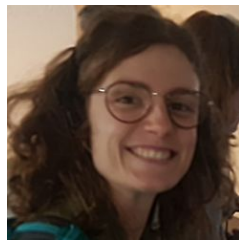


Estimating Ground Deformation in Seismic Events with Iterative Deep Learning and Total Variation Regularization

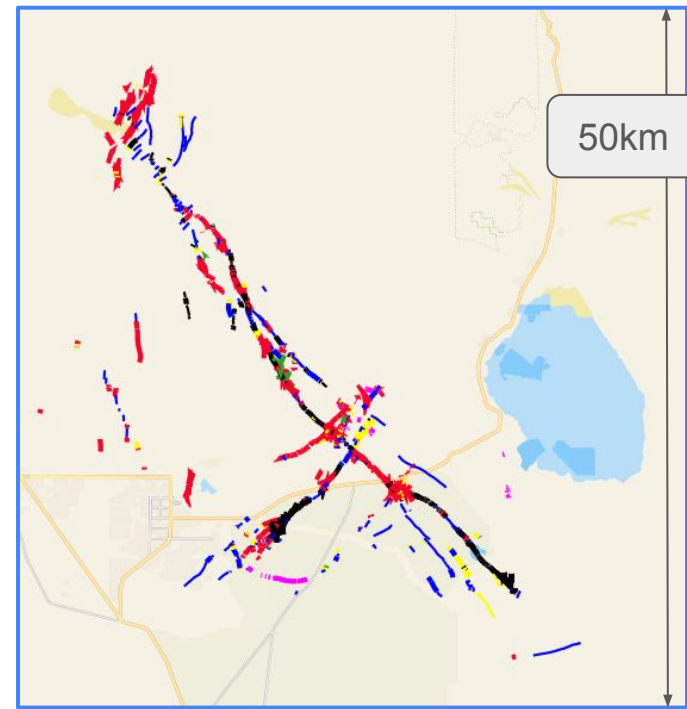
Juliette Bertrand, Sophie Giffard Roisin, James Hollingsworth, Julien Mairal



The San Andreas Fault



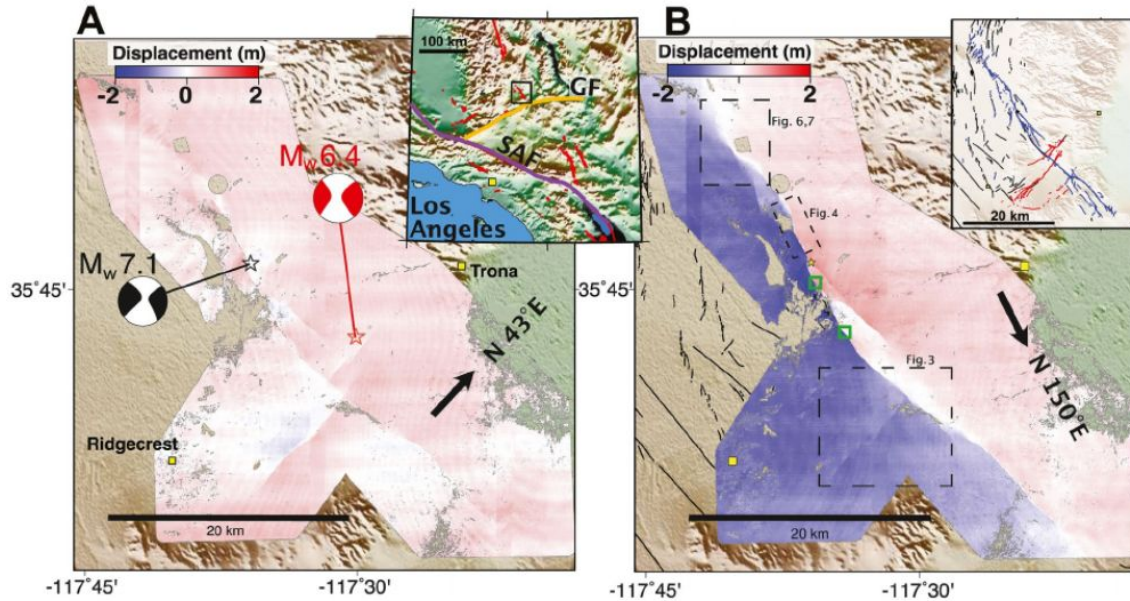
The San Andreas fault runs close to a number of major cities in California.
Image credit: Dimitrios Karamitros/Shutterstock.com



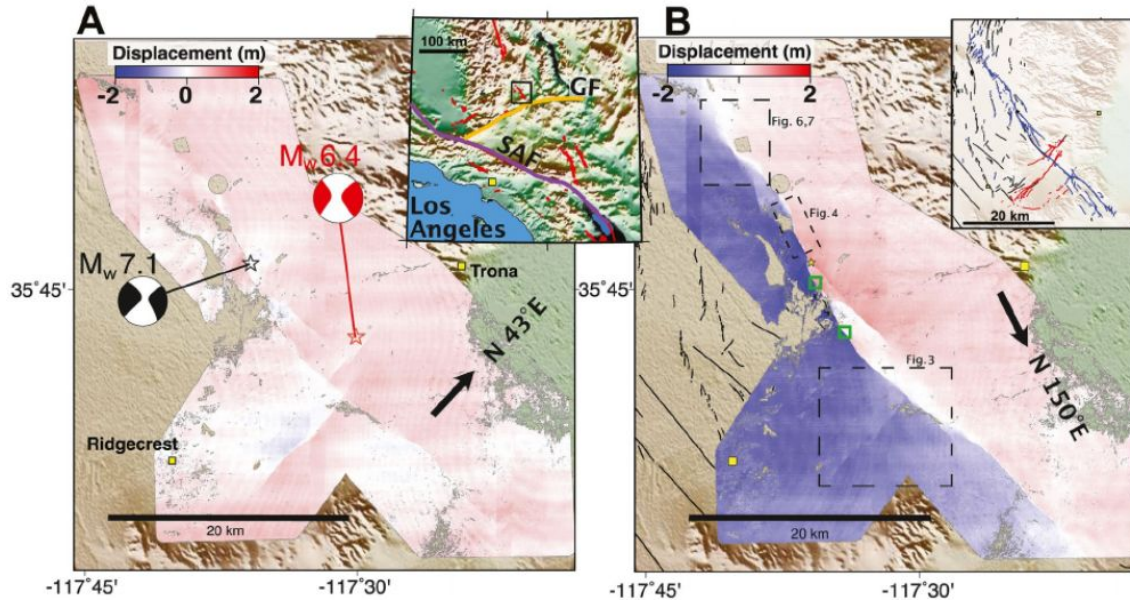
● 3 main shocks:

- 6.4
- 5.4
- 7.1

Need for Dense Ground Displacement Fields



Need for **Dense** Ground Displacement Fields



Direct field measurements:

