Machine Learning for Error Characterization and Correction in InSAR Satellite Data

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AIST16 80NSSC17K0125
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ACI, AGS INSPIRE
ACI1442997, AGS-1343967
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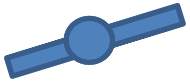
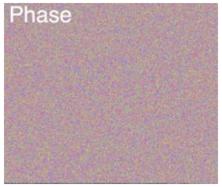
Overview - InSAR

Satellite Observations

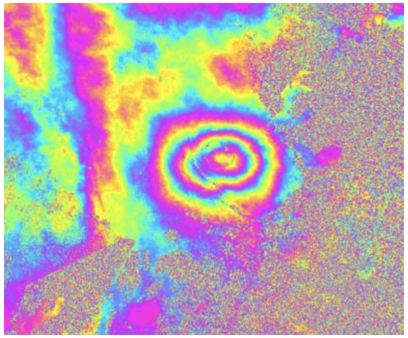




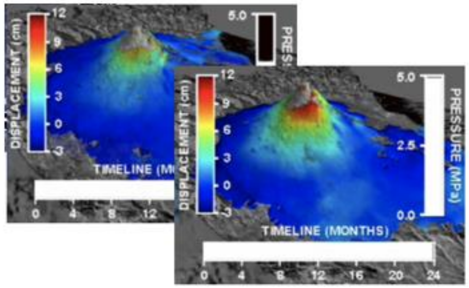
“First Time”

“Next Time”

“Magic of Interferometry”



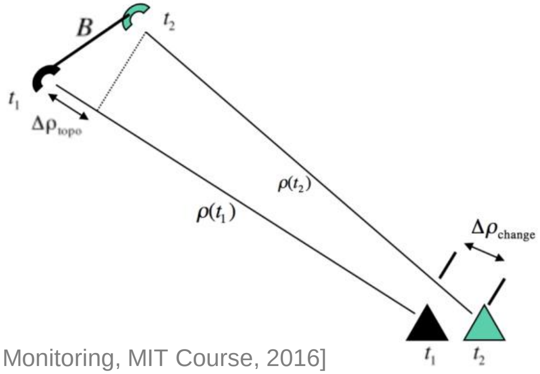
“unwrapping”



- Random phase in each image, but difference coherent
- One cycle of color represents one cycle of relative phase
- Interferometric phase proportional to topography and topographic change; known topography can be removed
- Sensitivity w.r.t change much greater than w.r.t topographic relief

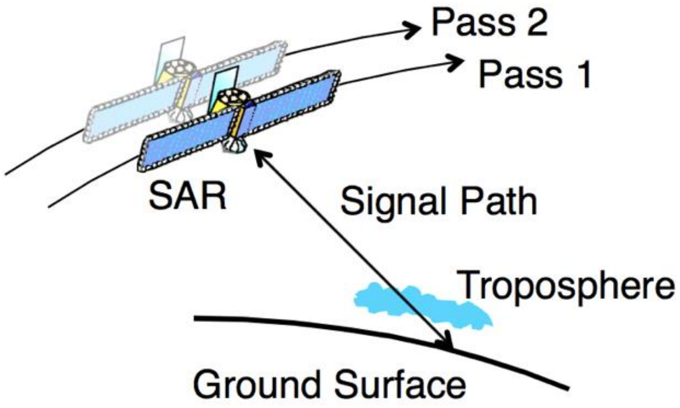
Study deformations of

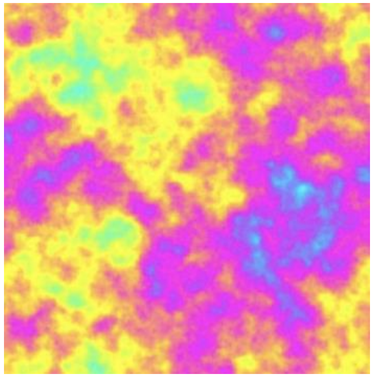
- Earthquakes
- Volcanoes
- …



[Content source: T.Herring, Pankratius&Herring: 12.S590 Geoinformatics for Natural Hazards Monitoring, MIT Course, 2016]

Overview - InSAR





Simulated phase artifacts due to differential tropospheric delay between pass 1 and 2

- Rapidly varying tropospheric delays are a problem
- Variations primarily due to changes in water vapor content along propagation path

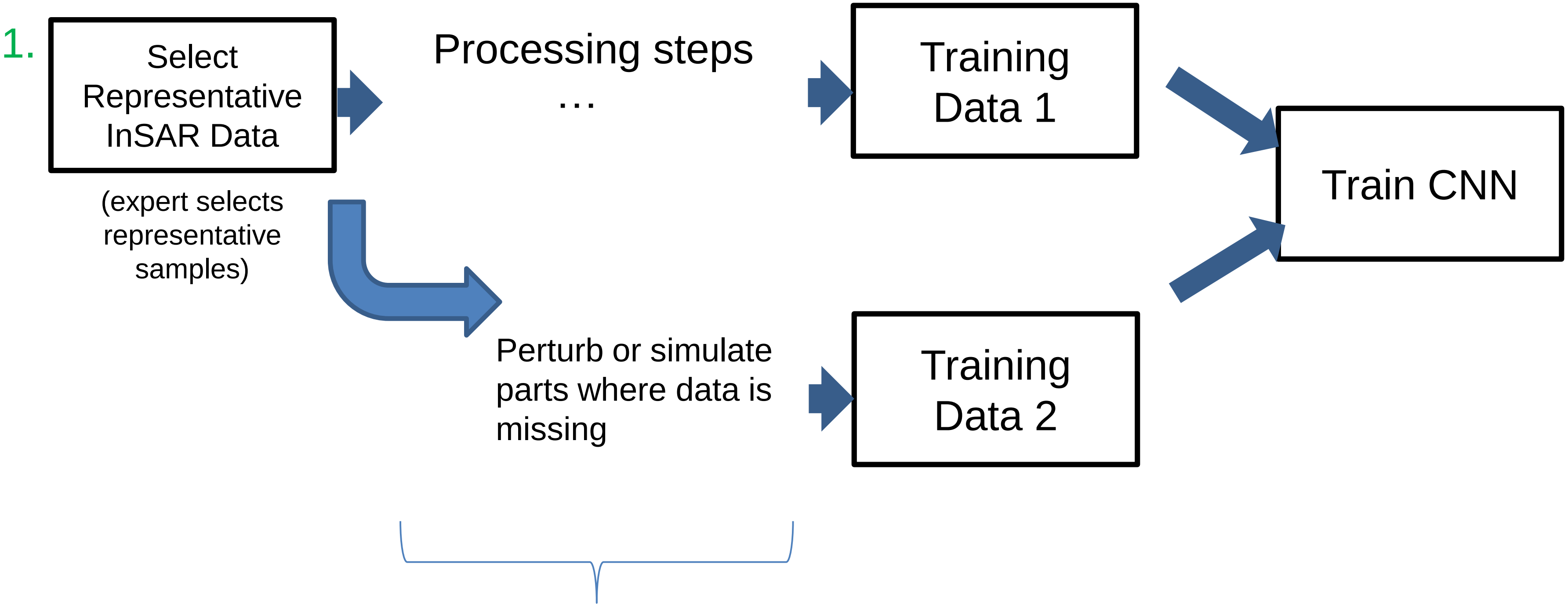
[Content source: T.Herring, Pankratius&Herring: 12.S590 Geoinformatics for Natural Hazards Monitoring, MIT Course, 2016]

Overview

Exploration:

- Machine learning to identify which parts of InSAR interferograms are primarily caused by tropospheric effects versus real surface deformations
- Problem: Sparse training sets
- Discussing approach and early results

Principles (work in progress)



1. Select Representative InSAR Data

(expert selects representative samples)

Processing steps
…

Training Data 1

Perturb or simulate parts where data is missing

Training Data 2

Train CNN

- Allow for perturbations / parameterization for training set augmentation
- Based on domain knowledge, rules of geophysics, atmospheric science, etc.
- Information from domain knowledge infusion as a way to overcome sparsity problem

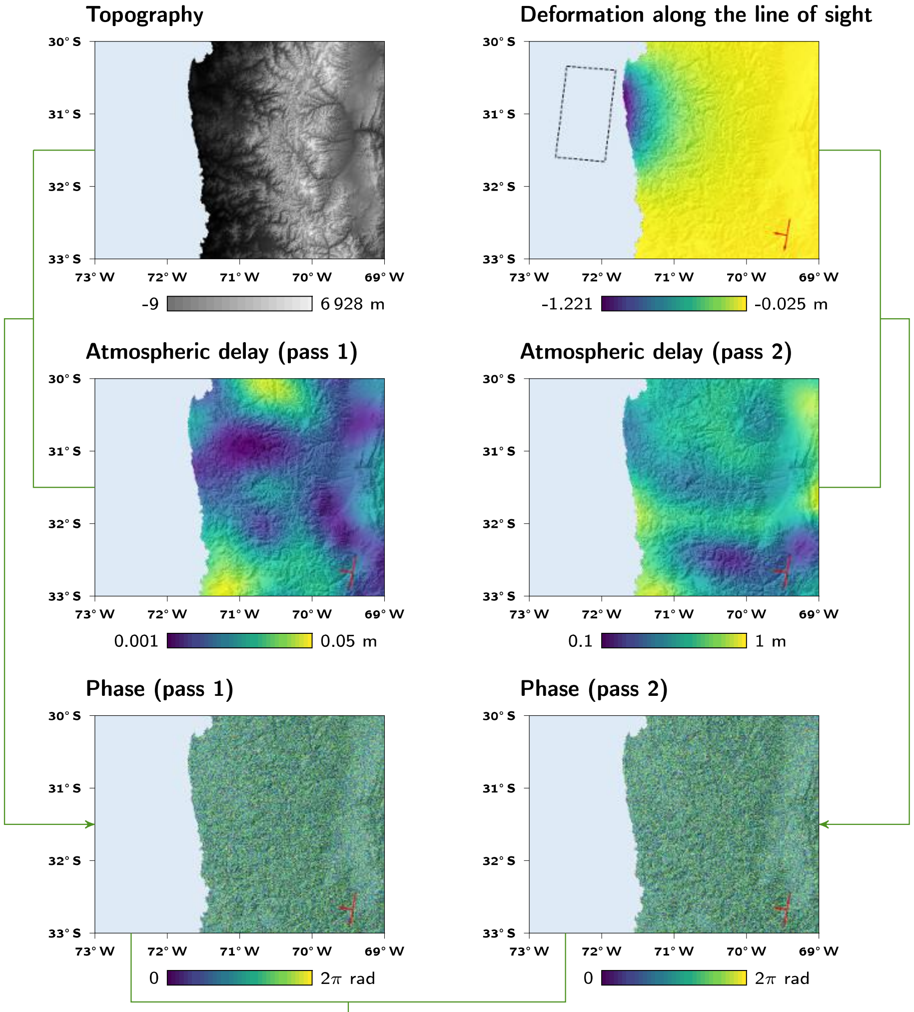
Example: Synthetic Interferogram Simulation

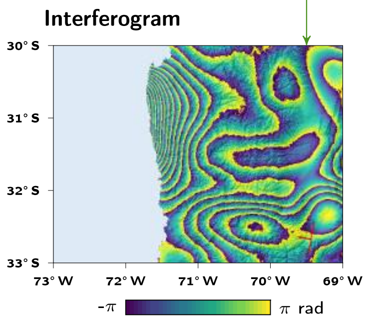
- InSAR interferograms are influenced by the topography and topographic changes (e.g., deformation, landslides), but also by the atmosphere or by satellite’s orbital variations

- Simulator models different signal sources within an interferogram to help assess the effectiveness / efficiency of different corrections

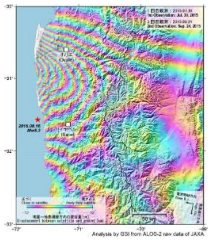
→ Explore “what if” scenarios

→ E.g., “what if we had a slightly different atmospheric correction model?”





