

Measuring glacier dynamic by massive processing of satellite image time series

Emmanuel Trouvé with contributions from:

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Why monitoring glaciers?



Climate change, global warming

- Ice sheet and glacier melting
 - ➔ Sea-level rise
 - ➔ Decrease of water resources
- Glacier and permafrost warming
 - ➔ Increase in natural hazard
- Glacier retreat
 - ➔ Economical consequences: power generation, tourism...

Argentière glacier, 1890 - 2008

Alpine museum of Chamonix



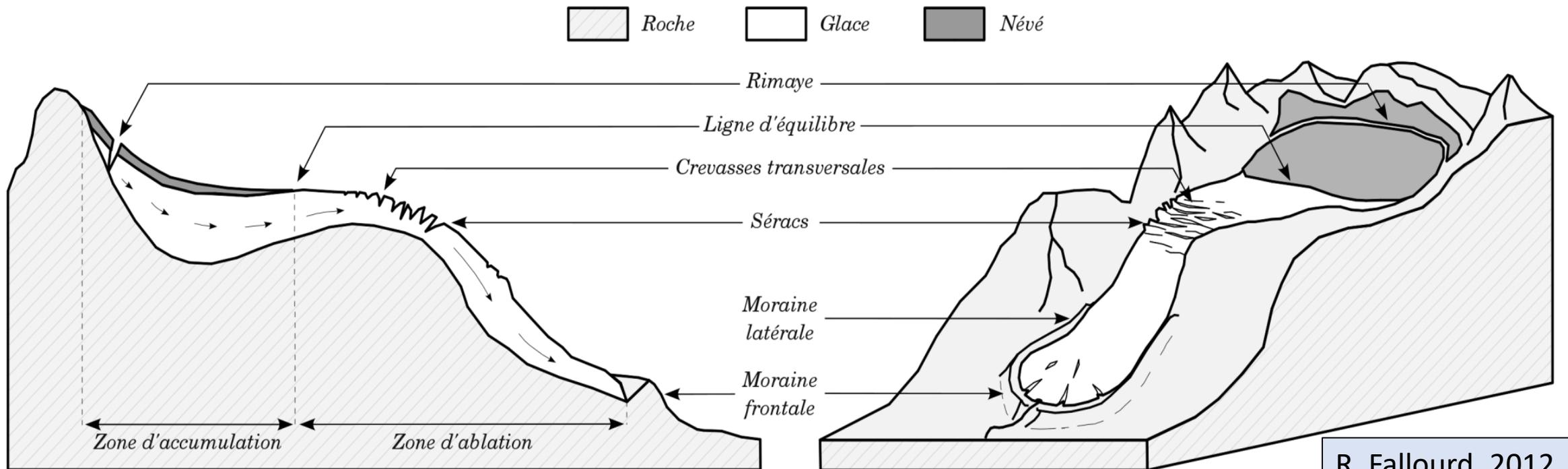
Photos : Sylvain Couttrand



Sought-after information



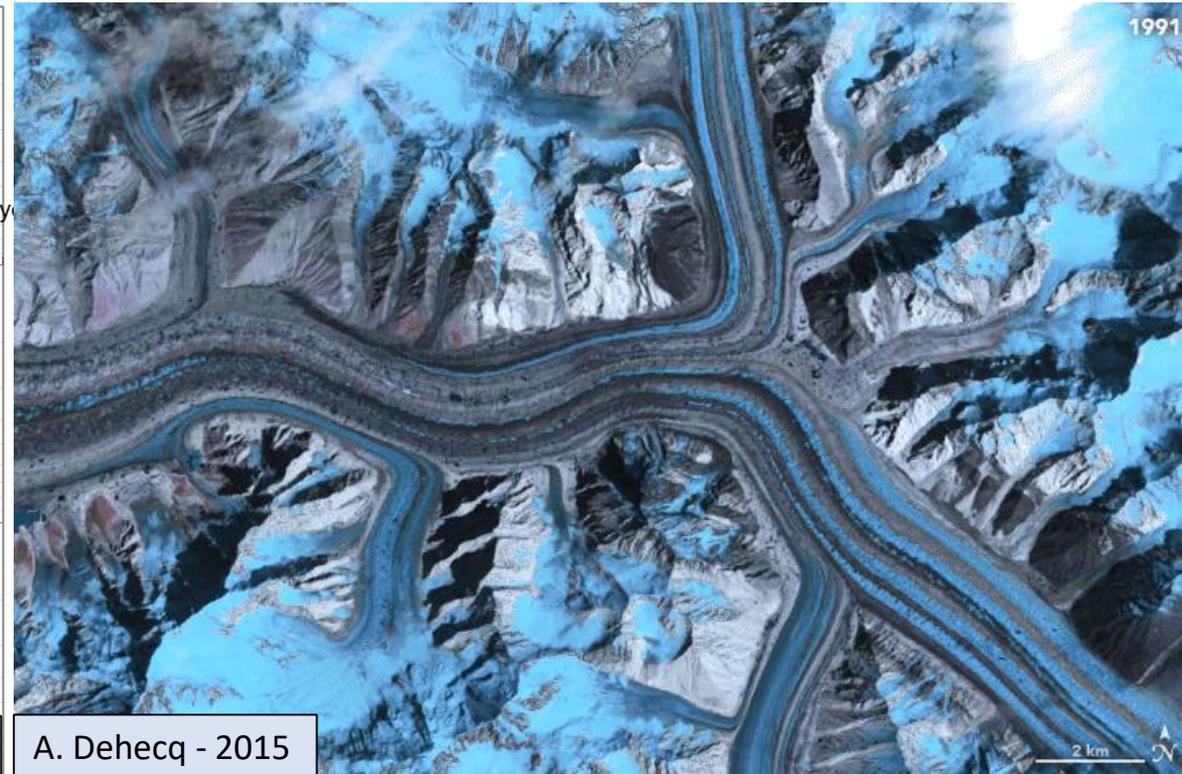
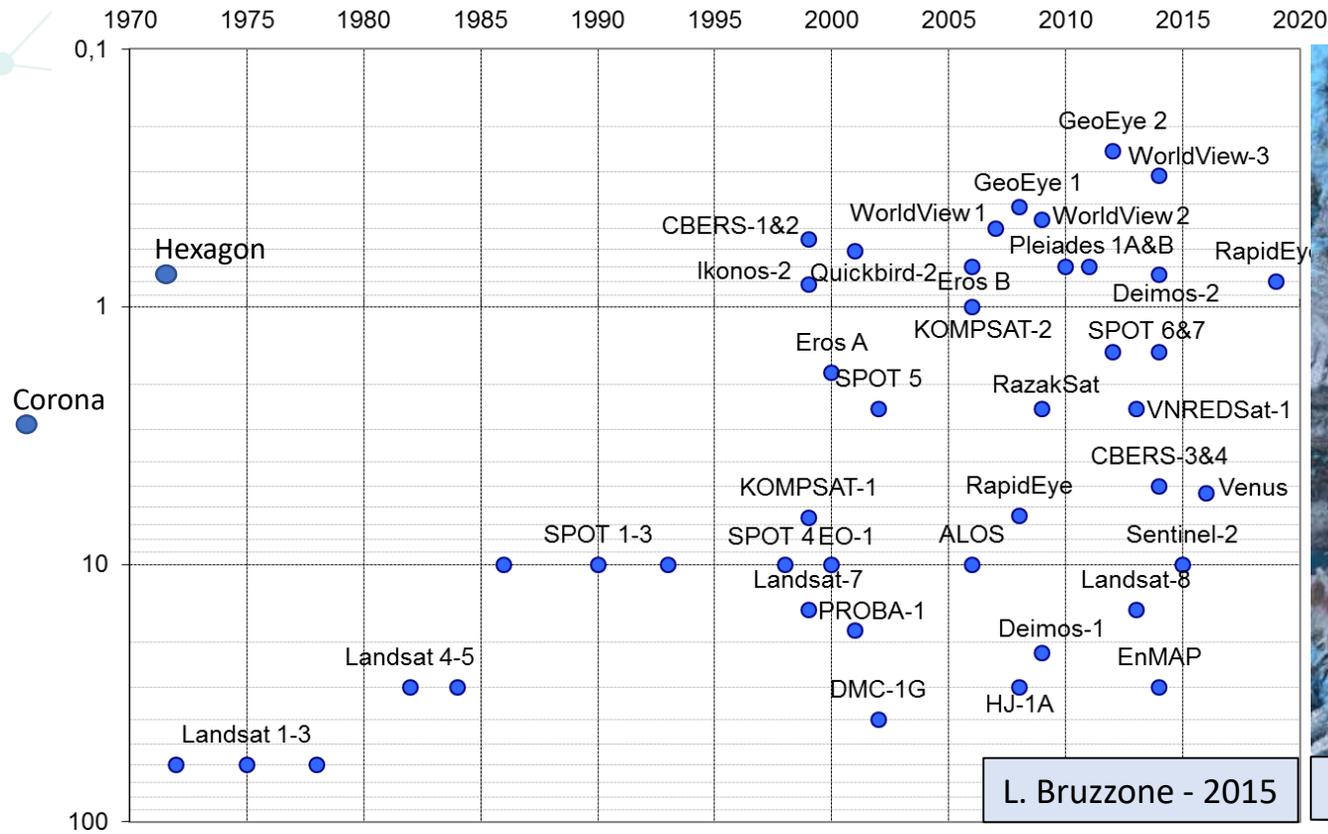
- Area => retreat
- Surface state, equilibrium line => accumulation/ablation zones
- Elevation => volume variation => mass balance
- Surface velocity => ice thickness



R. Fallourd, 2012

Remote sensing observations

- Space borne optical data
 - ➔ Digital Elevation Models
 - ➔ Surface Displacement Fields

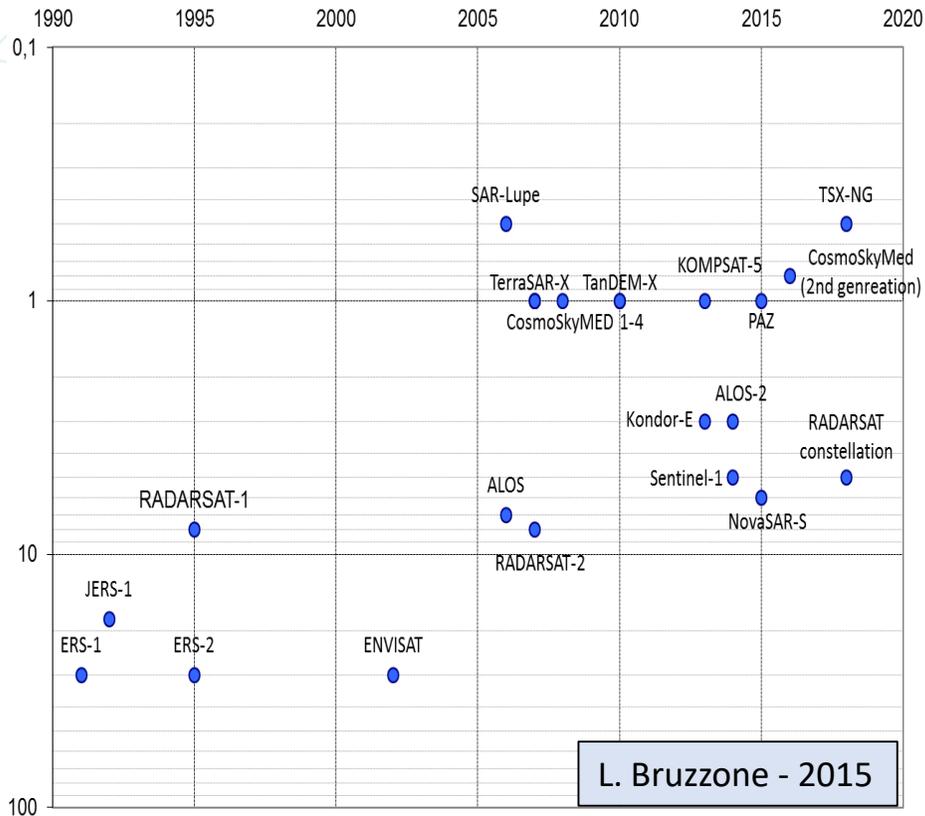
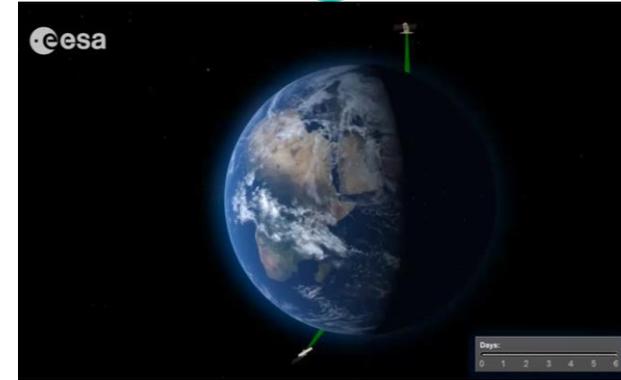