- Only **sparse** annotations

Optical Geodesy

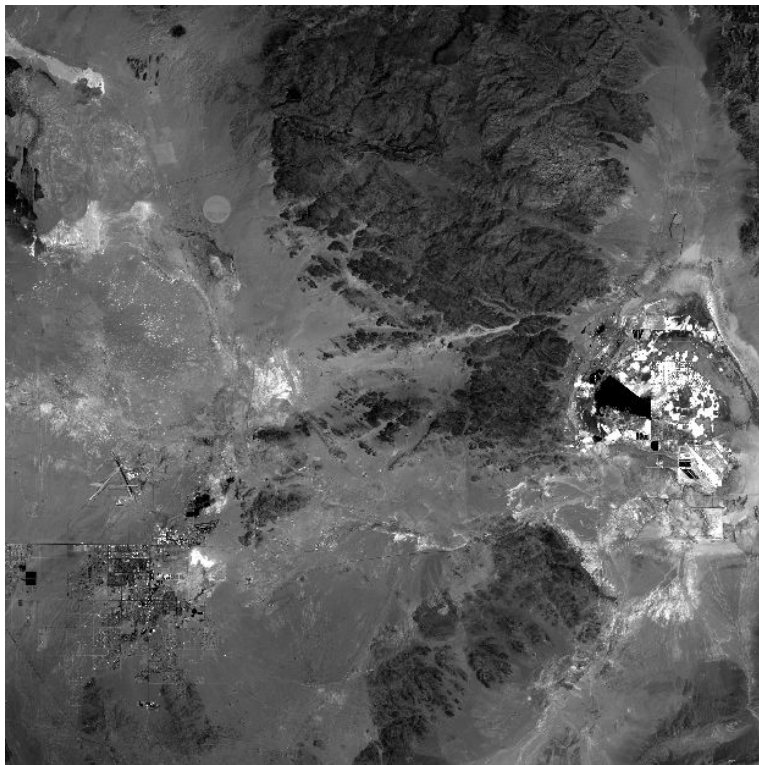
Pre-seismic image



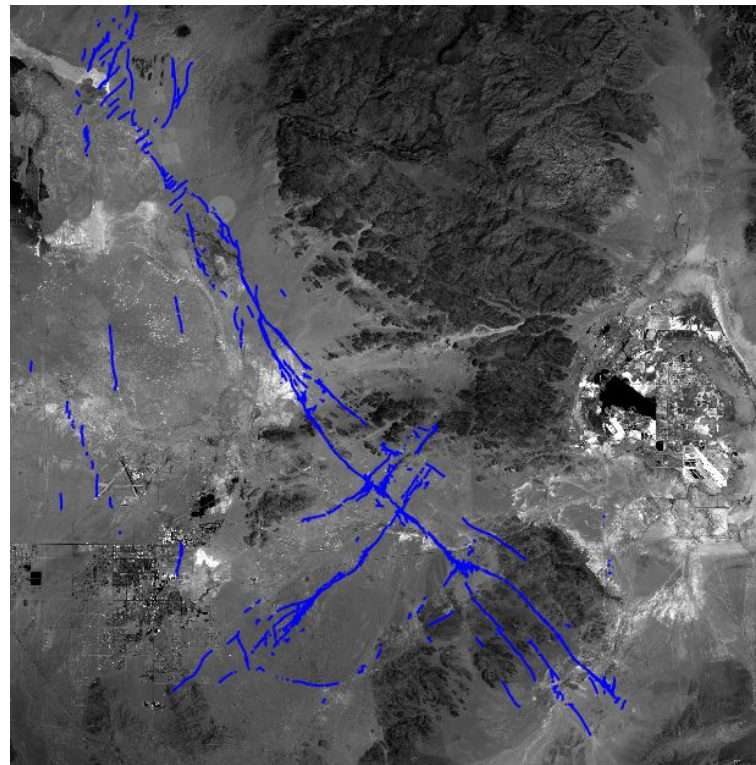
High spatial resolution: 1m/pxl

The California RidgeCrest - 2019

Pre-Seismic Image



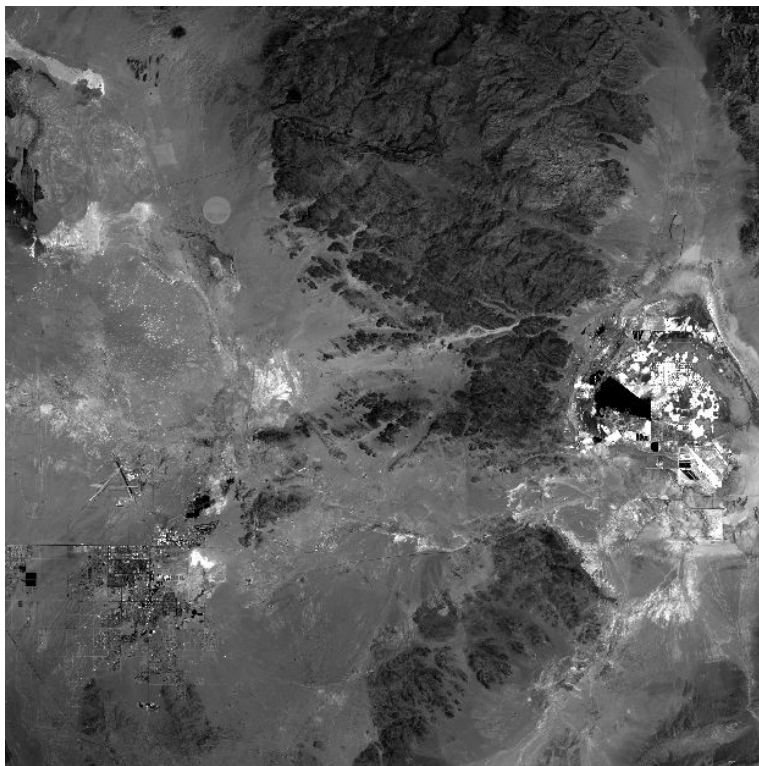
Post-Seismic Image with fault segmentation in blue



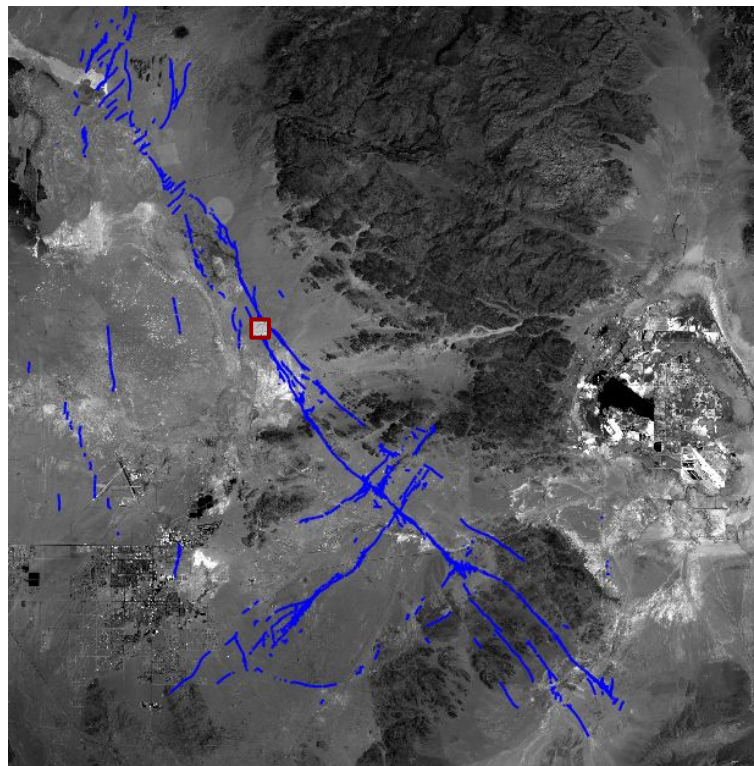
Medium spatial resolution: 15m/pxl
High spatial resolution: 1m/pxl

The California RidgeCrest - 2019

Pre-Seismic Image



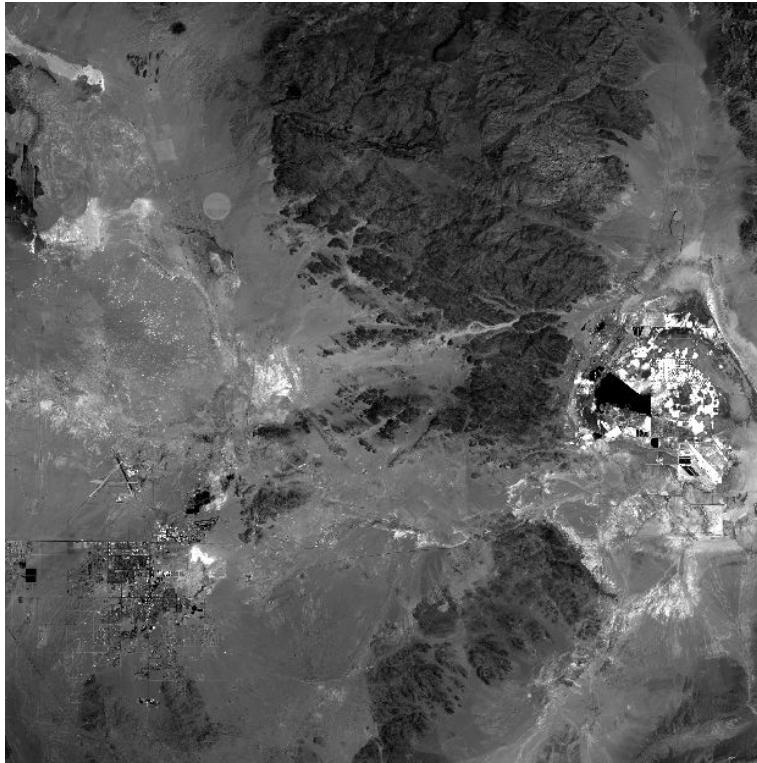
Post-Seismic Image



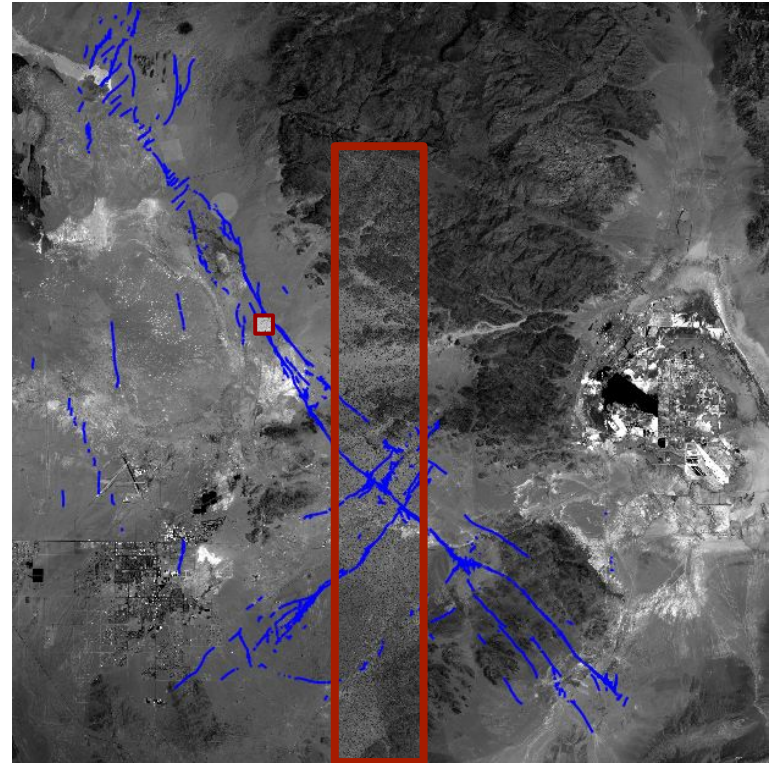
The California RidgeCrest - 2019

Medium spatial resolution: 15m/pxl
High spatial resolution: 1m/pxl
Very high spatial resolution: 50 cm/pxl

