National Aeronautics and Space Administration

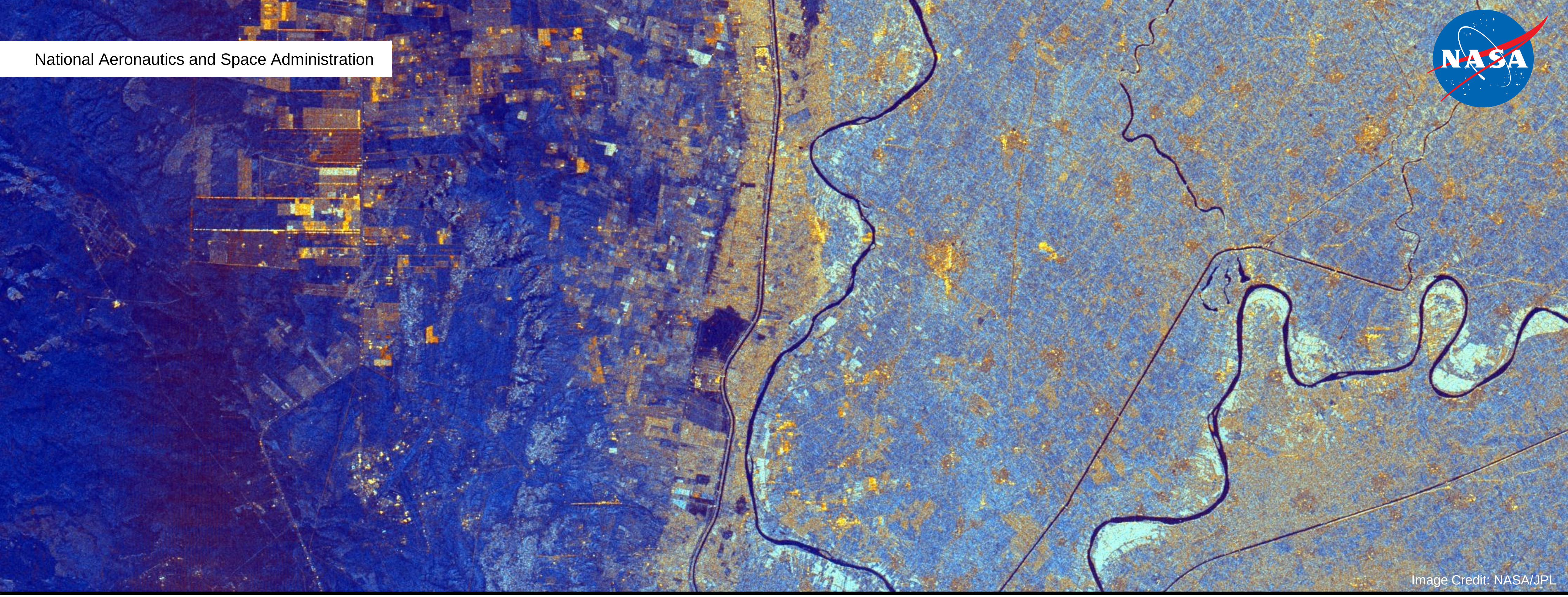

Image Credit: NASA/JPL

SAR Interferometry for Earthquake Studies

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16 August 2018

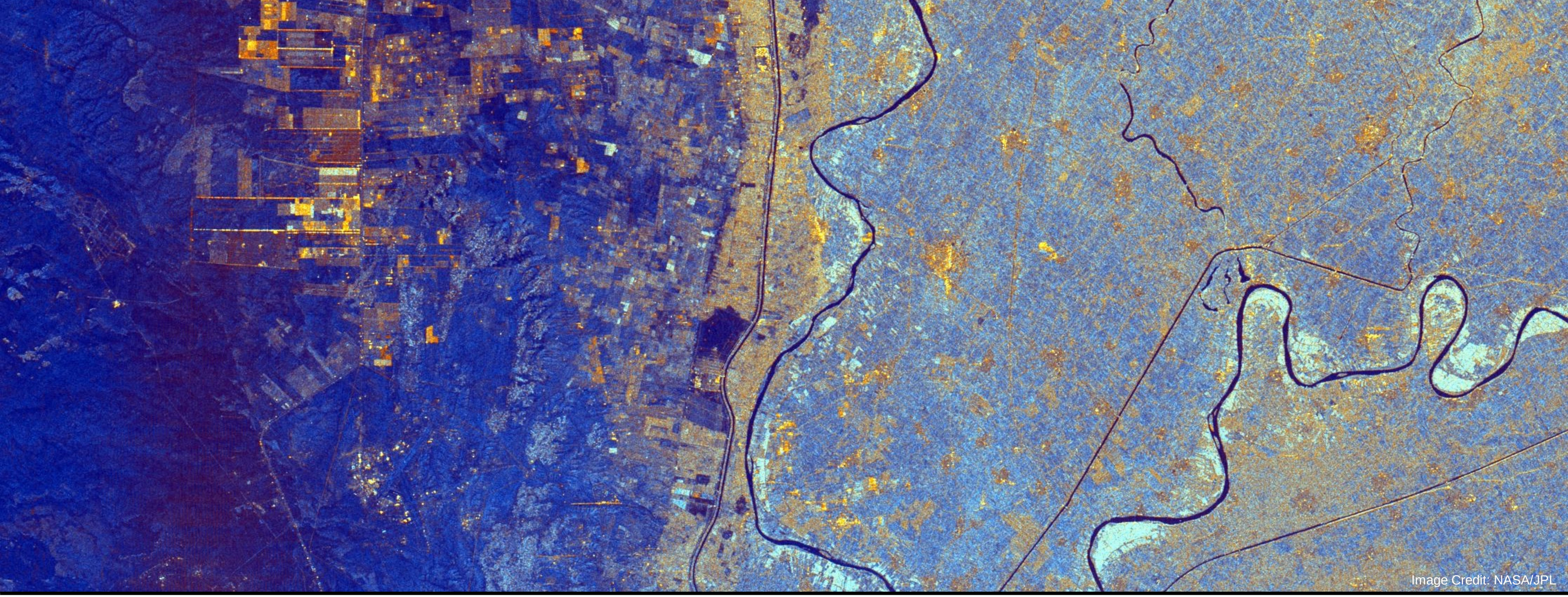
Learning Objectives

By the end of this presentation, you will be able to:

- Understand the basic physics of SAR interferometry
- Describe what SAR interferometric phase tells about the land surface
- Describe the necessary data processing for making an interferogram
- Understand the information content in SAR interferometric images

Prerequisites

- Basics of Synthetic Aperture Radar 2017
- SAR Processing and Data Analysis 2017
- Introduction to SAR Interferometry 2017



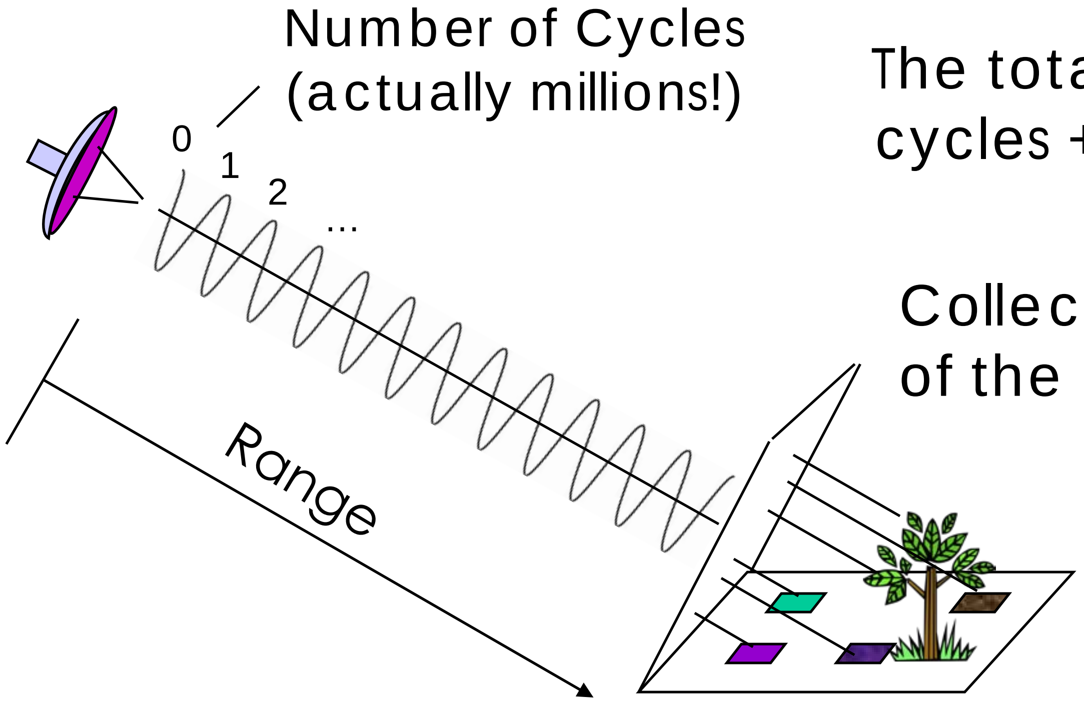
SAR Interferometry Theory (Review)

SAR Interferometry Theory

- Quick review of synthetic aperture radar interferometry theory
- See the 2017 ARSET training “Introduction to SAR Interferometry” for more details
- In SAR interferometry, it is all about the phase of the SAR signal

SAR Phase – A Measure of the Range and Surface Complexity

The phase of the radar signal is the number of *cycles of oscillation* that the wave executes between the radar and the surface and back again



The total phase is a two-way range measured in wave cycles + random components from the surface

Collection of random path lengths jumbles the phase of the echo

Only *interferometry* can sort it out!

Slide Courtesy of Paul Rosen (JPL)

A Simplistic View of SAR Phases

Phase of Image 1 $$\phi_1 = \frac{4\pi}{\lambda} \cdot \rho_1 + other\ constants + \ n_1$$

Phase of Image 2 $$\phi_2 = \frac{4\pi}{\lambda} \cdot \rho_2 + other\ constants + \ n_2$$

1. The “other constants” cannot be directly determined
2. “Other constants” depends on scatterer distribution in the resolution cell, which is unknown and varies from cell to cell
3. The only way of observing the range change is through interferometry (cancellation of “other constants”)

Slide modified from Paul Rosen (JPL)

SAR Interferometry Applications

- Mapping/Cartography
  - SAR interferometry was used for the 2000 Shuttle Radar Topography Mission (SRTM), new 2018 release as NASADEM
  - Radar Interferometry from airborne platforms is routinely used to produce topographic maps as digital elevation models (DEMs)
    - 2–5 meter circular position accuracy
    - 5–10 m post spacing and resolution
    - 10 km by 80 km DEMs produced in 1 hr on a mini-supercomputer
    - NASA SAR topography presently acquired by GLISTIN
  - Radar imagery is automatically geocoded, becoming easily combined with other (multispectral) data sets
  - Applications of topography enabled by interferometric rapid mapping
    - Land use management, classification, hazard assessment, intelligence, urban planning, short and long time scale geology, hydrology

Slide Modified from Paul Rosen (JPL)

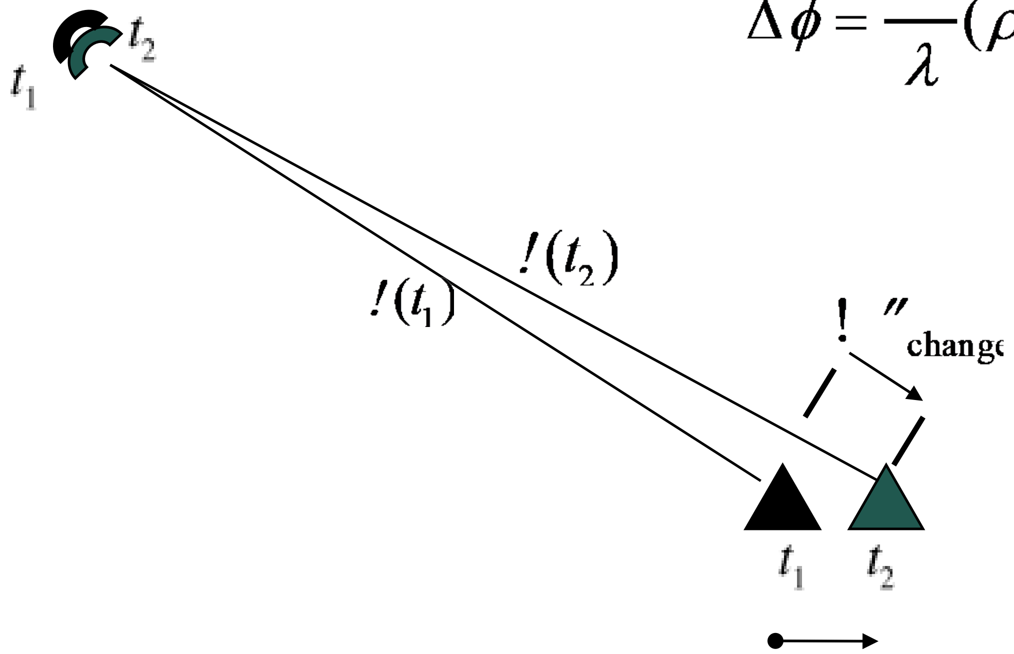
SAR Interferometry Applications

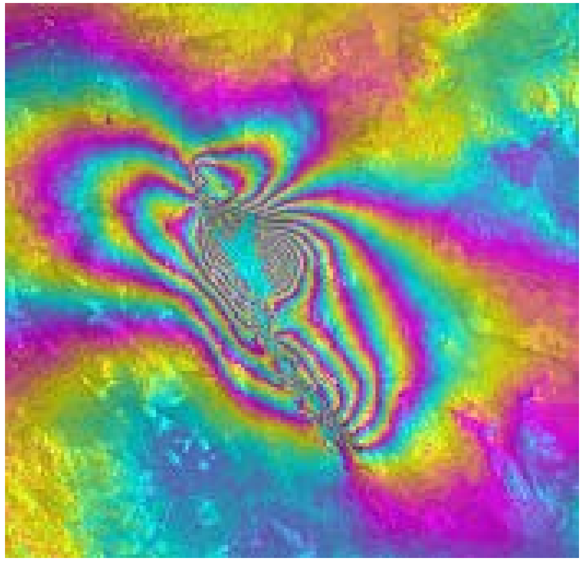
- Deformation Mapping and Change Detection
  - Repeat Pass Radar Interferometry from spaceborne platforms is routinely used to produce topographic change maps as digital displacement models (DDMs).
    - 0.1–1 centimeter relative displacement accuracy
    - 10–100 m post spacing and resolution
    - 10–350 km wide DDMs produced rapidly once data is available
  - Applications include
    - Earthquake and volcano monitoring and modeling, landslides and subsidence
    - Glacier and ice sheet dynamics
    - Deforestation, change detection, disaster monitoring

Differential Interferometry

- When two observations are made from the same location in space but at different times, the interferometric phase is proportional to any change in the range of a surface feature directly.

$$\Delta\phi = \frac{4\pi}{\lambda}\left(\rho(t_1) - \rho(t_2)\right) = \frac{4\pi}{\lambda}\Delta\rho_{\text{change}}$$





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Differential Interferometry Sensitivities

- The reason differential interferometry can detect millimeter-level surface deformation is that the differential phase is much more sensitive to displacements than to topography.

$$\frac{\partial \phi}{\partial h} = \frac{2\pi p b \cos(\theta - \alpha)}{\lambda \rho \sin\theta} = \frac{2\pi p b_\perp}{\lambda \rho \sin\theta}$$ Topographic Sensitivity

$(\phi \Leftrightarrow \Delta\phi)$ $$\frac{\partial \phi}{\partial \Delta\rho} = \frac{4\pi}{\lambda}$$ Displacement Sensitivity

$$\sigma_{\phi_{topo}} = \frac{\partial \phi}{\partial h}\sigma_h = \frac{4\pi}{\lambda}\frac{b_\perp}{\rho \sin\theta}\sigma_h$$ Topographic Sensitivity Term

$$\sigma_{\phi_{disp}} = \frac{\partial \phi}{\partial \Delta\rho}\sigma_{\Delta\rho} = \frac{4\pi}{\lambda}\sigma_{\Delta\rho}$$ Displacement Sensitivity Term

Since $\frac{b}{\rho} << 1$ ==> $\frac{\sigma_{\phi_{disp}}}{\sigma_{\Delta\rho}} >> \frac{\sigma_{\phi_{topo}}}{\sigma_h}$

Meter Scale Topography Measurement - Millimeter Scale Topographic Change

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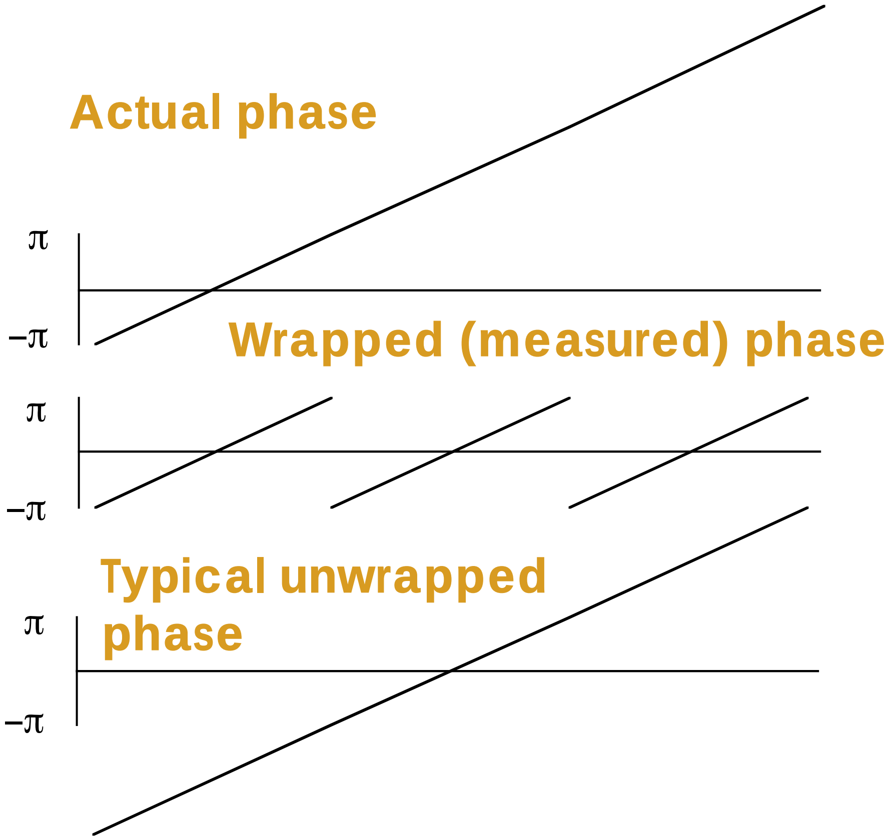
Phase Unwrapping

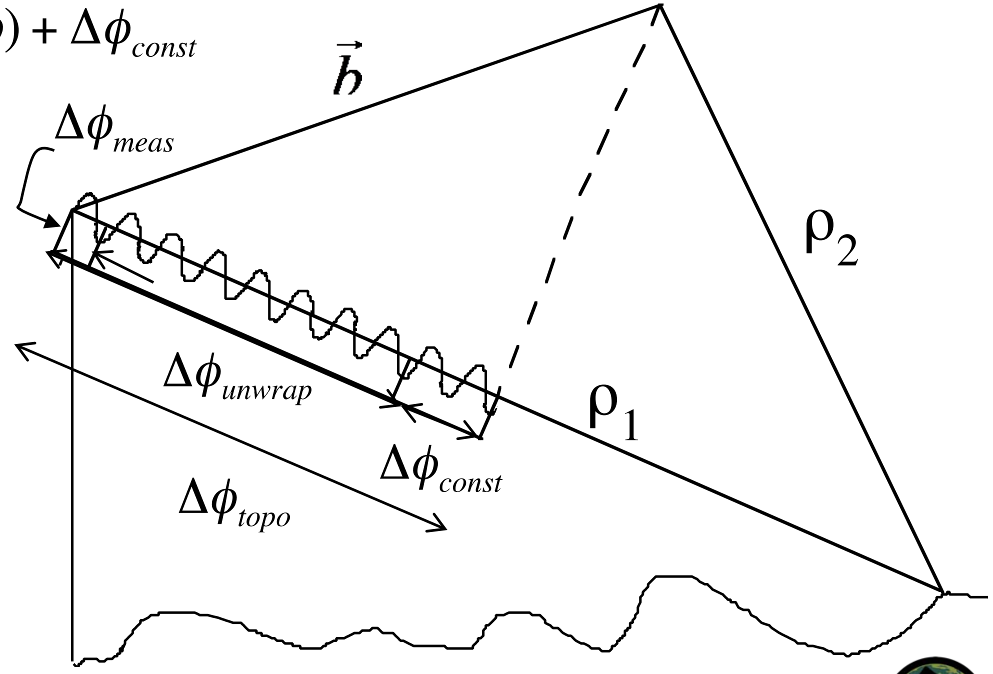
- From the measured, wrapped phase, unwrap the phase from some arbitrary starting location, then determine the proper 2p phase “ambiguity”



$$\Delta\phi_{topo} = \frac{2\pi p}{\lambda}(\rho_1 - \rho_2) = \frac{2\pi p}{\lambda}\vec{b} \bullet \vec{l}$$

$$\Delta\phi_{meas} = \mathrm{mod}(\Delta\phi_{topo}, 2\pi)$$

$$\Delta\phi_{unwrap}(s,\rho) = \Delta\phi_{topo}(s,\rho) + \Delta\phi_{const}$$



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Correlation* Theory

- InSAR signals decorrelate (become incoherent) due to
  - Thermal and Processor Noise
  - Differential Geometric and Volumetric Scattering
  - Rotation of Viewing Geometry
  - Random Motions Over Time

