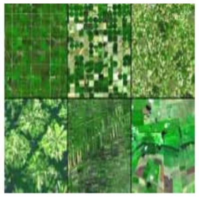







Tracking 3D Ground Changes using Multi-Temporal Stereo Satellite Imagery

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

California Institute of Technology

Keck Workshop - June 17, 2014

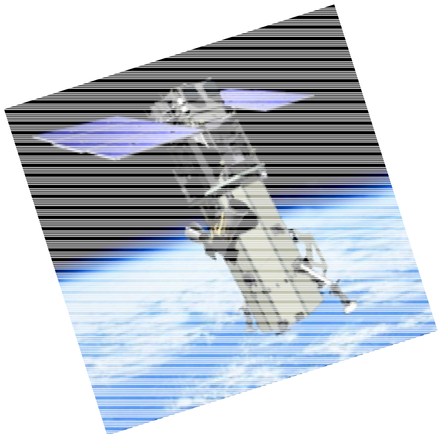
CALIFORNIA INSTITUTE OF TECHNOLOGY
THOR Terrestrial Hazard Observation and Reporting

Keck INSTITUTE FOR SPACE STUDIES

GORDON AND BETTY MOORE FOUNDATION

NASA

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

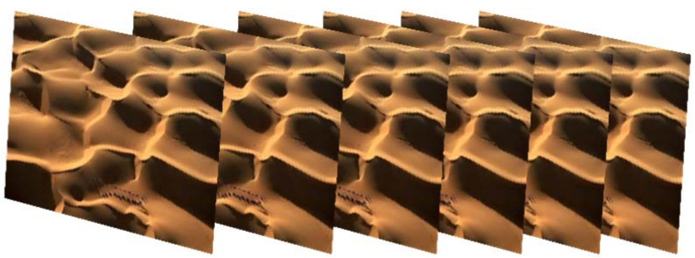


❶ **Satellite imagery** acquired at different times, any resolution, possibly by different sensors

Measuring surface processes from optical imagery

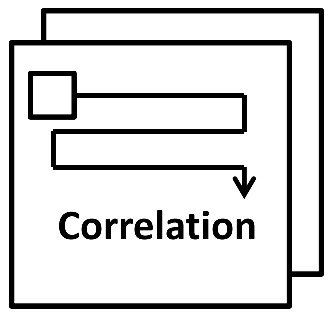
COSI-Corr

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

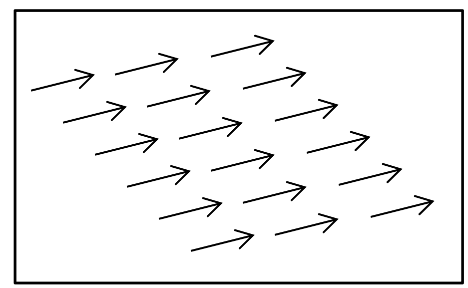


Time

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



❹ **Ground deformation**

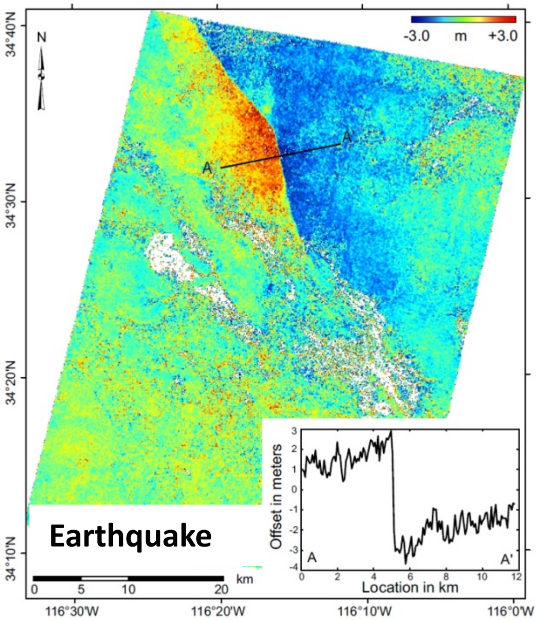


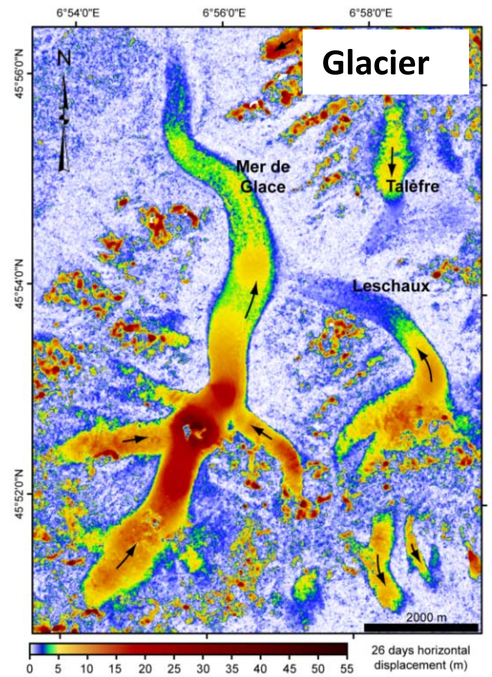
Vector field

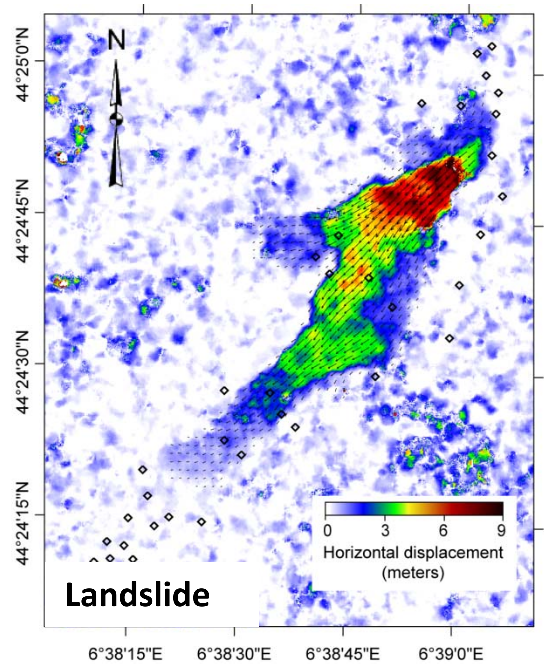
Leprince et al., IEEE TGRS, 2007

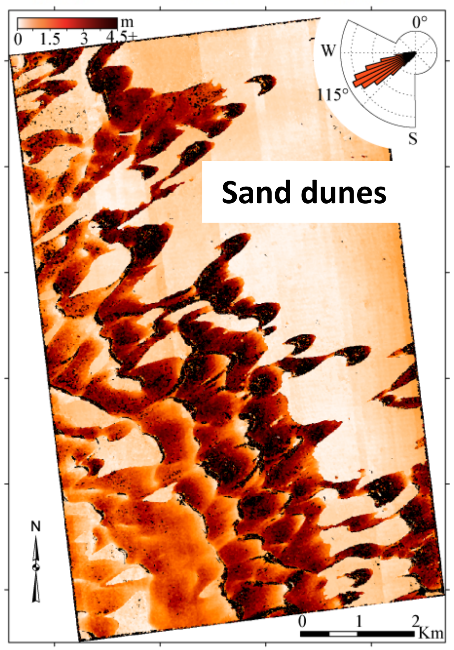
http://www.tectonics.caltech.edu/slip_history/spot_coseis/