Example of interferogram

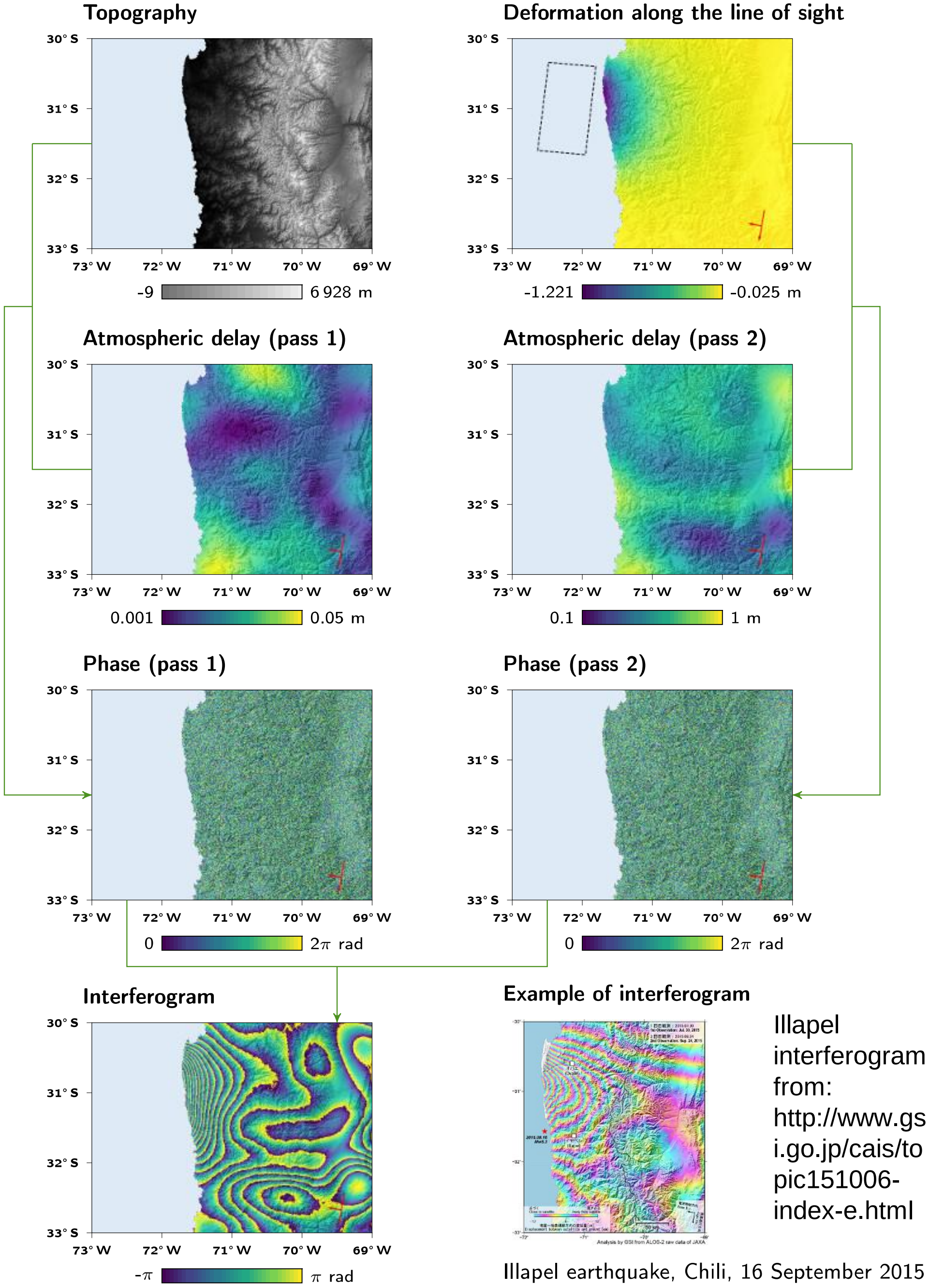


Illapel interferogram from: http://www.gsi.go.jp/cais/topic151006-index-e.html

Illapel earthquake, Chili, 16 September 2015

Example: Synthetic Interferogram Simulation

- Synthetic interferograms defined by:
    - Look angle
    - Earth’s shape (as a sphere or an ellipsoid)
    - Topography (from SRTM data)
    - Surface deformation (from elastic halfspace models)
    - Atmospheric delay (from geostatistical simulation)
    - Temporal decorrelation (from geostatistical simulation)

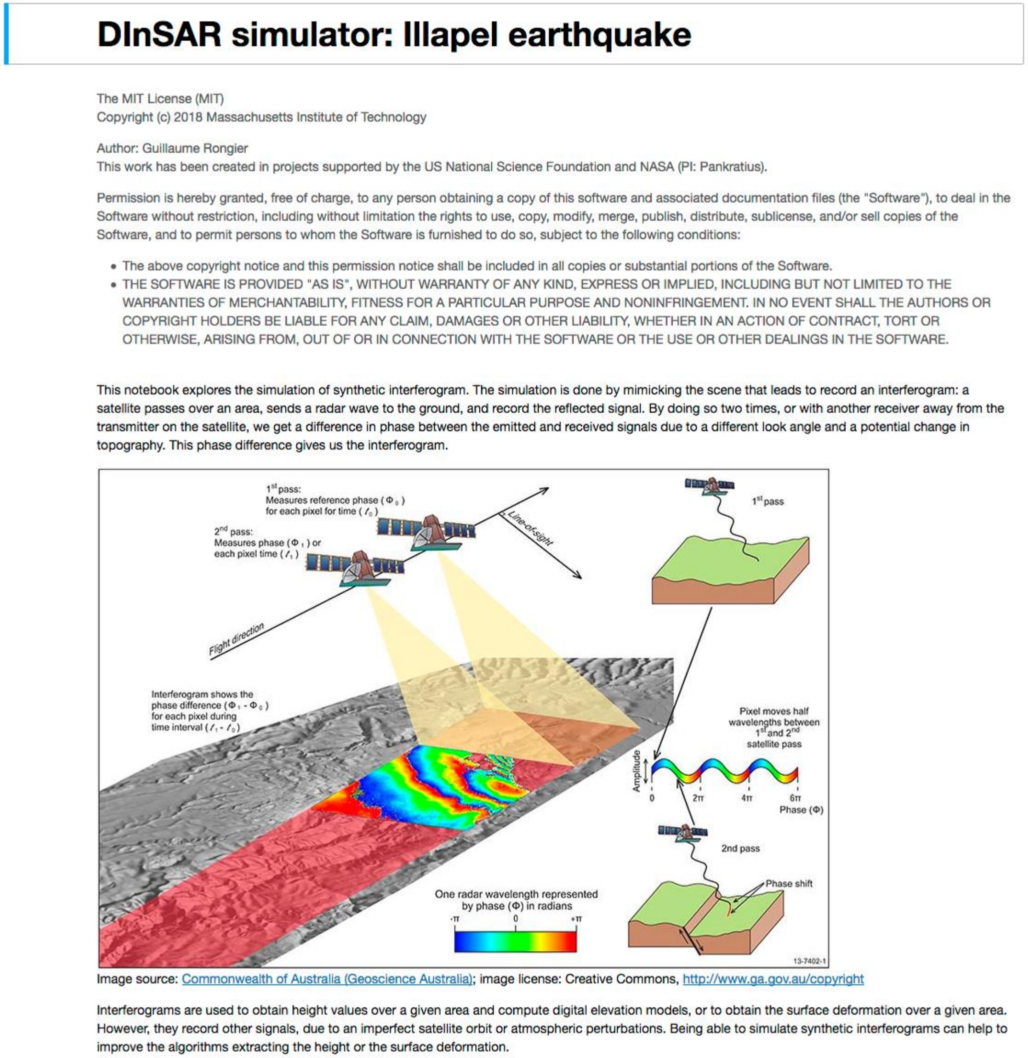


Illapel interferogram from: http://www.gsi.go.jp/cais/topic151006-index-e.html

Illapel earthquake, Chili, 16 September 2015

Interferogram Simulation

- Workflow illustrated in two Jupyter notebooks to be released on Github https://github.com/MITeaps/pyinsar
  - The first notebook shows different ways of creating interferograms and allows for control of parameters such as no deformation / delay / decorrelation
  - The second notebook contains examples, e.g., the 2015 Illapel Earthquake



DInSAR simulator: Illapel earthquake

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Author: Guillaume Rongier
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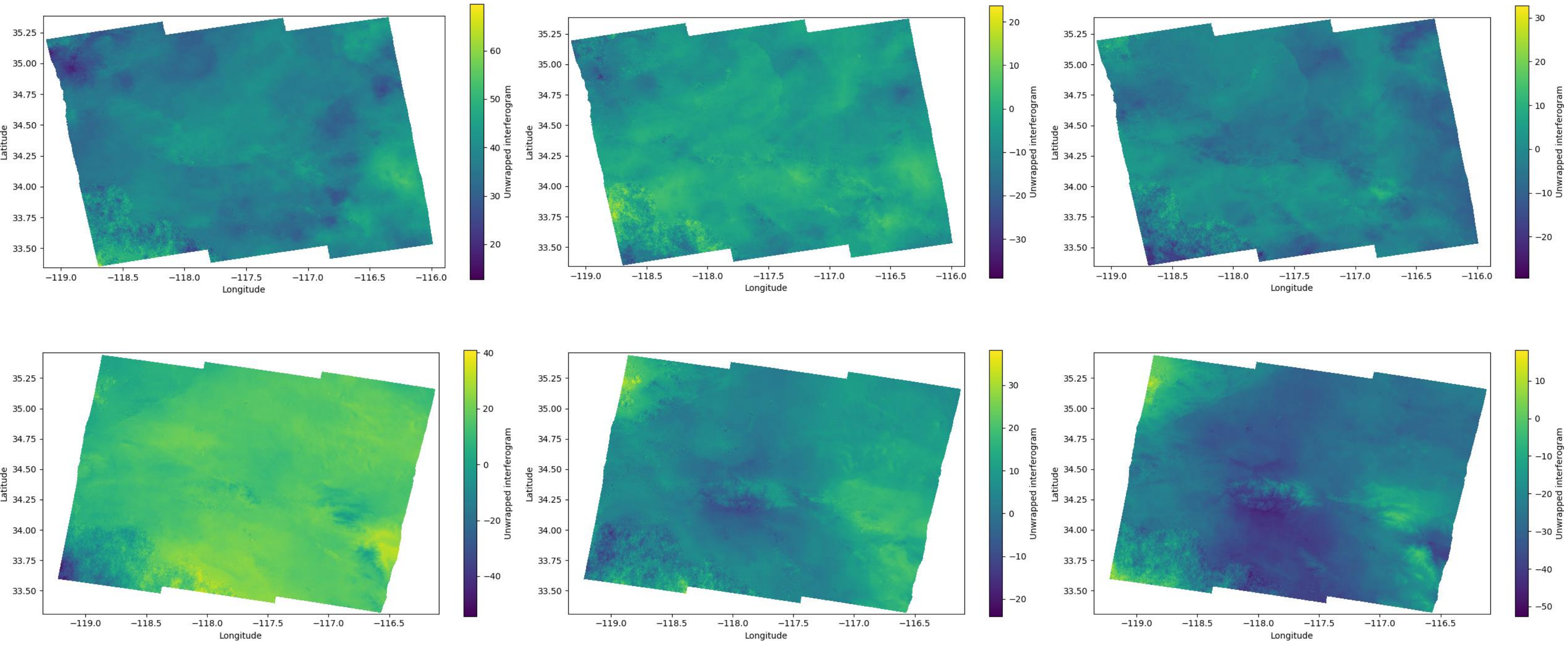
This notebook explores the simulation of synthetic interferogram. The simulation is done by mimicking the scene that leads to record an interferogram: a satellite passes over an area, sends a radar wave to the ground, and record the reflected signal. By doing so two times, or with another receiver away from the transmitter on the satellite, we get a difference in phase between the emitted and received signals due to a different look angle and a potential change in topography. This phase difference gives us the interferogram.

Image source: [Commonwealth of Australia (Geoscience Australia)](); image license: Creative Commons, http://www.ga.gov.au/copyright

Interferograms are used to obtain height values over a given area and compute digital elevation models, or to obtain the surface deformation over a given area. However, they record other signals, due to an imperfect satellite orbit or atmospheric perturbations. Being able to simulate synthetic interferograms can help to improve the algorithms extracting the height or the surface deformation.