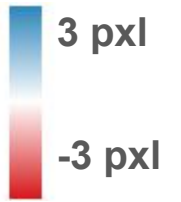
Pre-Seismic Image



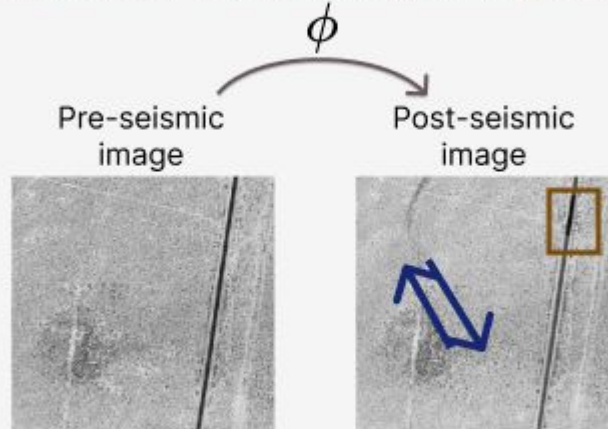
Post-Seismic Image



Estimating Ground Displacement Fields



Input: Pre-Post Seismic Image Pair



Seismic ground deformation
+
Week to year temporal gap

Output: Inverse Flow Field

$$\mathbf{d} = \phi^{-1}$$

u : EW ground displacement



v : NS ground displacement

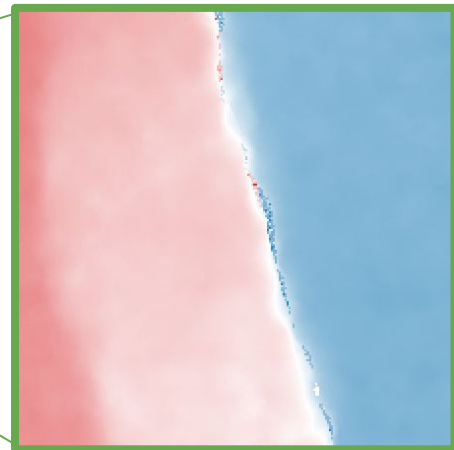
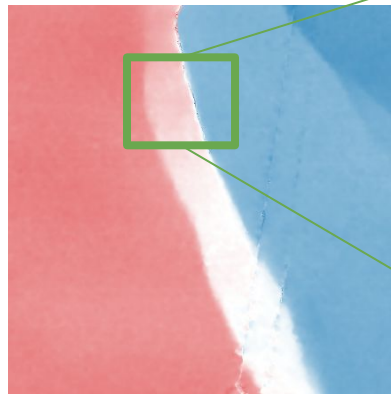
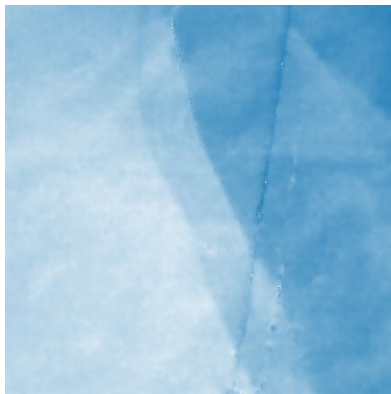


Subpixel accuracy
Sharp fault lines
Smooth deformation away from the fault

COSI-Corr: a very competitive baseline, achieving subpixel accuracy

- COSI-Corr:
 - Performs correlation and co-registration
 - Correlation is computed in the frequency domain
 - Achieves subpixel accuracy
 - Highly sensitive to temporal perturbations

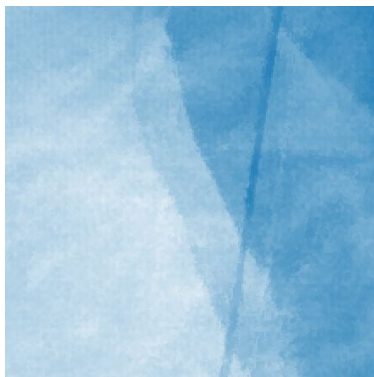
COSI-Corr estimate in the EW direction **COSI-Corr estimate in the NS direction**



MicMac: a spatial domain correlator with regularization

- Micmac:
 - Performs correlation
 - Correlation is computed in the spatial domain
 - Achieves subpixel accuracy, specifically robust to small window size (achieve higher accuracy for high resolution images)
 - Incorporate a regularization to reduce noise

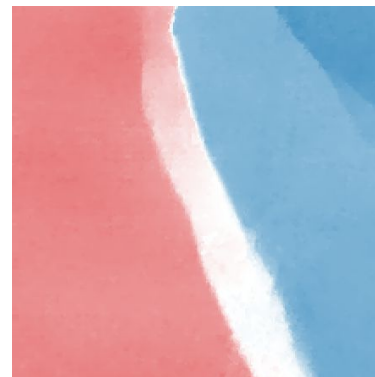
MicMac estimate in the EW direction (no regularization)



MicMac estimate in the EW direction (with regularization)



MicMac estimate in the NS direction (with regularization)



Is Deep Learning a possible solution?

- The challenges:
 - No ground-truth data
 - Sub-pixel accuracy
 - Temporal perturbations create noise in the estimates
 - Robustness to different satellite imagery going from very high resolution (50cm) to medium resolution (15m)

- A first baseline: GeoFlowNet

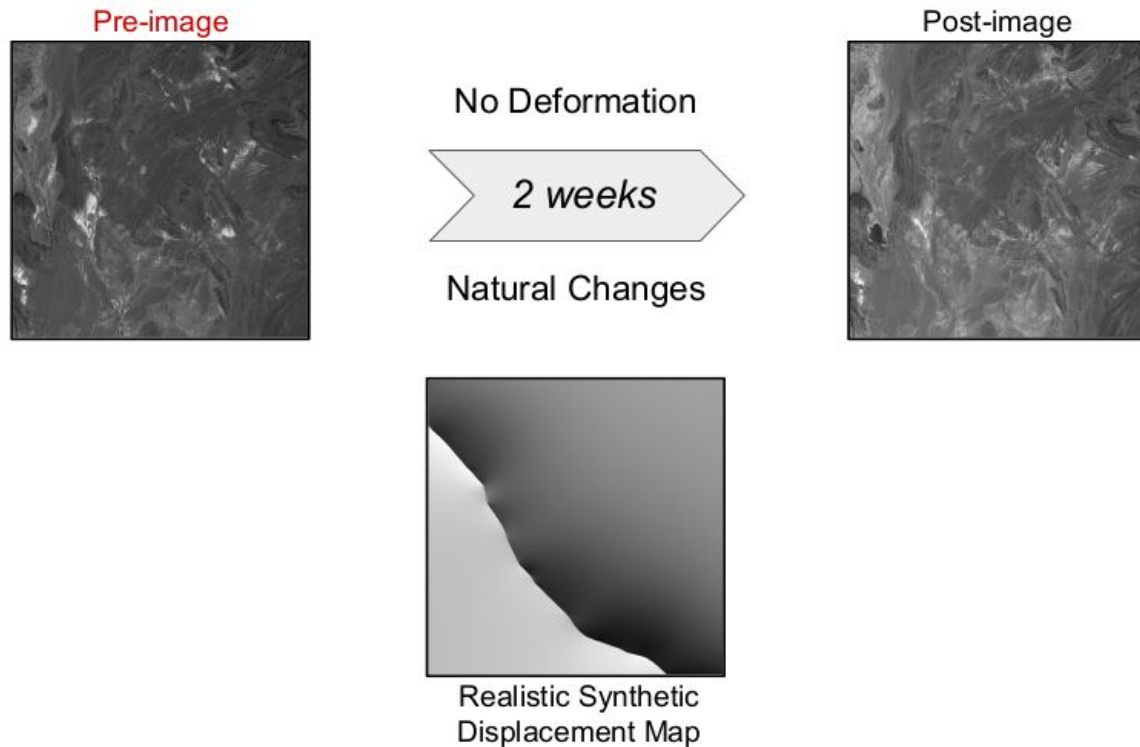
- Our key ingredients:
 - Iterative Deep Learning
 - Total Variation Regularization

No Ground truth data

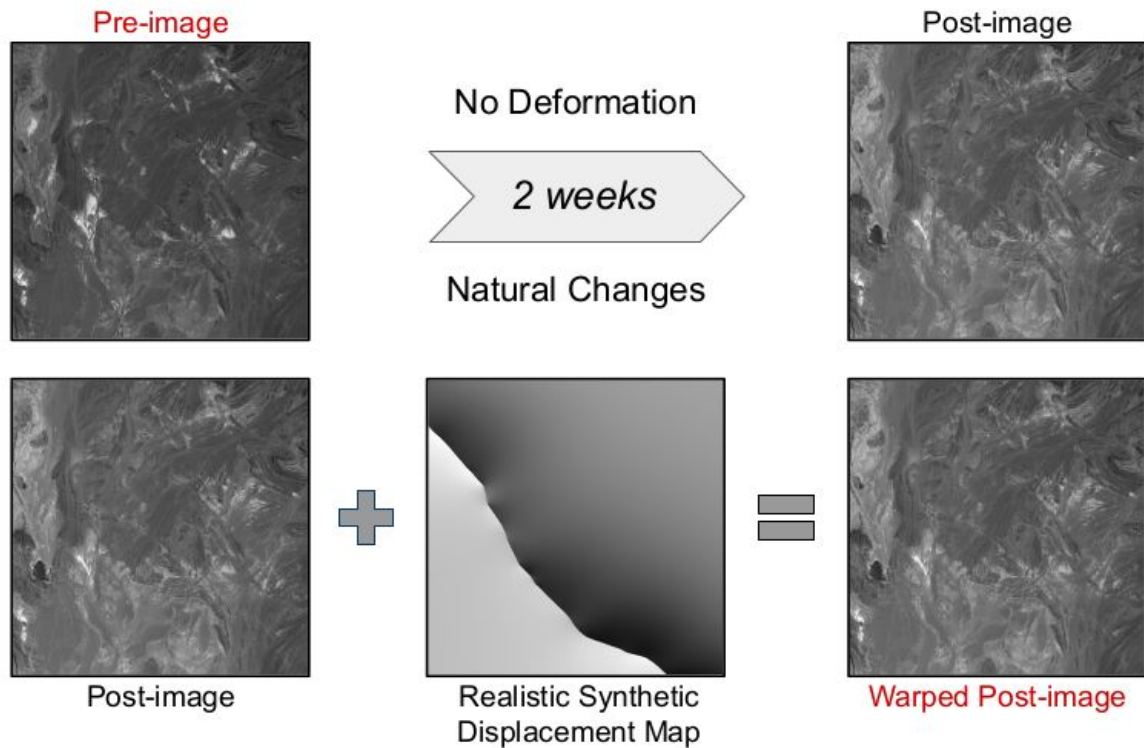
No Ground-Truth Data: a Need for a Synthetic Simulator