L. Bruzzone - 2015

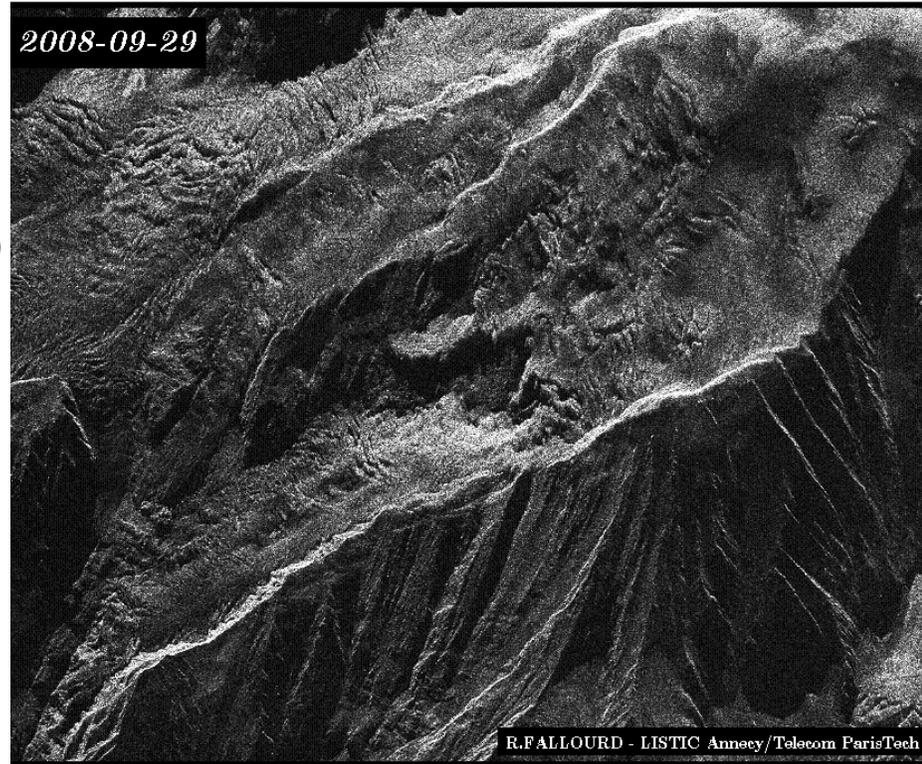
A. Dehecq - 2015

Remote sensing observations

- Space borne SAR data
 - ➔ Digital Elevation Models (SRTM, TanDEM-X)
 - ➔ Surface Displacement Fields: amplitude + phase (InSAR)

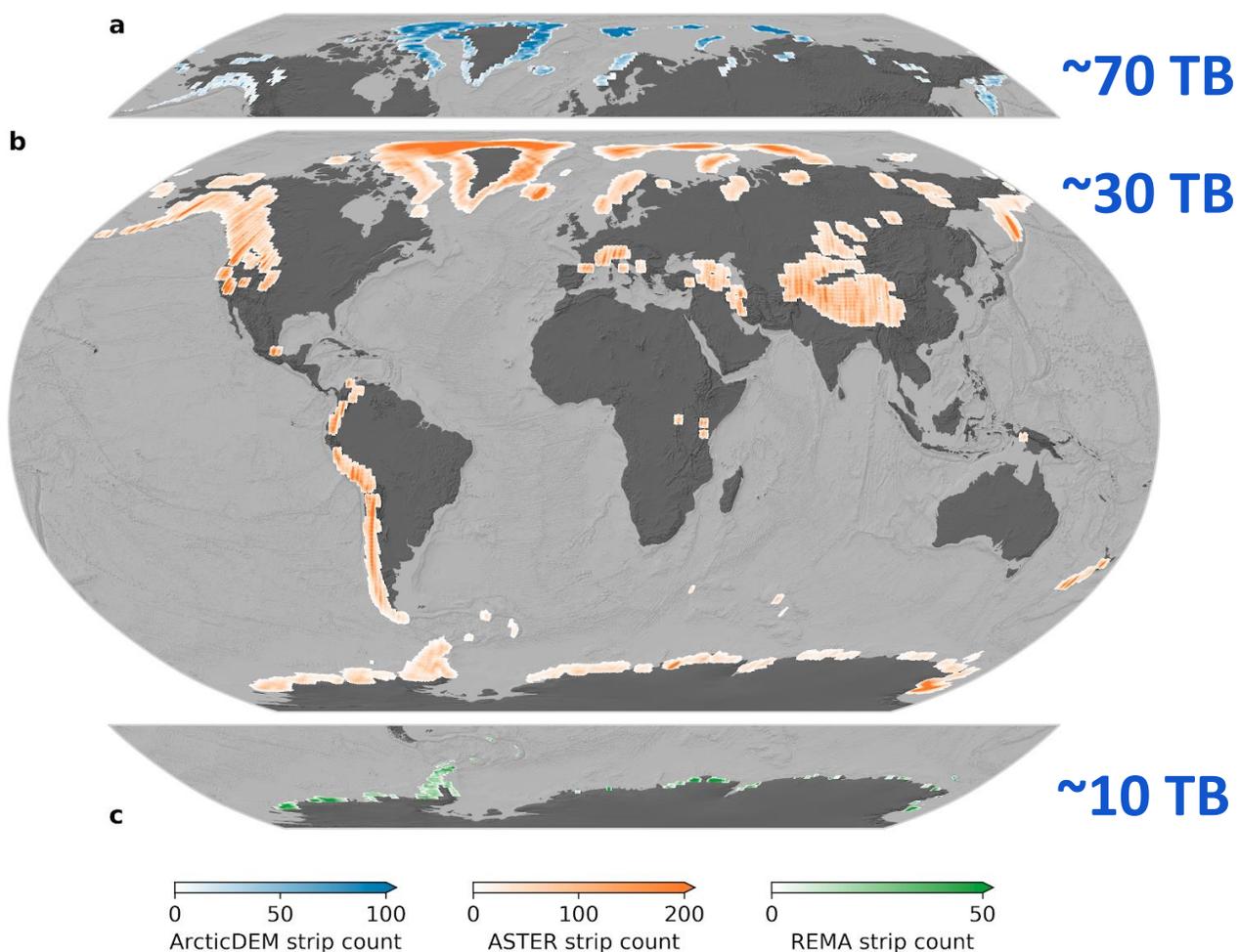


L. Bruzzone - 2015

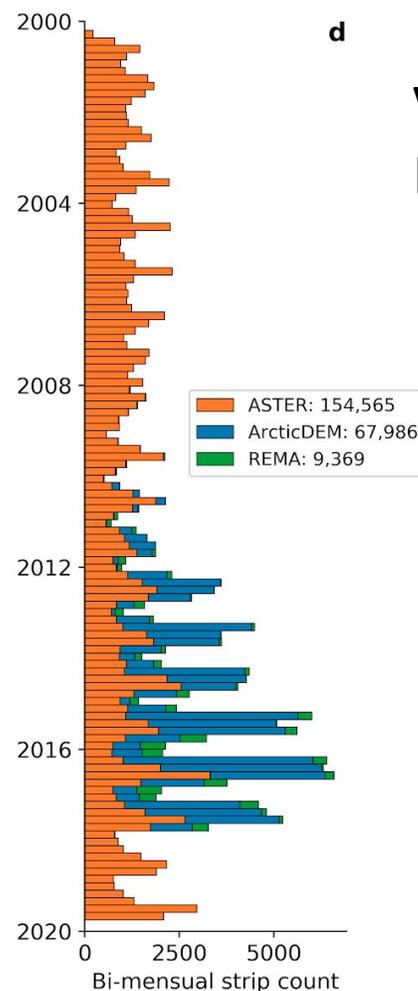




Digital elevation models estimated from ASTER and WorldView spanning 2000 to 2020



Coverage of ASTER and WorldView (ArcticDEM, REMA) DEMs



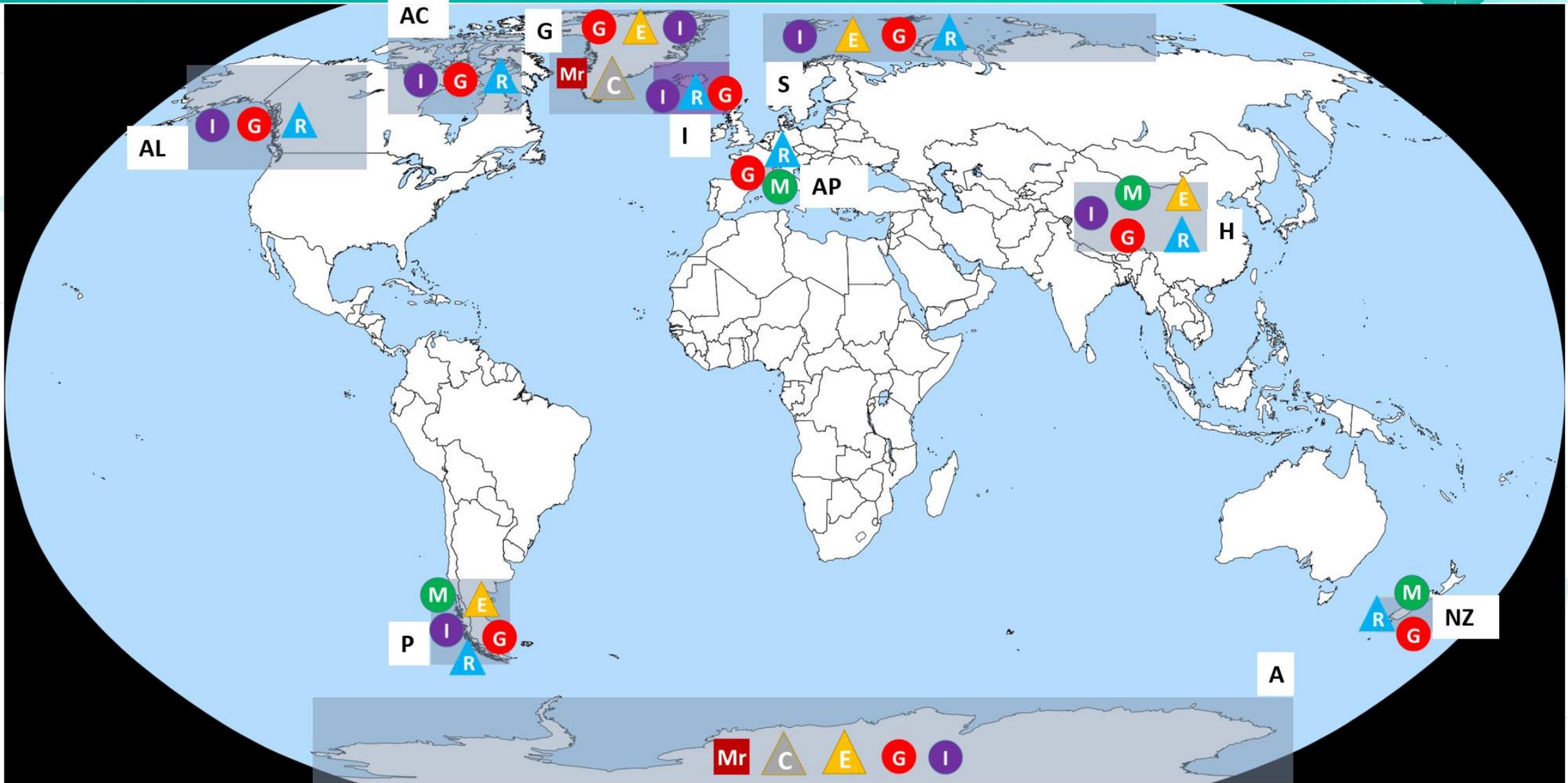
d Reference (stable): TanDEM-X
Validation: ICESat, IceBridge & HR DEMs (Pléiades, LiDAR, SPOT)

During 2000-2019, glaciers lost 266 ± 16 Gt yr⁻¹, or half a meter per year, equivalent to ~4% of their volume.

