Measuring earth surface deformation, glacier dynamics and geomorphic changes from times series of optical satellite images with COSI-Corr

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Motivation

1. The surface of Earth and other planet changing as a result of both internal and external dynamic processes.

2. The volume of remote sensing data available is increasing exponentially, driven by commercial and defense applications.

3. Science opportunities have emerged also because of development of specific techniques to exploit those data.

➔ Our goal: to provide tools (open source) to exploit optical sensing data for the Earth and Planetary sciences

Overview

- COSI-Corr presentation
- New COSI-Corr release
- Application to glacier flow monitoring using optical time series images

COSI-Corr: Co-registration of Optically Sensed Images and Correlation

- Alignment of satellite and aerial images with sub-pixel accuracy: sub-pixel accuracy ten times smaller than the size of pixel
- Tracking and monitoring of ground motion, displacement, or changes
- Measure and track 3D surface motion (not distributed)
- ENVI toolbox for download since 2007 (last release 2014)
- Developed with IDL (+ C++, FORTRAN)
- Implements (Tools):

PRE-PROCESSING
- Co-registration
- Viewing geometry optimization
- Rectifications
- Resampling

CORRELATION
- Precise correlation
  - Spatial
  - Phase

POST-PROCESSING
- Filtering
- Denoising
- Resampling
- Vector Field

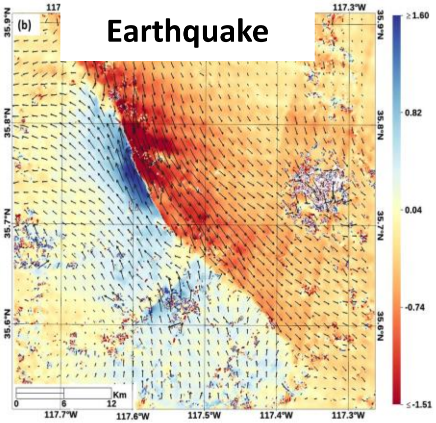
The software package is available at : http://www.tectonics.caltech.edu/slip_history/spot_coseis/index.html

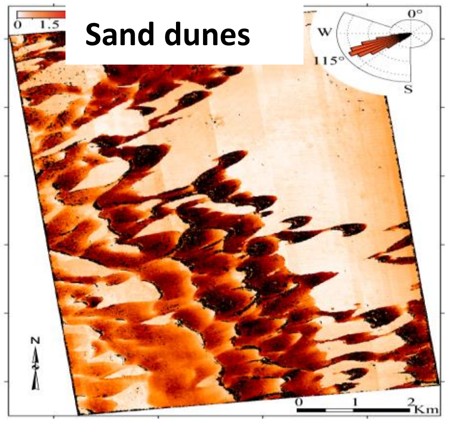
COSI-Corr: supported platforms

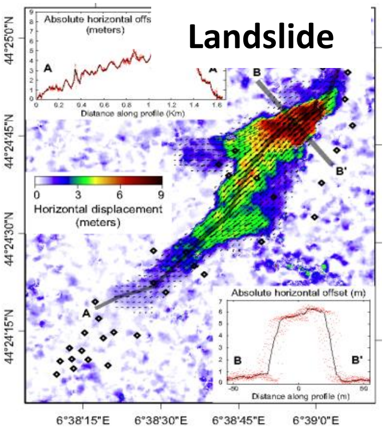
- Sensor-agnostic, can use any imagery, even old archives to document long-term landscape evolution
- Currently available for the following platforms (Pushbroom and aerial frames cameras):
  - Aerial photographs (films and digital)
  - All spot satellites
  - ASTER instruments
  - Quickbird satellite
  - Wolrdview
  - HiRISE and CTX instruments (Mars), and LROC-Na instruments (MOON)

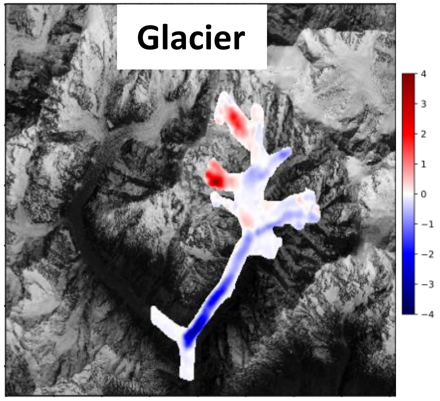
COSI-Corr application

- Common applications: Tectonics , Geomorphology and Glaciology









Cosi-Corr workflow 1/2 (Pre-processing)

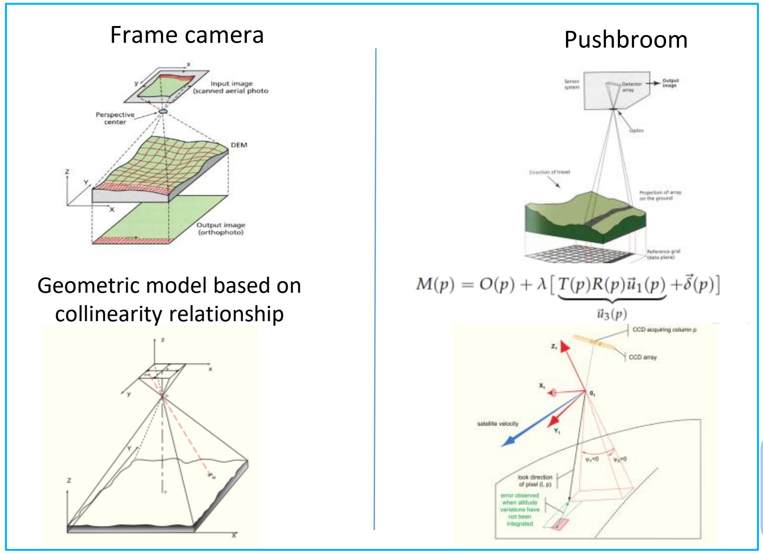
Pre-event raw image

- Acquisition parameters
- Platform attitude
- Camera model

Compute the ancillary file *

Select GCPs between raw image and reference image

Reference 1 : Shaded DEM Or Orthoimage



Post-event raw image

- Acquisition parameters
- Platform attitude
- Camera model

Compute the ancillary file *

Select GCPs between raw image and pre-event ortho

Optimization

Orthorectify patches → Resample image patches → Correlate patches + find relative displacement with reference → Deduce viewing correction δ for co-registration → Orthorectify patches

Orthorectification & Resampling

Pre-event Ortho image

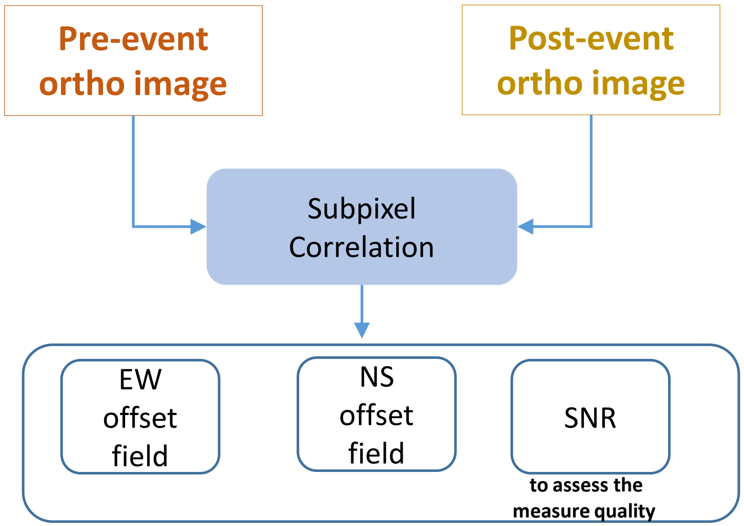
Post-event Ortho image

Orthorectification is solved as an inverse problem to facilitate rigorous resampling of the raw image and to avoid introduction of aliasing .
We use sinc kernel weighted with a Hanning window

*Ancillary file regroups the meta data from the sensor into one single file to be used during the processing.

