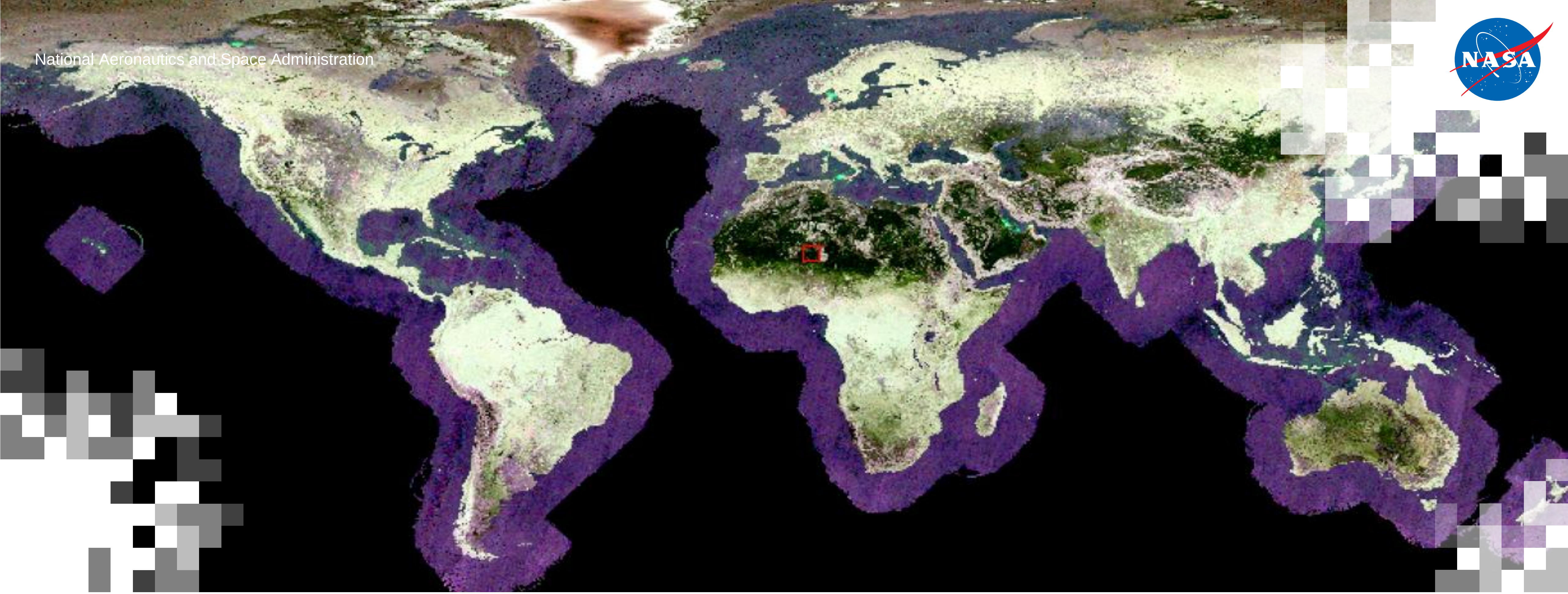
National Aeronautics and Space Administration