Europeans Alps lost about 30% of their volume.

R. Hugonnet & al., Nature 2021

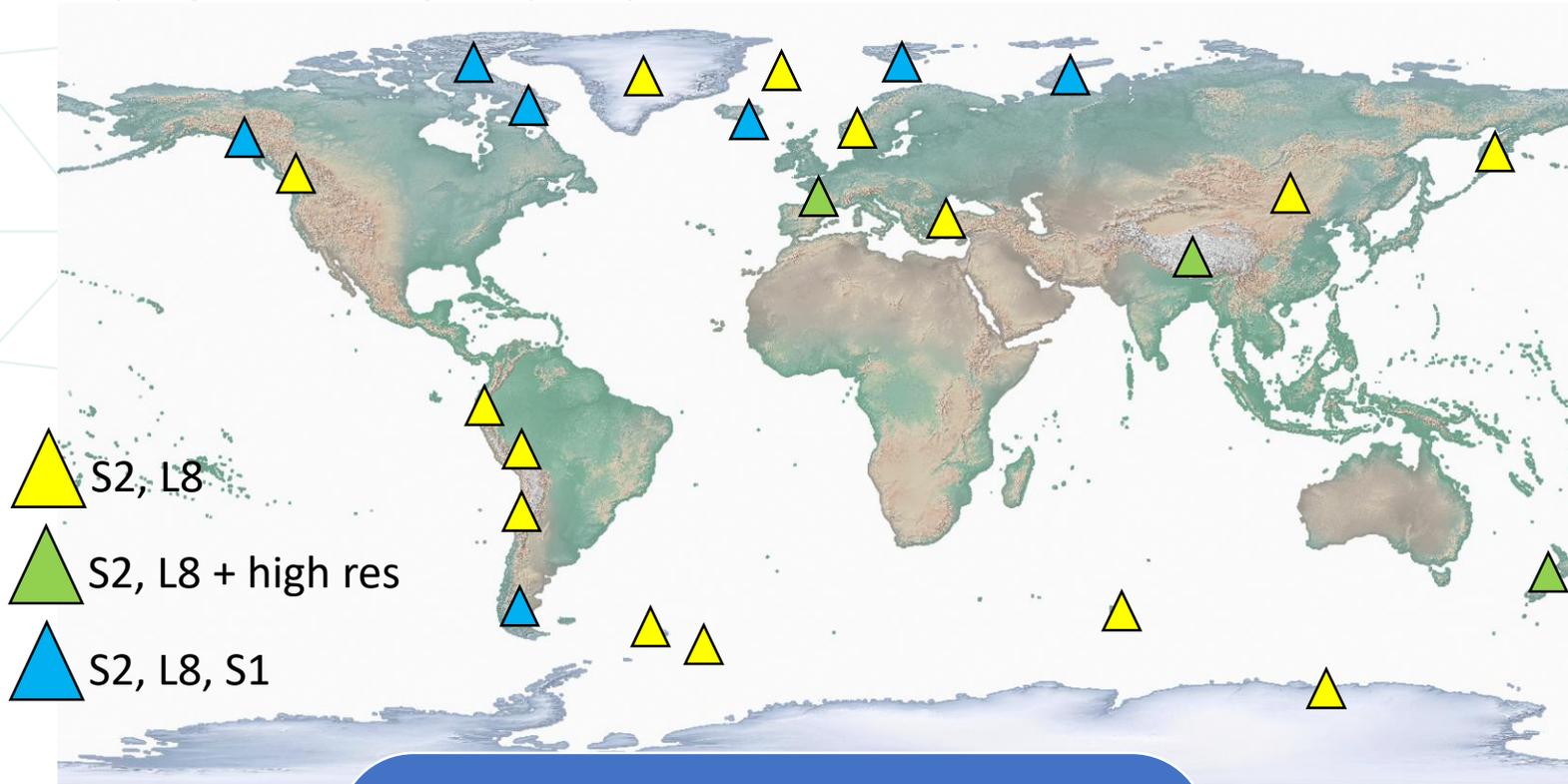
Available ice velocity maps around the world



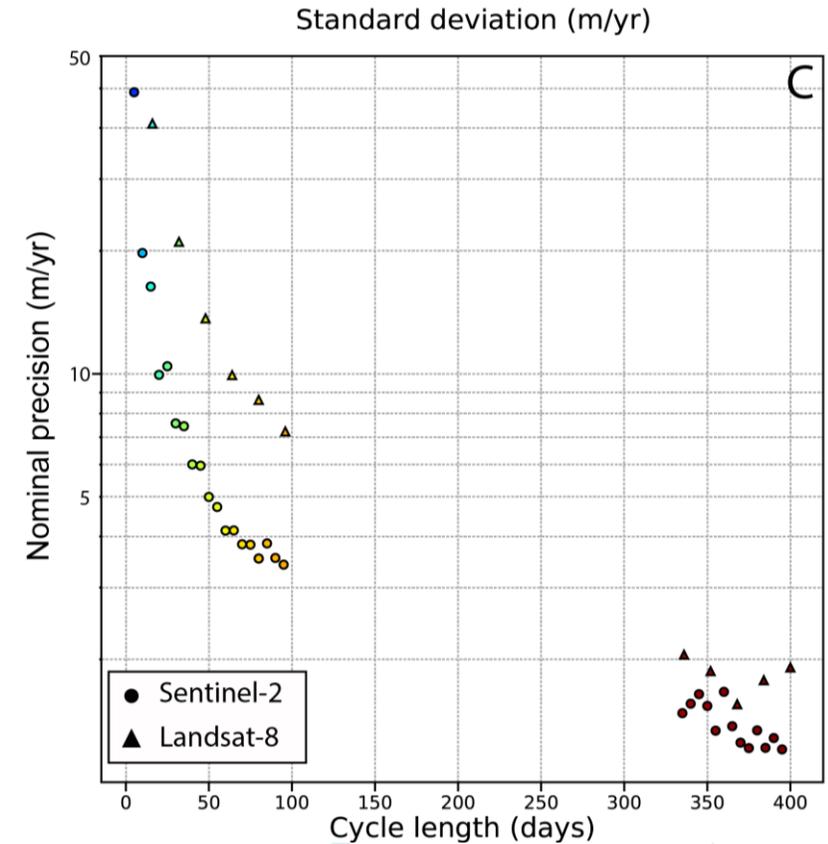
| | | | | | | | |
|---|--|--|--|--|---|--|-----------------------------|
| <p>optic</p> <p>I ITS_LIVE G GOLIVE</p> <p>M Millan et al., 2019 Mr MEaSURES</p> | | <p>SAR</p> <p>C CPOM R RETREAT</p> <p>E ENVEO Mr MEaSURES</p> | | <p>AL : Alaska</p> <p>AC: Canadian Arctic</p> <p>G: Greenland</p> | <p>I : Island</p> <p>S: Svalbard</p> <p>AP: Alps</p> | <p>H : Himalaya</p> <p>NZ: Southern Alps</p> <p>A: Antarctica</p> | <p>P : Patagonia</p> |
|---|--|--|--|--|---|--|-----------------------------|

01/04/2022

Large scale displacement fields produced by IGE pipeline



| Sensors | Number of image pairs (2017-2018) |
|------------|-----------------------------------|
| Sentinel-2 | $670 \cdot 10^3$ |
| Landsat-8 | $135 \cdot 10^3$ |
| Sentinel-1 | $7 \cdot 10^3$ |

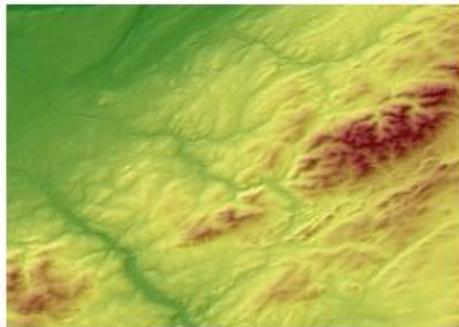


Median of the weighted standard deviation on ice-free areas

R. Millan & al., Rem. Sens. 2019

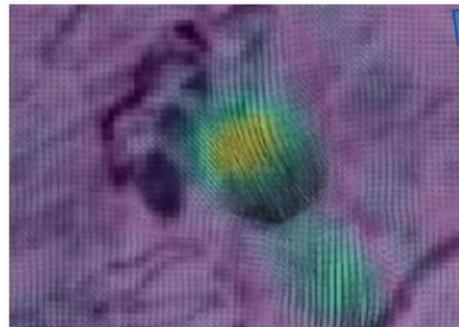
On line processing for DEM and DF

Merci de vous connecter avant de commencer.
(Lors de la première connexion, suivre les instructions)



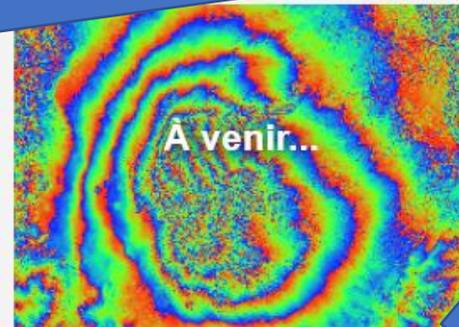
DSM-OPT

DSM-OPT signifie «Digital Surface Models from OPTical stereoscopic very-high resolution imagery». (Modèle Numérique de Surface à partir d'images stéréo très haute résolution)



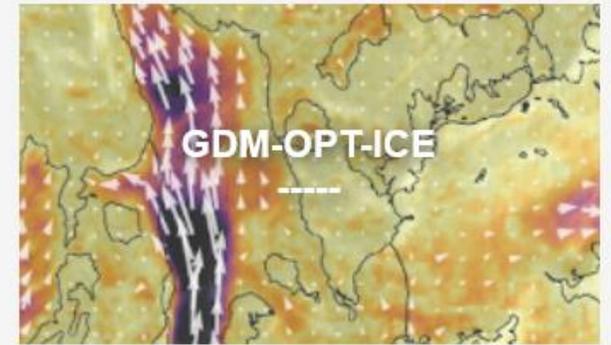
GDM-OPT

GDM-OPT signifie Ground Deformation Monitoring with OPTical image time series (Suivi des déformations du sol à partir de séries temporelles d'images optiques).



GDM-SAR

GDM-SAR signifie Ground Deformation Monitoring with inSAR image time series (Suivi des déformations du sol à l'aide de séries temporelles d'images radar).



GDM-OPT-ICE

GDM-OPT signifie Ground Deformation Monitoring with OPTical image time series (Suivi de la déformation du sol à partir de séries temporelles d'images optiques).

La version **GDM-OPT-ICE** du service est conçue pour suivre la cinématique des **glaciers et des calottes glaciaires**. Il permet le traitement à la demande des séries temporelles d'images Sentinel-2.

InSAR + offset tracking ?