Cosi-Corr workflow 2/2 (Correlation and Post-processing)

Correlation



Post-Processing

Denoising NLMF

Image De-striping

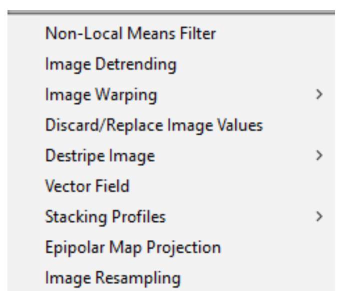
Image de-trending

Vector field

Masking

Stacking profiles

Image wraping



Correlation

Given two images i1 and i2 such that: $i_2(x,y) = i_1(x-\Delta_x, y-\Delta_y)$

➔ How to retrieve (Δ_x, Δ_y)?

Multi scale Statistical correlation (NCC)

$$NCC_{i_1,i_2}(\Delta_x,\Delta_y) = \frac{\sum_{N_x}\sum_{N_y}(i_1(x,y)-\bar{i}_1)(i_2(x+\Delta_x,y+\Delta_y)-\bar{i}_2)}{\sqrt{\sum_{N_x}\sum_{N_y}(i_1(x,y)-\bar{i}_1)^2\sum_{N_x}\sum_{N_y}(i_2(x+\Delta_x,y+\Delta_y)-\bar{i}_2)^2}}$$

Multi-scale phase correlation

- Fourier Shift Theorem

$$i_2(x,y) = i_1(x-\Delta_x, y-\Delta_y)$$
$$I_2(\omega_x,\omega_y) = I_1(\omega_x,\omega_y)e^{-j(\omega_x\Delta_x+\omega_y\Delta_y)}$$

- Normalized Cross-spectrum

$$C_{i_1i_2}(\omega_x,\omega_y) = \frac{I_1(\omega_x,\omega_y)I_2^*(\omega_x,\omega_y)}{|I_1(\omega_x,\omega_y)I_2^*(\omega_x,\omega_y)|} = e^{j(\omega_x\Delta_x+\omega_y\Delta_y)}$$

- Finding the relative displacement

$$\phi(\Delta_x,\Delta_y) = \sum_{\omega_x=-\pi}^{\pi}\sum_{\omega_y=-\pi}^{\pi} W(\omega_x,\omega_y)|C_{i_1i_2}(\omega_x,\omega_y) - e^{j(\omega_x\Delta_x+\omega_y\Delta_y)}|^2$$

W weighting matrix. (Δ_x,Δ_y) such that ϕ minimum.

- ❖ At high noise level, statistical methods performs better than phase correlation method,
- ❖ Using iterative re-weighted method on W mitigates the strong noise-free requirement of the image in the phase correlation formulation and adds more robustness to the solution

Overview

- COSI-Corr presentation
- **New COSI-Corr release**
- Application to glacier flow monitoring using optical time series images

New COSI-Corr release 1/2

➢ Open source command line tool

- Python , C++
- GDAL
- Could be used as standalone package or added to other free software such as ASP, MICMAC …

➢ Pre-processing tools

- Optimization with RPC
- Automatic tie points determination and GCP generation

➢ Correlation

- Regularization

New COSI-Corr release 1/2

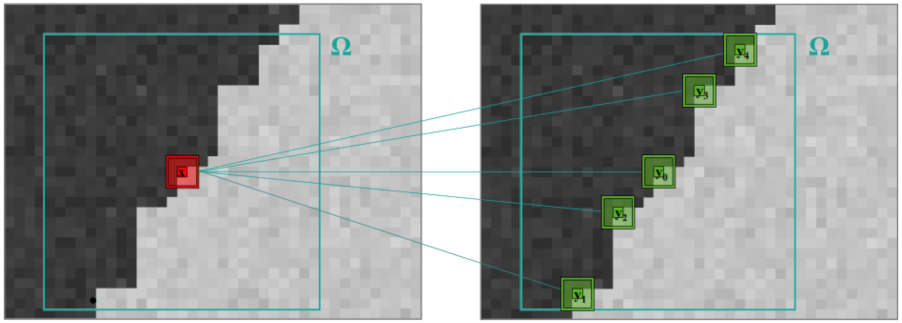
- **Post-Processing**
  - Time series analysis tools
  - Upgrade NLMF
  - PCA (reconstruction and denoising)
  - Local multiscale median filter
  - Offset correction (de-ramping)
  - Update the de-stripping tool

  (Offset correction and de-stripping:) Similar to Coregis (Stumpf et al., 2018)

- **3D deformation measurement**

NLMF

- Average of pixels with similar configuration in whole Gaussian neighborhood:



$$NL_h[u](\mathbf{x}) = \frac{1}{C(\mathbf{x})} \int_{\Omega} e^{-\frac{1}{h^2} \int_{\mathbb{R}^2} G_a(t) |u(\mathbf{x}+t) - u(\mathbf{y}+t)|^2 dt} \; u(\mathbf{y}) \, d\mathbf{y}$$

- Traditional NLMF uses a Gaussian weighting template with fixed weight coefficients when measuring the similarity of neighborhood distance
- When the noise level is large , the Gaussian weighting template with fixed weight coefficient will be subject to noise interference

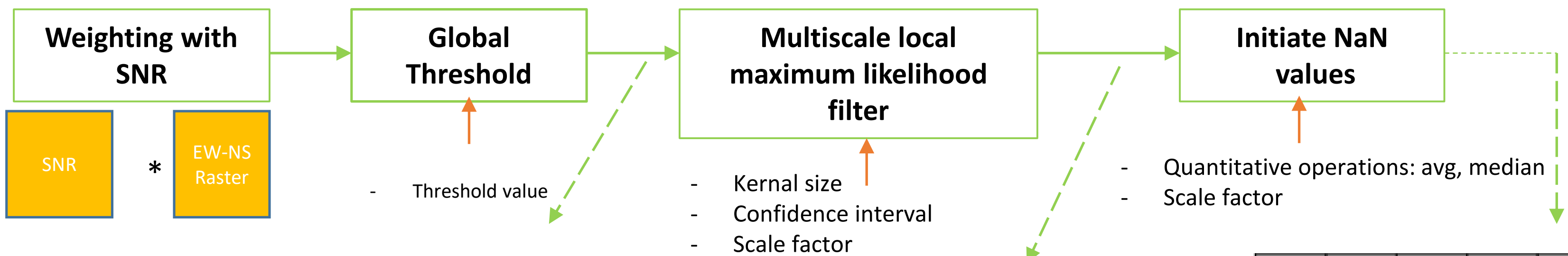
To resolve the problem

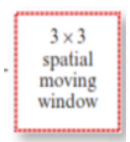
- Adjusting the Gaussian weight coefficient with Laplace operator.
- An improved Non-Local Means Algorithms for Image Denoising (Leng,K. et al., 2017)

$$weight_j = \left| \frac{G_{x_0,y_0} \nabla^2 f(x_0, y_0)}{|\Sigma_{x,y} G_{x,y} \nabla^2 f(x,y)|} \right|$$

Local multiscale median filter

- Remove outliers of erroneous matches due to: clouds, snow cover or surfaces waters …
- Local spatial filtering
- Initialize the PCA (in the spatial domain)





0.11	0.2	0.19	0.21	0.24
1.2	0.21	0.26	0.24	-.13
-1.2	2.3	0.27	0.21	0.01
0.28	0.29	-0.3	2.3	0.13
Nan	0.4	Nan	0.19	0.2