Training Sets

- Example from atmospheric delay training set: 6 Sentinel-1 interferograms over the Los Angeles basin processed and provided by Prof. Gareth Funning (UC Riverside)

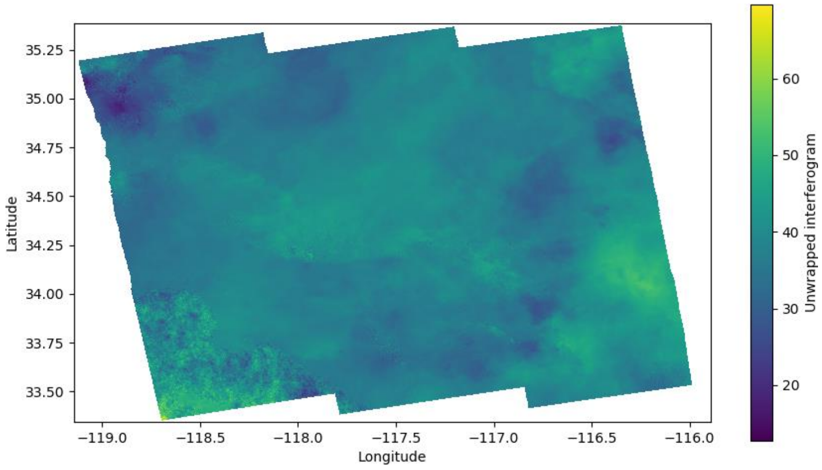


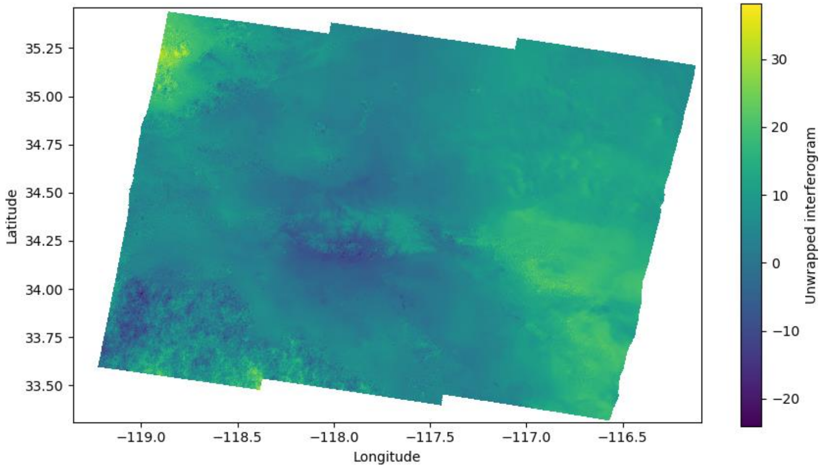
Training Sets

Exploration

- Real atmospheric delays can be observed
  - if we extract the components due to look angle and topography (leveraging SRTM data)
  - if the deformation is small enough compared to the delay (often the case when using small temporal baselines)

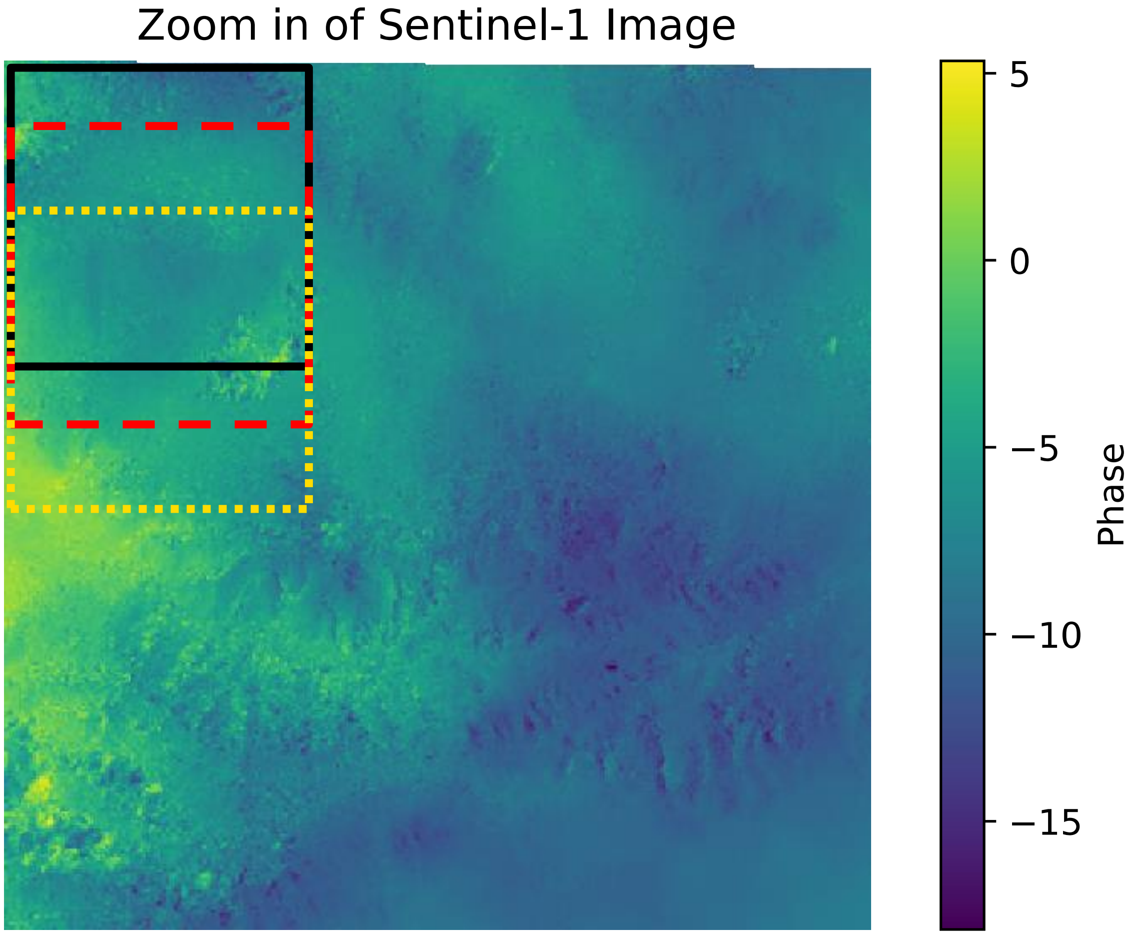
→ Useful in a machine learning approach to characterize/extract remaining atmospheric delays from interferograms





Training Sets

- Data taken using Sentinel-1
- Selecting 100x100 pixel tiles from image
- More overlap means more training images at the expense of increased similarity
- Additionally, tiles may be augmented



Training Sets - Augmentation

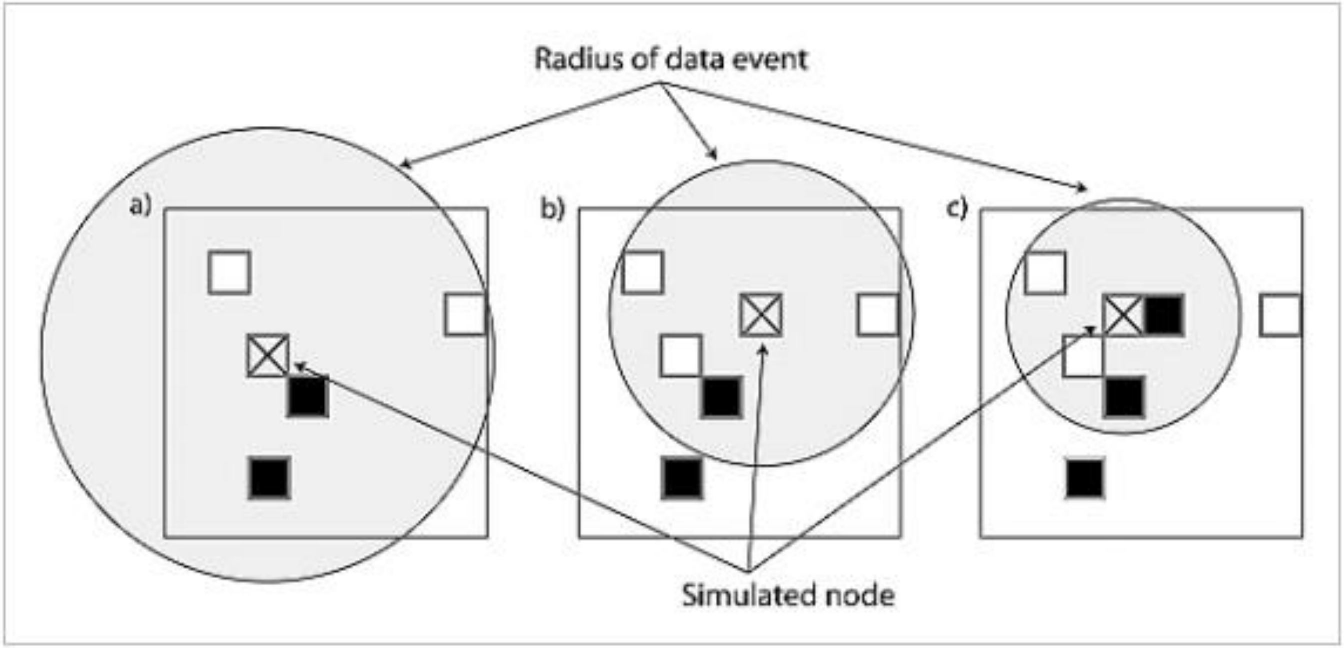
- Size of training set has key impact on classification result

- Data augmentation increases the size of the training set through domain knowledge, e.g., defined by physical properties of phenomena

- Create new training examples for the network by:
  - Scaling
  - Rotation
  - Mirroring
  - Noise addition

Training Sets - Augmentation

- In addition, exploring other methods, such as Direct Sampling (Mariethoz et al., 2010, Meerschman et al., 2013) to generate ‘realistic’ delay artefacts and include neighborhood information

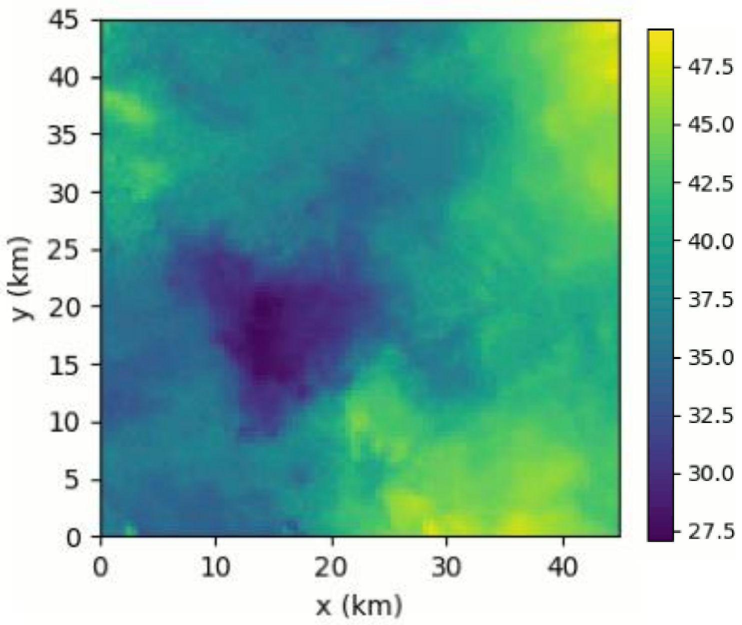


Source: Mariethotz et al., 2010, https://doi.org/10.1029/2008WR007621

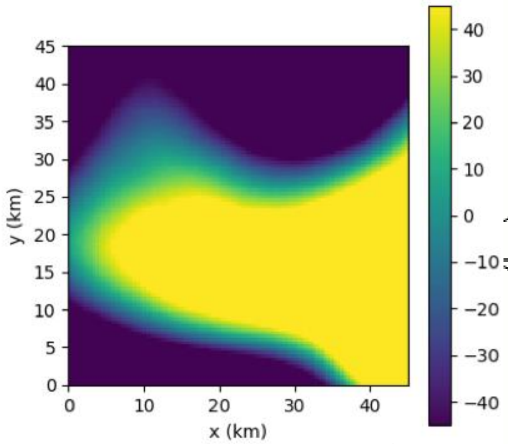
Training Sets - Augmentation

- Direct sampling can scale, rotate, perturb existing structures; improve training of network with structures absent in a sparse training set

Starting Image



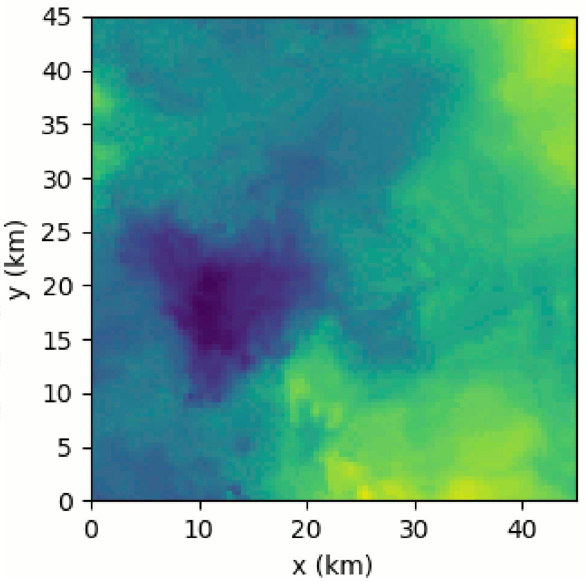
Apply Transforms



Example Instance of Generated Individual Rotation Angle Transform (°)

