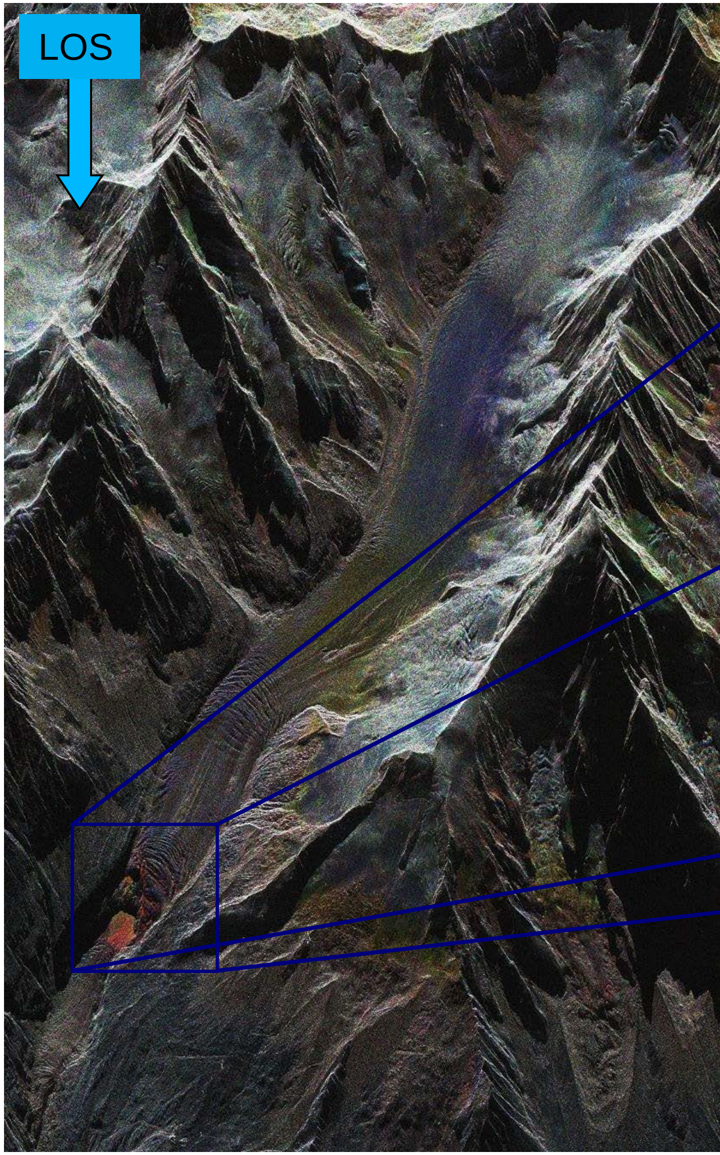
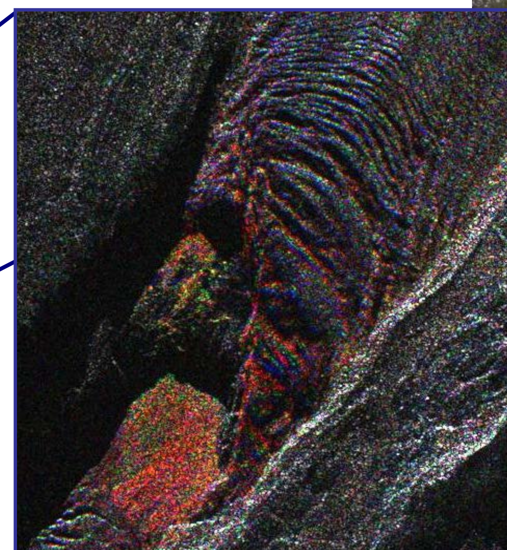
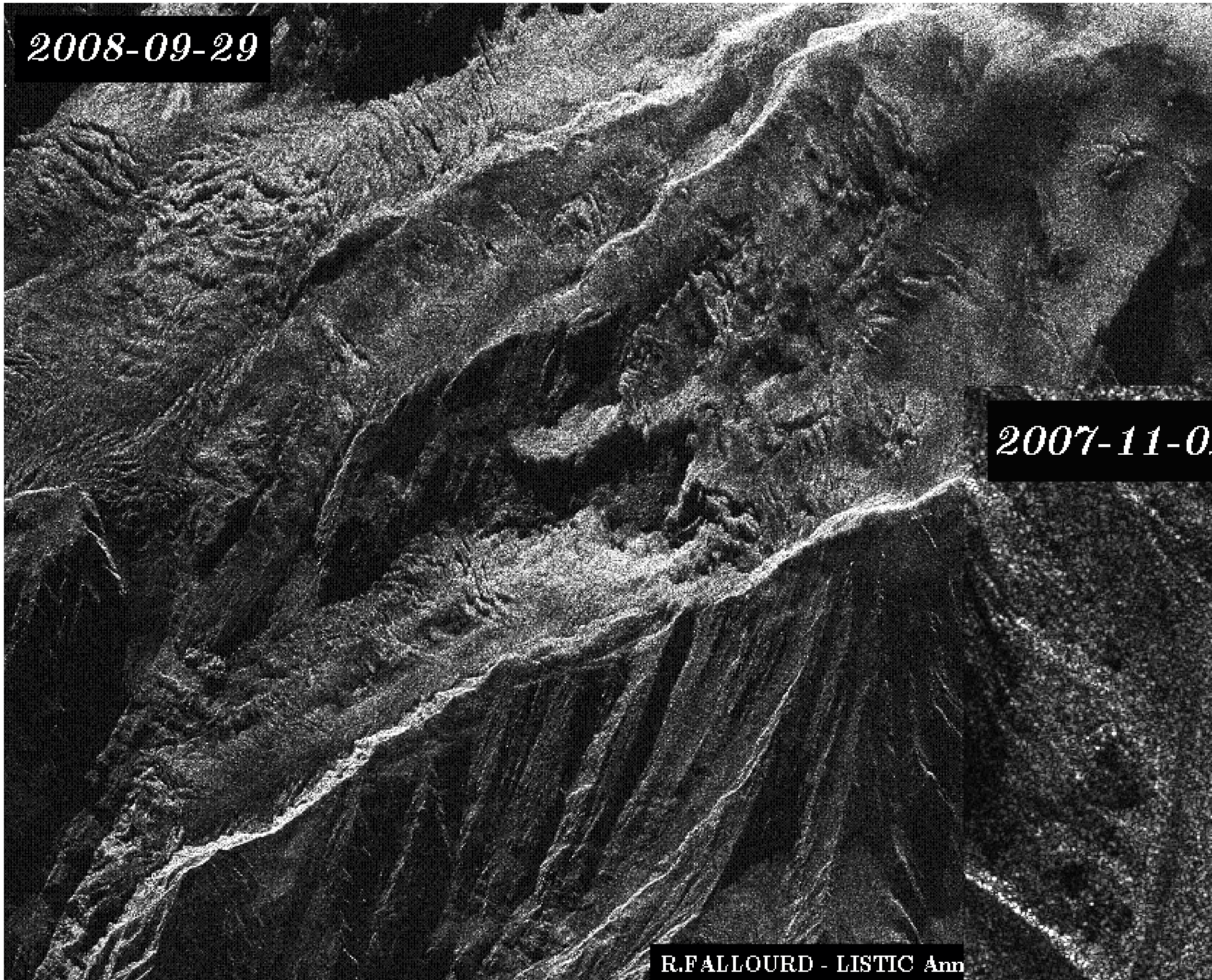
Multi-temporal HR SAR images - TerraSAR-X (~2m)



Argentière glacier ,
RGB composition
29/09/08,
10/10/08,
21/10/08

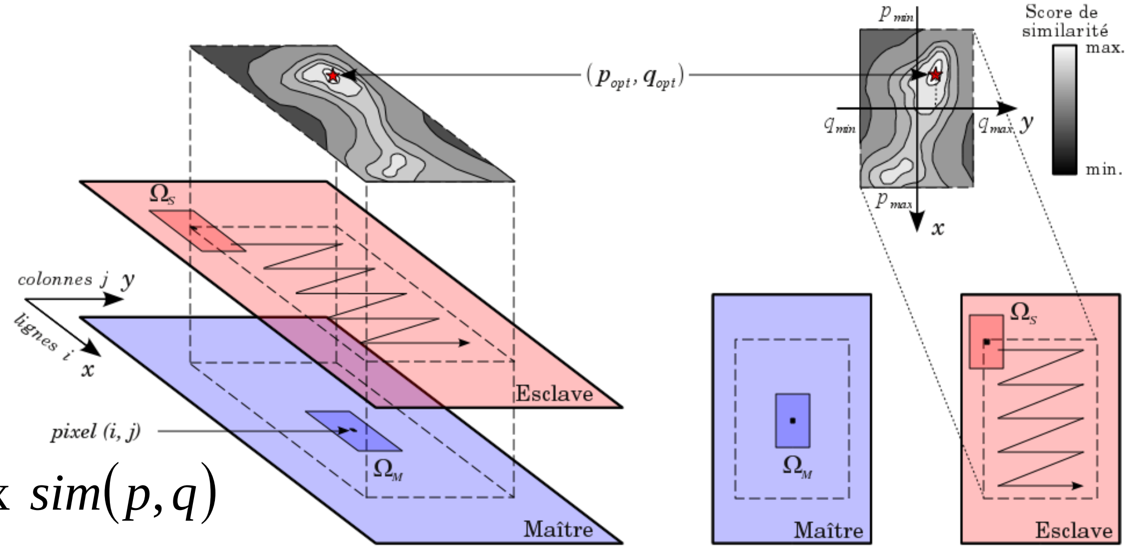


Target / Feature tracking



Offset tracking

- Principle



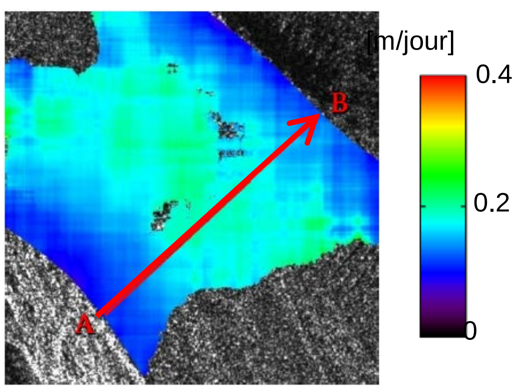
$$\vec{V}(i,j) = \left(p_{opt}, q_{opt}\right) = \underset{(p,q)\in\Delta}{\arg\max}\; sim(p,q)$$

- Similarity functions

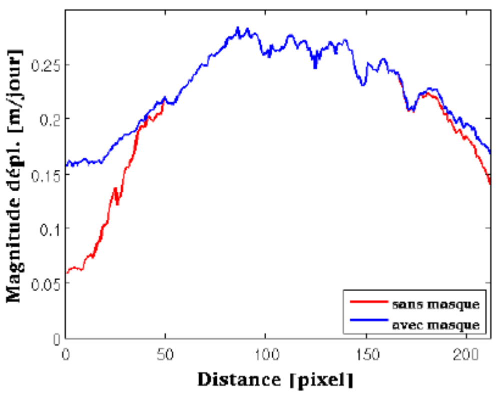
Normalized Cross-correlation	$NCC(p,q) = \dfrac{\sum_{(k,l)\in\Omega_M} I_m(k,l) I_s(k+p,l+q)}{\sqrt{\sum_{(k,l)\in\Omega_M} \lvert I_m(k,l)\rvert^2 \sum_{(k,l)\in\Omega_M} \lvert I_s(k+p,l+q)\rvert^2}}$
Decorrelated speckle [Erten et al. 2009]	$UML(p,q) = \sum_{(k,l)\in\Omega_M} \left(\underline{I}_m(k,l) - \underline{I}_s(k+p,l+q) - 2\ln\left(1+e^{(\underline{I}_m(k,l)-\underline{I}_s(k+p,l+q))}\right)\right)$
Correlated speckle [Erten et al. 2009]	$CML(p,q) = \left(\underline{I}_m(k,l) - \underline{I}_s(k+p,l+q) - 2\ln\left(1+e^{(\underline{I}_m(k,l)-\underline{I}_s(k+p,l+q))}\right)\right)$ $\ldots - \left(1+\dfrac{1}{2N}\right)\ln\left(1-\dfrac{4\rho e^{(I_m(k,l)-I_s(k+p,l+q))}}{\left(1-e^{(I_m(k,l)-I_s(k+p,l+q))}\right)}\right)$

Potential and limits

- Large windows (at least 64x64)
- Speckle:
  - If correlated ➔ speckle tracking (lower precision than InSAR in LOS)
  - If not ➔ texture/feature tracking in textured areas, on targets…
- Border effect ➔ mask / adaptive windows