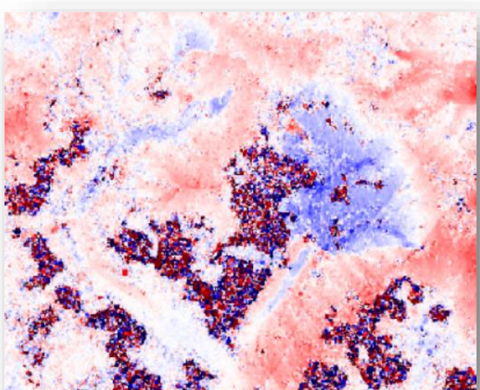
Input map

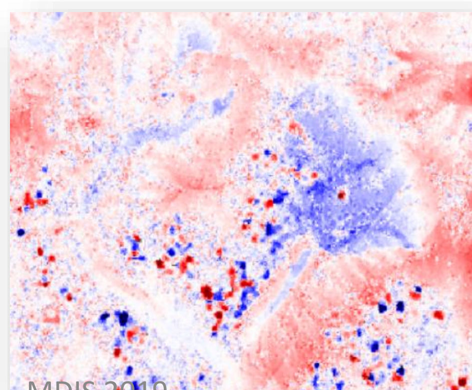
0.11	0.2	0.19	0.21	0.24
1.2	0.21	0.26	0.24	-.13
-1.2	Nan	0.27	0.21	0.01
0.28	0.29	Nan	Nan	0.13
Nan	0.4	Nan	0.19	0.2

Filtered map

0.11	0.2	0.19	0.21	0.24
1.2	0.21	0.26	0.24	-.13
-1.2	0.25	0.27	0.21	0.01
0.28	0.29	0.25	0.25	0.13
Nan	0.4	Nan	0.19	0.2

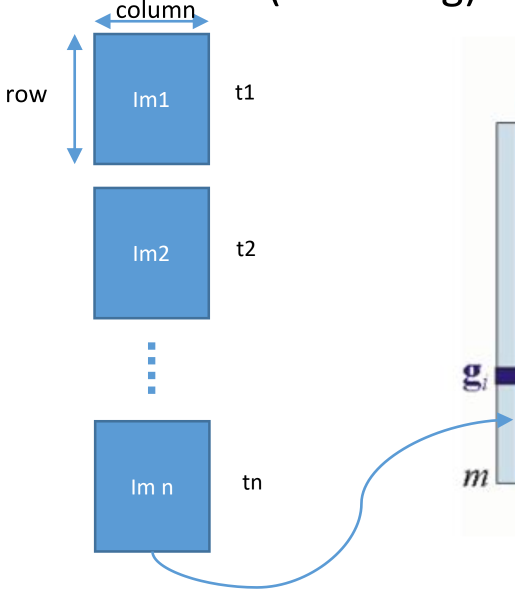
Initialized map

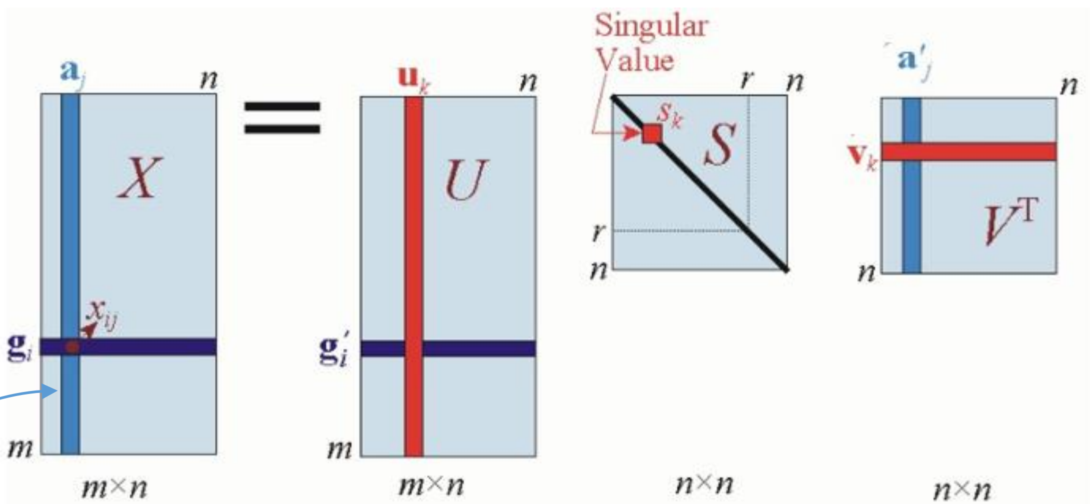


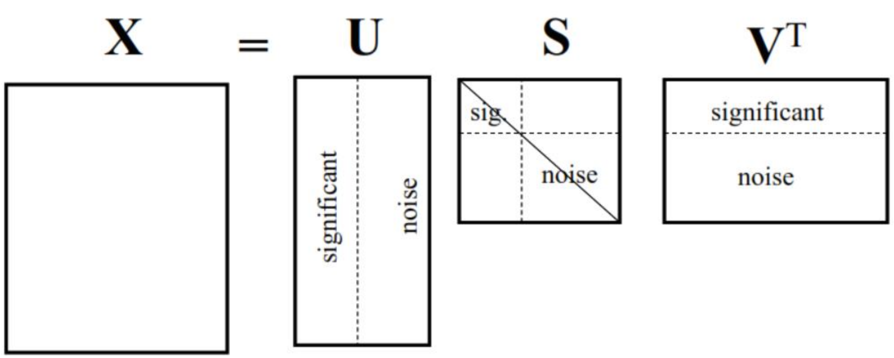


PCA (time series analysis)

- Noise removal (improve data quality)
- Local temporal filtering (temporal filtering)
- Re-weighting matrix
- Visualization (modeling)