Interferometric SAR for Landslide Observations

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December 2019

Learning Objectives

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

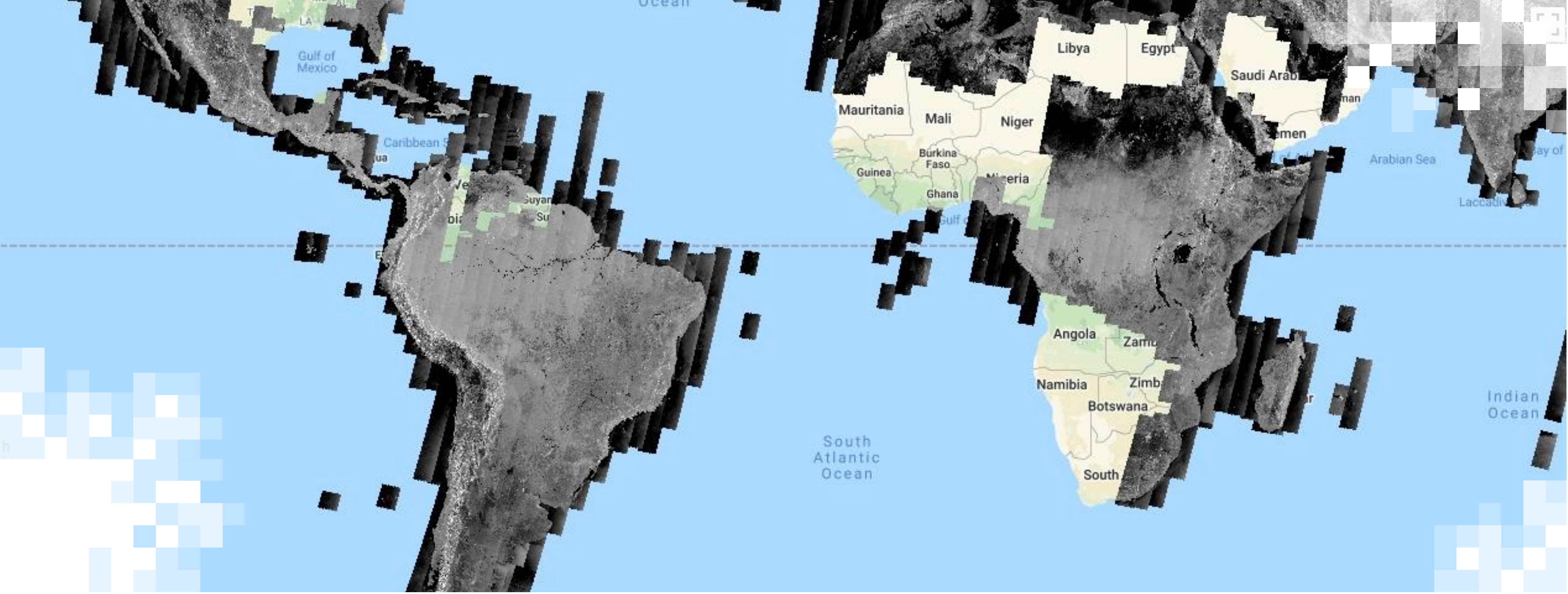
- Understand the basic physics of SAR interferometry and SAR pixel tracking
- Describe what SAR interferometric phase tells about the land surface and landslides
- Describe the necessary data processing for making an interferogram
- Understand the information in SAR interferometric images about land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

Prerequisites

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

Acknowledgments

- JPL: N. Pinto, Y. Zheng, P. Agram, E. Gurrola, UAVSAR processing team
- NASA AFRC & JSC: J. McGrath, pilots and staff
- USGS: J. Coe, W. Schulz
- UC Berkeley: R. Bürgmann, B. Delbridge
- U of Maryland: Mong-Han Huang
- NASA Earth Surface and Interior, Geodetic Imaging, NISAR Science Team programs



