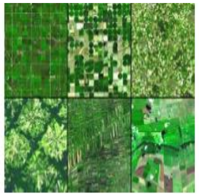
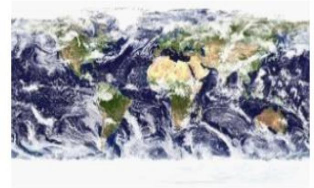







COSI-Corr: A Solution for 3D Change Detection using Optical Imagery

Sébastien Leprince, Francois Ayoub, Jiao Lin, Bruno Conejo, and Jean-Philippe Avouac

California Institute of Technology

JACIE - March 2014

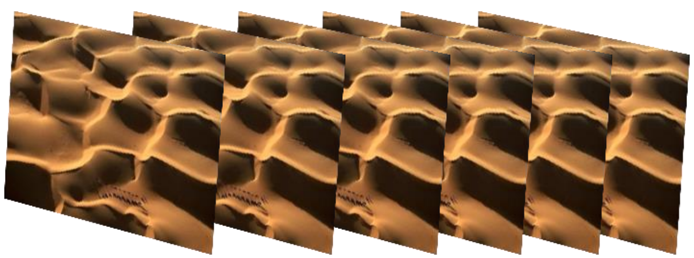
COSI-Corr: Co-registration of Optically Sensed Images and Correlation

❶ **Satellite imagery** acquired at different times, any resolution, possibly by different sensors

Measuring surface processes from optical imagery

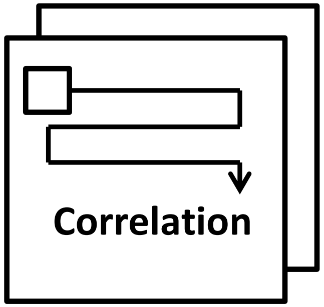
COSI-Corr

❷ **Automatic registration** with accuracy of 1/10 of the pixel size (sub-pixel)

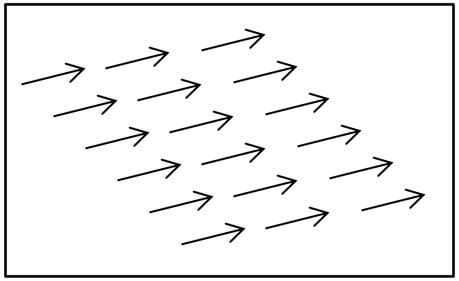


Time

❸ **Automatic comparison** of images to measure motion



❹ **Ground deformation**



Vector field

Leprince et al., IEEE TGRS, 2007

http://www.tectonics.caltech.edu/slip_history/spot_coseis/

Sub-Pixel Image Correlation: Locally Rigid Translations

- 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

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

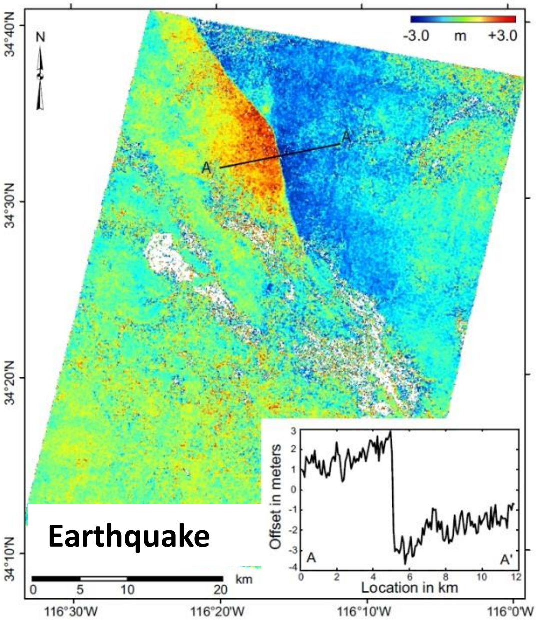
- Finding the relative displacement

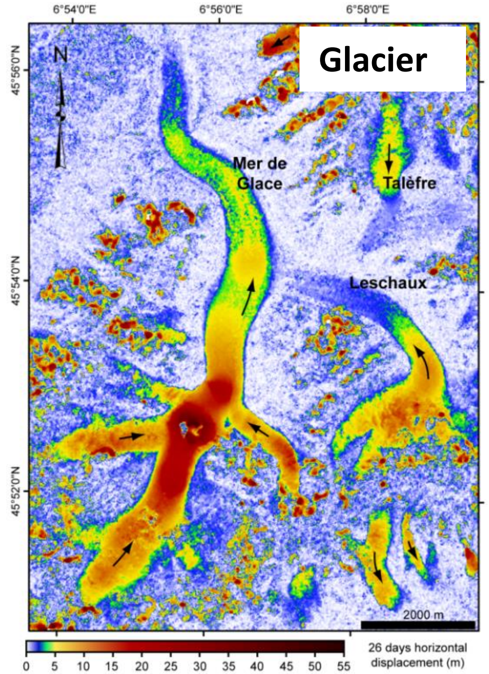
$$\phi(\Delta_x,\Delta_y) = \sum_{\omega_x=-\pi}^{\pi}\sum_{\omega_y=-\pi}^{\pi} W(\omega_x,\omega_y)|C_{i_1i_2}(\omega_x,\omega_y) - e^{j(\omega_x\Delta_x+\omega_y\Delta_y)}|^2$$

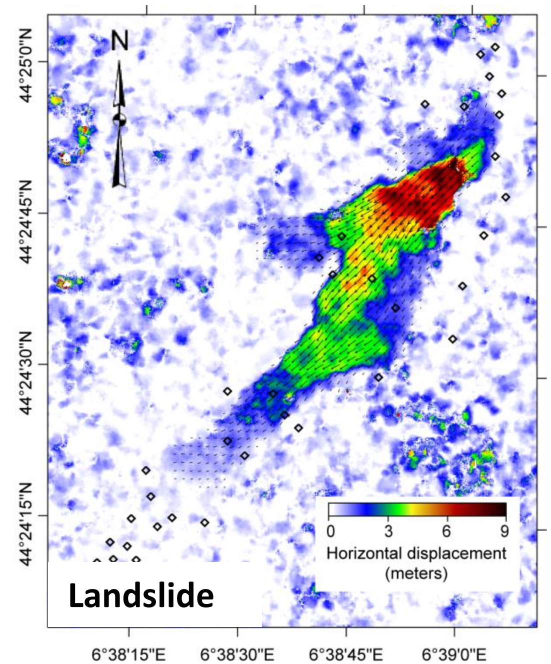
W weighting matrix. (Δ_x,Δ_y) such that ϕ minimum.

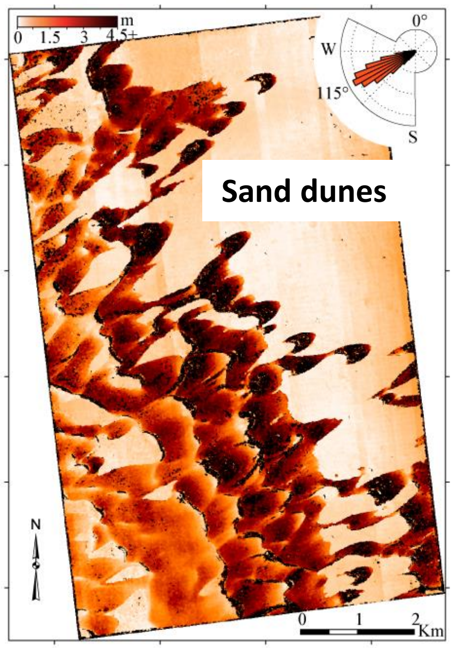
S. Leprince et al., IEEE TGRS, 2007

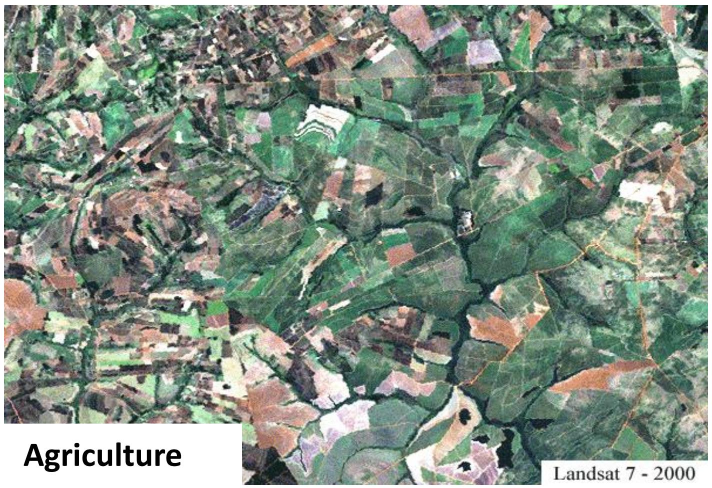
COSI-Corr: a wide range of applications

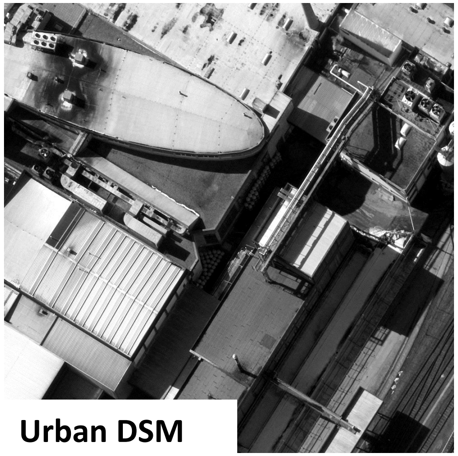










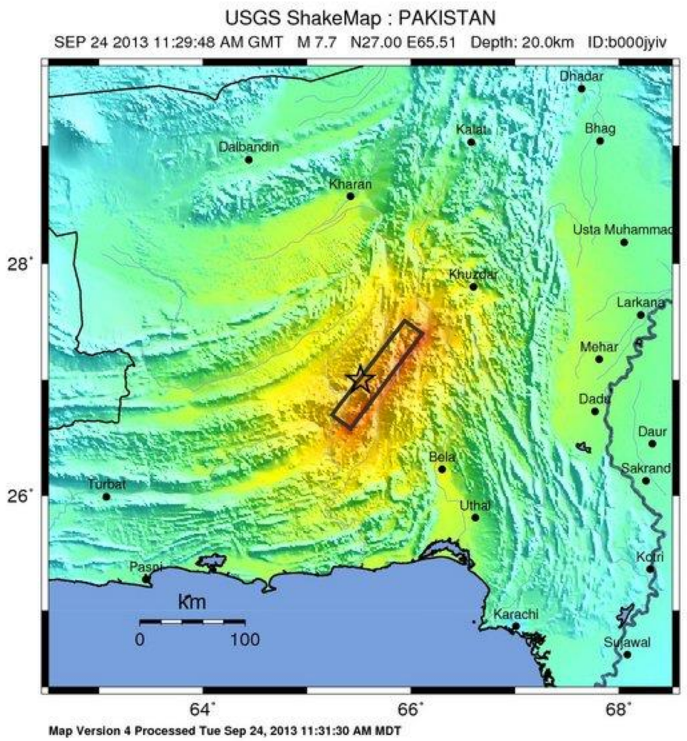


In This Presentation:

- First COSI-Corr results on Landsat 8 images
  - The Mw 7.7 Balochistan earthquake, Sept. 2013
- 3D change detection
  - General principles
  - Application to glacier flow monitoring in New Zealand using Worldview
  - Application to urban damage mapping after the Oklahoma tornado, May 2013, using Worldview

First Large Earthquake seen by Landsat 8:

The Sep. 24, 2013 Mw 7.7 Balochistan earthquake, Pakistan



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	<0.02	0.1	1.4	4.7	9.6	20	41	86	>178
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