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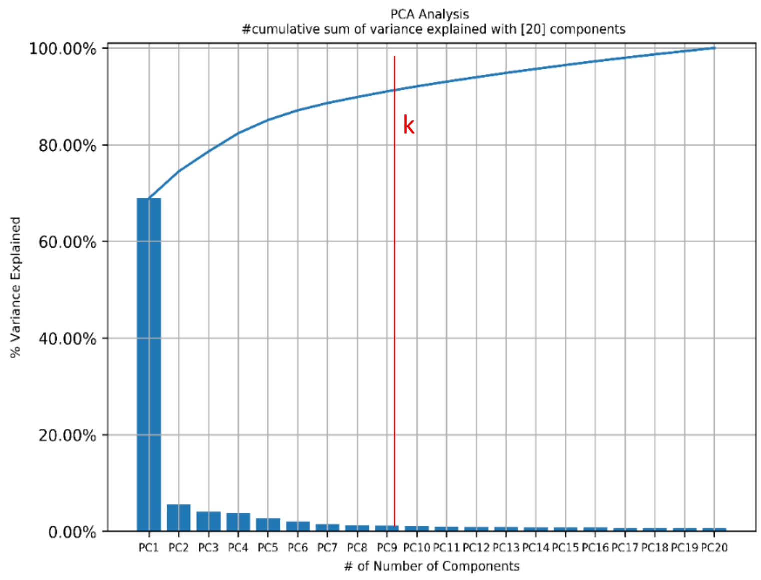
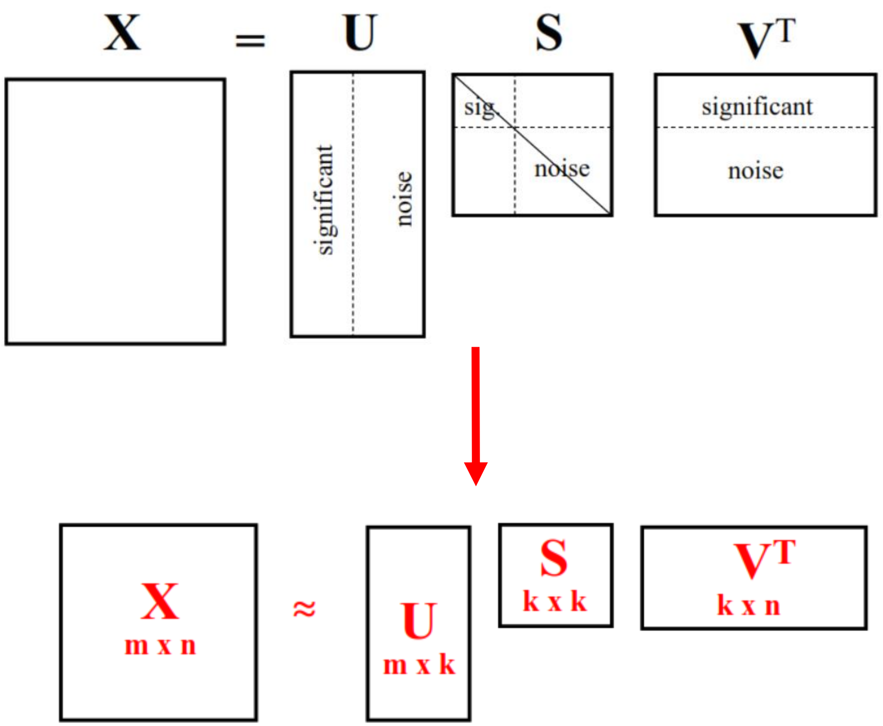
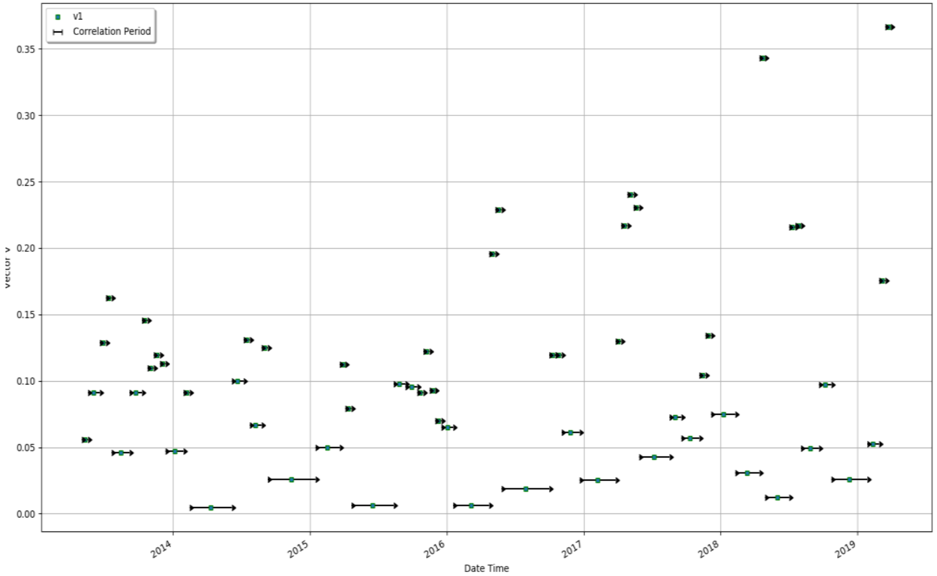
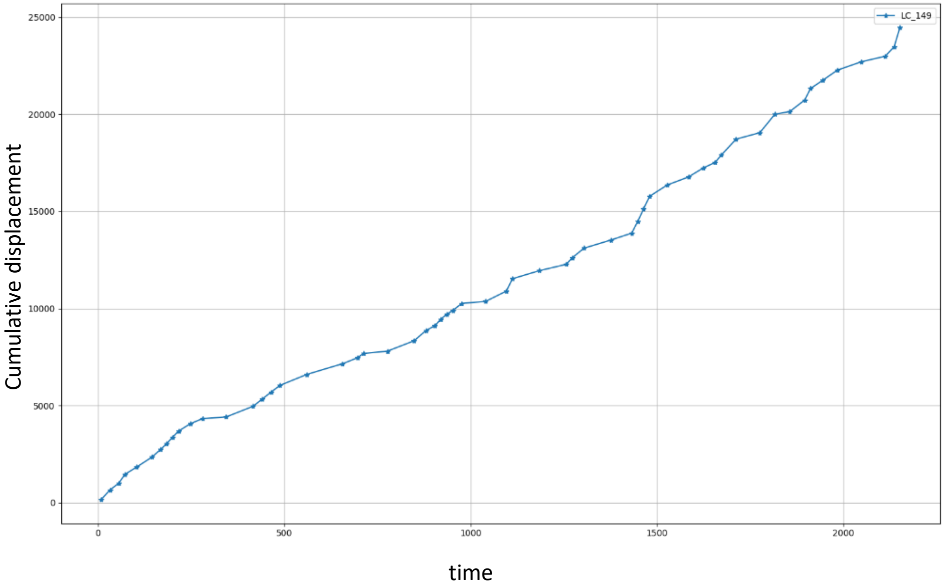




PCA (resampling)





$$\underset{m \times \tilde{n}}{\tilde{X}} \approx \underset{m \times k}{\mathbf{U}} \; \underset{k \times k}{\mathbf{S}} \; \underset{k \times \tilde{n}}{\widetilde{V^T}}$$

3D deformation measurement

1. **Optimize Viewing Parameters**
   - Pairwise image matching between all images,
   - Only keep tie-points on stable surfaces (e.g., bedrock),
   - Optimize external viewing parameters of all images jointly using regularized bundle adjustment.

2. **Produce Disparity Maps**
   - Project all images on reference surface (e.g. DTM, GTOPO or smoothed GDEM),
   - Cross-correlate image pairs using multi-scale, regularized image correlation.