Perturbed Images

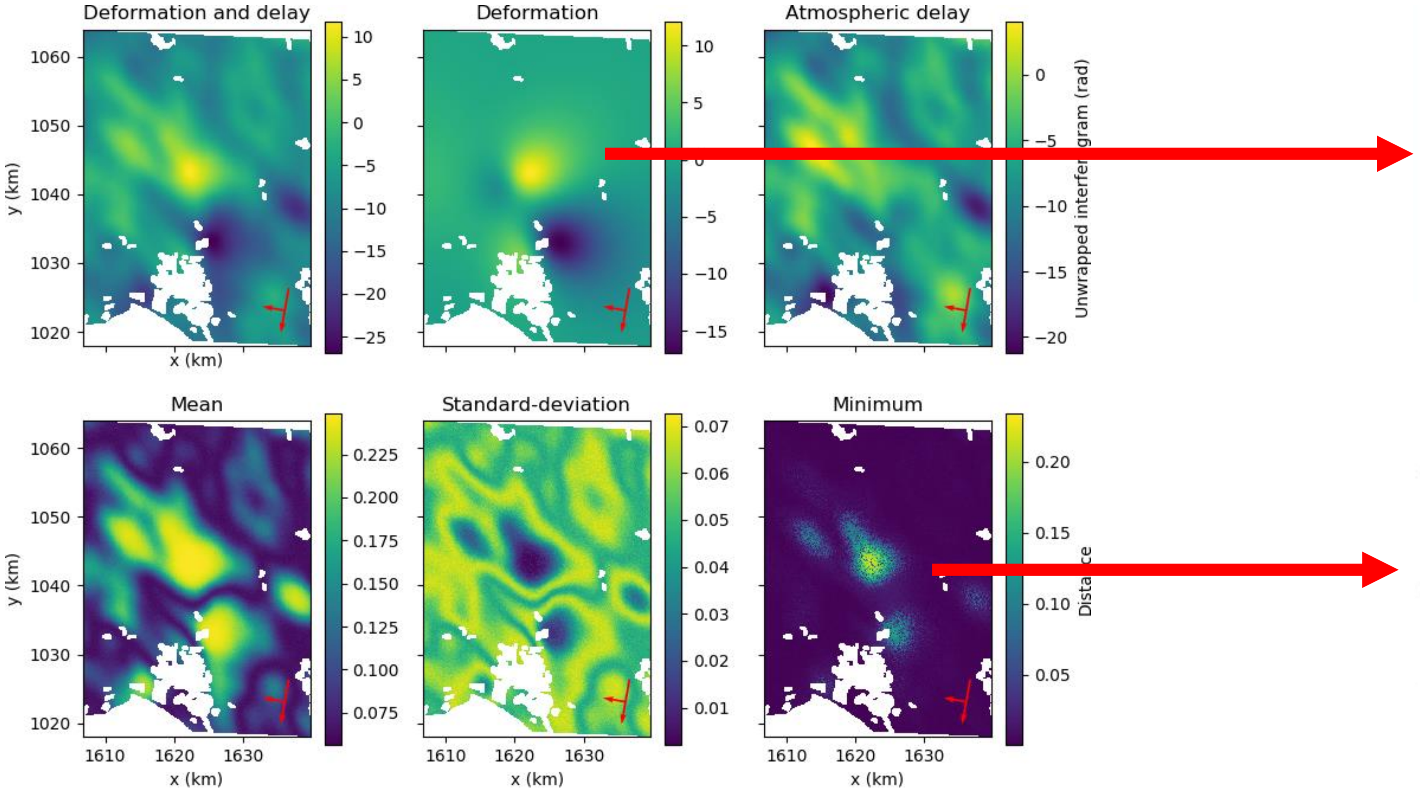
(animation)



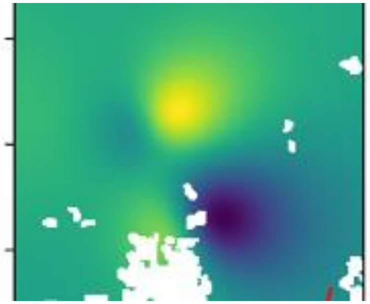
Training Sets - Augmentation

- Potentially, ‘enhanced’ sampling methods can also be explored as a comparative alternative to help identify areas with / without atmospheric delays, e.g.,

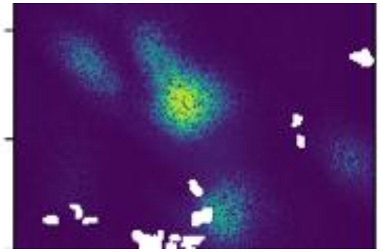
Simulation & direct sampling



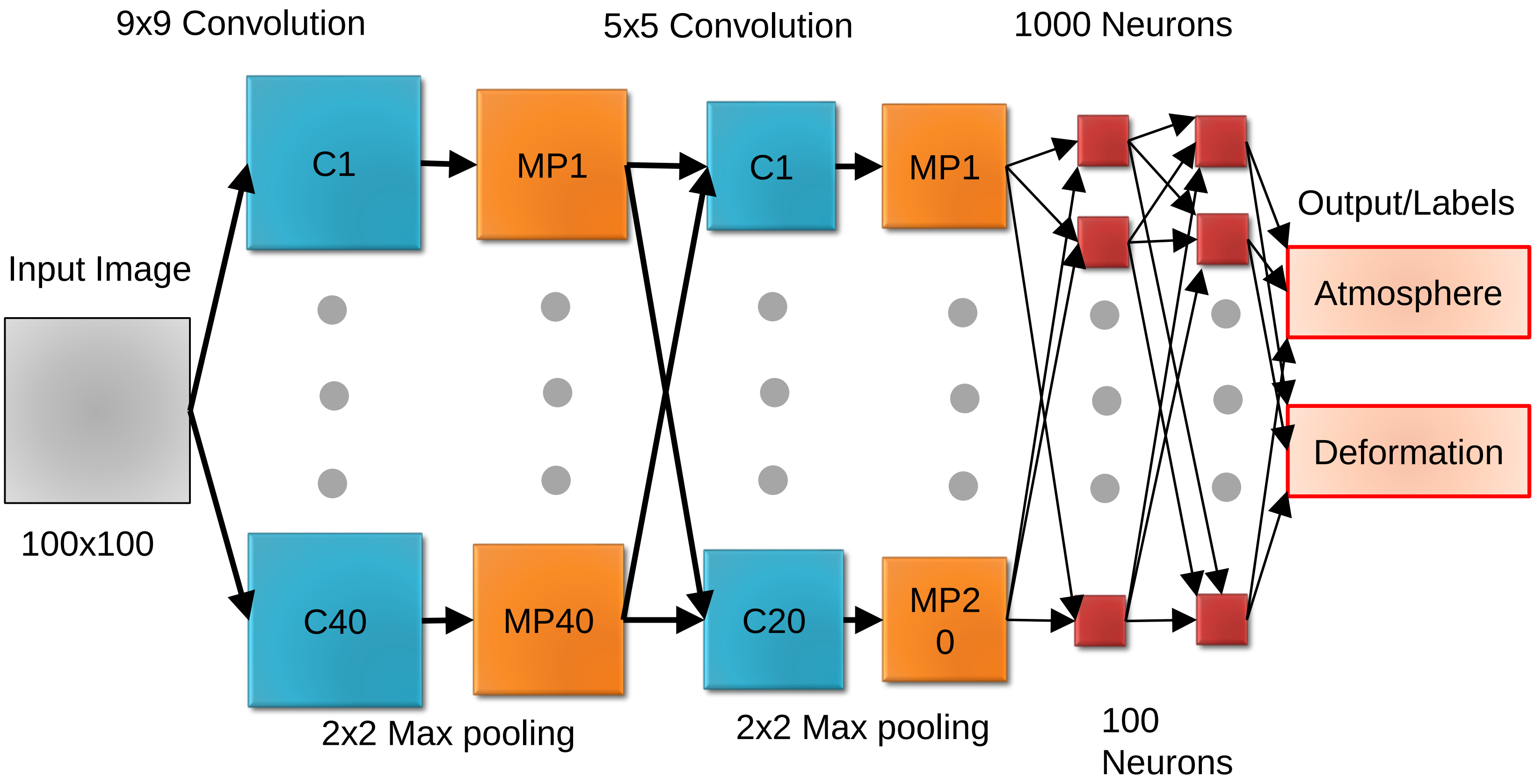
Actual deformation



Estimated deformation

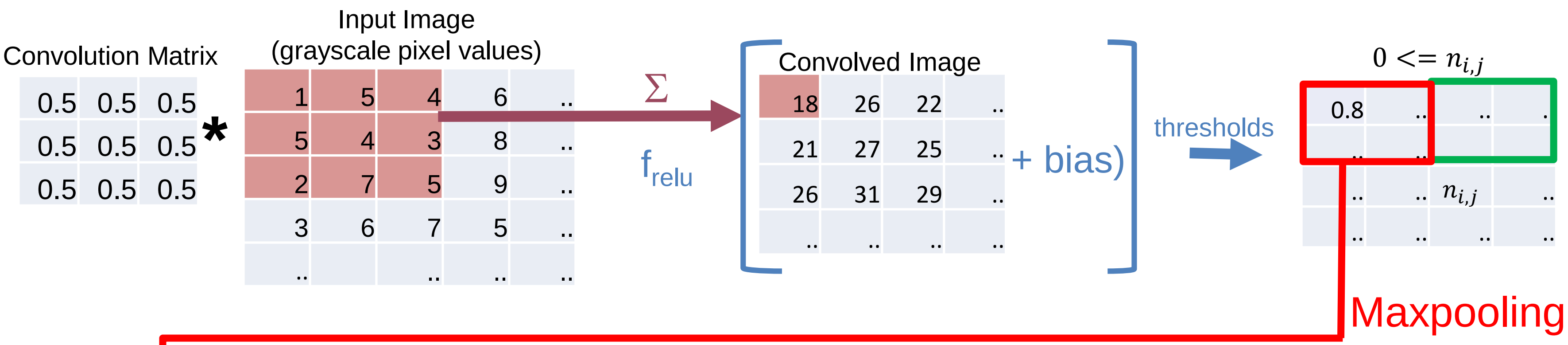


Learning – Convolutional Neural Network



Current implementation uses 100x100 pixels, which covers 10x10 km. This is large enough to capture most of the structure while providing a reasonable number of training examples.

Learning: Mini-Tutorial



Convolution Matrix

0.5	0.5	0.5
0.5	0.5	0.5
0.5	0.5	0.5

*

Input Image (grayscale pixel values)

1	5	4	6	..
5	4	3	8	..
2	7	5	9	..
3	6	7	5	..
..		..	..	..

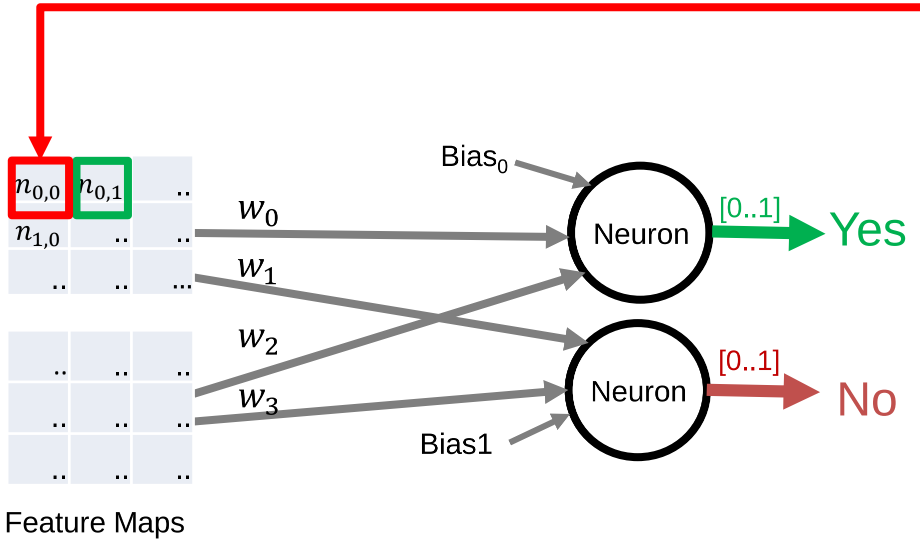
Convolved Image

18	26	22	..
21	27	25	..
26	31	29	..
..	..	..	..