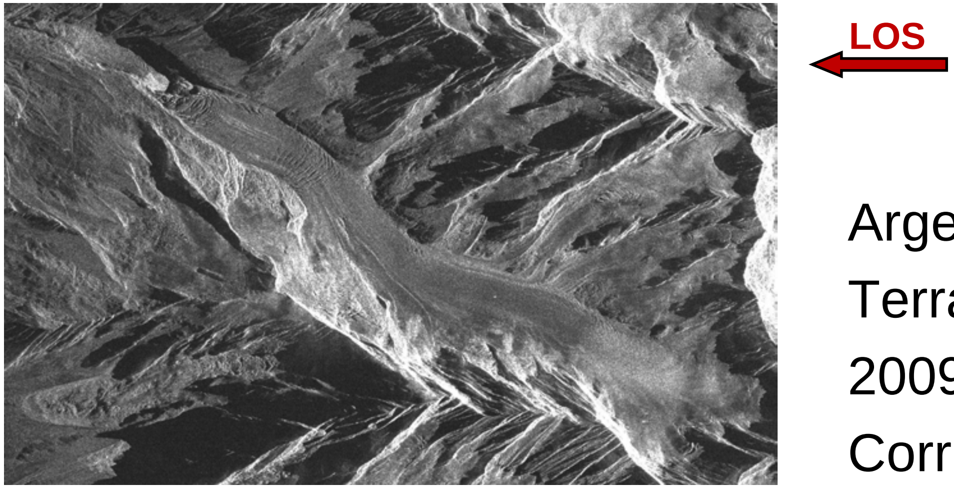


$$\left\|\vec{V}_{SAR}\right\| = \sqrt{(v_{LOS})^2 + (v_{az})^2}$$



Transversal profile

Offset tracking over Argentière glacier

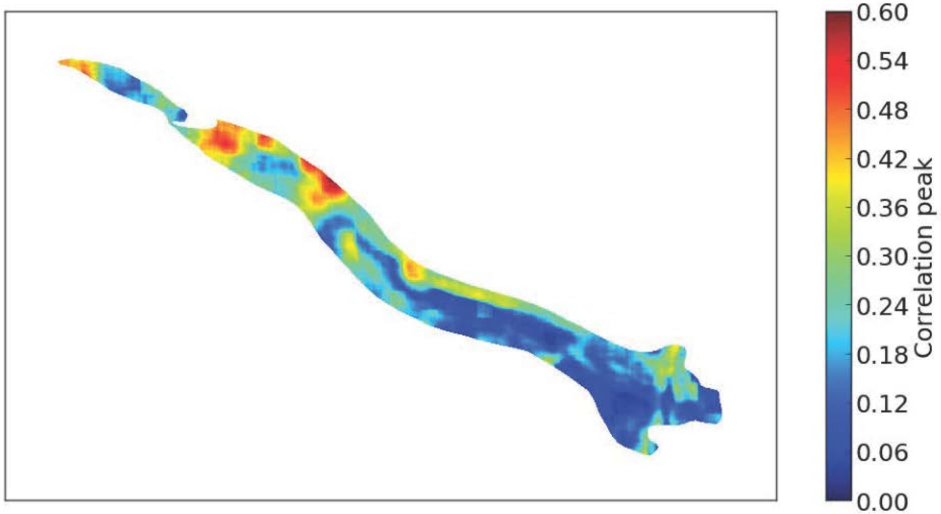


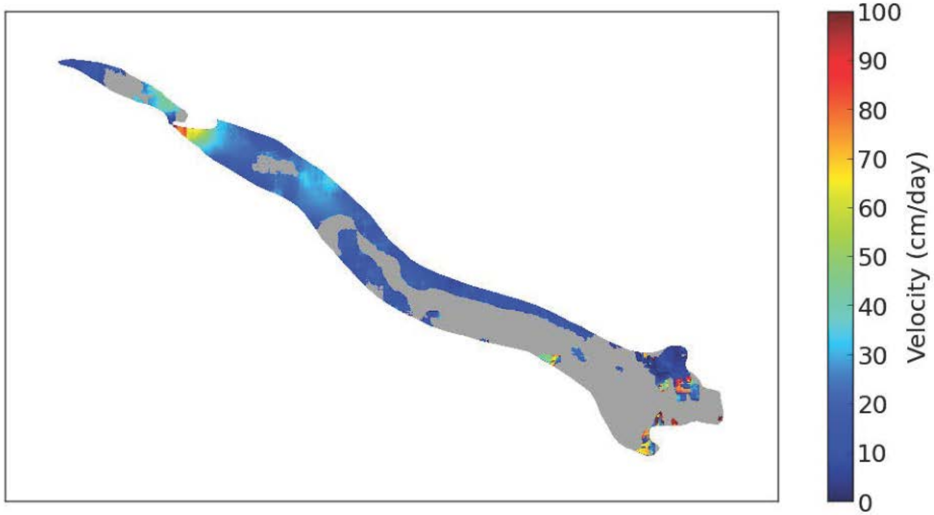
Argentière glacier

TerraSAR-X stripmap (~2m)

2009/08/14-2009/08/25 pair

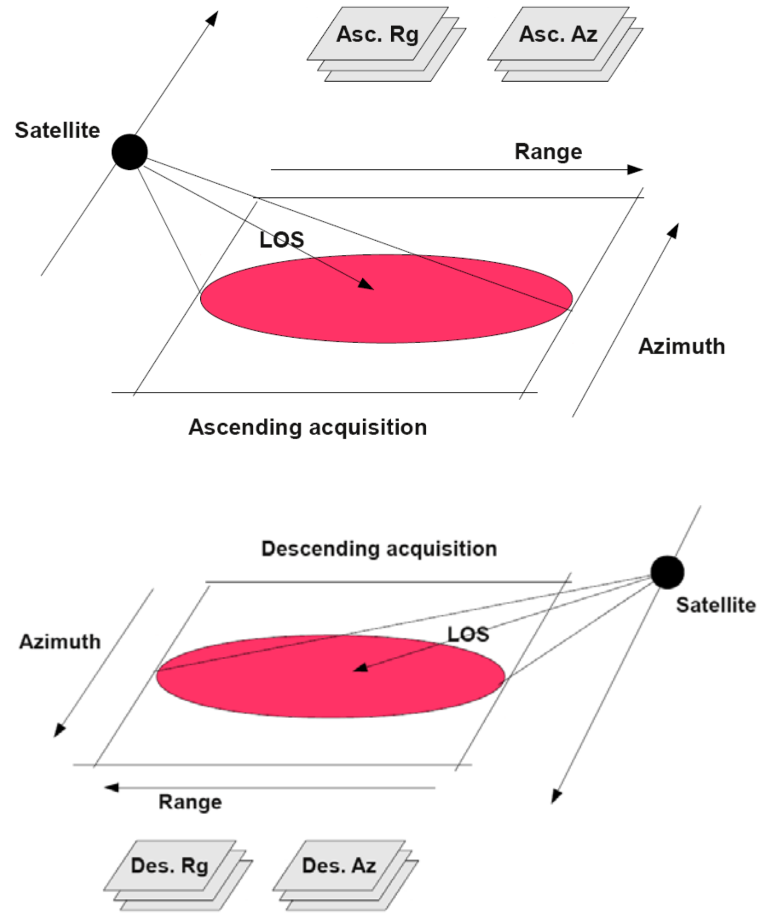
Correlation threshold: 0.2





Combining multiple displacement measurements

- D-InSAR:
  ➔ 1D displacement (LOS)
- Offset tracking:
  ➔ 2D displacement in
  LOS and azimuth directions
- Ascending and descending passes
  ➔ 4 projections
- Multi-temporal data
  ➔ repeated measurements
- Inversion strategies / uncertainty management [Yan 11, 12]
  ➔ 3D displacement (E, N, Up)
  ➔ Physical model parameters



3D displacement fields

- Requierement:
  - ~simultaneous Asc/Des pairs
  - Textured areas visible in both geometries
  - DEM for orthorectification
- Inverse problem:

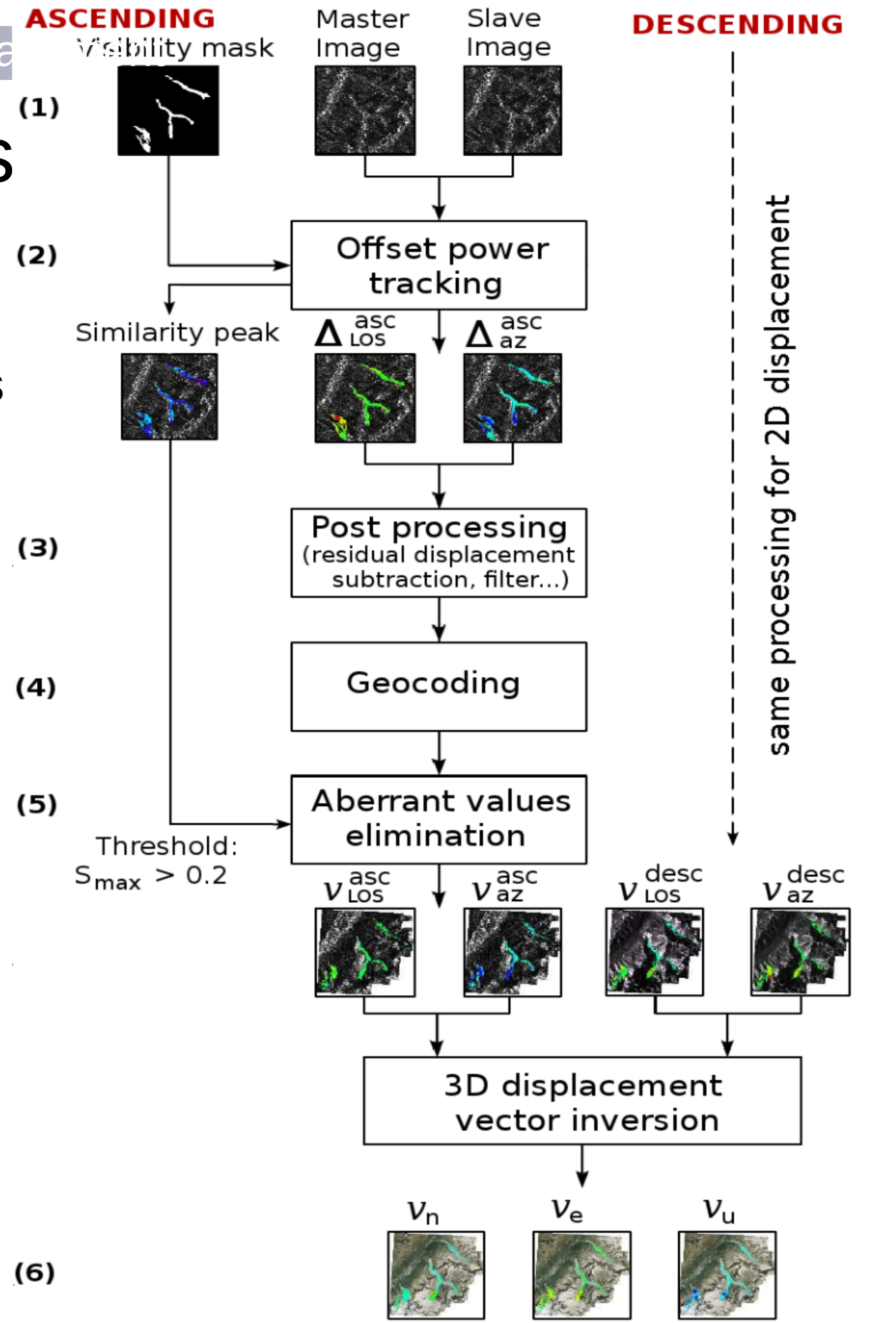
$$\mathbf{V} = \mathbf{P} \times \mathbf{D} \qquad \mathbf{D} = [v_e, v_n, v_u]^t$$