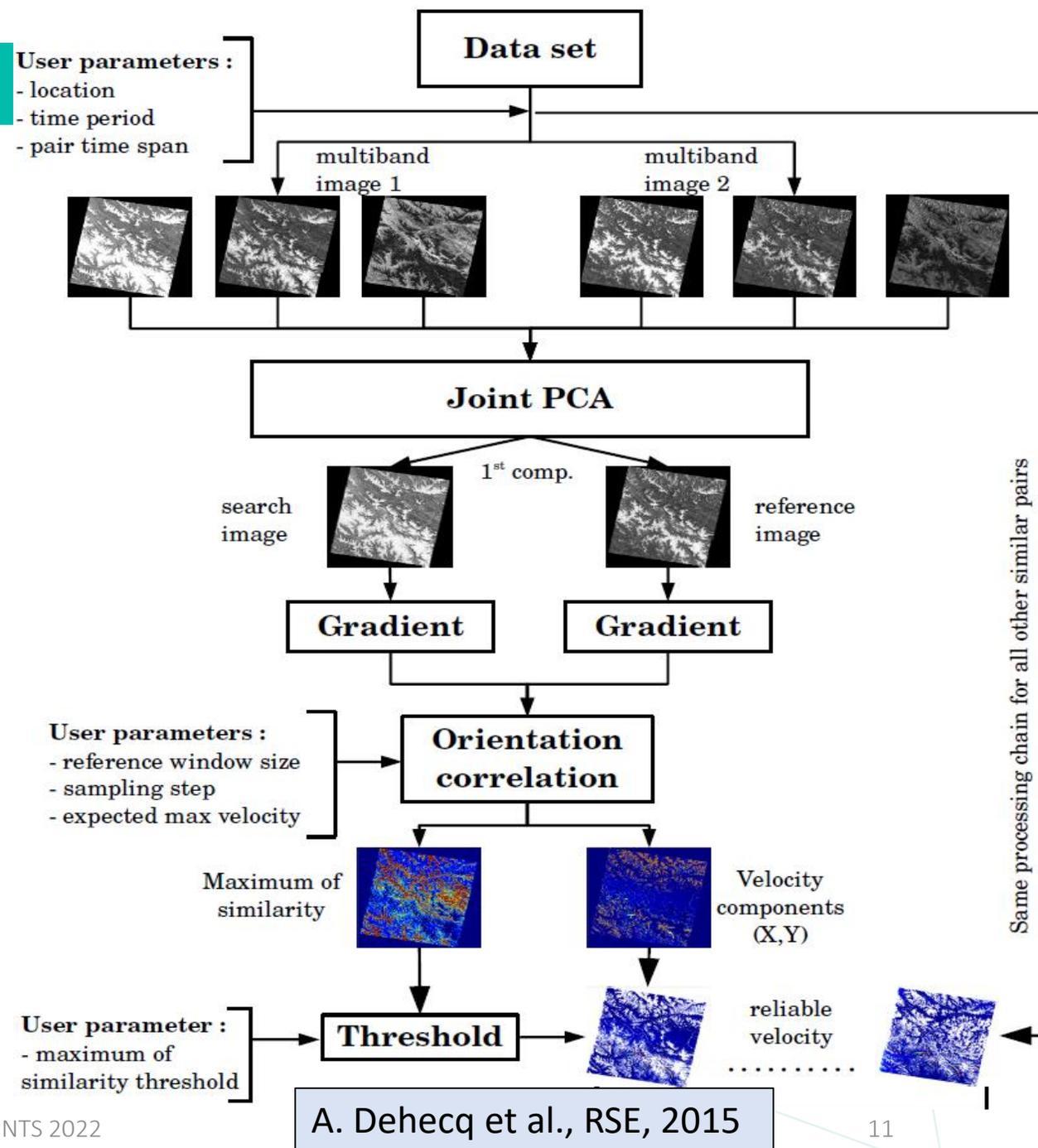
<https://www.poleterresolide.fr/services-de-calculs-a-la-demande>

- Introduction
 - Why monitoring glaciers?
 - Sought-after information
 - Remote sensing observations
 - Glacier DEM and velocity around the world
- ➔ • Computing displacement fields
 - Optical and SAR offset tracking pipelines
 - Improving SAR displacement measurements
 - Amplitude: correlation stacking, autofocus
 - InSAR: multi-temporal filtering
- Combining multiple displacement fields
 - Deriving annual velocities
 - Measuring intra-annual velocity
- Perspectives



Computing DF from optical data

- Main steps
 - Image pair selection
 - Band selection
 - Tracking (max of similarity)
 - Filtering each pair (confidence)
- Main difficulties
 - Clouds
 - Shadow
 - Saturation (snow, ice)
 - Surface changes
 - Resolution



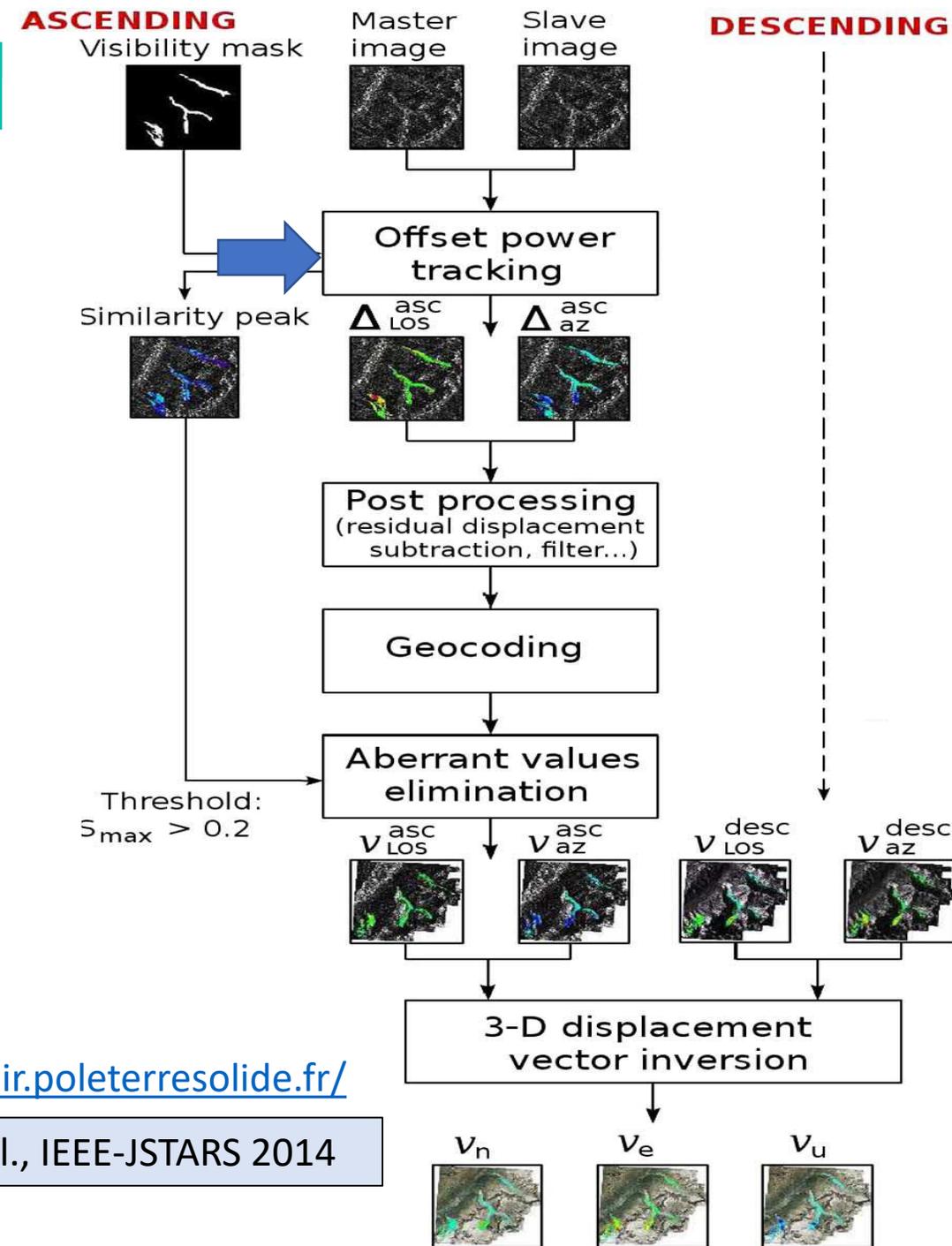
Computing DF from SAR data

• Main steps

- Image pair selection
- Tracking (max of similarity)
- Filtering each pair (confidence)
- Combing Asc/Des DF

• Main difficulties

- Shadow and layover
- Speckle (uncorrelated)
- Surface changes
- Resolution
- Ortho-rectification