+ bias)

$0 <= n_{i,j}$

0.8	..	..	.
..	..		
..	..	$n_{i,j}$	..
..	..	..	..

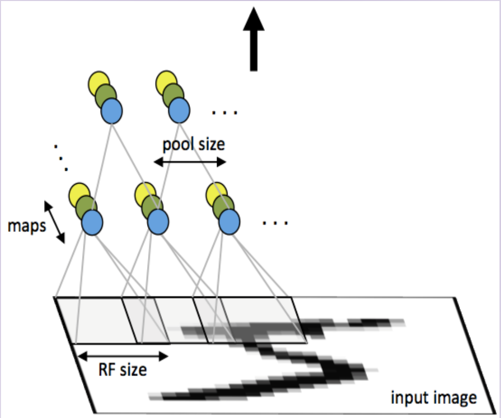


$n_{0,0}$	$n_{0,1}$	..
$n_{1,0}$	..	..
..	..	...

..	..	..
..	..	..
..	..	..

Feature Maps

Layer addition

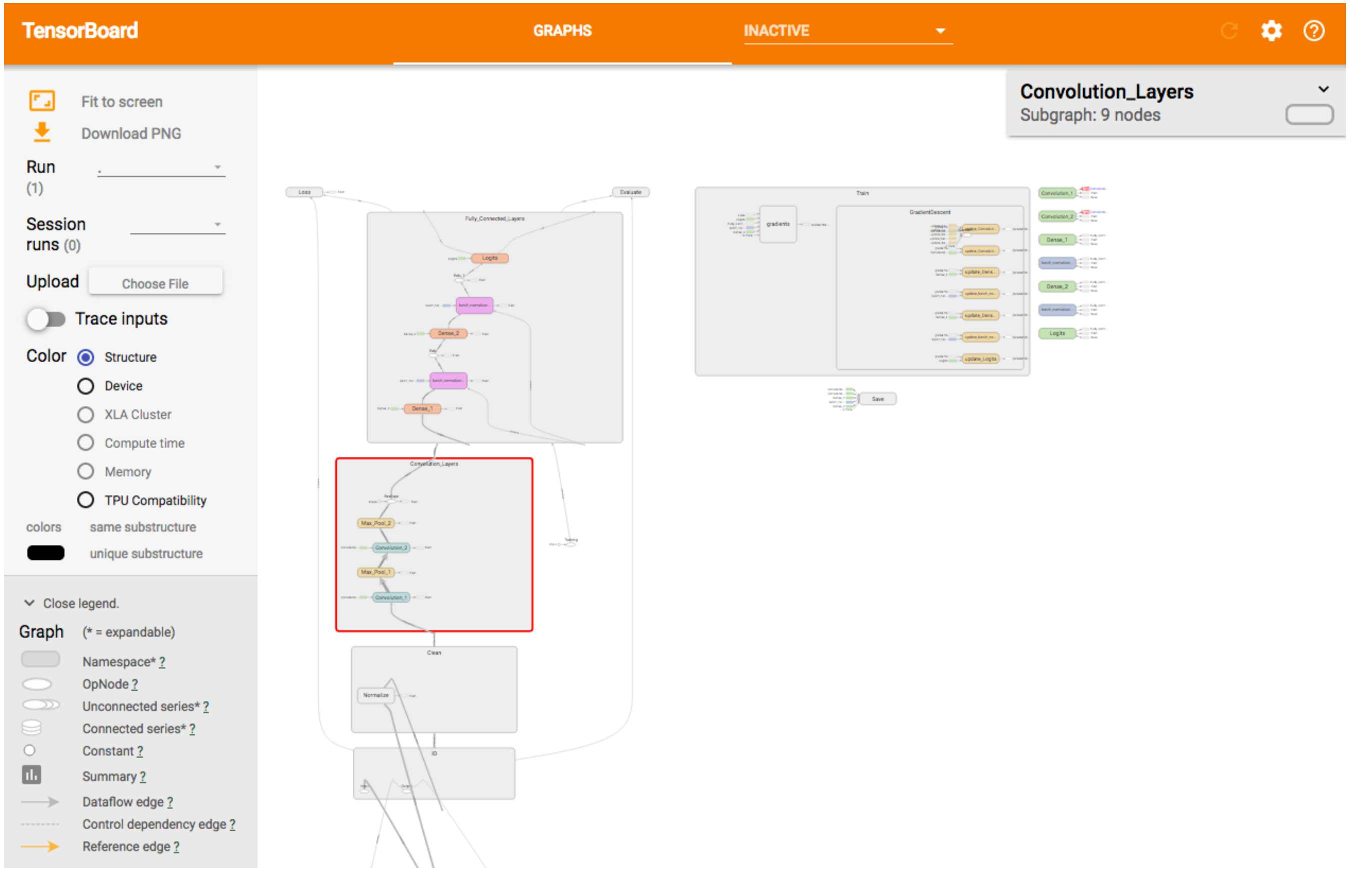


http://ufldl.stanford.edu/tutorial/supervised/ConvolutionalNeuralNetwork/

How to adjust all parameters? → Done in training phase (not discussed here)

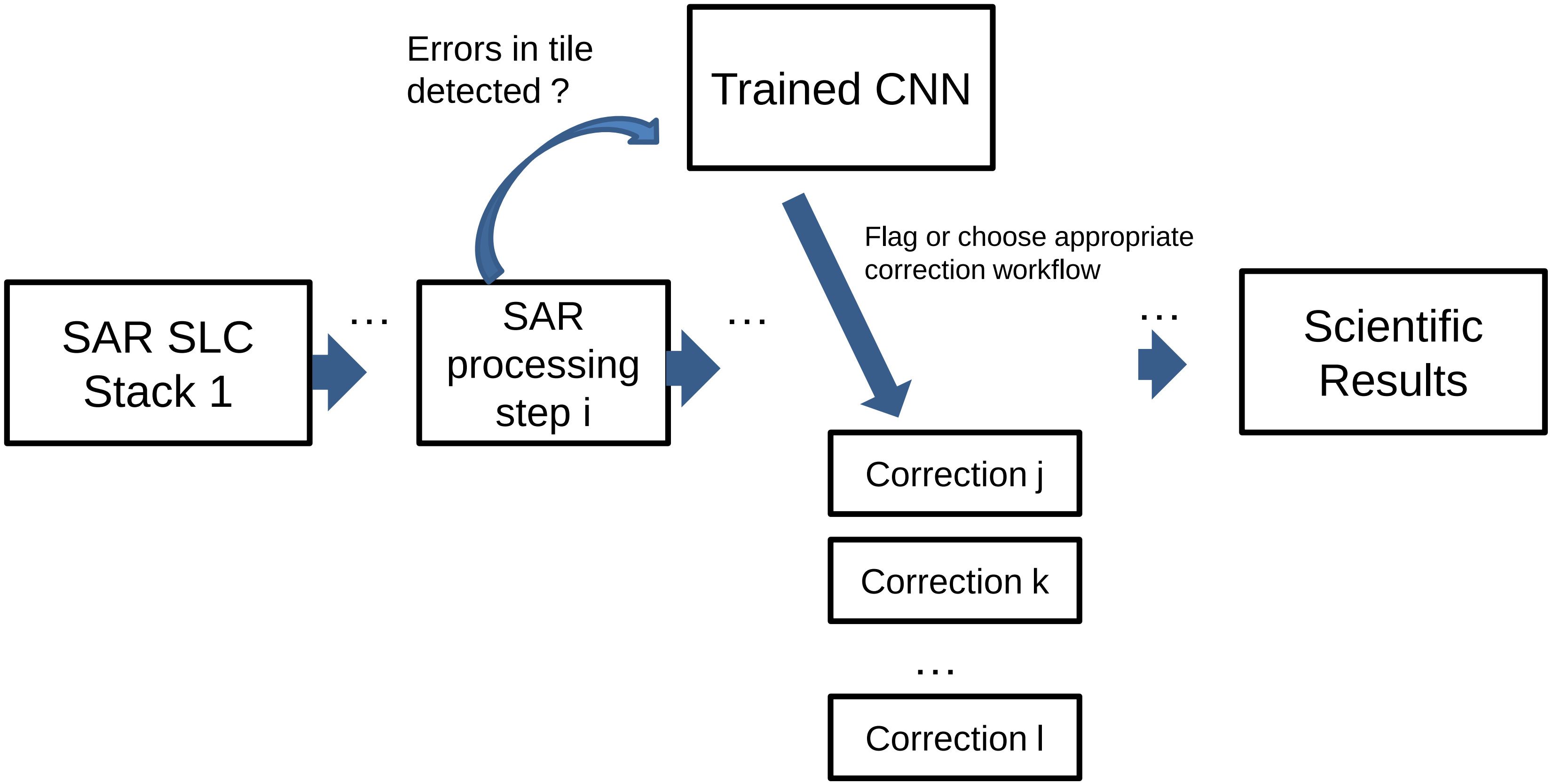
Learning

Exploring Convolutional Neural Network approach in TensorFlow



Usage

After training, the CNN can be used to augment InSAR data processing and decide on flagging tiles of interferograms and potential automatic synthesis of processing pipelines



Errors in tile detected ?

Trained CNN

Flag or choose appropriate correction workflow

SAR SLC Stack 1

…

SAR processing step i

…

…

Scientific Results

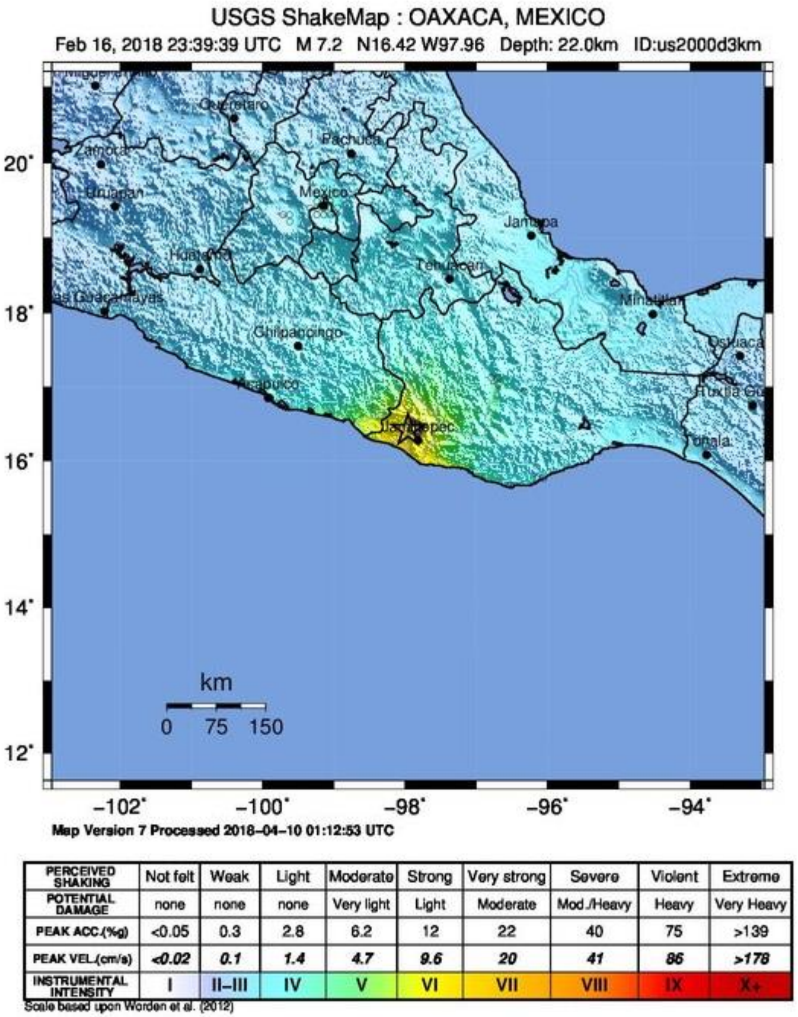
Correction j

Correction k

…

Correction l

Case Study: Oxaca/Mexico M7.2 Earthquake



USGS ShakeMap : OAXACA, MEXICO

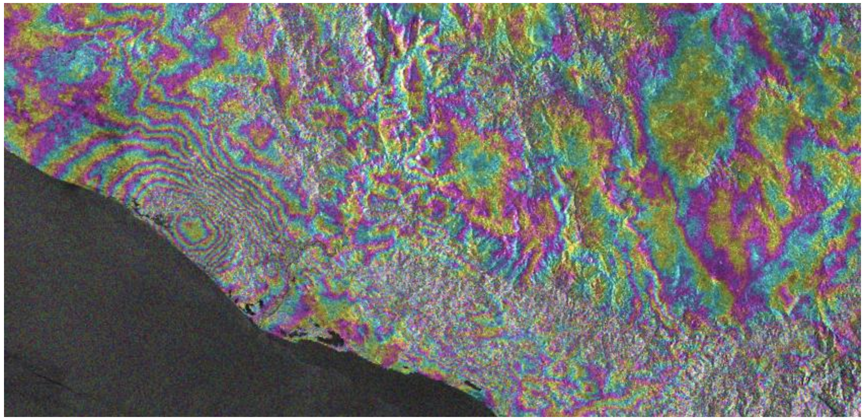
Feb 16, 2018 23:39:39 UTC M 7.2 N16.42 W97.96 Depth: 22.0km ID:us2000d3km