$\mathbf{P}$ *projections Asc / Des*

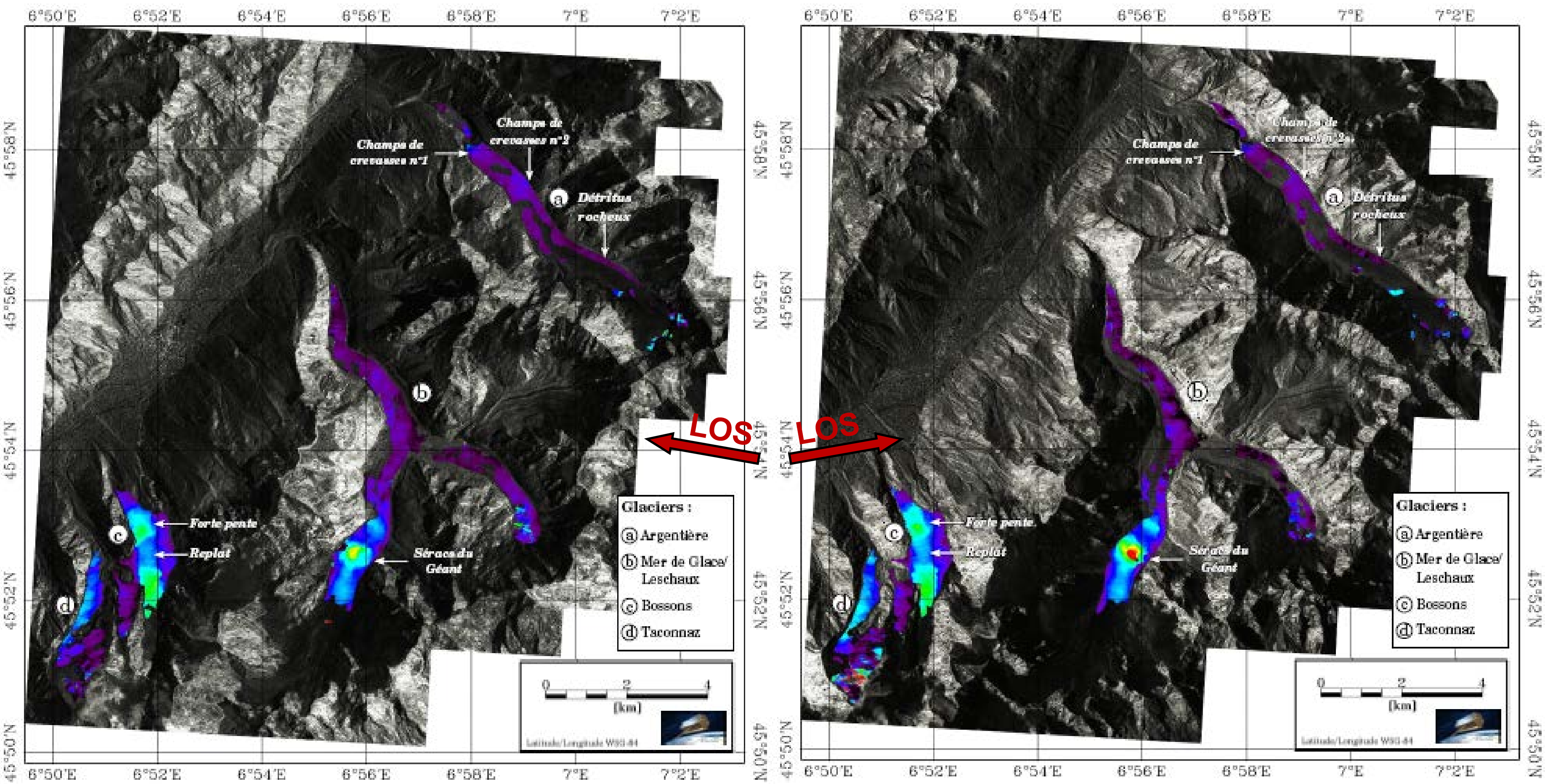
$\mathbf{V}$ *measuments*

- Least square solution:

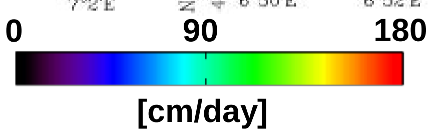
$$\mathbf{D} = \left(\mathbf{P}^t \times \mathbf{P}\right)^{-1} \times \mathbf{P}^t \times \mathbf{V}$$



TSX Ascending/Descending 2D displacement fields

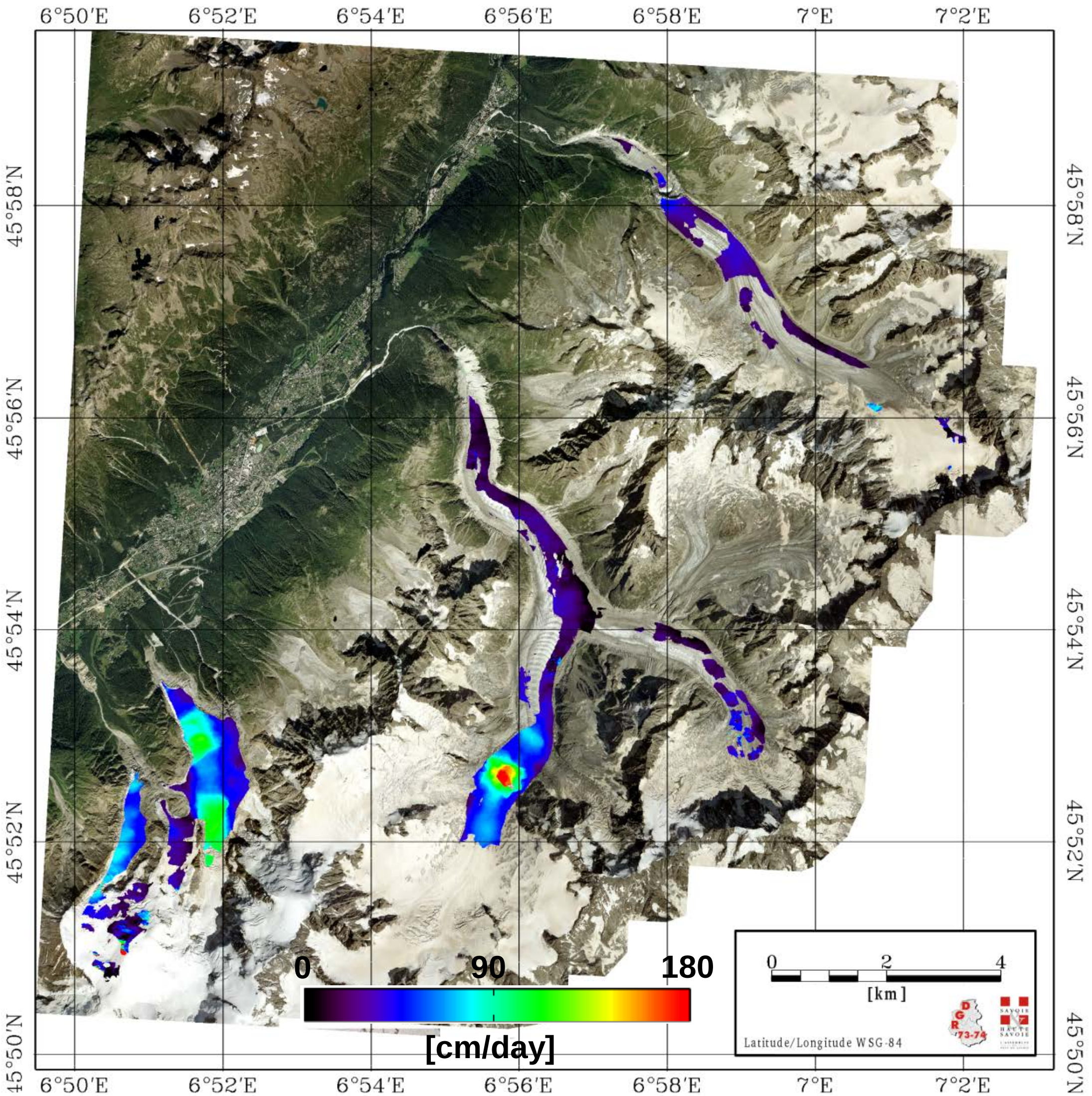


Descending 2009/08/14-25



Ascending 2009/08/16-27

3D glacier displacement field from high resolution amplitude images



Chamonix Mont-Blanc

- TerraSAR-X stripmap images, res.: ~2m
- 11-day pairs
- Descending and ascending (d+2)
  [Fallourd 11, 12]

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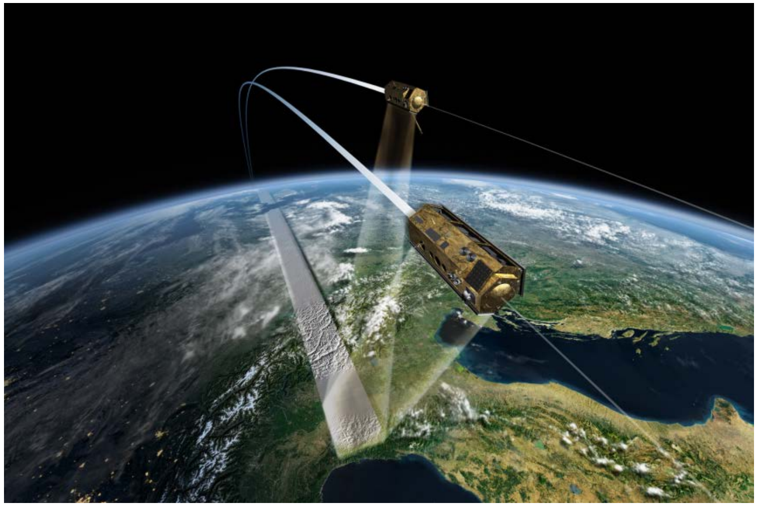
TanDEM-X mission



- 2 SAR satellites, 250-500m baseline
- primary objective : global DEM with vertical relative accuracy of 2m (4m slope >20%) and 12m posting
- dual baseline processing:
  - 2 acquisitions with heights of ambiguity of 25-30m and 35-40m
  - for difficult terrains, several acquisitions with different geometries (look direction, incidence angle...)
- Difficulties for glaciological applications:
  - rapid changes (ablation/accumulation)
  - Snow / firn / ice penetration

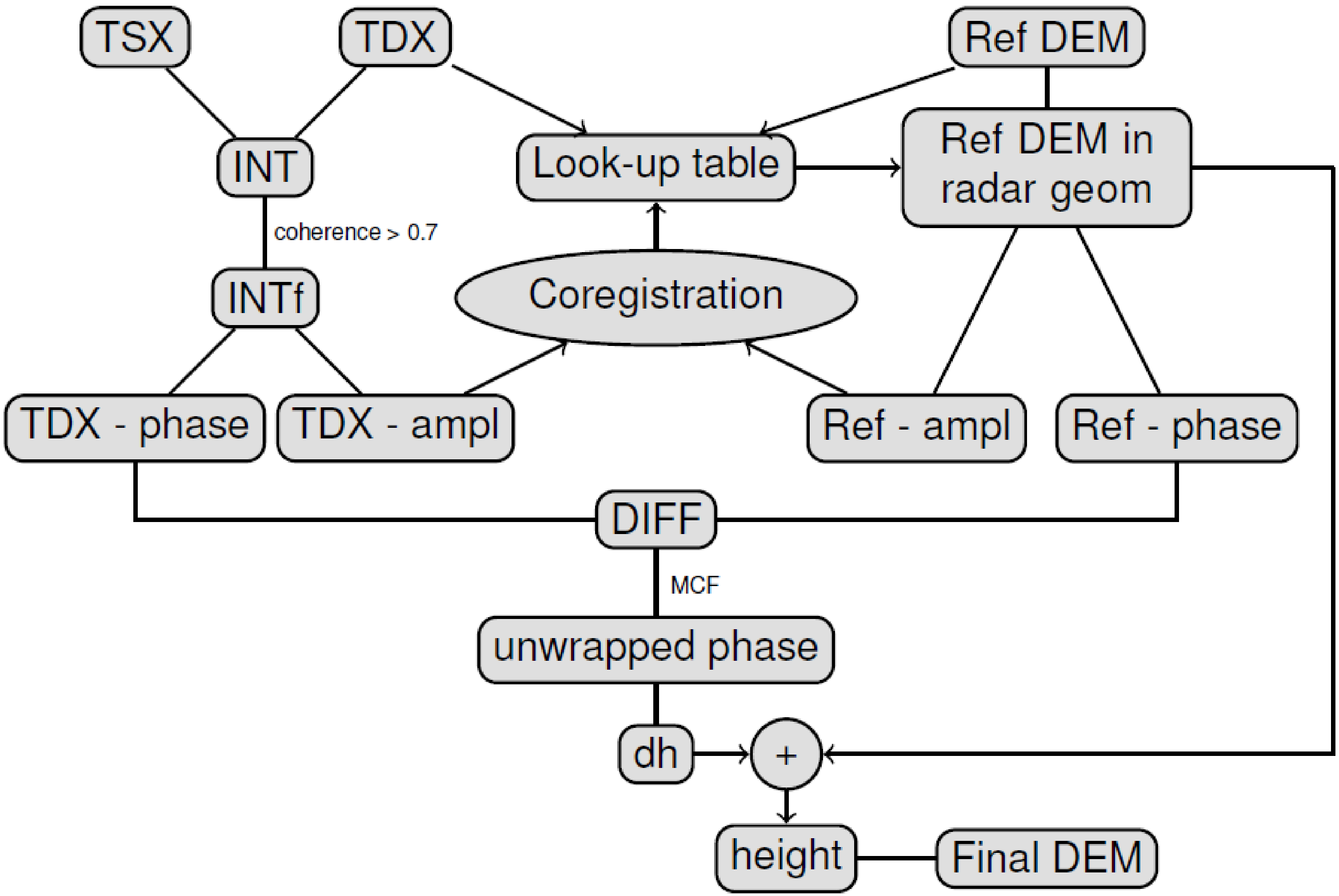
TanDEM-X pairs over Chamonix Mont Blanc

Date	Orbit	Bperp (m)	HoA (m)	Incidence
2012/05/13	Ascending	176.3	30.3	44°
2012/05/24	Ascending	170.8	31.0	44°
2013/02/01	Ascending	122.8	58.8	44°
2013/10/21	Descending	80.4	63.7	37°
2013/11/12	Descending	95.0	62.3	37°