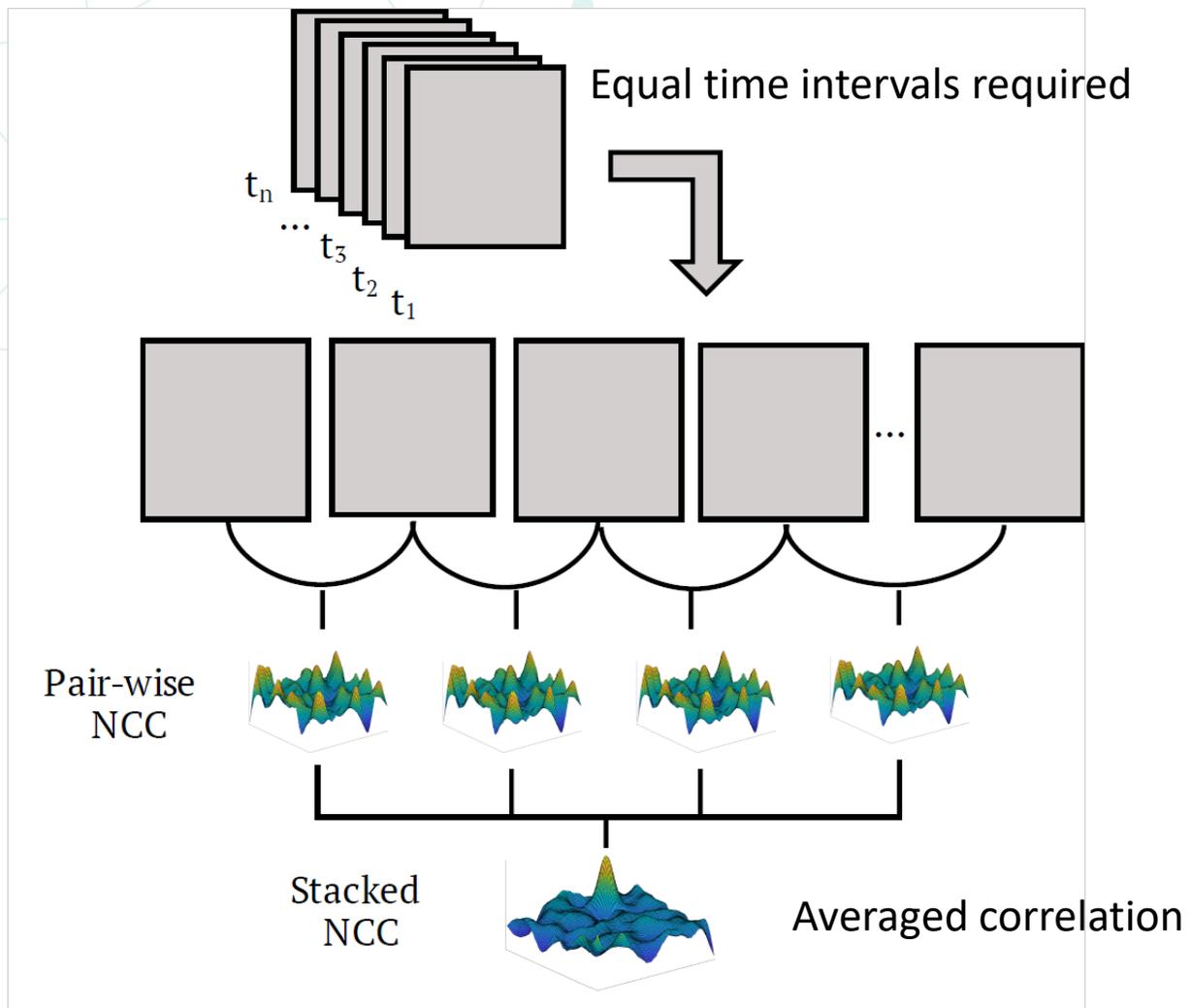
<https://efidir.poletterresolide.fr/>

F. Ponton et al., IEEE-JSTARS 2014

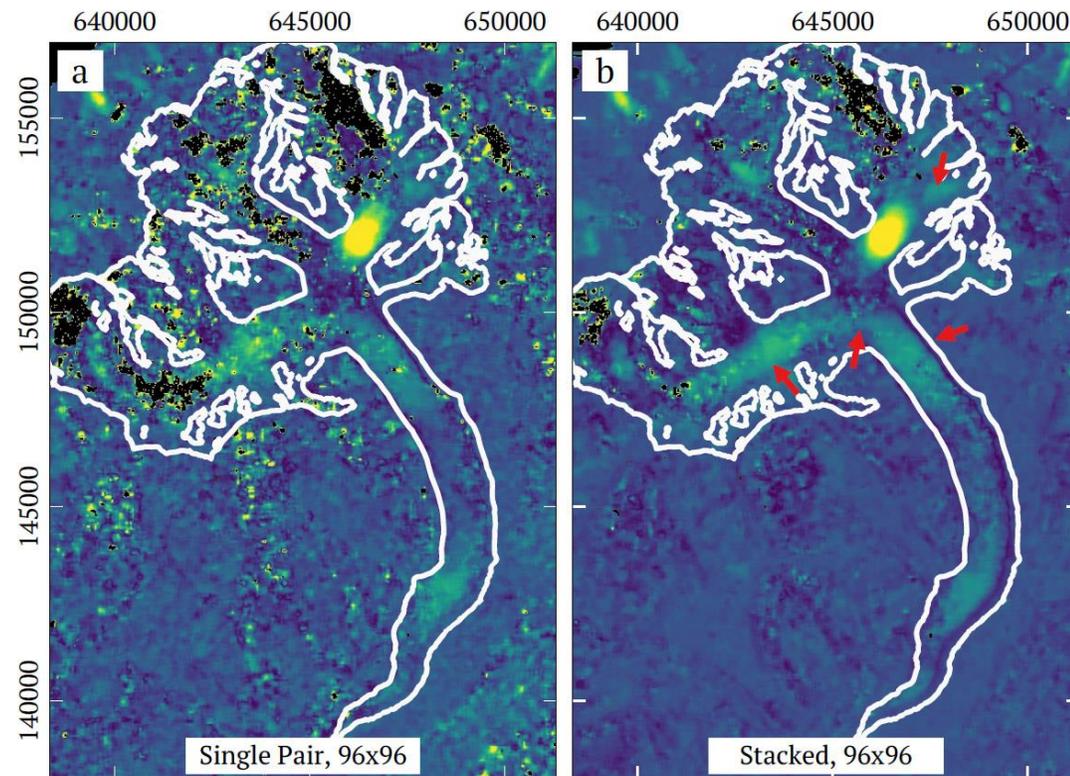
Journée PNTS 2022

01/04/2022

Cross Correlation stacking



S. Li, S. Leinss, et al., IEEE-JSTARS, 2021.



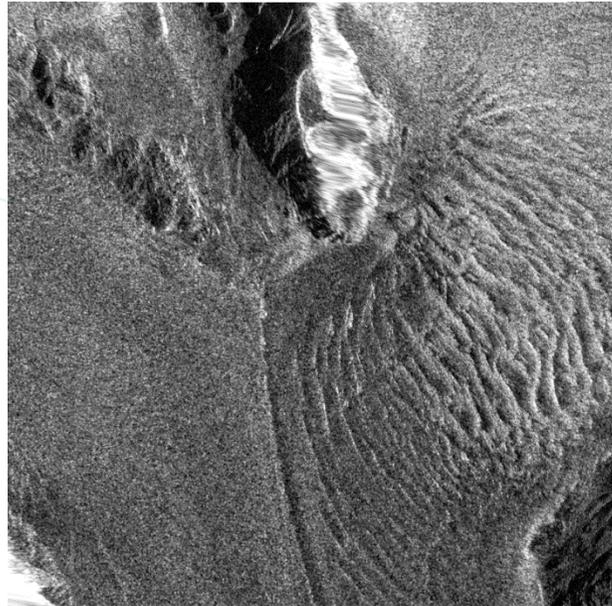
Pair-wise cross correlation

Computationally efficient method by Fourier domain processing of the correlation method.

Autofocusing temporally multilooked SAR time series

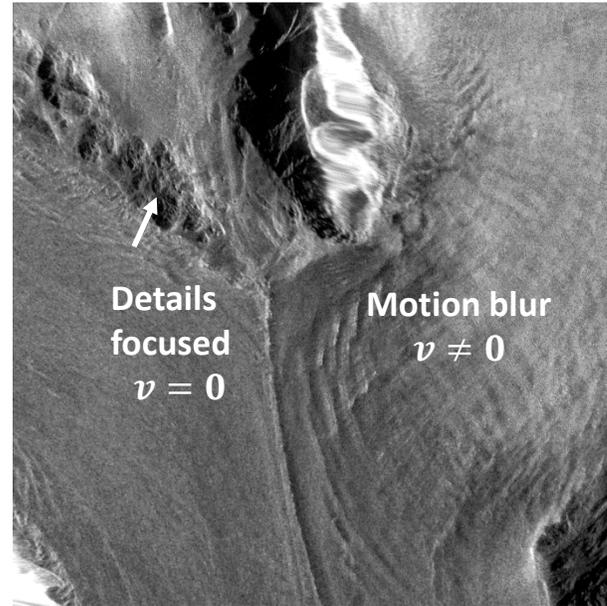


Single radar image



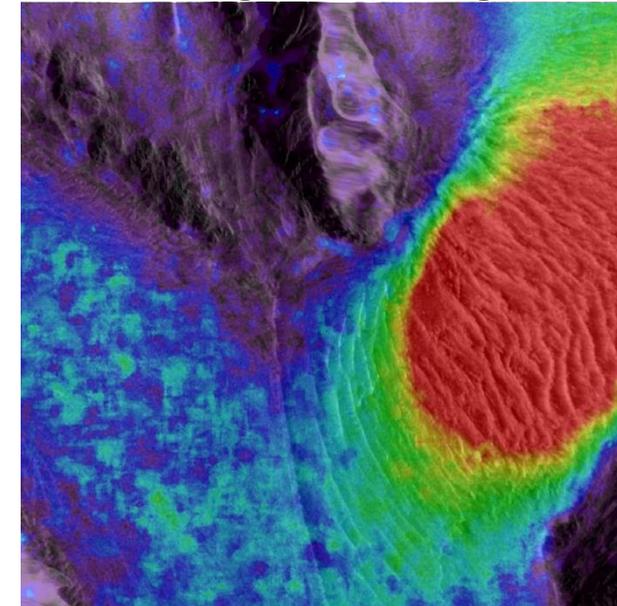
-- strong radar speckle (noise).

Temporal average of 12 images



+ stable features appear focused
-- glacier surface shows motion blur

Velocity-compensated average of 12 image

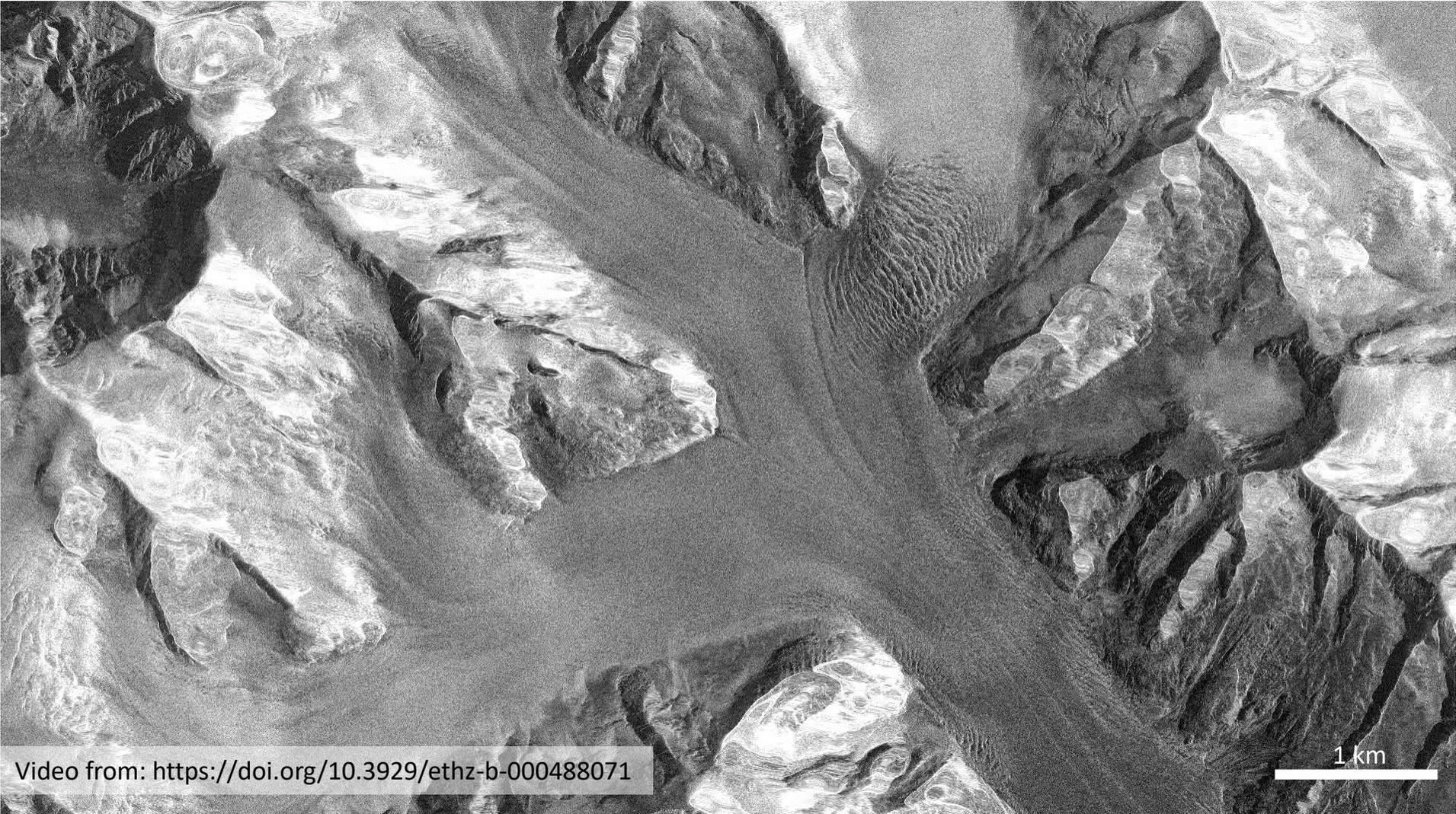


+ stable *and* moving features well visible.
+ velocity is found when temporal average appears focused.

Averaging image series to improve cross correlation works only when the velocity is known, or can be determined simultaneously during averaging

➔ Apply an autofocus method.

Time series of input backscatter images (TanDEM-X)



Autofocused, temporally multilooked time series



Results - Velocity magnitude



Test site:

Aletsch Glacier, Switzerland

Radar images: TanDEM-X

Winter 2011/2012

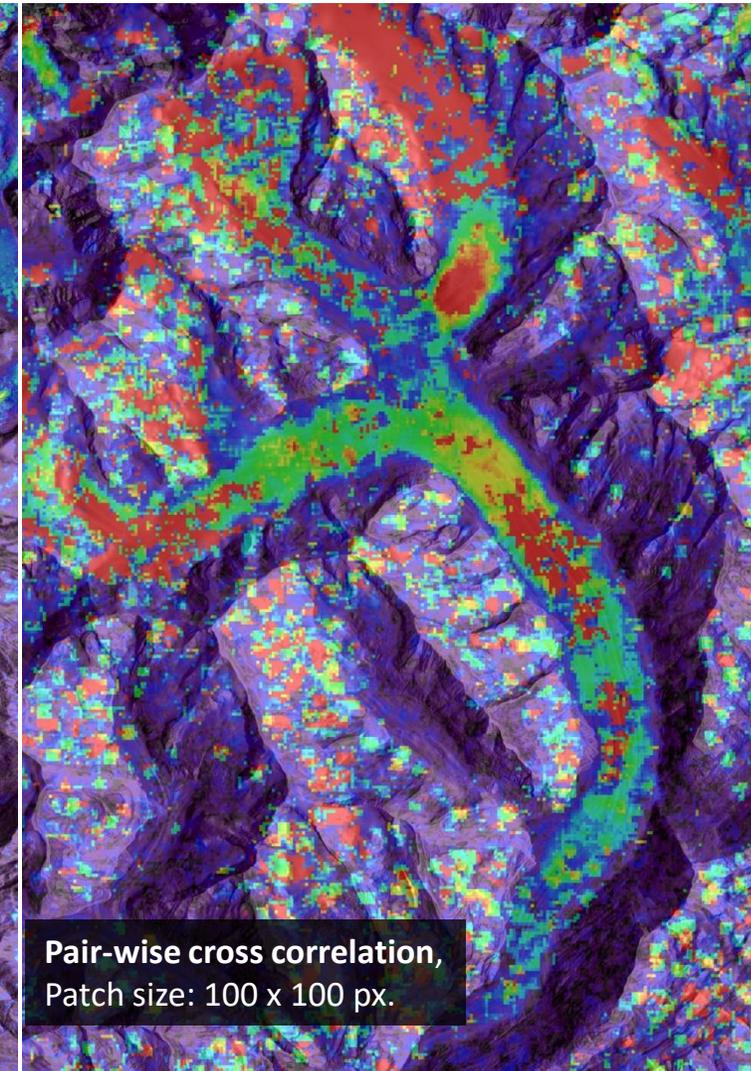
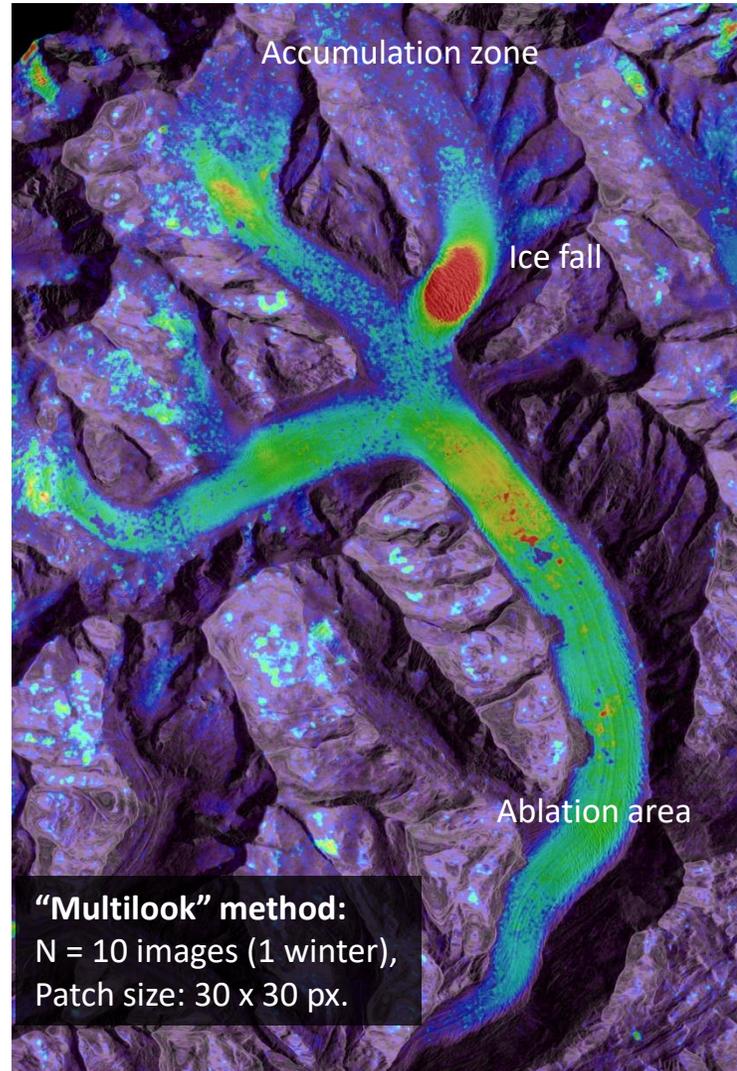
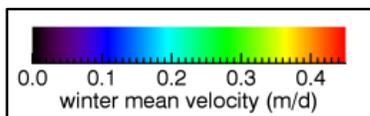
(11 days repeat cycle).

Autofocusing multilooked time series (left)

provides robust velocity estimates (even in the accumulation zone) with high area coverage and high spatial resolution (60 x 60 m).

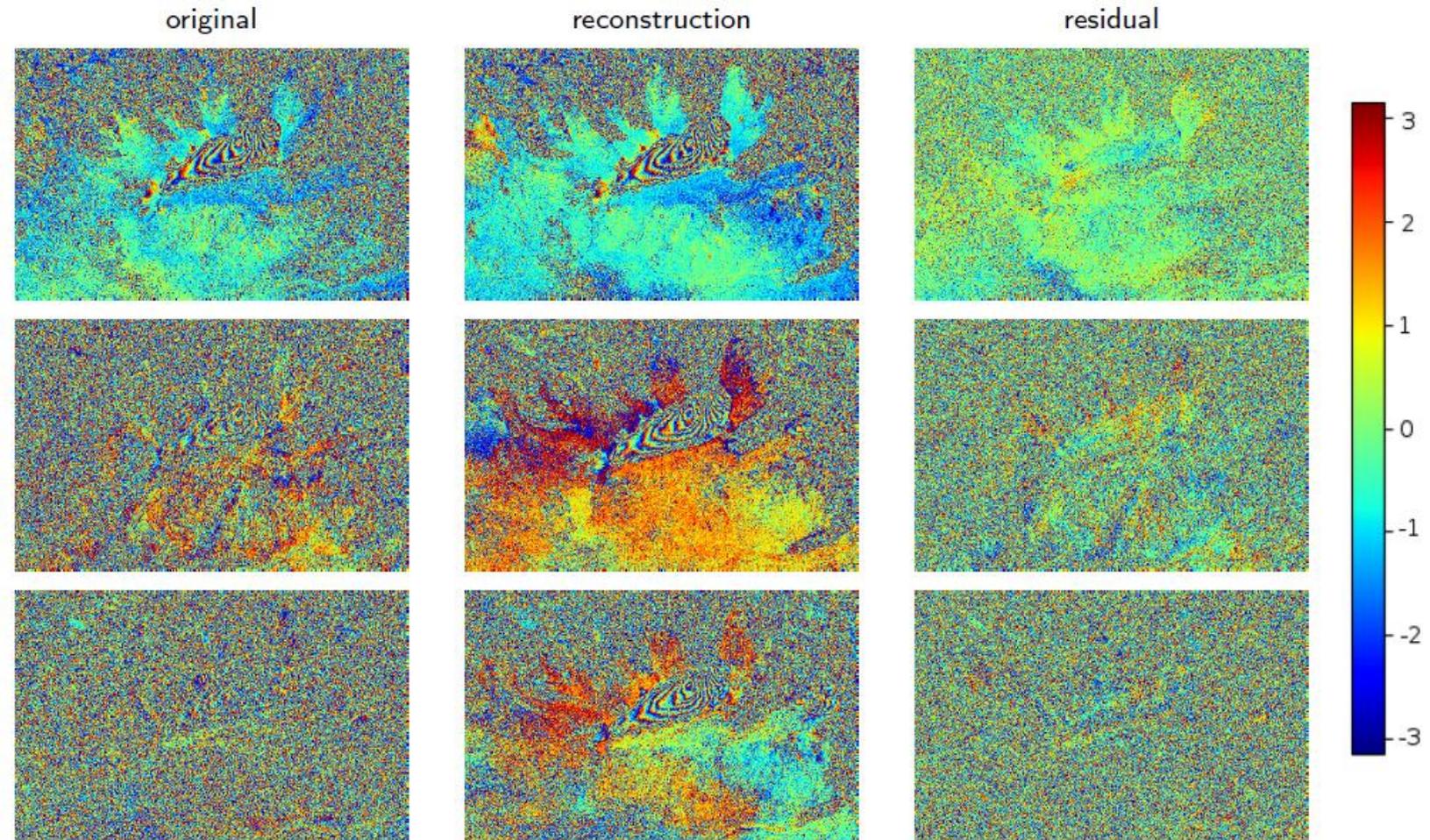
With pair-wise cross-correlation (right)

many areas cannot be tracked, even with larger correlation windows (200x200m).



InSAR improvement by multitemporal PM filtering

- PM method applied on wrapped phase:
Extraction of coherent displacement signal from interferogram time series for decorrelated areas



Sentinel -1 A/B data, Gorner glacier, Switzerland

3 dates: 2016/12/17-2016/12/23, 2017/02/03-2017/02/09, 2017/03/05-2017/03/11

Prébet et al., IEEE-TGRS 2019.



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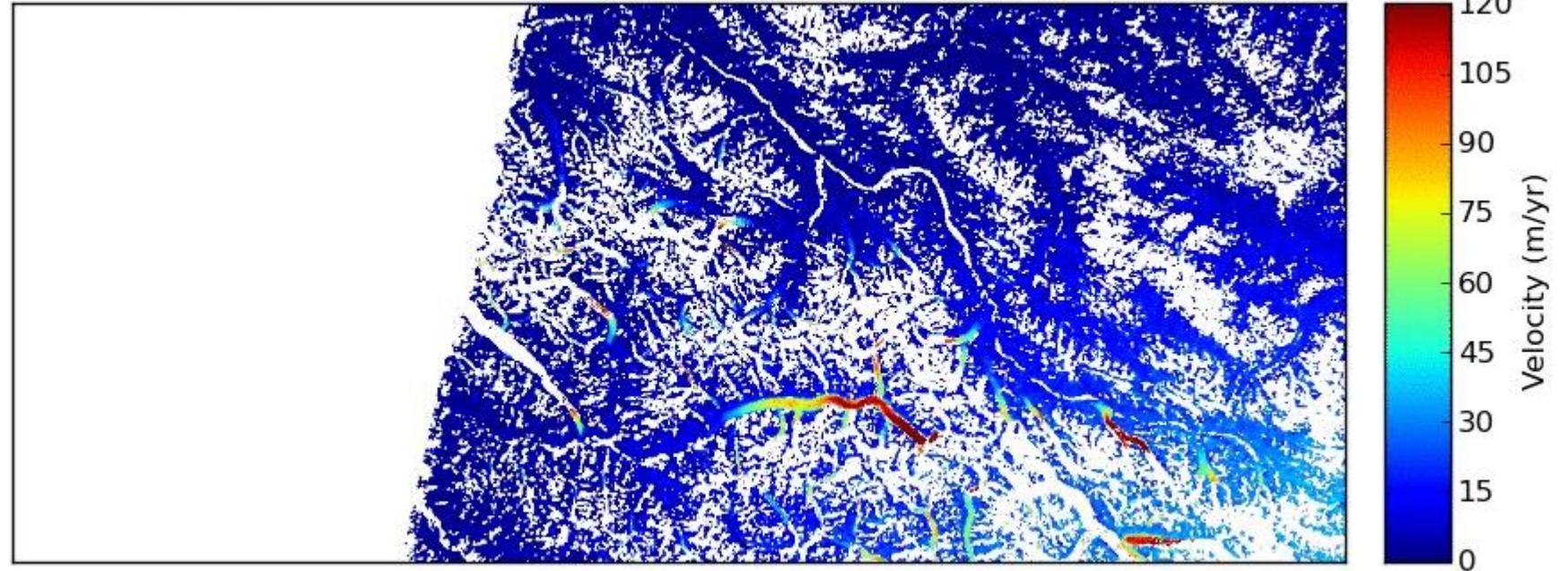
- Advantages

- Redundancy → reduction of uncertainty
- Complementarity → increased coverage

- Limitations

- Reduced temporal resolution
- Heterogeneous measurements

1 pairs



Fusion of annual velocity maps (Landsat images),
Median value in a spatial (170x170 m²) and temporal (3 years) neighborhood