Map Version 7 Processed 2018–04–10 01:12:53 UTC

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. (2012)

- Feb. 16, 2018, in a subduction zone
- Data: Sentinel on SCIKIT-data access DATA INTERFACES FOR PYTHON
- Validation: compare processed interferograms on SARVIEWS Hazard Portal

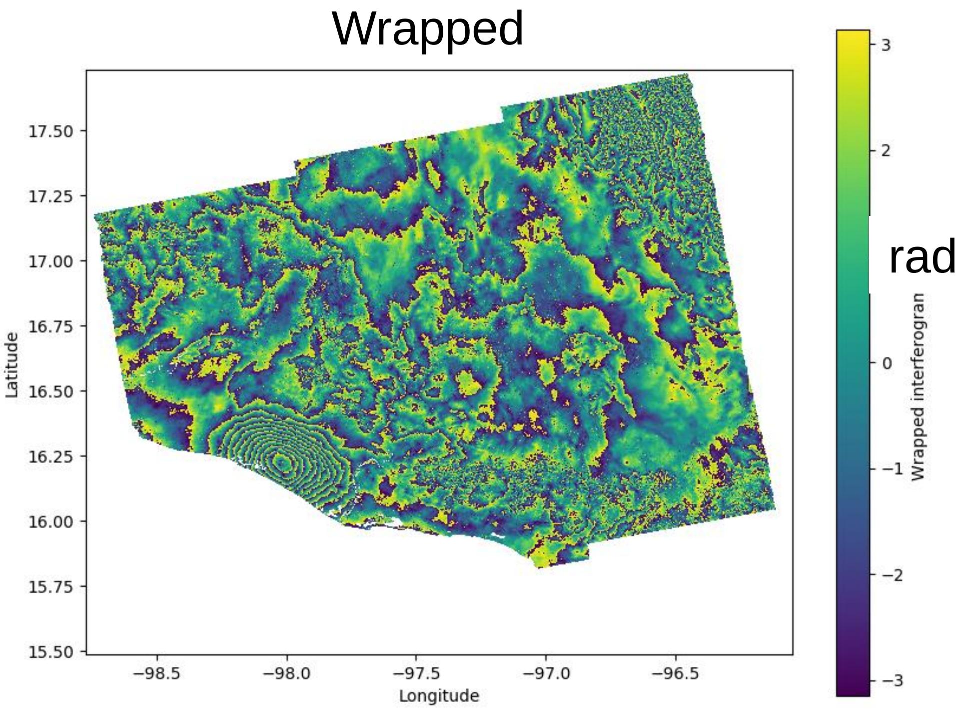


sarviews-hazards.alaska.edu/Event/61/

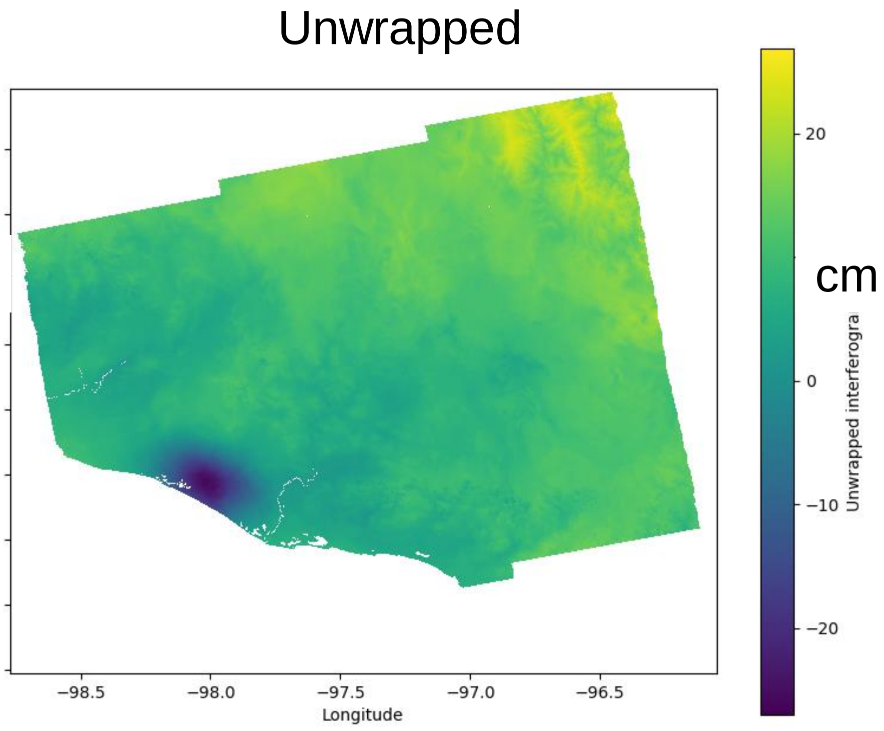
Case Study – Oxaca Earthquake Interferogram

- Sentinel 1-B SLC data
- https://vertex.daac.asf.alaska.edu (Alaska Satellite Facility)
- Processing: InSAR Scientific Computing Environment (WinSAR Consortium)

Pair: (2018-02-05 , 2018-02-17)
Event: 2018-02-16


Wrapped

rad

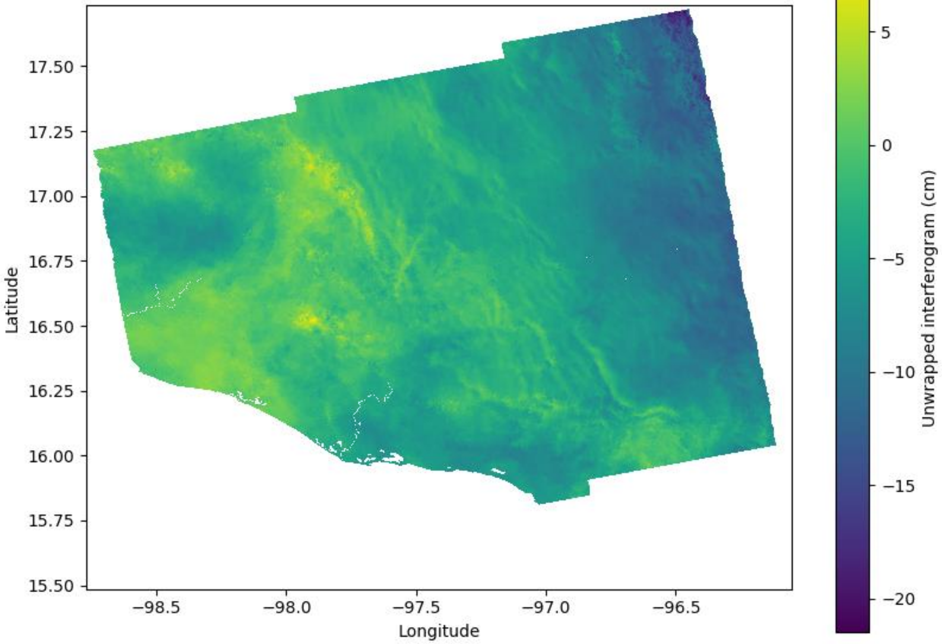

Unwrapped

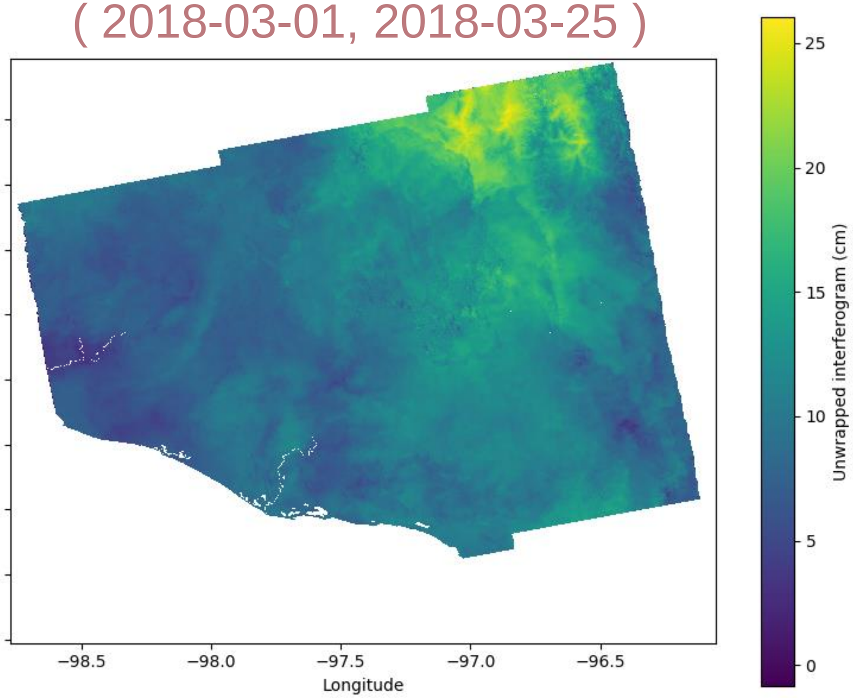
cm

Case Study – Atmospheric Delay – Preparations for Learning

Assessing interferograms before and after the earthquake (i.e., no deformation) to improve understanding of observable structures and artifacts

Event: 2018-02-16


Interferogram Before
(2017-11-01, 2017-11-13)


Interferogram After
(2018-03-01, 2018-03-25)

Case Study – Atmospheric Delay – Preparations for Learning

- Next: Aggregate information from several interferograms (14)
- Compare structures from interferograms with / without event

→ Structural Similarity Index (SSI) on 61x61 pixel cells

[Wang et al., IEEE, 2004]

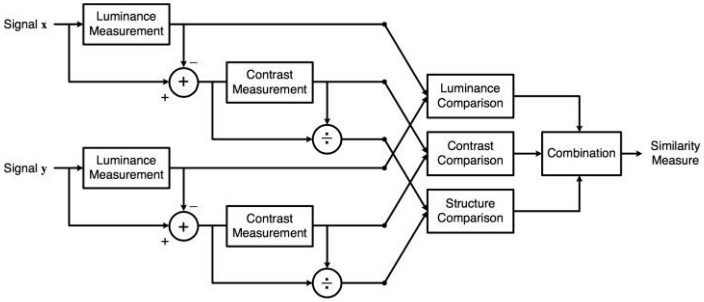
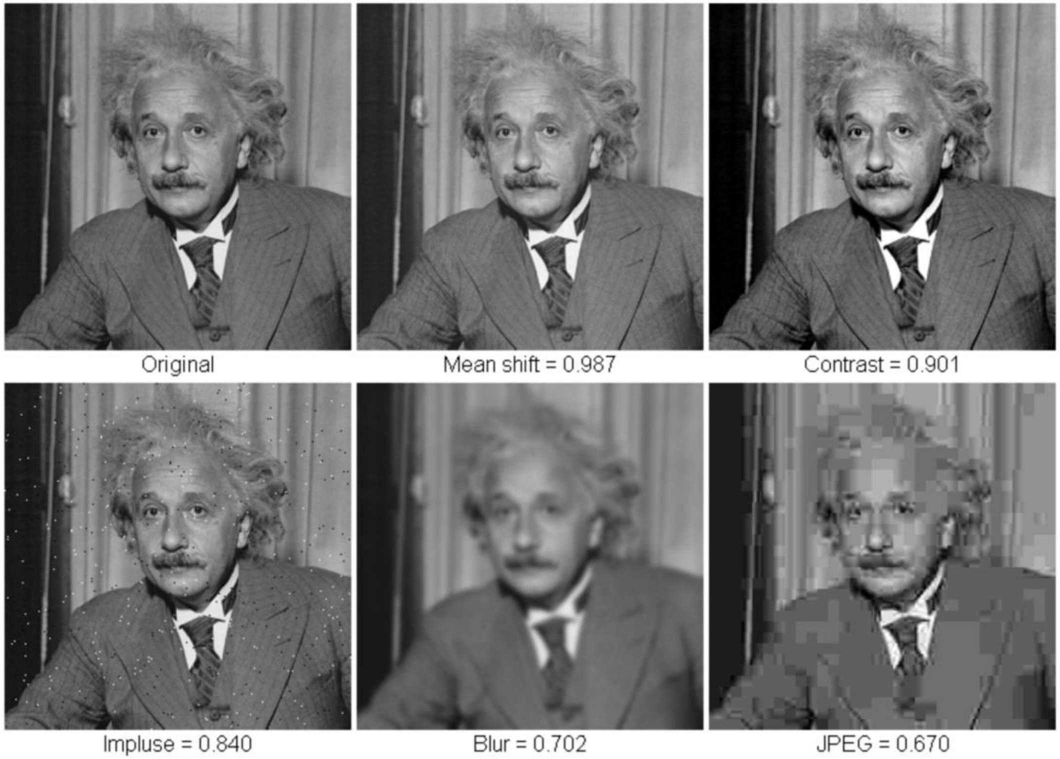


Fig. 3. Diagram of the structural similarity (SSIM) measurement system.