No Ground-Truth Data: a Need for a Synthetic Simulator

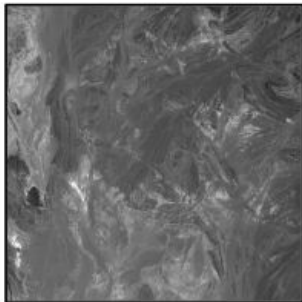
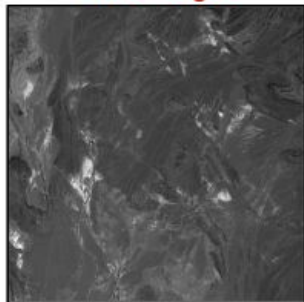


No Ground-Truth Data: a Need for a Synthetic Simulator

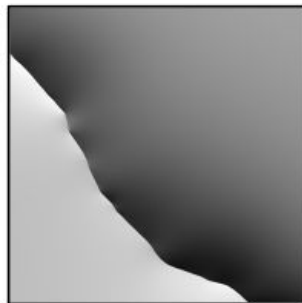


No Ground-Truth Data: a Need for a Synthetic Simulator

Pre-image



Warped Post-image



Realistic Synthetic
Displacement Map

No ground truth data: A pseudo ground truth evaluation benchmark

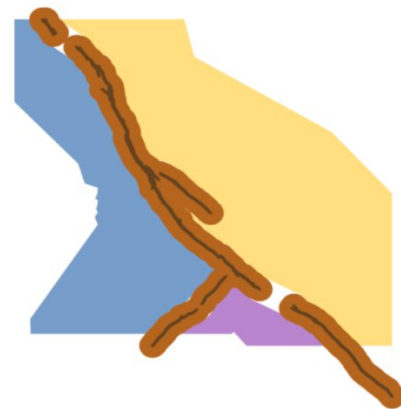
COSI-Corr Estimates after smoothing
SPOT-6 (2m/pxl)



Automatic fault detection



Region and fault segmentation



A need for subpixel accuracy

A Need for Sub-Pixel Accuracy

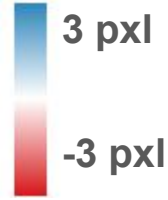
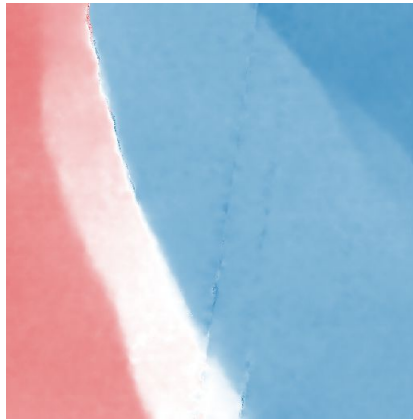
**Pre-seismic
image**



**Post-seismic
image**



**COSI-Corr estimate in
the NS direction**



A Need for Sub-Pixel Accuracy

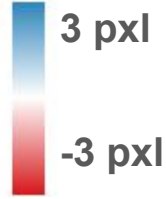
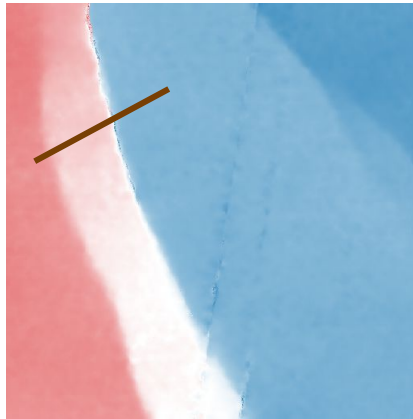
**Pre-seismic
image**



**Post-seismic
image**



**COSI-Corr estimate in
the NS direction**



A Need for Sub-Pixel Accuracy

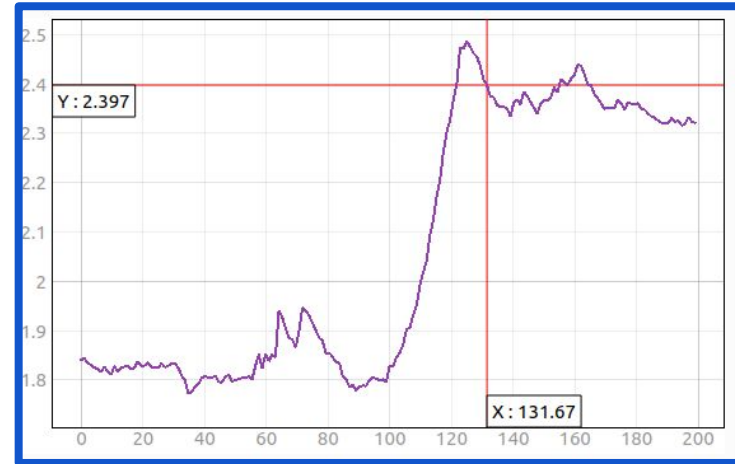
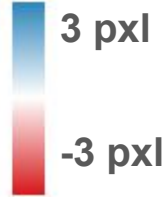
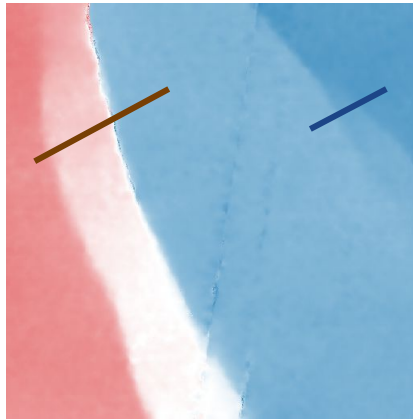
Pre-seismic image