- Decorrelation relates to the local phase standard deviation of the interferogram phase
  - Affects height and displacement accuracy
  - Affects ability to unwrap phase

*"Correlation" and "Coherence" are often used synonymously

Slide modified from Paul Rosen (JPL)

InSAR Correlation Components

- Correlation effects multiply, unlike phase effects that add
- Low coherence or decorrelation for any reason causes loss of information in that area

$\gamma = \gamma_v \gamma_g \gamma_t \gamma_c$

where

γ_v is volumetric (trees)

γ_g is geometric (steep slopes)

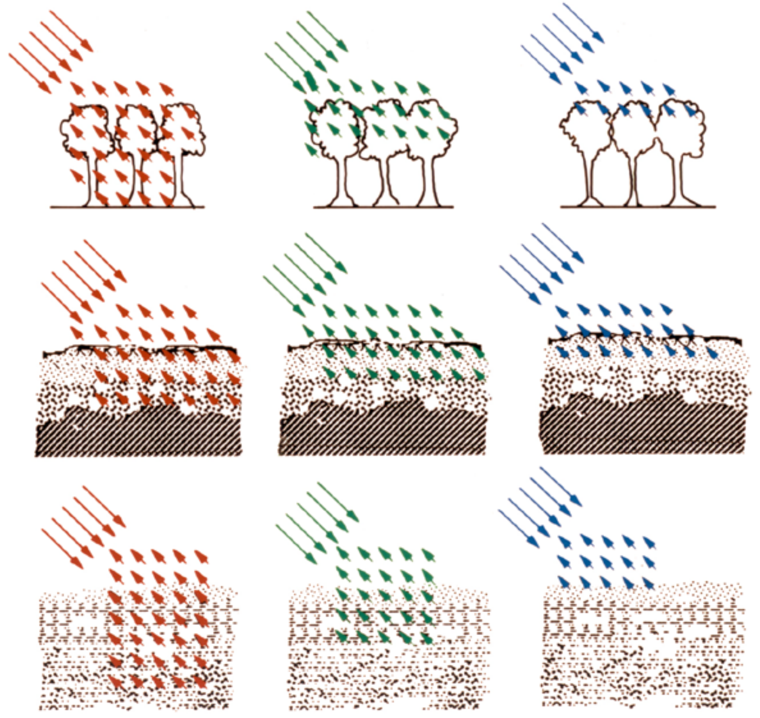
γ_t is temporal (gradual changes)

γ_c is sudden changes

Wavelength: A Measure of Surface Scale

Light interacts most strongly with objects around the size of the wavelength

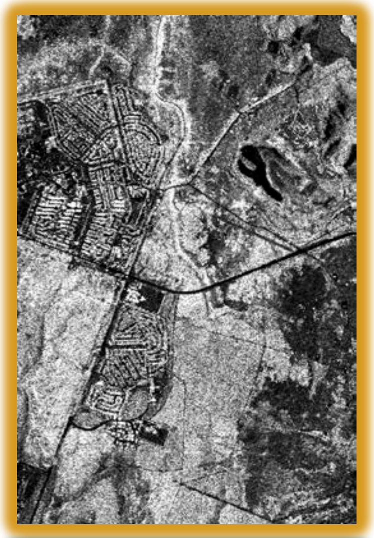
L (24 cm) C (6 cm) X (3 cm)



Forest: Leaves reflect X-band wavelengths but not L-band

Dry Soils: Surface looks rough to X-band but not L-band

Ice: Surface and layering look rough to X-band but not L-band



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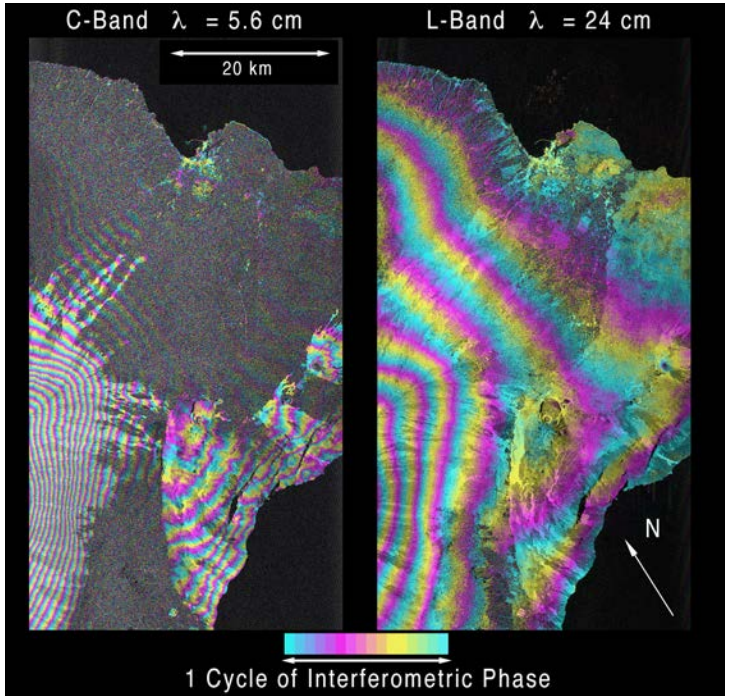
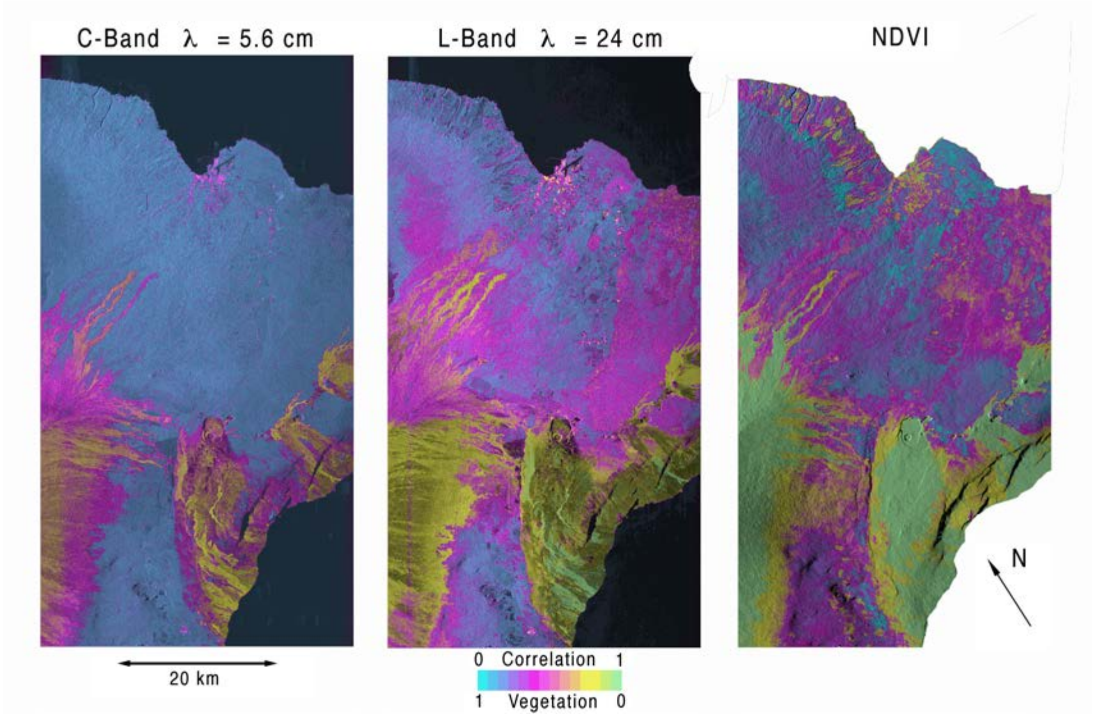
Coherent Change Detection

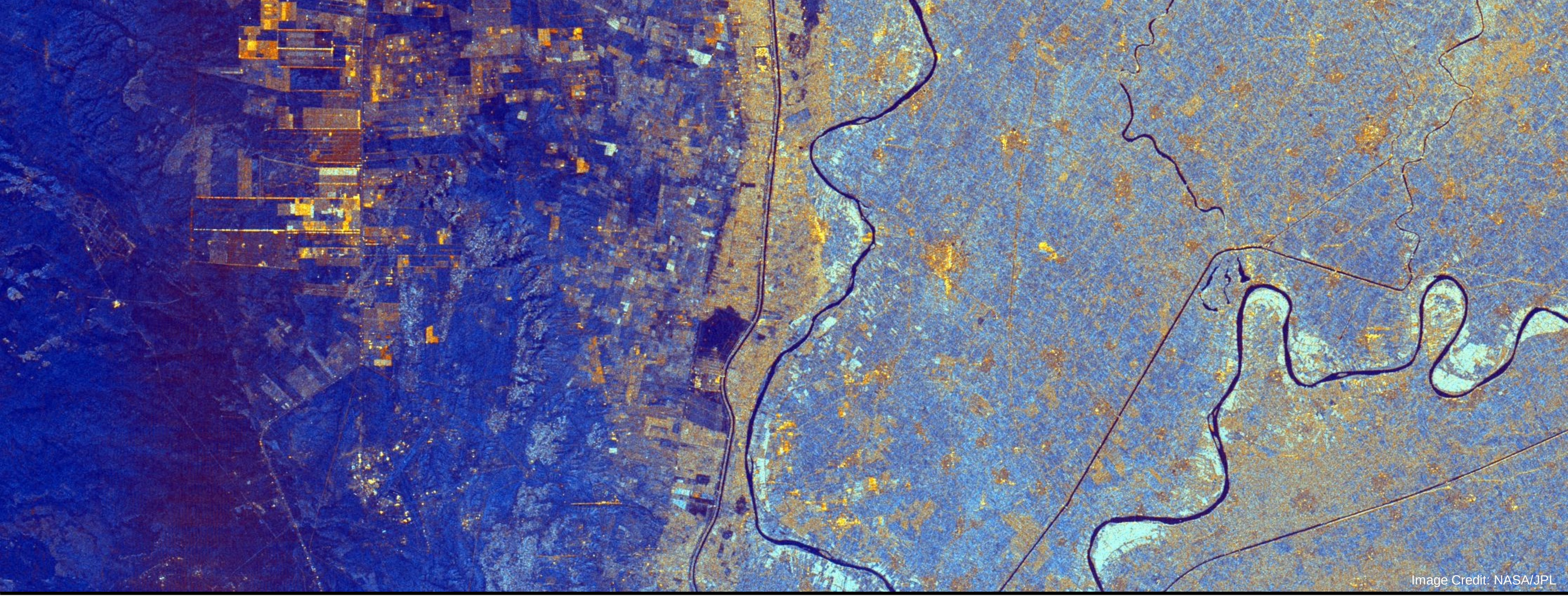
SIR-C L and C-band Interferometry

- 6-month time separated observations to form interferograms
- Simultaneous C and L band



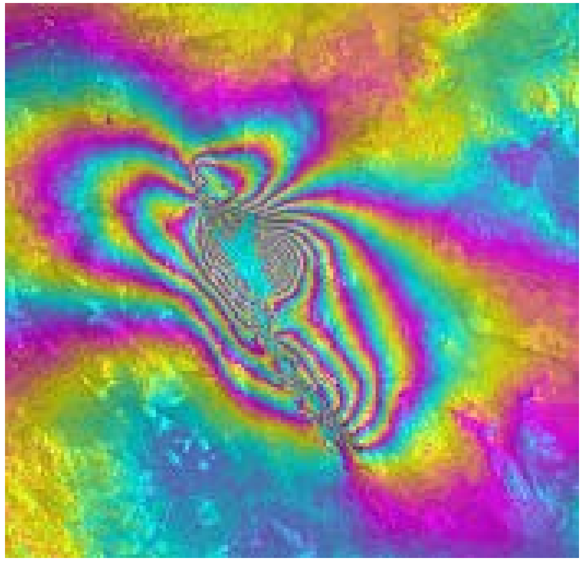


InSAR experiments have shown good correlation at L-band

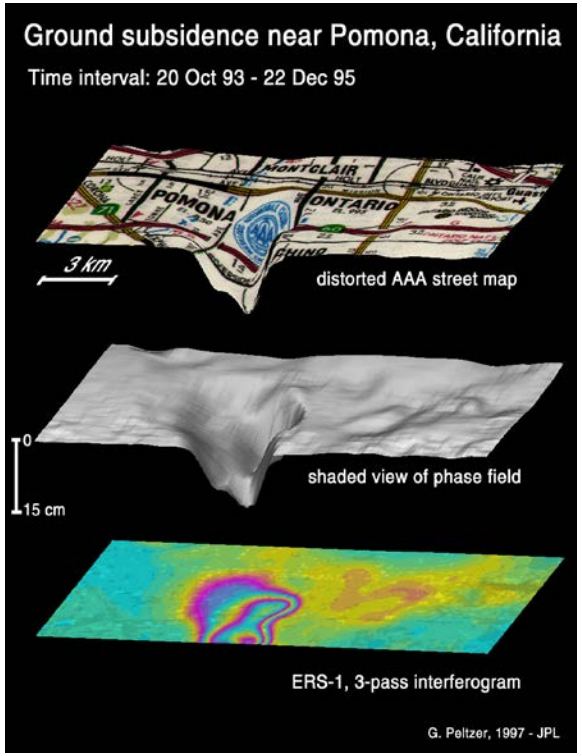


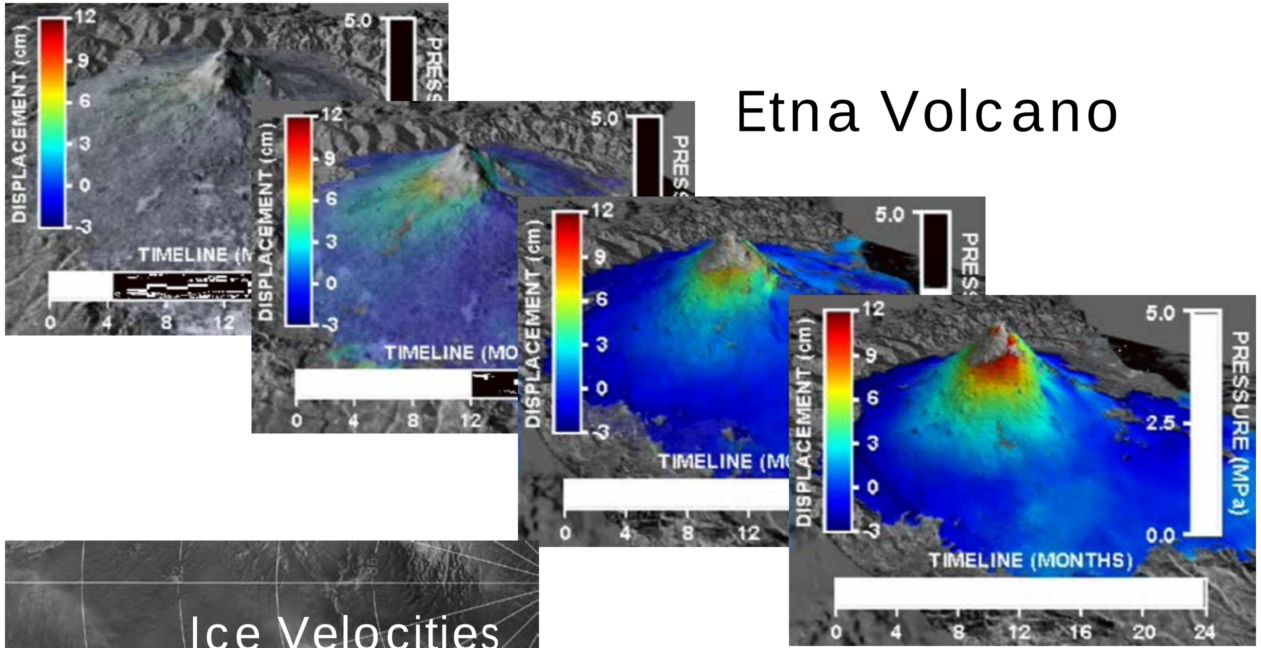
InSAR Applications—Earthquakes, etc.

Some Examples of Deformation

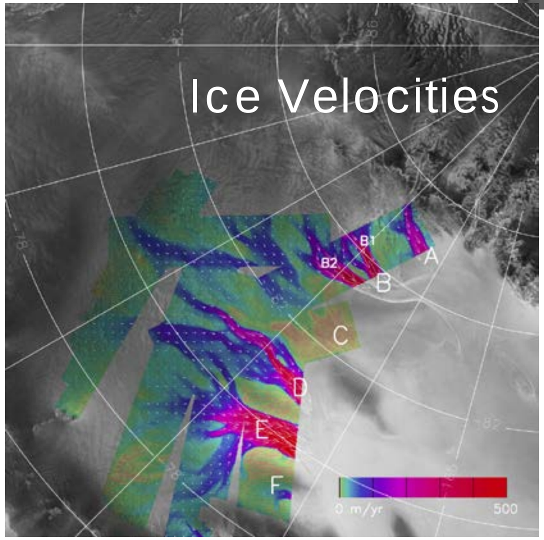


Hector Mine Earthquake





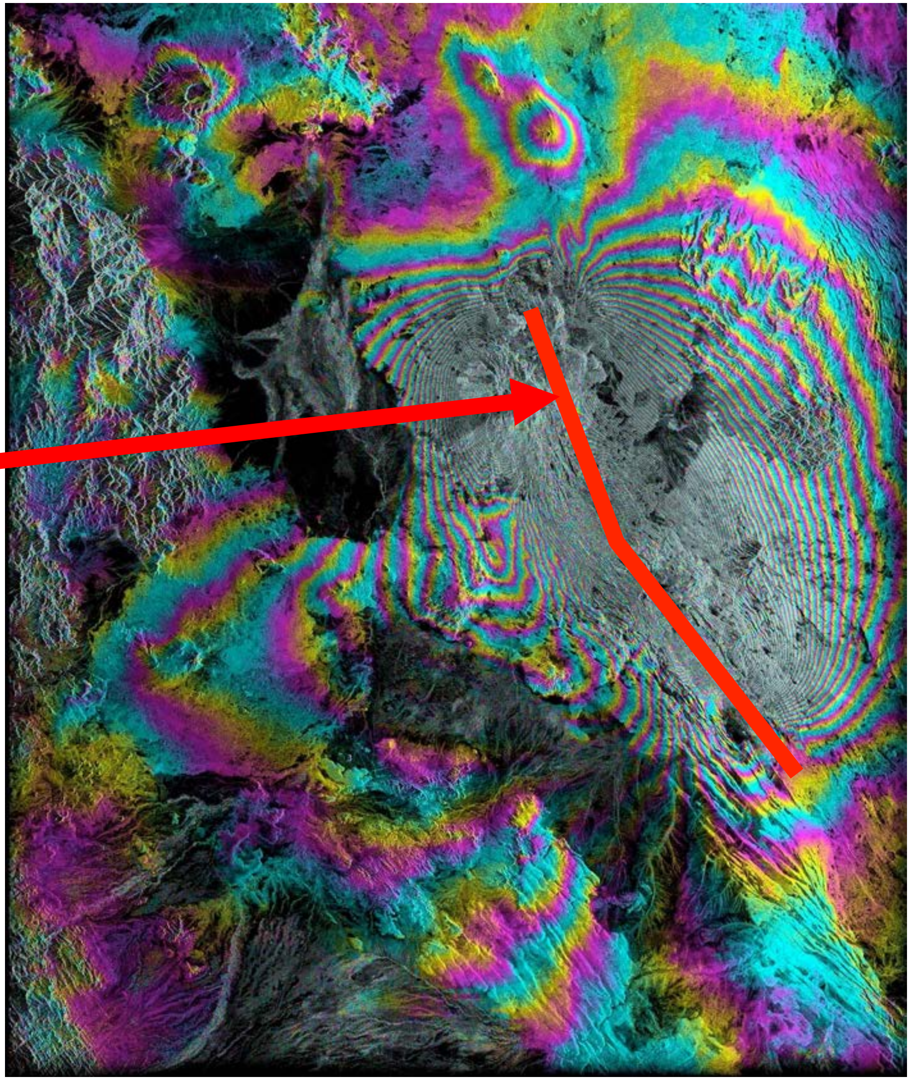
Etna Volcano



Joughin et al , 1999

Slide modified from Paul Rosen (JPL)