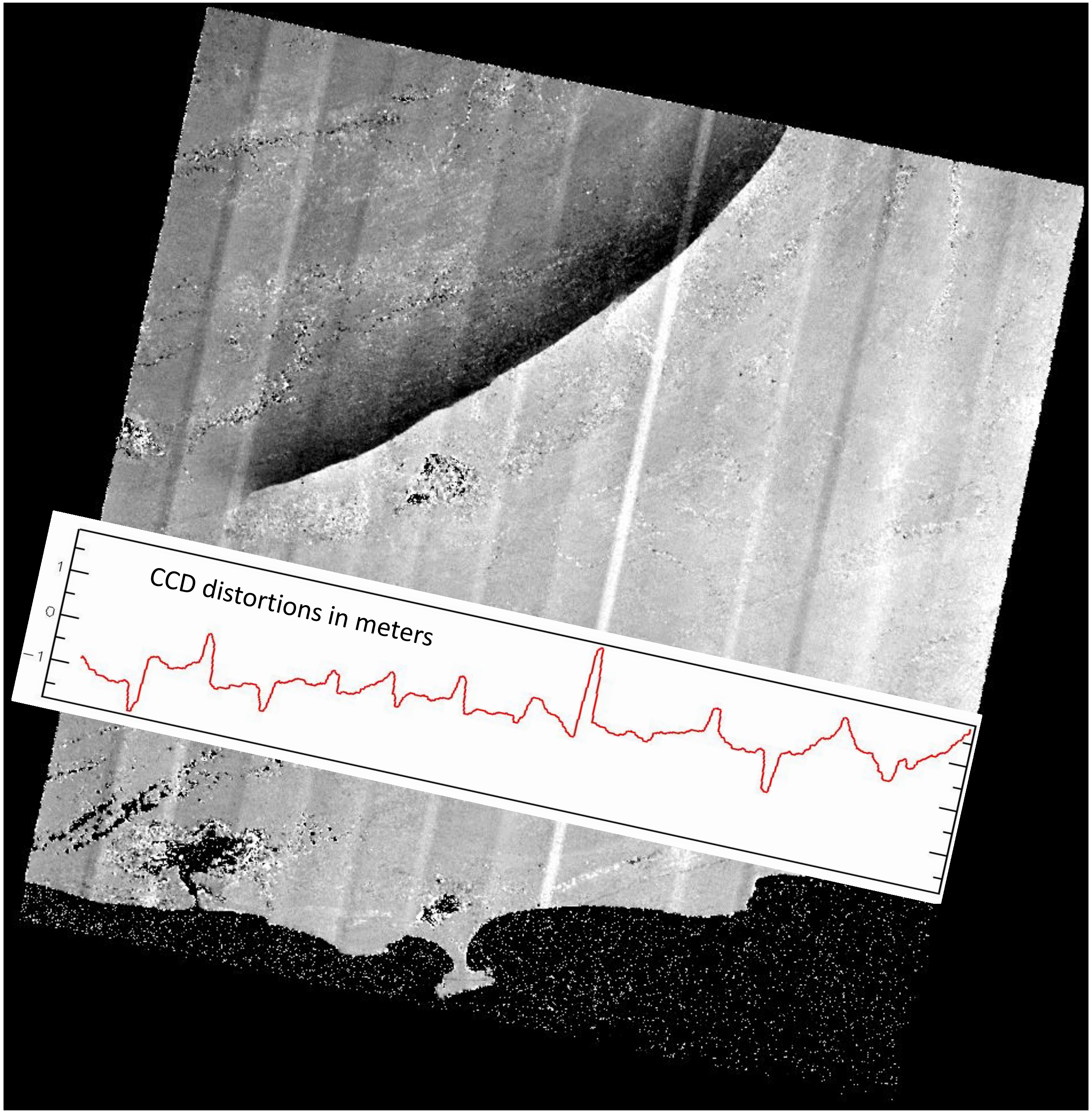
Scale based upon Worden et al. (2011)

Studied fault rupture using Landsat 8, Panchromatic band at 15 m GSD.

Images acquired:

- September 10, 2013 - 14 days before the event,
- September 26, 2013 - 2 days after the event).
- Fault rupture covered 2 Landsat scenes with extent of 200 km.
- Applied Standard COSI-Corr 2D processing.

Balochistan Earthquake seen by Landsat 8

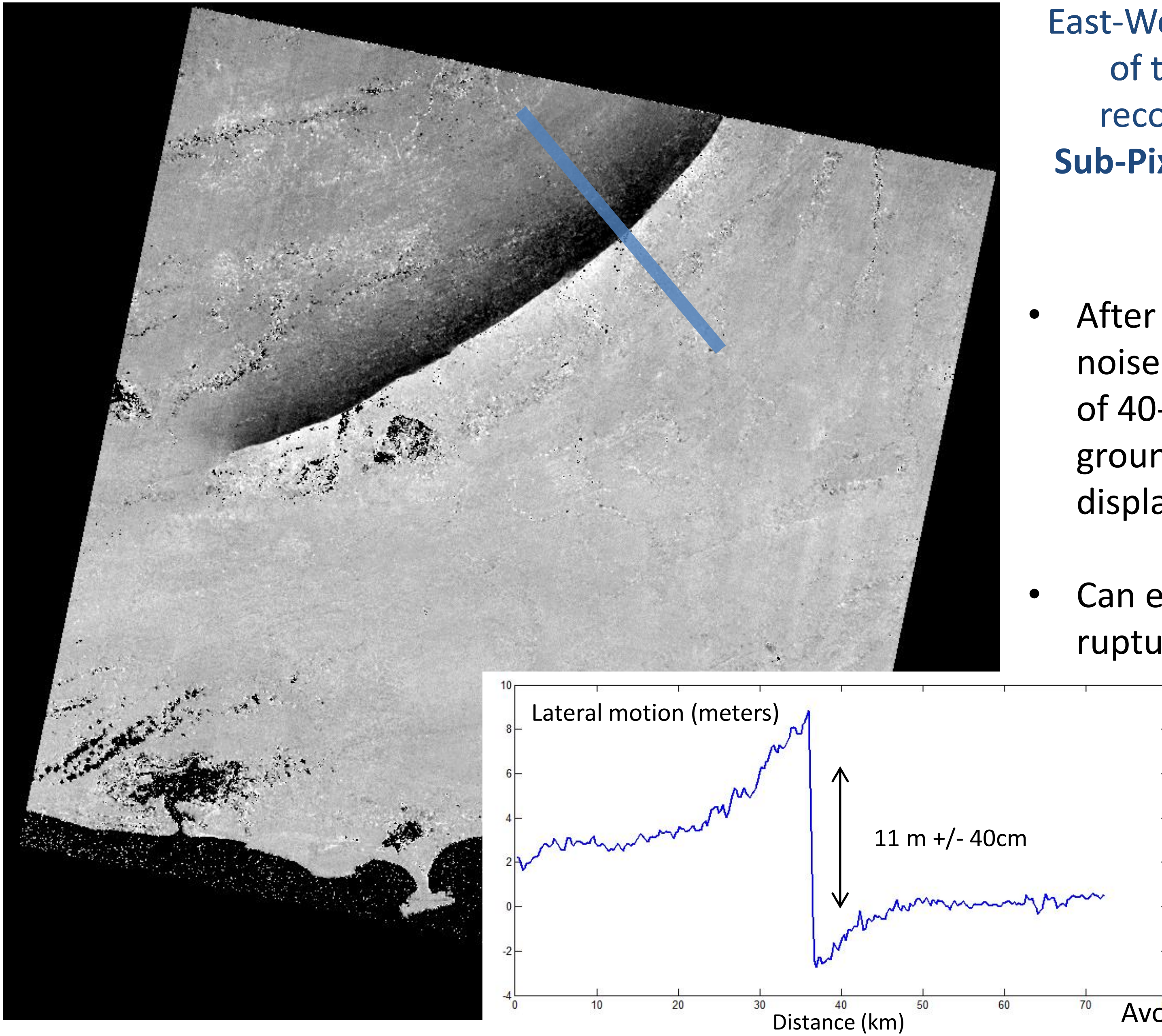


East-West component of the rupture recovered from **Sub-Pixel correlation**

- Distortions from CCD misalignments,
- Biases of up to 1.5m, or 1/10 of pixel size,
- Very good registration of Landsat 8 images!

Avouac et al., EPSL, 2014

Balochistan Earthquake seen by Landsat 8

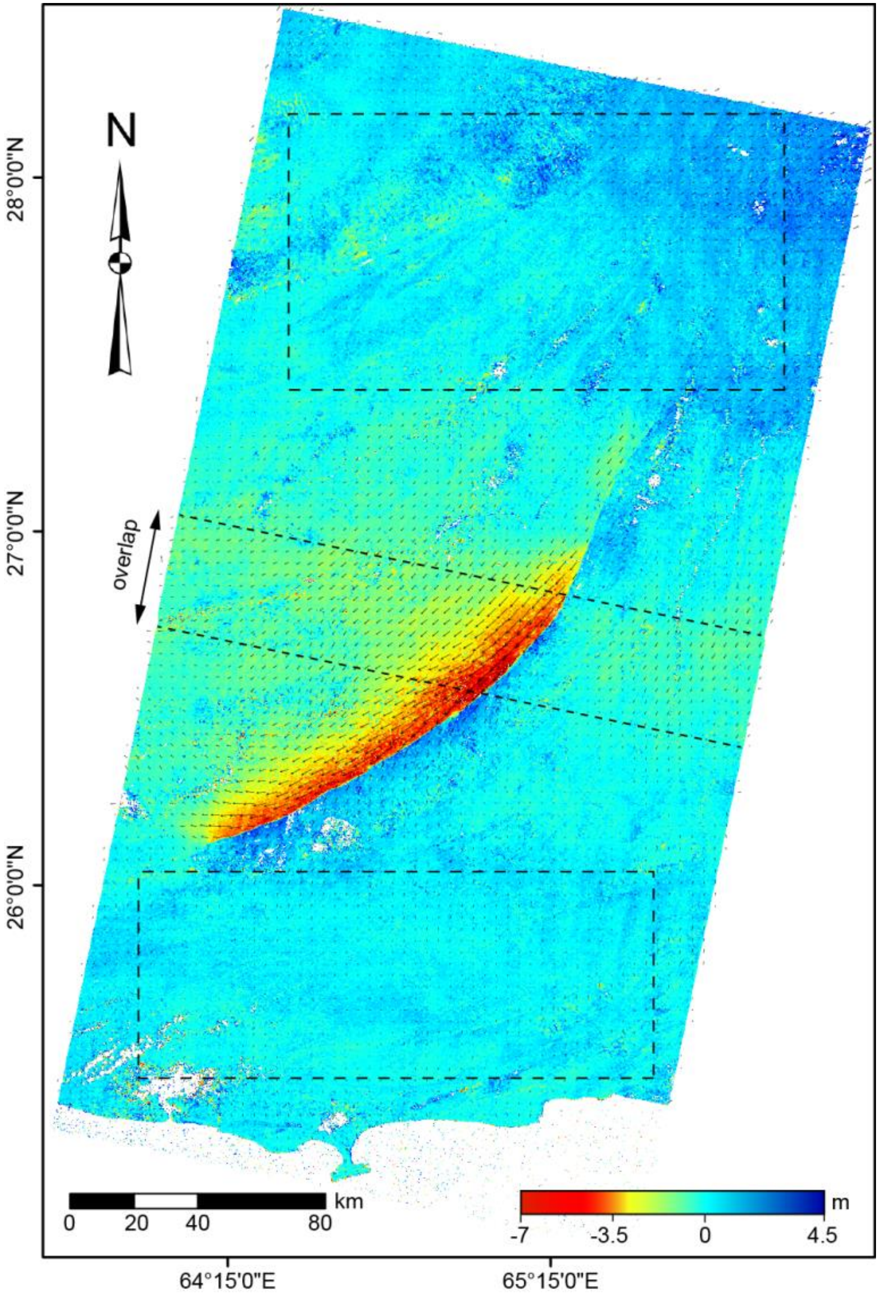


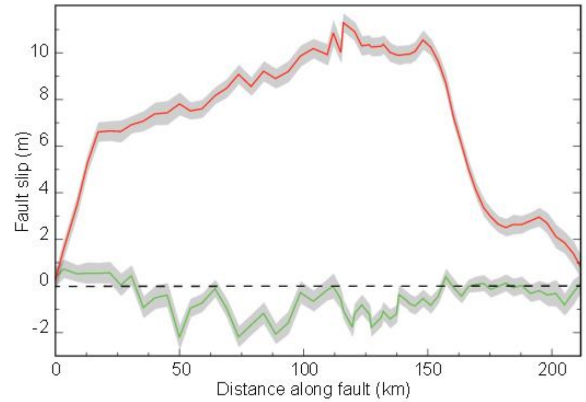
Avouac et al., EPSL, 2014

East-West component of the rupture recovered from **Sub-Pixel correlation**

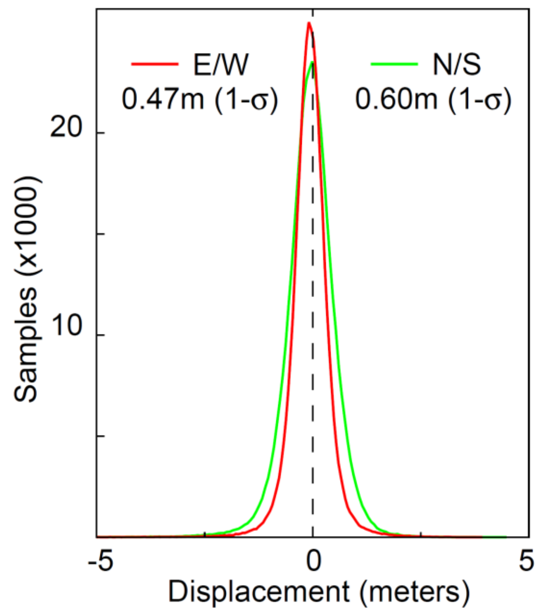
- After destriping noise on the order of 40-60 cm on ground displacement
- Can extract reliable rupture map