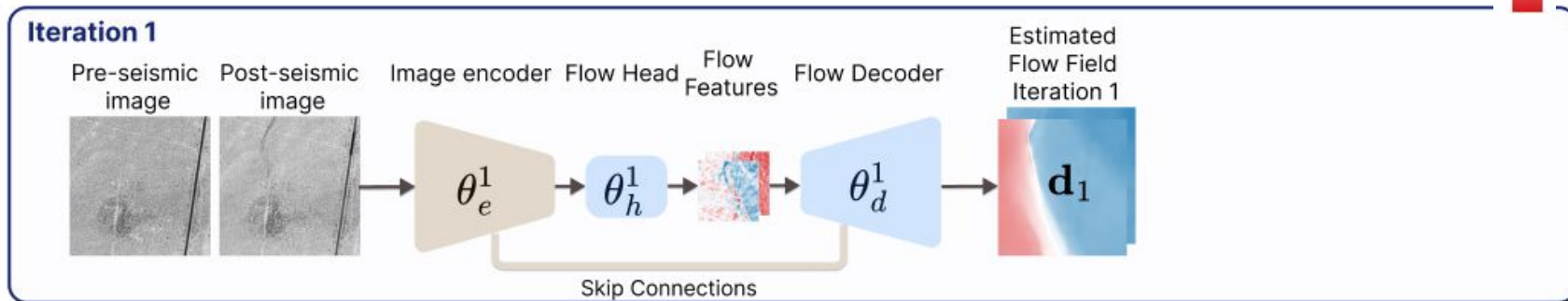
Post-seismic image



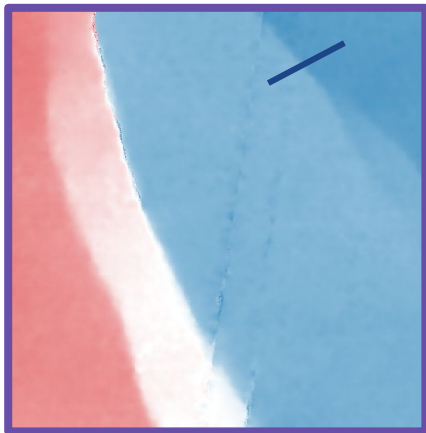
COSI-Corr estimate in the NS direction



GeoFlowNet - 1 iteration of encoder-decoder network



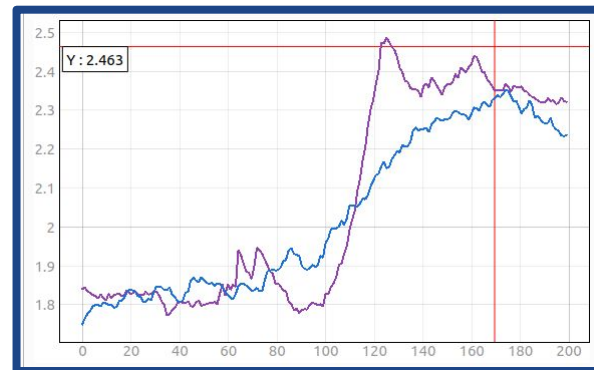
COSI-Corr



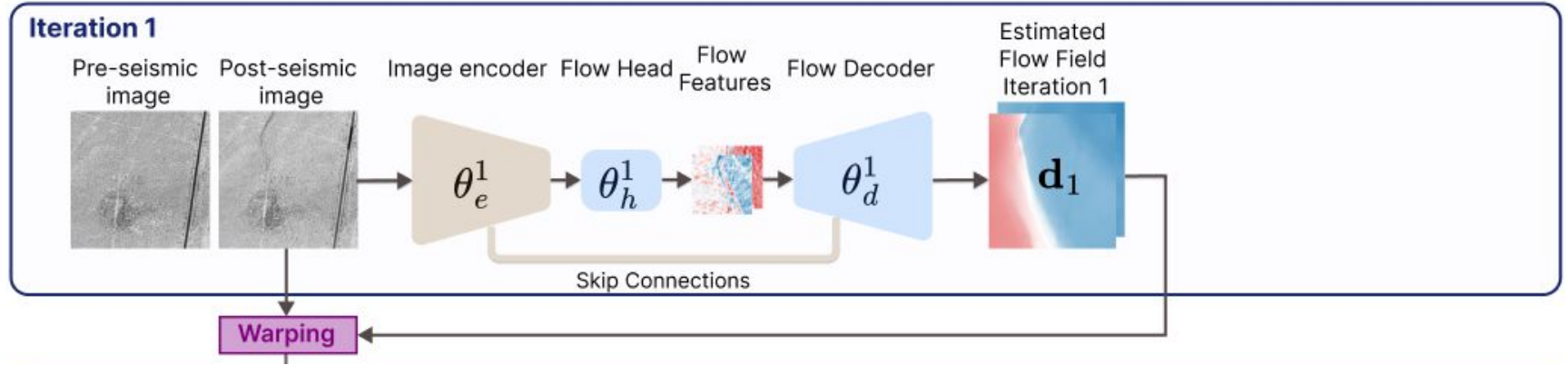
GeoFlowNet



— COSI-Corr
— GeoFlowNet

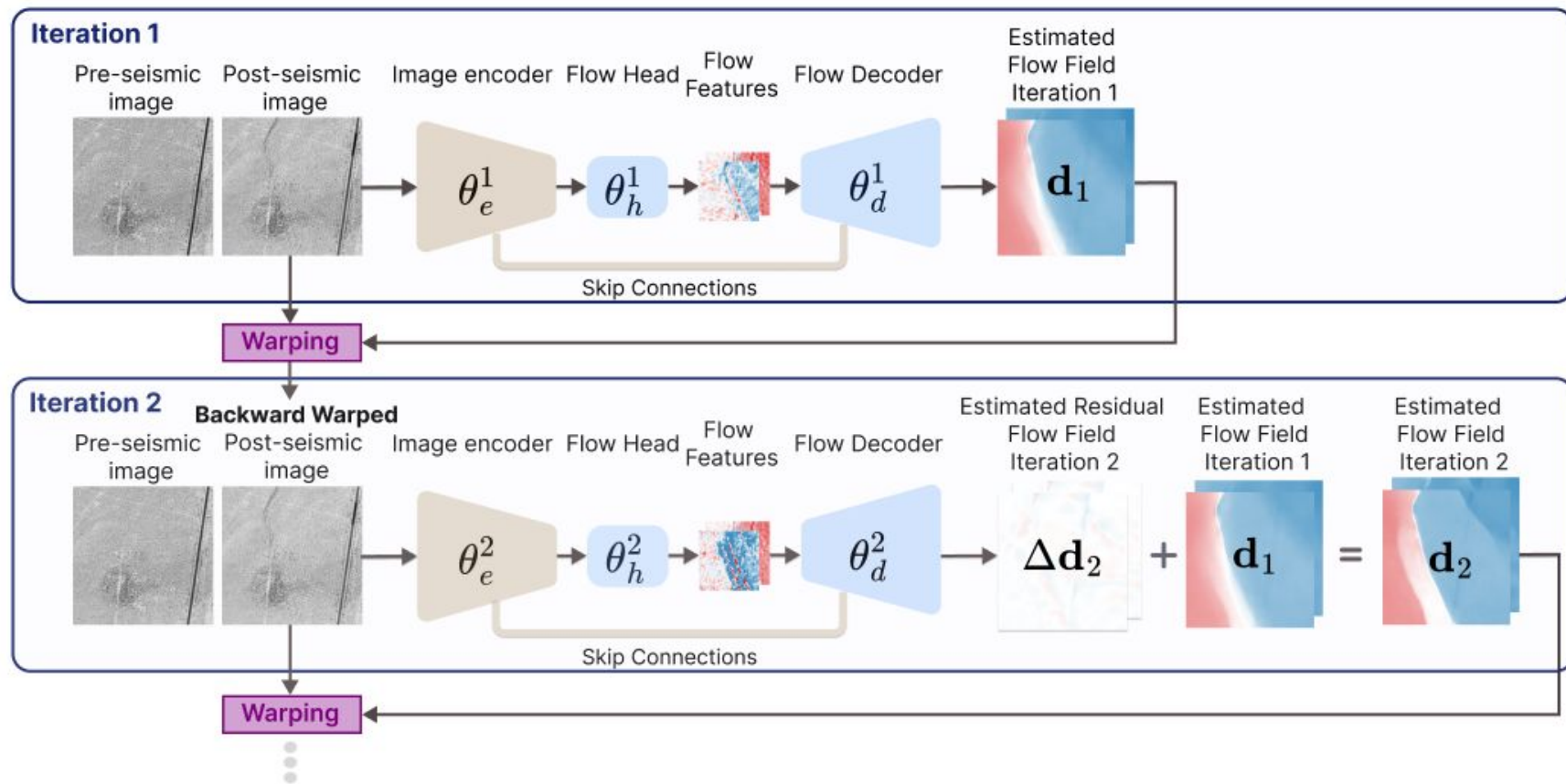


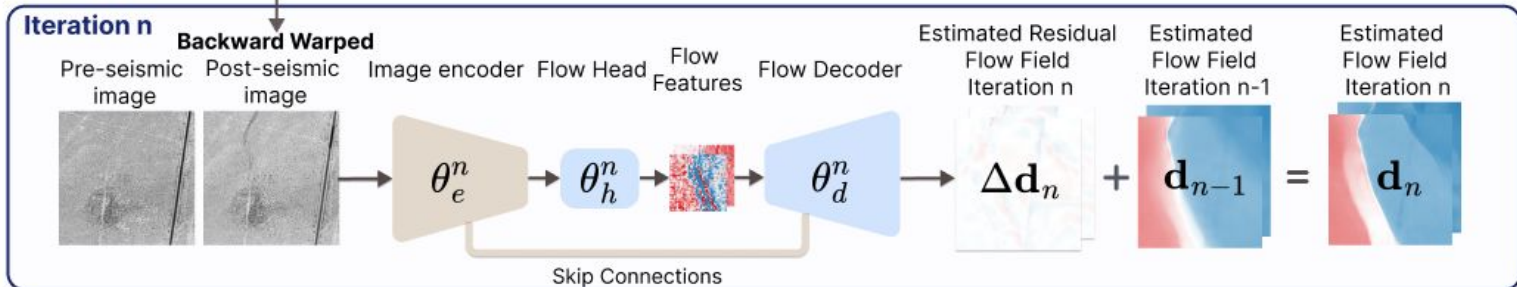
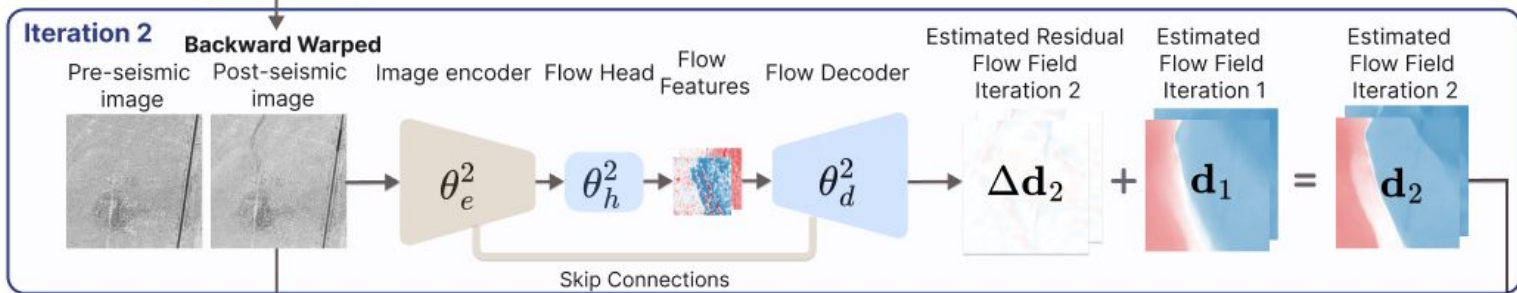
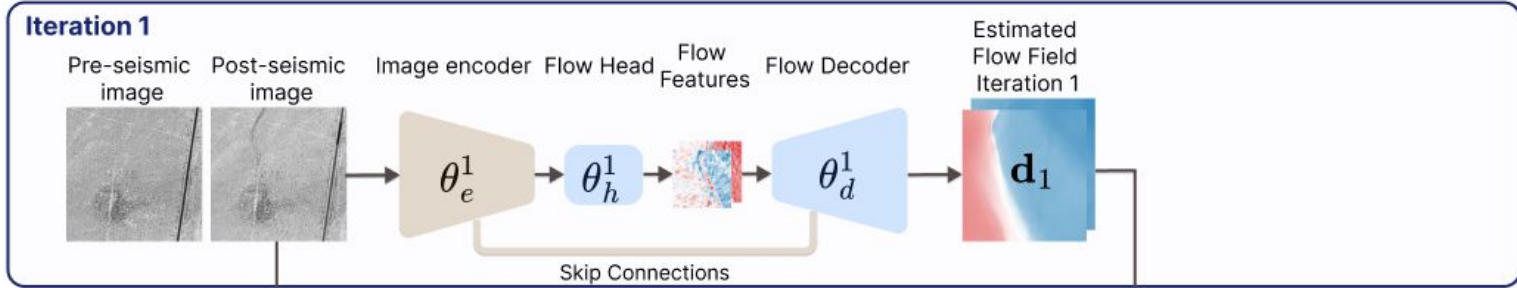
Adding explicit warping layer