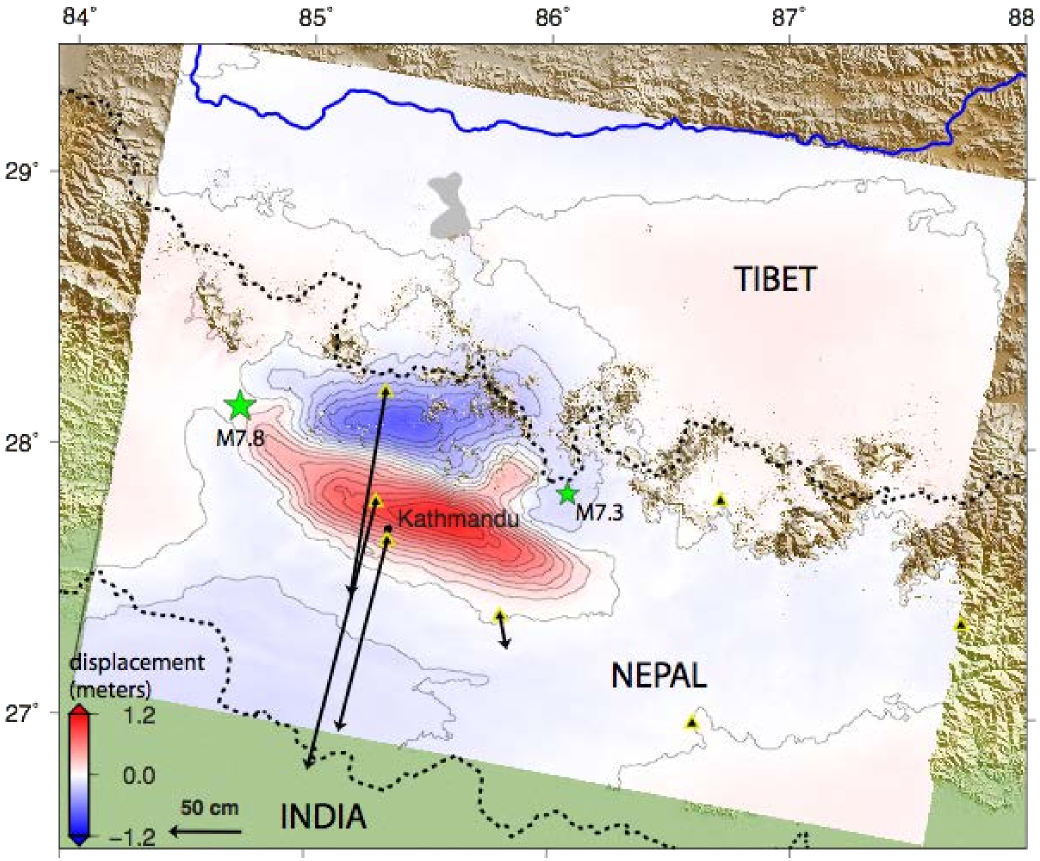
Asal Rift Dike Injection



Envisat interferogram 6 May – 28 Oct 2005; form Tim Wright, U. Leeds

2015 M7.8 Gorkha Earthquake in Nepal

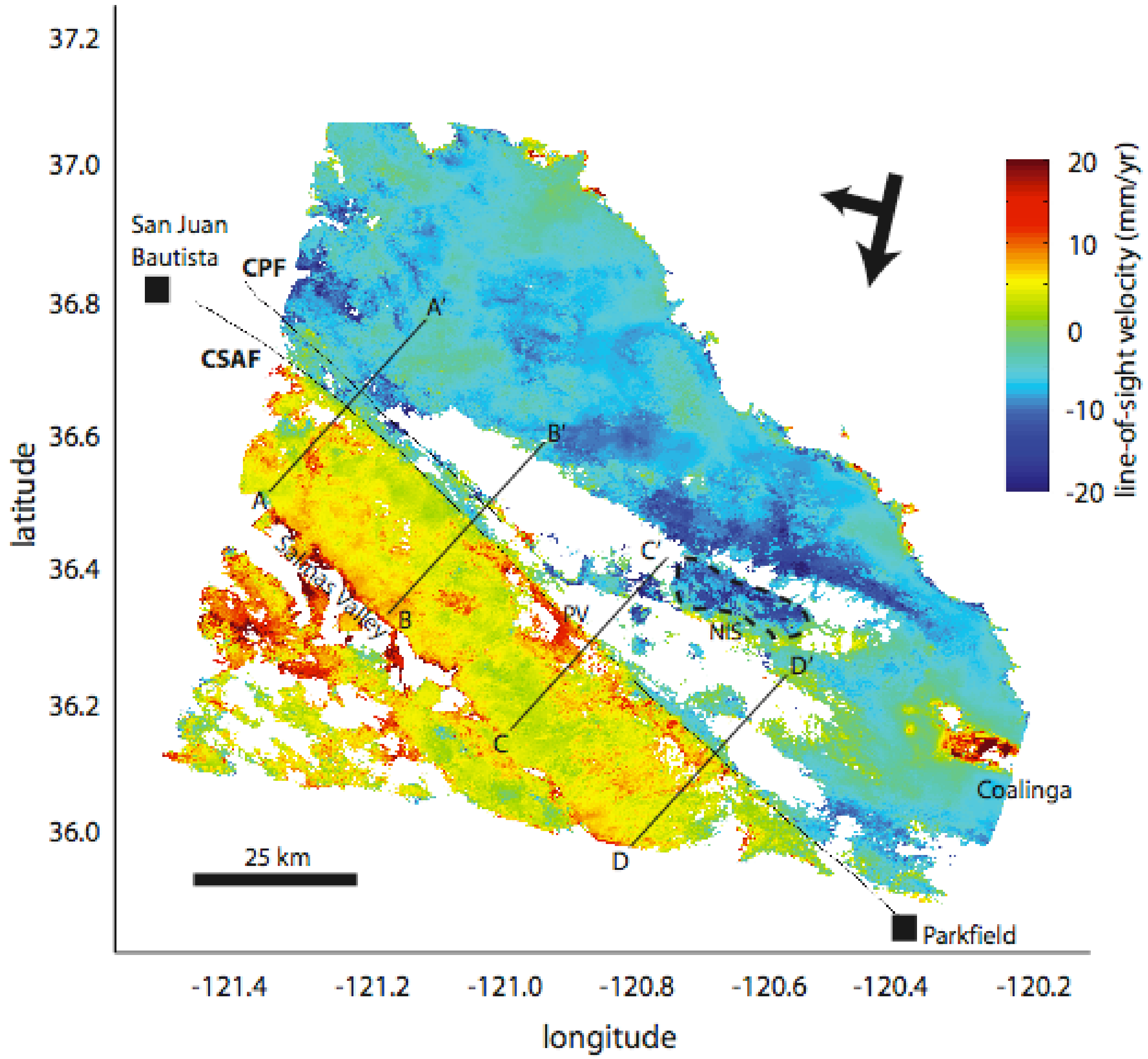
- ALOS-2 ScanSAR interferogram
- Descending line-of-sight (LOS) perpendicular to horizontal
- InSAR phase only sees vertical component
- High Himalayas dropped down as much as 1.2 m
- Yue, H., et al. (2017), Depth varying rupture properties during the 2015 Mw 7.8 Gorkha (Nepal) earthquake, Tectonophysics, v. 714-715, p. 44-54, doi:10.1016/j.tecto.2016.07.005.



Slip pulse and resonance of the Kathmandu basin during the 2015 Gorkha earthquake, Nepal

GPS data from Galetzka, J., et al. (2015), *Science*, *349* (6252), 1091-1095

Creep on the San Andreas Fault

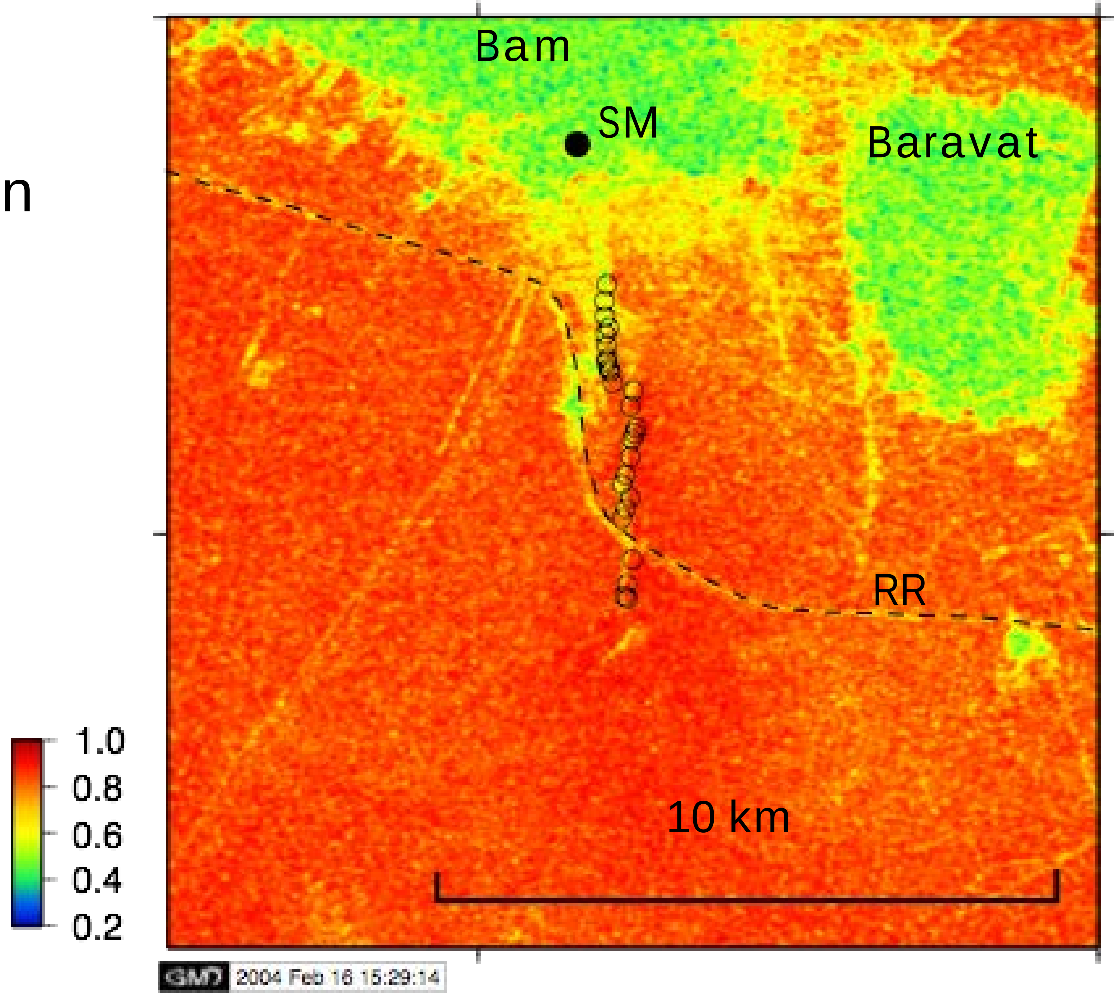


Stack of 12 ERS interferograms spanning May 1992-Jan 2001

Figures from Isabelle Ryder, UC Berkeley

Decorrelation Shows Surface Ruptures

2003 M6.5 Bam earthquake in Iran



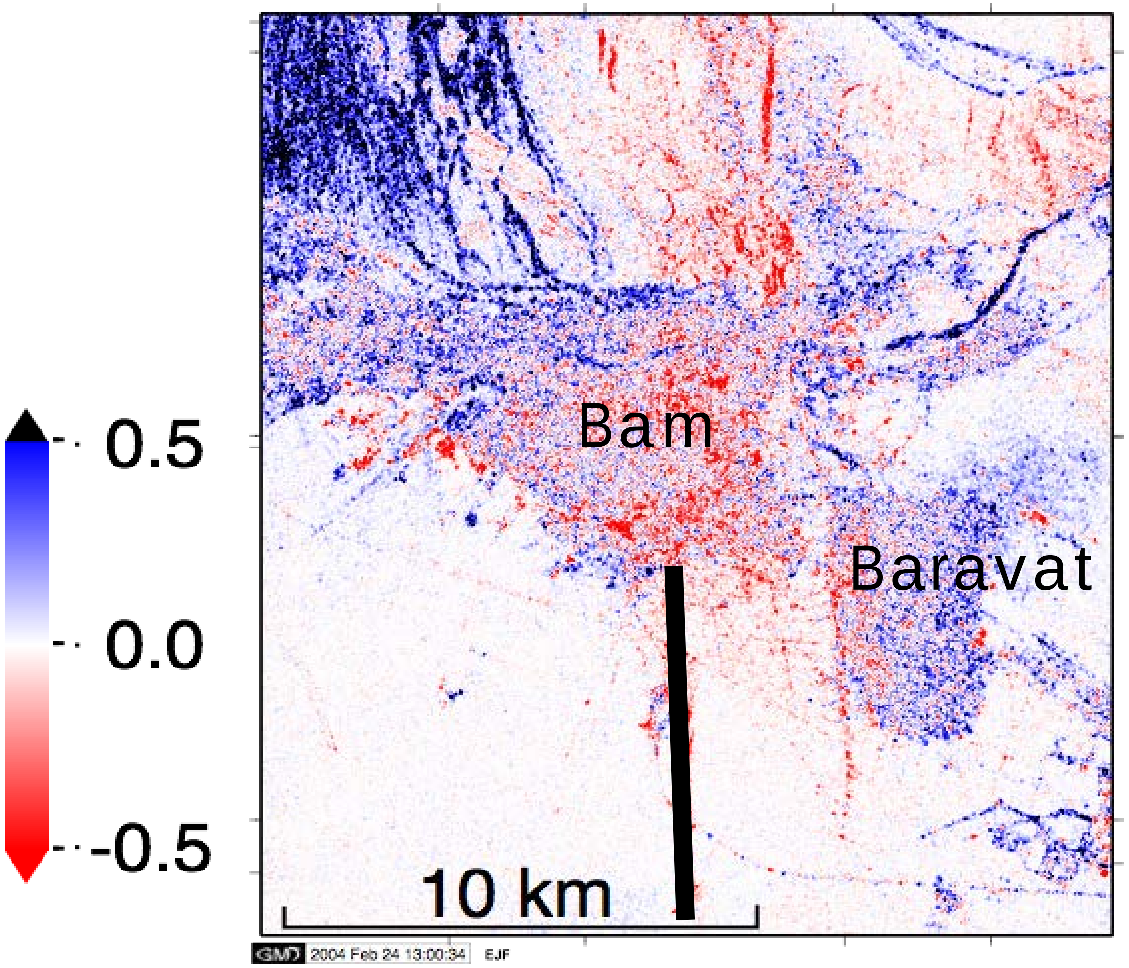
Envisat 35 days
2003/12/3 – 2004/1/7

Descending track

Bperp 580 m

Fielding, E. J., M. Talebian, P. A. Rosen, H. Nazari, J. A. Jackson, M. Ghorashi, and R. Walker (2005), Surface ruptures and building damage of the 2003 Bam, Iran, earthquake mapped by satellite synthetic aperture radar interferometric correlation, *J. Geophys. Res.*, *110*(B3), B03302, doi:10.1029/2004JB003299.

Correlation change

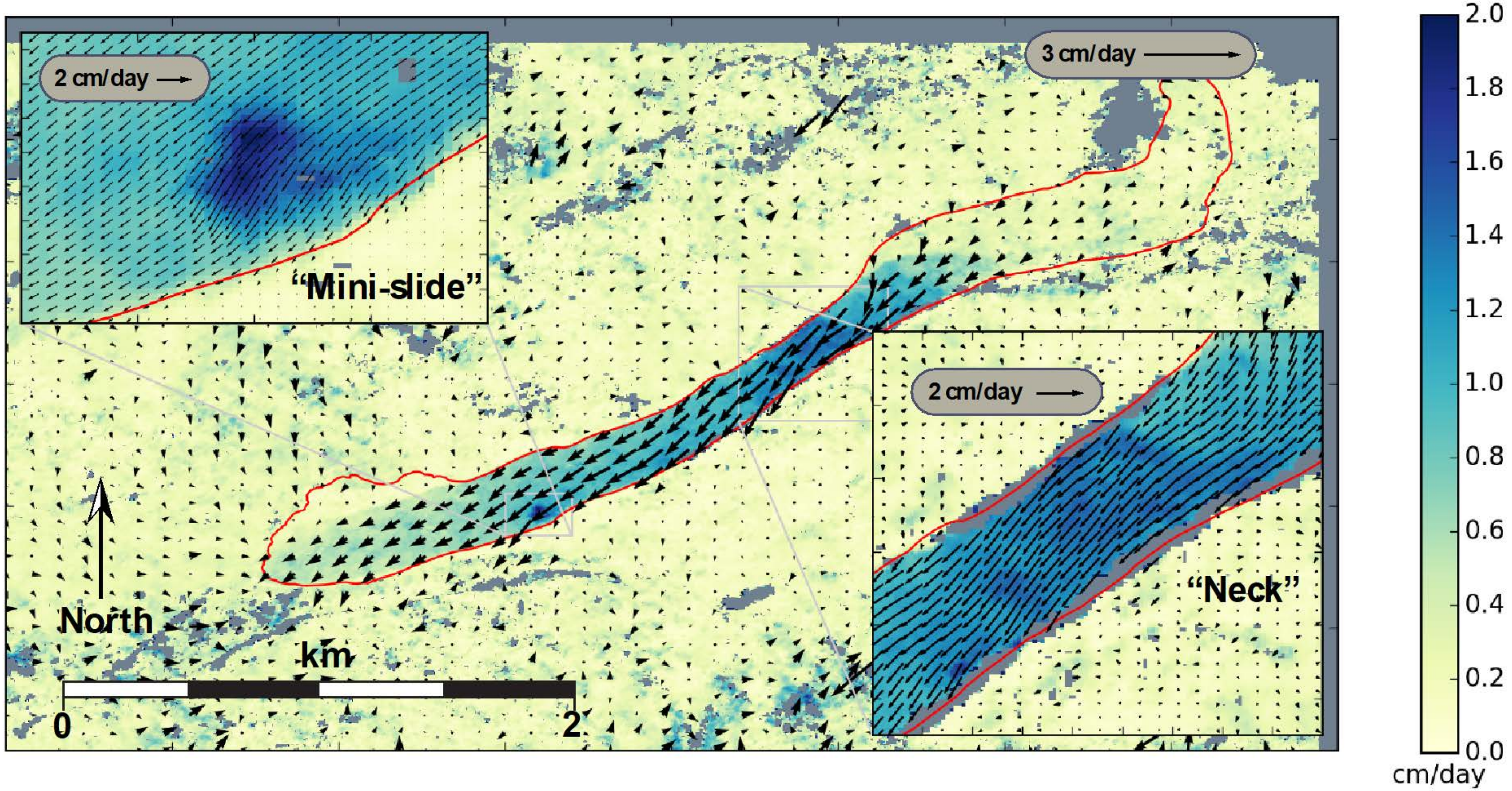


Envisat co-seismic correlation minus pre-seismic correlation

red is co-seismic decorrelation

Landslide Motion

Combination of Four NASA UAVSAR InSAR Flight Lines



cm/day

Delbridge, B. G., R. Bürgmann, E. Fielding, S. Hensley, and W. H. Schulz (2016), Three-dimensional surface deformation derived from airborne interferometric UAVSAR: Application to the Slumgullion Landslide, J. Geophys. Res. Solid Earth, 121(5), 3951--3977, doi:10.1002/2015JB012559.

SAR satellites	repeat cycle (days)	wave-length (cm)
European ERS-1/ERS-2 '92-'01(-2011)	35 (1,3,183)	6
Canadian Radarsat-1 1995-2013	24	6
European Envisat '03-Sep.'10 ('10-Apr.'12)	35 (30)	6
Japanese ALOS Jan. 2006–Apr. 2011	46	24
German TerraSAR-X '07, TanDEM-X '10	11	3
Italian COSMO-SkyMed 4x launch '07-'10	16 (1,4,7,8)	3
Canadian Radarsat-2 launched Dec. 2007	24	6

new SAR spacecraft

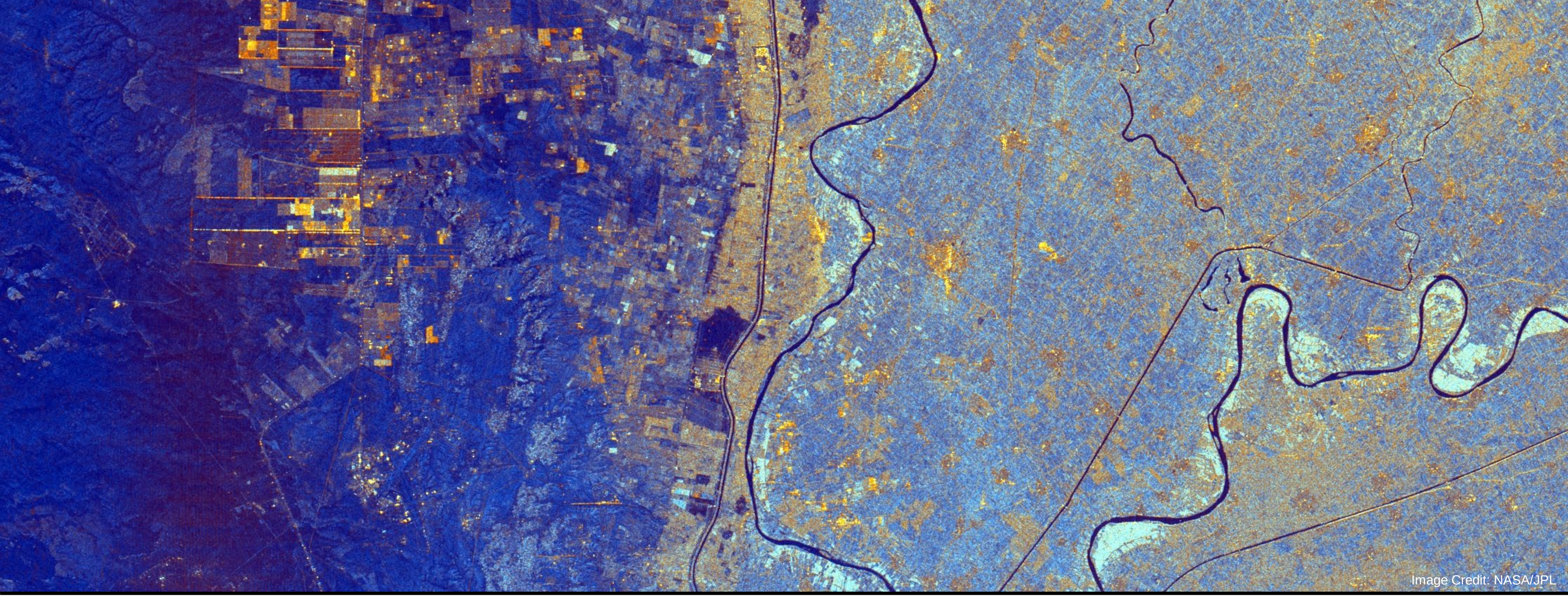
satellite (launch or planned)	repeat cycle (days)	wave-length (cm)
European Sentinel-1 (A: Apr. 2014, B: May 2015)	12(6)	6
Japanese ALOS-2 (May 2014)	14	24
Indian RISAT-1 (Apr. 2012)	25	6
NASA-ISRO SAR (NISAR) mission (2021)	12	12,24