A. Dehecq et al., RSE, 2015

Time series inversion based on temporal closure

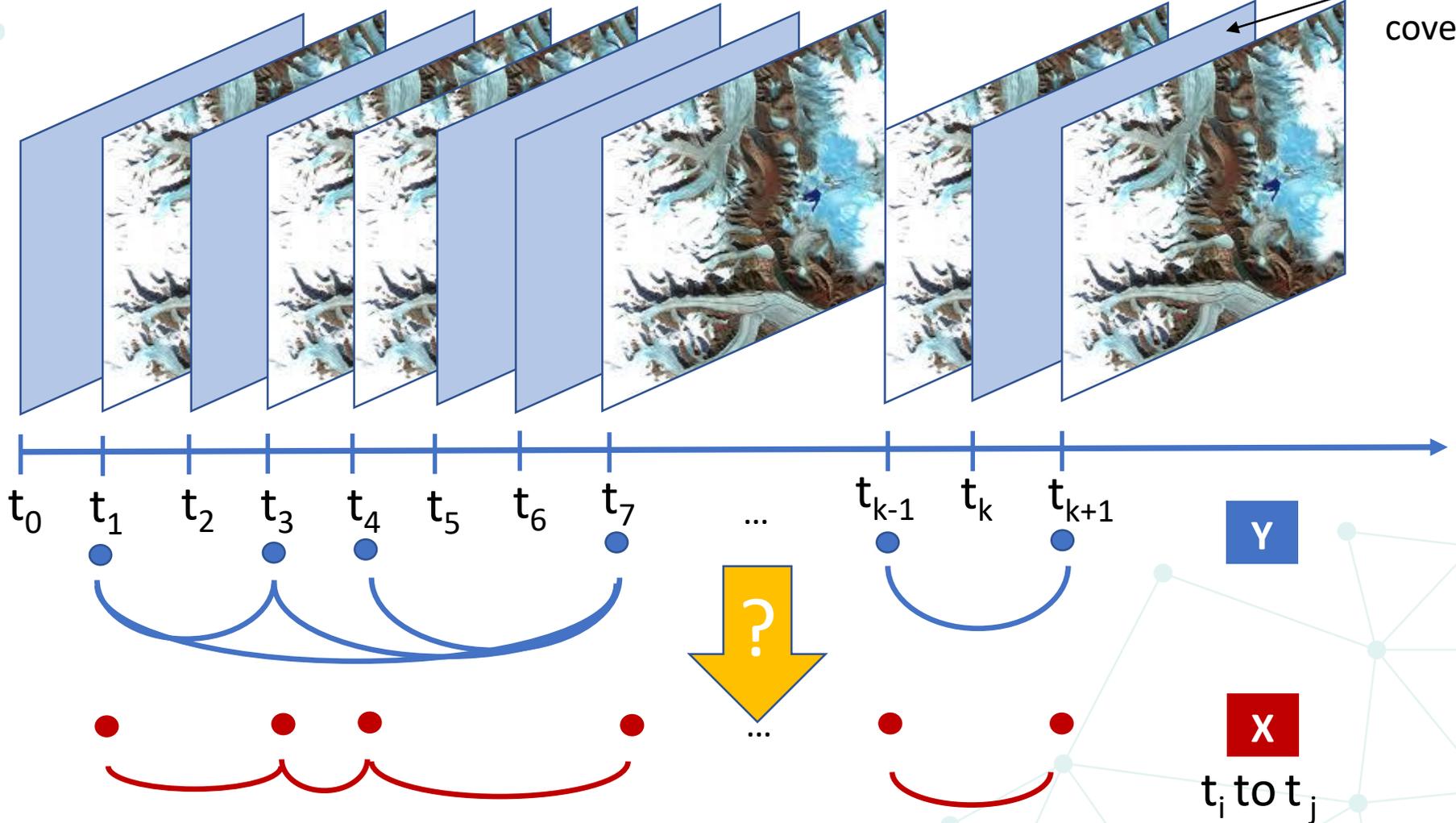


LISTIC

Cloud cover

- Advantages

- More interpretable
- Less gaps
- Less redundancy
- Reduced uncertainty



Input: Displacements Y

Output: Displacements X

Irregular sampling:
only on the observed dates

Berardino et al., 2002; Bontemps et al., 2018 ; Altena et al., 2019 ...

Time series inversion based on temporal closure

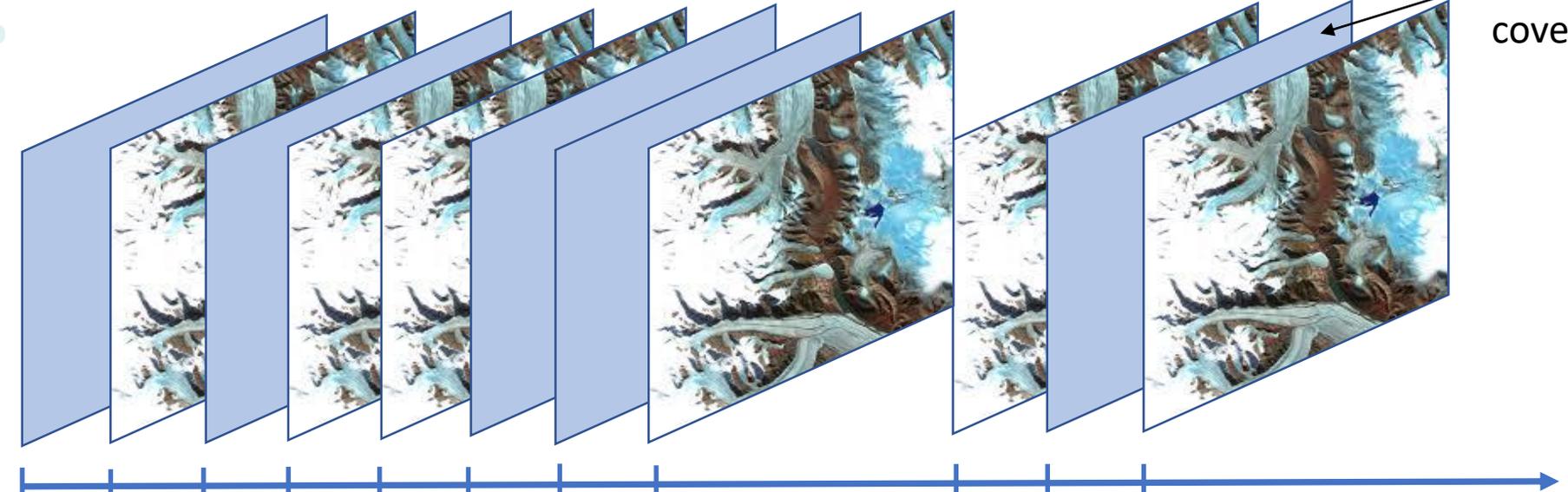


LISTIC

Cloud cover

- Advantages

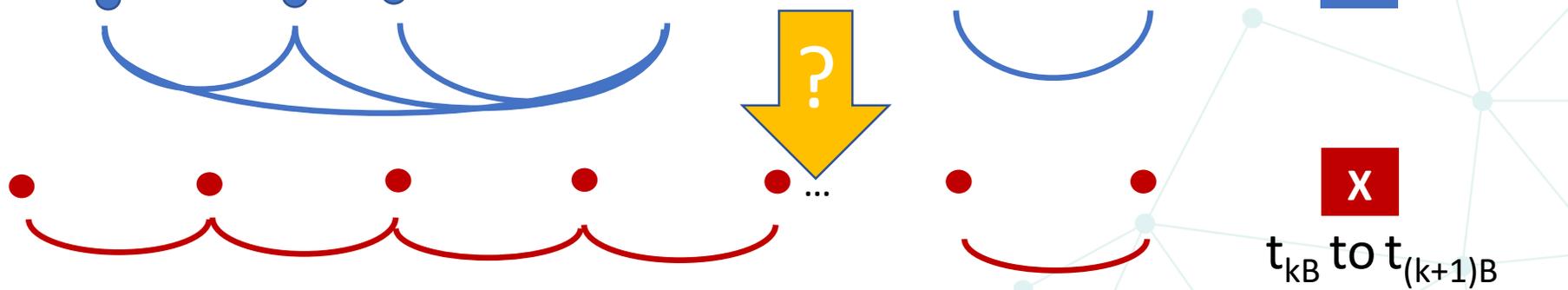
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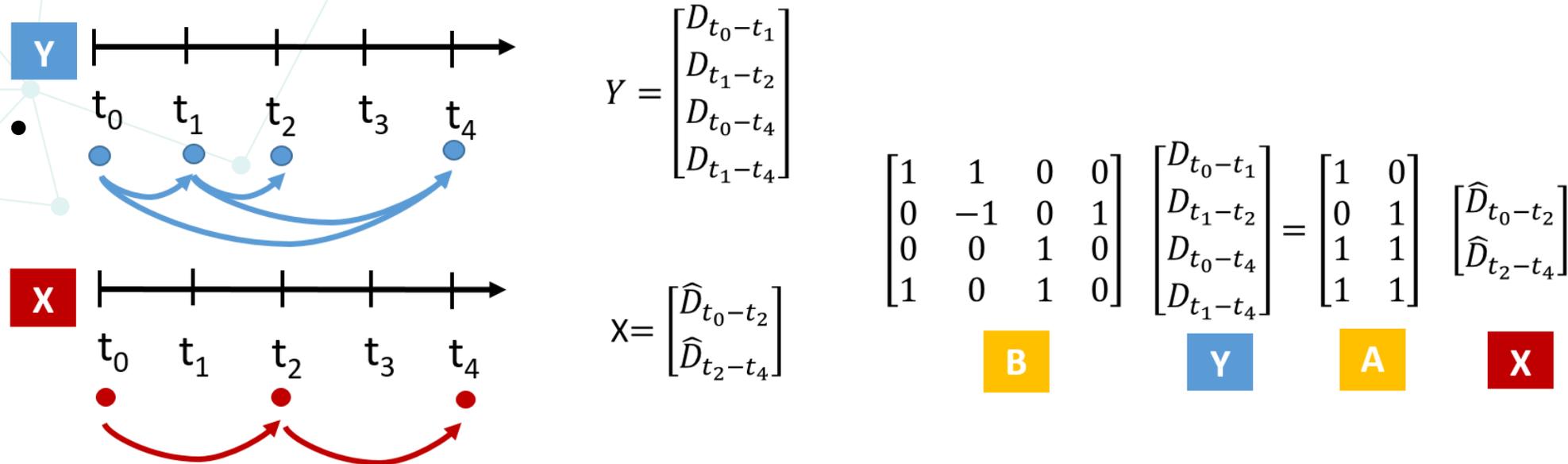


Output: Displacements X





- Example of the temporal closure using the proposed method:



- Inversion of the system $BY = AX$ by Iterative Reweighted Least Square

Weight
Regularisation
Cost Function: $\operatorname{argmin}_{\vec{x}} \left\| W(AX - Y) \right\|_2 + \lambda \left\| \Gamma X \right\|^2$

Charrier et al., IEEE-TGRS 2022

Time series inversion – performance assessment



$$RMSE_{stable} = \sum_{(i,j) \in w} \sqrt{\frac{1}{N} \sum_{t=0}^N \|\vec{V}(i,j,t)\|^2}$$