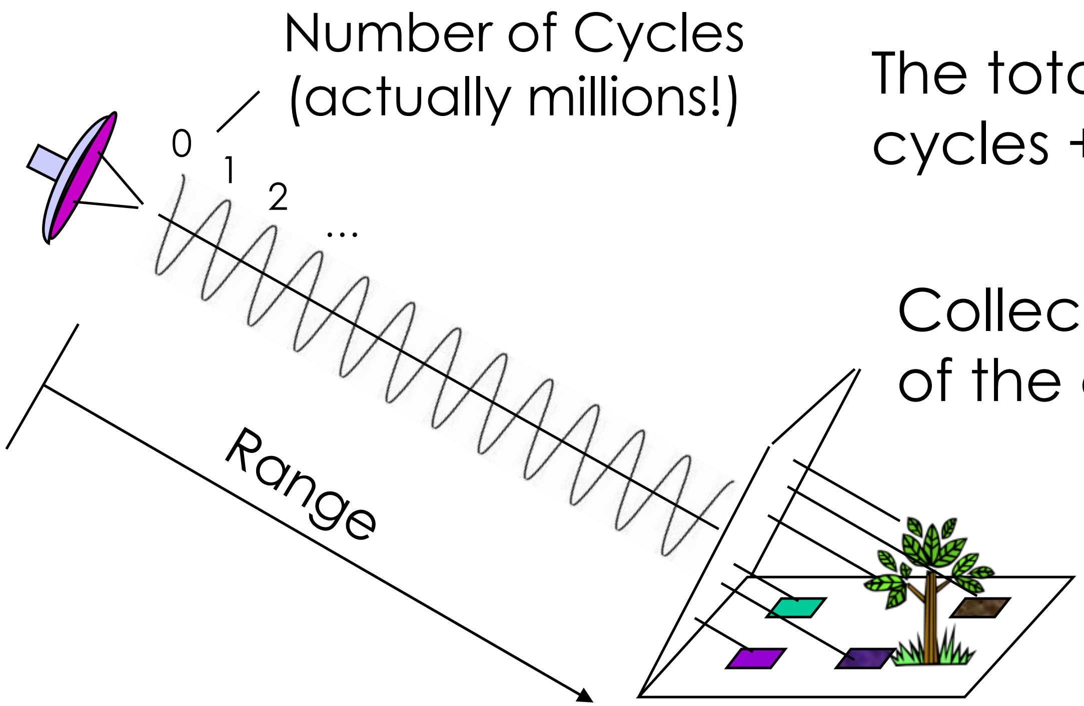
SAR Interferometry Theory (Review)

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 modified from 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)