STN (Jaderberg *et al.*, 2015)

And Iterative Refinements (IR)

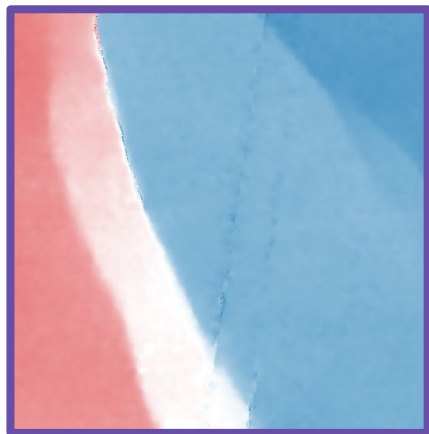




Iterative Refinement achieves subpixel accuracy



COSI-Corr



GeoFlowNet



**Iterative
Refinements**

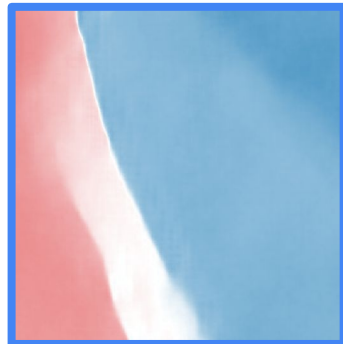
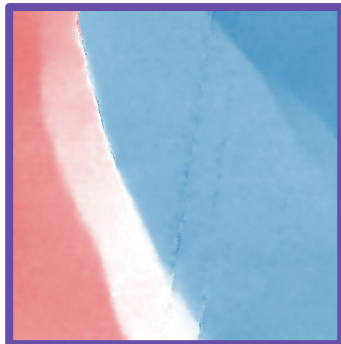


Iterative Refinement achieves subpixel accuracy

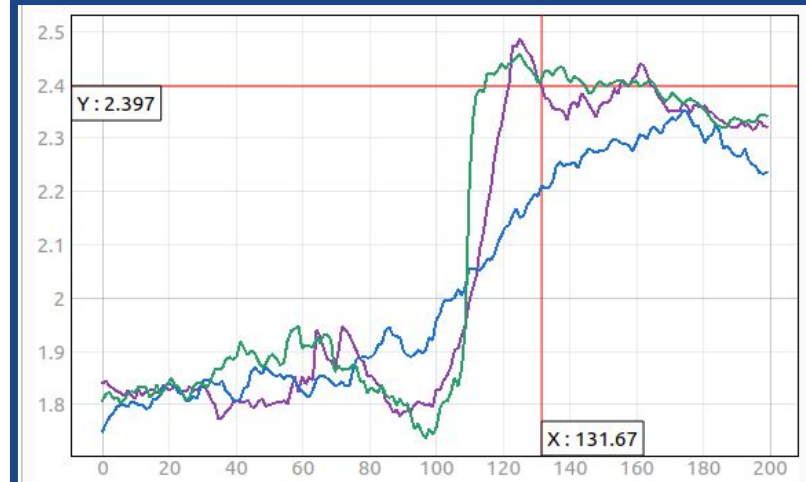
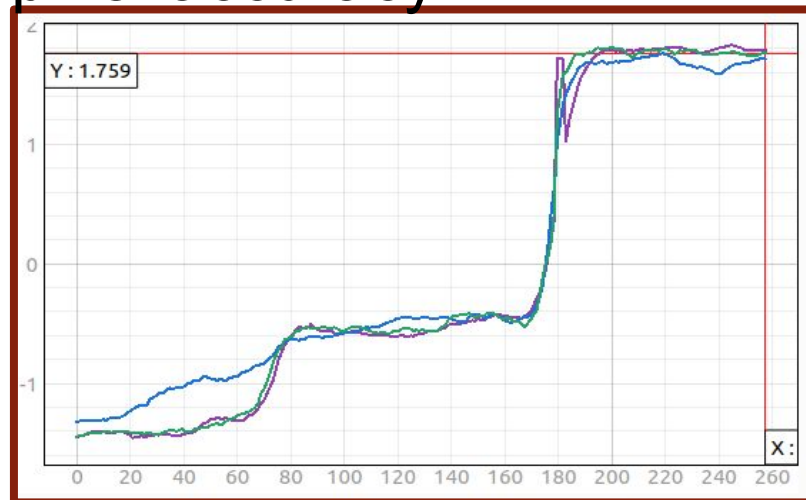
COSI-Corr

GeoFlowNet

Iterative Refinements



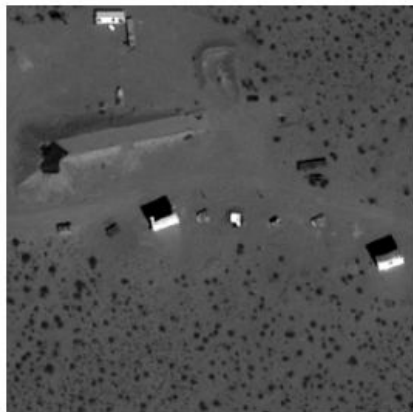
- COSI-Corr
- GeoFlowNet
- Iterative Refinements



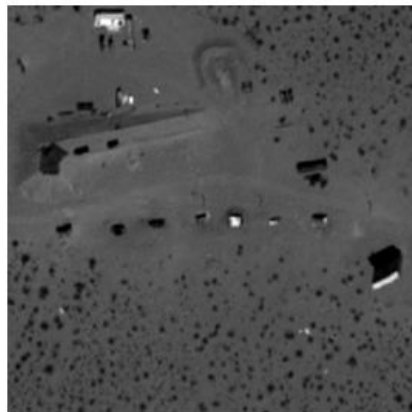
A need to be robust to temporal perturbations

A Need to Be Robust to Temporal Perturbations

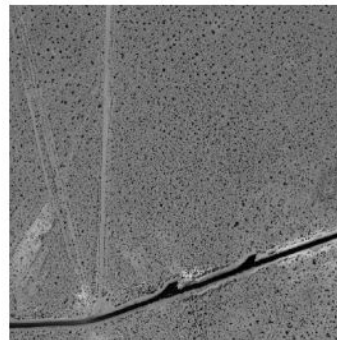
**Pre-seismic
image**



**Post-seismic
image**



**Pre-seismic
image**



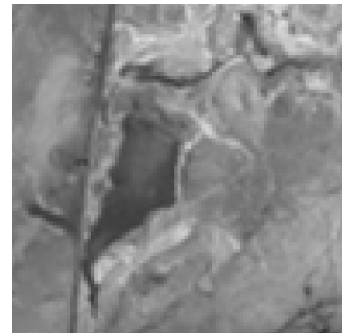
**Post-seismic
image**



**Pre-seismic
image**

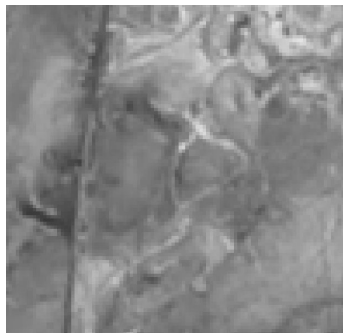


**Post-seismic
image**



A Need to Be Robust to Temporal Perturbations

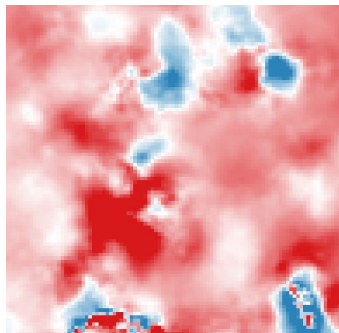
**Pre-seismic
image**



**Post-seismic
image**



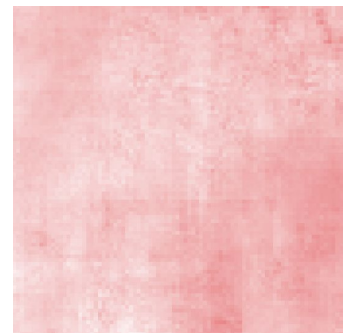
COSI-Corr



GeoFlowNet

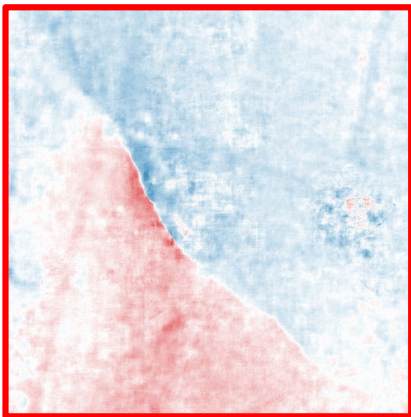


**Iterative
Refinements**

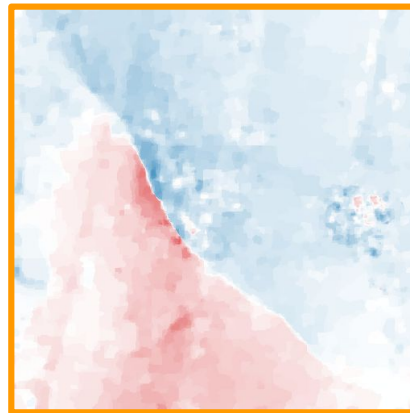


Applying a non convex regularization

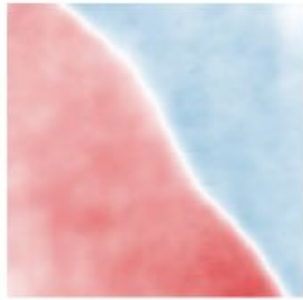
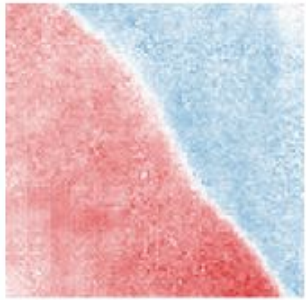
$$\mathbf{df}_{\text{denoised}} = \arg \min_{\mathbf{df} \in \mathbb{R}^{H \times W \times 2}} \left(\underbrace{\|\mathbf{df} - \mathbf{df}_{\text{noisy}}\|_2^2}_{\text{Data Fidelity Term}} + \underbrace{\lambda \psi(\mathbf{df})}_{\text{Smoothness Term}} \right)$$