Balochistan Earthquake seen by Landsat 8





Parallel and normal slip distributions



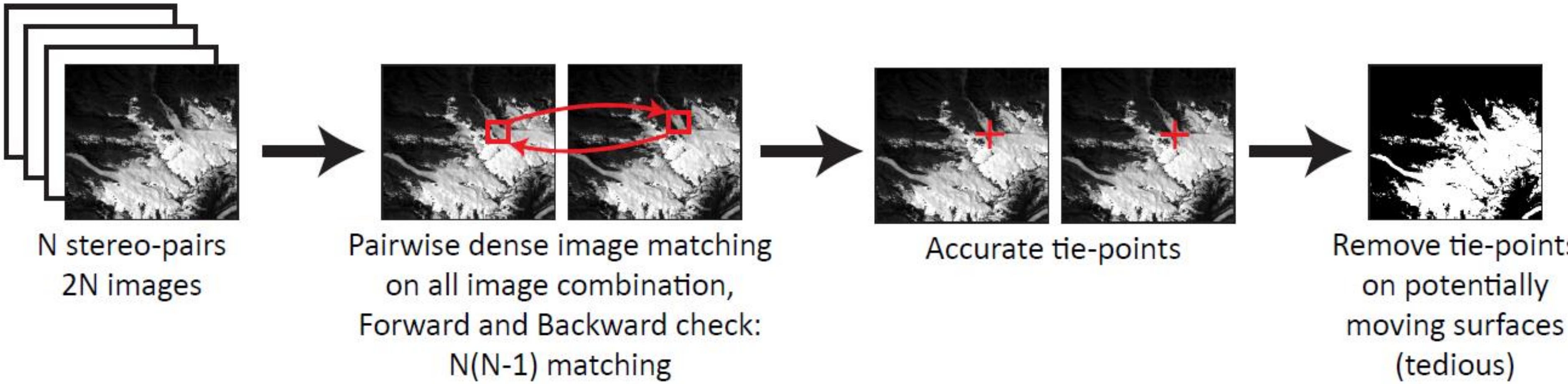
Noise level better than 1/20 of pixel size once corrected for CCD distortions.

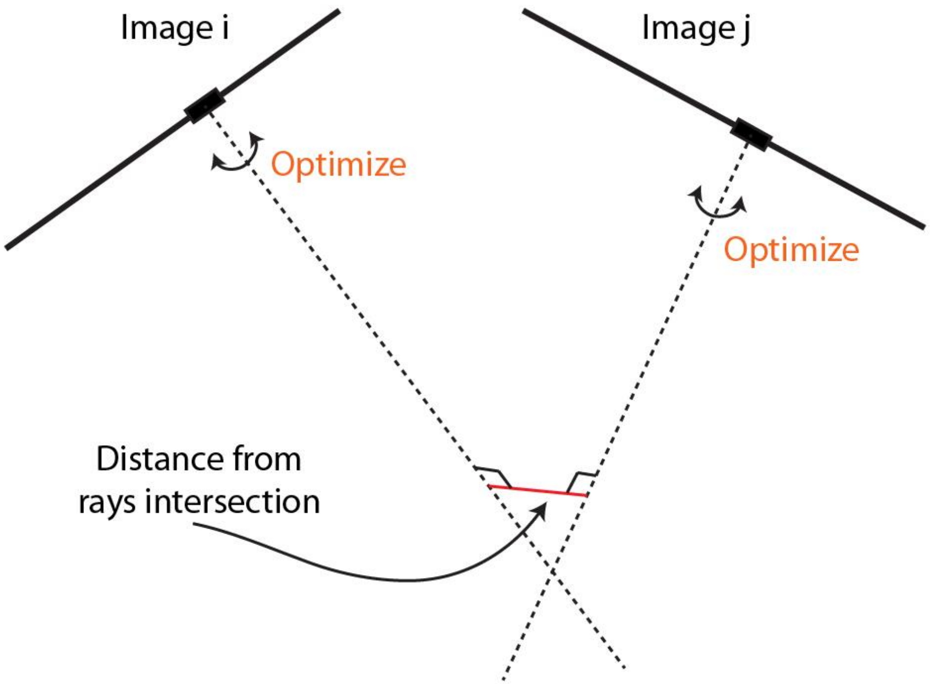
Avouac et al., EPSL, 2014

3D and 4D Processing Flow

1. Optimize Viewing Parameters

Optimize Viewing Parameters





Jointly optimize external parameters:

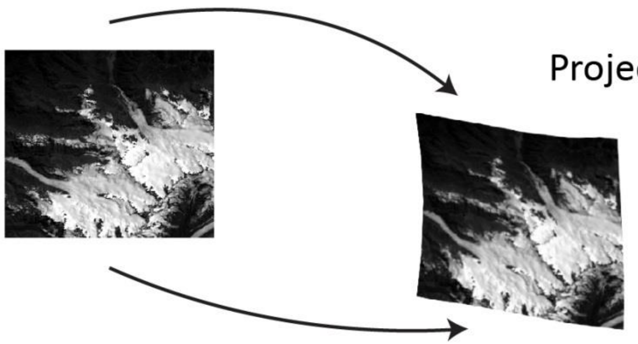
- roll, pitch, yaw angles: r(t), p(t), y(t)
- Spacecraft position in time x(t), y(t), z(t)
- 2^{nd} order polynomials approximation
- If no GCP, regularized solution to stay within instrument uncertainties.

3D and 4D Processing Flow

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**

Produce Disparity Maps



Project each image onto common reference surface (smooth topo surface)

Given a stereo-pair of images (I_S,I_T) how to retrieve the disparity map *d*?

Image Matching Framework with Regularization

$$E(d) = E_M(I_S, I_T \circ (id + d) + E_R\,(d)$$

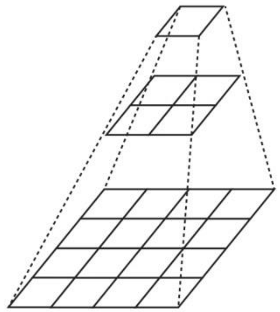
$$E_M(I_S, I_T \circ (id + d)) \approx \sum_{x \in I_S} S(I_S, I_T \circ (id + d(x)), x)$$

- S: Similarity criteria (ZNCC)
- $d(x)$: *d* constant on patch

$$E_R(d) \approx \sum_{x \in I_S} \sum_{y \sim x} w(x,y)\,|d(x) - d(y)|$$

- $|d(x) - d(y)|$: Piecewise constant prior
- $w(x,y)$: Weighs the prior
- $y \sim x$: Neighbors of pixel *x*

Produce Disparity Maps



Use of multi-scale pyramidal approach to lower the complexity

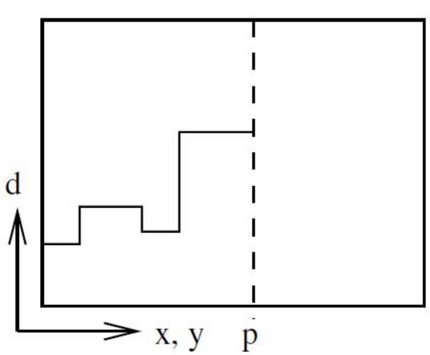
Regularization: Semi-Global Matching (SGM) – current implementation

$$d^* = \underset{d}{\operatorname{argmin}} \left(\sum_{x \in I_S} S(I_S, I_T \circ (id + d(x)), x) + \sum_{x \in I_S} \sum_{y \sim x} w(x,y)\, |d(x) - d(y)| \right)$$

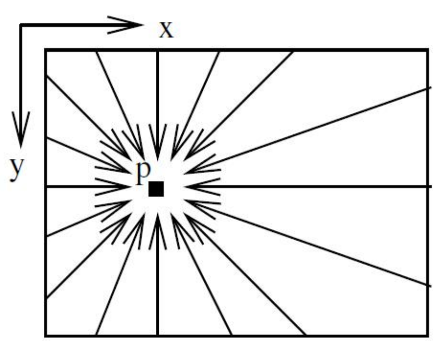
Non convex problem => variational approaches won't work

=> Restrict d(x) to a finite set of value and rewrite as first order *Markov Random Field*

(a) Minimum Cost Path $L_r(p, d)$



(b) 16 Paths from all Directions r



Only regularize along 1D directions and aggregate costs. Reduces complexity.

Hirschmuller, CVPR, 2005

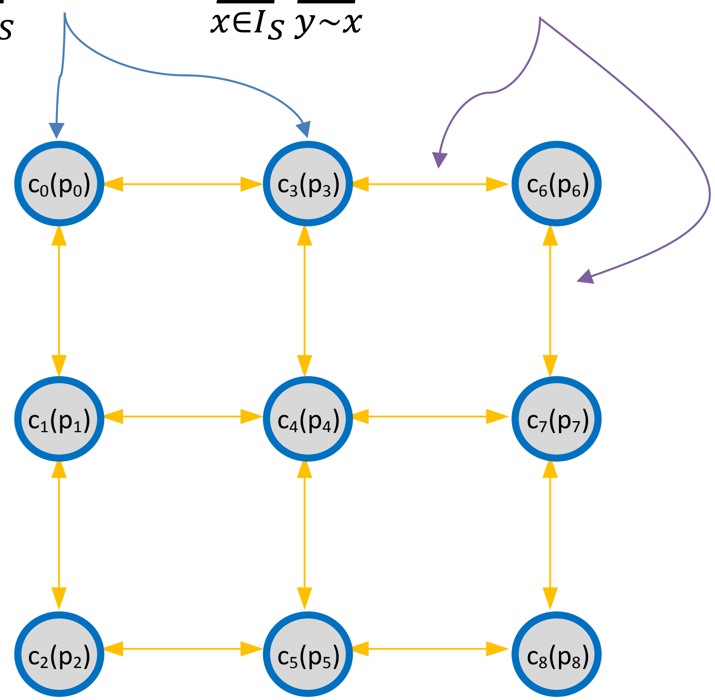
Produce Disparity Maps

Regularization: Global Matching (GM) – under implementation

$$d^* = \underset{d}{\operatorname{argmin}} \left(\sum_{x \in I_S} S(I_S, I_T \circ (id + d(x)), x) + \sum_{x \in I_S} \sum_{y \sim x} w(x,y) \, |d(x) - d(y)| \right)$$

=> Restrict d(x) to a finite set of value and rewrite as first order *Markov Random Field*

$$p^* = \underset{p_x}{\operatorname{argmin}} \left(\sum_{x \in I_S} c_x(p_x) + \sum_{x \in I_S} \sum_{y \sim x} w_{xy} \, |\delta(p_x) - \delta(p_y)| \right)$$