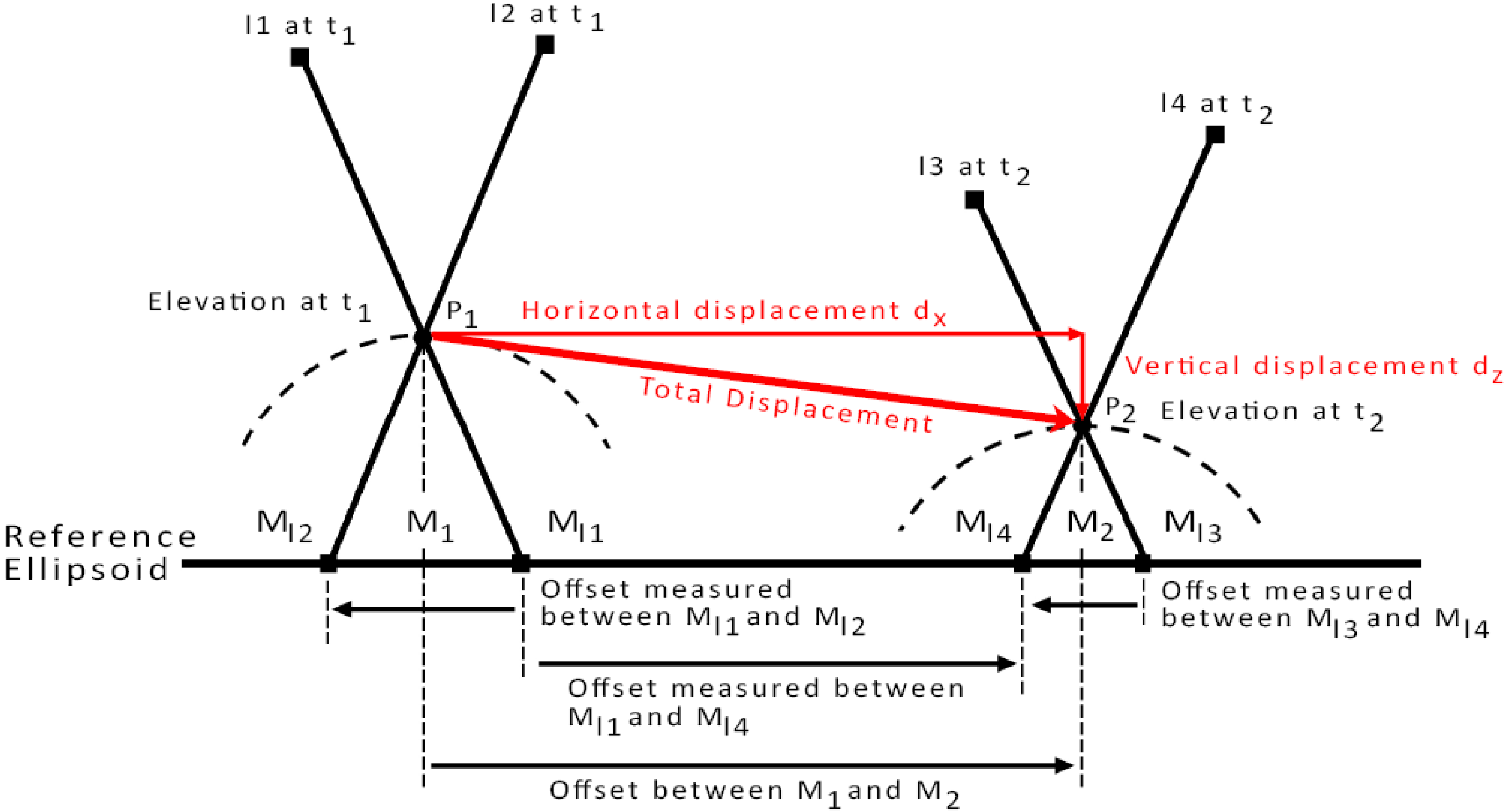
3. **Produce Point and Vector clouds (3D)**
   - Triangulate disparity maps,
     - (x_1, y_1, z_1)
     - (x_2, y_2, z_2)
     - $(x_1, y_1, z_1, D_x, D_y, D_z)$
   - Output surface models at all times.

4. **Grid Point Clouds and Vector Clouds**
   - Use standard gridding libraries on each components (only external processing).

3D deformation measurement

- Solving for 3-D displacements and the topography with 4 images.
- Triangulate multiple disparity maps to retrieve 3D topography and displacement fields

(Avouac, J.-P., 2015)

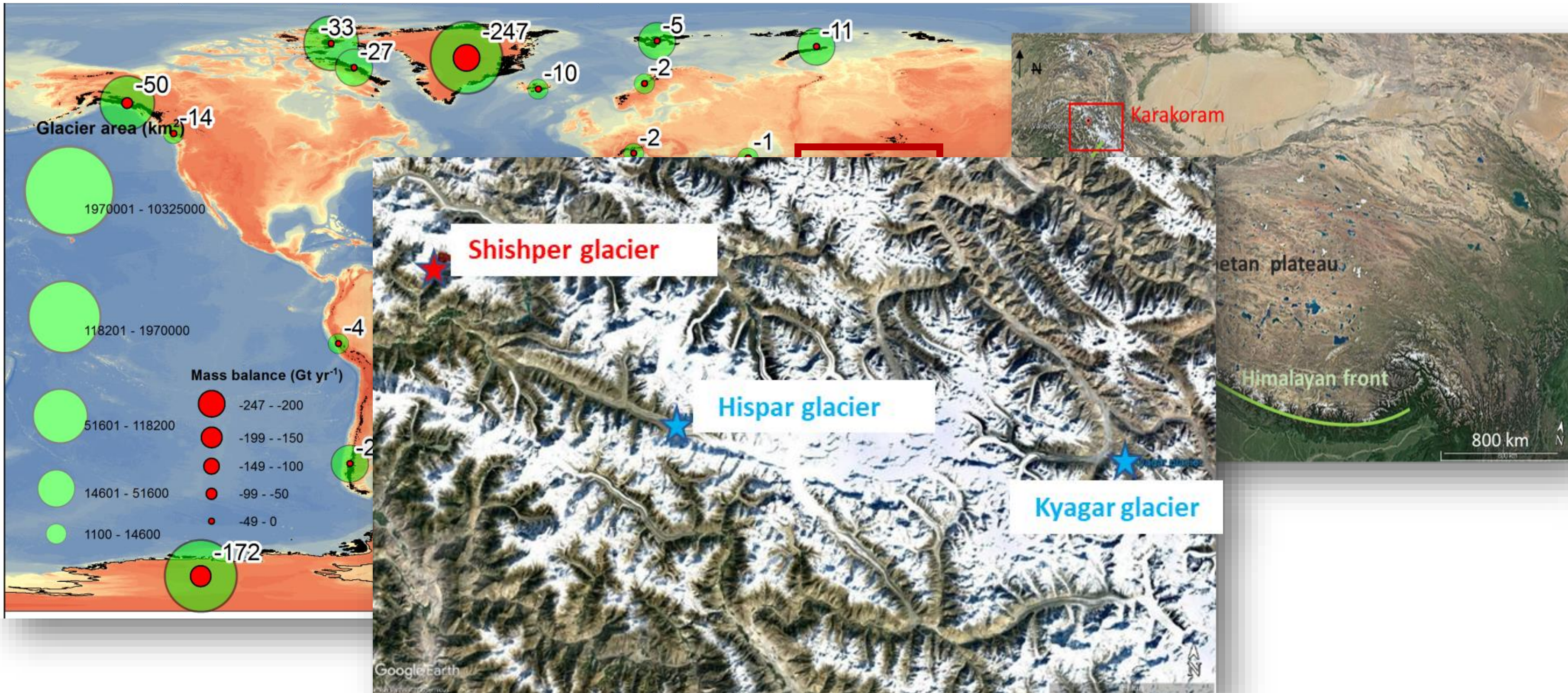


Overview

- COSI-Corr presentation
- New COSI-Corr release
- **Application to glacier flow monitoring using optical time series images**