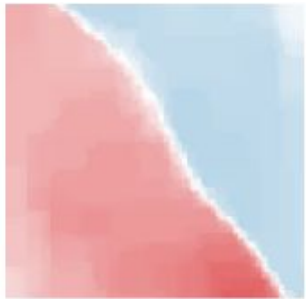
Denoising



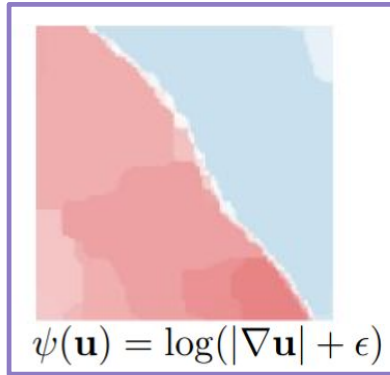
Impact of the smoothness term



$$\psi(\mathbf{u}) = \|\nabla \mathbf{u}\|_2^2$$

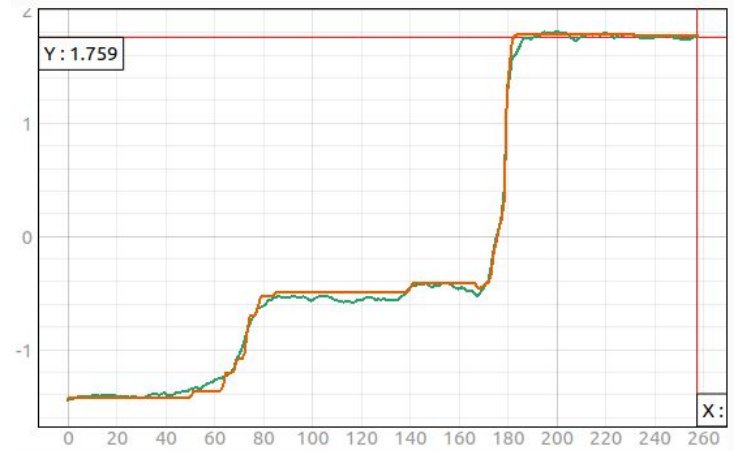


$$\psi(\mathbf{u}) = |\nabla \mathbf{u}|$$



$$\psi(\mathbf{u}) = \log(|\nabla \mathbf{u}| + \epsilon)$$

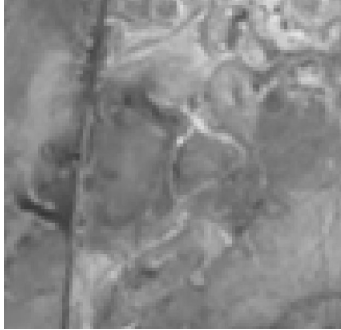
— Iterative Refinements
— Microflow



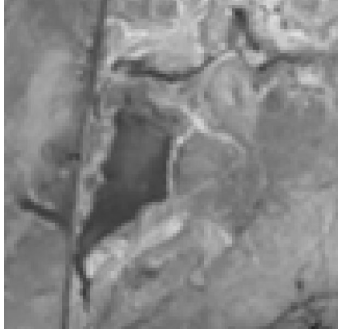
A Need to Be Robust to Temporal Perturbations



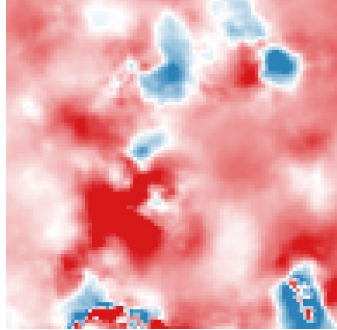
**Pre-seismic
image**



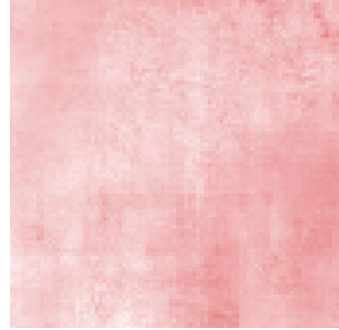
**Post-seismic
image**



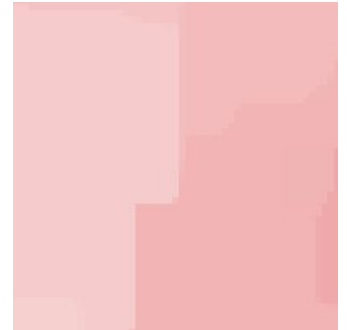
COSI-Corr



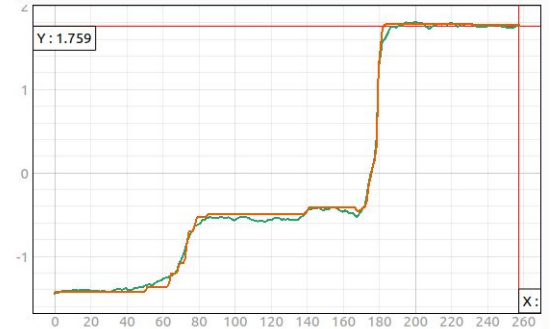
**Iterative
Refinements**



MicroFlow



- Iterative Refinements
- Microflow



A Need to Be Robust to Temporal Perturbations

0.2 pxl
-0.2 pxl

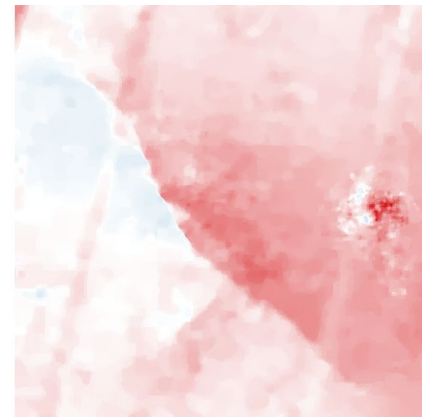
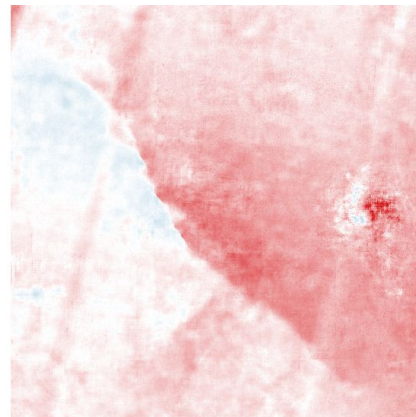
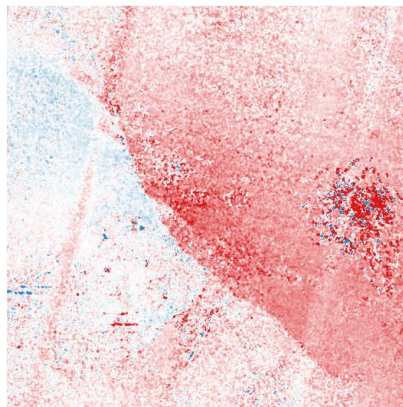
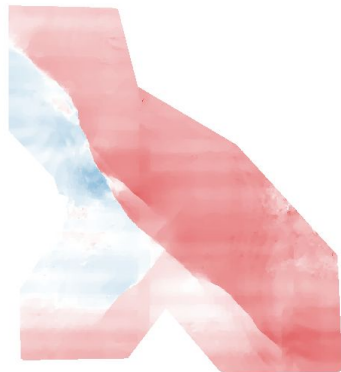
**Pseudo
groundtruth**

COSI-Corr

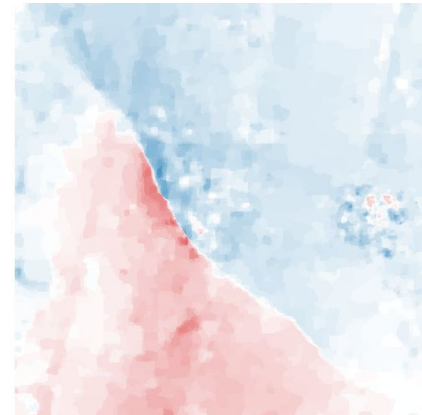
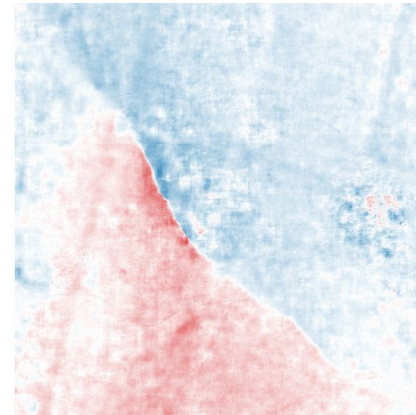
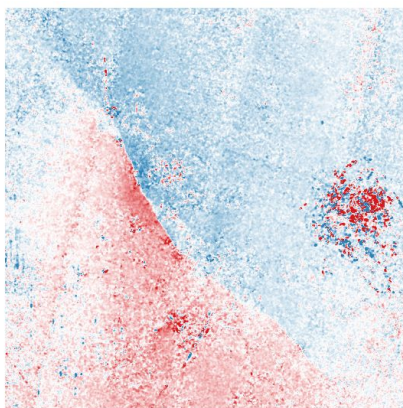
**Iterative
Refinements**