Original

Mean shift = 0.987

Contrast = 0.901

Impluse = 0.840

Blur = 0.702

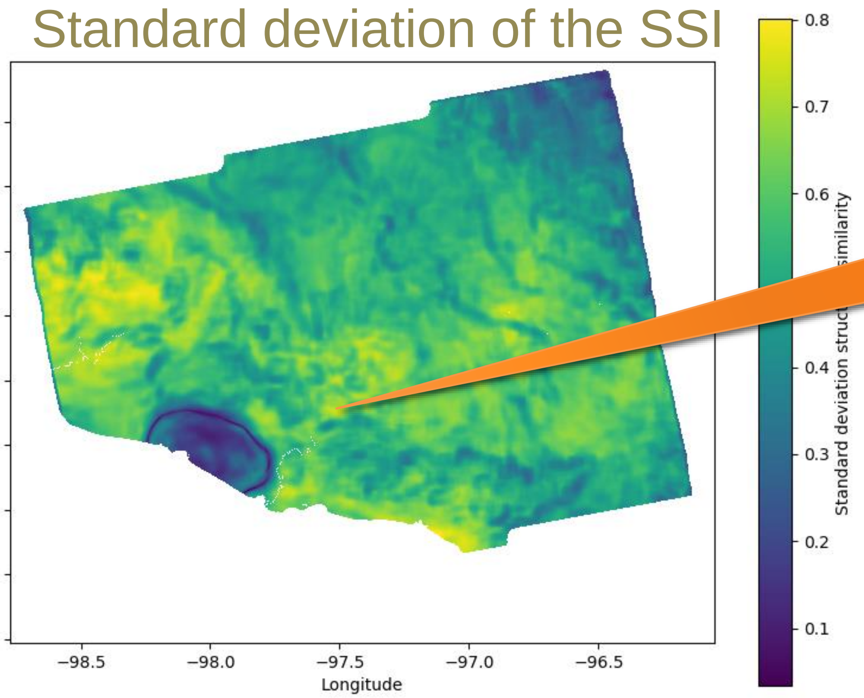
JPEG = 0.670

SSIM Results

Source: https://www.nsf.gov/news/mmg/media/images/ssim-demo.png

Case Study – Atmospheric Delay – Preparations for Learning

- Compute SD of SSI


Standard deviation of the SSI

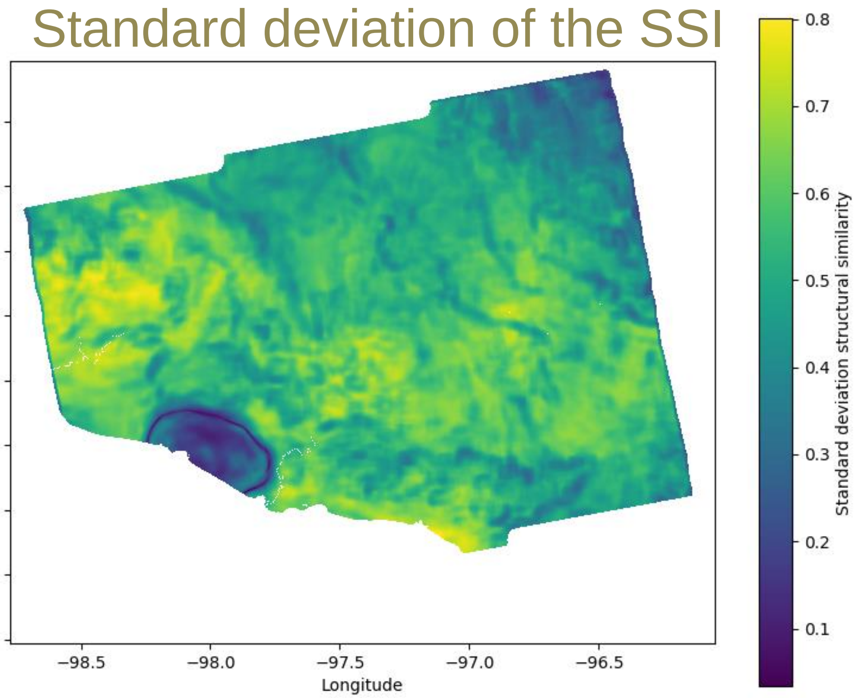
High SD → probably noise, less related to event

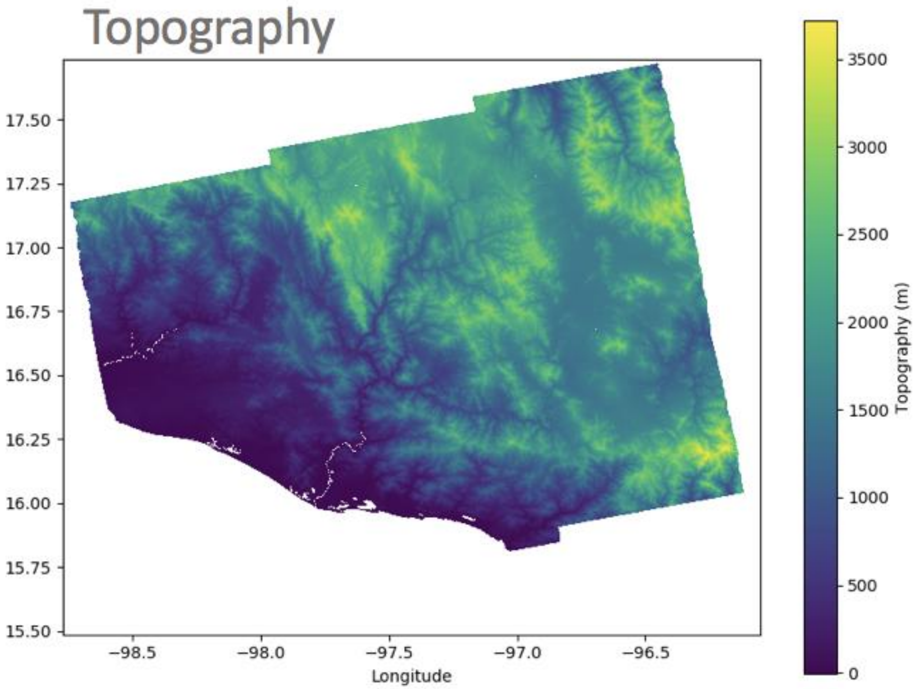
Now we know “where” to learn…

however…

Case Study – Atmospheric Delay

- Some artifacts related to topography, region, certain valleys, etc.
- Need to include this spatial information as specific domain knowledge


Standard deviation of the SSI


Topography

- …work in progress. More to do.

- Next: Perspectives
  - going beyond ML / Neural Networks

Paths to More Abstraction → Symbolic AI

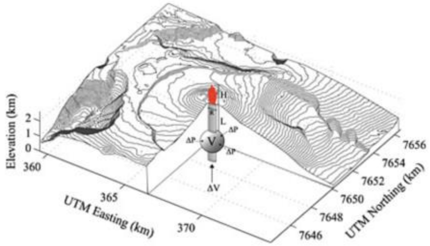
Model / Theory Generation

- Algebra for models
- Genetic programming

Closing the loop with current and future empirical observations

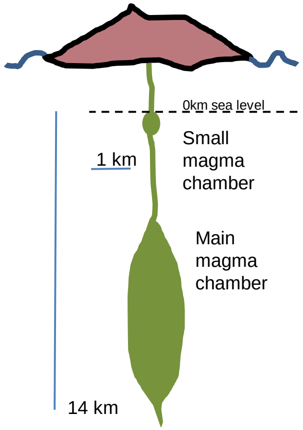
- Derivation of invariants: will always be true if a generated theory was right
- Derivation of falsification test cases
  - One example that contradicts a theory, if observed
  - Reveals information on what part of the theory is invalid
  - Theory "Adversary"

Volcanology Examles



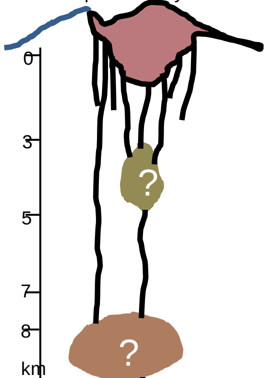
[Hibert et al., GRL '15]

Mt. St. Helens



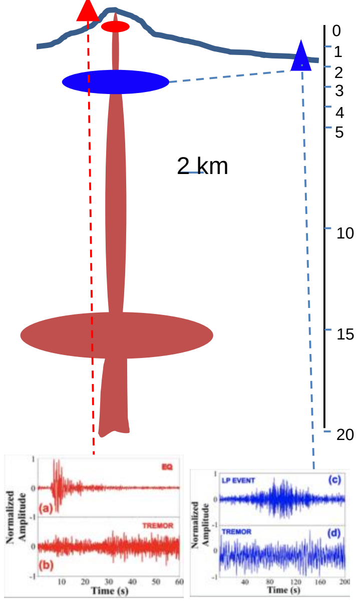
[Earle, Physical Geology, 2015, Fig. 4.12]

Mt. Somma – Vesuvius plumbing system



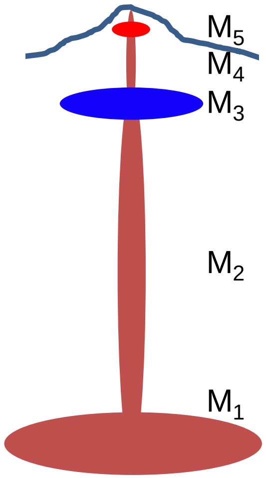
[Balcone-Boissard et al., Nature Scientific Reports 6, 21726, 2016; Fig. 1]

Stromboli



[Giovanetti et al. Remote Sens., 8(4), 2016, Fig 3]

Symbolic Model Examples



$$M_{seed} = M_1 \oplus M_2 \oplus M_3 \oplus M_4 \oplus M_5$$

perturb

$$\begin{aligned}\mathfrak{P}(M_{seed}) &= \mathfrak{P}(M_1 \oplus M_2 \oplus M_3 \oplus M_4 \oplus M_5)\\ &= \mathfrak{P}(M_1) \oplus \mathfrak{P}(M_2) \oplus \mathfrak{P}(M_3) \oplus \mathfrak{P}(M_4) \oplus \mathfrak{P}(M_5)\end{aligned}$$

M_i includes info on
- variables
- dom(variables)
- constraints(variables)

$$M_{1_1} \ldots M_{1_n}$$

trim

$$\begin{aligned}\mathfrak{T}(M_{seed}) &= \mathfrak{T}(M_1 \oplus M_2 \oplus M_3 \oplus M_4 \oplus M_5)\\ &= M_1 \oplus M_2 \oplus M_3 \oplus M_4\end{aligned}$$

extend

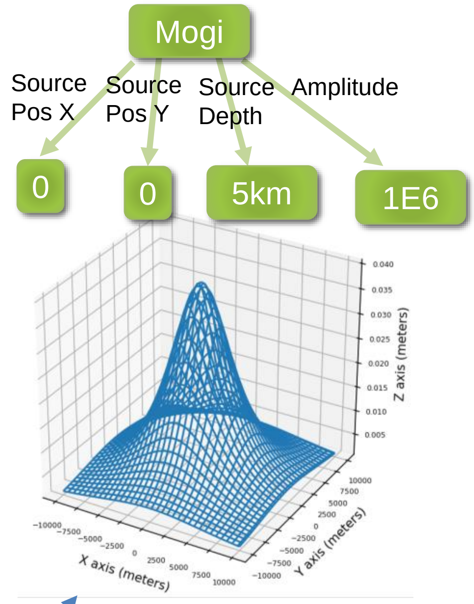
$$\begin{aligned}\mathfrak{E}(M_{seed}, M_6) &= \mathfrak{E}(M_1 \oplus M_2 \oplus M_3 \oplus M_4 \oplus M_5; M_6)\\ &= M_1 \oplus M_2 \oplus M_3 \oplus M_4 \oplus M_5 \oplus M_6\end{aligned}$$