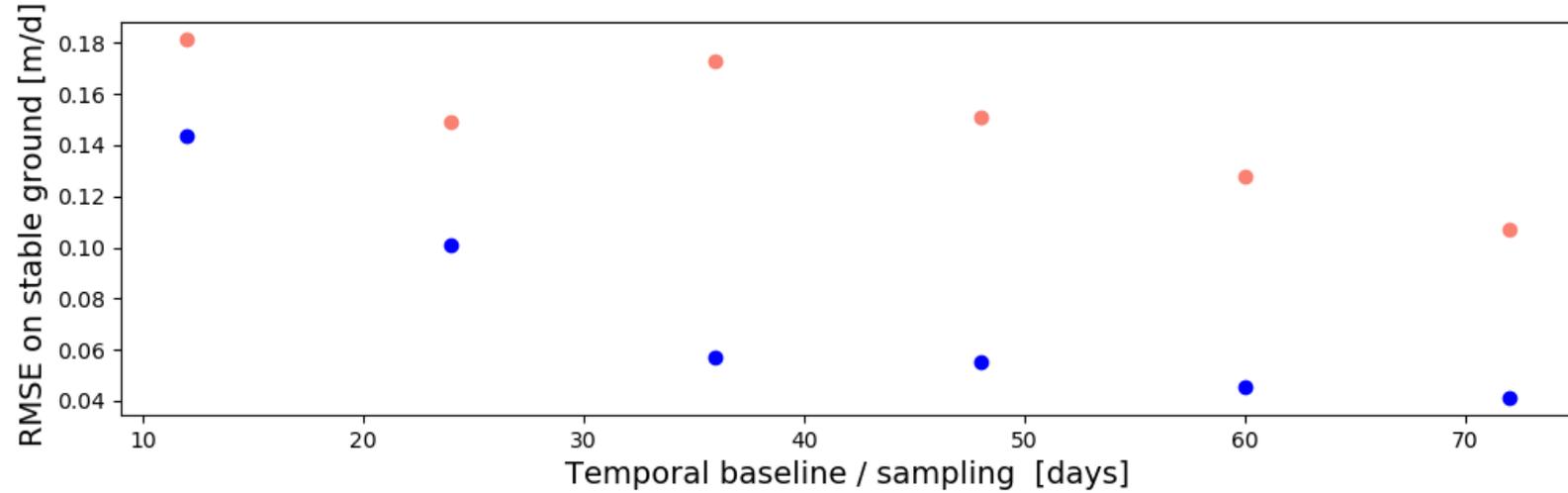
RMSE ↘ 😊

RMSE ↗ 😞

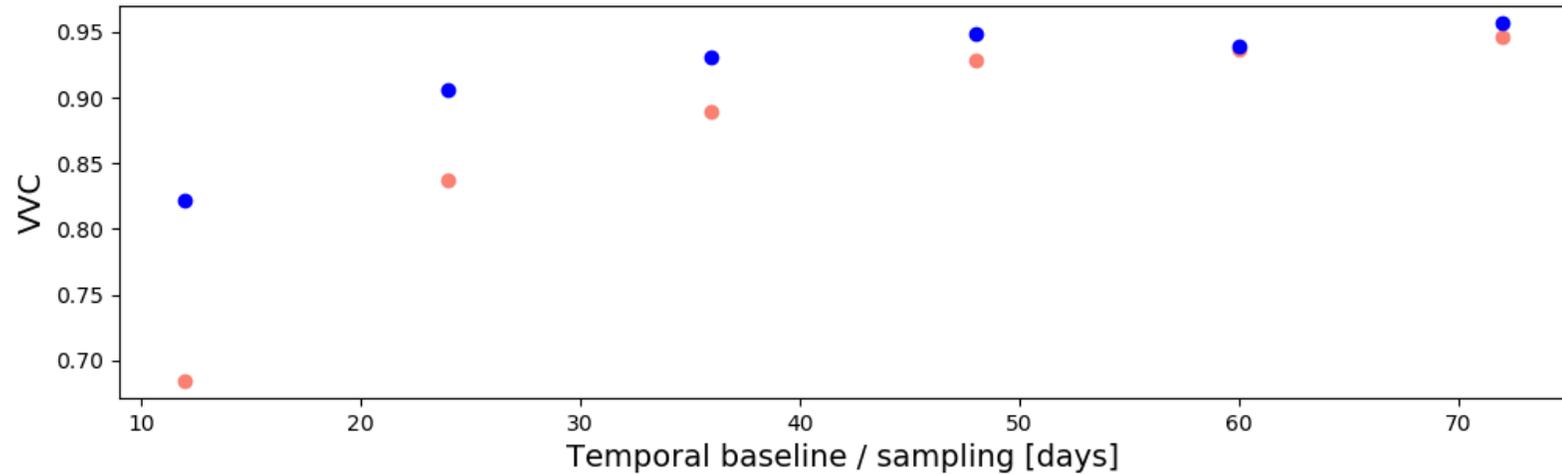
$$VVC_{fast g.} = \sum_{(i,j) \in w} \left\| \left\| \sum_{t=0}^N \frac{\vec{V}(i,j,t)}{\|\vec{V}(i,j,t)\|} \right\| \right\|$$

VVC ↗ 😊

VVC ↘ 😞



● Velocity observations ● Leap Frog velocity time series



● Velocity observations ● Leap Frog velocity time series

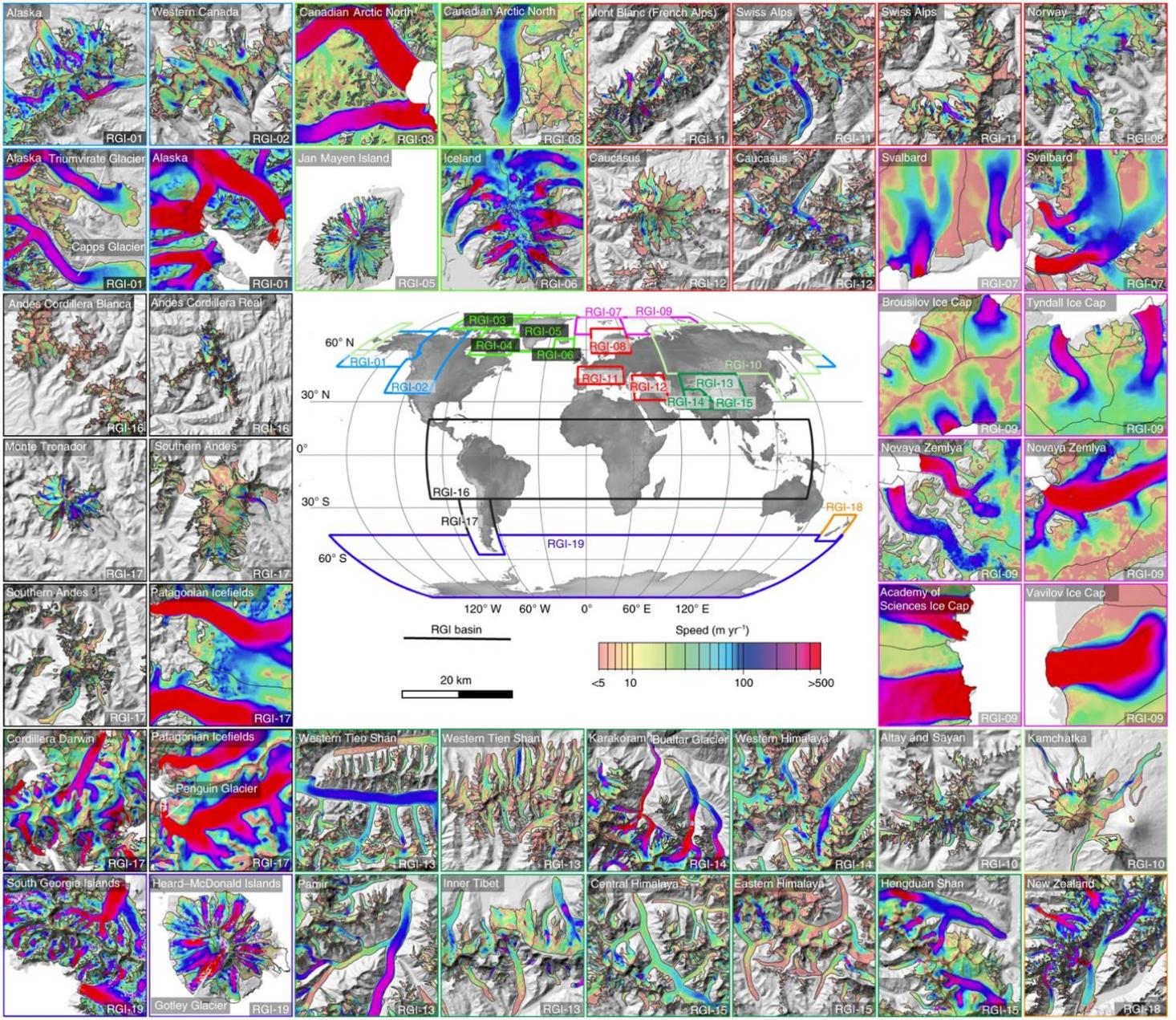
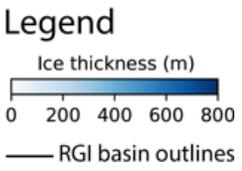
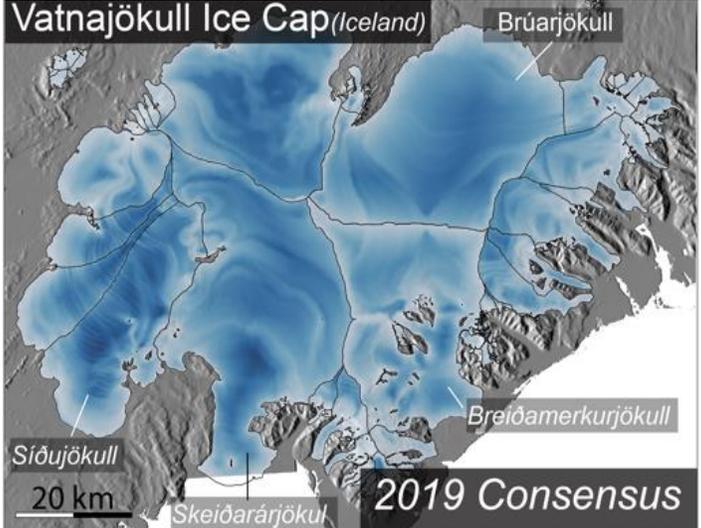
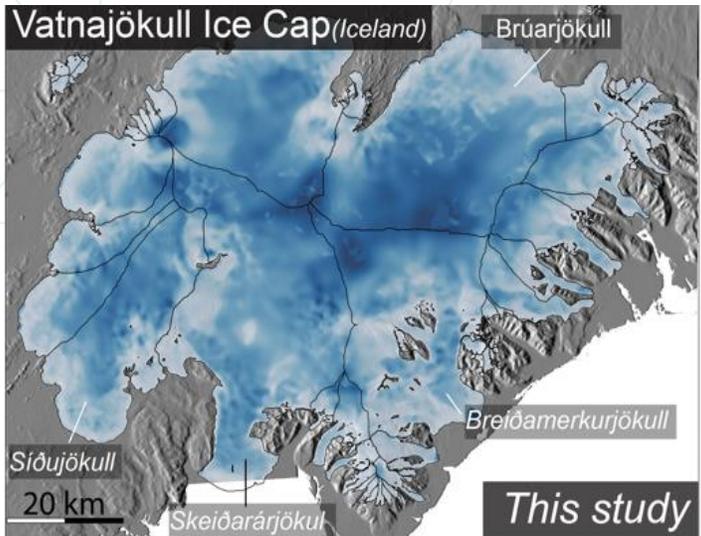
Charrier et al., IEEE-TGRS 2022



- More and more EO data, increased spatial and temporal resolutions
- Computing displacement fields
 - Still new methods to be developed: faster, more reliable, using SITS...
 - Computer vision, Machine Learning...
- Combining multiple displacement fields
 - Imputation of missing data (spatial/temporal)
 - Fusion of heterogeneous sources:
 - Different sensors => different projections
 - Different methods/groups => Different spatial and temporal resolutions, different uncertainty
- Extracting physical knowledge
 - Inversion of physical model parameters / Data assimilation
 - Knowledge discovery by IA/data mining approaches

Ice velocity and thickness of the world's glaciers

Romain Millan^{1,2}, Jérémie Mouginot^{1,3}, Antoine Rabatel¹ and Mathieu Morlighem^{3,4}



Centre world map illustrates the coverage by RGI region²⁶. The 44 panels are 25 × 25 km portions of ice velocity, representative of the glacier diversity across all RGI regions. The ice speed is colour coded on a logarithmic scale overlaid on shaded relief. RGI regions are assigned a colour that is also used for the frames of the ice velocity panels.



- L. Charrier, Y. Yan, E. Koeniguer, S. Leinss, E. Trouvé, (2022), “Extraction of velocity time series with an optimal temporal sampling from displacement observation networks”. In: *IEEE Trans. Geosci. Remote Sens.*.
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- Dehecq, A., Gourmelen, N., Gardner, A. S., Brun, F., Goldberg, D., Nienow, P. W., Berthier, E., Vincent, C., Wagnon, P., & Trouvé, E. (2019). Twenty-first century glacier slowdown driven by mass loss in High Mountain Asia. *Nature Geoscience*, 12(1), 22-27. <https://doi.org/10.1038/s41561-018-0271-9>
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- S. Li, S. Leinss, et al. “Cross-Correlation Stacking for Robust Offset Tracking Using SAR Image Time-Series”. *J. Sel. Topics Appl. Earth Observ. Remote Sens.* (2021).
- Millan, R., Mouginot, J., Rabatel, A., Jeong, S., Cusicanqui, D., Derkacheva, A., & Chekki, M. (2019). Mapping Surface Flow Velocity of Glaciers at Regional Scale Using a Multiple Sensors Approach. *Remote Sensing*, 11(21), 2498. <https://doi.org/10.3390/rs11212498>
- Millan, R., Mouginot, J., Rabatel, A., & Morlighem, M. (2022). Ice velocity and thickness of the world’s glaciers. *Nature Geoscience*, 15(2), 124-129. <https://doi.org/10.1038/s41561-021-00885-z>
- R. Prébet, Y. Yan, M. Jauvin, E. Trouvé. A Data-Adaptive EOF-Based Method for Displacement Signal Retrieval From InSAR Displacement Measurement Time Series for Decorrelating Targets. *IEEE Transactions on Geoscience and Remote Sensing*, 2019, 57(8), pp.5829-5852,