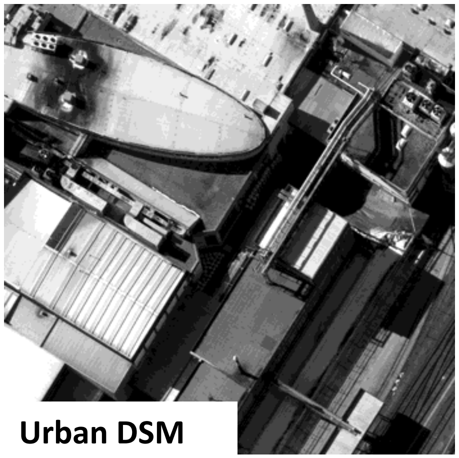
COSI-Corr: a wide range of applications



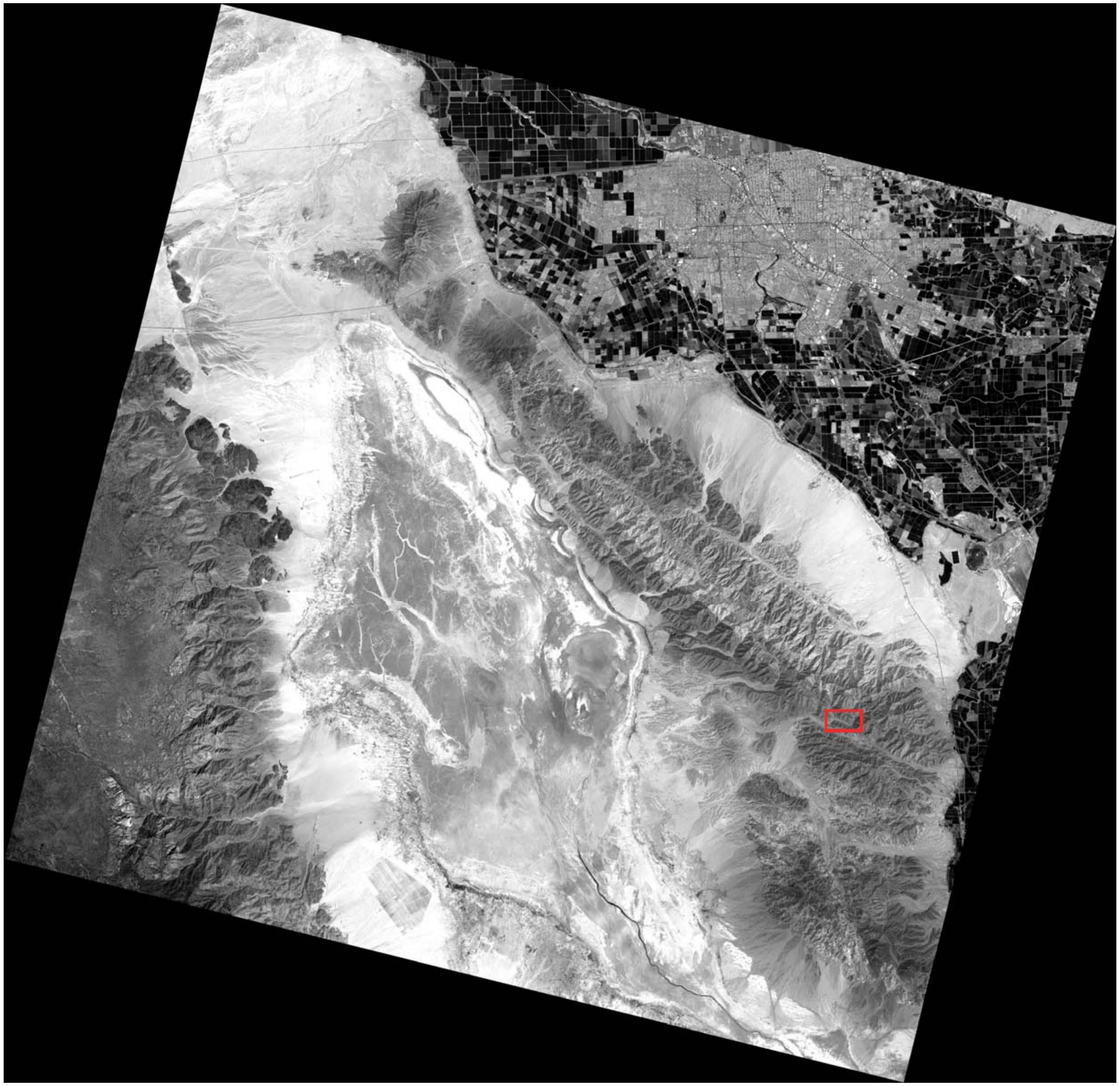








The April 2010 El-Mayor Cucapah Earthquake, Mw 7.2



SPOT 5 images
2.5 m GSD

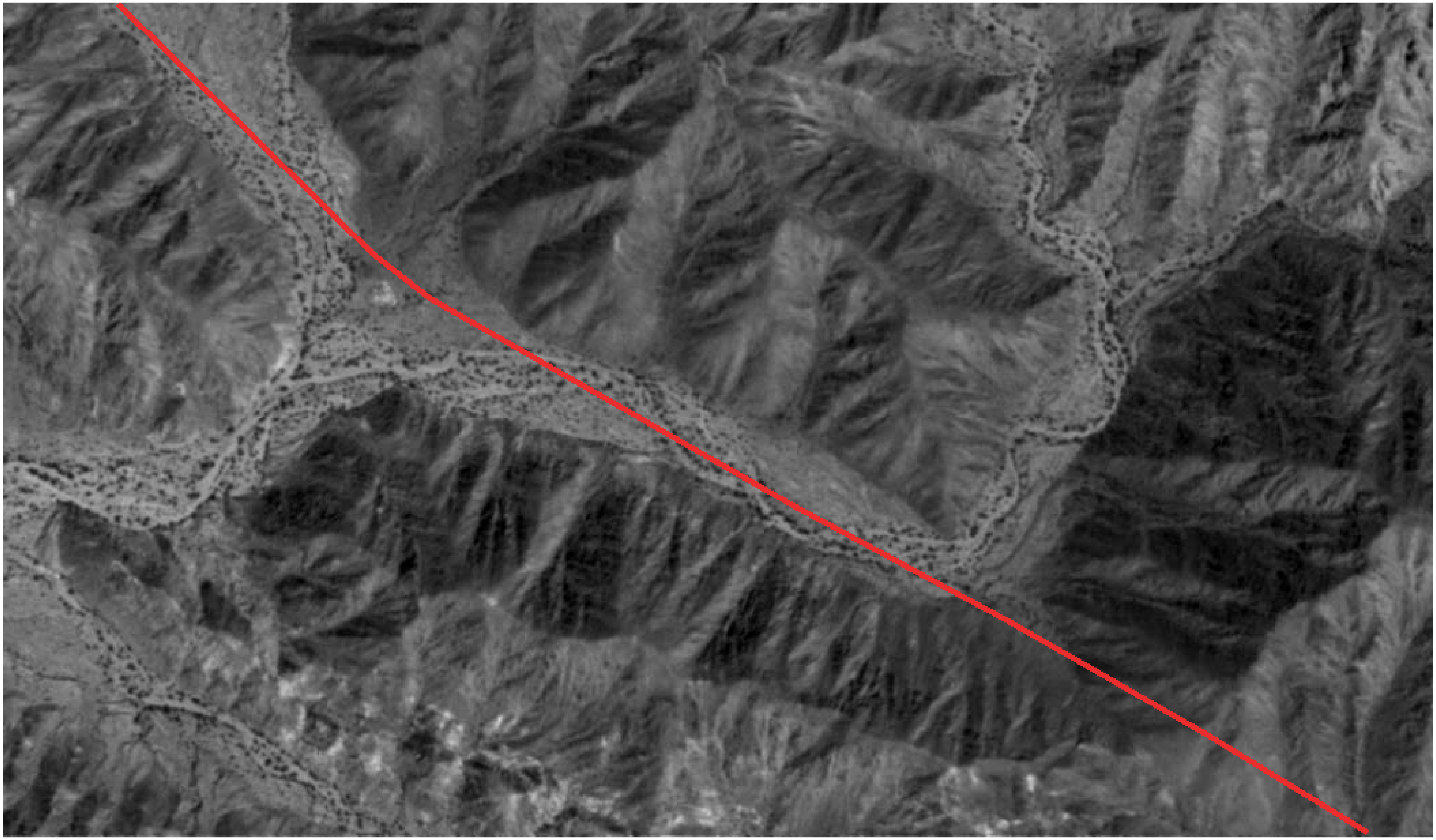
2009/05/26
2010/04/08

Images provided by
USGS
Rich Briggs
Ken Hudnut

Before/After Earthquake Imagery

Can you see the ground moving?

Before/After Earthquake Imagery



Can you see the ground moving?

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

$$C_{i_1 i_2}(\omega_x,\omega_y) = \frac{I_1(\omega_x,\omega_y)I_2^*(\omega_x,\omega_y)}{|I_1(\omega_x,\omega_y)I_2^*(\omega_x,\omega_y)|} = e^{j(\omega_x\Delta_x+\omega_y\Delta_y)}$$

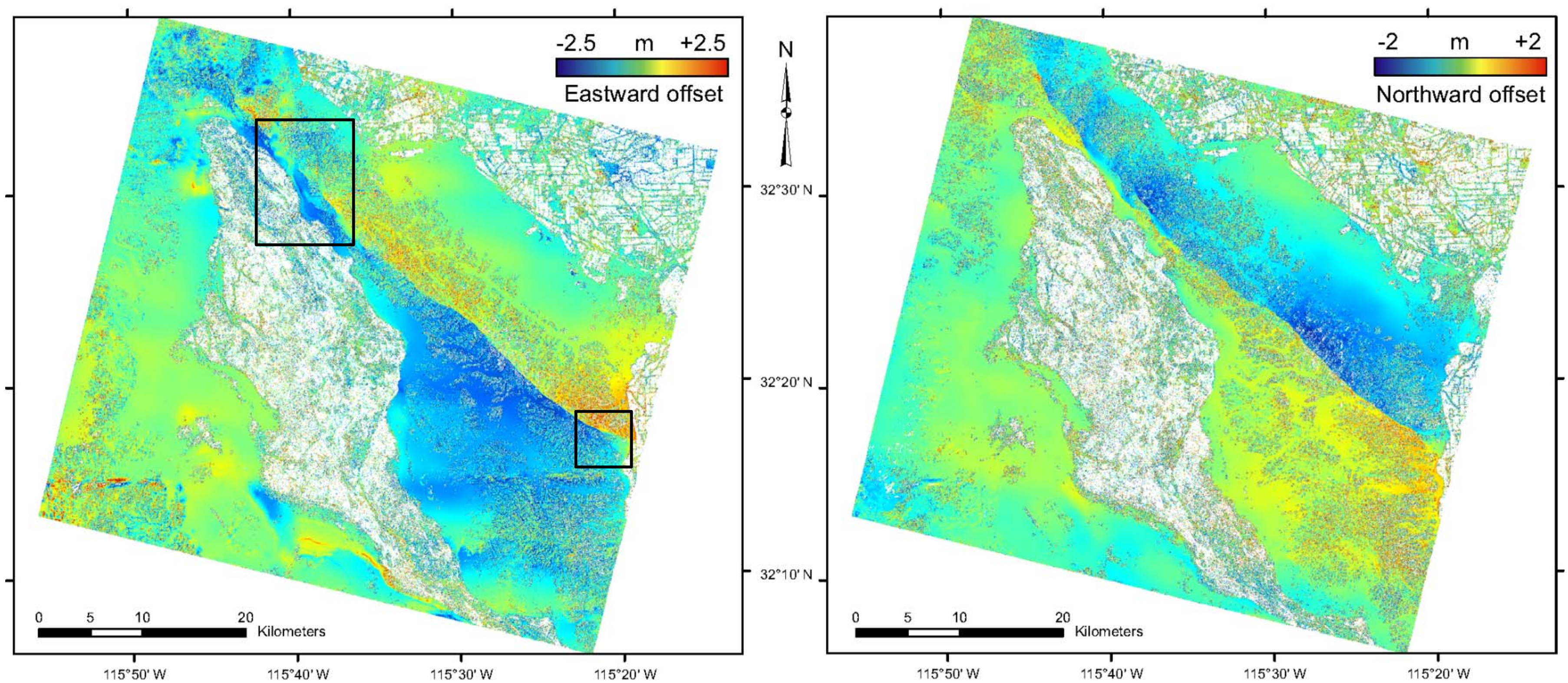
- Finding the relative displacement

$$\phi(\Delta_x,\Delta_y) = \sum_{\omega_x=-\pi}^{\pi}\sum_{\omega_y=-\pi}^{\pi} W(\omega_x,\omega_y)|C_{i_1 i_2}(\omega_x,\omega_y) - e^{j(\omega_x\Delta_x+\omega_y\Delta_y)}|^2$$

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

S. Leprince et al., IEEE TGRS, 2007

Horizontal Displacement Field from SPOT Imagery

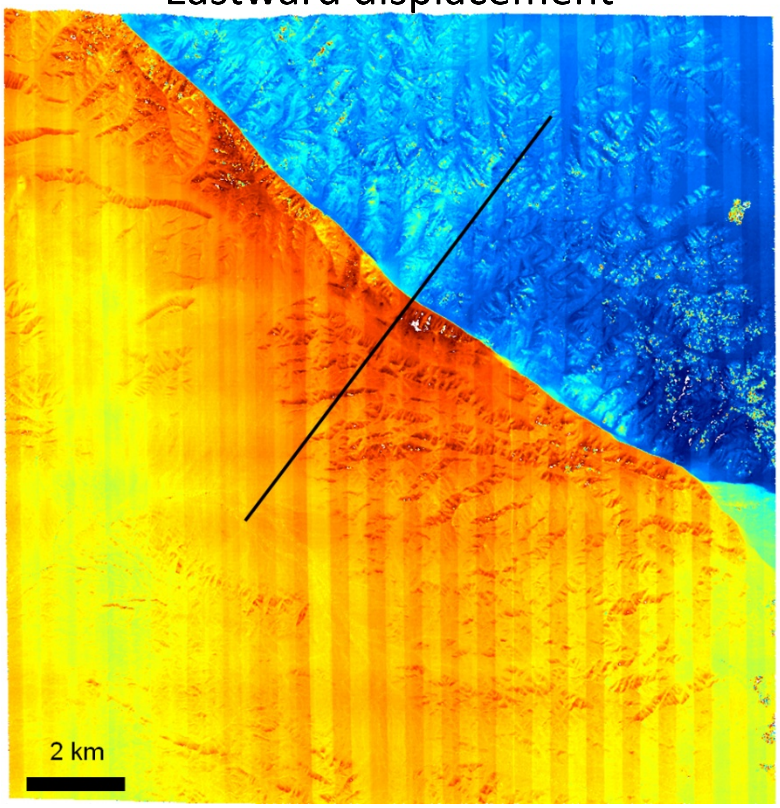


Ground rupture well identified and recovered with 1/10 pixel accuracy (~25 cm)

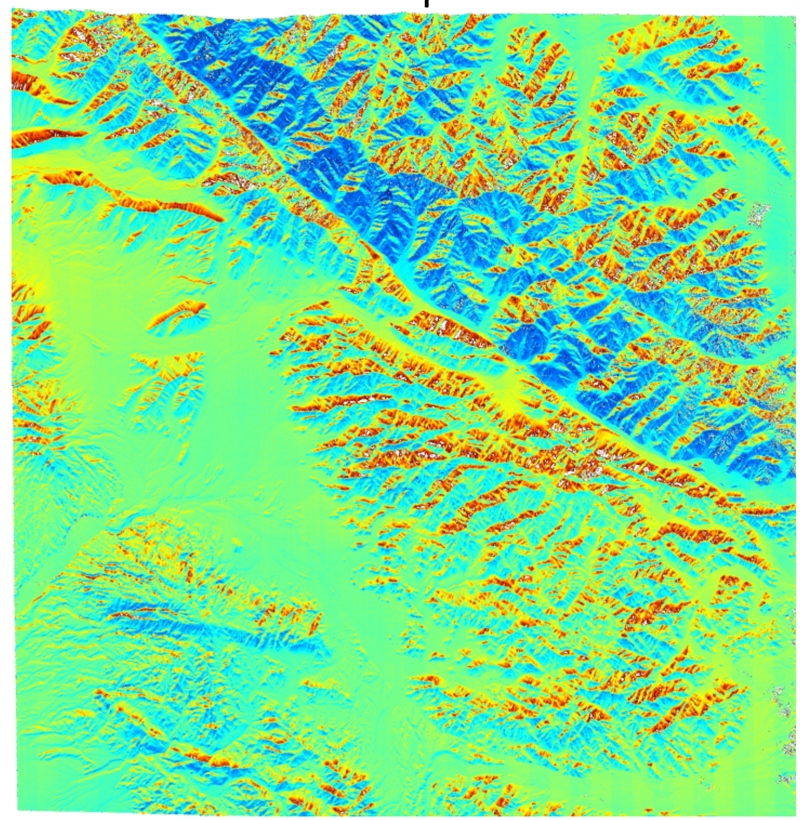
Wei et al., Nature Geoscience, 2011

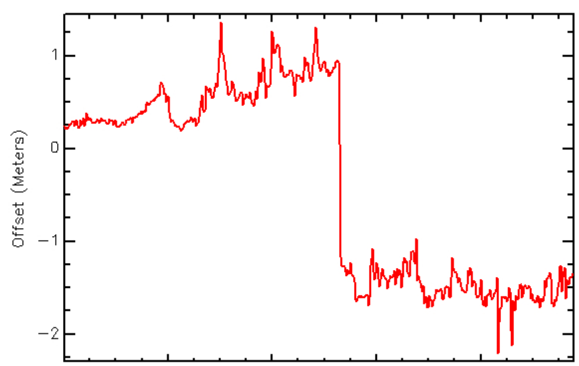
Horizontal Displacement using Worldview - 50 cm GSD

Eastward displacement



Northward displacement





PB: large incidence angle bring topography residuals in parallax direction (here mostly Northward).

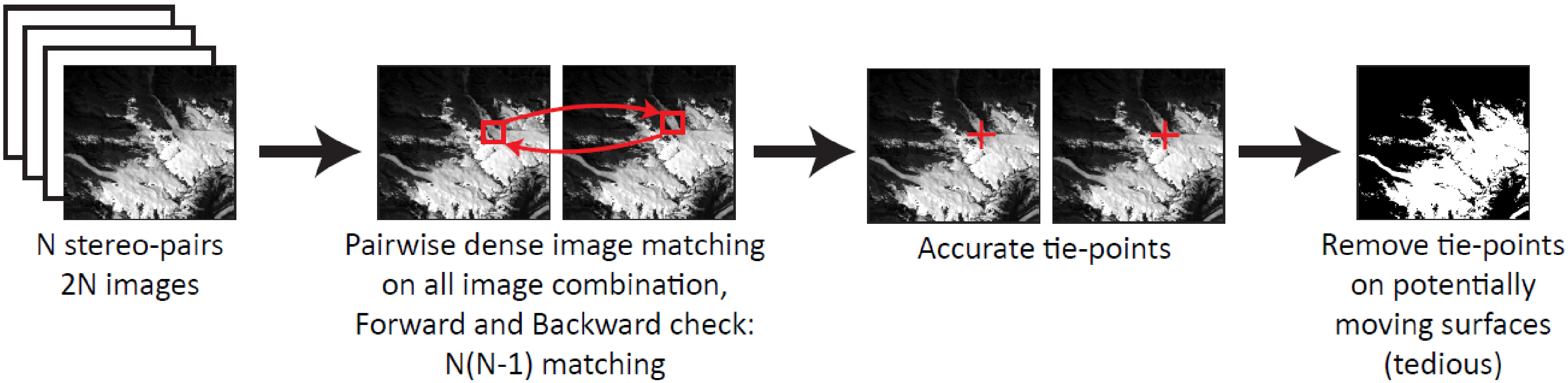
Solution: Use several images before and after the event.