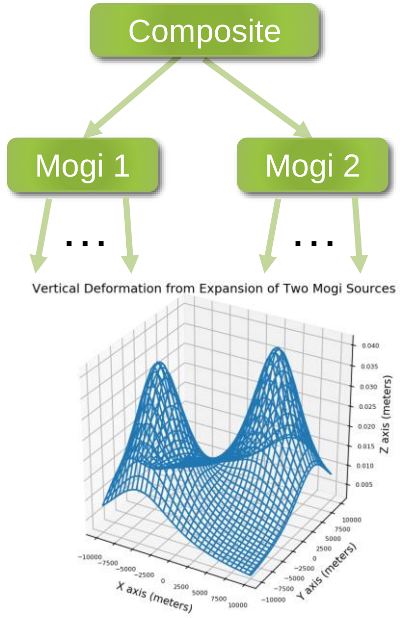
generate

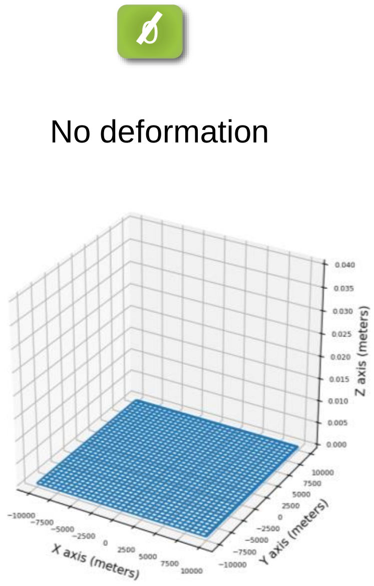
$$\mathfrak{G}(space(M)) = M_i \text{ with } M_i \in space(M)$$

Remark: more elaborate modeling requires introduction of a type system, constraints / domain-specific rules, …

Examples for M_i



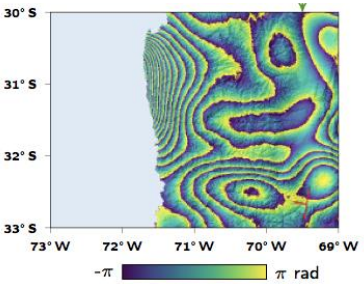


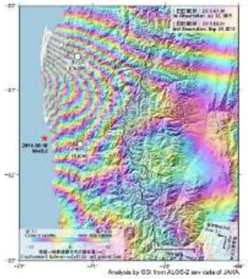


Compute Interferogram

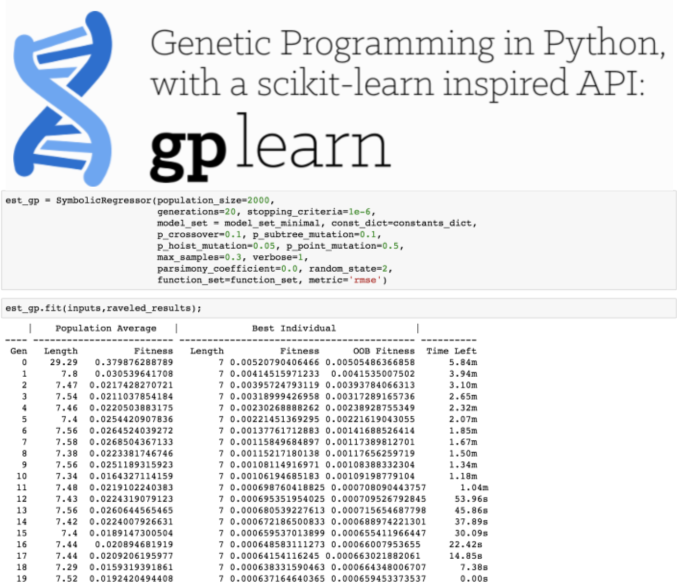
add machine-learned noise components

Compare with real-world InSAR satellite or UAV interferogram





[Rude, Pankratius, Rongier: work in progress]



Genetic Programming in Python, with a scikit-learn inspired API:

gplearn

```
est_gp = SymbolicRegressor(population_size=2000,
                           generations=20, stopping_criteria=1e-6,
                           model_set = model_set_minimal, const_dict=constants_dict,
                           p_crossover=0.1, p_subtree_mutation=0.1,
                           p_hoist_mutation=0.05, p_point_mutation=0.5,
                           max_samples=0.3, verbose=1,
                           parsimony_coefficient=0.0, random_state=2,
                           function_set=function_set, metric='rmse')
```

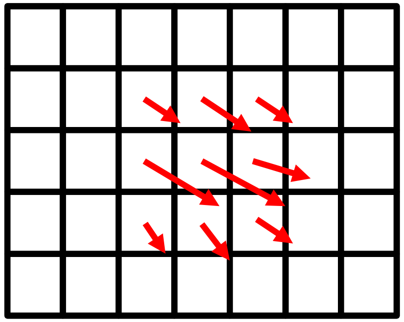
```
est_gp.fit(inputs,raveled_results);
```

```
    |    Population Average    |             Best Individual              |
---- ------------------------- ------------------------------------------ ----------
 Gen   Length          Fitness   Length          Fitness      OOB Fitness  Time Left
   0    29.29   0.379876288789        7 0.00520790406466 0.00505486366858      5.84m
   1      7.8   0.030539641708        7 0.00414515971233  0.0041535007502      3.94m
   2     7.47  0.0217428270721        7 0.00395724793119 0.00393784066313      3.10m
   3     7.54  0.0211037854184        7 0.00318999426958 0.00317289165736      2.65m
   4     7.46  0.0220503883175        7 0.00230268888262 0.00238928755349      2.32m
   5      7.4  0.0254420907836        7 0.00221451369295 0.00221619043055      2.07m
   6     7.56  0.0264524039272        7 0.00137761712883 0.00141688526414      1.85m
   7     7.58  0.0268504367133        7 0.00115849684897 0.00117389812701      1.67m
   8     7.38  0.0223381746746        7 0.00115217180138 0.00117656259719      1.50m
   9     7.56  0.0251189315923        7 0.00108114916971 0.00108388332304      1.34m
  10     7.34  0.0164327114159        7 0.00106194685183 0.00109198779104      1.18m
  11     7.48  0.0219102240383        7 0.000698760418825 0.000708090443757      1.04m
  12     7.43  0.0224319079123        7 0.000695351954025 0.000709526792845     53.96s
  13     7.56  0.0260644565465        7 0.000680539227613 0.000715654687798     45.86s
  14     7.42  0.0224007926631        7 0.000672186500833 0.000688974221301     37.89s
  15      7.4  0.0189147300504        7 0.000659537013899 0.000655411966447     30.09s
  16     7.44   0.020894681919        7 0.000648583111273 0.00066007953655     22.42s
  17     7.44  0.0209206195977        7 0.00064154116245 0.000663021882061     14.85s
  18     7.29  0.0159319391861        7 0.000638331590463 0.000664348006707      7.38s
  19     7.52  0.0192420494408        7 0.000637164640365 0.000659453373537      0.00s
```

Examples Related to Earthquakes

- Generating examples of surface deformation from Earthquakes
- Simulating Earthquakes using a Grid of Okada faults
- Each cell can have a different direction and distance travelled

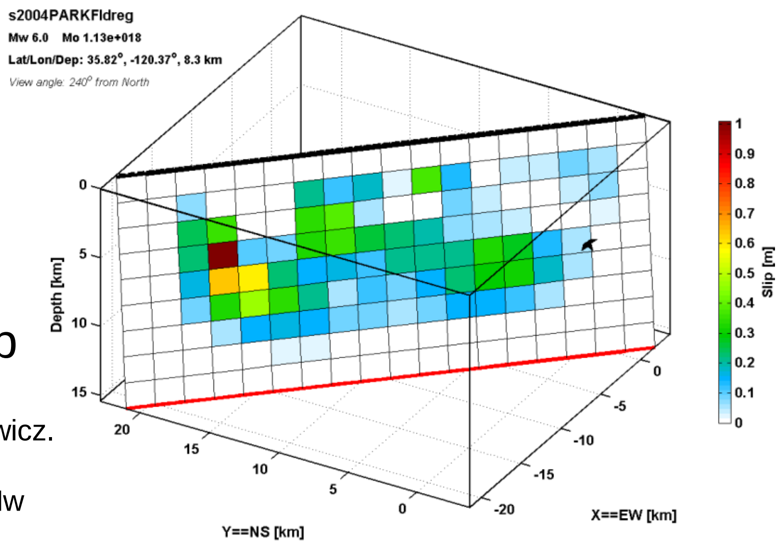
Fault simulated as several individual tiles



Arrows indicate direction and magnitude of slip

Models from the Finite-Source Rupture Model Database

Parkfield (Calif.)

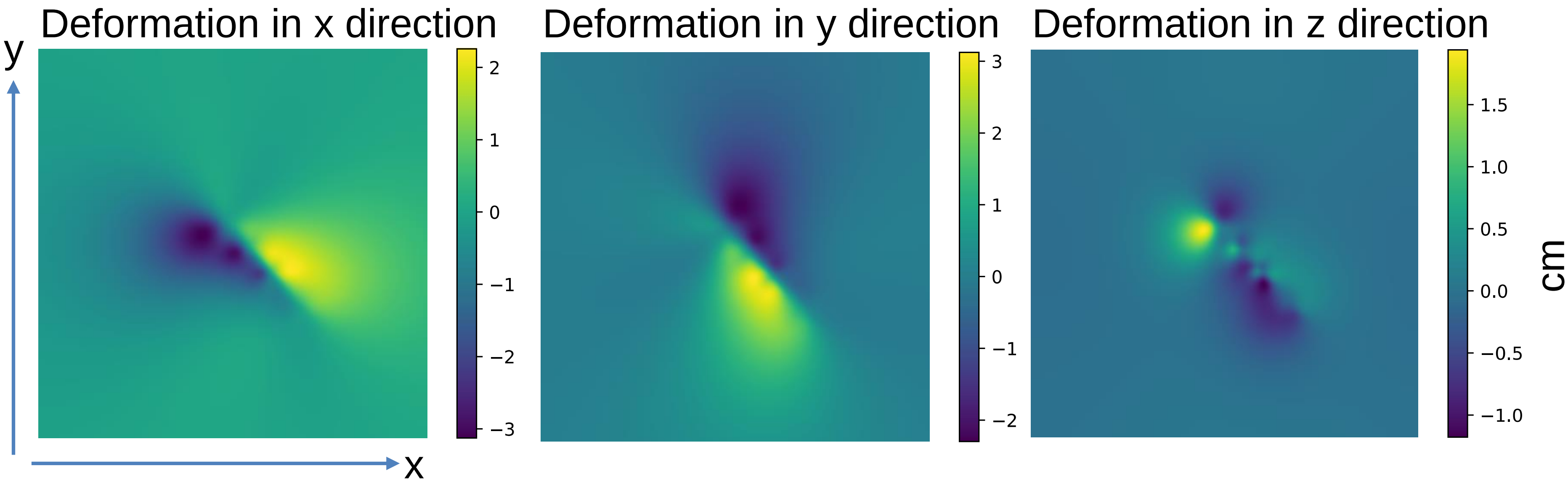


Color of each cell indicates amount of slip

Dreger, D. S., L. Gee, P. Lombard, M. H. Murray, and B. Romanowicz. 2005. Rapid finite-source analysis and near-fault strong ground motions: Application to the 2003 M-w 6.5 San Simeon and 2004 Mw 6.0 Parkfield earthquakes. Seis. Res. Lett. 76 (1):40-48.

Examples Related to Earthquakes

Simulated Deformation



- Earthquake simulation yields surface deformations in 3 directions
- The sensitivity to the different directions depends on relative position of the satellite and the deformation
- Different interferograms can be generated from different satellite paths and heights

Thanks!

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