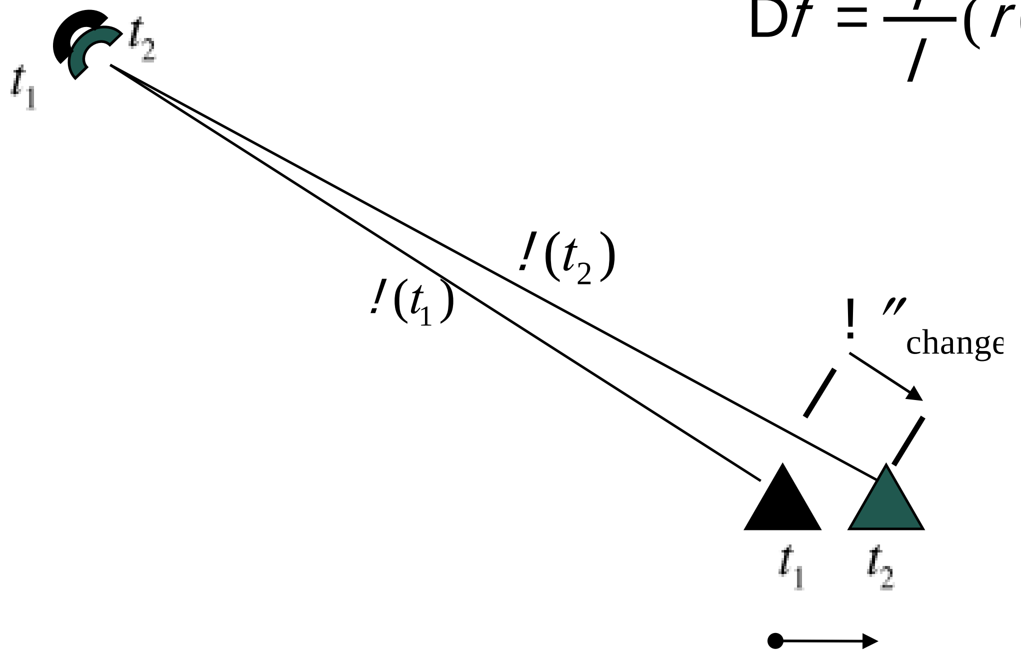
SAR Interferometry Applications

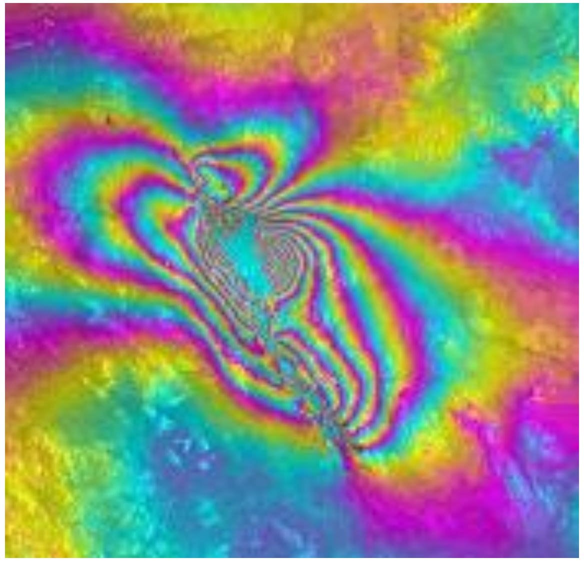
- Deformation Mapping and Change Detection
  - Repeat Pass Radar Interferometry from spaceborne platforms is routinely used to produce topographic change maps as digital displacement models (DDMs).
    - 0.1–1 centimeter relative displacement accuracy
    - 10–100 m post spacing and resolution
    -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

$$\Delta\phi = \frac{4\pi}{\lambda}\left(r(t_1) - r(t_2)\right) = \frac{4\pi}{\lambda}\Delta r_{change}$$





Slide modified from Paul Rosen (JPL)

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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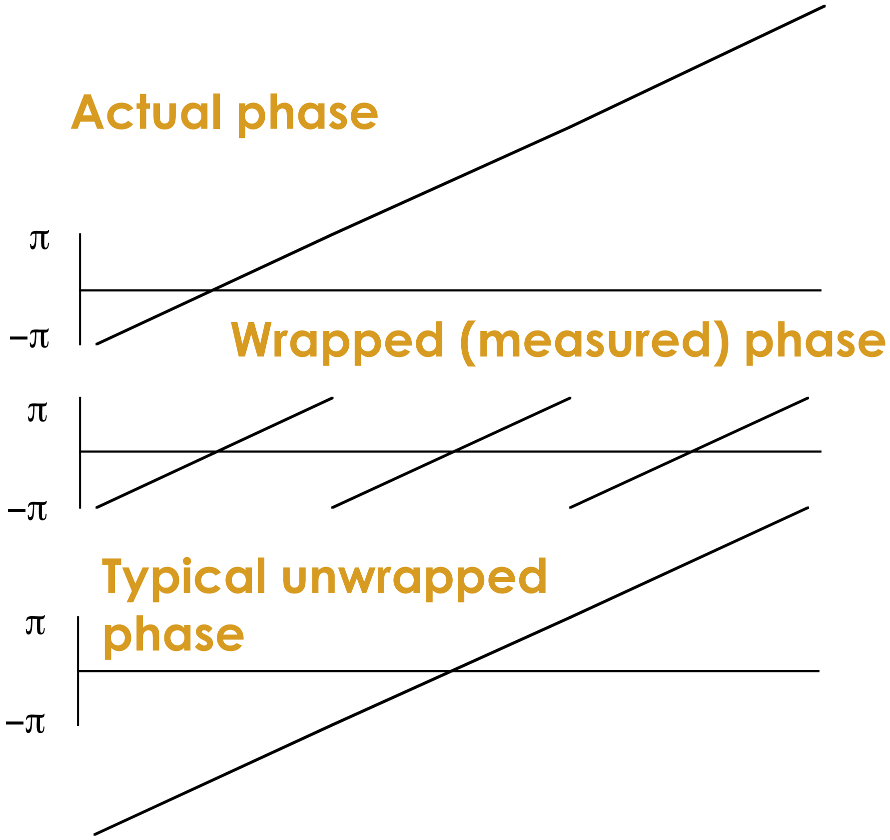
Phase Unwrapping