Complex problem (NP-Hard) but several effective techniques exist, e.g. Fast Primal-Dual from Komodakis, Tziritas and Paragios

3D and 4D Processing Flow

1. **Optimize Viewing Parameters**
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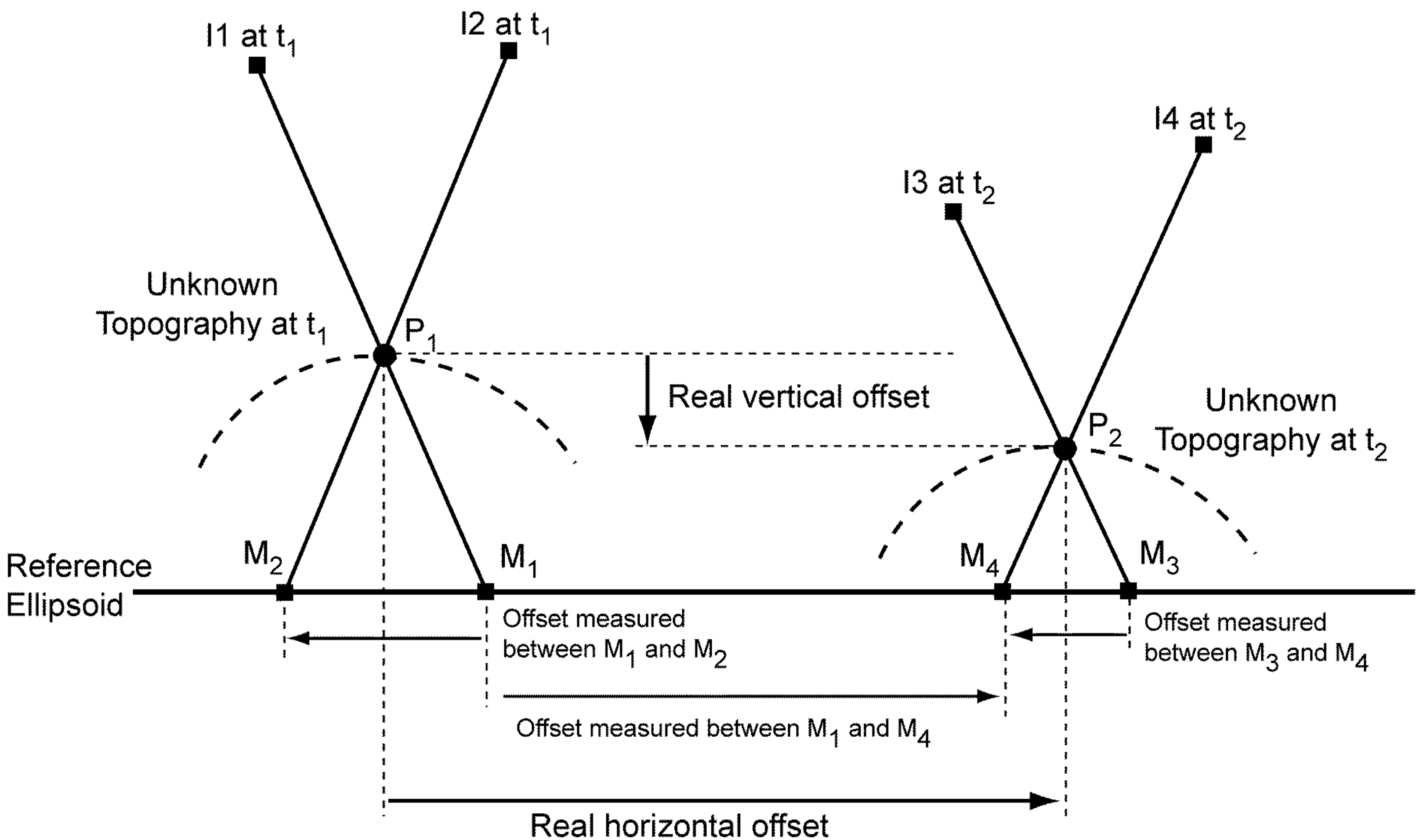
   - Optimize external viewing parameters of all images jointly using regularized bundle adjustment.

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

3. **Produce Point and Vector clouds (3D, 4D)**

Produce Point and Vector clouds (3D, 4D)

Triangulate multiple disparity maps to retrieve 3D topography and displacement fields



3D and 4D Processing Flow

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   - Cross-correlate image pairs using multi-scale, regularized image correlation.

3. **Produce Point and Vector clouds (3D, 4D)**
   - 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.

3D and 4D Processing Flow

1. **Optimize Viewing Parameters**
   - Pairwise image matching between all images,
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     - (x_2, y_2, z_2)
     - $(x_1, y_1, z_1, D_x, D_y, D_z)$
   - Output surface models at all times.

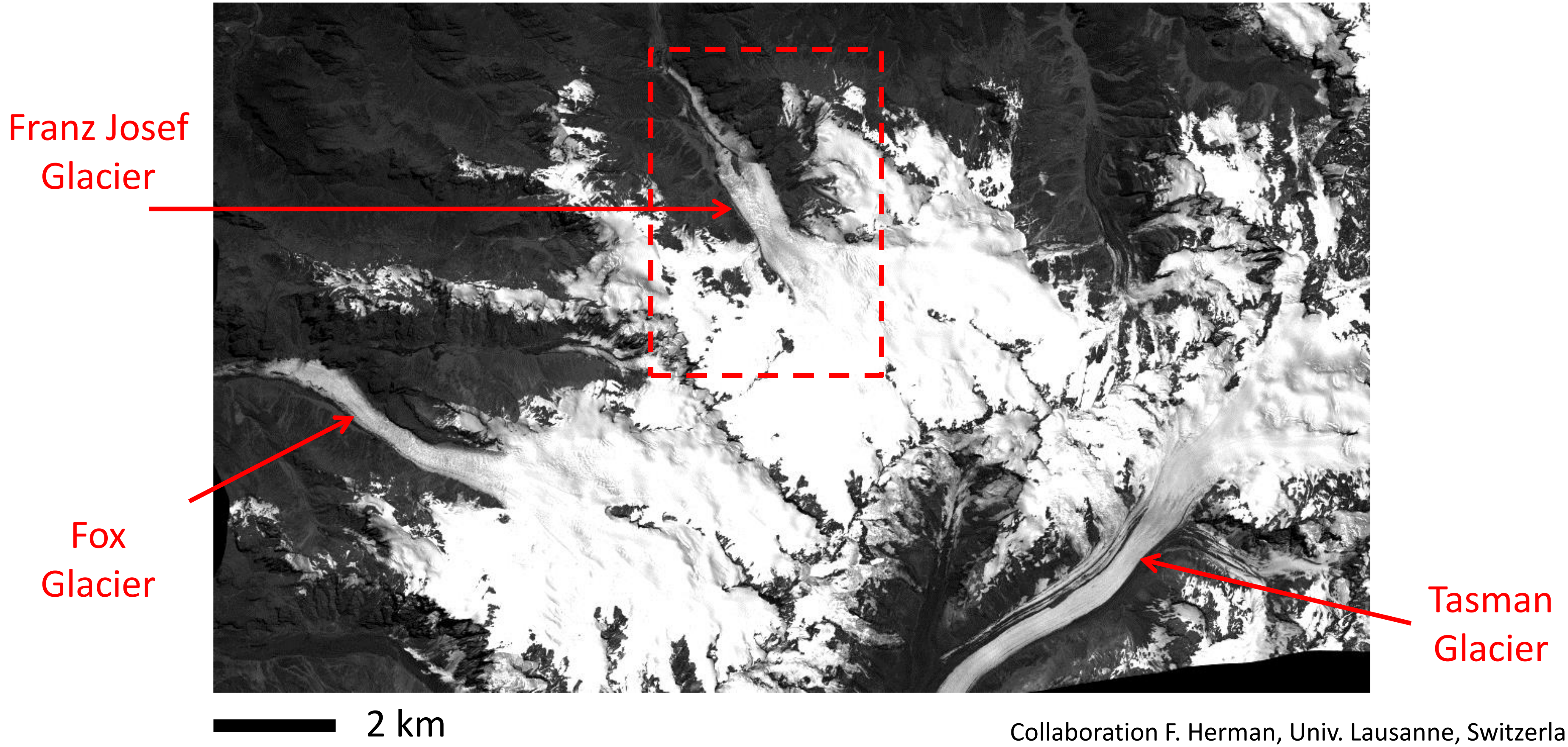
4. **Grid Point Clouds and Vector Clouds**
   - Use standard gridding libraries on each components (only external processing).

Monitoring Glacier Flow in New Zealand

Multi-temporal Stereo Acquisitions using Worldview GSD 50 cm:

- ***January 30, 2013*** *(x2)*
- ***February 9, 2013*** *(x2)*
- ***February 28, 2013*** *(x2)*

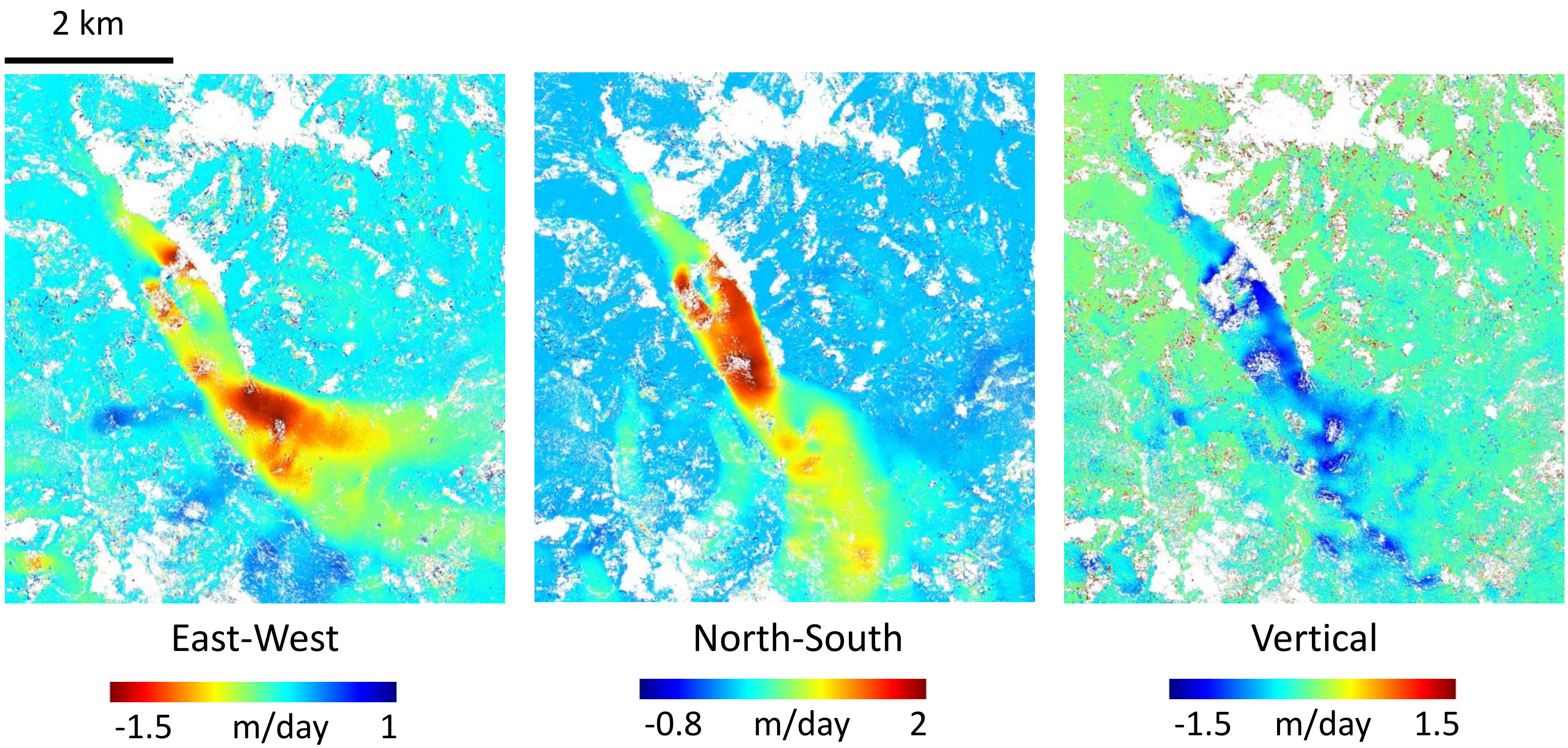
- Bundle adjustment between all images,
- Multi-scale image matching due to large disparities (up to 1000 pixels),
- Regularized matching because of occlusions