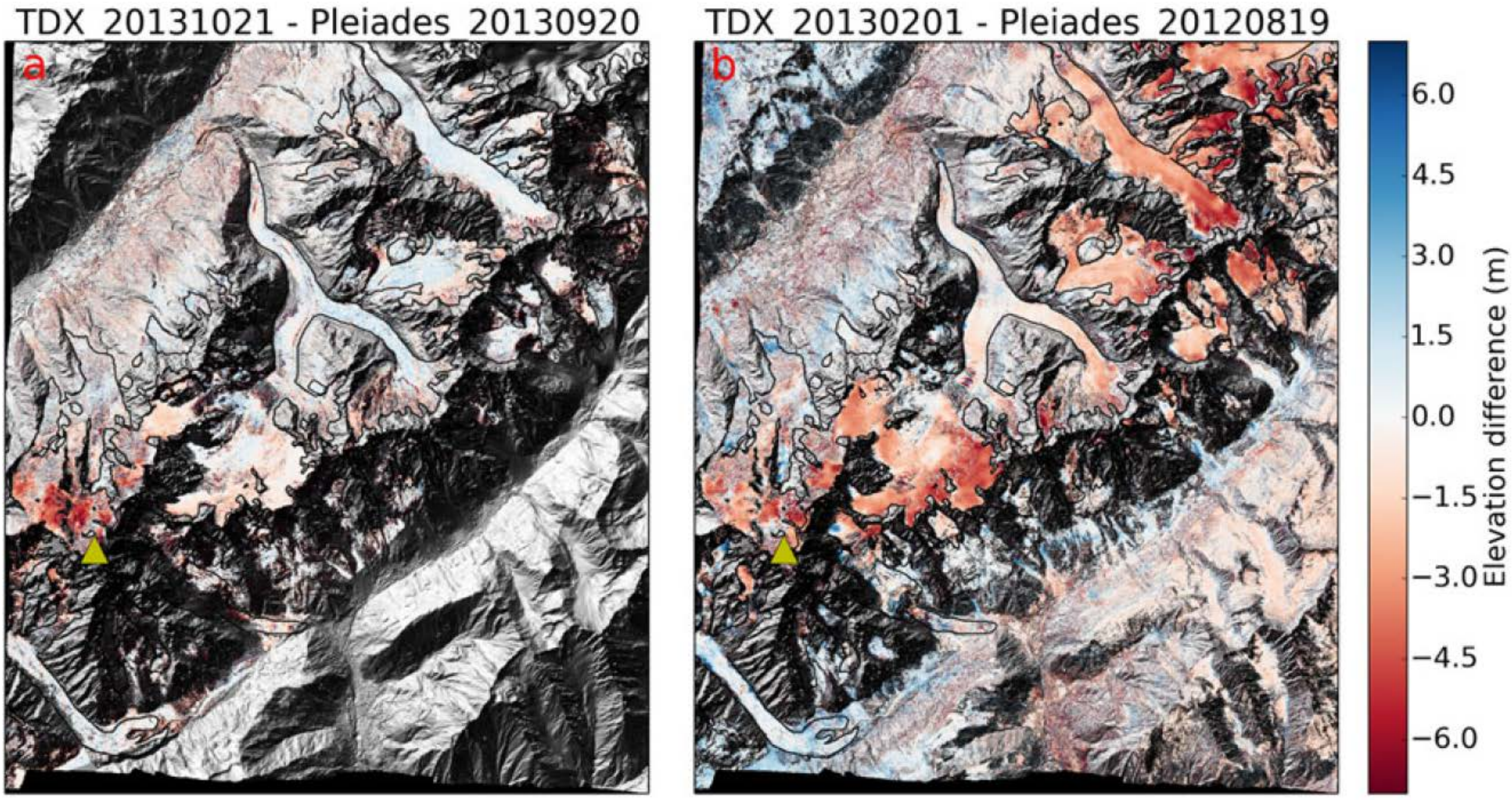
Reference DEMs

Source	Date	Posting (m)
Pléiades	2012/08/19	4
Pléiades	2013/09/20	4
SRTM-C	Feb. 2000	30

Processing chain



TanDEM-X – Pléiades elevation difference



[Dehecq 2016]

TanDEM-X – Pléiades elevation difference

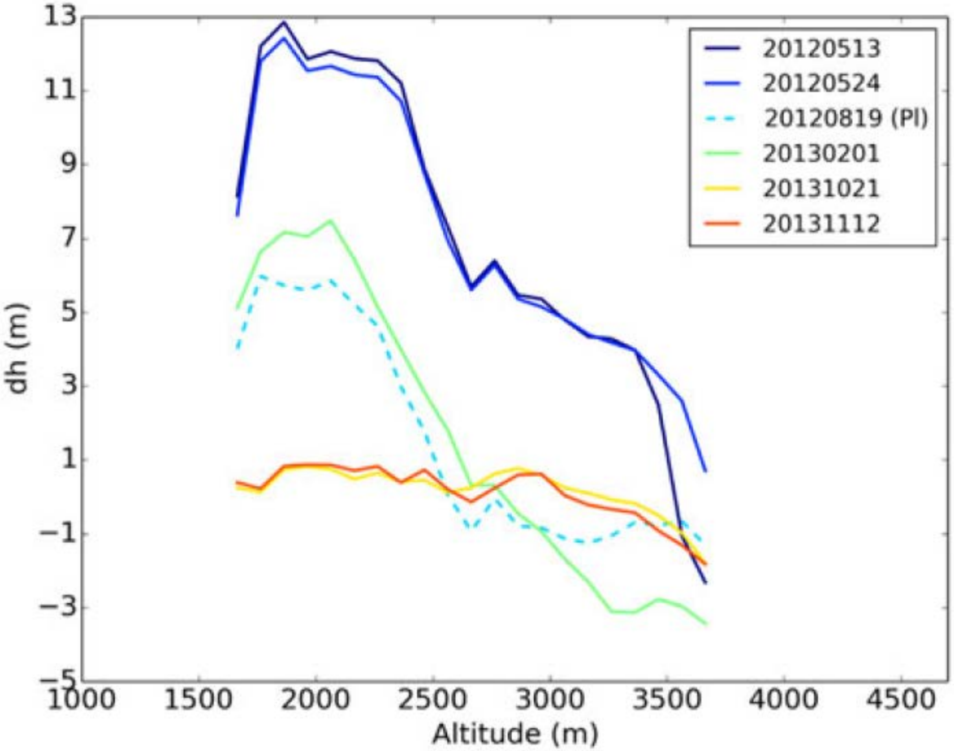
- Uncertainty assessed below 2000-m a.s.l., excluding glaciers, vegetation and slopes > 40°,
- Reference: Pléiades 2012/08/19

TDX pair	Mean (m)	Median (m)	MAD
2012/05/13	1.41	1.88	3.10
2012/05/24	1.16	1.56	2.97
2013/02/01	0.83	1.94	2.65
2013/10/21	-1.14	-0.07	1.92
2013/11/12	-1.33	-0.14	1.99

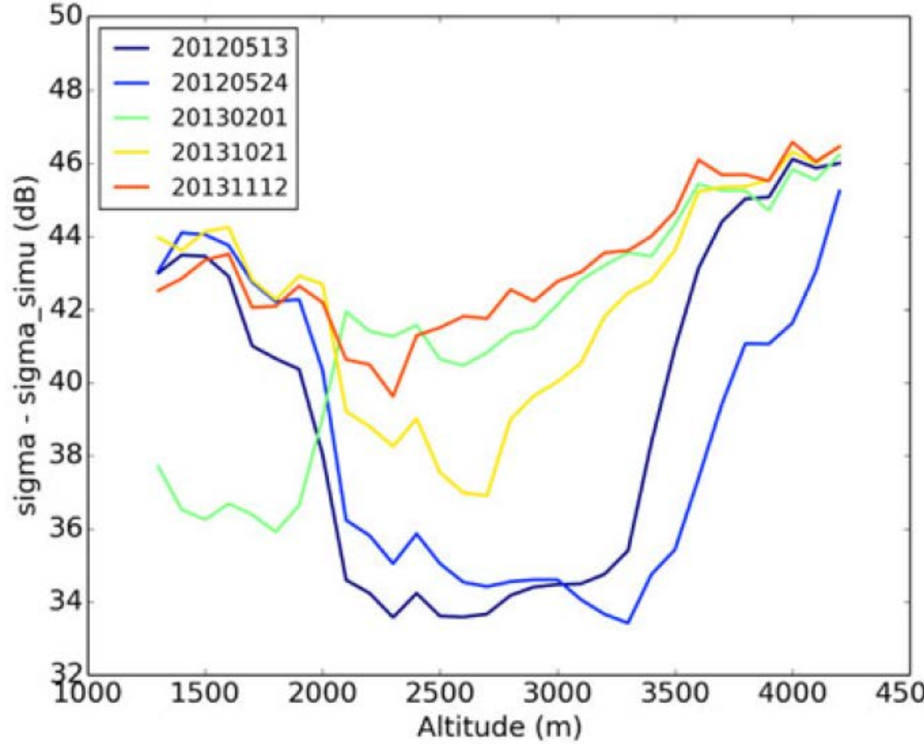
[Dehecq 2016]

Limitations

- radar penetration in dry snow



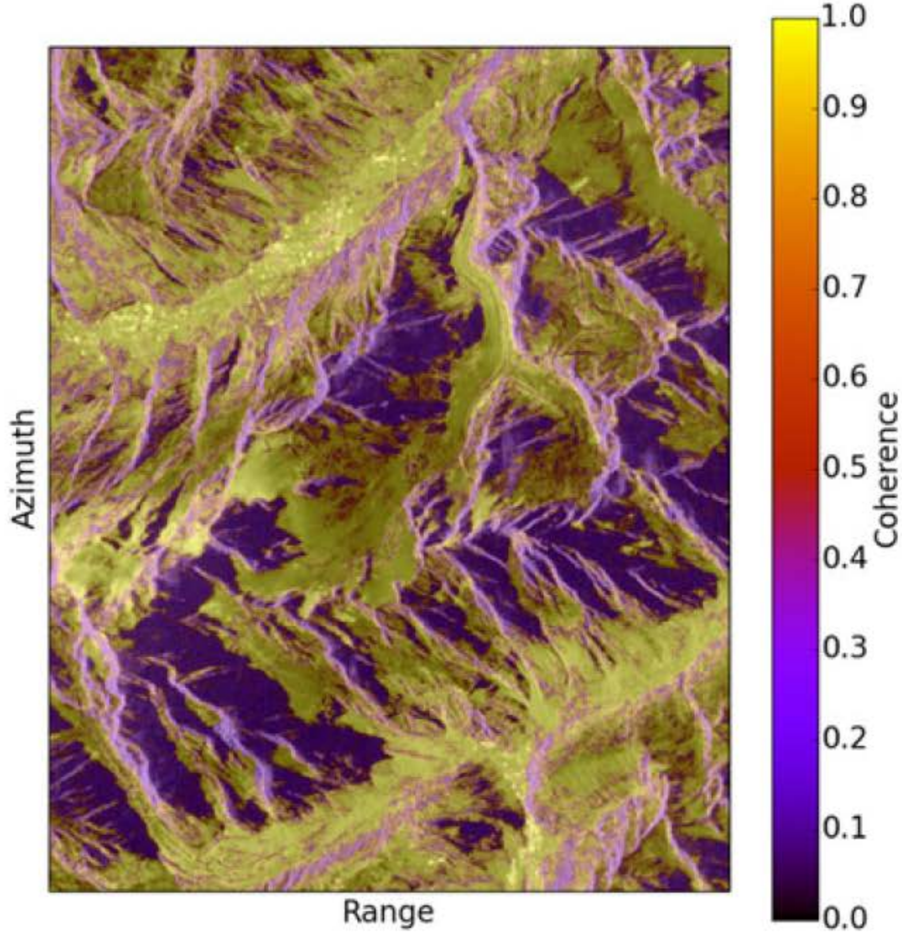
Elevation difference on the Mer-de-Glace between:
- 5 TDX+Pléiades 2012 DEMs
- the Pléiades 2013/09/20 DEM