NASA-ISRO SAR Mission (NISAR)

- High spatial resolution with frequent revisit time
- Earliest baseline launch date: 2021
- Dual frequency L- and S-band SAR
  - L-band SAR from NASA and S-band SAR from ISRO
- 3 years science operations (5+ years consumables)
- All science data will be made available free and open
- https://nisar.jpl.nasa.gov

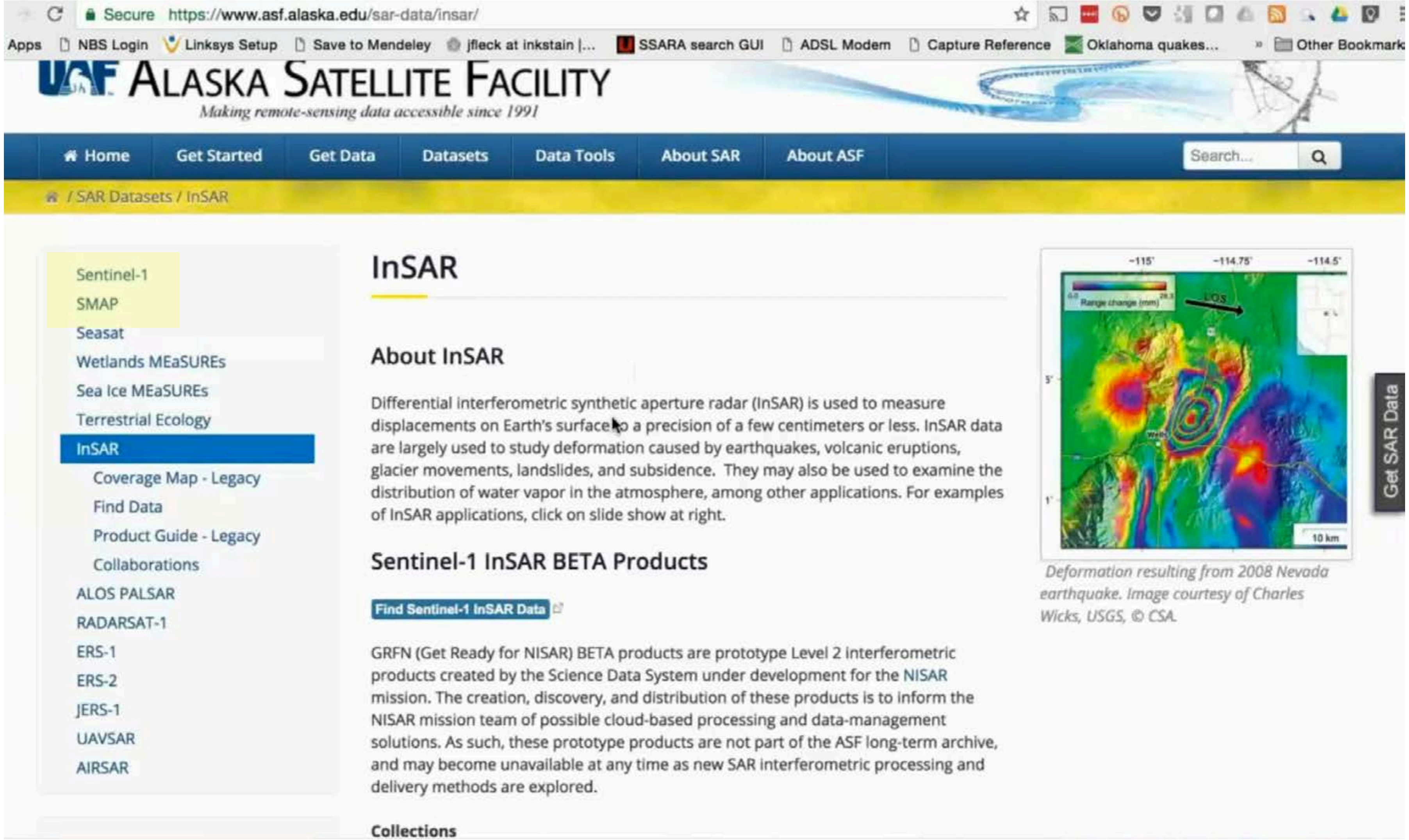
NISAR Characteristic:	Would Enable:
L-band (24 cm wavelength)	Low temporal decorrelation and foliage penetration
S-band (12 cm wavelength)	Sensitivity to light vegetation
SweepSAR technique with Imaging Swath >240 km	Global data collection
Polarimetry (Single/Dual/Quad)	Surface characterization and biomass estimation
12-day exact repeat	Rapid Sampling
3-10 meters mode-dependent SAR resolution	Small-scale observations
3 years since operations (5 years consumables)	Time-series analysis
Pointing control < 273 arcseconds	Deformation interferometry
Orbit control < 500 meters	Deformation interferometry
>30% observation duty cycle	Complete land/ice coverage
Left/Right pointing capability	Polar coverage, North and South
Noise Equivalent Sigma Zero ≤ -23 db	Surface characterization of smooth surfaces

Slide Courtesy of Paul Rosen (JPL)



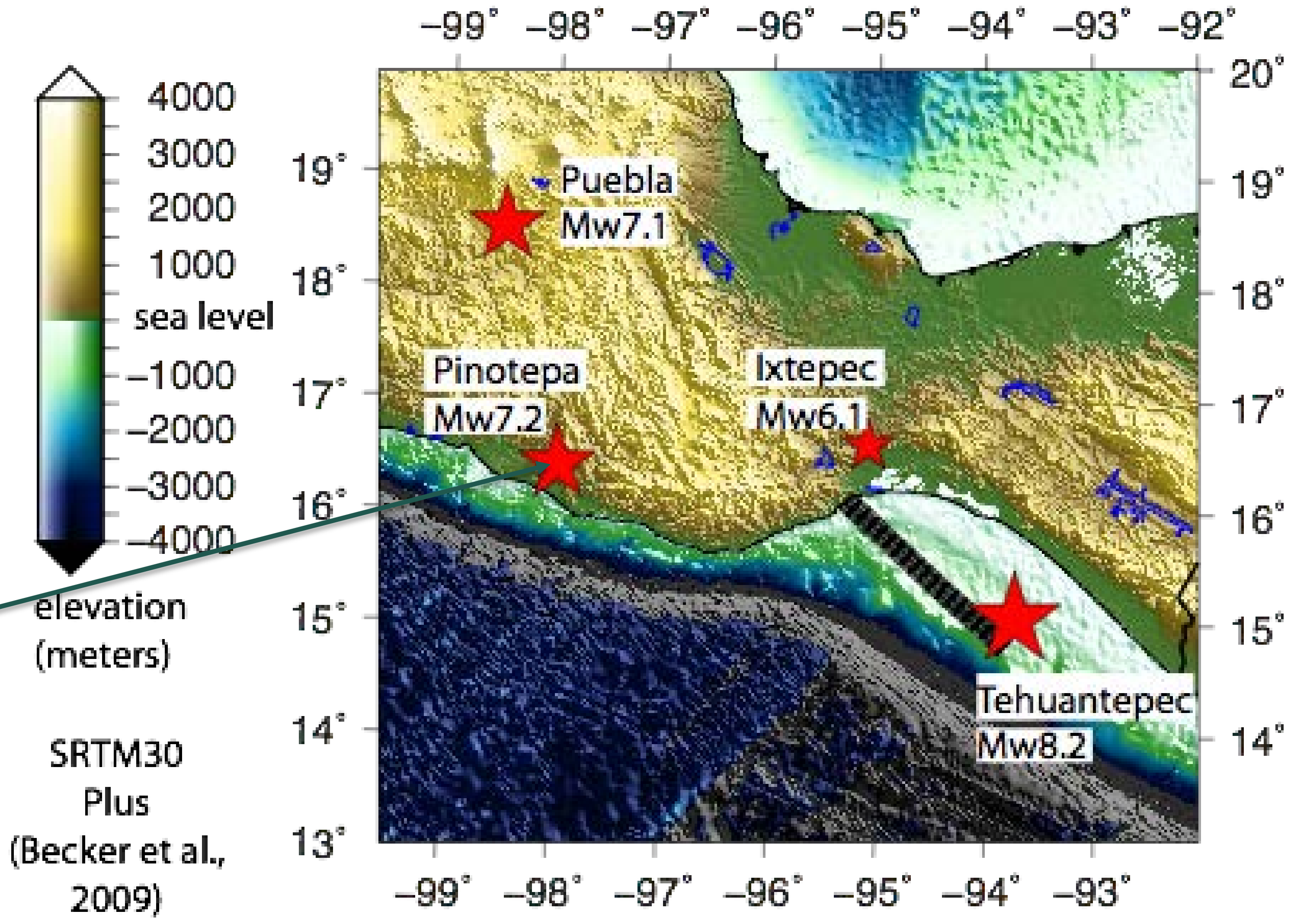
Accessing, Opening, and Displaying SAR Interferometry Data

How to Get Data for InSAR



Southern Mexico Earthquakes 2017–2018

We will look at the 16 February 2018 Mw 7.2 earthquake near Pinotepa in Oaxaca



Accessing Sentinel-1 Data for Interferometry

1. Go to the Alaska Satellite Facility Sentinel Data Portal: https://vertex.daac.asf.alaska.edu/
2. Identify the area (-99,16,-99,15,-97,15,-97,16,-99,16) and dates (2018-02-05, 2018-02-17) of interest (M7.2 Pinotepa earthquake in Oaxaca, Mexico)
3. Identify images of interest (Sentinel-1 A/B)
4. Select path 5
5. Click **Search**
6. Select Granule: S1B_IW_RAW__0SDV_20180205T003836_20180205T003909_009481_0110E0_FEAF (Frame 49)
7. Download the L1 Single Look Complex (SLC) (4.76 GB) Product
8. Similarly download SLC for Granule: S1B_IW_RAW__0SDV_20180217T003836_20180217T003908_009656_0116A5_3F00 (Frame 49)

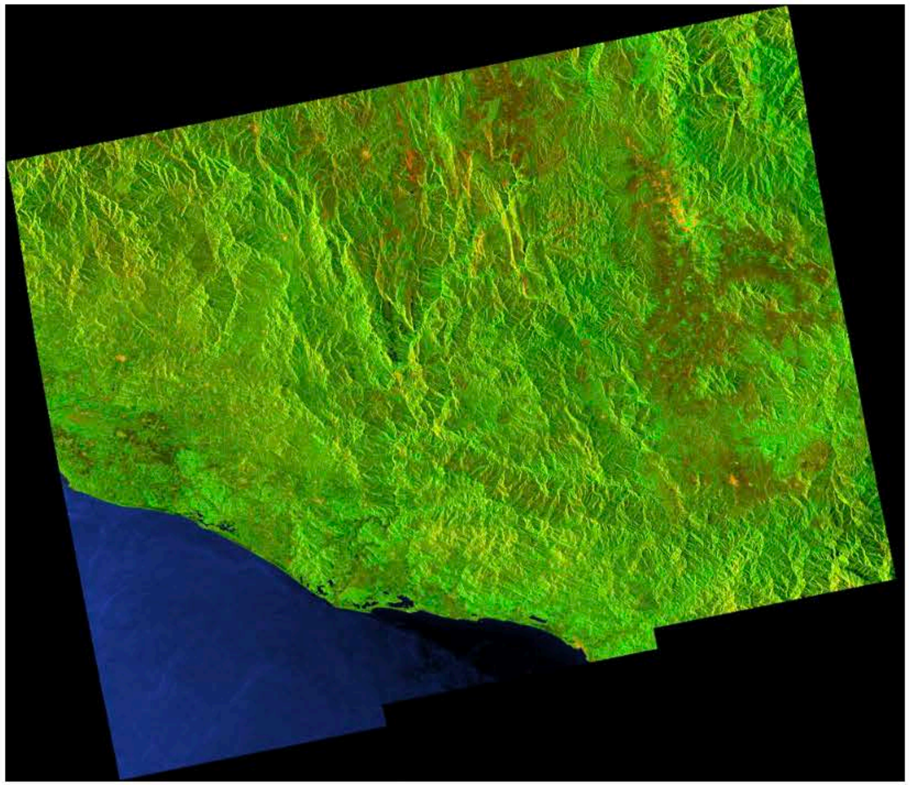
Accessing Sentinel-1 Data for Interferometry

Dataset: Sentinel-1B
Granule: S1B_IW_RAW__0SDV_20180205T003836_20180205T003909_009481_0110E0_FEAF

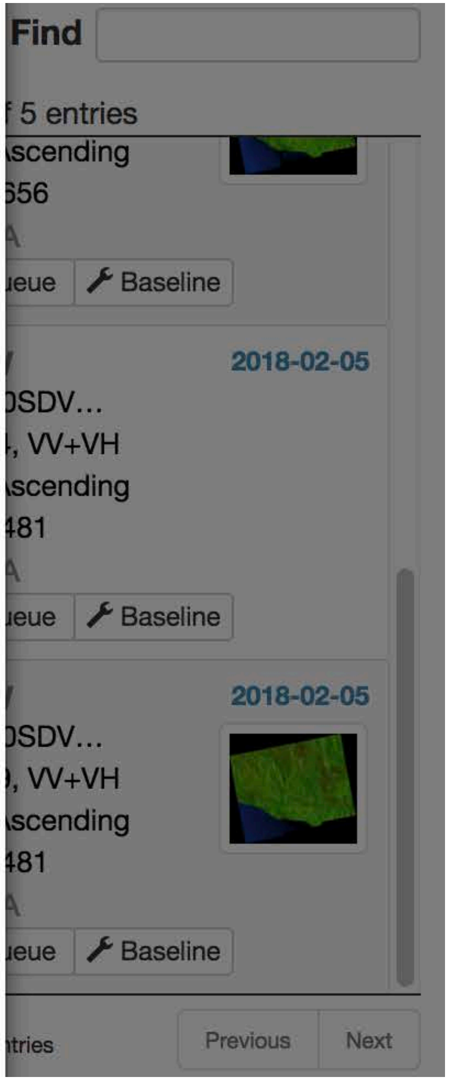
Granule Details

- Acquisition Date: 2018-02-05
- Beam mode: IW
- Path: 5
- Frame: 49
- Ascending/Descending: Ascending
- Polarization: VV+VH
- Absolute Orbit: 9481
- Frequency: C-Band

Products	Download
L1 Detected High-Res Dual-Pol (GRD-HD) (1.07 GB)	+ Queue Download
L2 Ocean (OCN) (5.57 MB)	+ Queue Download
L1 Single Look Complex (SLC) (4.76 GB)	+ Queue Download



Full Resolution Browse Image



Opening the Data with the Sentinel Toolbox

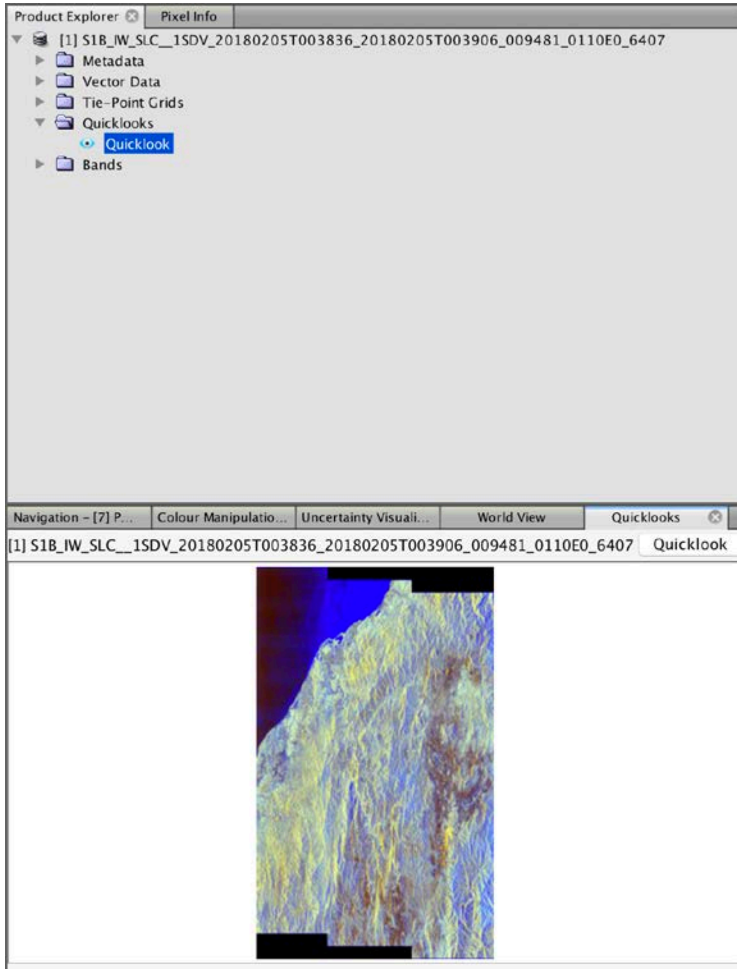
We use the same Toolbox as for SAR amplitude analysis

- Initiate the Sentinel Toolbox (SNAP) by clicking on its desktop icon
- In the Sentinel Toolbox interface, go to the File menu and select Open Product
- Select the folder containing your Sentinel-1 SLC file, and double click on the .zip file (do not unzip the file; the program will do it for you)

Opening the Data with the Sentinel Toolbox

SLC Data Has a Different Format Than GRDH

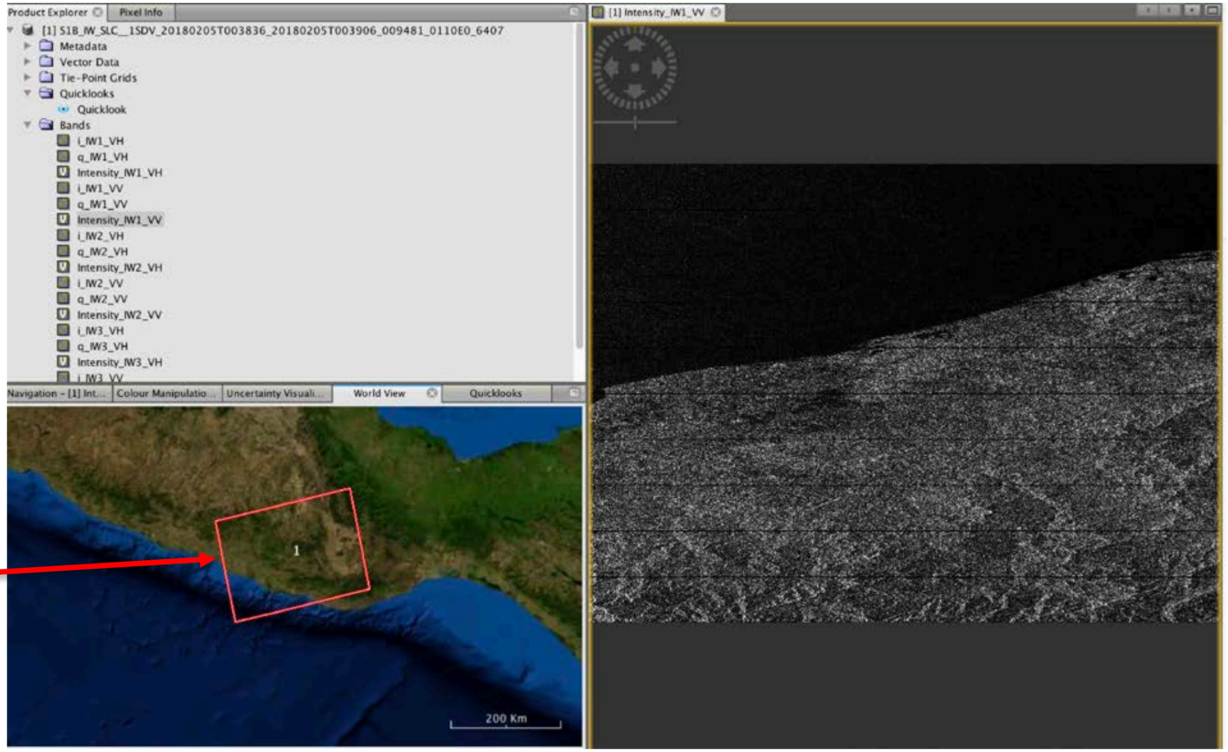
1. The Product Explorer window of the Sentinel Toolbox contains your file. Double click on the file to view the directories within the file, which contain information relevant to the image, including:
   - Metadata: parameters related to orbit and data
   - Tie Point Grids: interpolation of latitude/longitude, incidence angle, etc.
   - Quicklooks: viewable image of whole scene in radar coordinates
   - Bands: complex values for each subswath “i” and “q” and intensity (intensity is the amplitude squared, a virtual band)