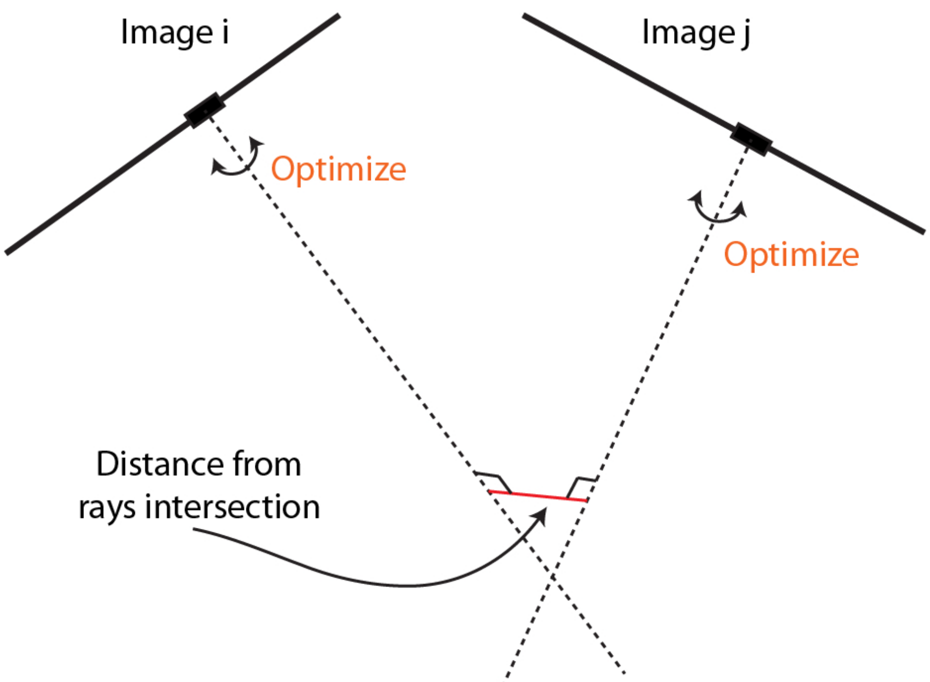
Artifacts from CCD misalignment.

3D and 4D Processing Flow

1. **Optimize Viewing Parameters**

Optimize Viewing Parameters





Jointly optimize external parameters:

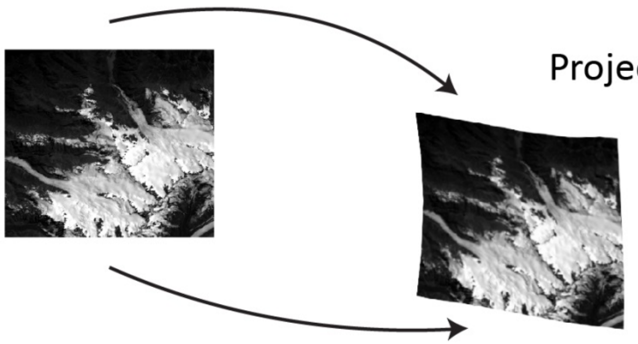
- roll, pitch, yaw angles: r(t), p(t), y(t)
- Spacecraft position in time x(t), y(t), z(t)
- 2^{nd} order polynomials approximation
- If no GCP, regularized solution to stay within instrument uncertainties.

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

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

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

- $S(\ldots)$ → 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*

3D and 4D Processing Flow

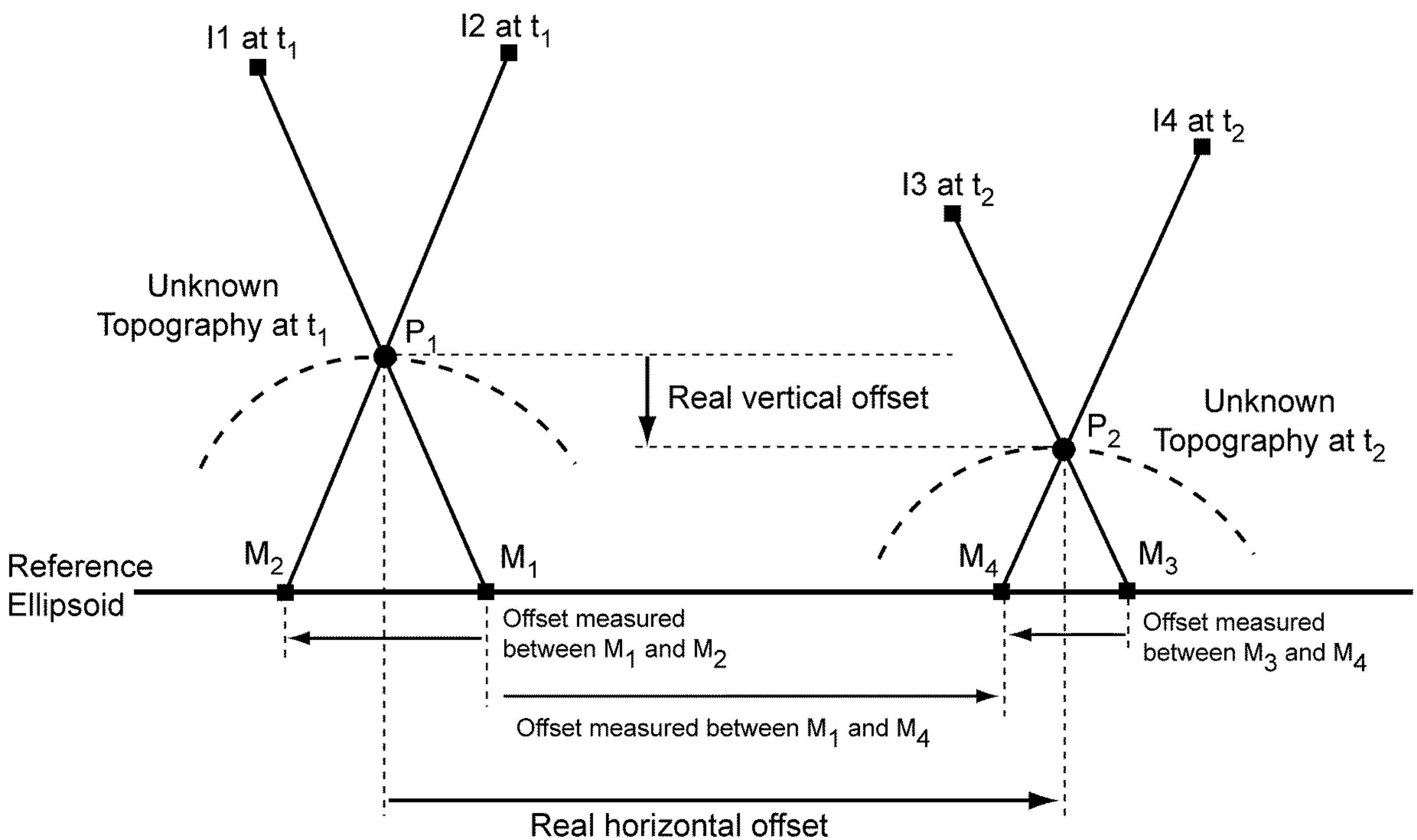
1. **Optimize Viewing Parameters**
   - Pairwise image matching between all images,
   - Only keep tie-points on stable surfaces (e.g., bedrock),
   - Optimize external viewing parameters of all images jointly using regularized bundle adjustment.

2. **Produce Disparity Maps**
   - 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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   - 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)**
   - 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,
   - Only keep tie-points on stable surfaces (e.g., bedrock),
   - Optimize external viewing parameters of all images jointly using regularized bundle adjustment.

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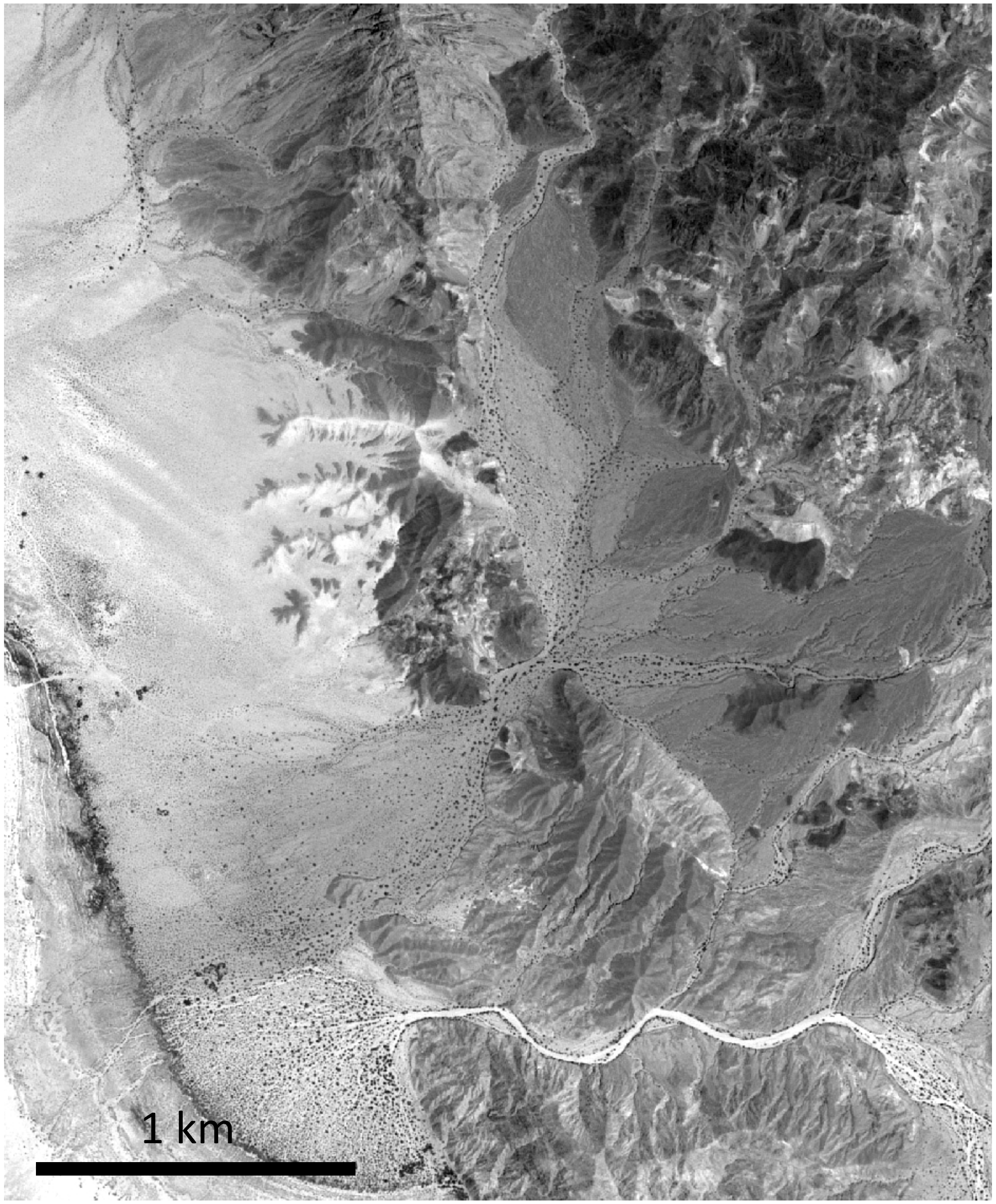
     - (x_2, y_2, z_2)
     - $(x_1, y_1, z_1, D_x, D_y, D_z)$
   - Output surface models at all times.