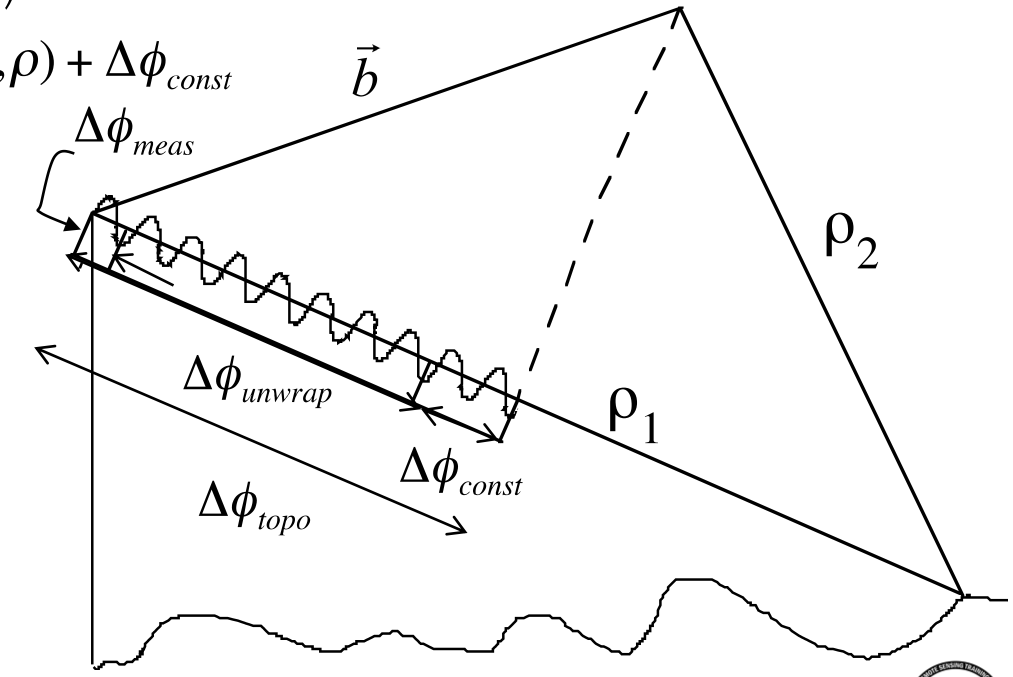
- From the measured, wrapped phase, unwrap the phase from some arbitrary starting location, then determine the proper 2-pi phase “ambiguity”



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

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

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



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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

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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

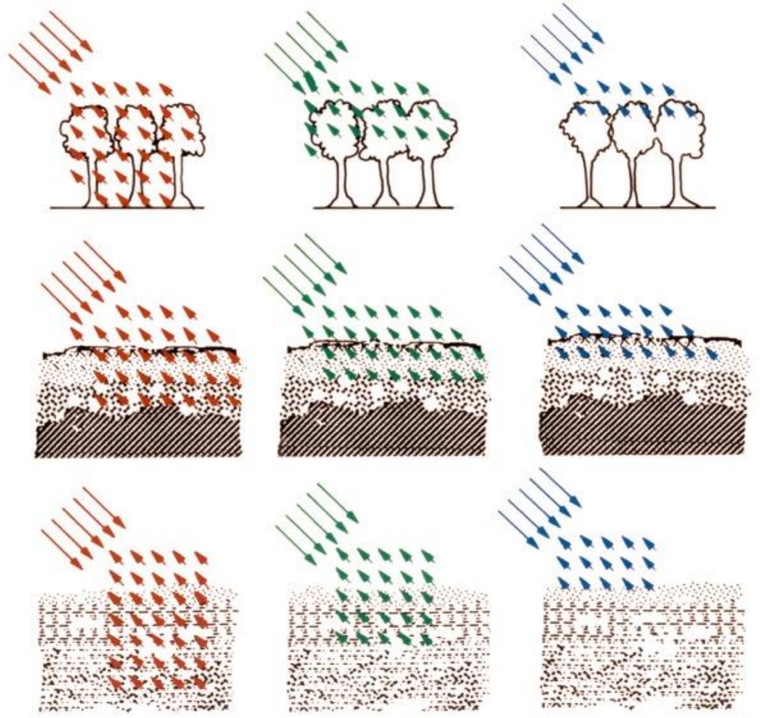
Light interacts most strongly with objects around the size of the wavelength