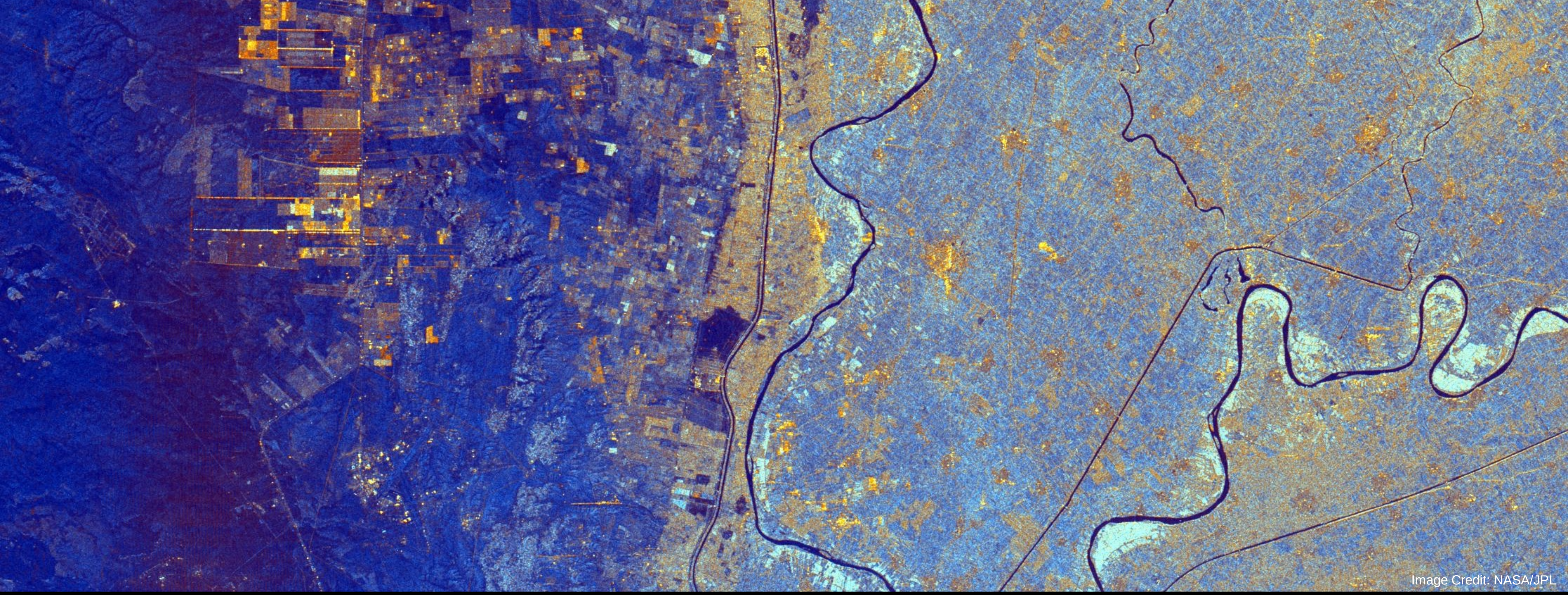


Opening the Data with the Sentinel Toolbox

Viewing Subswath Images

2. The Worldview image (lower left) shows the footprint of the whole image selected
3. Select intensity image for swath IW1 VV
   – **Note**: Each SAR image is flipped north—south because it is oriented the same way it was acquired (ascending track in this case)



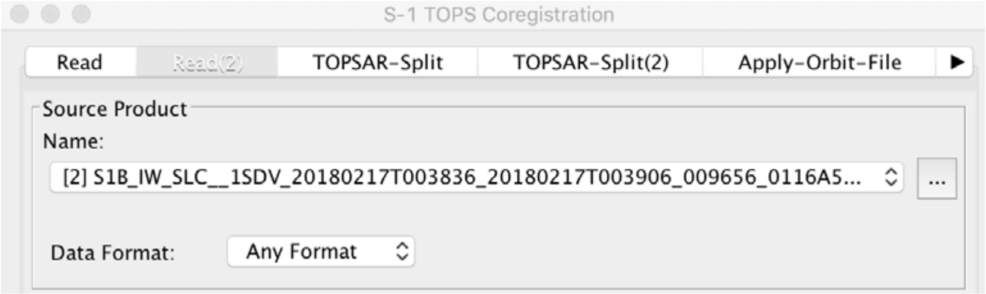


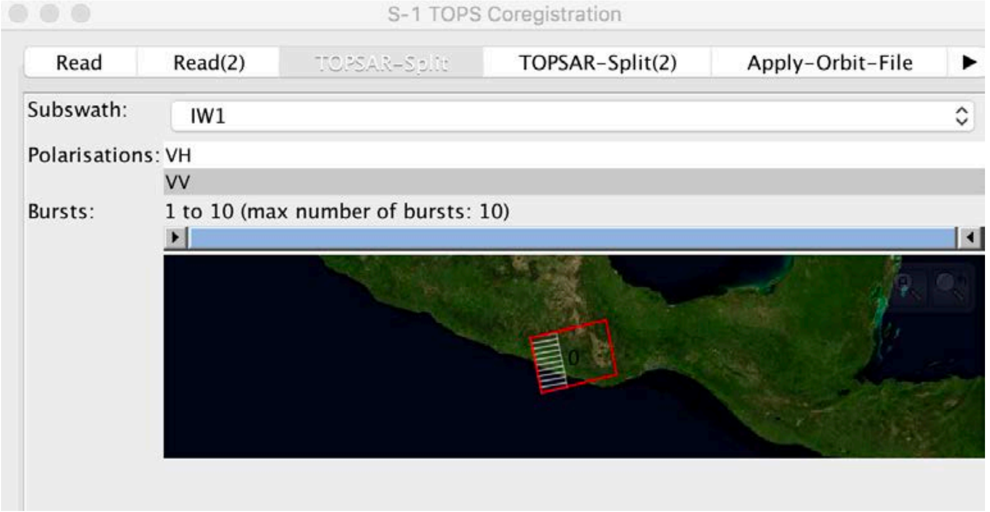
InSAR Processing

Interferometry Data Preparation

Coregistering the Scenes

1. The first step of interferometry is to coregister two SLC images
2. From the top main menu bar, select **Radar,** then **Coregistration,** then **S1 TOPS Coregistration**, and then **S1 TOPS Coregistration** again
   - In the **Read** tab, select the 20180205 SLC and in the **Read(2)** tab select the 20180217 SLC
   - In **TOPSAR-Split** and **TOPSAR-Split(2)** tabs, select Subswath: IW1 Polarisations: VV
   - In the **Write** tab, select the directory where you want to save your processing results

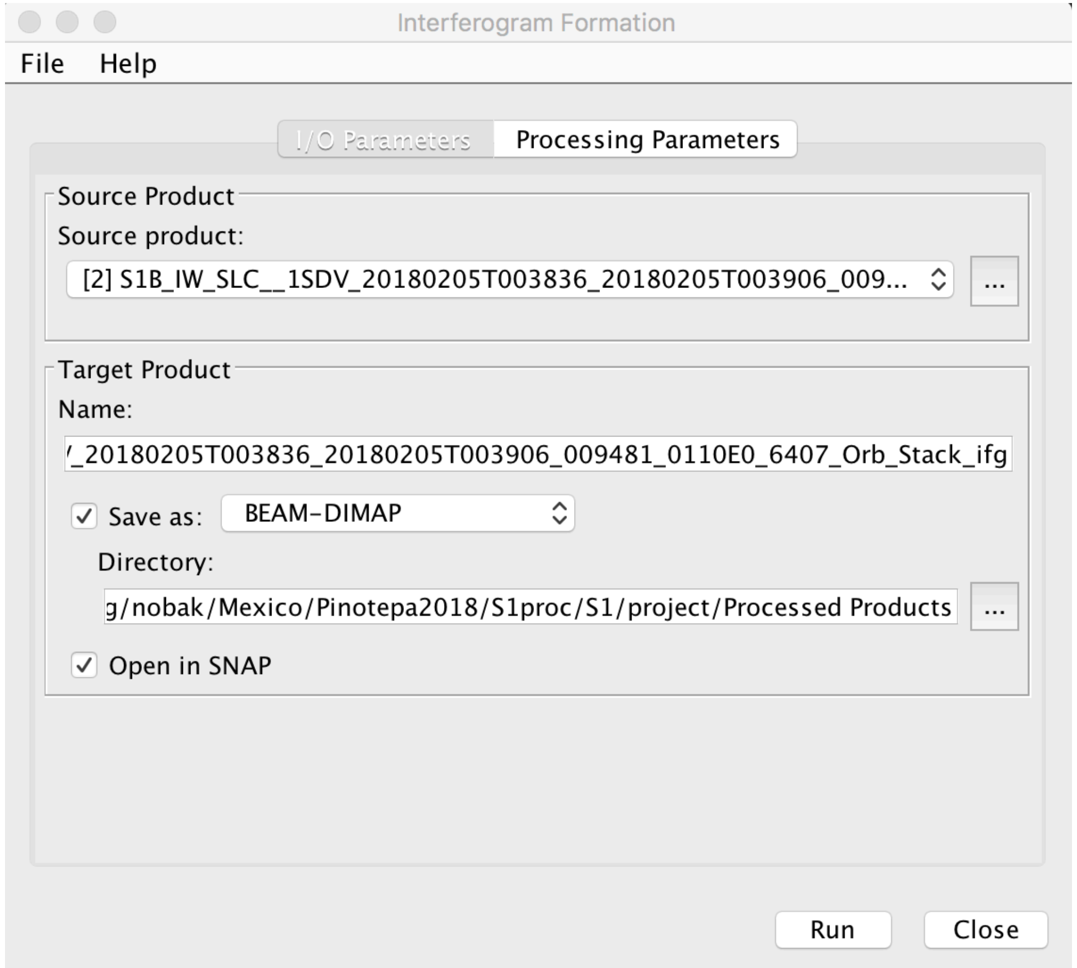




Interferometric Processing

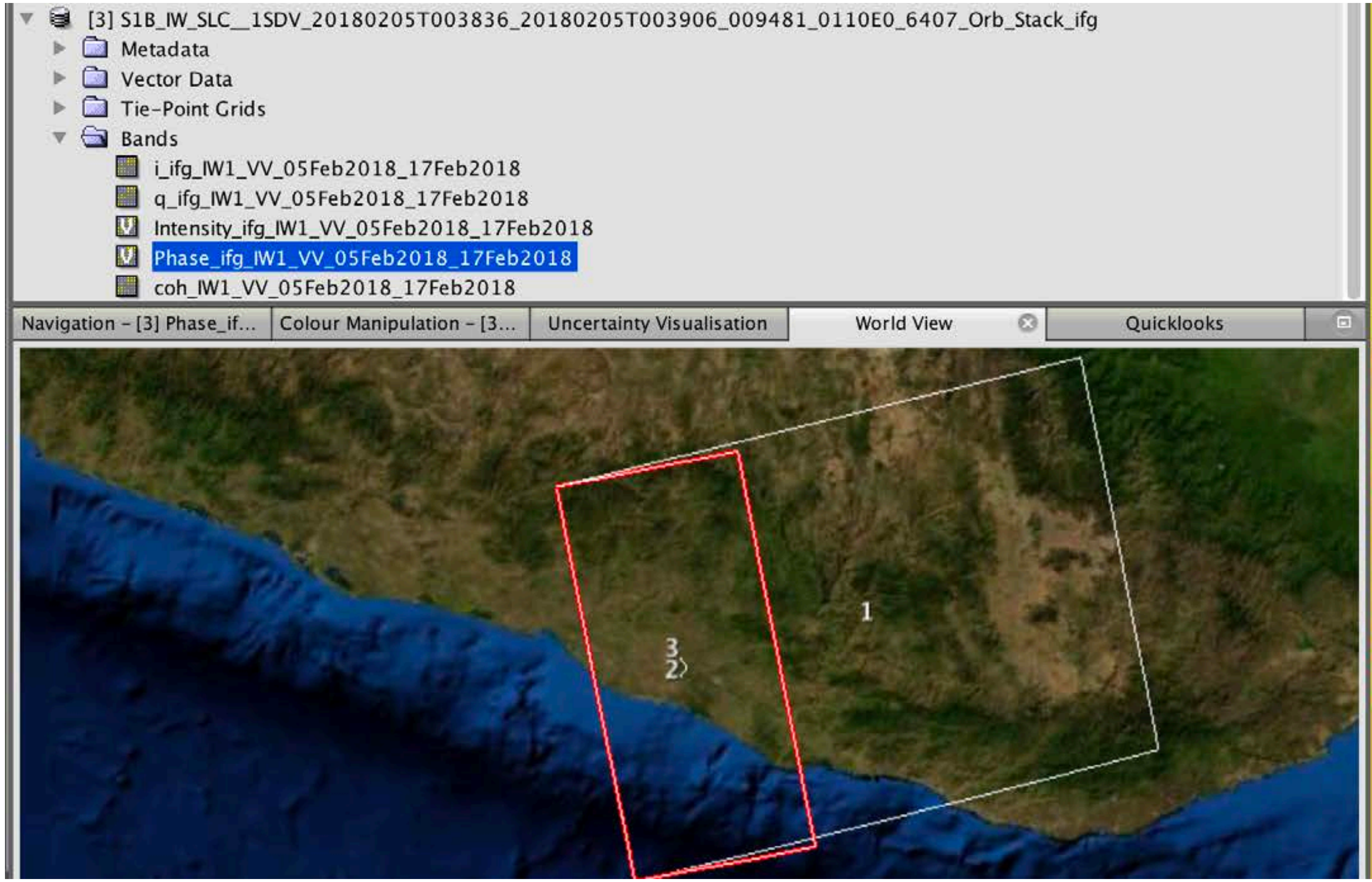
Forming a Raw Interferogram

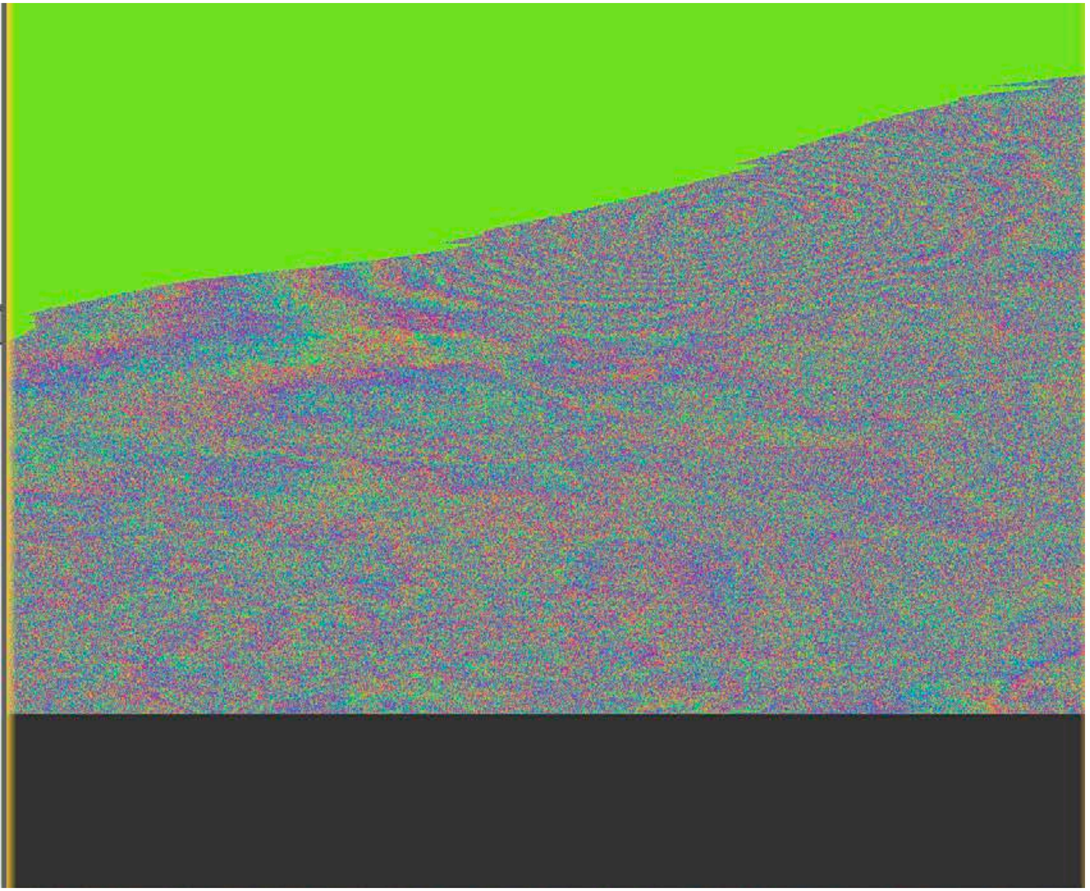
1. Second step of interferometry is to make an interferogram out of the coregistered SLC images
2. From the top main menu bar, select **Radar,** then **Interferometric,** then **Products**, and then **Interferogram Formation**
   - In **I/O Parameters** tab, select the "Orb_Stack" product created by the coregistration step
   - By default, the output target is in same directory and adds "ifg" to the name
   - For basic processing, no need to change defaults in **Processing Parameters** tab



Interferometric Processing

Viewing a Raw Interferogram — Phase Image





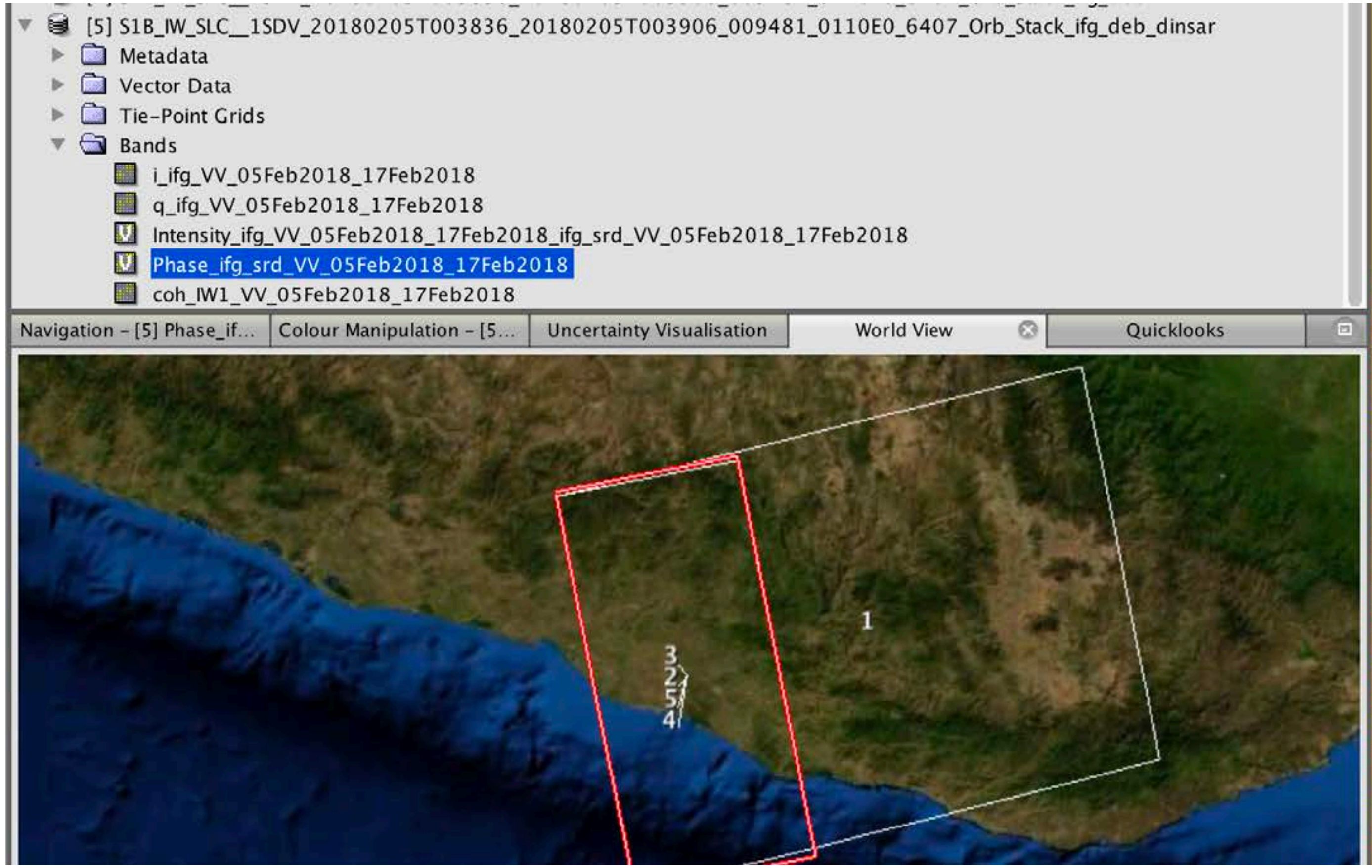
Interferometric Processing

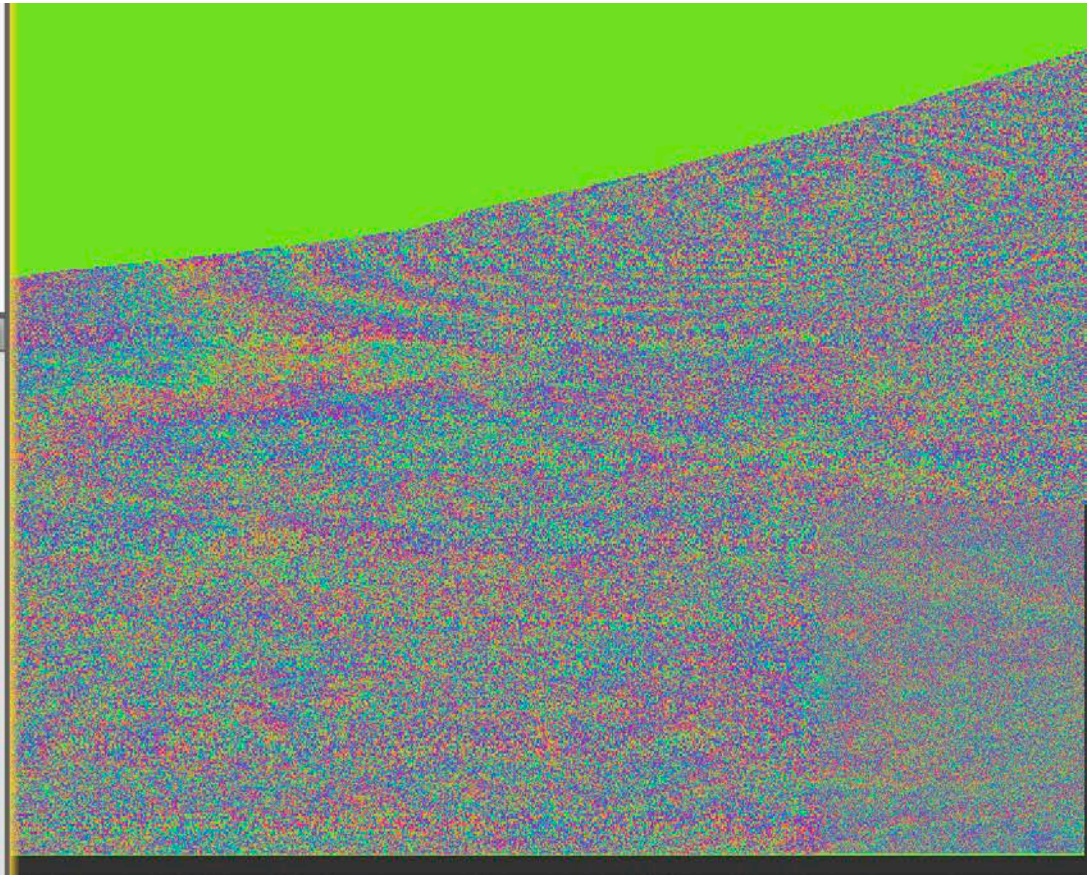
TOPS Deburstintg and Topographic Phase Removal