Collaboration F. Herman, Univ. Lausanne, Switzerland

Monitoring Glacier Flow in New Zealand

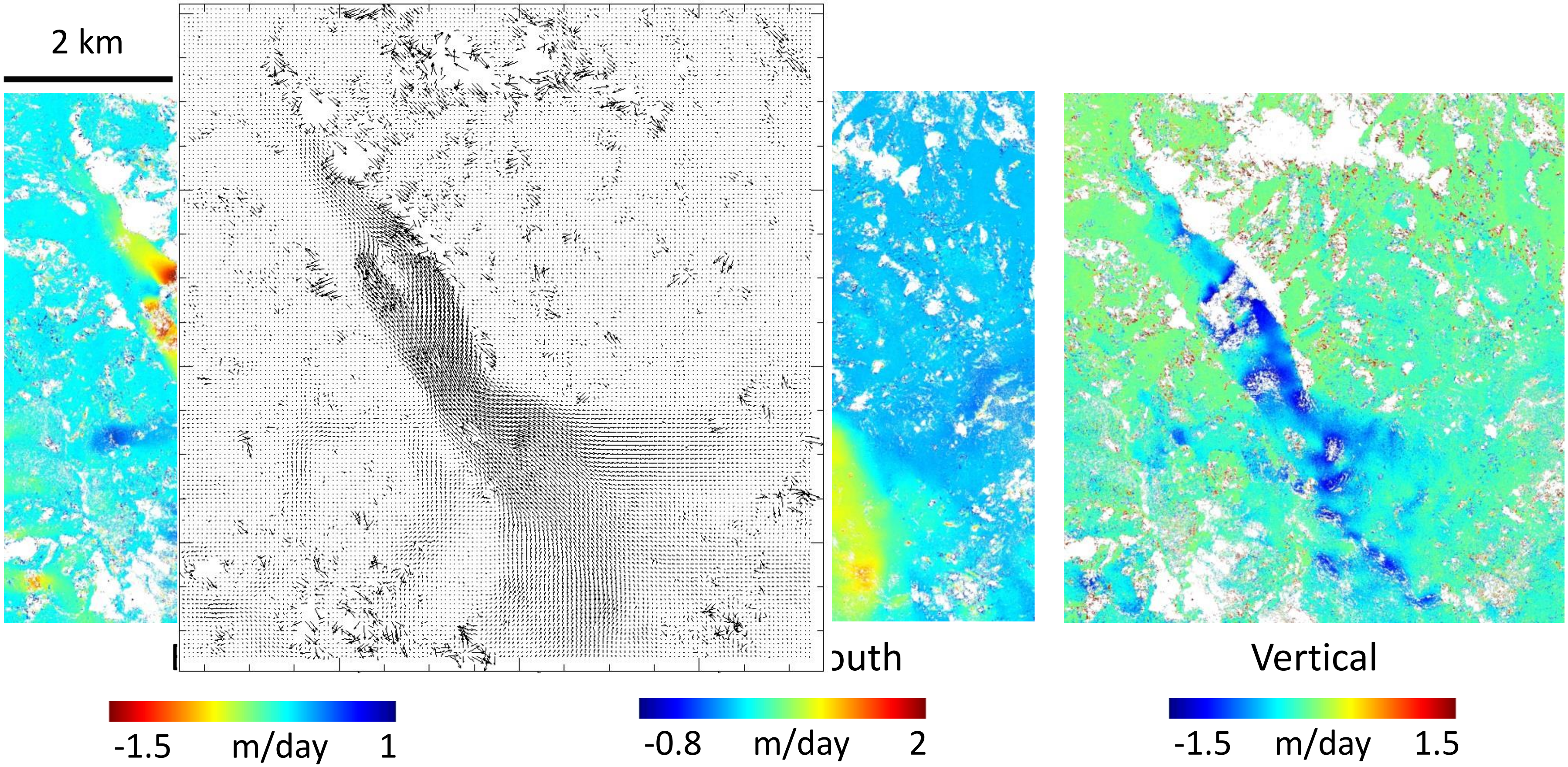
3D motion between January 30 and February 9, 2013



Measurements with intersection errors larger than 2m (20cm/day) have been removed (white areas).

Monitoring Glacier Flow in New Zealand

3D motion between January 30 and February 9, 2013



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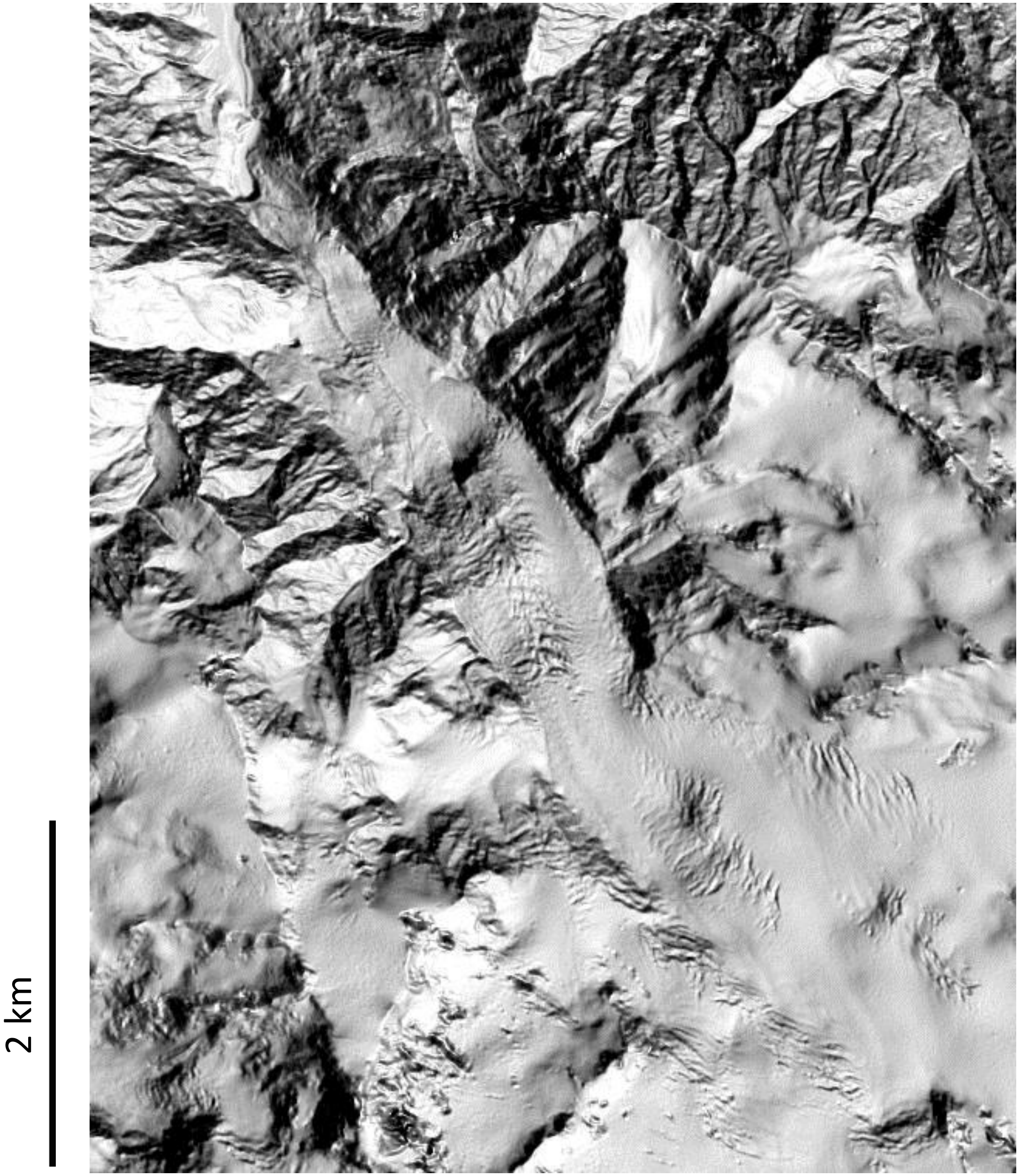
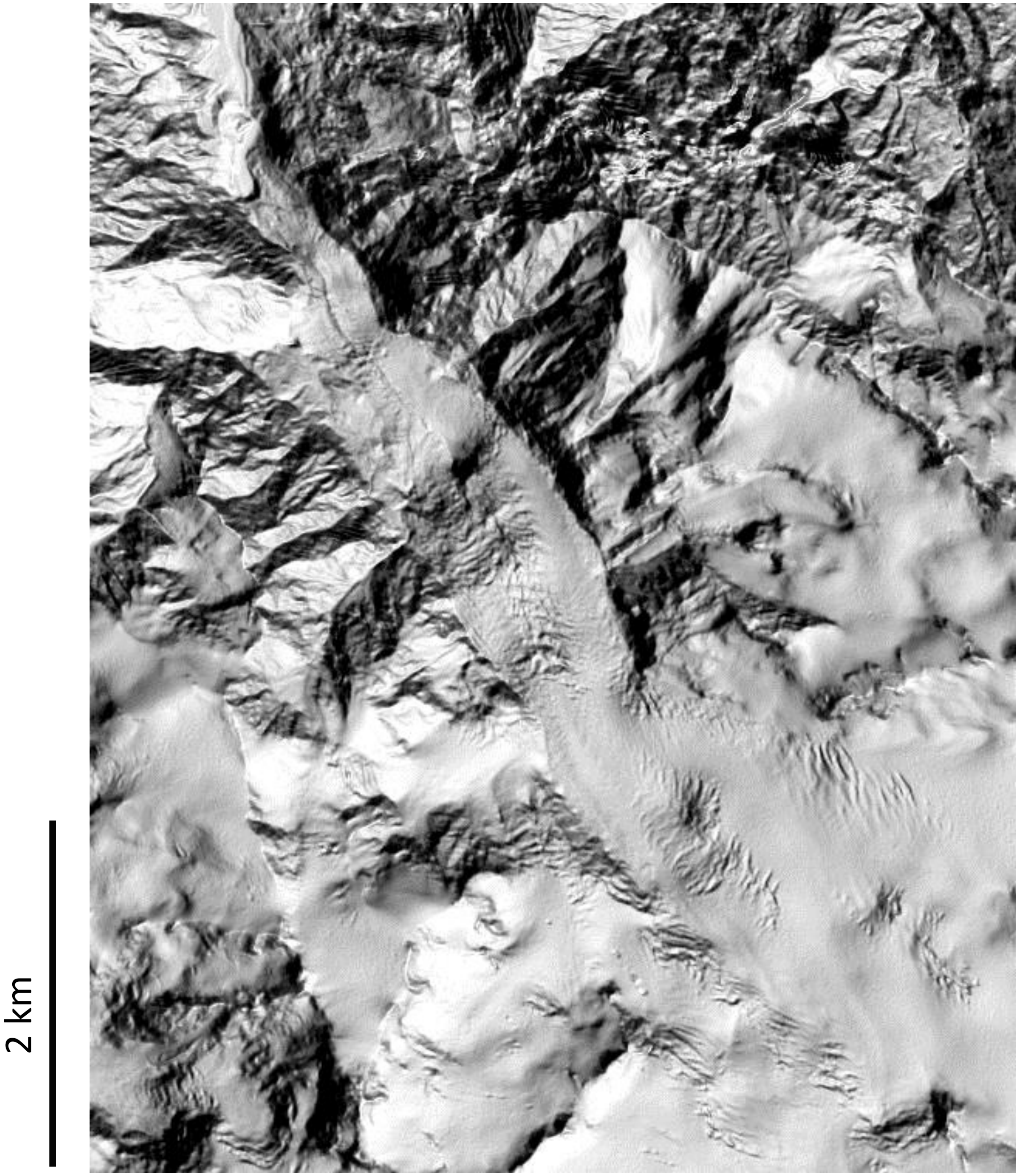
Monitoring Glacier Flow in New Zealand