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

El-Mayor Cucapah EQ, 2010, 3D displacement field



Pre-earthquake images:

- Quickbird **09/21/2006**,
  Along-track angle -1.23°
  Across-track angle -9.8°

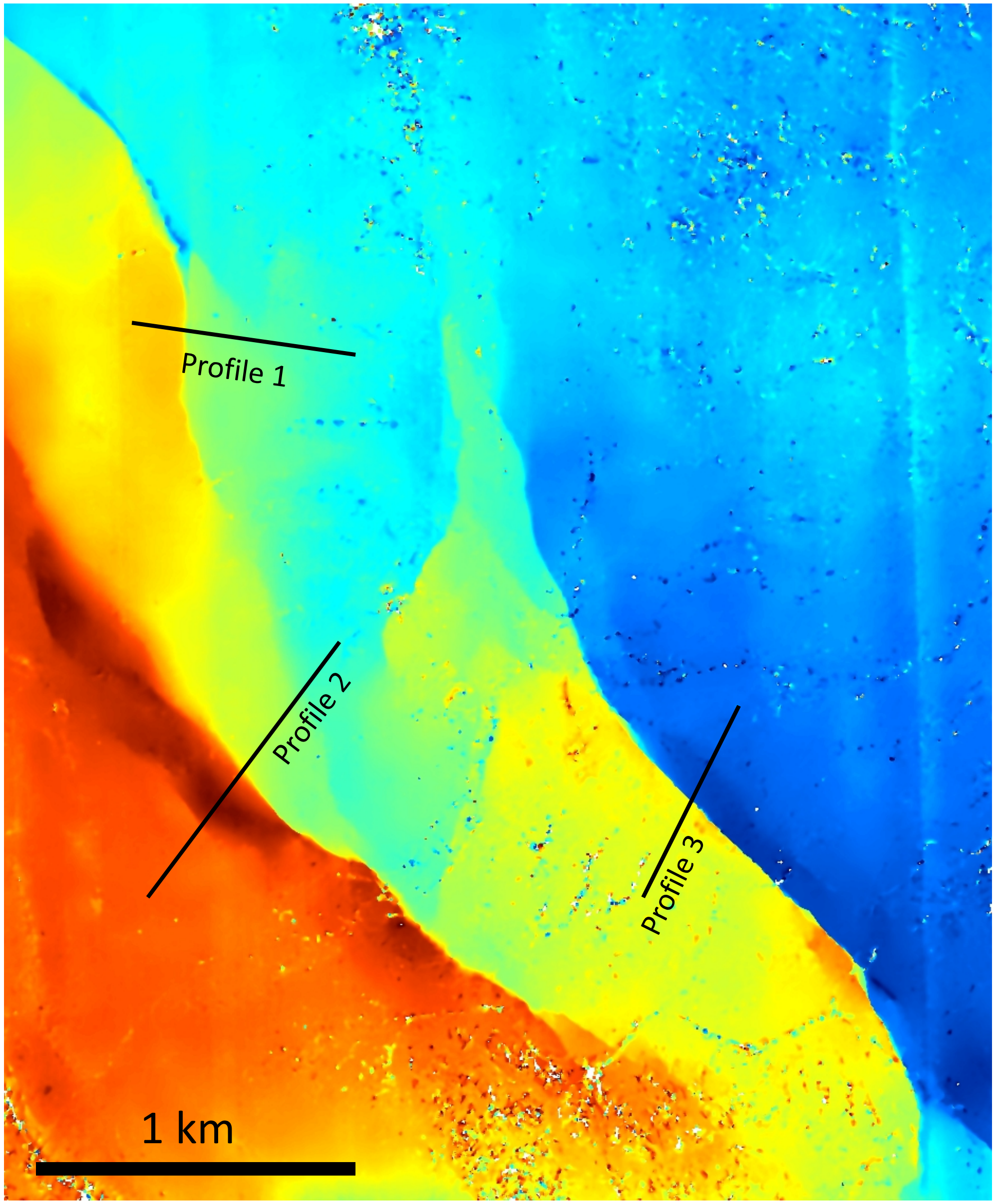
- Worldview **09/16/2008**,
  Along-track angle -10.8°
  Across-track angle 13.5°

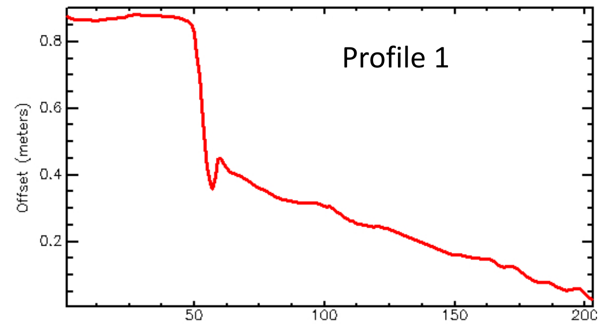
Post-earthquake images:

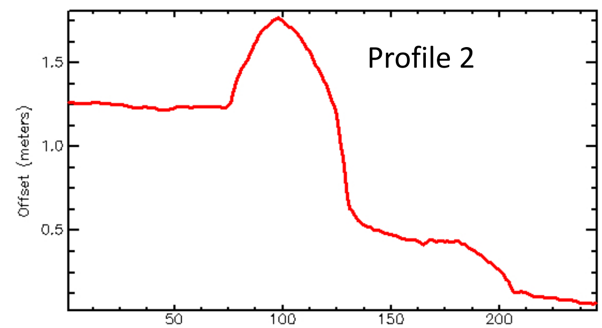
- Worldview **04/10/2011**,
  Along-track angle -13.8 °
  Across-track angle -22.5°

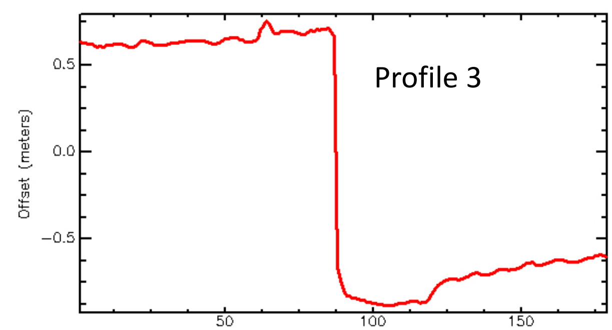
- Worldview **05/19/2011**,
  Along-track angle 14.1°
  Across-track angle 21.6°

El-Mayor Cucapah EQ, 2010, 3D displacement field



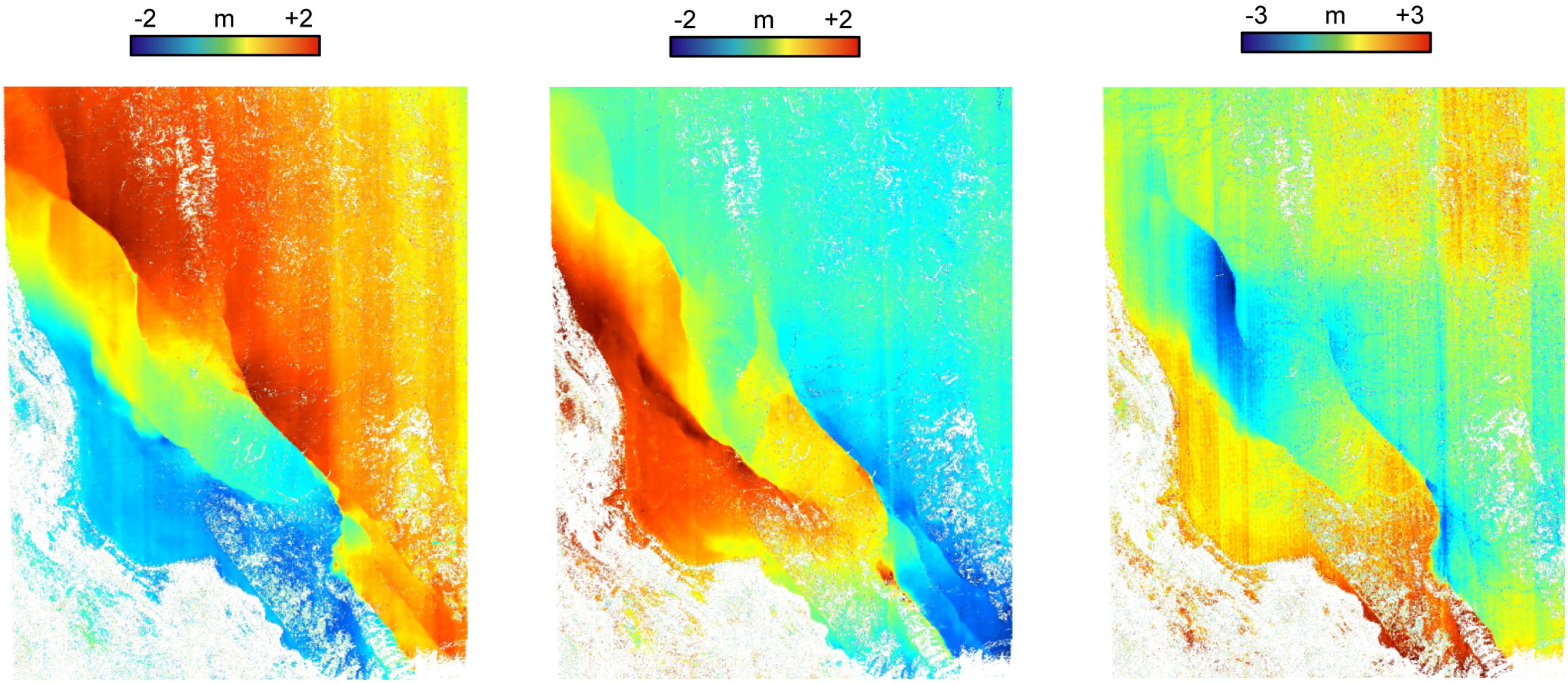






Measurement accuracy better than 10 cm

El-Mayor Cucapah EQ, 2010, 3D displacement field



Eastward ground motion

Northward ground motion

Vertical ground motion

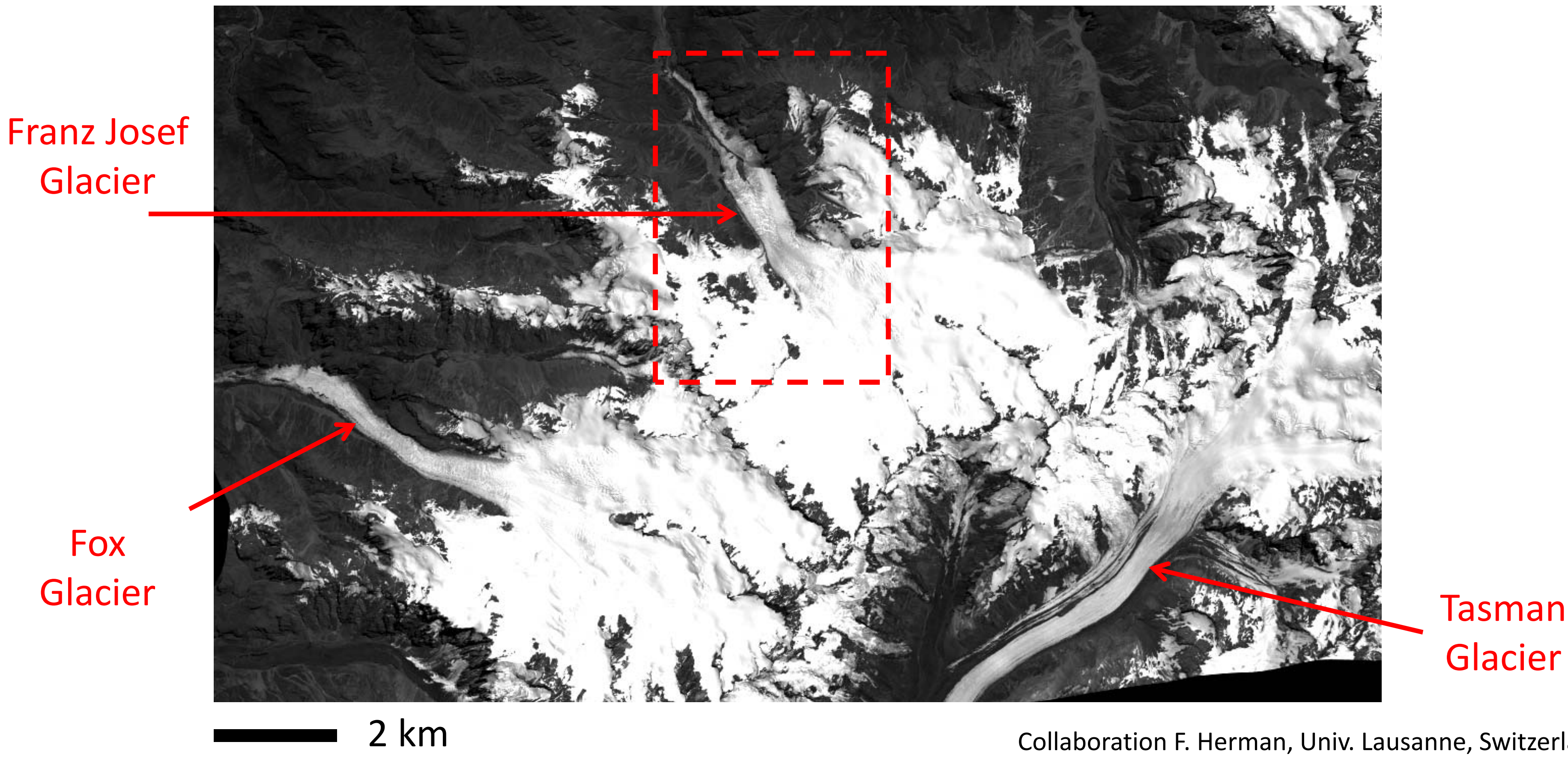
CCD and jitter artifacts largest source of bias