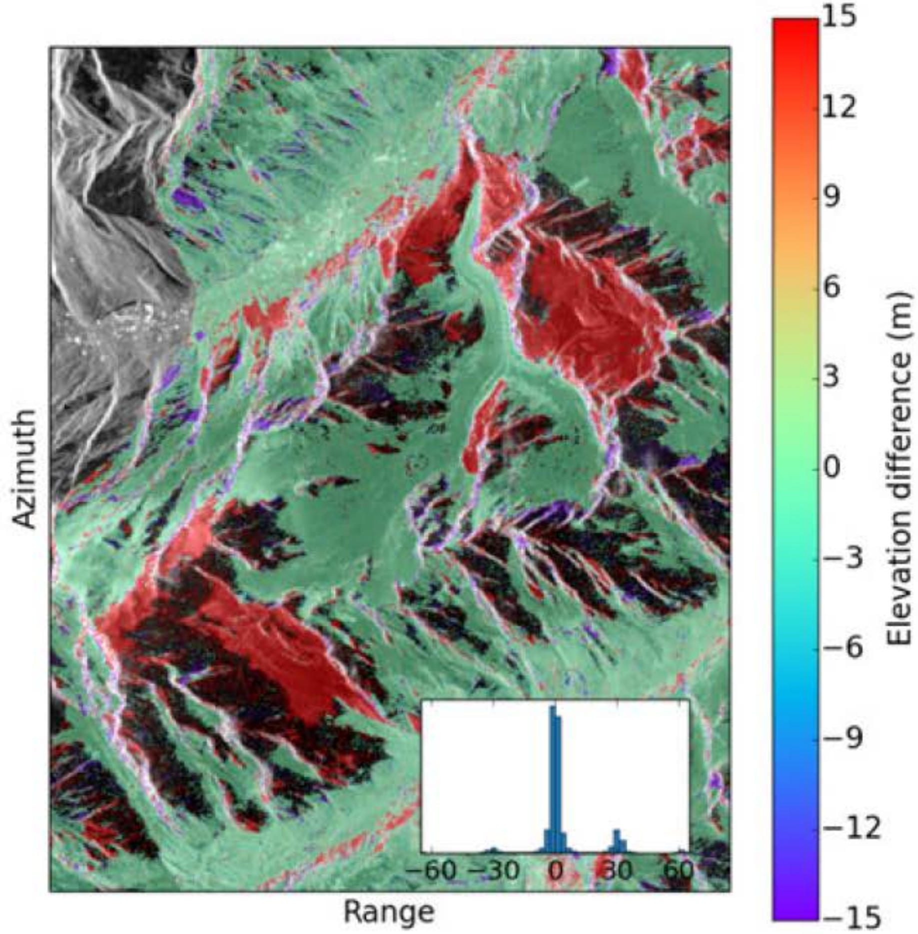
Flattened backscattering coef in dB for the 5 TDX pairs, for all glaciers

Limitations

- Unwrapping errors using SRTM as reference DEM

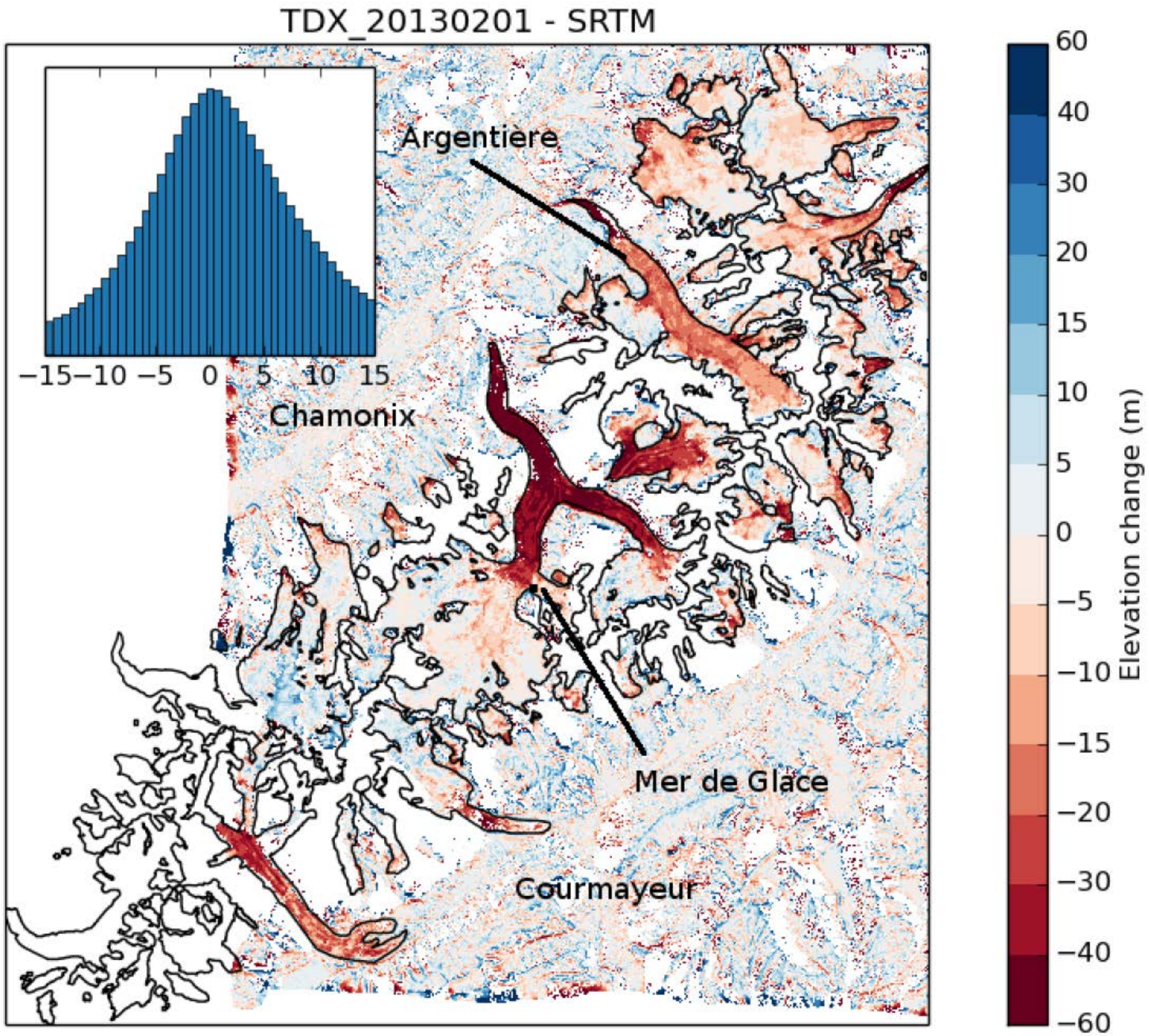


Coherence



Elevation difference: TDX pair 2012/05/13 (HoA = 30.3 m) - Pléiades 2013 (right)

TanDEM-X – SRTM elevation difference



Overview

1. Surface displacement by differential interferometry
   - Potential and limits
   - Processing steps
   - Results from ERS tandem data
2. 2D/3D surface displacement by offset tracking
   - Potential and limits
   - Processing steps
   - Results from TerraSAR-X stripmap images
3. Surface elevation by SAR interferometry
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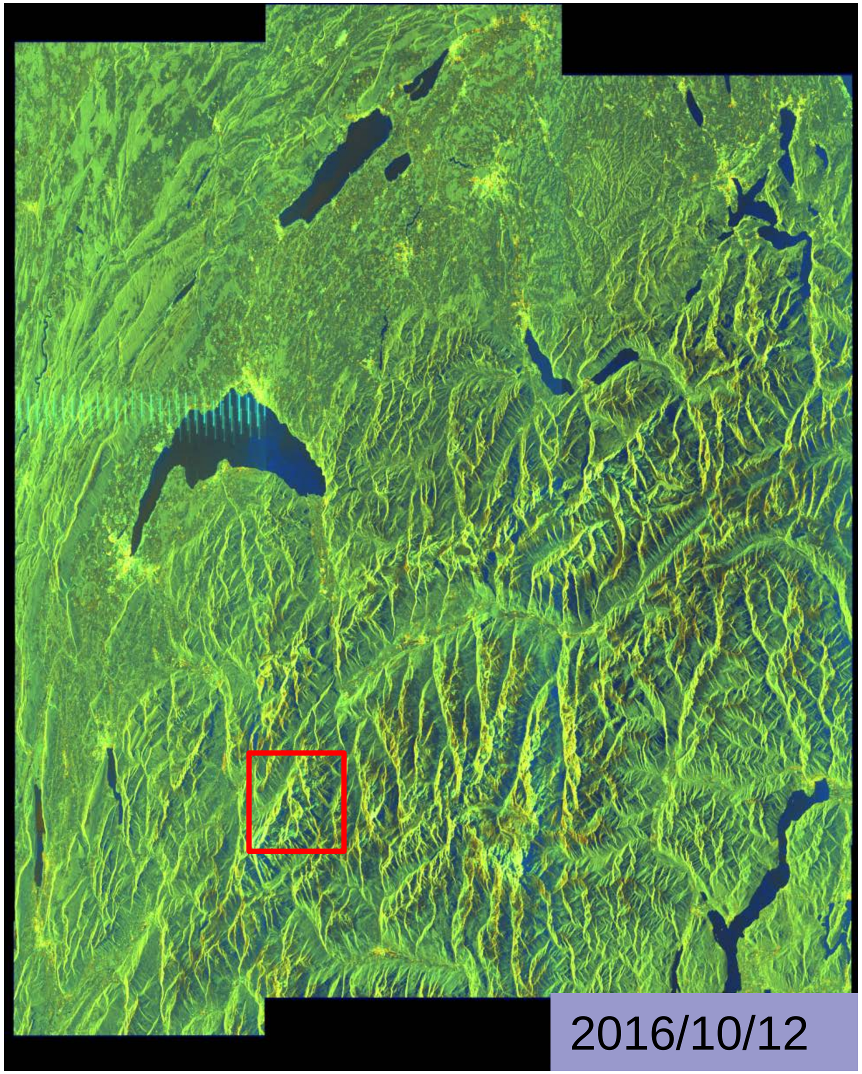
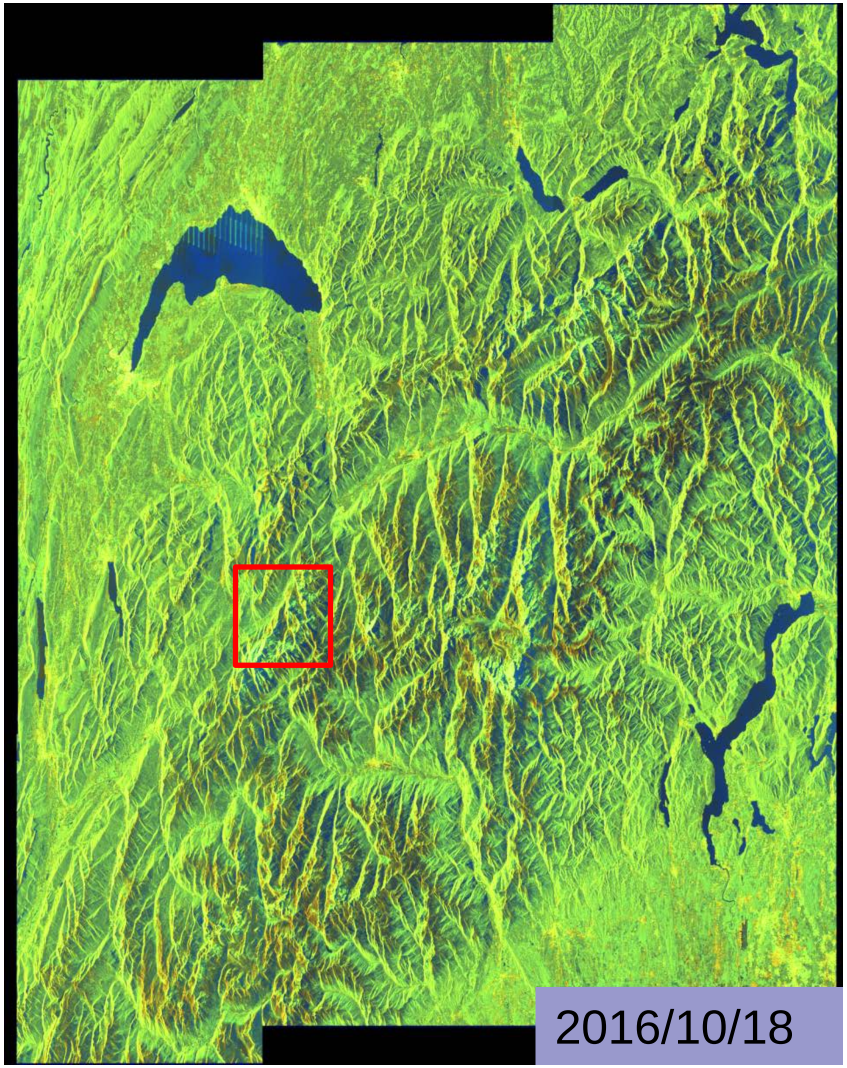
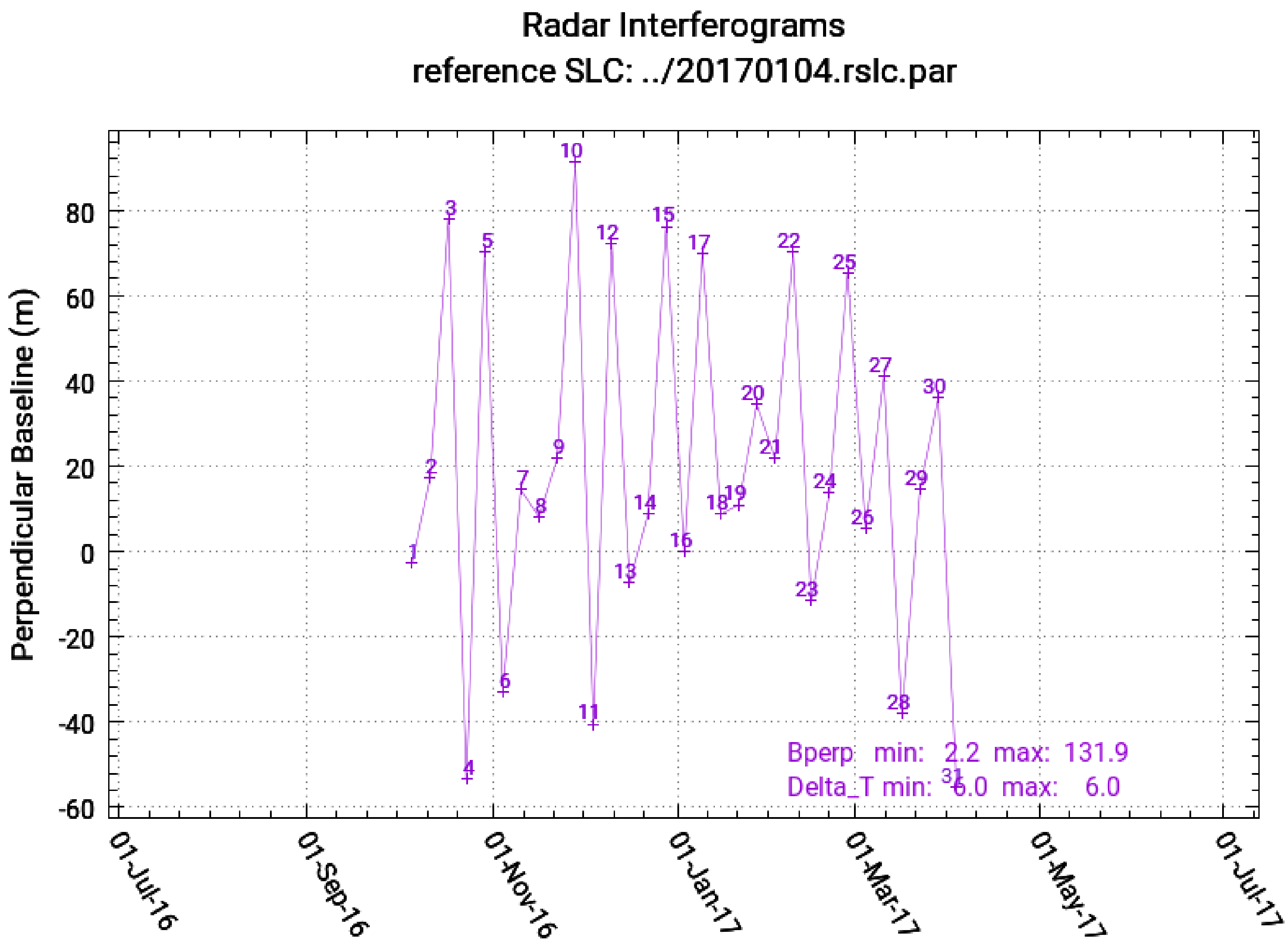
4. How about Sentinel-1?
5. Perspectives