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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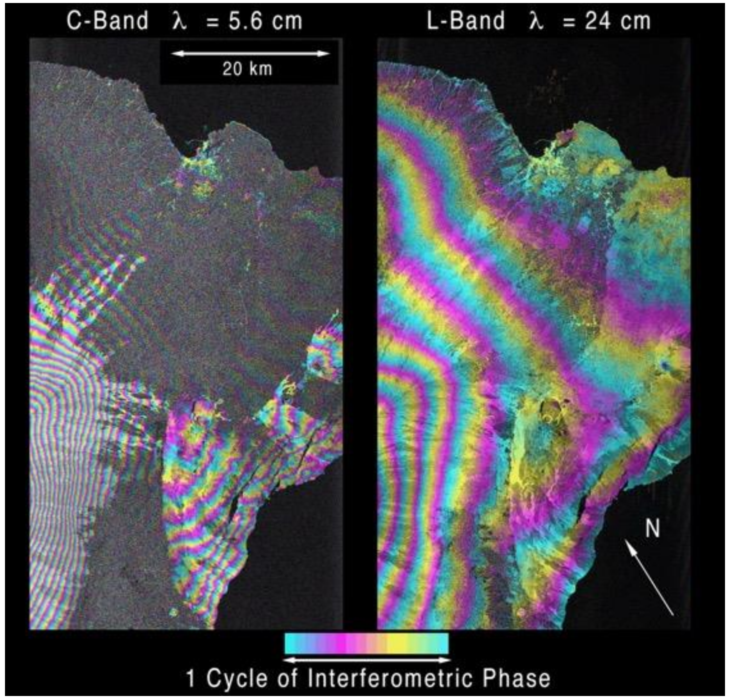
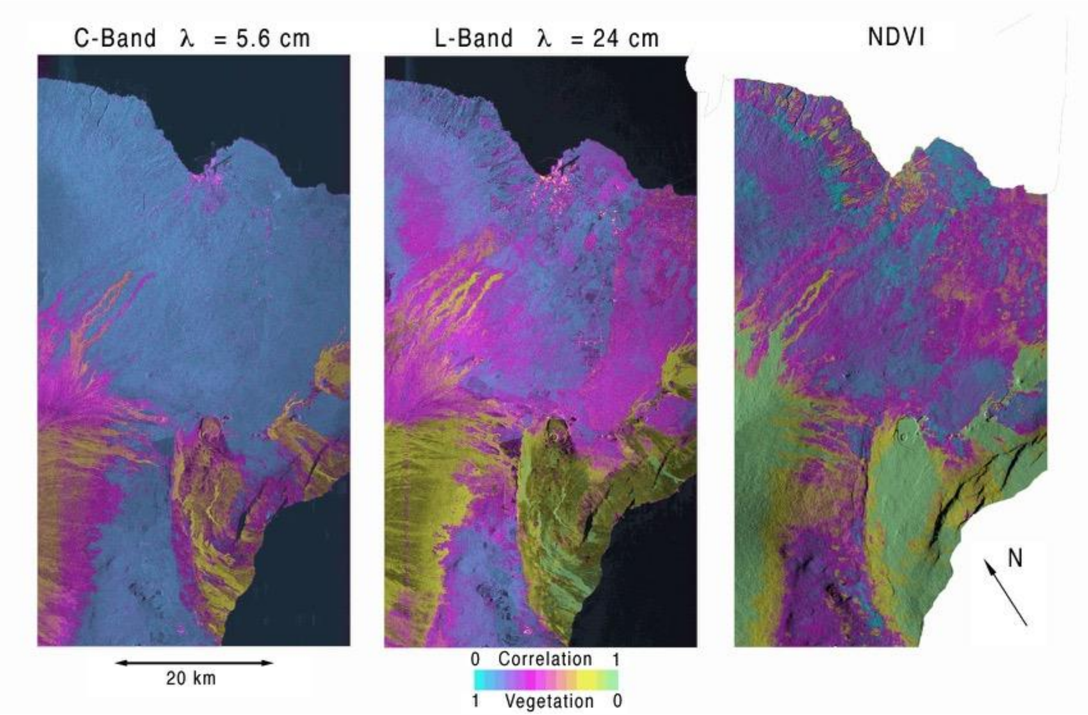
Coherent Change Detection