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)*

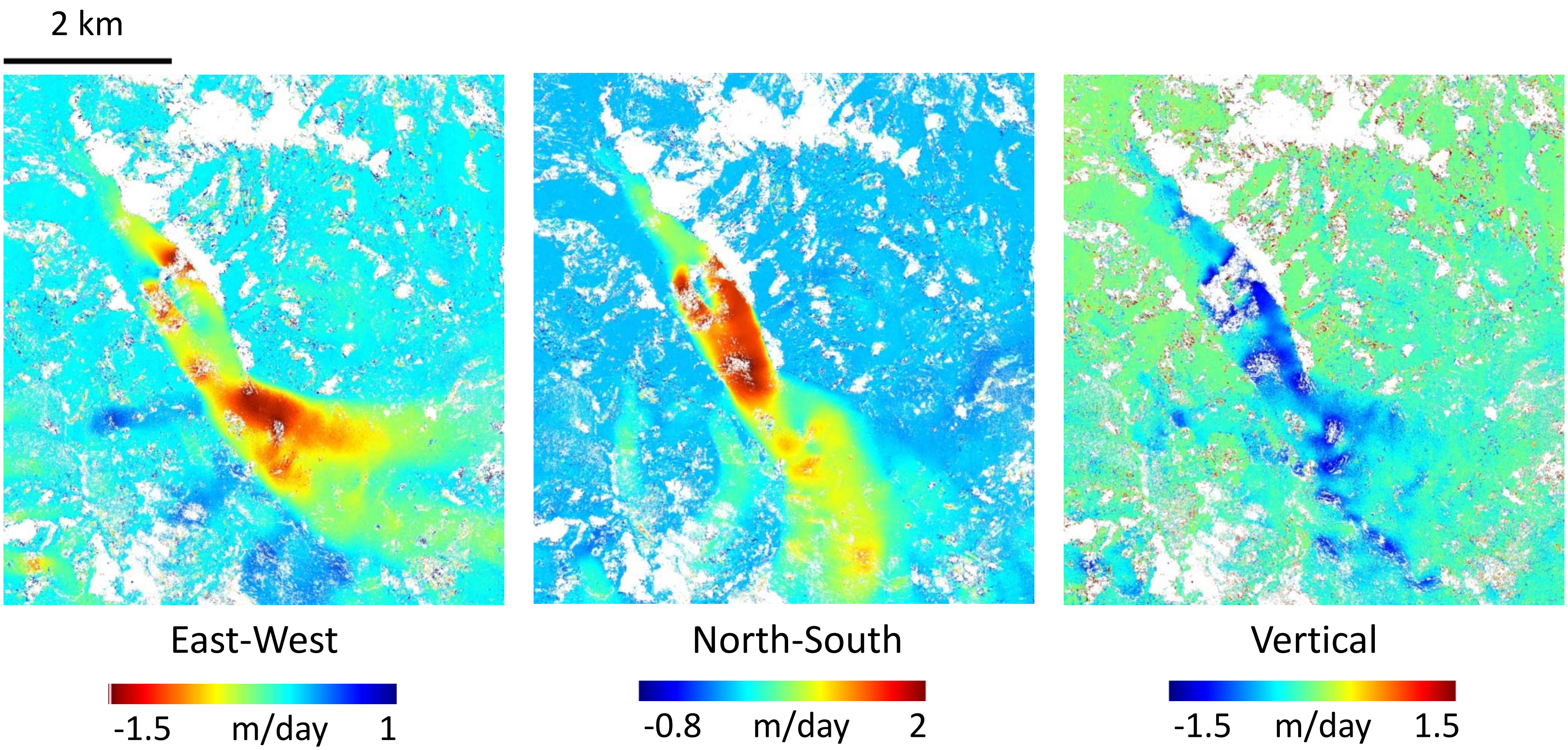
- Bundle adjustment between all images,
- Multi-scale image matching due to large disparities (up to 1000 pixels),
- Regularized matching because of occlusions



Collaboration F. Herman, Univ. Lausanne, Switzerland

Monitoring Glacier Flow in New Zealand

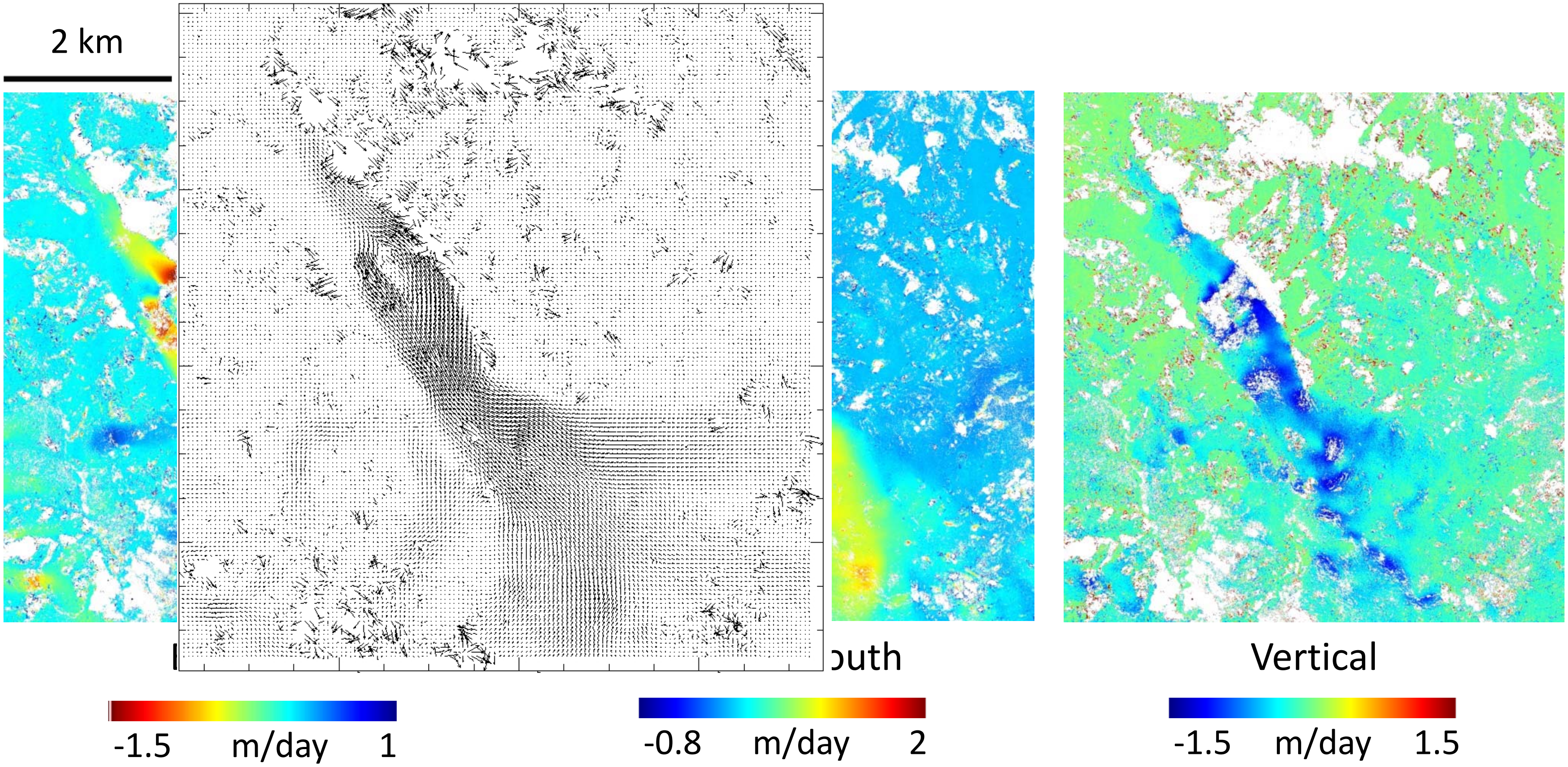
3D motion between January 30 and February 9, 2013



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

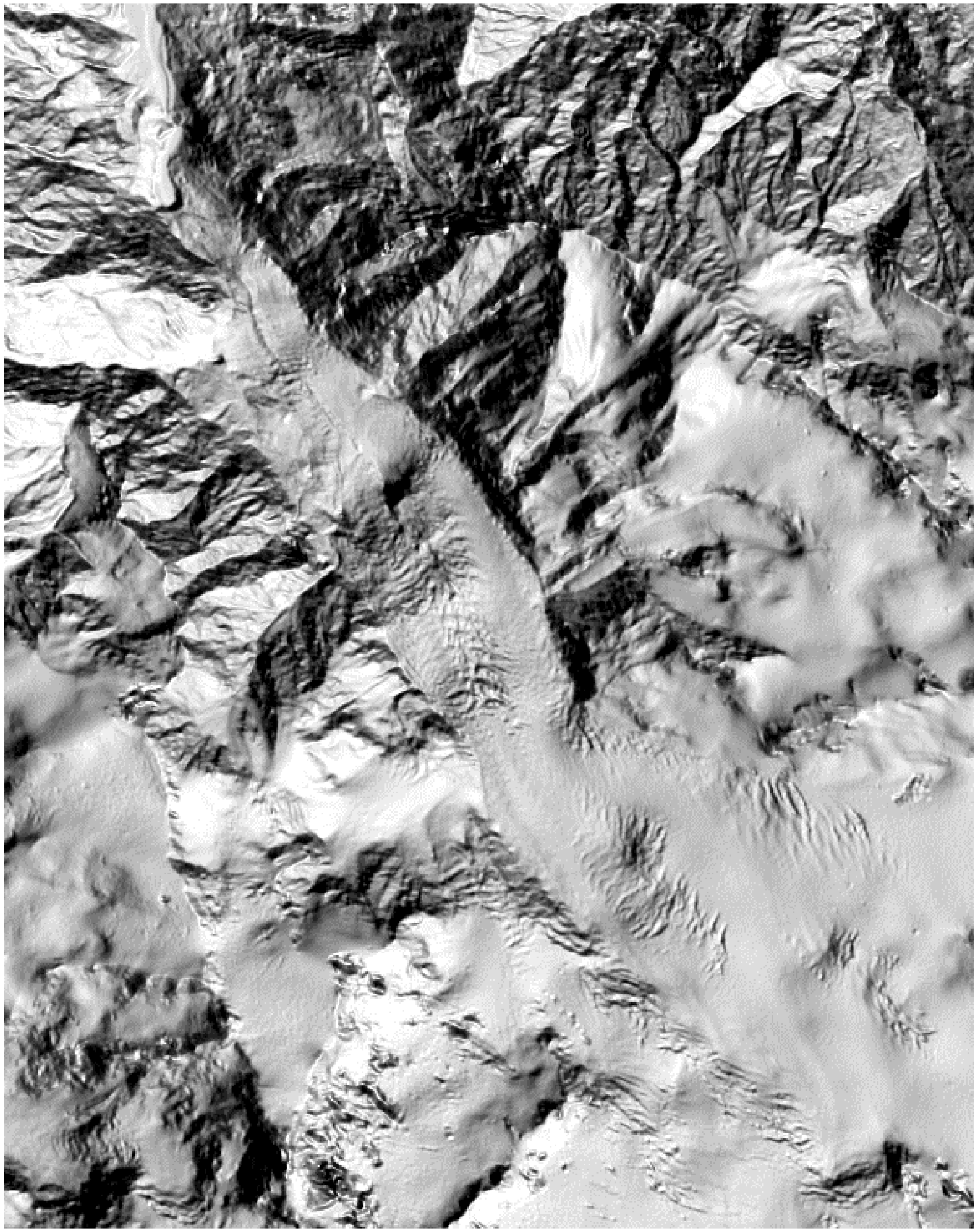
Monitoring Glacier Flow in New Zealand

3D motion between January 30 and February 9, 2013



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

Monitoring Glacier Flow in New Zealand

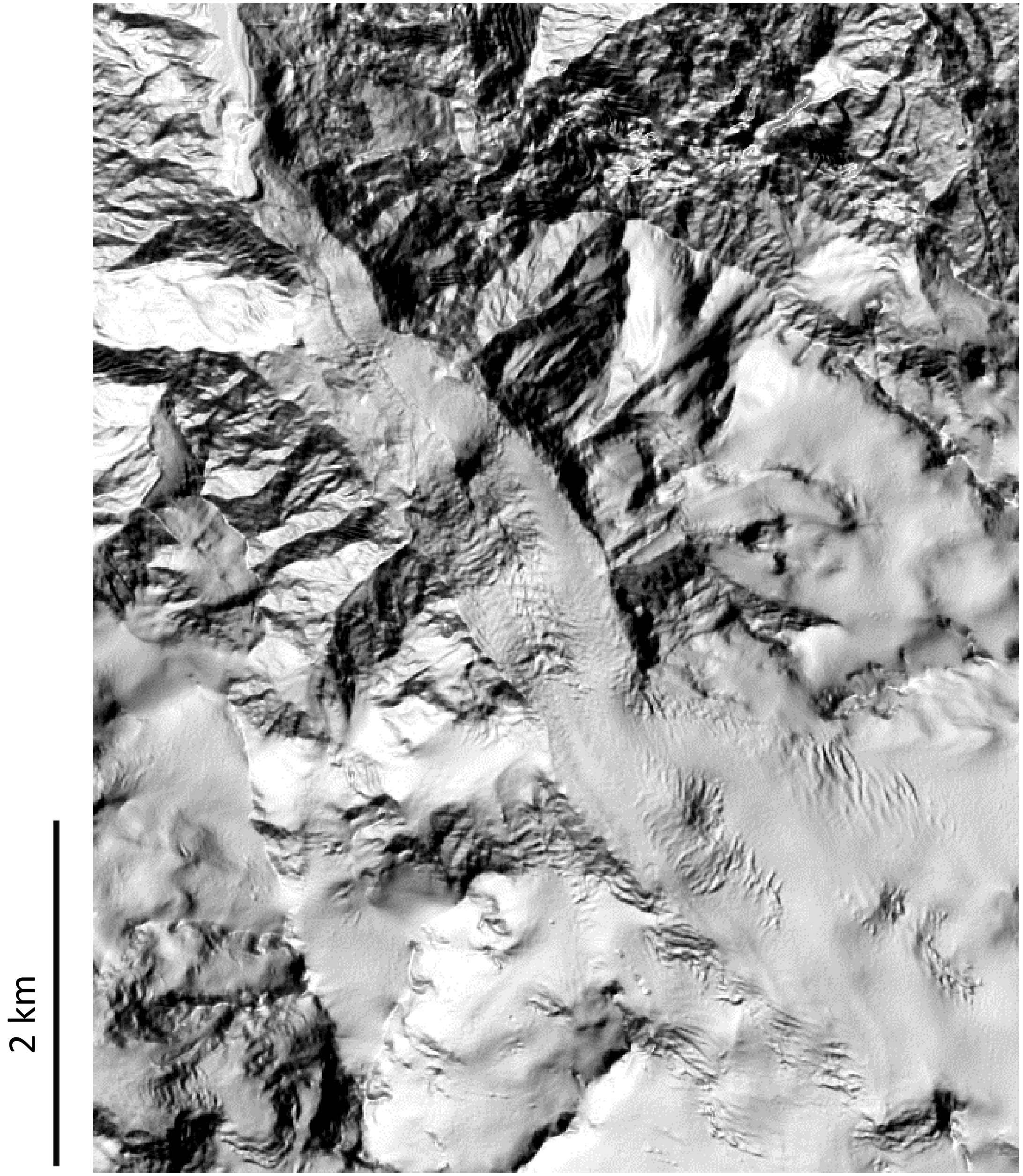


2 km

1m GSD Shaded Elevation Model generated from stereo pair:

January 30, 2013

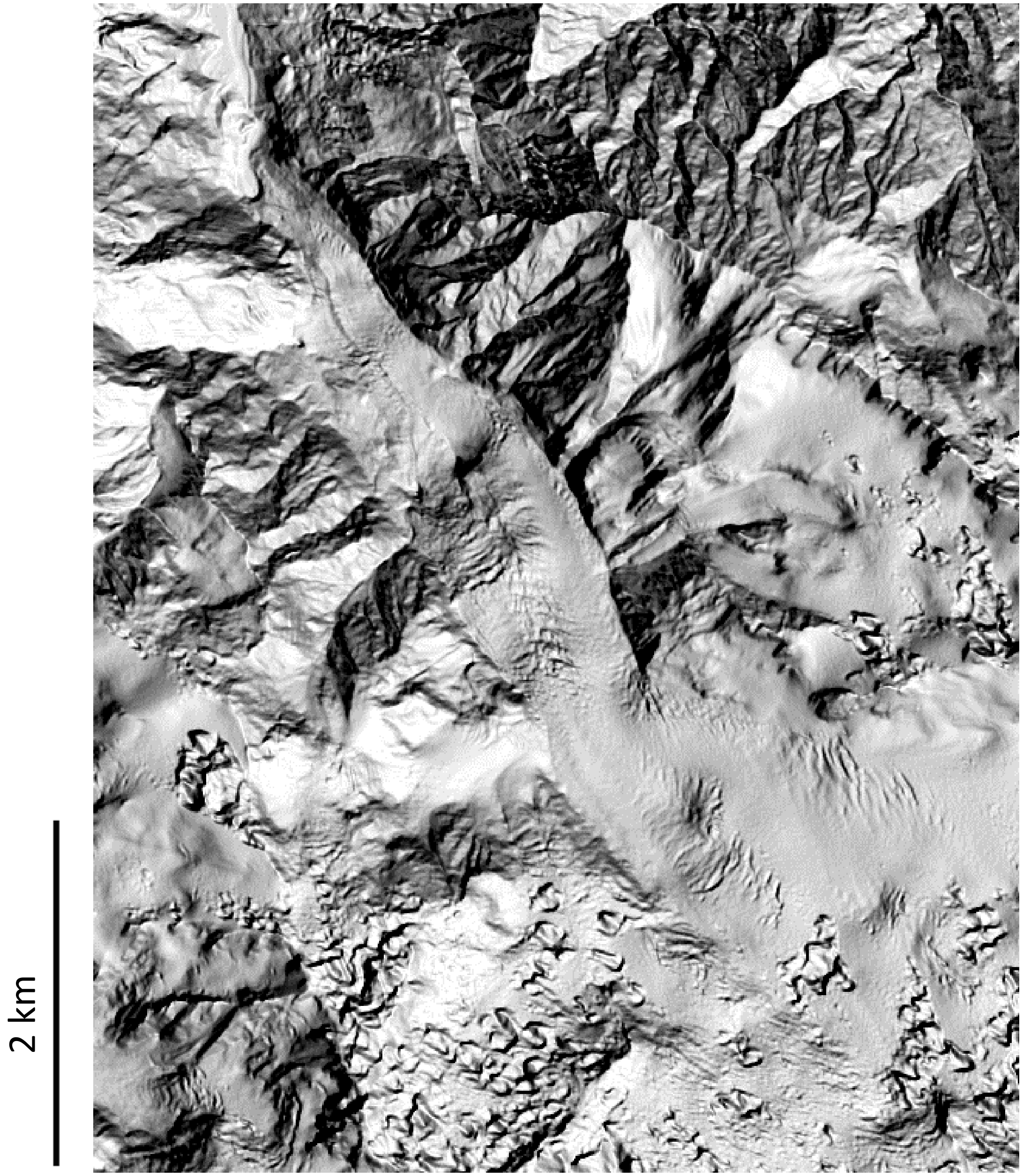
Monitoring Glacier Flow in New Zealand



1m GSD Shaded Elevation Model generated from stereo pair:

February 9, 2013

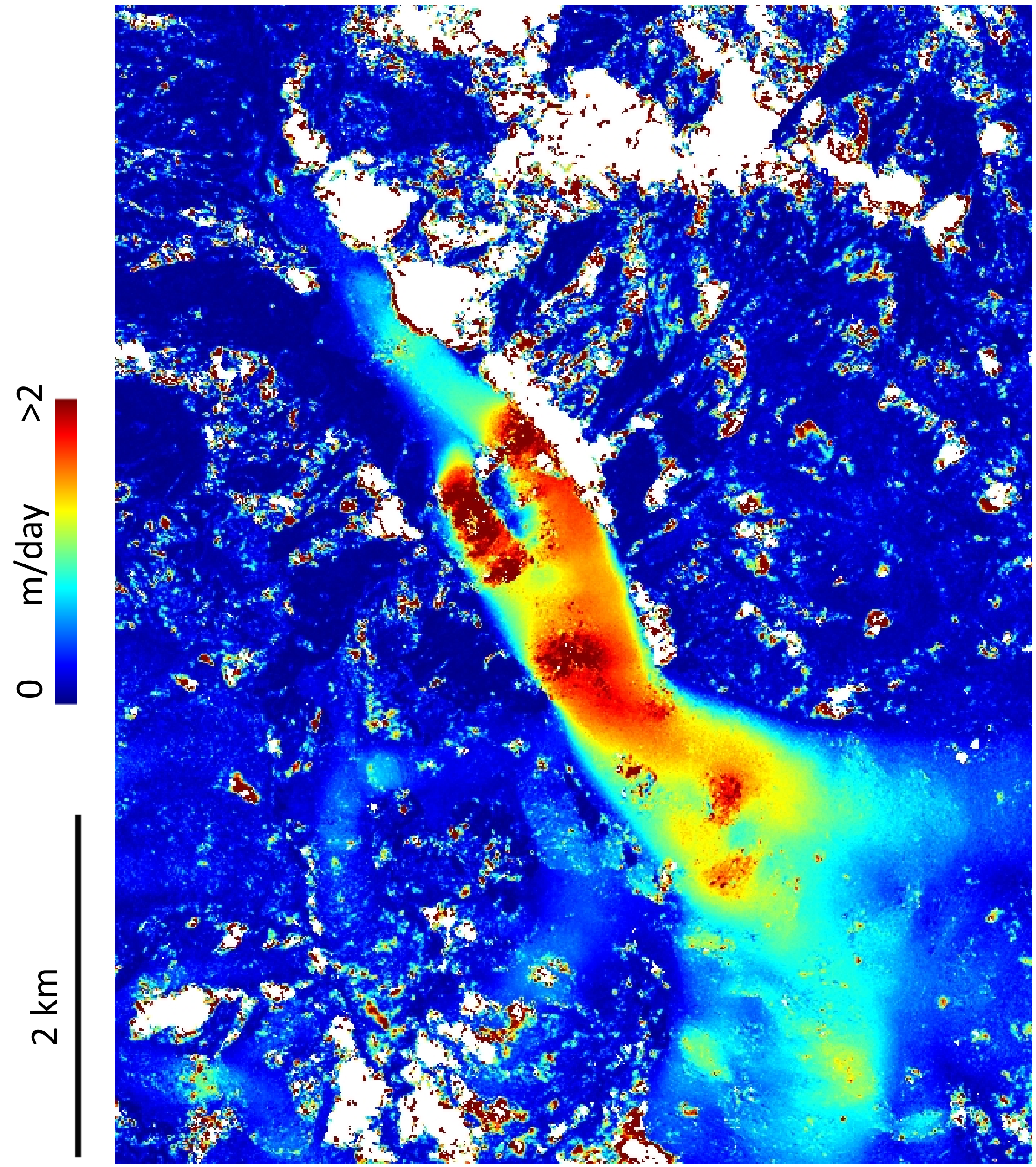
Monitoring Glacier Flow in New Zealand



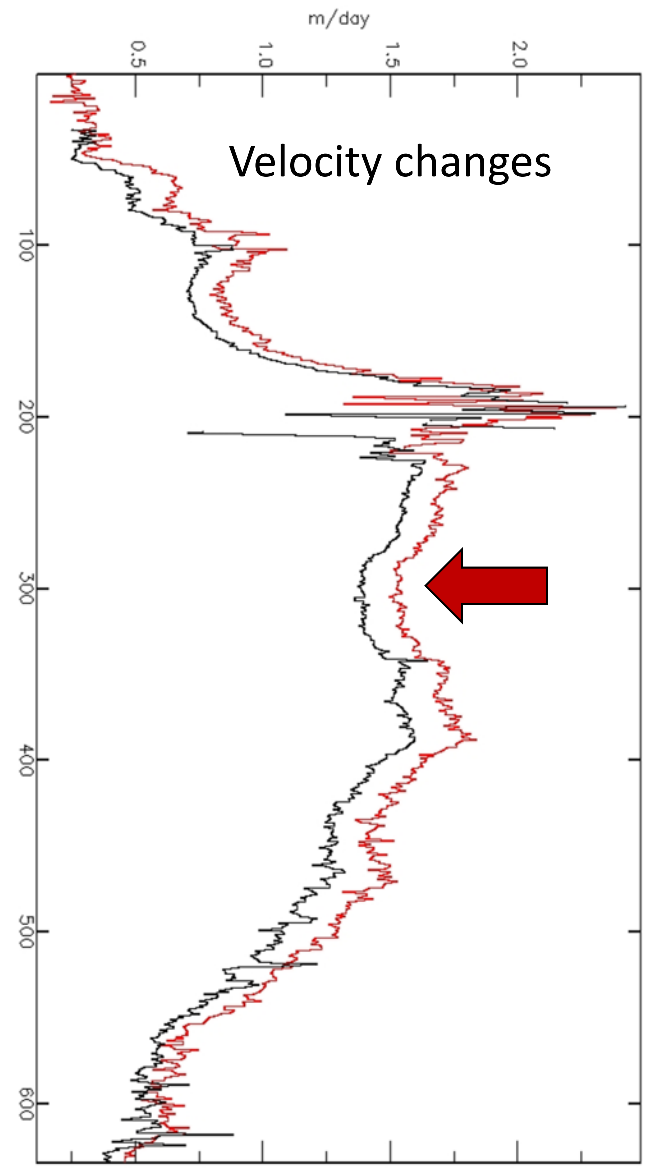
1m GSD Shaded Elevation Model generated from stereo pair:

February 28, 2013

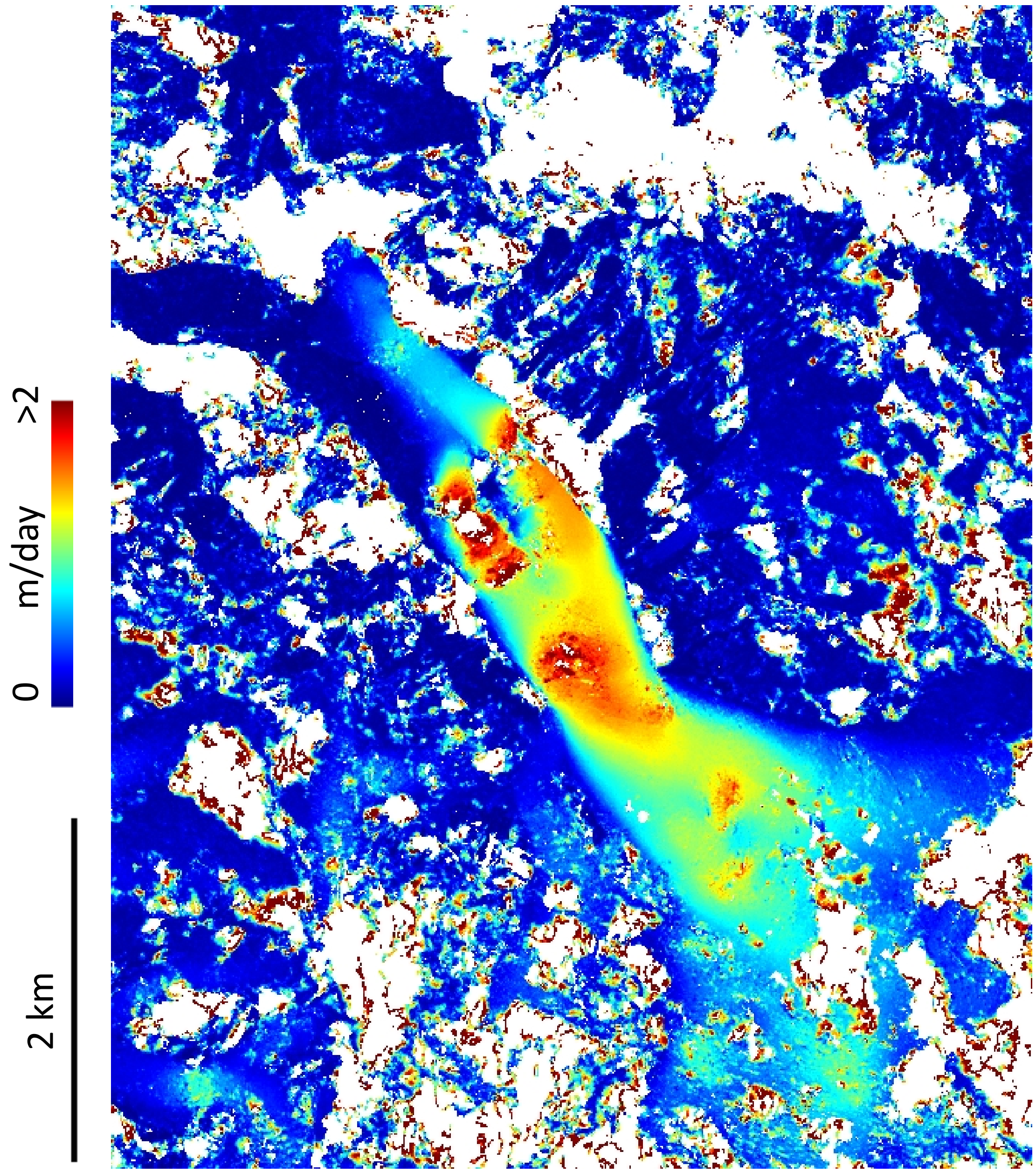
Monitoring Glacier Flow in New Zealand



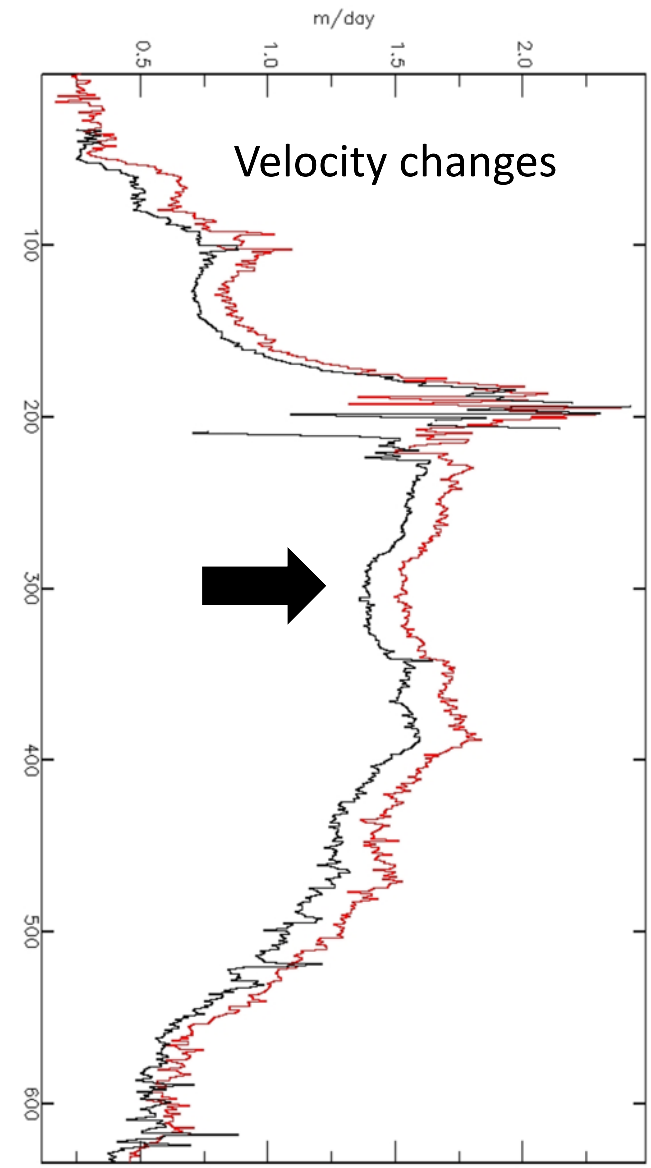
Jan 30 – Feb 9, 2013



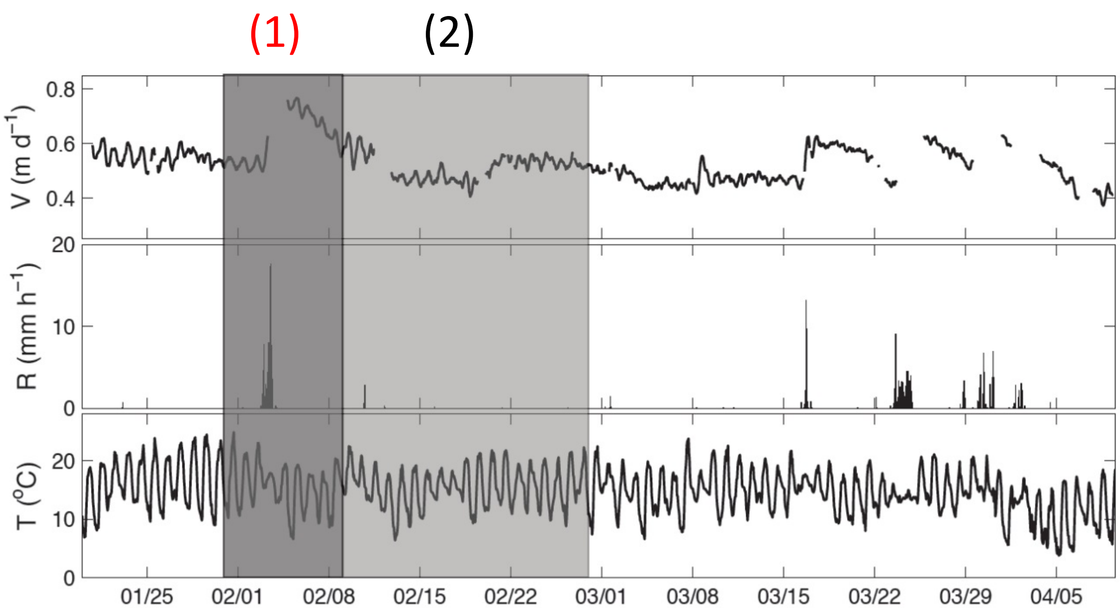
Monitoring Glacier Flow in New Zealand



Feb 9 – Feb 28, 2013

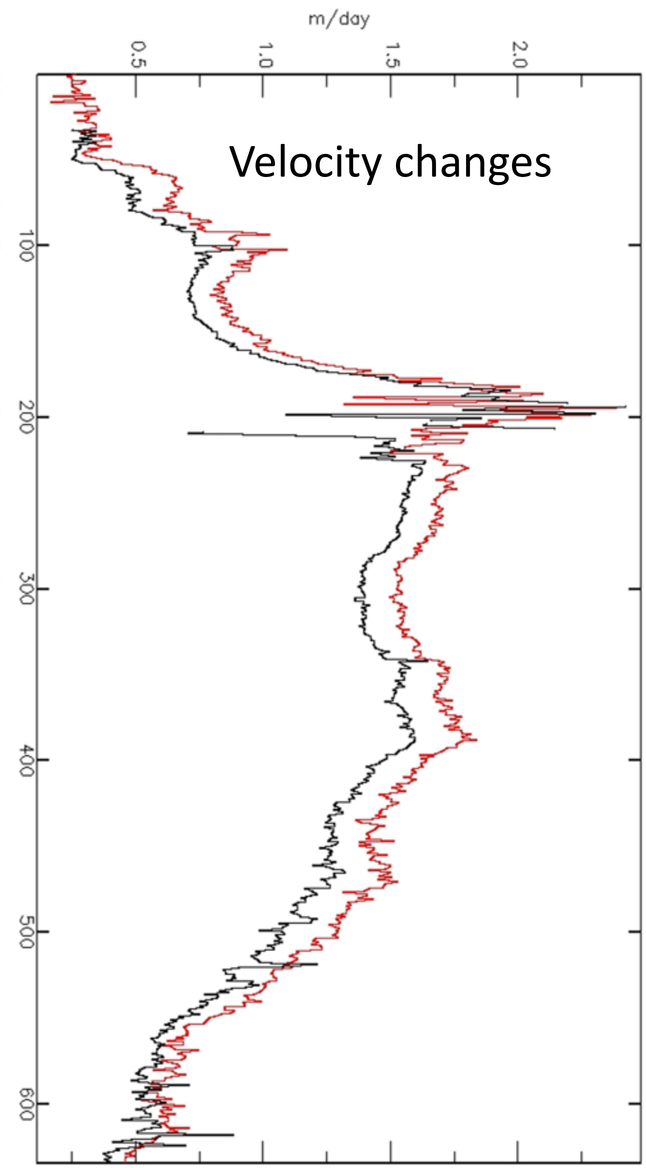


Monitoring Glacier Flow in New Zealand



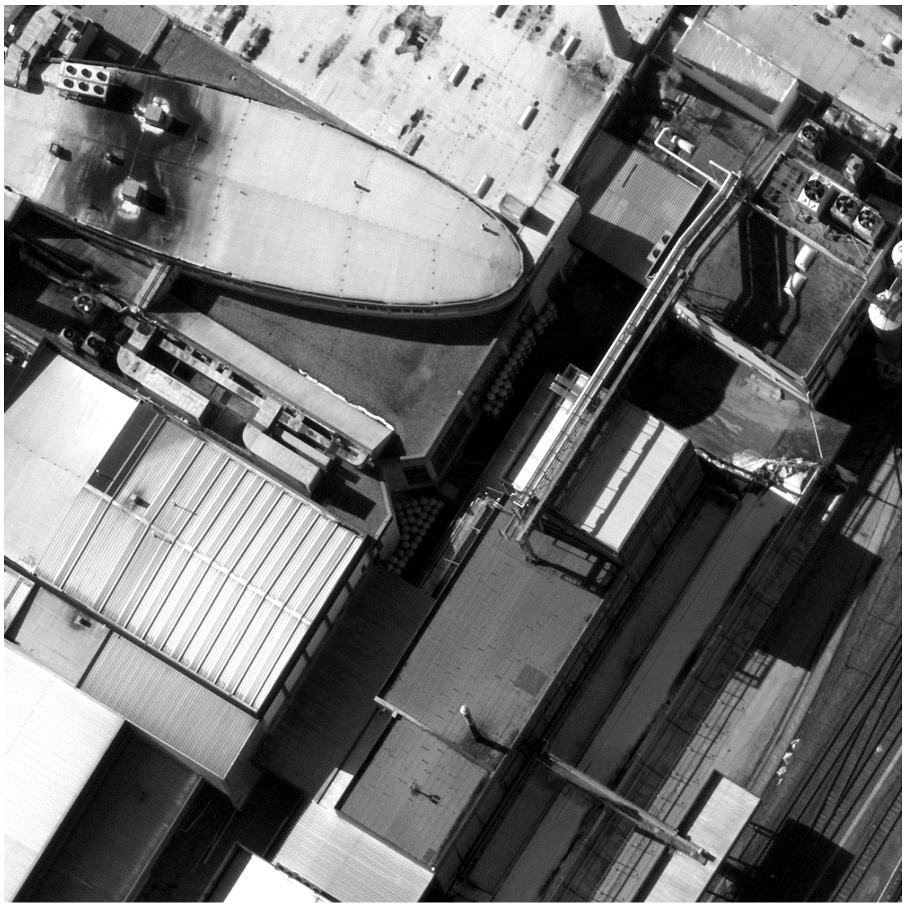
Velocity (GPS), Precipitations, Temperatures