Sentinel 1 – Ascending orbit 88 - Quicklook

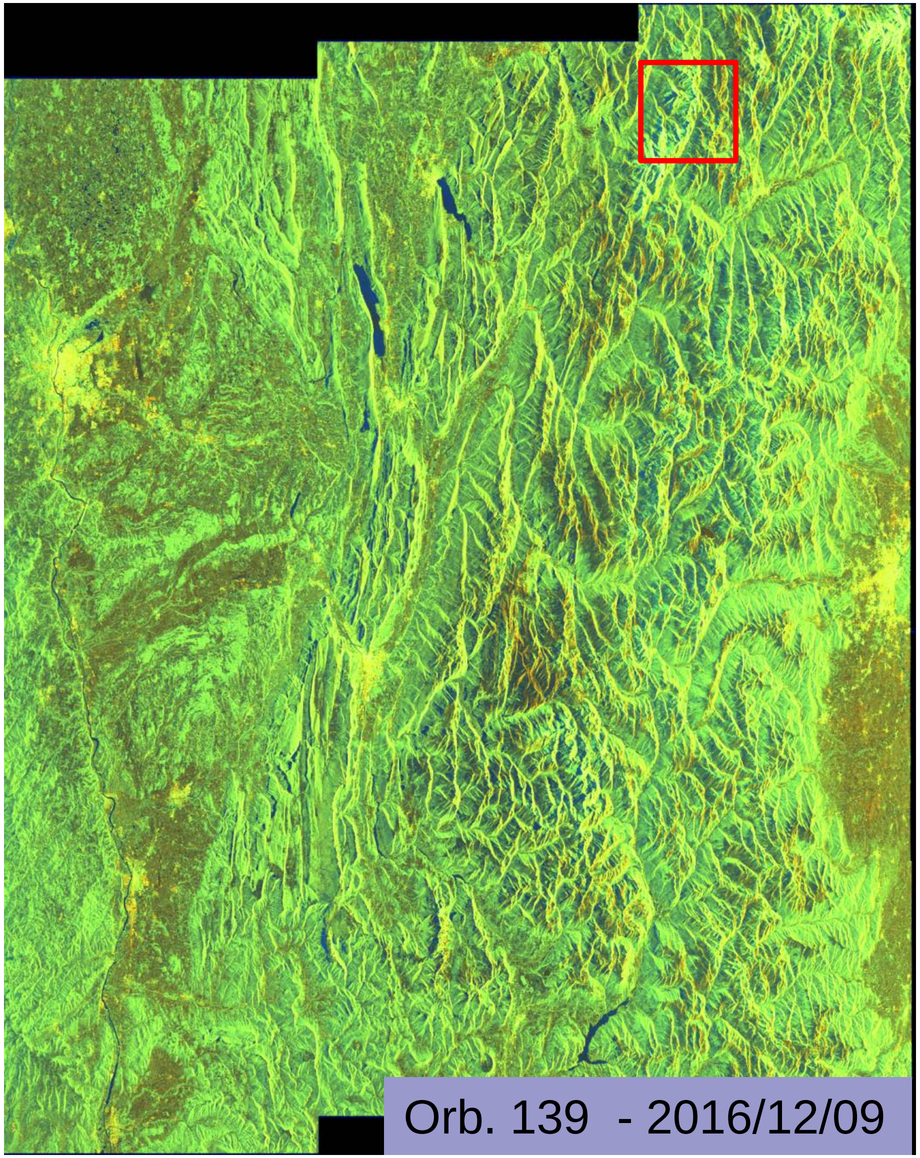


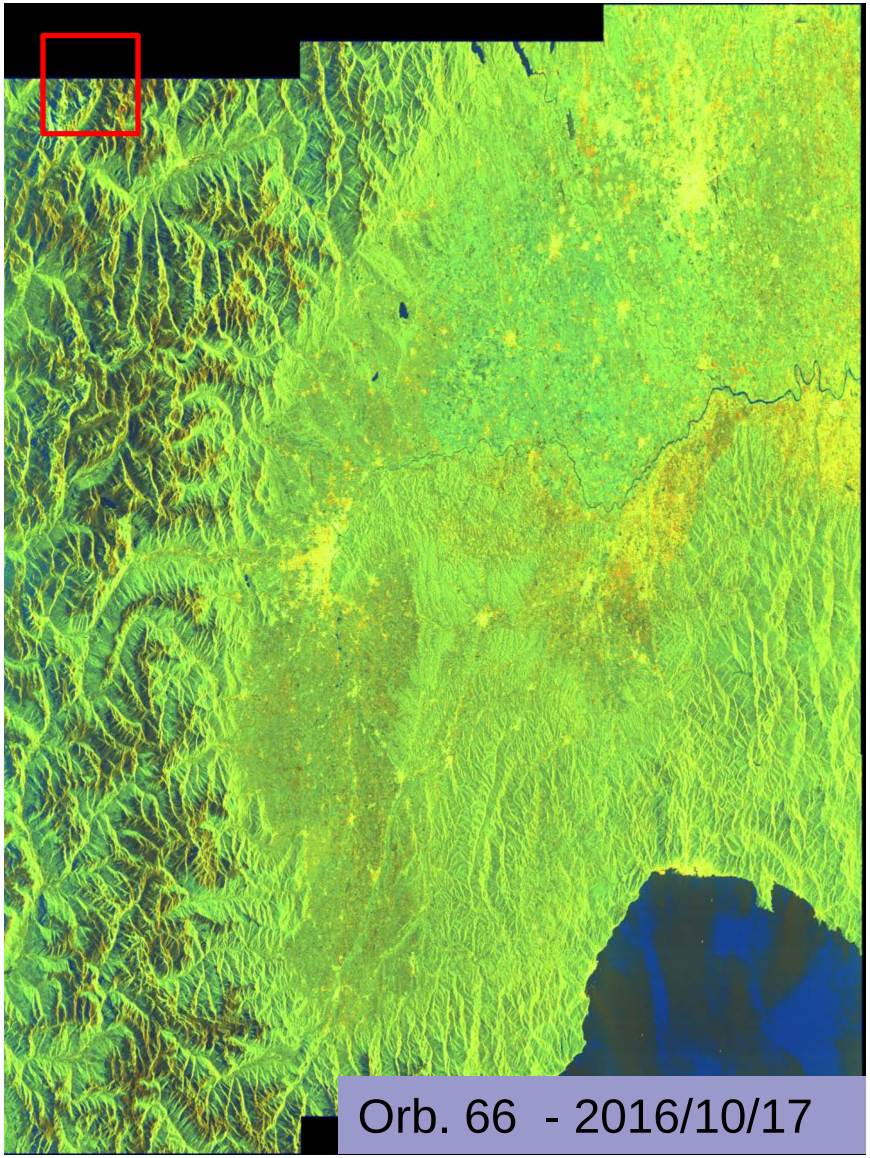


Sentinel 1 – Ascending orbit – Perp. baseline

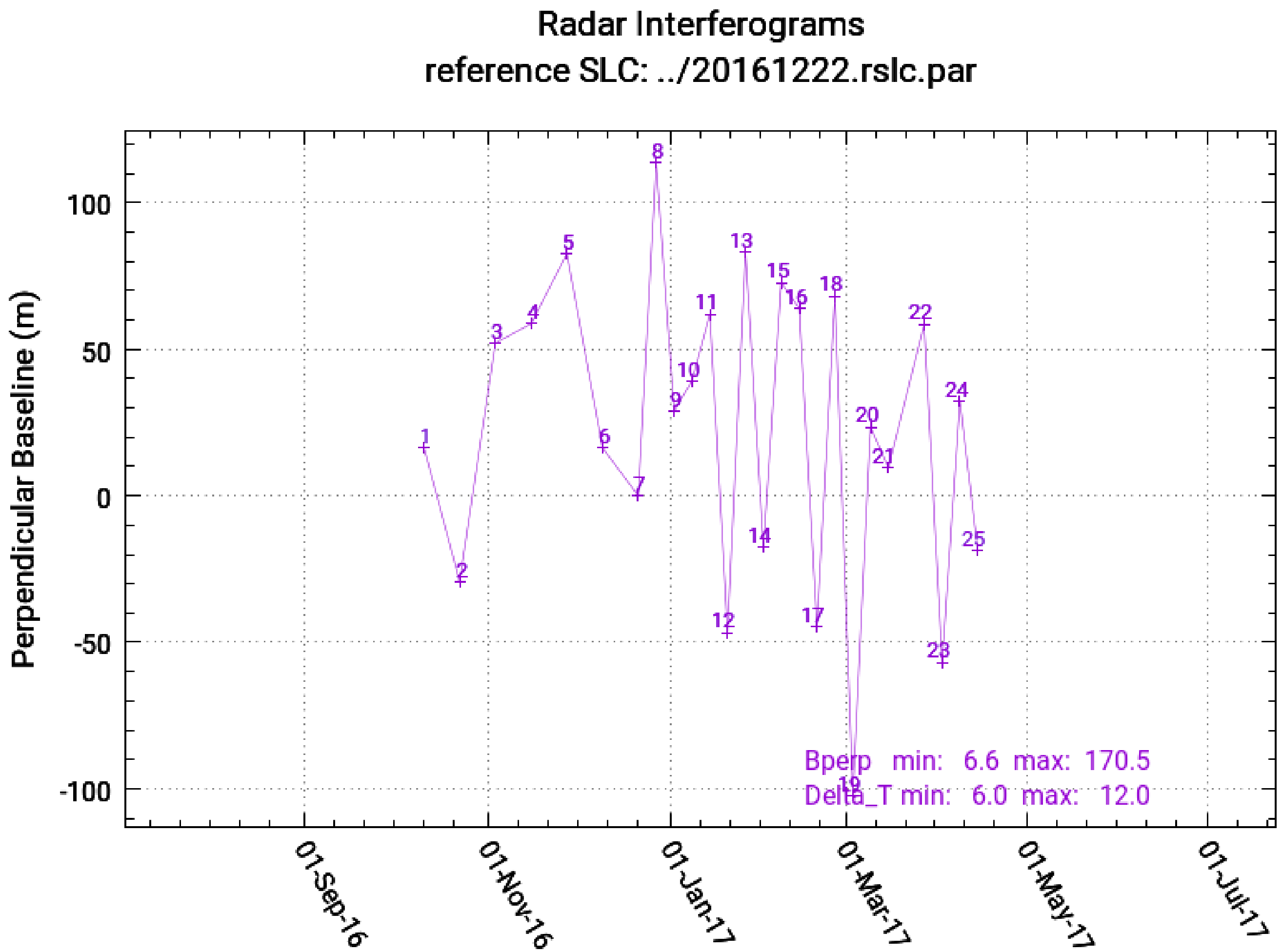


Sentinel 1 – Descending orbits - Quicklook