1m GSD Shaded Elevation Model generated from stereo pair:

January 30, 2013

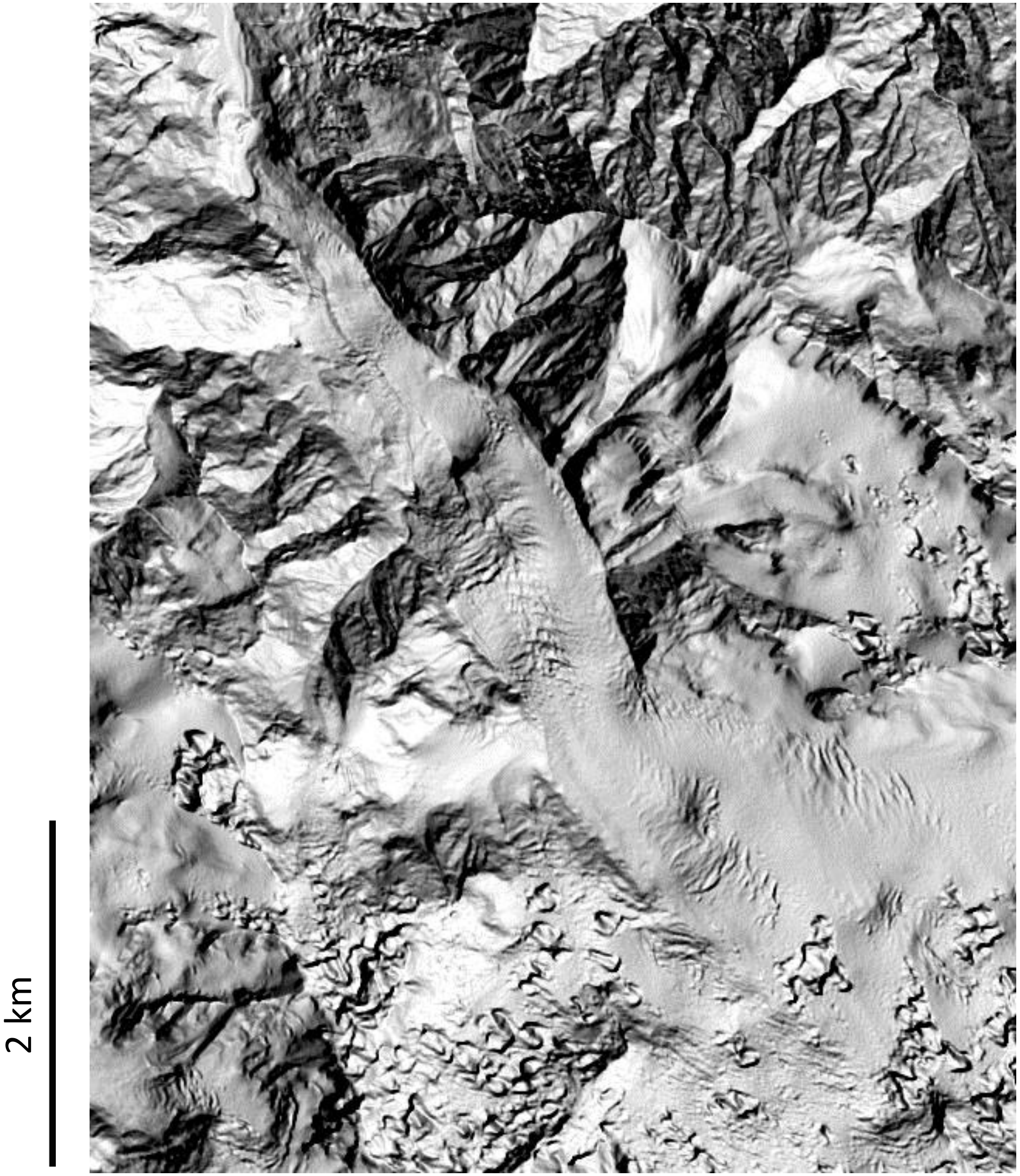
Monitoring Glacier Flow in New Zealand



1m GSD Shaded Elevation Model generated from stereo pair:

February 9, 2013

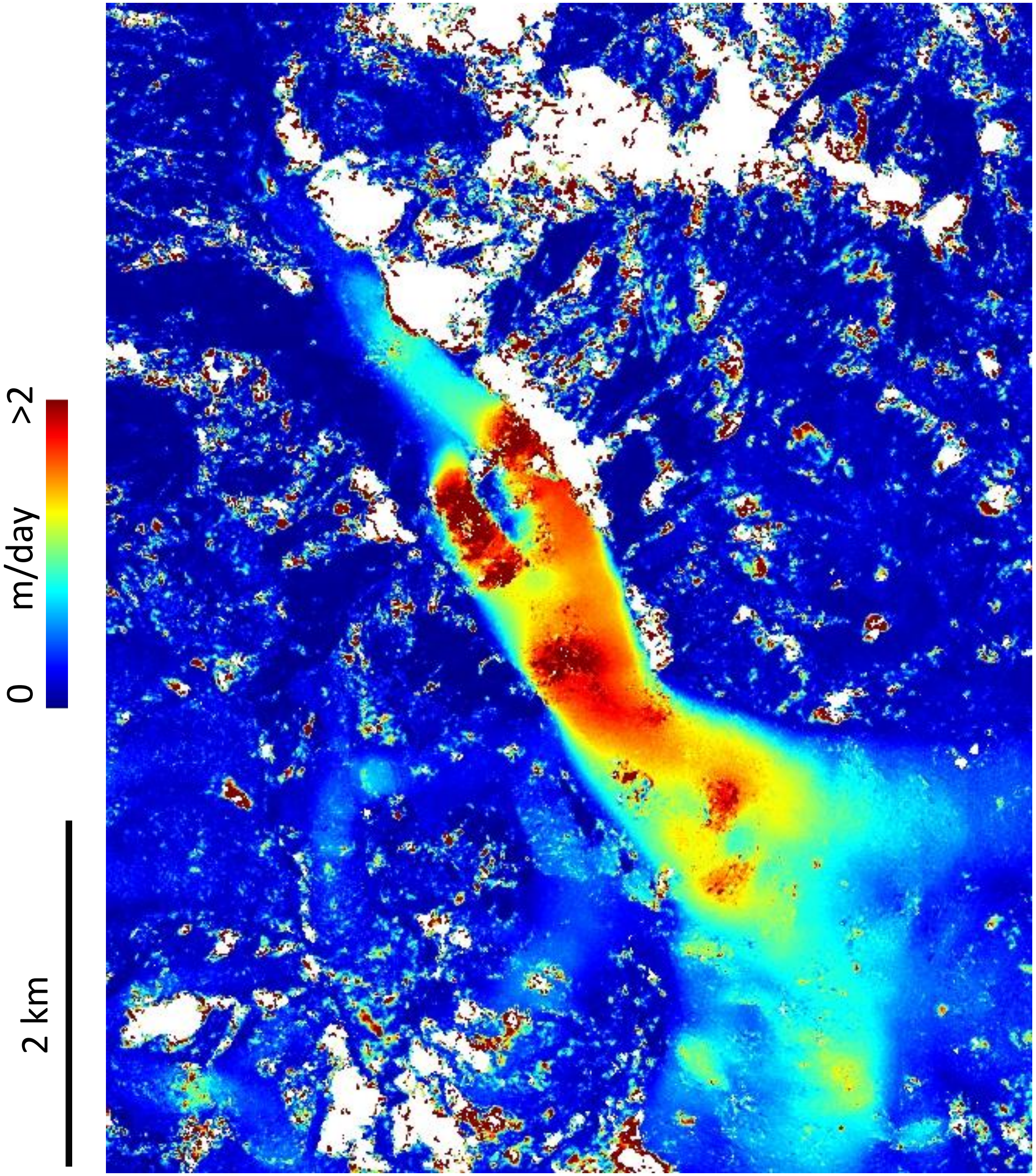
Monitoring Glacier Flow in New Zealand



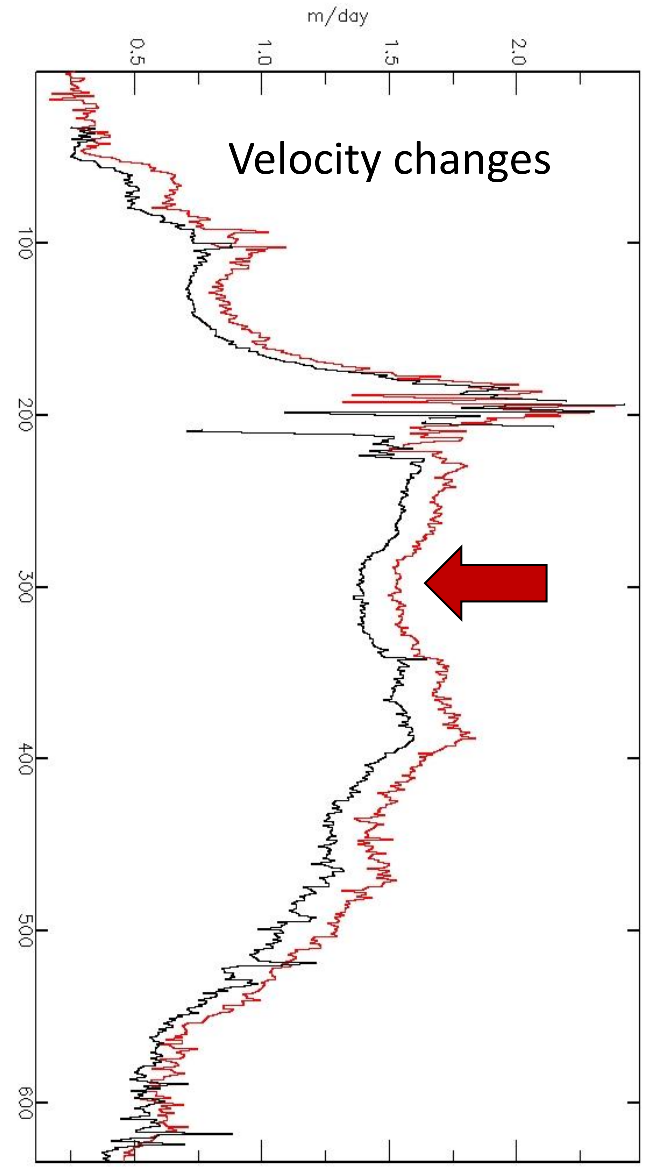
1m GSD Shaded Elevation Model generated from stereo pair:

February 28, 2013

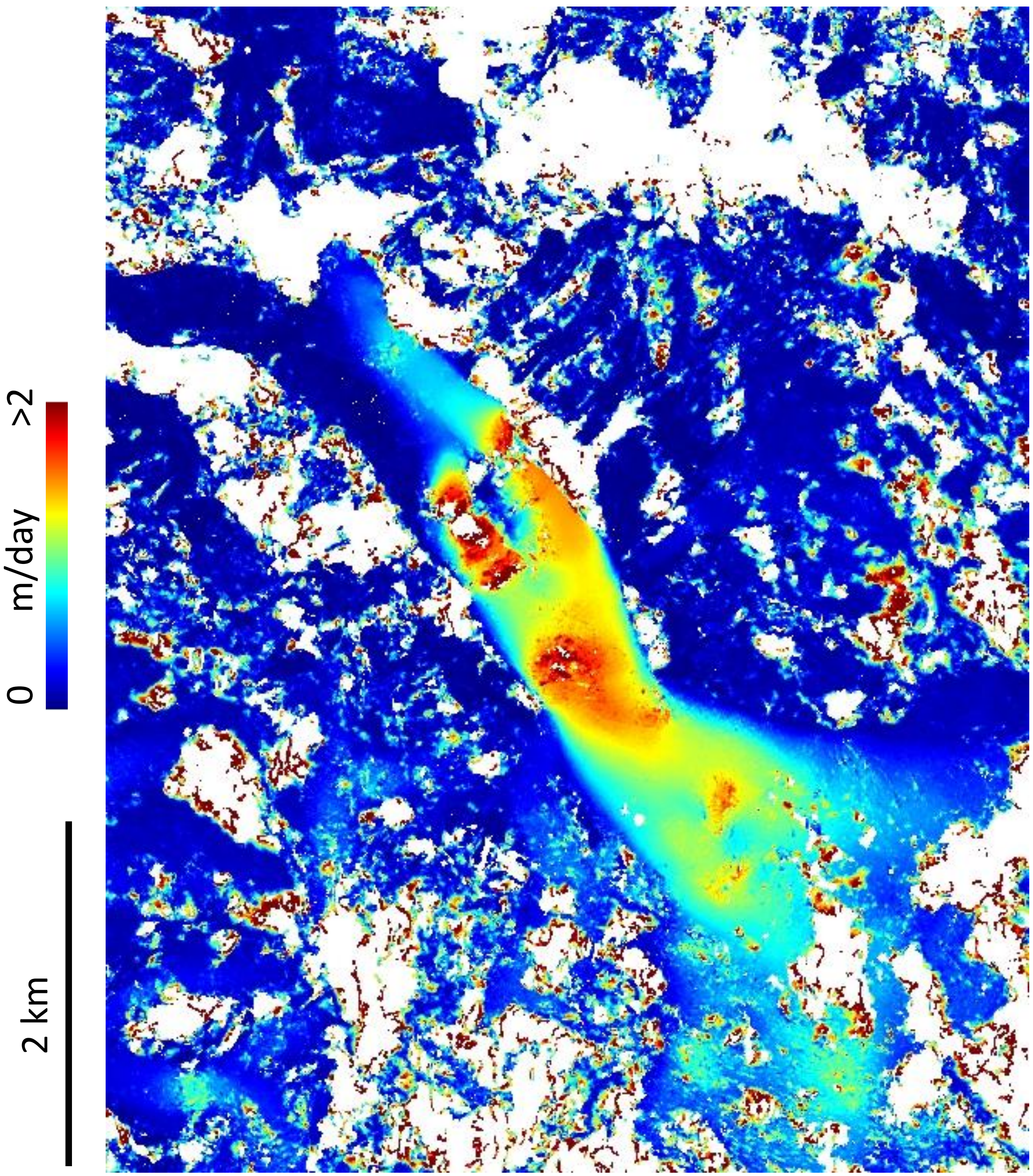
Monitoring Glacier Flow in New Zealand



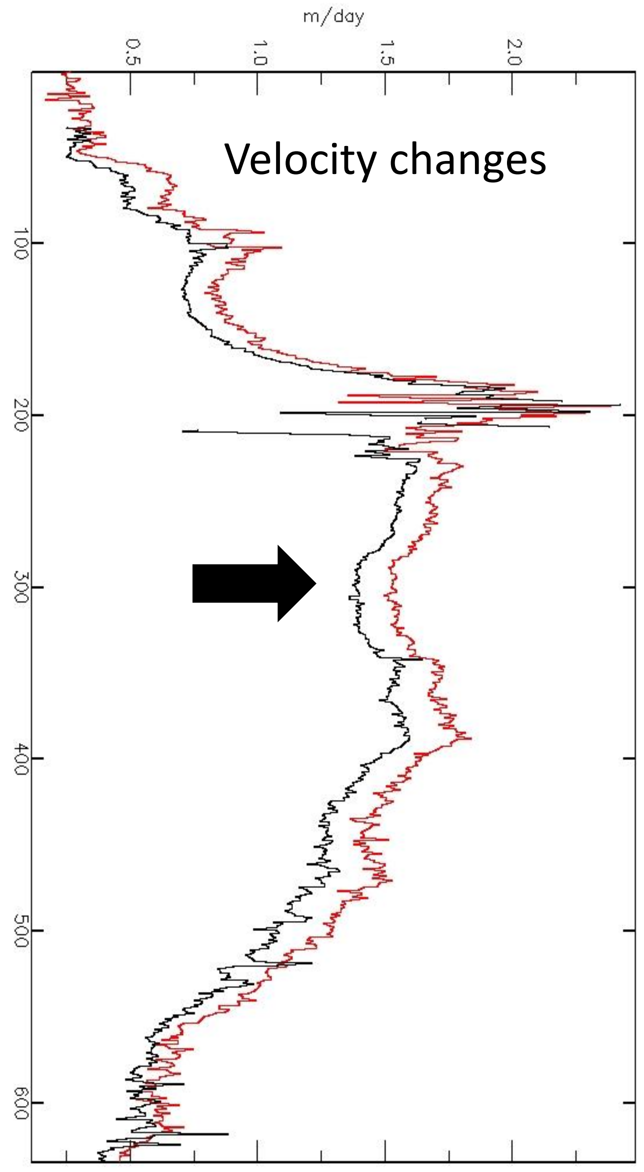
Jan 30 – Feb 9, 2013



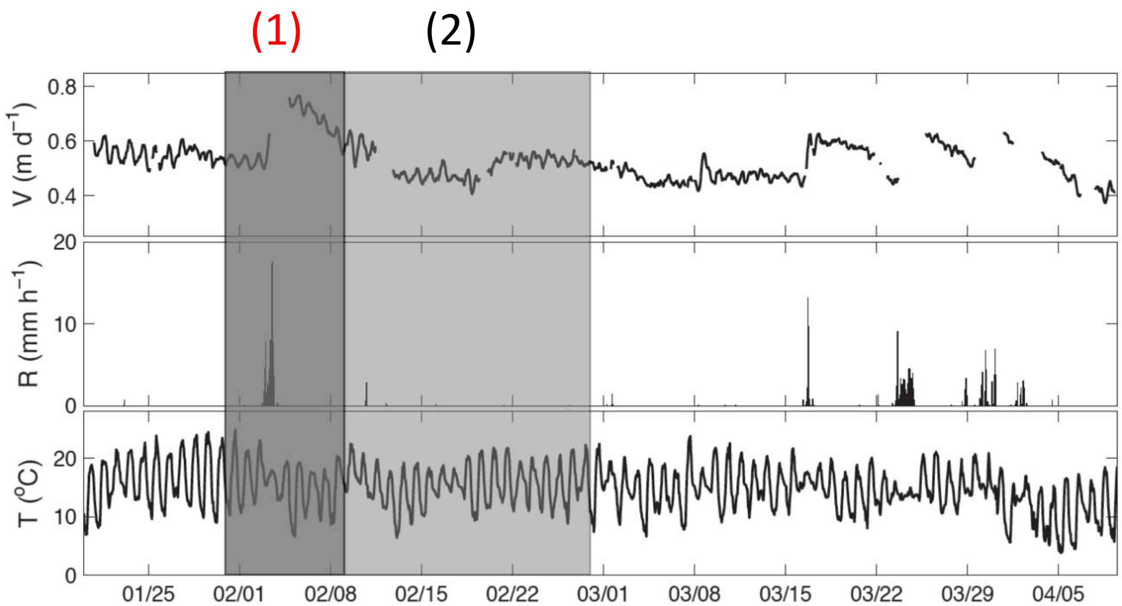
Monitoring Glacier Flow in New Zealand



Feb 9 – Feb 28, 2013

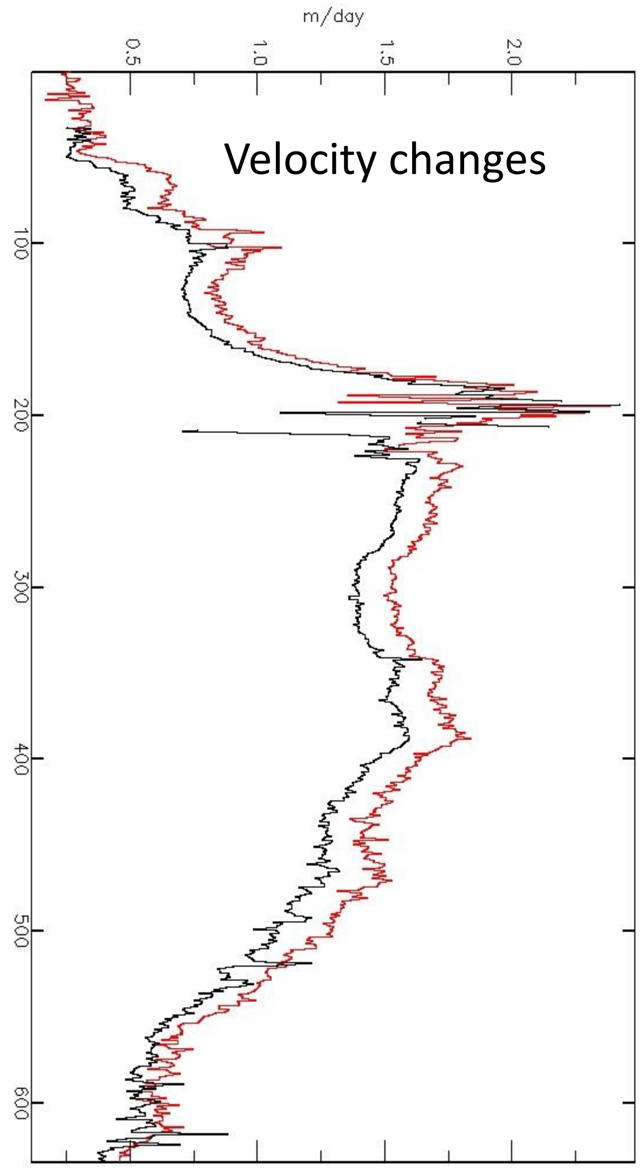


Monitoring Glacier Flow in New Zealand



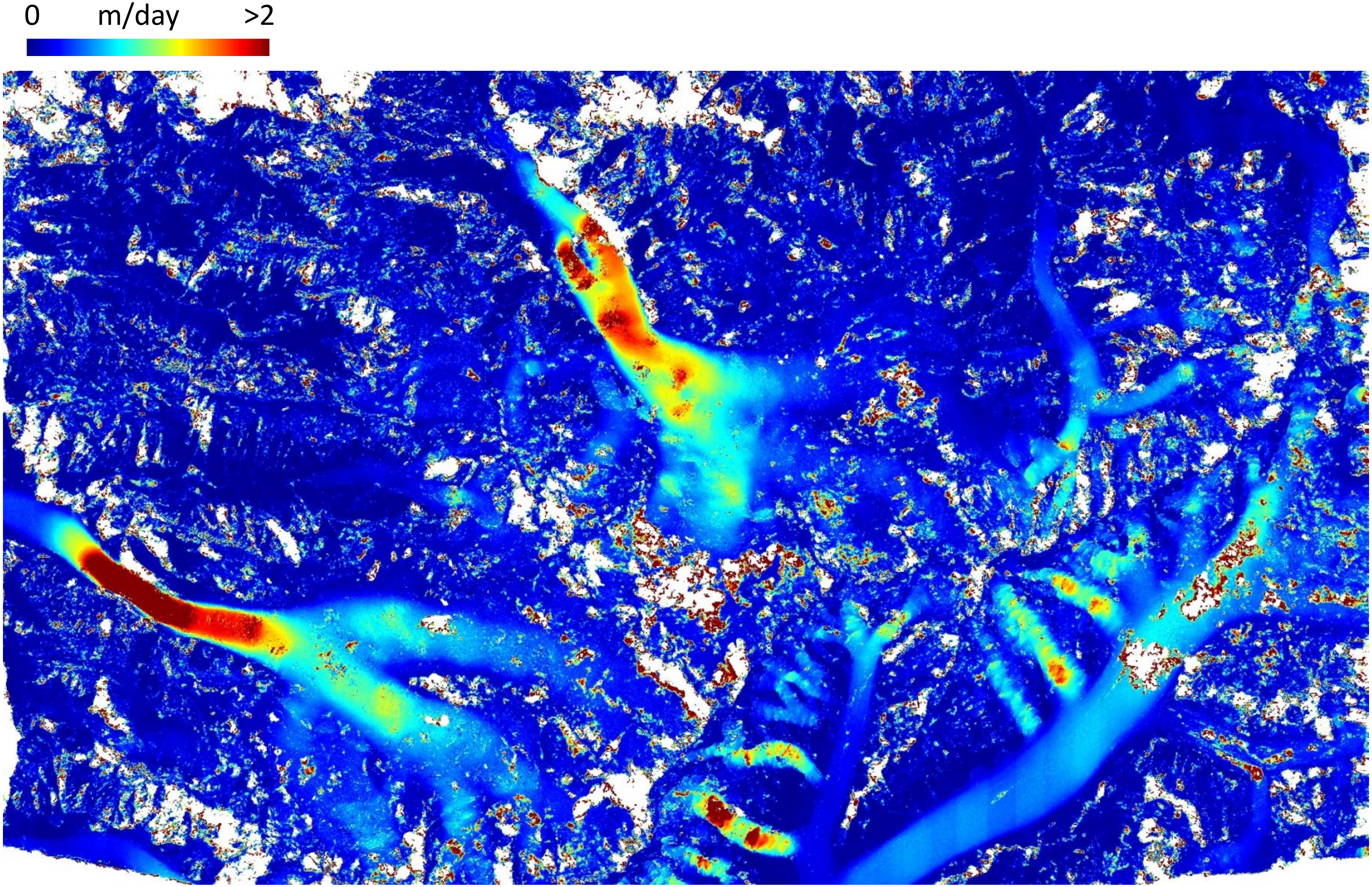
Velocity (GPS), Precipitations, Temperatures