MicroFlow

EW



NS



Quantitative results

Synthetic Benchmark

Method	EPE (fault) ↓			EPE (non-fault) ↓			Smoothness (fault) ↑			Smoothness (non-fault) ↓		
	very small	small	medium	very small	small	medium	very small	small	medium	very small	small	medium
COSI-Corr	0.293	1.108	3.756	0.264	0.284	0.363	0.245	1.395	4.180	0.138	0.173	0.299
MicMac	0.355	1.287	-	0.267	0.301	-	0.360	1.402	-	0.166	0.203	-
GeoFlowNet	0.228	0.894	3.188	<u>0.144</u>	0.244	0.351	0.265	2.328	6.425	0.039	0.082	0.189
SeaRAFT (with pretraining)	0.239	<u>0.868</u>	2.481	0.133	0.184	0.219	0.238	2.436	8.546	0.010	0.035	0.107
Iterative Refinements	0.234	0.809	2.895	0.156	0.207	0.245	0.297	2.392	6.869	0.058	0.084	0.171
Ours	<u>0.234</u>	0.806	<u>2.891</u>	0.155	<u>0.206</u>	<u>0.245</u>	0.283	2.377	6.841	<u>0.023</u>	<u>0.047</u>	<u>0.136</u>

Pseudo-ground truth benchmark

Method	EPE ↓				Smoothness			
	(fault)	(100m)	(1km)	(non-fault)	(fault ↑)	(100m ↓)	(1km ↓)	(non-fault ↓)
COSI-Corr	0.075	0.061	0.050	0.045	0.204	0.222	0.072	0.053
MicMac	0.089	0.071	0.060	0.052	0.258	0.262	0.098	0.068
GeoFlowNet	0.056	0.056	0.048	0.043	0.074	0.088	0.023	0.015
SeaRAFT (with pretraining)	0.058	0.055	0.050	0.037	0.126	0.145	<u>0.017</u>	<u>0.005</u>
Iterative Refinements	<u>0.050</u>	<u>0.044</u>	<u>0.035</u>	<u>0.035</u>	0.121	0.139	0.032	0.022
Ours	0.047	0.040	0.032	0.030	0.118	<u>0.130</u>	0.016	0.003

A need to be robust to different satellite
imagery

Landsat-8: a medium-resolution sensor (15m/pxl)



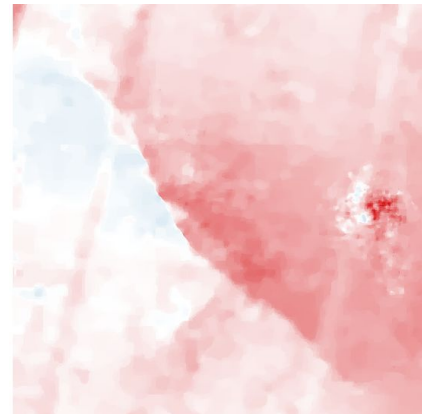
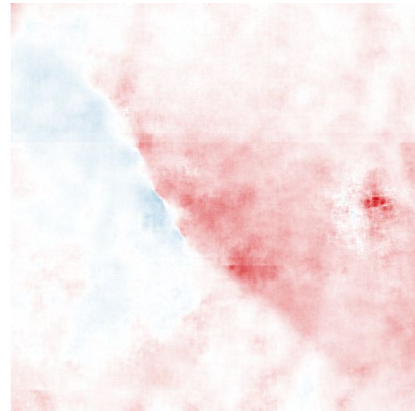
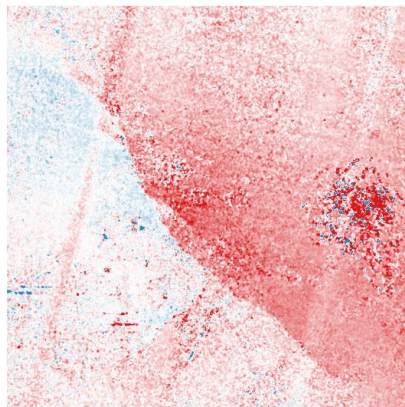
**Pseudo
groundtruth**

COSI-Corr

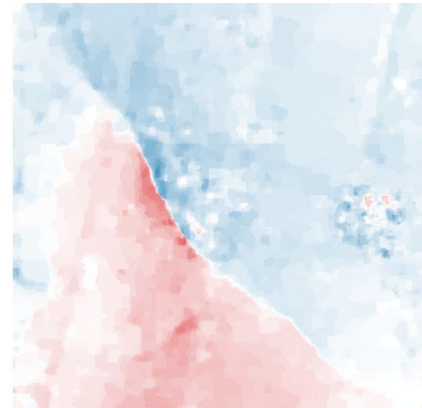
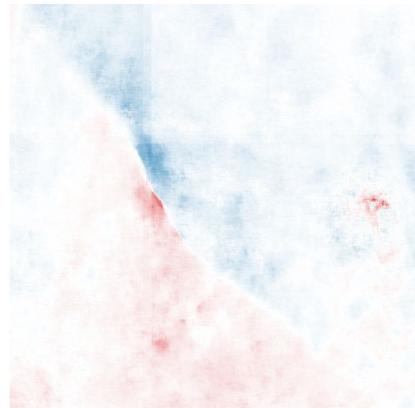
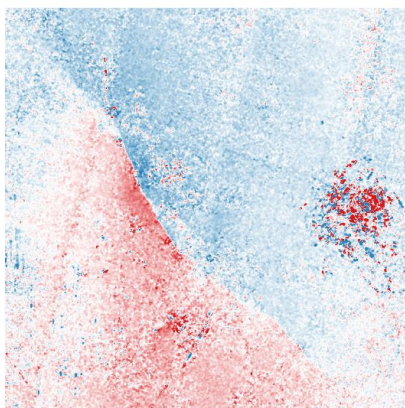
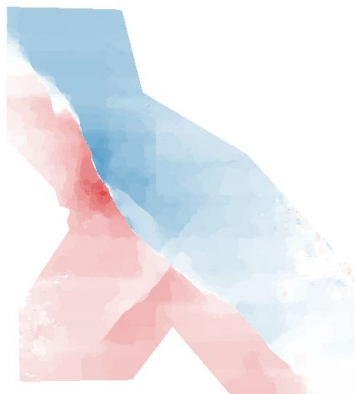
GeoFlowNet

MicroFlow

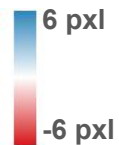
EW



NS



ADS: a very high resolution sensor (50cm/pxl)



COSI-Corr

GeoFlowNet

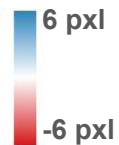
MicroFlow

SeaRaft

EW



ADS: a very high resolution sensor (50cm/pxl)



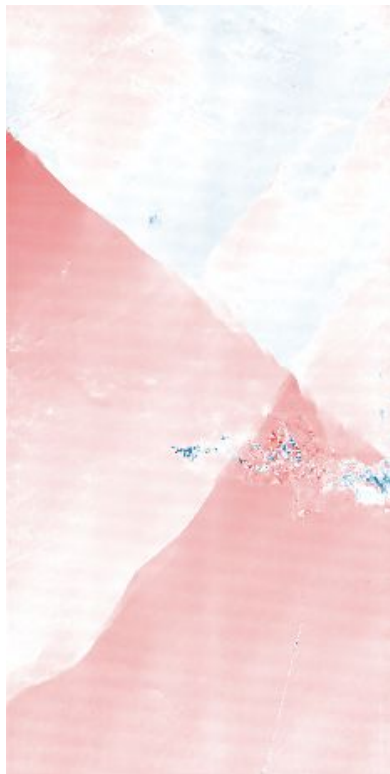
COSI-Corr

GeoFlowNet

MicroFlow

SeaRaft

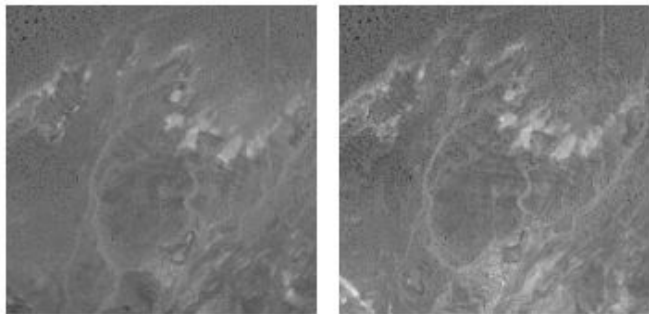
NS



ADS: zoomed-in example

**Pre-seismic
image**

**Post-seismic
image**



1. COSI-Corr 2. MicMac 3. GeoFlowNet 4. SEA-RAFT 5. Ours



Key Take Away

- Deep Learning models can help estimating the ground displacement fields
 - Trained with only a semi-synthetic dataset, it generalizes well to the real-world examples
 - Two key ingredients in the model:
 - Iterative Refinements with explicit warping helps achieving subpixel accuracy, and recovering small to very small displacement faults
 - Non-convex a posteriori regularization helps reducing the noise due to temporal change