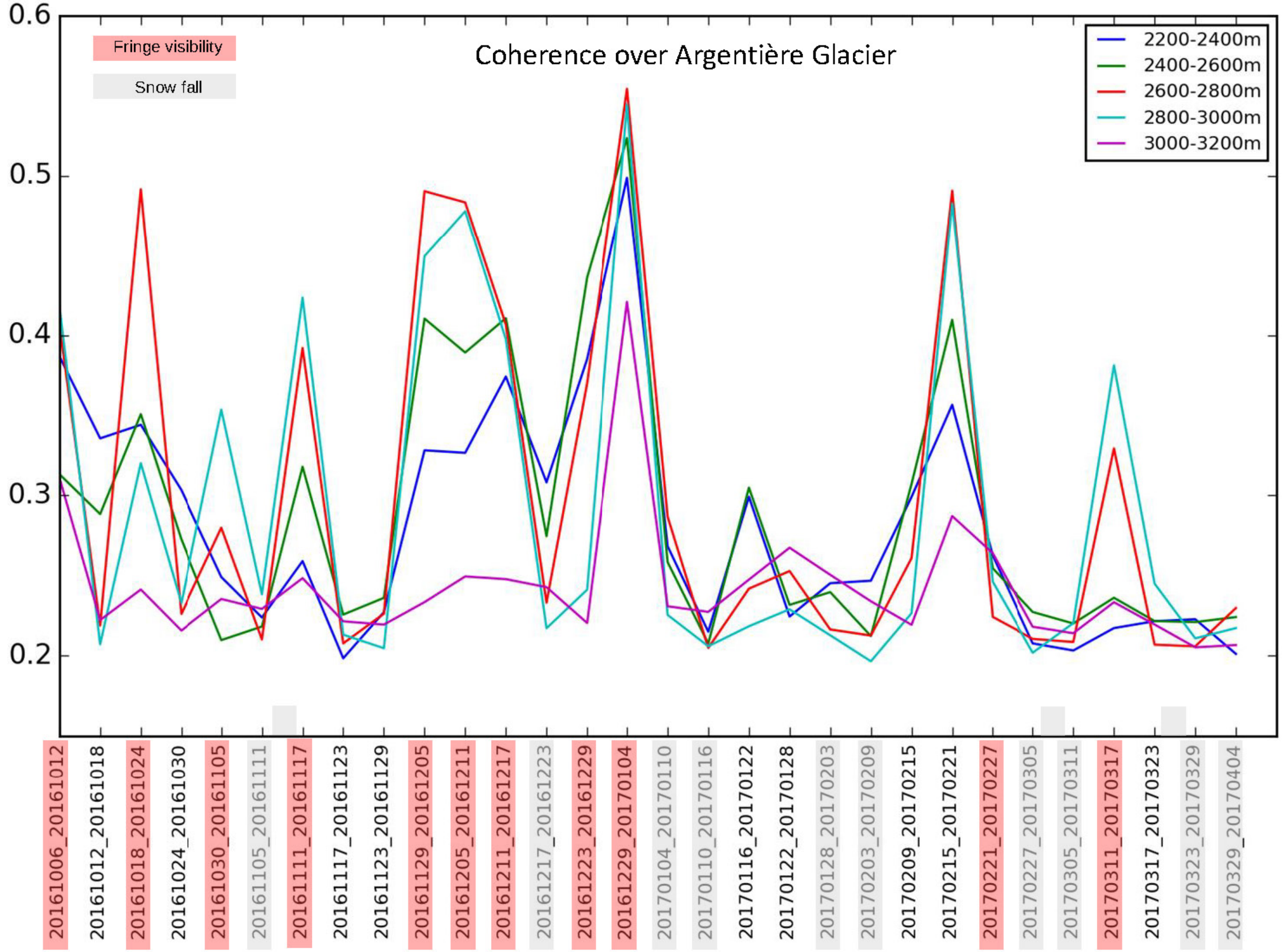




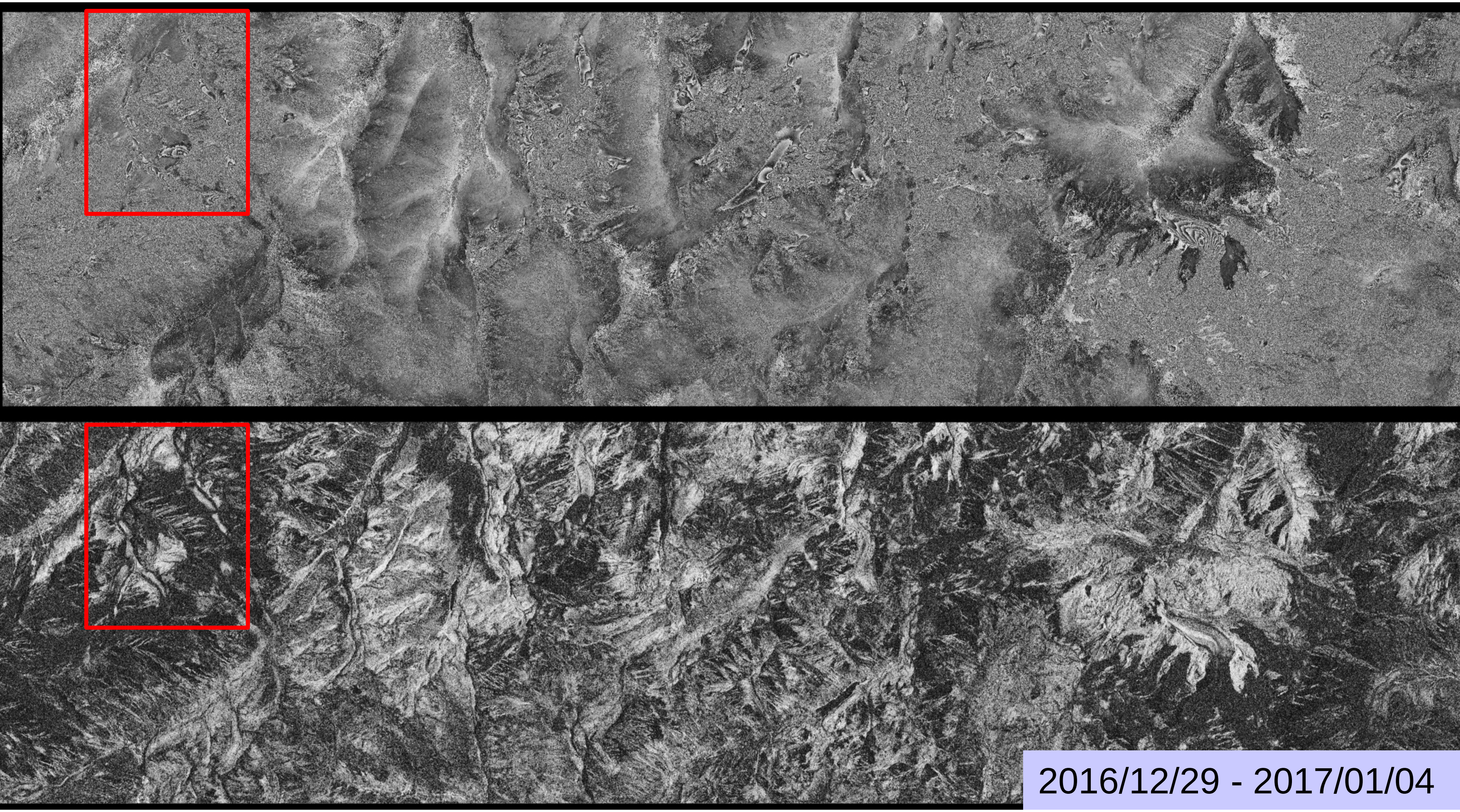
Sentinel 1 – Descending orbit – Perp. baseline



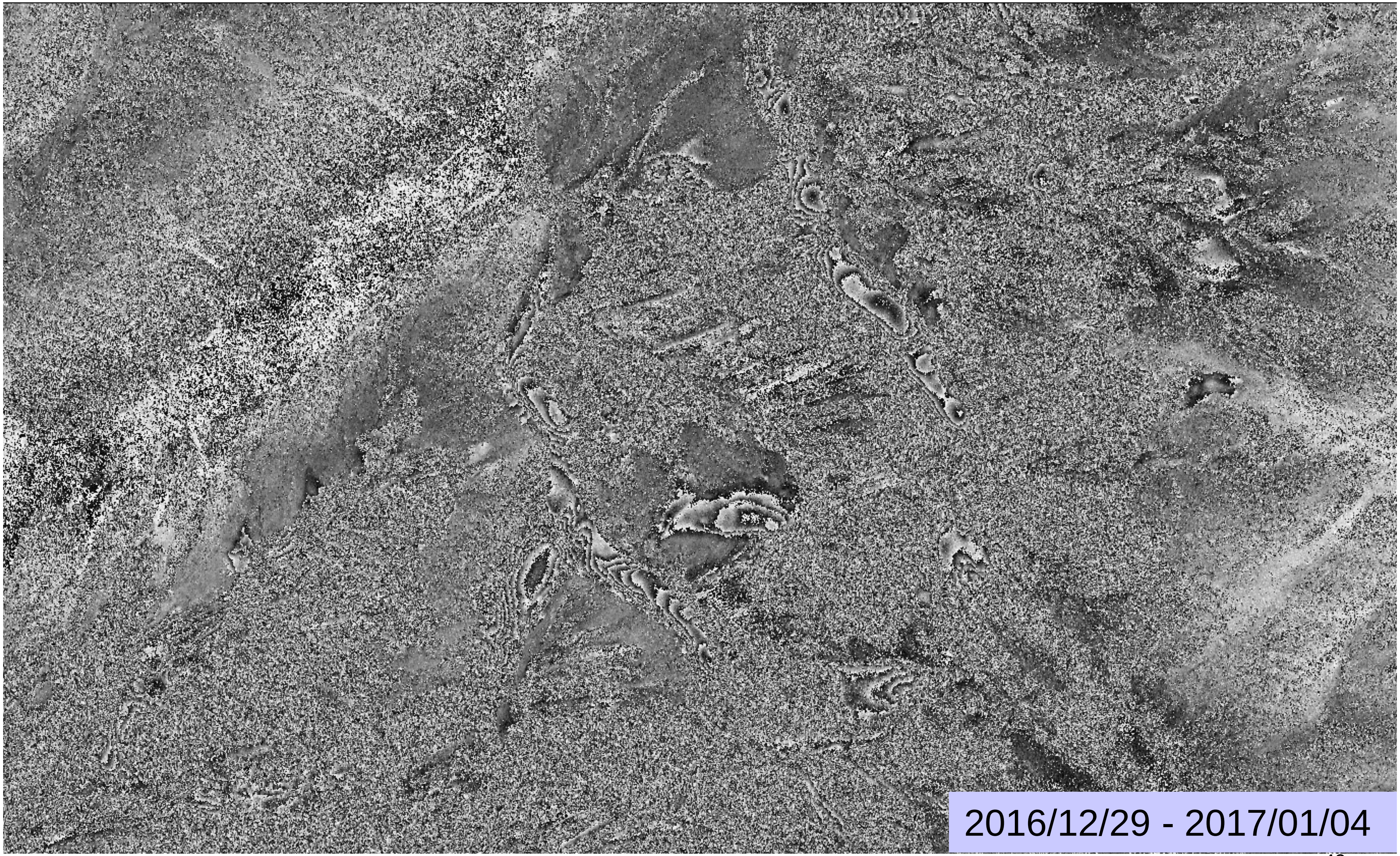
Sentinel1-Ascending, coherence time profile