B. Anderson (pers. Com.)
Univ. Wellington, NZ



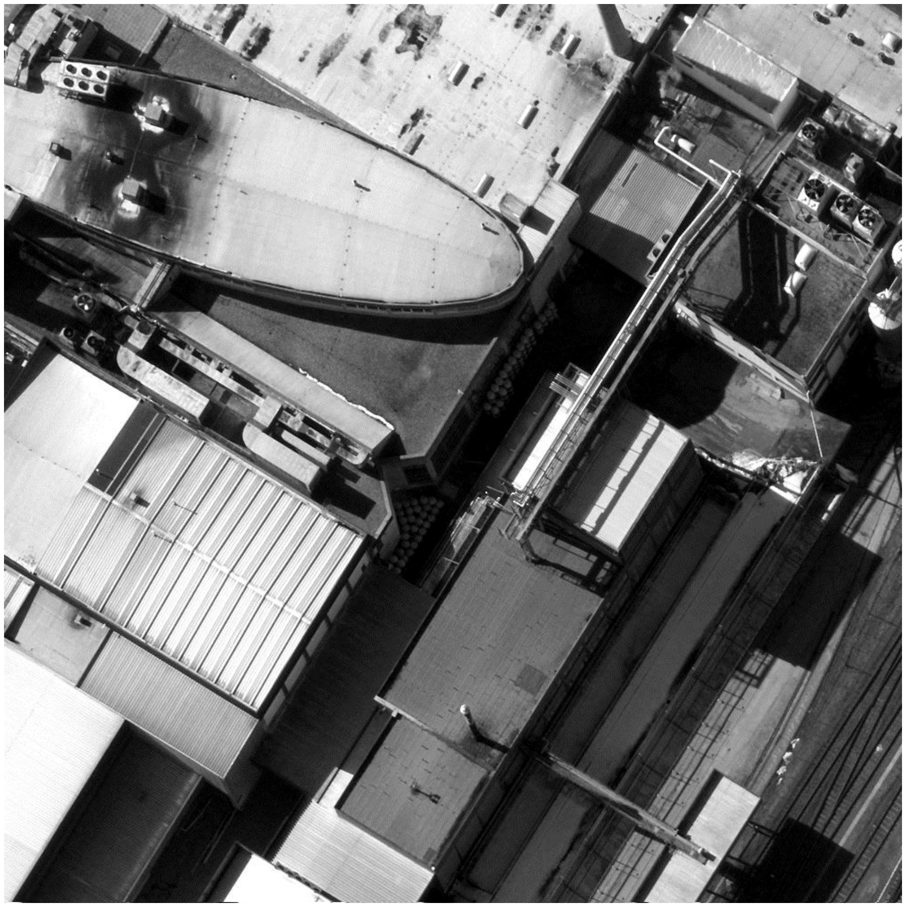
Glacial dynamics strongly affected by hydrology

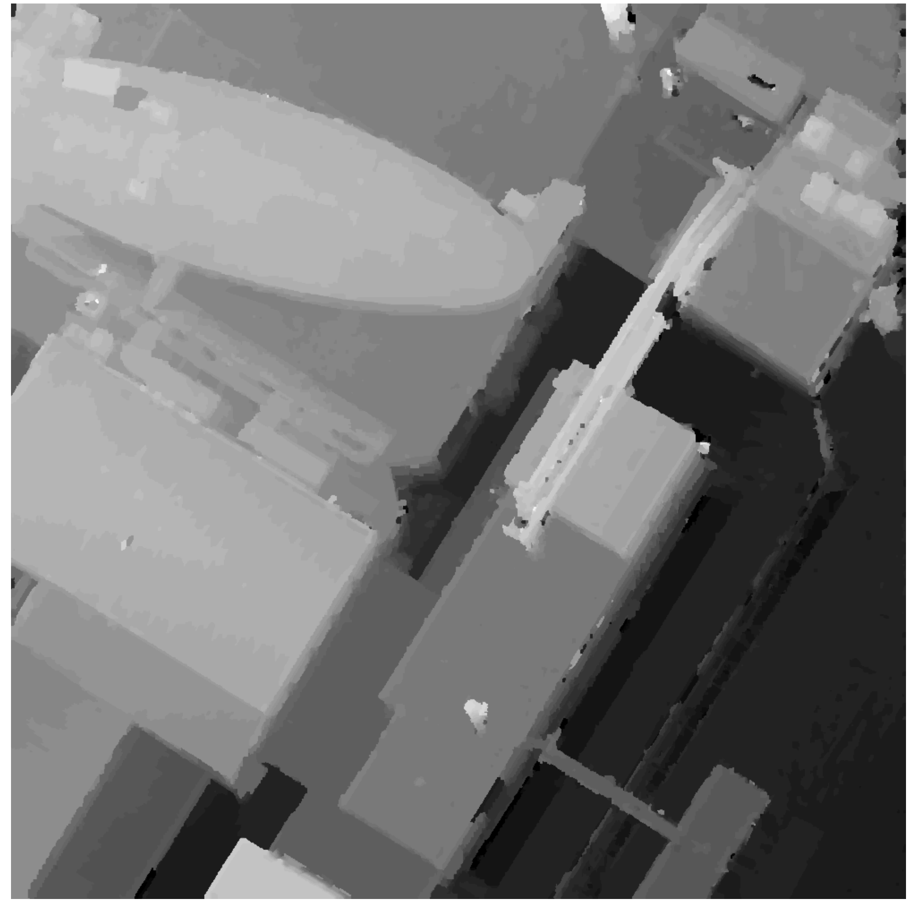
Monitoring Glacier Flow in New Zealand



Average daily velocity of up to 4 m/day at the Fox Glacier

Extracting Urban Topography





COSI-Corr DSM extraction using high resolution aerial photographs. Now to be extended to pushbrrom stereo acquisitions.

Oklahoma May 20, 2013 – Tornado damages in Moore

Facts:

- Peak winds estimated at 210 mph (340 km/h)
- 25 casualties
- 377 injured
- $2 billion damages

Idea:

- Detecting building damages by comparing high resolution DSM produced from Worldview stereo imagery.

Imagery:

- Pre-event: WV1 stereo pair acquired on May 17, 2012
- Post-event: WV1 stereo pair acquired on June 21, 2013

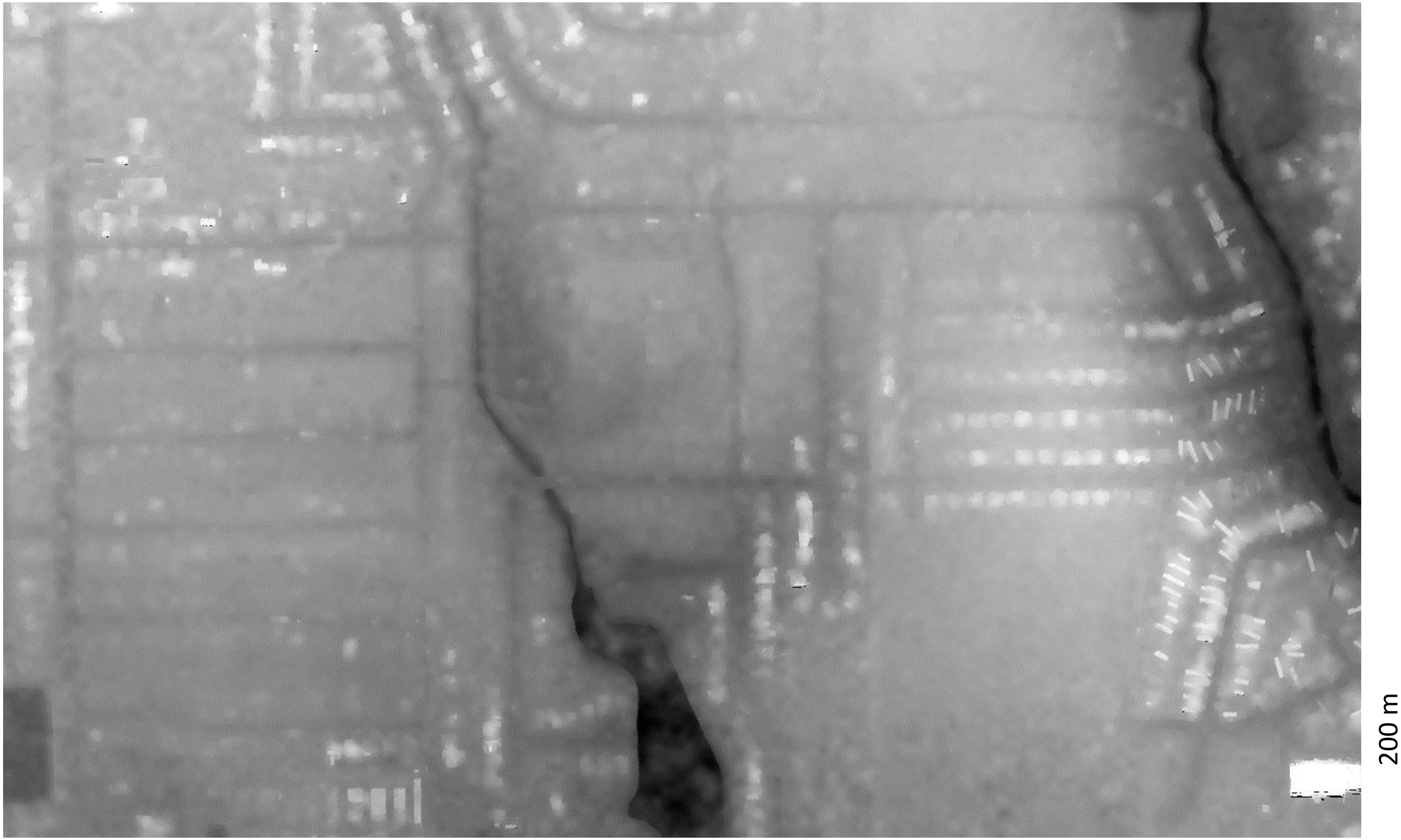
Imagery courtesy of DigitalGlobe.

Oklahoma May 20, 2013 – Tornado damages in Moore

City of Moore, Oklahoma, after tornado, 2013

City of Moore, Oklahoma, before tornado, 2012

Oklahoma May 20, 2013 – Tornado damages in Moore



Digital Surface Model - City of Moore, Oklahoma, before tornado, 2012 / after tornado, 2013

Conclusions

- Well established methods to measure 2D ground deformations,
- Landsat 8 allows accurate measurement of ground deformation and flow tracking (earthquakes, glaciers, sand dunes), far exceeding the geometrical quality of other sensors at similar GSD,
- Extension to 3D monitoring,
- Generic methods to monitor a variety of surface processes (fault rupture, landslides, sand dune migration, glaciers, etc.),
- Still improving the urban DSM change detection workflow, stay tuned!