1. Next step of interferometry with Sentinel-1 TOPS mode (IWS) data is “deburstintg” or combining the bursts. This is not necessary with Sentinel-1 or other stripmap SAR data.
2. From the top main menu bar, select **Radar,** then **Sentinel-1 TOPS**, and then **S-1 TOPS deburst**
   - In **I/O Parameters** tab, select the “Orb_Stack_ifg” product created by the interferogram formation step
   - By default, the output target adds “deb” to the name
   - No need to change **Processing Parameters** tab
3. Next step for all interferometry is to remove the topographic phase using a DEM.
4. From the top main menu bar, select **Radar,** then **Interferometric,** then **Products**, and then **Topographic Phase Removal**
   - In **I/O Parameters** tab, select the “Orb_Stack_ifg_deb” product created by the deburst step or “Stack_ifg” if not TOPS mode
   - By default, the output target adds “dinsar” to the name
   - The **Processing Parameters** tab shows the default is to download SRTM 3-arcsecond DEM, which is fine for basic processing but you might need another DEM in some cases

Interferometric Processing

Viewing Differential Interferogram — Phase Image





Interferometric Processing

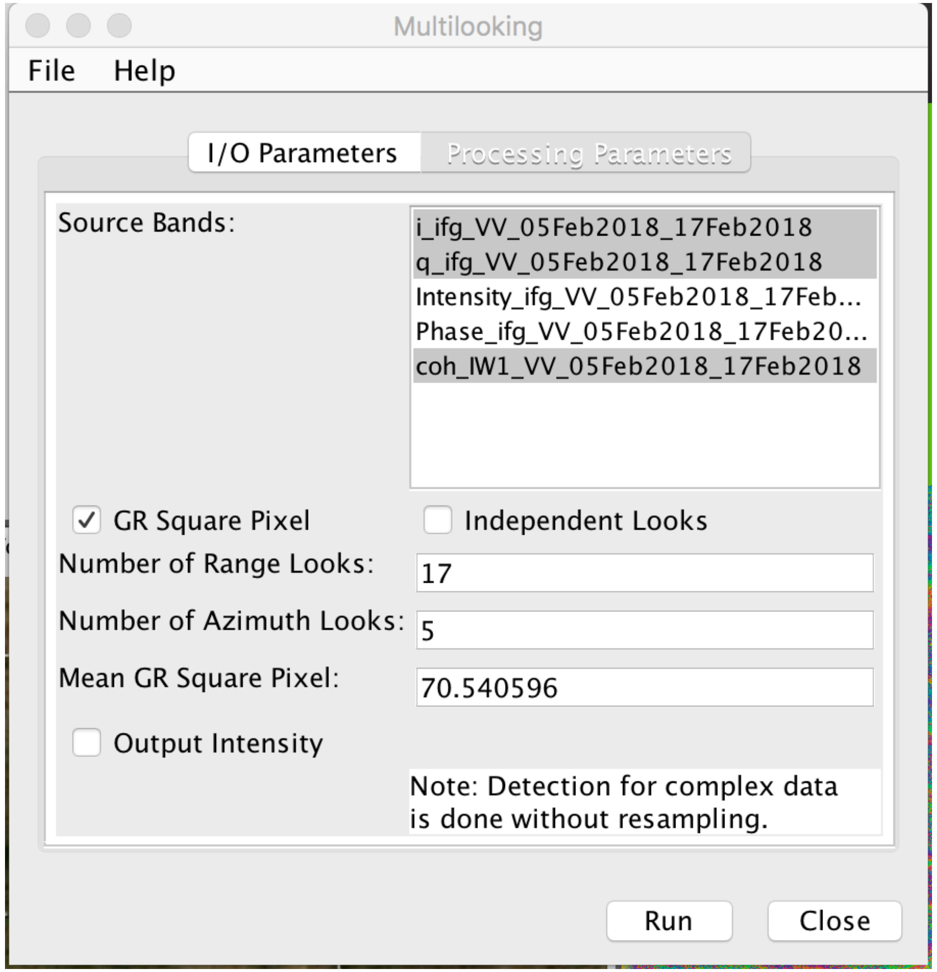
Filtering and Multi-Looking Interferogram

1. Two steps can reduce the noise level in the interferogram, filtering and multi-looking. We apply filtering first, but you can also do multi-looking first.
2. From the top main menu bar, select **Radar,** then **Interferometric,** then **Filtering**, and then **Goldstein Phase Filtering**
   – In **I/O Parameters** tab, select the "dinsar" product created by the previous step
   – By default, the output target adds "flt" to the name
   – For basic processing, no need to change defaults in **Processing Parameters** tab
3. Multi-looking is averaging multiple pixels in each direction, what radar engineers call "taking multiple looks". It results in larger pixels and can greatly reduce the noise.
   – The amount of multi-looking you should do depends on the spatial resolution you need and the spacing of the fringes

Interferometric Processing

Multi-Looking Interferogram

1. The Pinotepa earthquake has a depth of about 25 km, so the fringes are widely spaced. There is also no surface rupture, so we can do more spatial averaging without losing any earthquake signal.
2. From the top main menu bar, select **Radar** and then **Multilooking**
   – In **I/O Parameters** tab, select the "dinsar_flt" product created by the filtering step and, by default, the output target adds "ML" to the name
   – In **Processing Parameters** tab, select Source Bands "i_ifg","q_ifg", and "coh". For this scene, I use 17 range looks and it calculates 5 azimuth looks to give ~70 m output pixels
   – Don't choose "Phase" band!

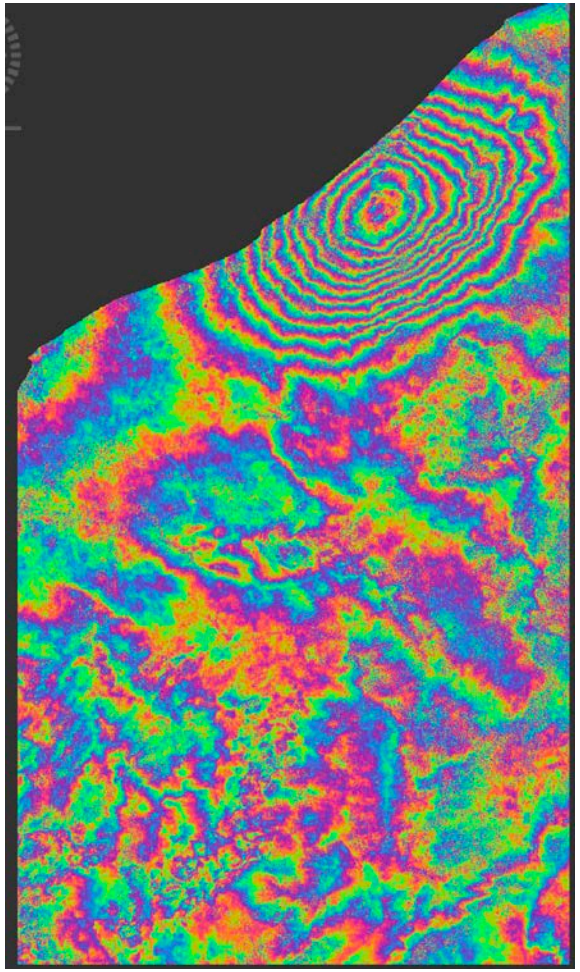


Interferometric Processing

Viewing Multi-Looked Interferograms

1. First, we need to make a new virtual phase band after multi-looking the complex interferogram
2. From the top main menu bar, select **Raster,** then **Data Conversion**, then **Complex i and q to Phase**
3. Now you can display the new phase band

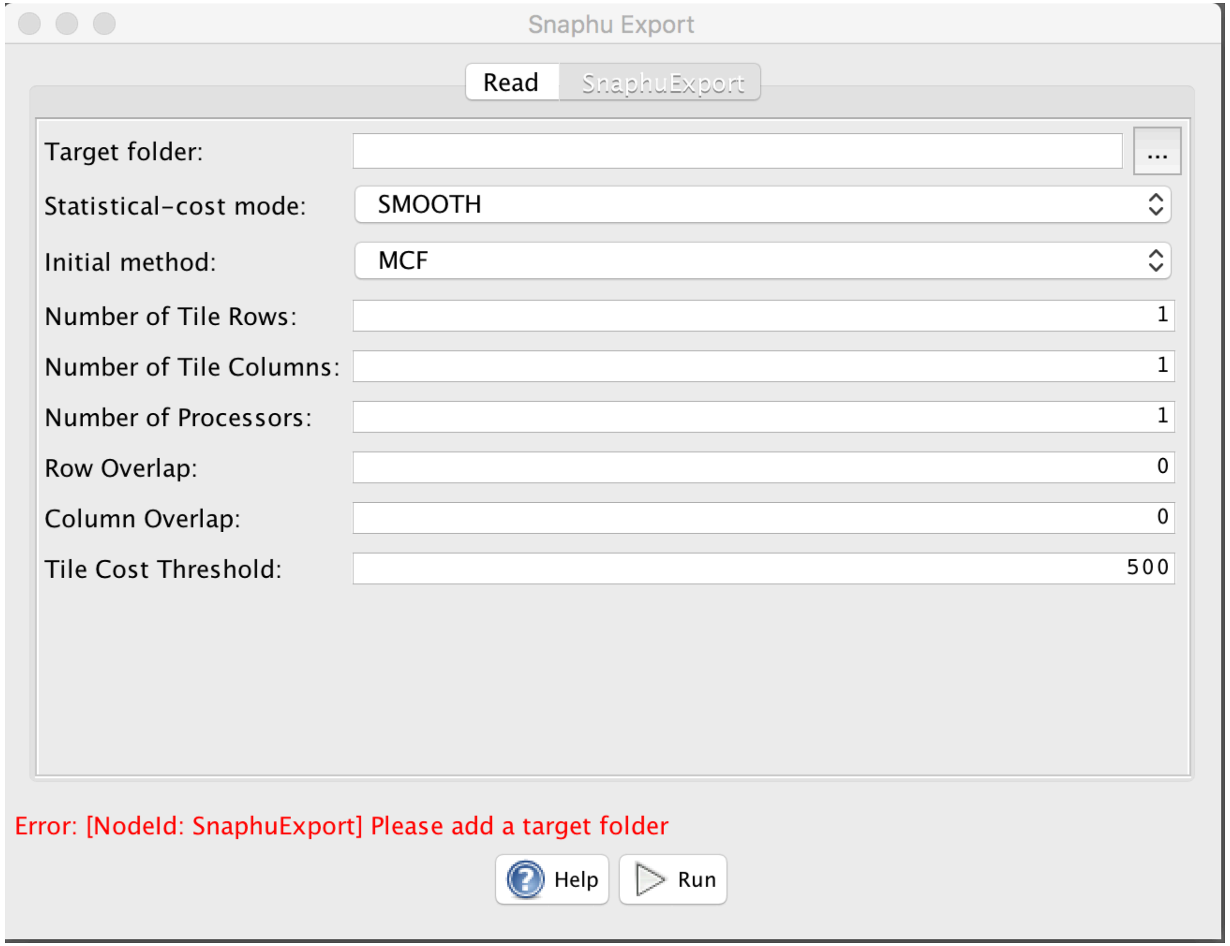
- The fringes are much less noisy
- Aspect ratio has changed so the pixels are roughly square on the ground
- New image is now 1207 pixels across, much smaller than original 20535 pixels



Interferometric Processing

Phase Unwrapping

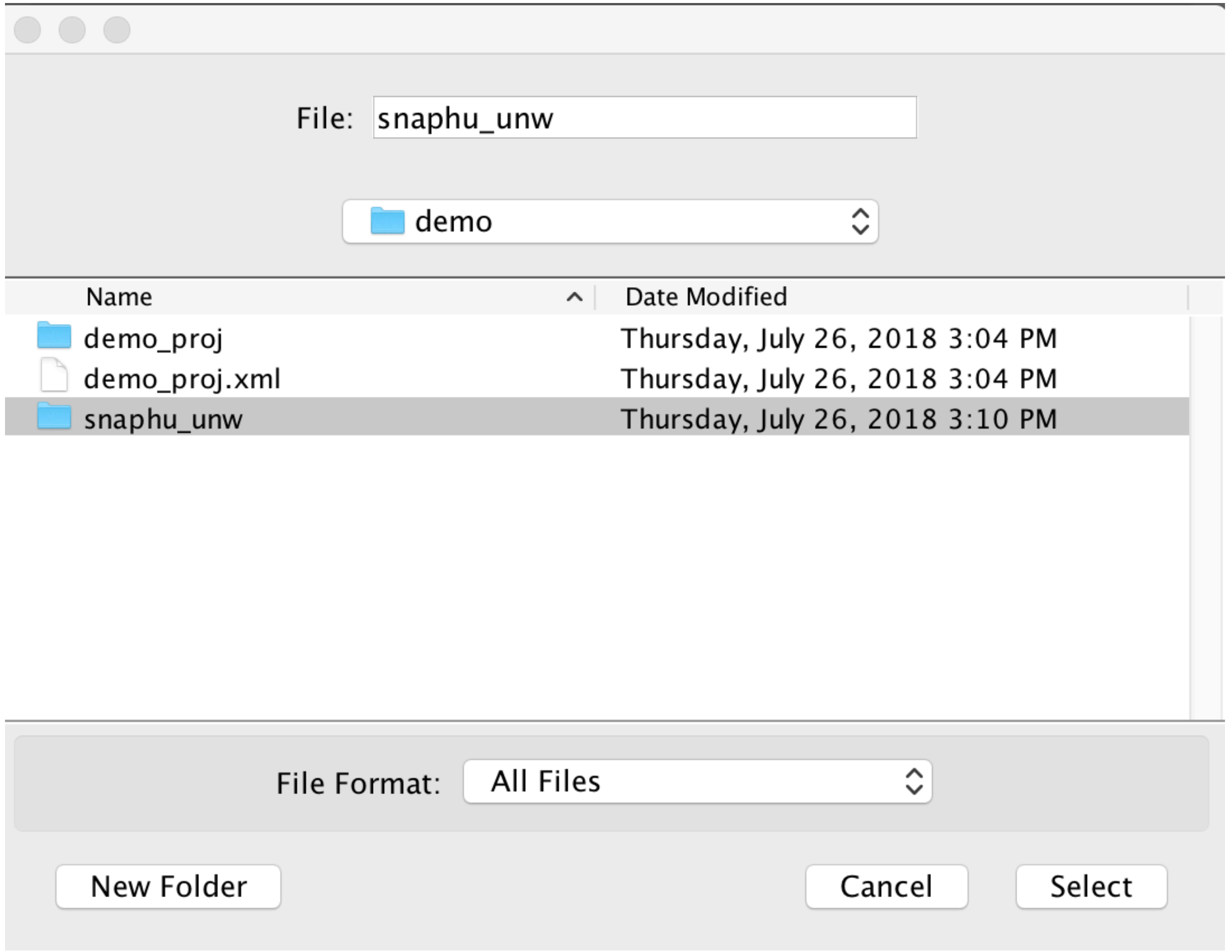
1. SNAP 6.0 does not include phase unwrapping. It has way to export interferogram to unwrap with third-party program Snaphu (Statistical-cost, Network-flow Algorithm for Phase Unwrapping) by Chen and Zebker.
2. From the top main menu bar, select **Radar,** then **Interferometric,** then **Unwrapping**, and then **Snaphu Export.**
   – In **Read** tab, select the "ML" product created by the multilooking step
   – In **Snaphu Export** tab, change the Statistical-cost mode to "SMOOTH"
   – Also change the number of tile rows and columns and number of processors to "1" because we don't need multiple tiles after multilooking



Interferometric Processing

Phase Unwrapping

1. In **Snaphu Export** tab, you also need to specify a target folder for exported files. I put the Snaphu files in a separate folder (here called “snaphu_unw”), so you need to create it either from the selection dialog or in another window.
2. The **Snaphu Export** pop-up dialog does not work quite right in SNAP 6.0. Workaround:
   - Navigate to directory that includes the “snaphu_unw” folder
   - The “select” button won’t work to chose the “snaphu_unw” folder
   - Type “snaphu_unw” in the **File:** box at the top, then choose Select
3. Now you can press **Run** button and SNAP exports the interferogram phase and coherence with a “snaphu.conf” file



Interferometric Processing

Phase Unwrapping

1. **Installing Snaphu**: ESA now provides pre-built binary executables for Linux and Windows 32- or 64-bit systems at http://step.esa.int/main/third-party-plugins-2/snaphu/.
   For Mac or other machines, you need to download from Stanford and build it yourself (“make” in “src” usually works).

   You also need to add the snaphu/bin directory to your path.
2. After the **Snaphu Export** step in Snap, you have to run the Snaphu program on the command line:
   - Navigate to the “snaphu_unw” folder and open it
   - You should see folder with name of product you exported, e.g. S1B_IW_SLC__1SDV_20180205T003836_20180205T003906_009481_0110E0_6407_Orb_Stack_ifg_deb_dinsar_flt_ML17
   - Move to that folder
3. You should see the wrapped interferogram phase “Phase_ifg*.img”, coherence “coh_*.img”, and a “snaphu.conf” file.
4. The beginning of the “snaphu.conf” file shows the command to run Snaphu, e.g.,

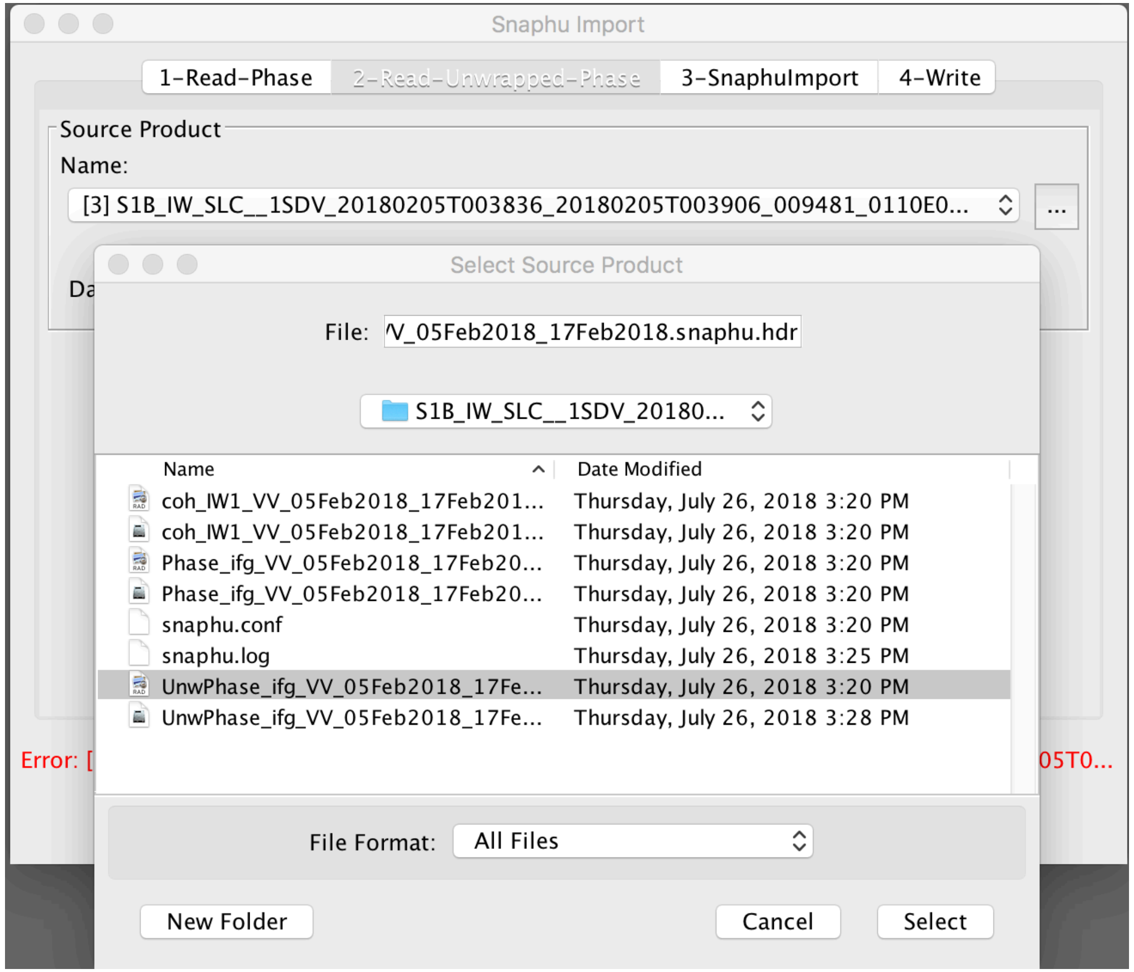
```
# Command to call snaphu:
#
#       snaphu -f snaphu.conf Phase_ifg_VV_05Feb2018_17Feb2018.snaphu.img 1207
```