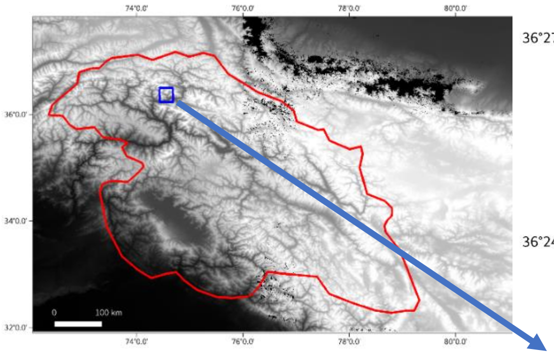
Location of the Shishper glacier

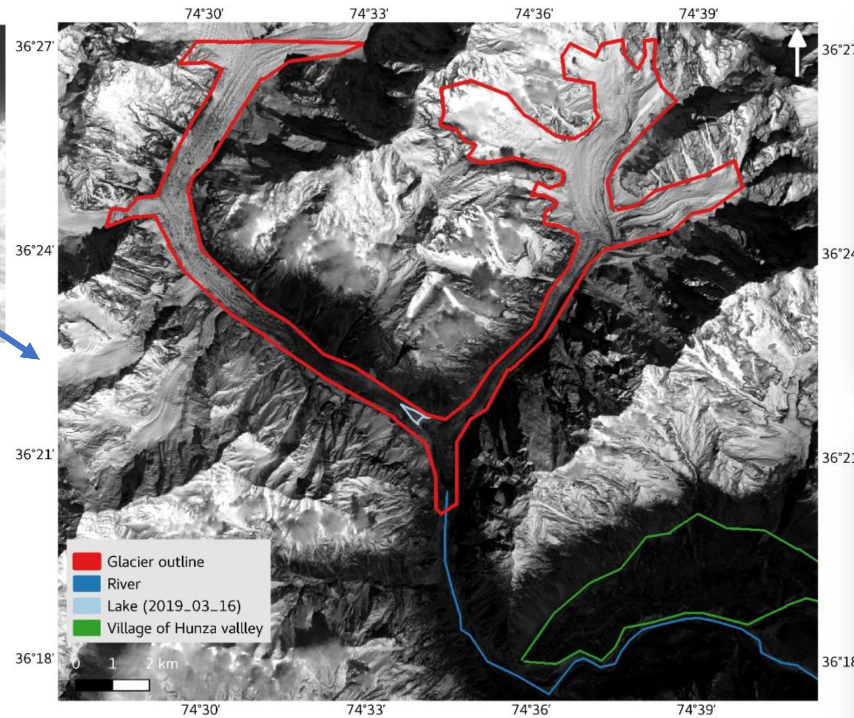
Current world-wide glaciers (Randolph Glacier Inventory) & Mass balance 2012-2016 (ice sheets: Bamber et al., 2018)

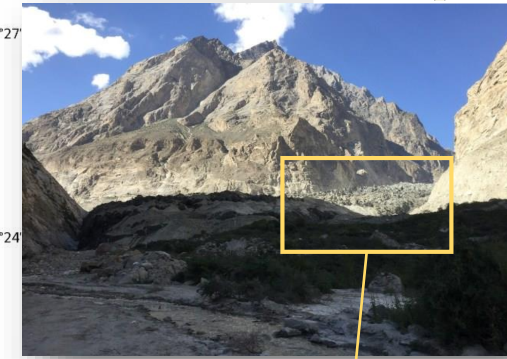


- **Negative mass balance = melting worldwide**
- **Several glacier surges were recorded during the last decades in the Karakoram region**
- Hispar glacier : Paul et al., 2017
- Kyagar glacier : Round et al., 2017
- Shishper glacier : Begum et al., 2019

Why studying this glacier ?



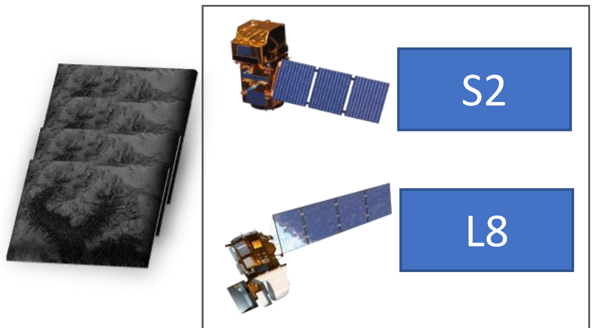




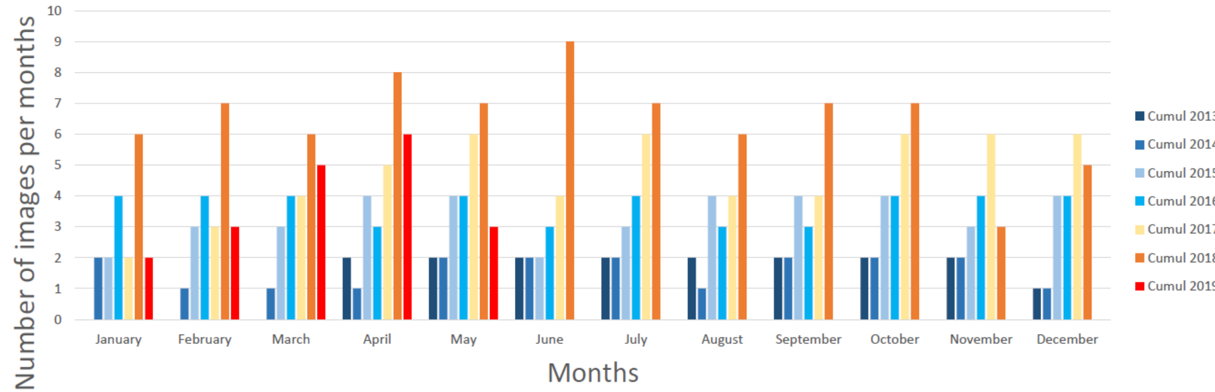
- ✓ **Surge reported in July 2018 in local press**
- ✓ **No velocity pattern studies of this surge**
- ✓ **Risk of GLOF** (Glacial lake outburst floods)
- ✓ **Risk : 40,000 people living downstream in the Hunza valley**

Dataset and workflow

Number of images : 273



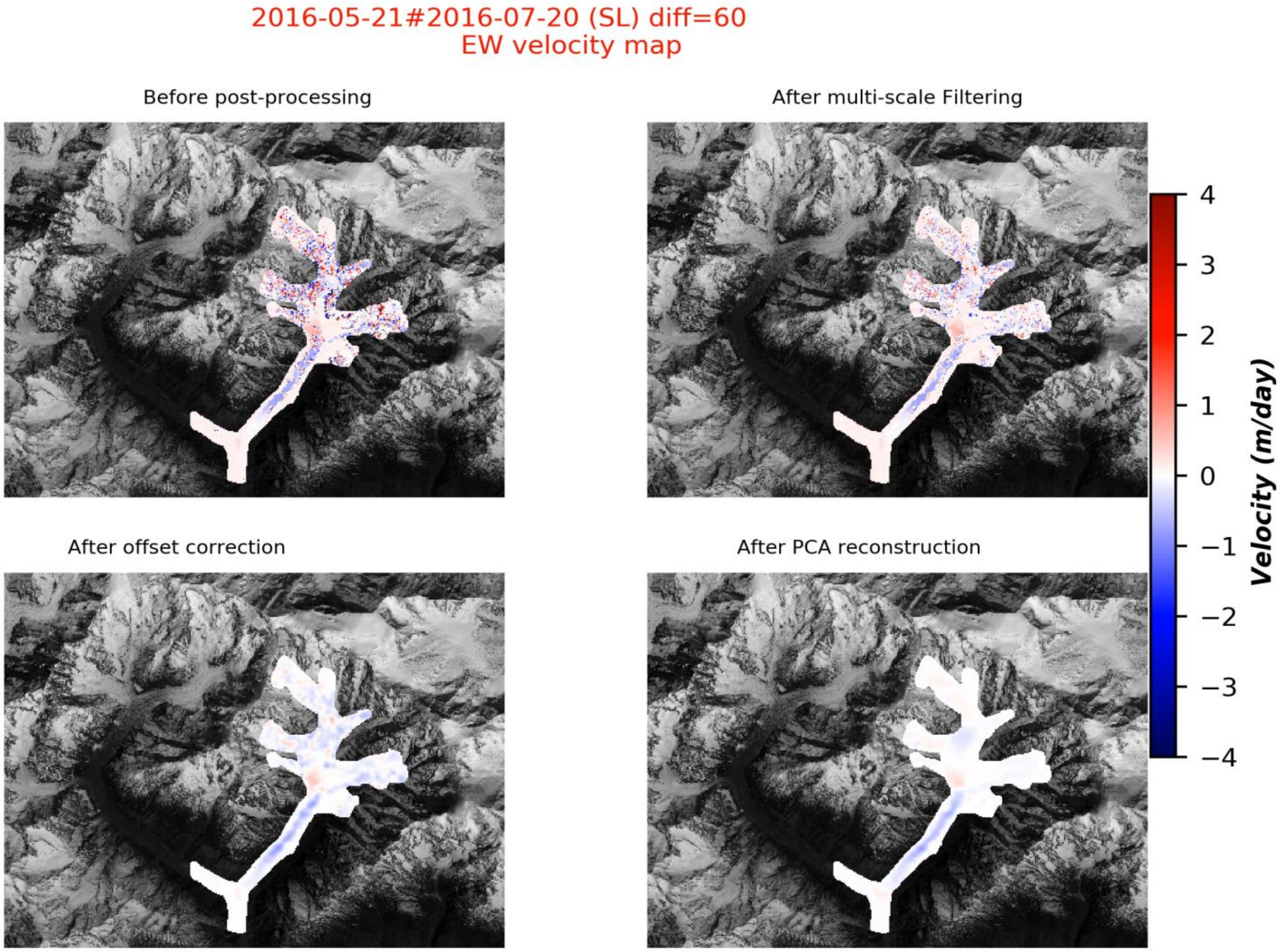
Available dataset from Landsat-8 and Sentinel-2 Imagery for Shishper Glacier Study between 2013-2019