Sentinel1-Ascending, D-InSAR (1 burst)

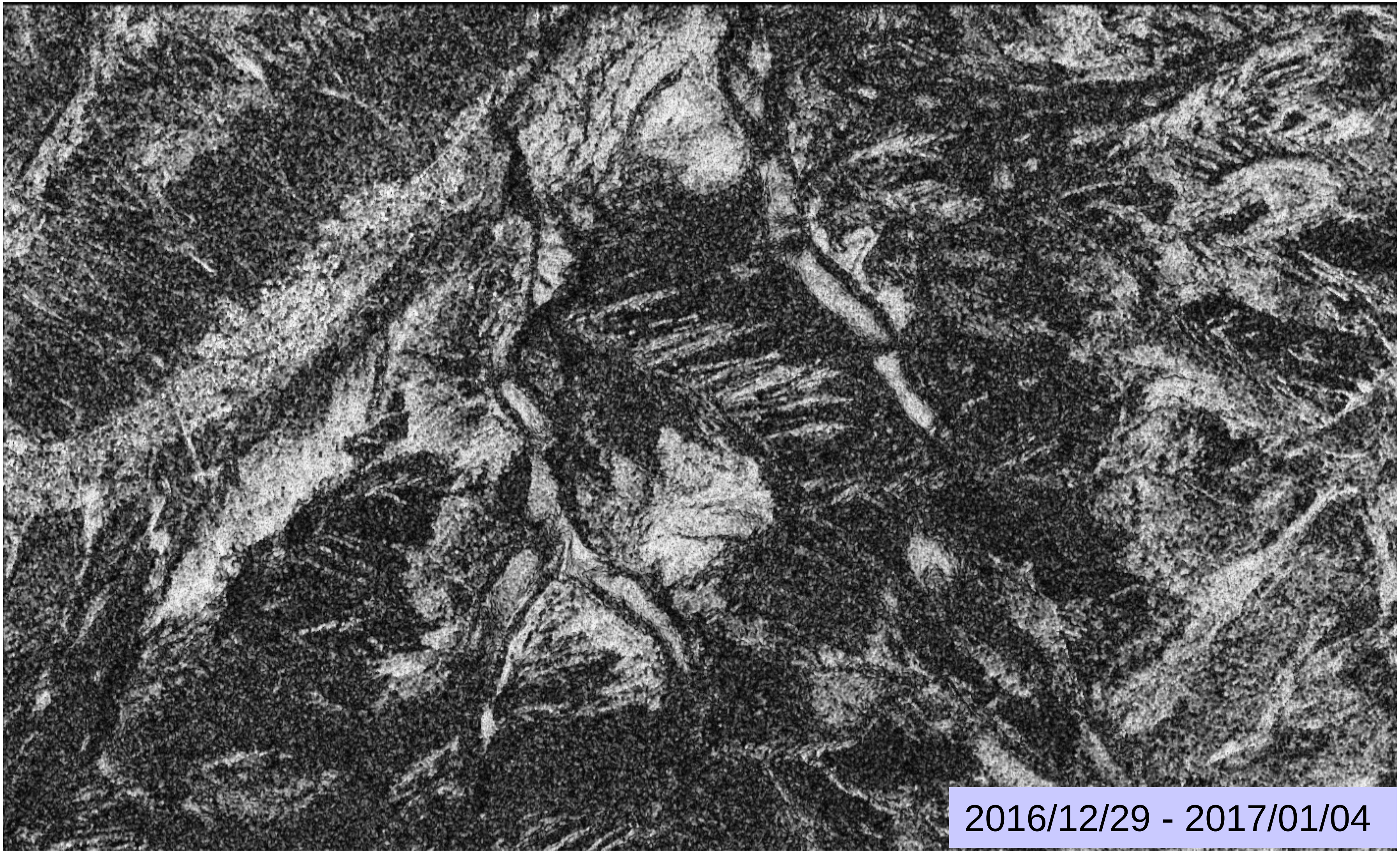


Sentinel1-Ascending, D-InSAR interferogram

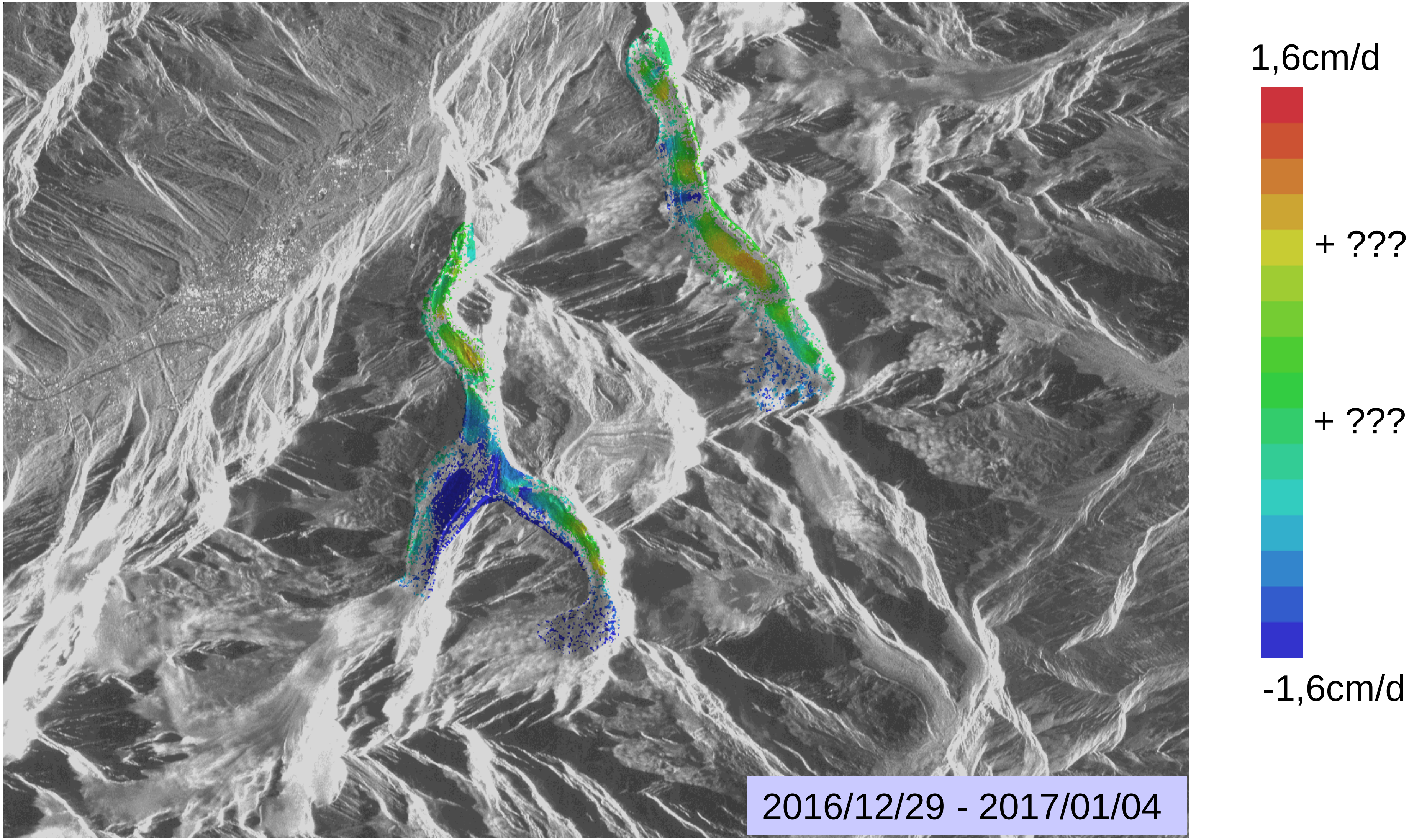


2016/12/29 - 2017/01/04

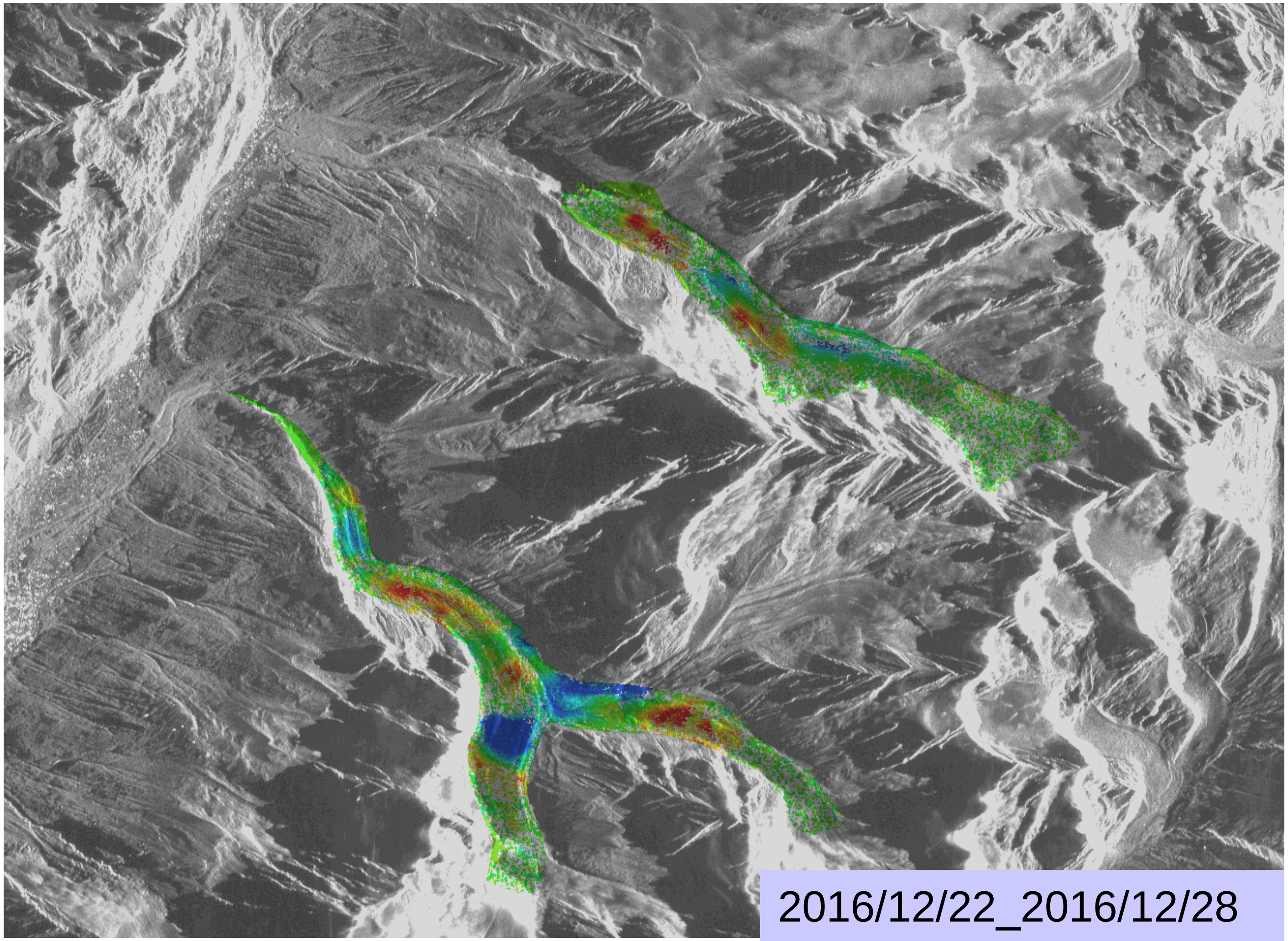
Sentinel1-Ascending - Coherence



Sentinel1-Ascending, LOS displacement



Sentinel1-Descending, LOS displacement



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Glacier monitoring by spaceborne SAR data

- Displacement fields
  - InSAR: New opportunity with Sentinel-1 6-day interferograms
  - Multi-interferogram: displacement signal / atmospheric perturbations
  - Phase unwrapping: additional information to solve ambiguity
  - Offset tracking with high resolution datat ➔ 2D/3D displacement
  - Spatial and temporal complementarity of InSAR and offset tracking
- Elevation changes
  - TanDEM-X: uncertainty due to penetration increases with the altitude
  - Use of pairs from the same periode of the year
- Surface/volume caracteristics
  - Full polarimetry: multivariate multitemporal data
  - Snow / firn evolution, data assimilation with snow pack models
  - BioMas (P band) ➔ PolInSAR for snow/ice features retrival ???


QUESTIONS?
BURKI

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