5. The Snaphu program can take a long time to run. At the end it writes unwrapped phase to “Unw_ifg*.img” file

Interferometric Processing

Phase Unwrapping

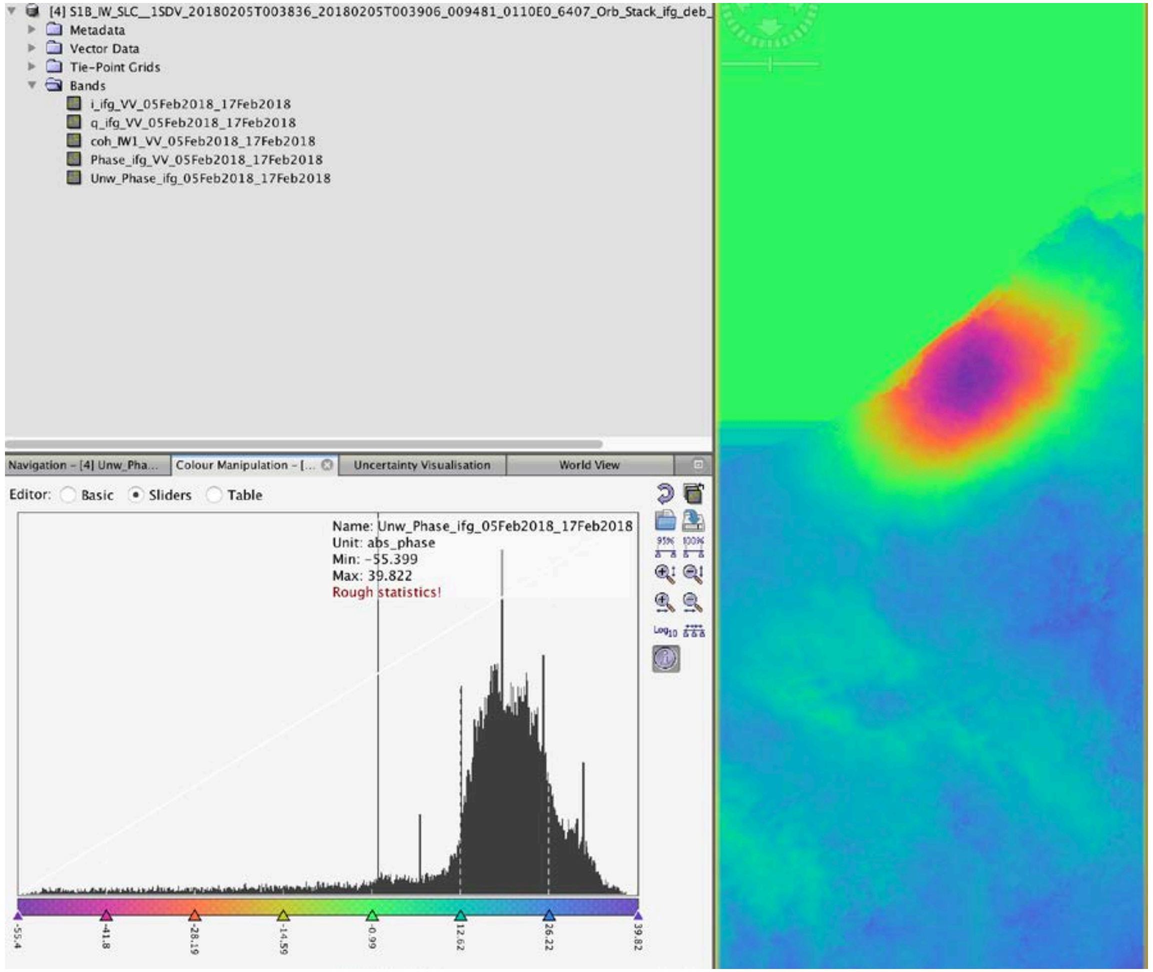
1. Now, we import the unwrapped phase. From the top main menu bar, select **Radar,** then **Interferometric,** then **Unwrapping**, and then **Snaphu Import.**
2. The **Read-Phase** tab should be set to the wrapped product that you exported.
3. In the **Read-Unwrapped-Phase** tab, select the unwrapped source product:
   - Navigate to folder where you exported for Snaphu
   - Select the "`UnwPhase_ifg*.snaphu.hdr`" file
4. Go to **Write** tab and check product output name (I add "_unw" to wrapped product name, so I get a new product)



Interferometric Processing

Phase Unwrapping

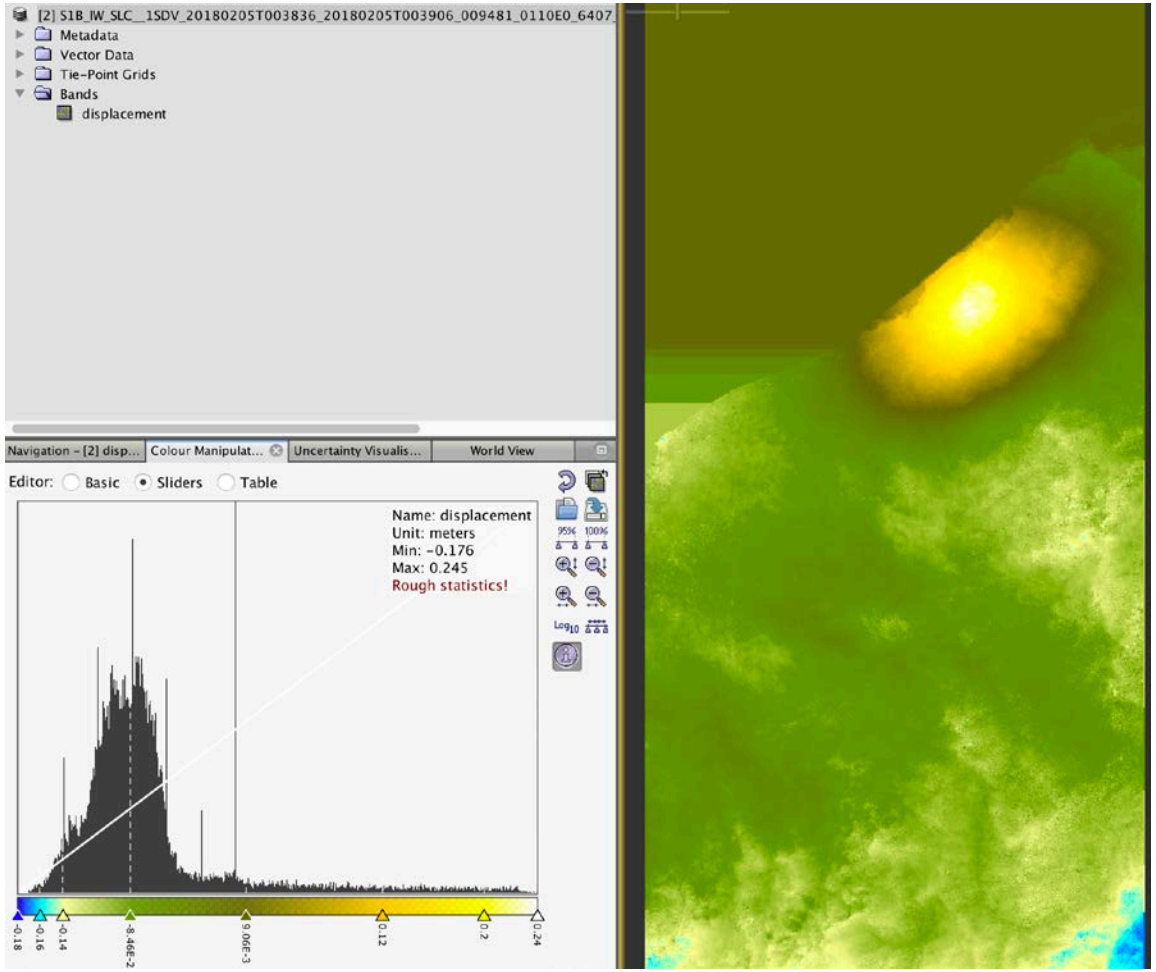
1. Finally, we can now display the unwrapped phase
   - Select the Unw_Phase_ifg band
   - Go to the Colour Manipulation tab and select "100%" to stretch color scale to full range of unwrapped data
   - Unwrapped phase is still in radians
   - Phase is reference image minus coregistered image. If reference image is earlier, then negative phase is land moving toward satellite (negative range change)



Interferometric Processing

Phase to Displacement

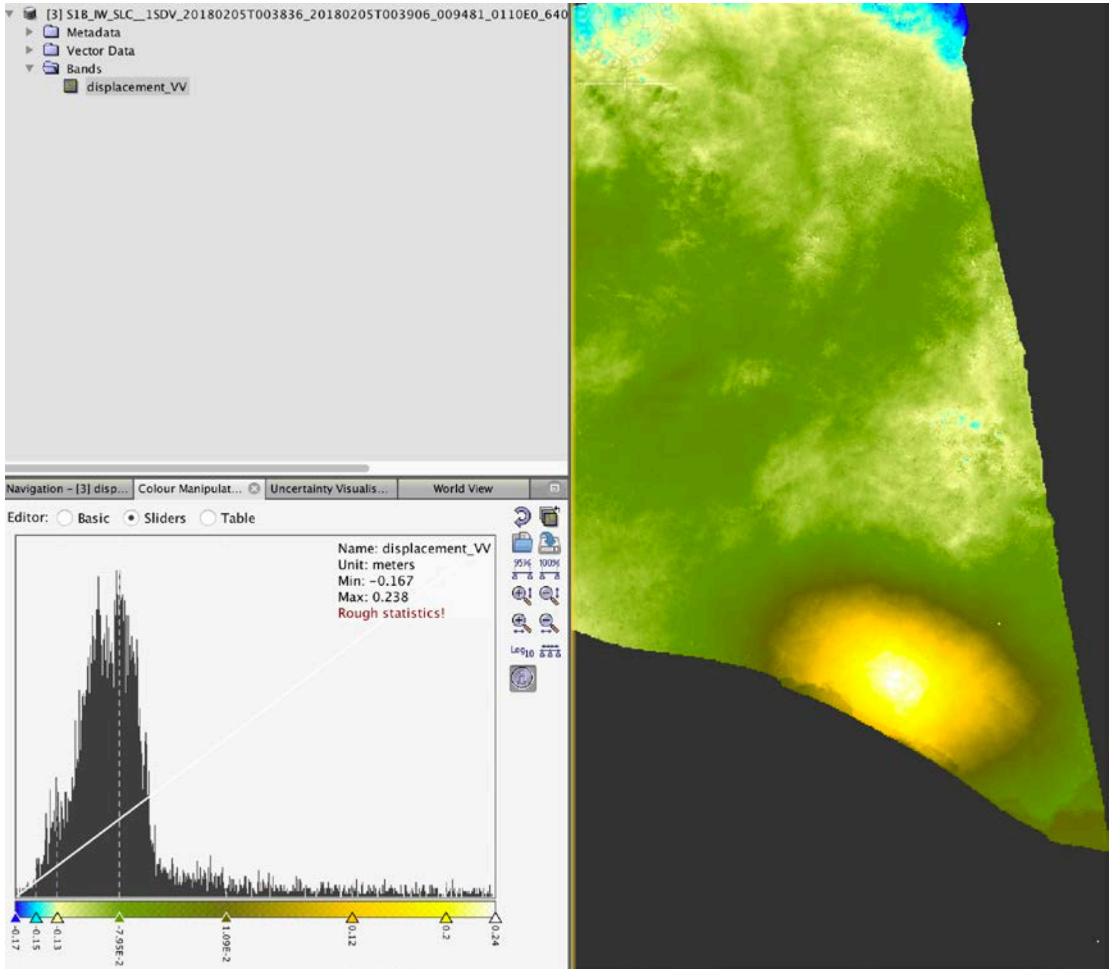
1. We can convert the unwrapped phase to displacements. From the top main menu bar, select **Radar,** then **Interferometric,** then **Products**, and then **Phase to Displacement.**
   - The **I/O Parameters** tab should be set to the unwrapped product that you imported.
   - default for target product name is to add “_dsp” to the name
2. Now, we can display **displacement** band of result. Again, better to stretch colors.
   - Displacements now in meters.
   - Sign was changed so positive displacement is “up” towards satellite

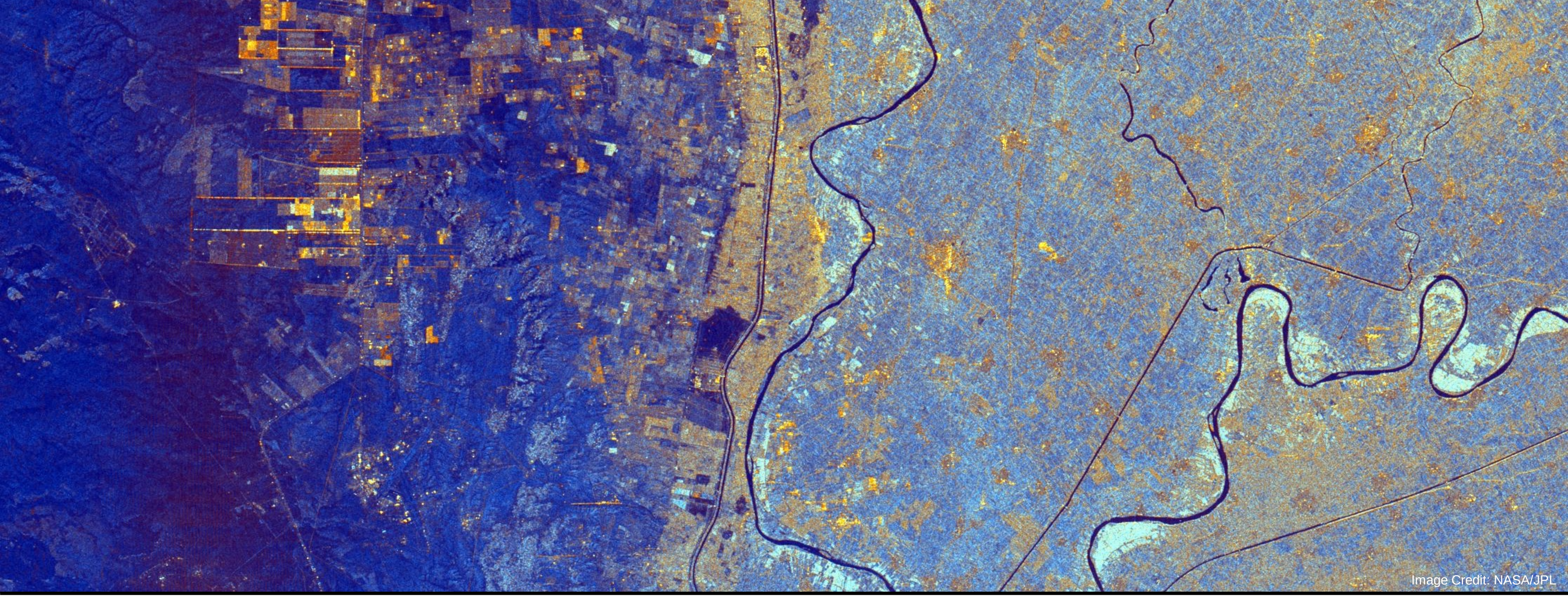


Interferometric Processing

Geocoding results—Terrain Correction

1. SNAP calls geocoding with topography "Terrain Correction." From the top main menu bar, select **Radar,** then **Geometric,** then **Terrain Correction**, and then **Range-Doppler Terrain Correction.**
   - The **I/O Parameters** tab should be set to the displacement product that you imported (or one of the other ML products).
   - default for target product name is to add "_TC" to the name
   - Under **Processing Parameters** tab, select the **Source Bands** and any additional **Output Bands**. You can also choose what DEM to use, output spacing, and map projection.
2. Now, we can display **displacement_vv** band of geocoded result. Again, better to stretch colors.
   - Displacements in meters with positive values "up" towards satellite in Line-of-Sight direction.
   - Product is now evenly spaced in latitude and longitude.



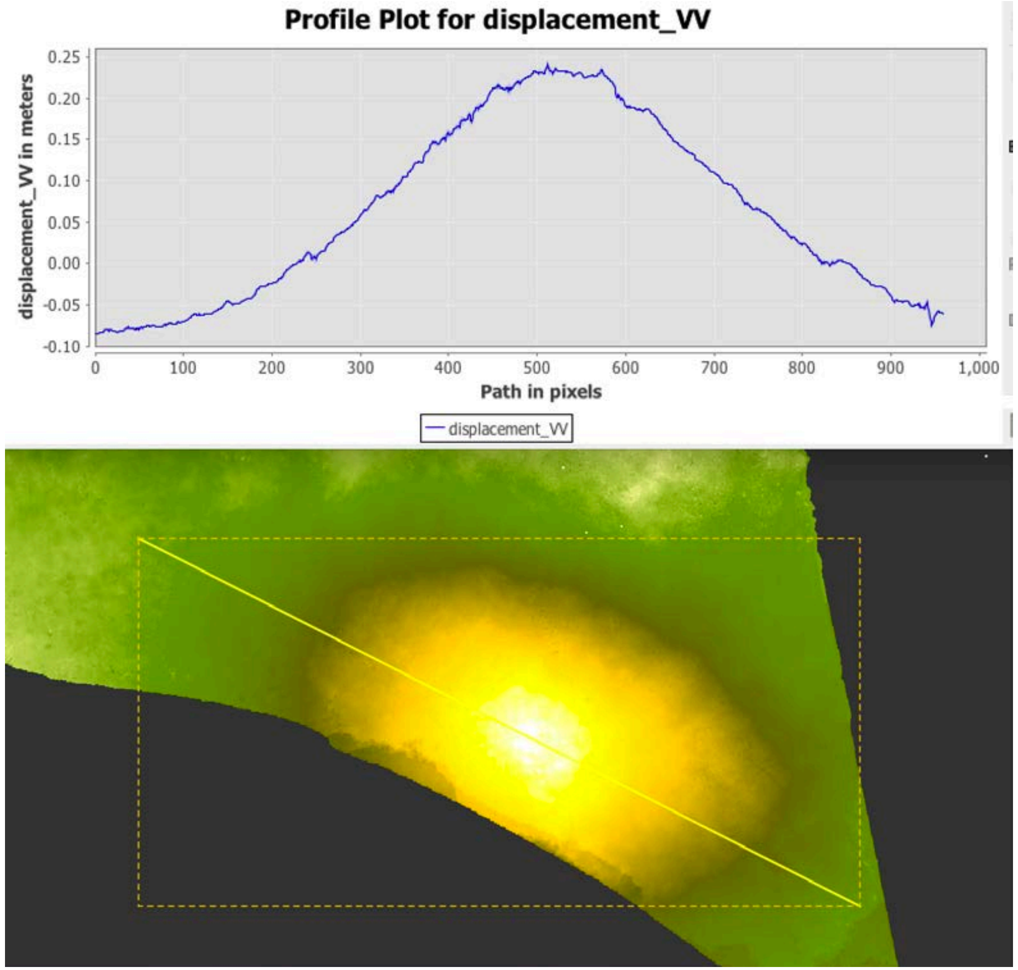


InSAR Analysis for Earthquakes

Earthquake Displacement Analysis

Displacement Profiles

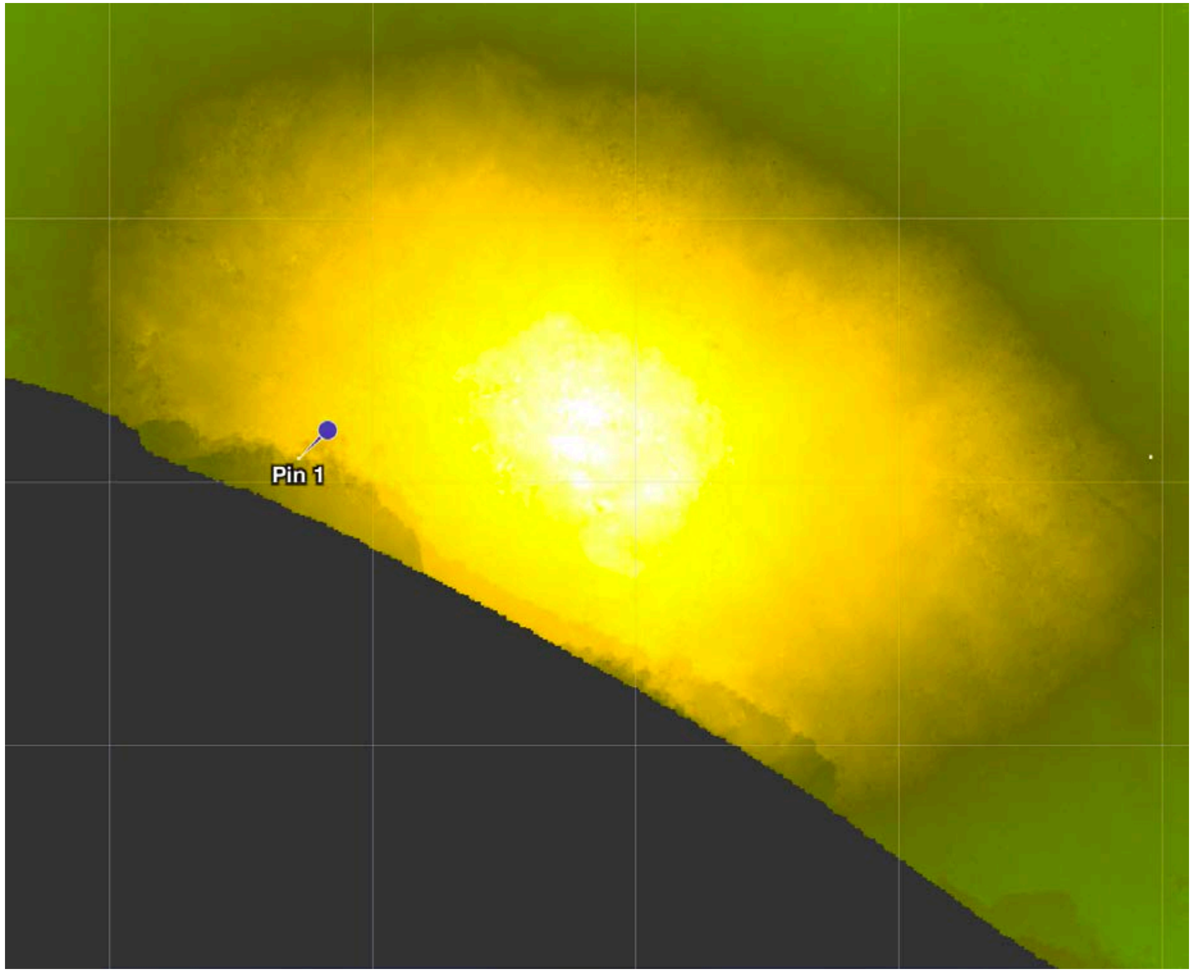
1. Use the line drawing tool (top bar of SNAP window) to draw a line across the signal.
2. Run **Analysis>Profile Tool** to see displacement along the profile
3. Remember that InSAR displacements are relative
   – In this case, displacement far from the signal is about -0.1 m, so that is probably the “true zero” offset
   – Maximum is about 0.24 m, but we need to subtract zero offset to get total displacement of about 0.35 m