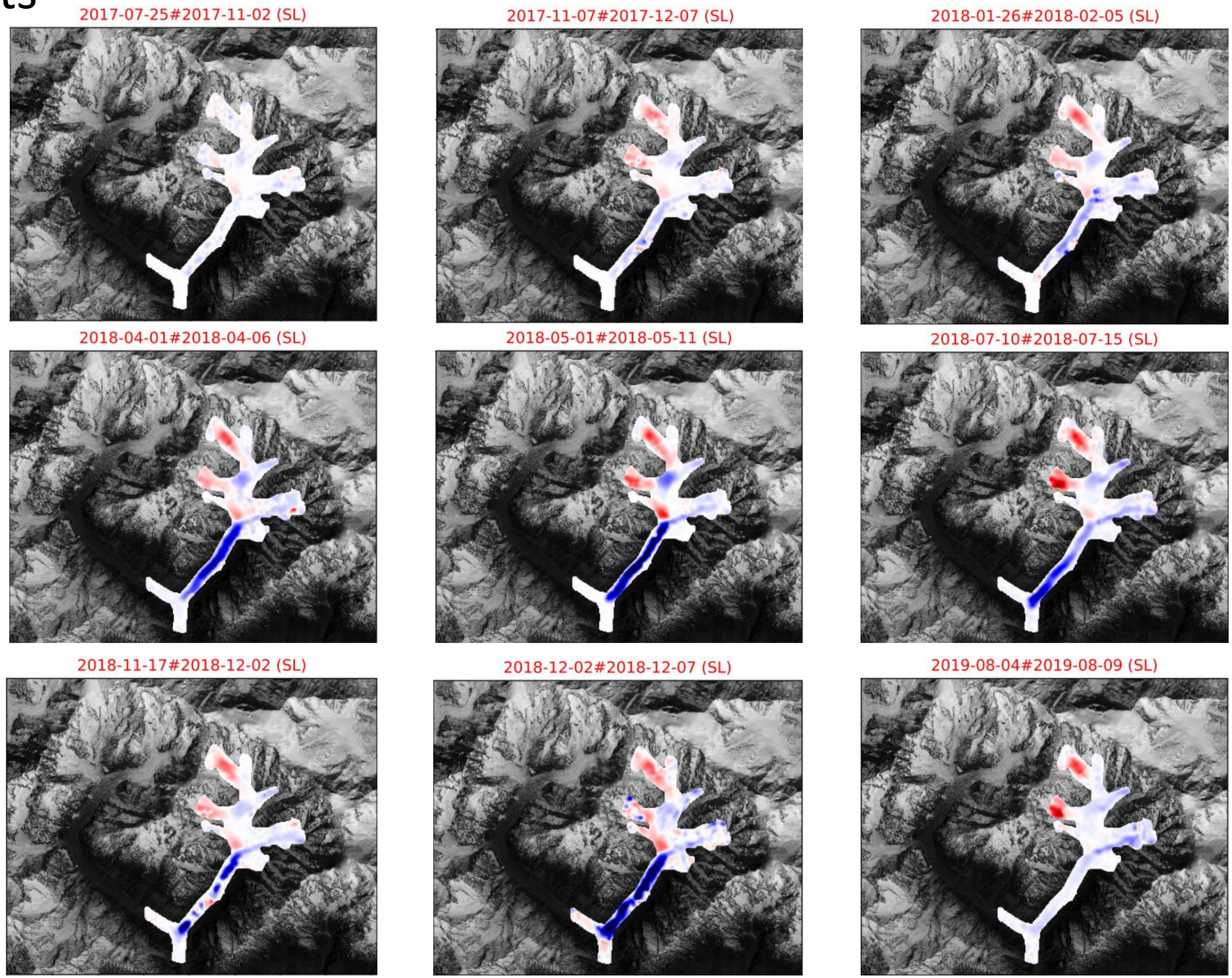
Subset on Shishper glacier → **Cloud-free images filtering** → **Multi-pairwise Correlation** → **Co-registration and Offset correction** → **Local multiscale filter** → **PCA** →

- Resampling
- Velocity evolution profiles
- DFTS

Results

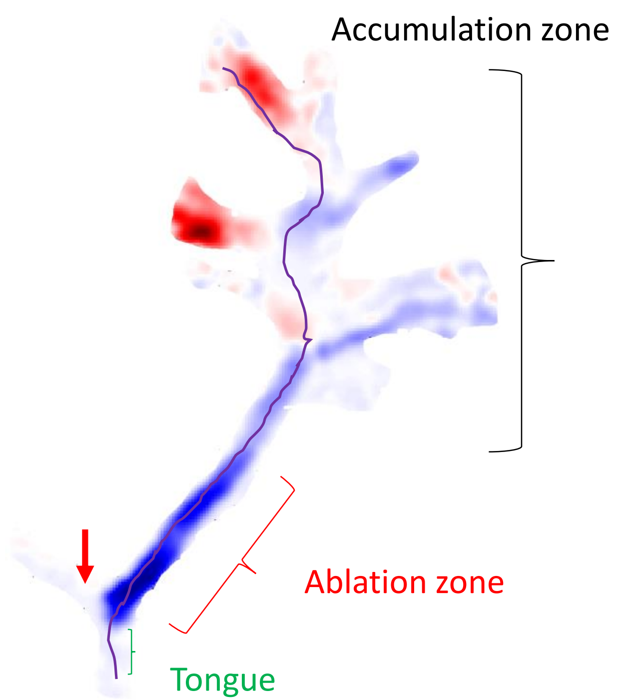

2016-05-21#2016-07-20 (SL) diff=60
EW velocity map
Before post-processing
After multi-scale Filtering
After offset correction
After PCA reconstruction
Velocity (m/day)
4
3
2
1
0
−1
−2
−3
−4