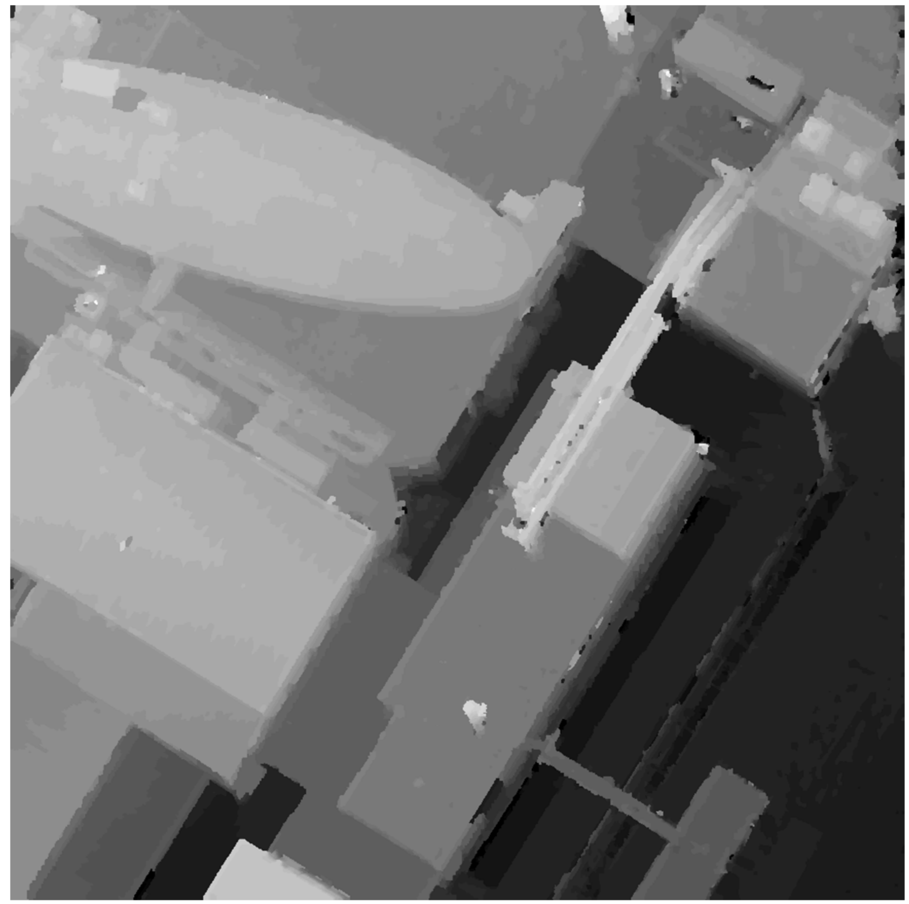
B. Anderson (pers. Com.)
Univ. Wellington, NZ



Glacial dynamics strongly affected by hydrology

Extracting Urban Topography

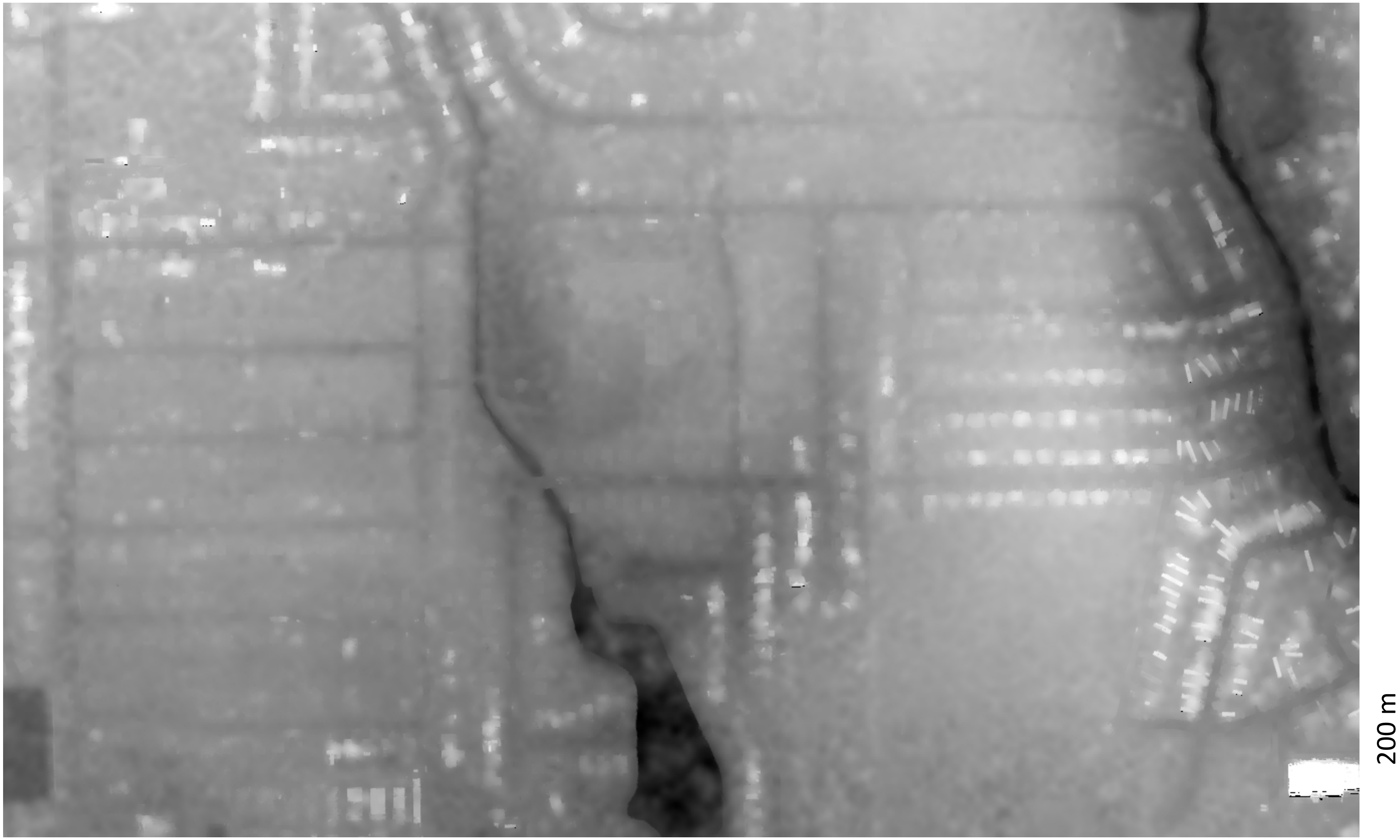




Automatic Mapping of Disasters with Stereo Imagery

City of Moore, Oklahoma, before tornado, 2012
City of Moore, Oklahoma, after tornado, 2013

Automatic Mapping of Disasters with Stereo Imagery

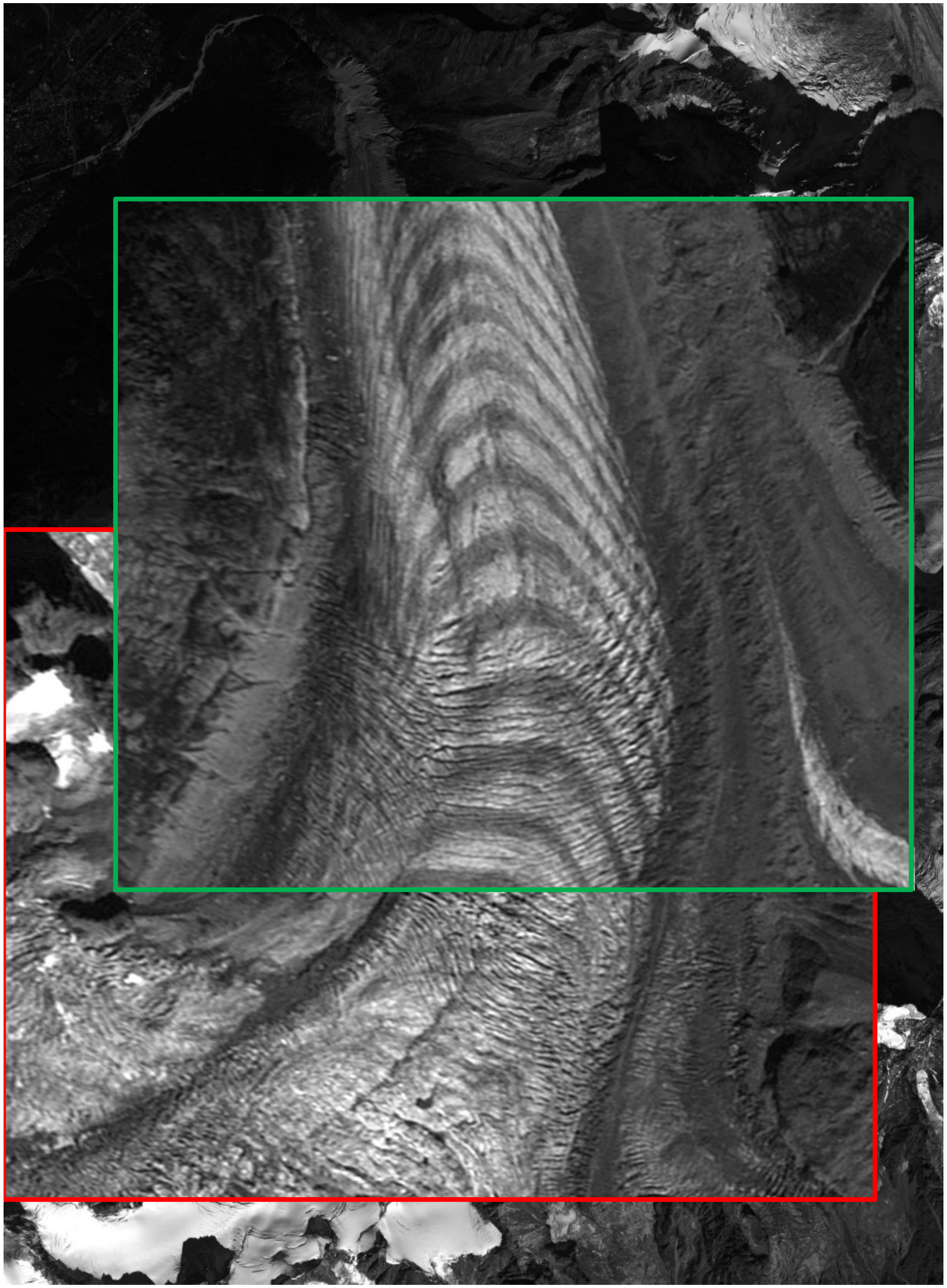


Digital Surface Model - City of Moore, Oklahoma, before tornado, 2012

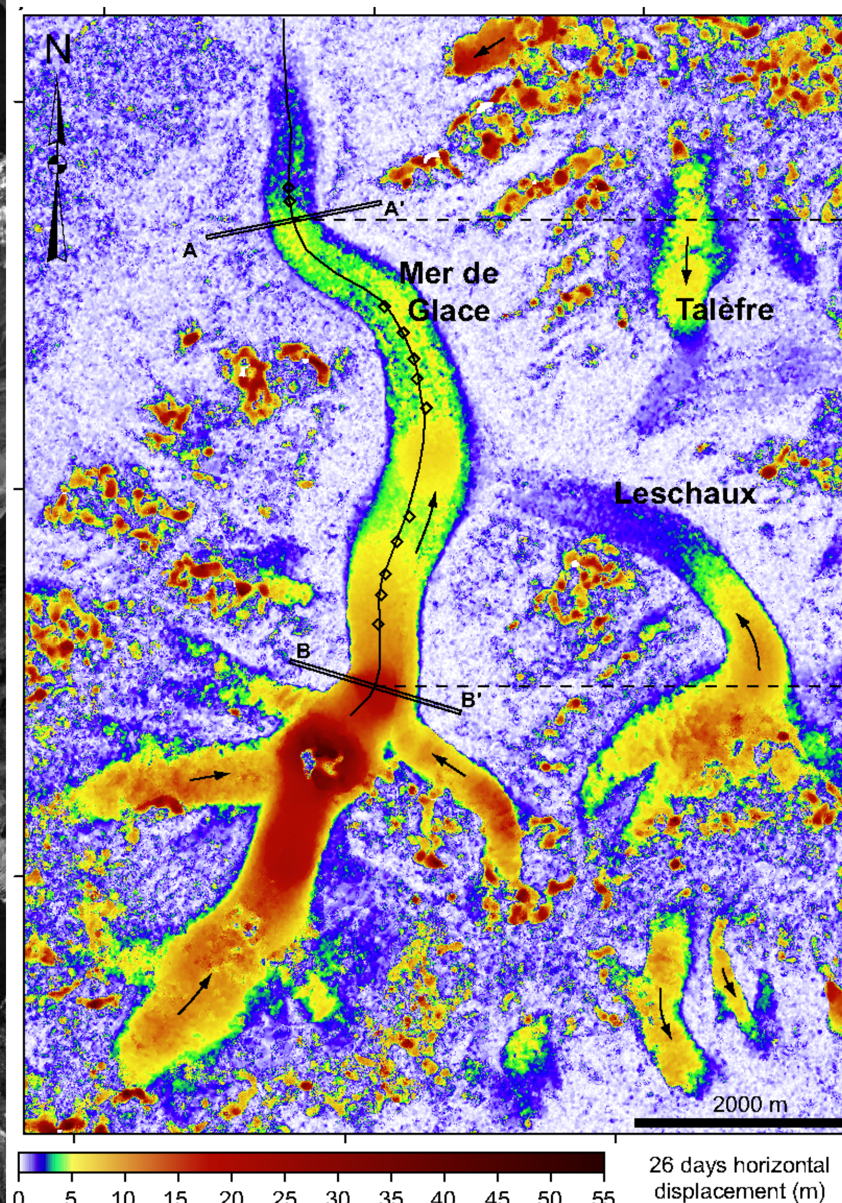
after tornado, 2013

Conclusions

- Rigorous methods to measure 3D ground deformation using remote sensing are becoming more popular,
- Generic methods to monitor a variety of surface processes (fault rupture, landslides, sand dune migration, glaciers, etc.),
- How can these new techniques help address the most pressing science questions?
- How should they be modified to best answer science questions? What are the main limitations?
- Would there be a need to develop new instruments?



Glacier flow: Mer de Glace



Leprince et al., EOS, 2008