Earthquake Displacement Analysis

Unwrapping Errors

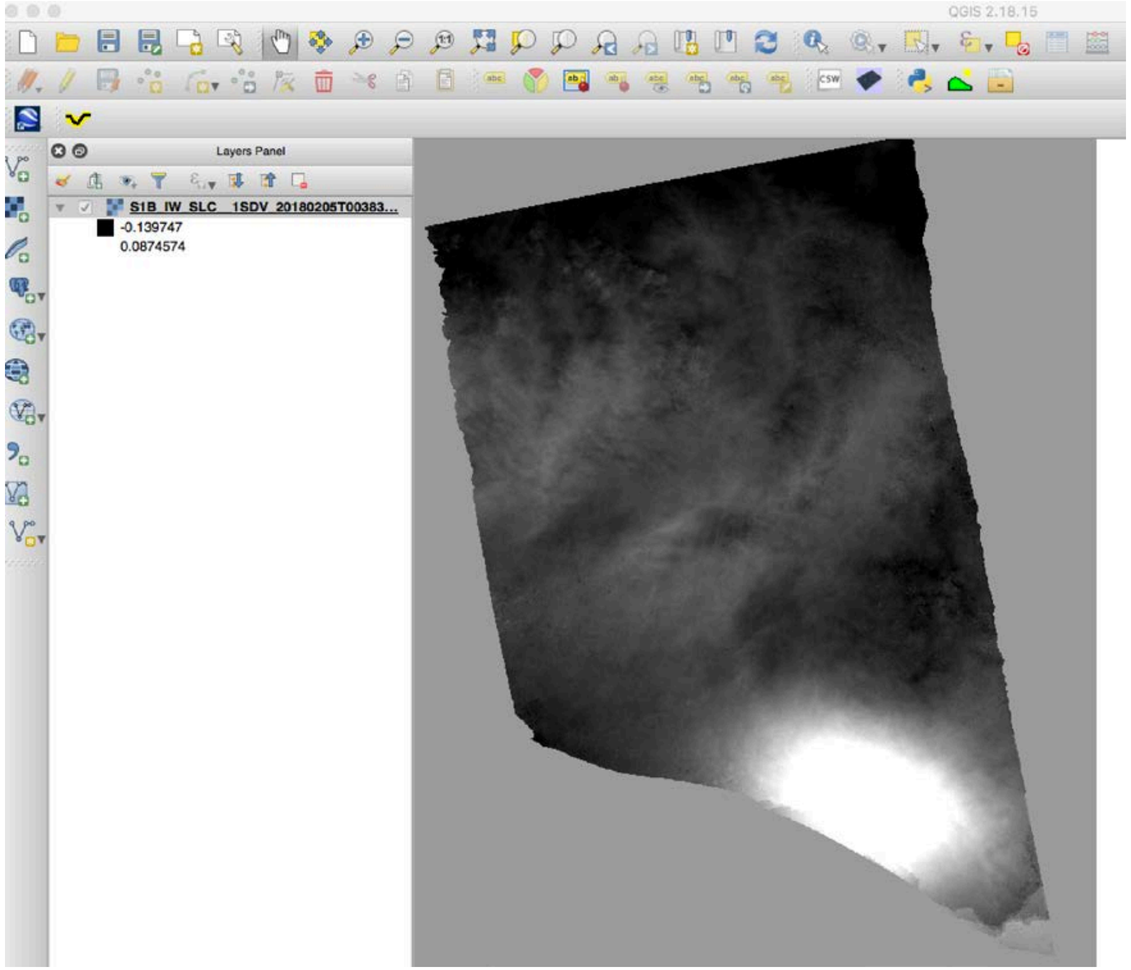
4. Zoom in to the main signal.
5. Notice the sharp discontinuities in the displacement near the coast in my interferogram (yours may be different):
   - Pin 1 in the figure points to the largest discontinuity
   - Go back and look at fringes of the wrapped interferogram
   - Wrapped interferogram has noise at that location but phase looks continuous, so this is likely a phase unwrapping error
   - You may need to adjust filtering and multilooking to get better unwrapping



Earthquake Displacement Analysis

Exporting Displacement Map

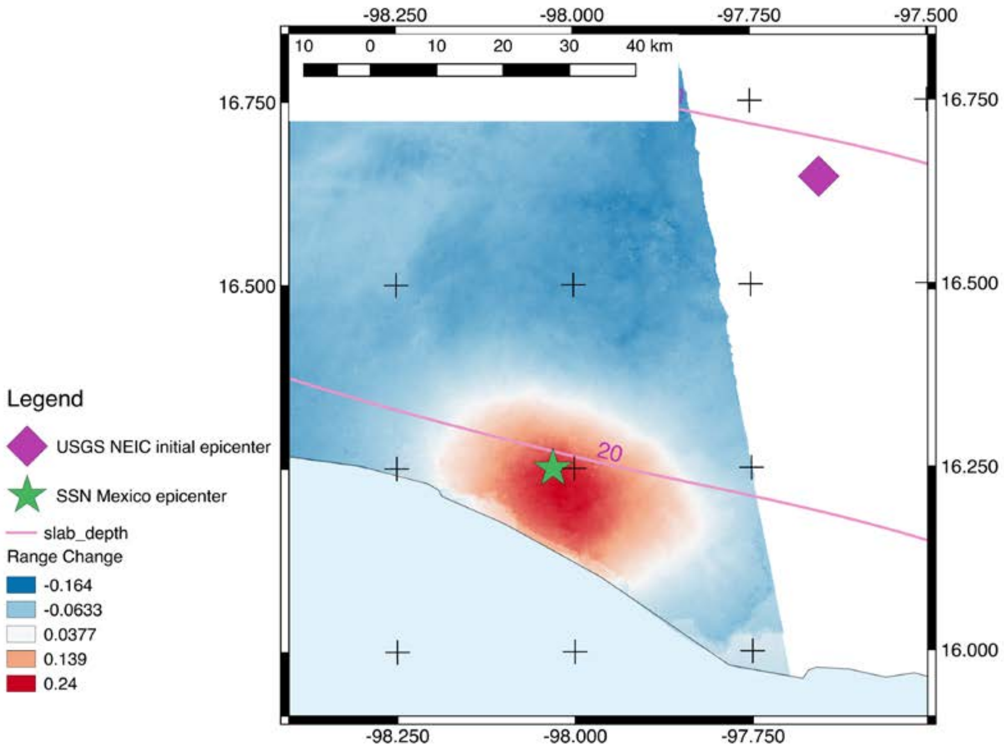
1. For more analysis, you may want to use Matlab, QGIS, ArcGIS or other analysis tools. QGIS is great free and open source tool (https://qgis.org).
2. You can export the geocoded displacement map with the **File>Export** function
3. For GIS analysis, the GeoTIFF format usually works well
4. In QGIS, can use "Add Raster Layer" to read the GeoTIFF file.



Earthquake Displacement Analysis

Comparing to Other Data

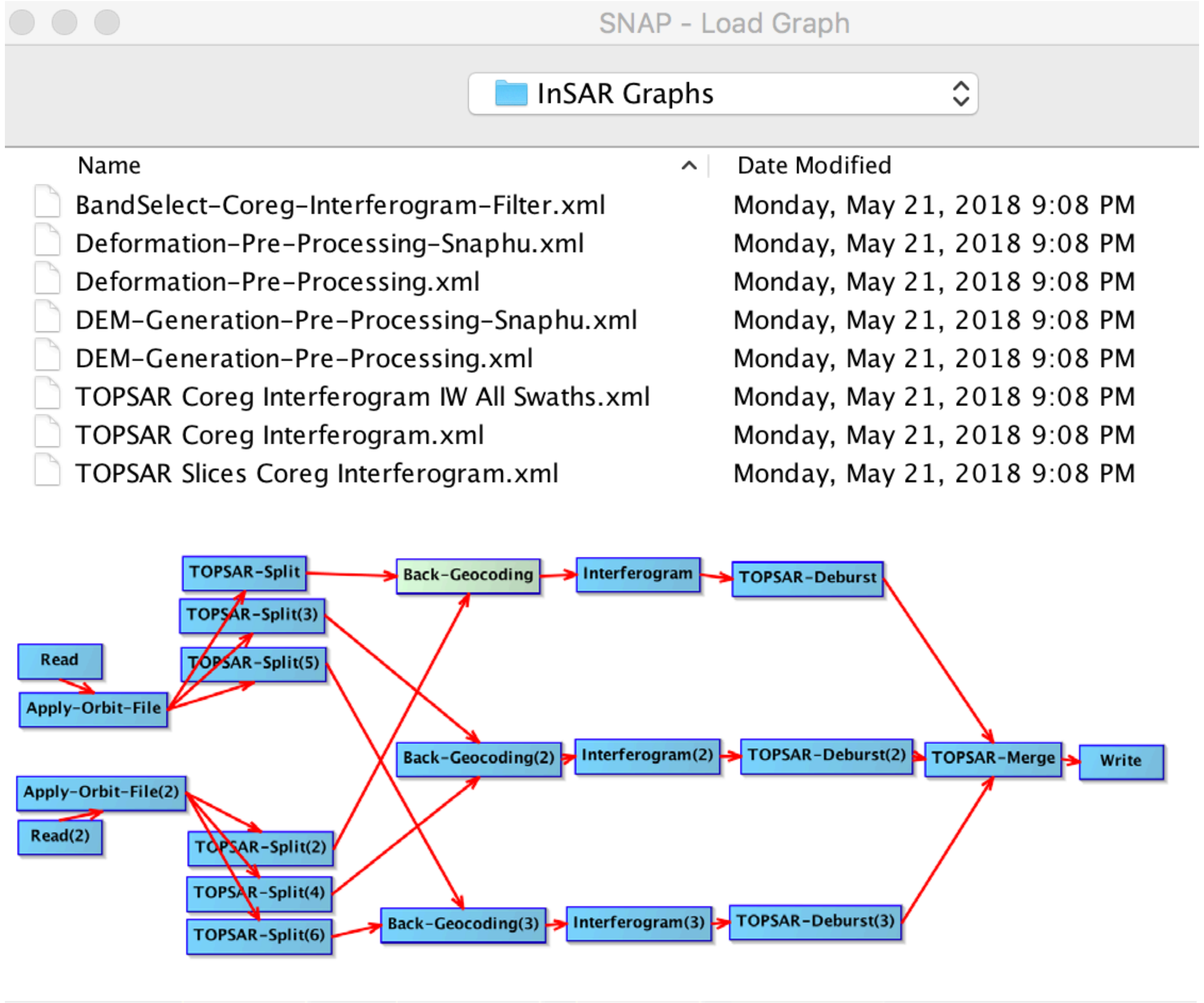
1. In QGIS, can modify the color scale, load other information from various sources
2. Can also add annotation like scale bars, labels, and legends in QGIS Print Composer
3. Here, I added epicenters from two sources (USGS preliminary and SSN Mexico preliminary) and contours on depth of the subducting slab from Slab1.0 database (Hayes et al., 2012)



Earthquake Displacement Analysis

Merging Subswaths

1. For this earthquake, most of the displacement is in the IW1 subswath that we processed from this track
2. For more complete analysis, we should process at least the adjacent IW2 subswath and then use **TOPSAR Merge**
3. SNAP has built-in Graphs or combinations of steps into a single workflow under **Tools>Graph Builder**, then **Load** button.
4. Running Graphs can take huge amount of memory (much more than running each step separately), but you can also use them to see correct order of steps (**TOPSAR Coreg Interferogram IW All Swaths.xml** shown here)



Earthquake Displacement Analysis

Getting Ready For NISAR

1. Caltech-JPL ARIA and ASF have joint project called Getting Ready for NISAR (GRFN)
2. Some sample “Beta” Sentinel-1 interferogram products were processed by ARIA and stored in ASF Archive
3. In our original ASF Vertex search, there was a GRFN product available that is two slices and all three subswaths stitched together: Granule `S1-IFG_STITCHED_TN005_20180217T003906-20180205T003836_s123_along-7556-v1.2.1-standard`
4. Can download **Unwrapped Interferogram and Coherence Map**

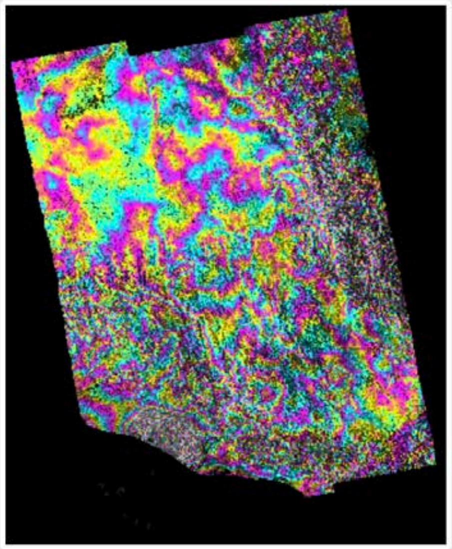
Granule Information

Dataset: Sentinel-1 Interferogram (BETA)
Granule: S1-IFG_STITCHED_TN005_20180217T003906-20180205T003836_s123_along-7556-v1.2.1-standard

Granule Details

- Acquisition Date: 2018-02-17
- Beam mode: IW
- Path: 5
- Frame: N/A
- Ascending/Descending: Ascending
- Polarization: VV
- Absolute Orbit: 9656
- Frequency: C-Band

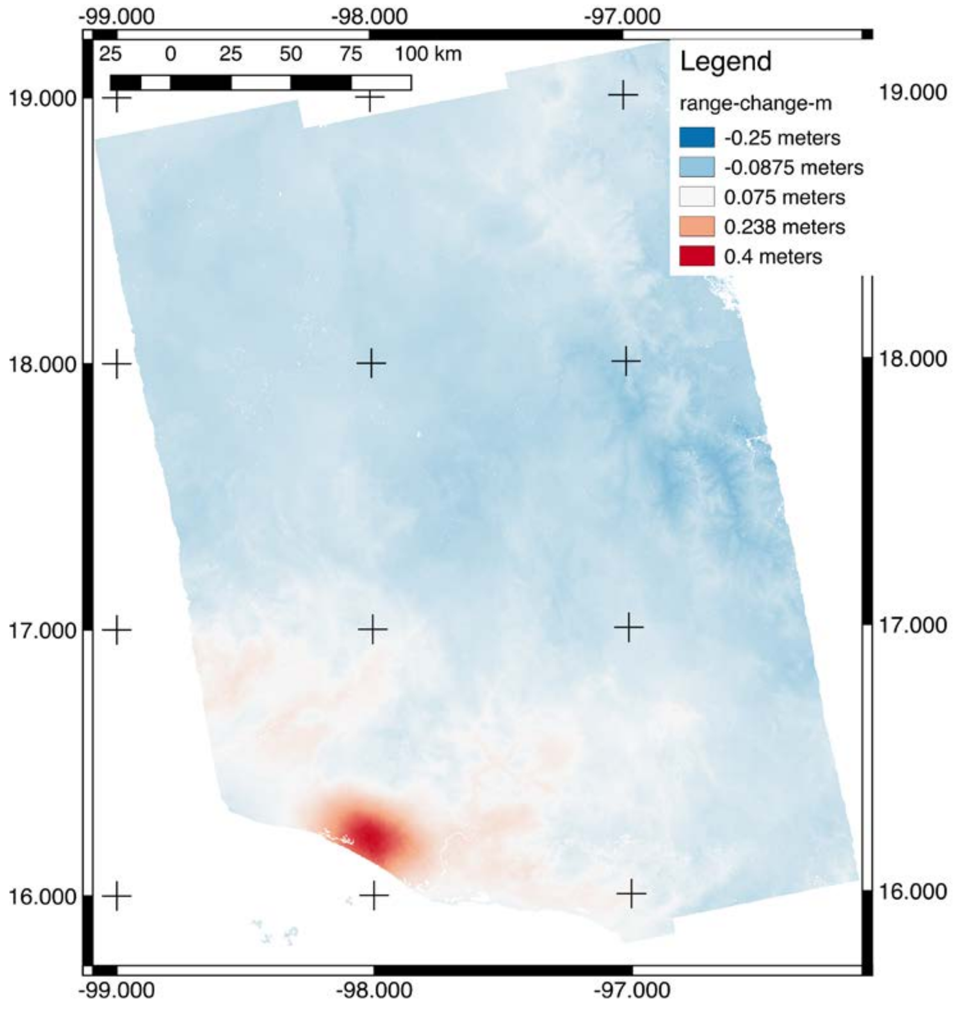
Products	Download
Sentinel-1 All Interferometric Products (BETA) (908.88 MB)	Queue / Download
Sentinel-1 Unwrapped Interferogram and Coherence Map (BETA) (284.71 MB)	Queue / Download
Sentinel-1 Full Resolution Wrapped Interferogram and DEM (BETA) (1.16 MB)	Queue / Download


Full Resolution Browse Image

Earthquake Displacement Analysis

Getting Ready For NISAR

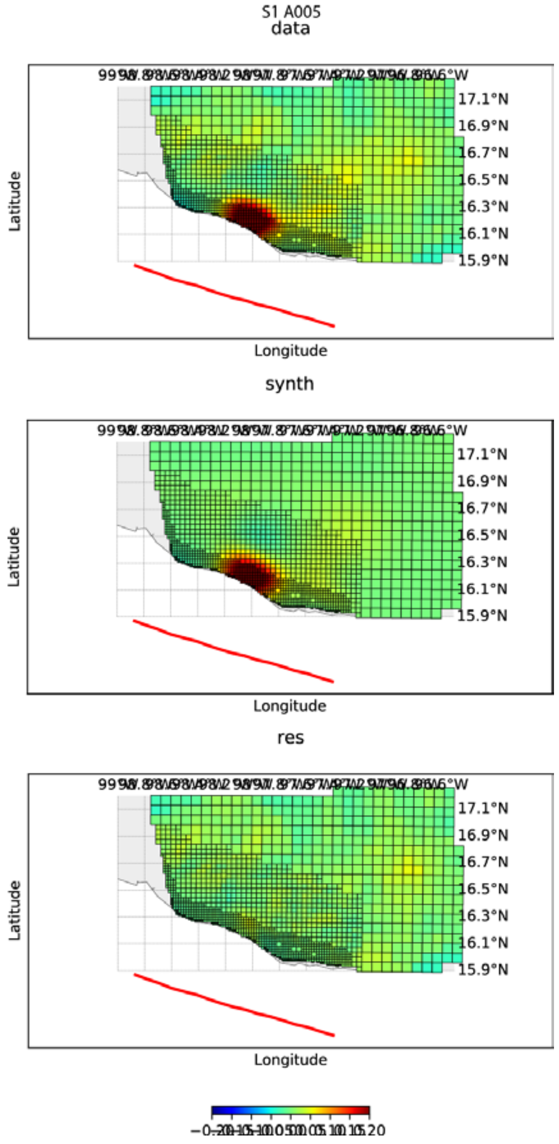
5. The GRFN Sentinel-1 “Beta” interferogram products are in the InSAR Scientific Computing Environment (ISCE) format
6. QGIS can read the “.vrt” file to load the raster layer
7. Map shown here is full stitched GRFN unwrapped interferogram converted to displacement
8. Note many variations far from earthquake that are likely due to water vapor in atmosphere



Earthquake Displacement Analysis

Earthquake Modeling

1. Fault slip modeling is an advanced geophysical topic
2. One or more interferograms can be used to estimate slip on fault at depth with inversion methods
3. Interferogram is sampled at about 500-1000 points (top)
4. Then inversion determines slip on fault and estimates synthetic interferogram (middle)
5. Difference or residual shows how well slip model fits data (bottom)



Earthquake Displacement Analysis

Earthquake Modeling

6. Map view of slip model on fault with 5 by 5 km patches
7. Fault from Slab database
8. Inversion with Caltech fully Bayesian slip inversion AlTar (Minson et al., 2012)
9. Used GPS, three Sentinel-1 interferograms (A005, D143, D070) and one ALOS-2 interferogram