Results

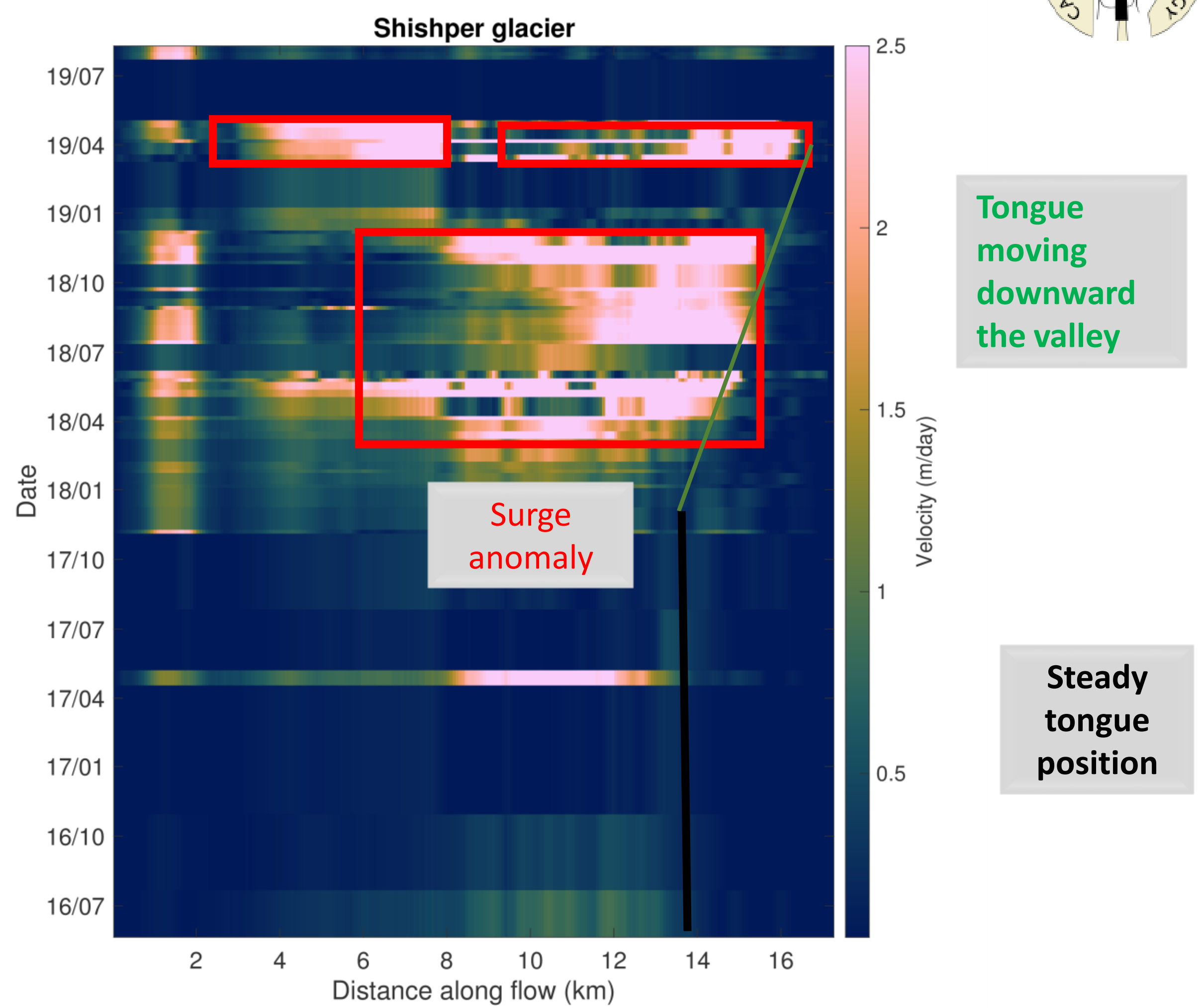


- **Apparition of the ice-dammed lake between 2018 and 2019**
- **Stronger and longer signal in 2019 at top and tongue**
- **2019 shows a stronger dynamic than previous years, even 2018**

Results

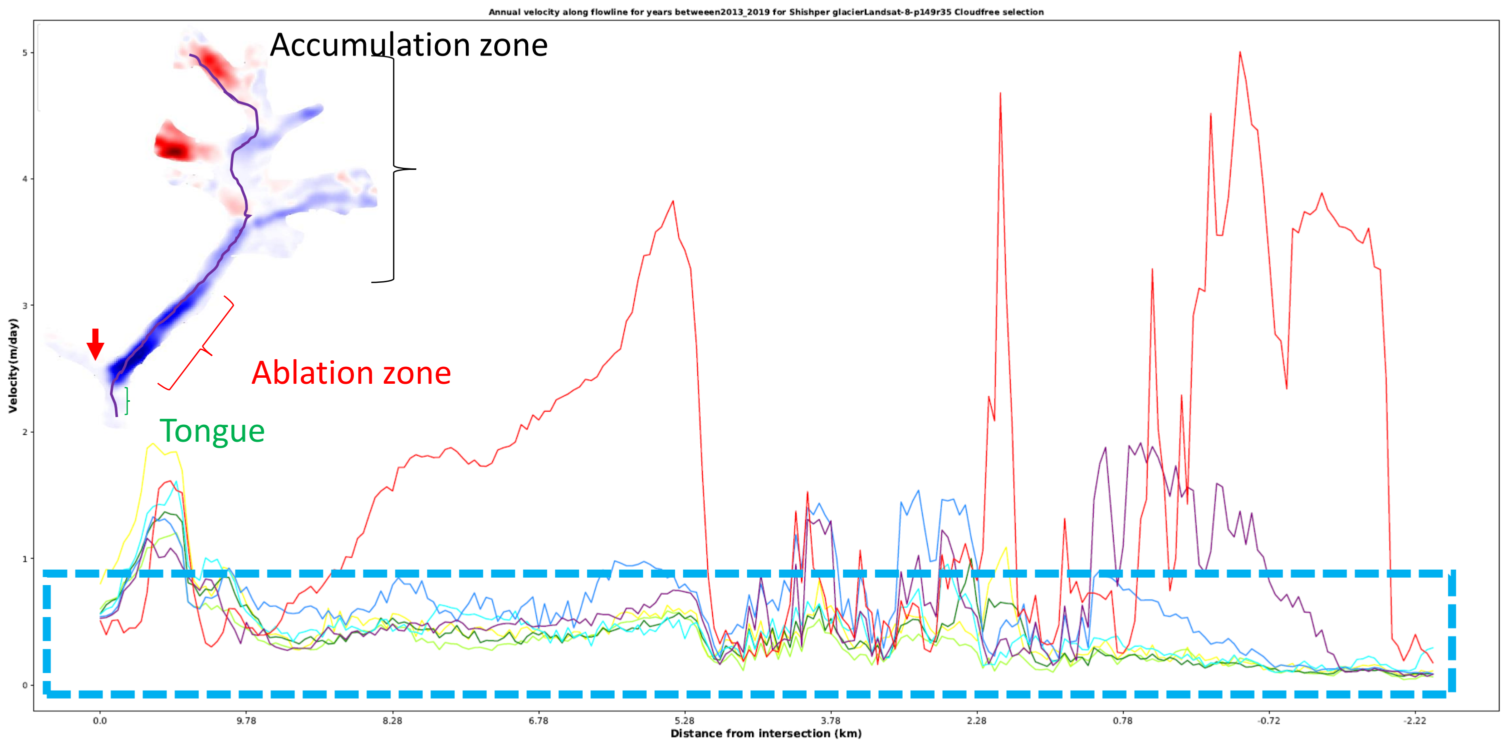


Accumulation zone
Ablation zone
Tongue



Shishper glacier
19/07
19/04
19/01
18/10
18/07
18/04
18/01
17/10
17/07
17/04
17/01
16/10
16/07
Date
2
4
6
8
10
12
14
16
Distance along flow (km)
2.5
2
1.5
1
0.5
Velocity (m/day)
Surge anomaly
Tongue moving downward the valley
Steady tongue position

Results



Tongue

2019 vmax = 3m/day

2018 vmax = 2m/day

2017 vmax = 0.5m/day

2013_2017 = seasonal baseline < 0.5 m/day