SIR-C L- and C-band Interferometry

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





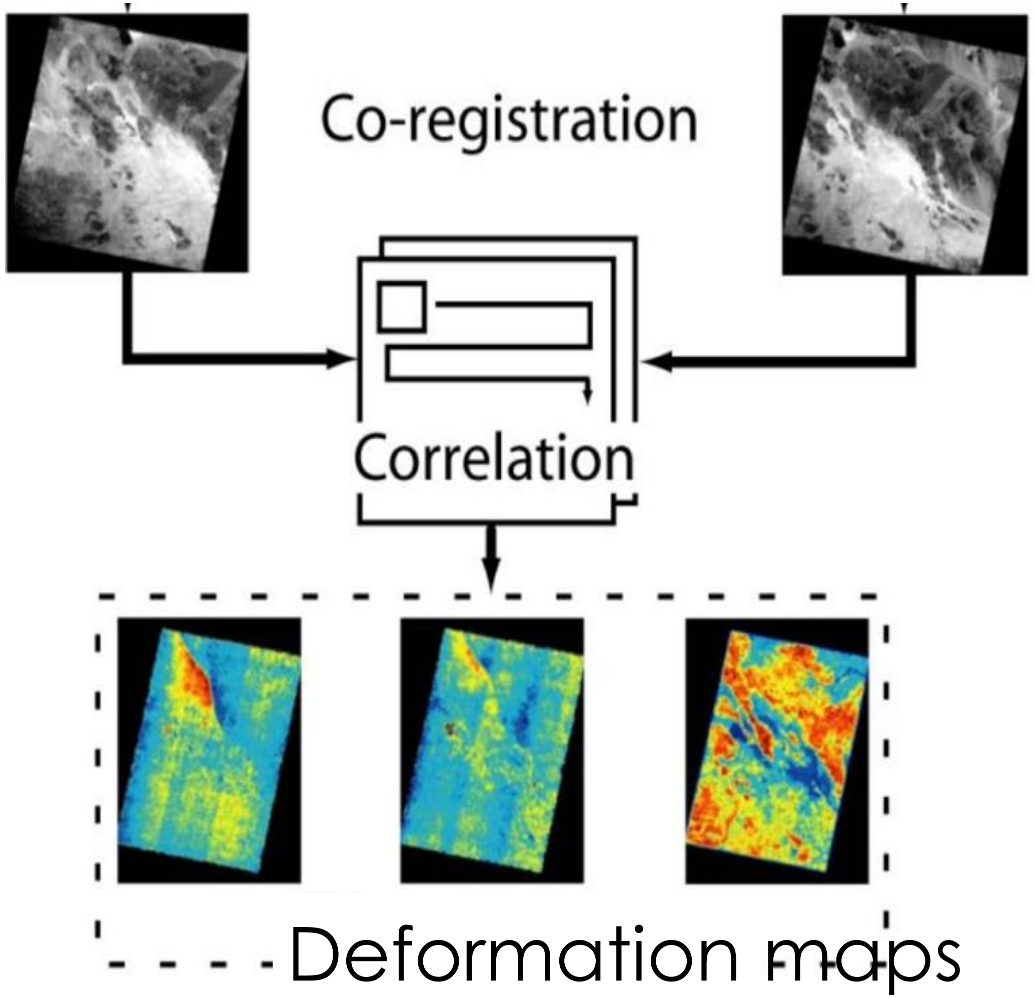
InSAR experiments have shown good correlation at L-band

Pixel Offset Tracking with SAR

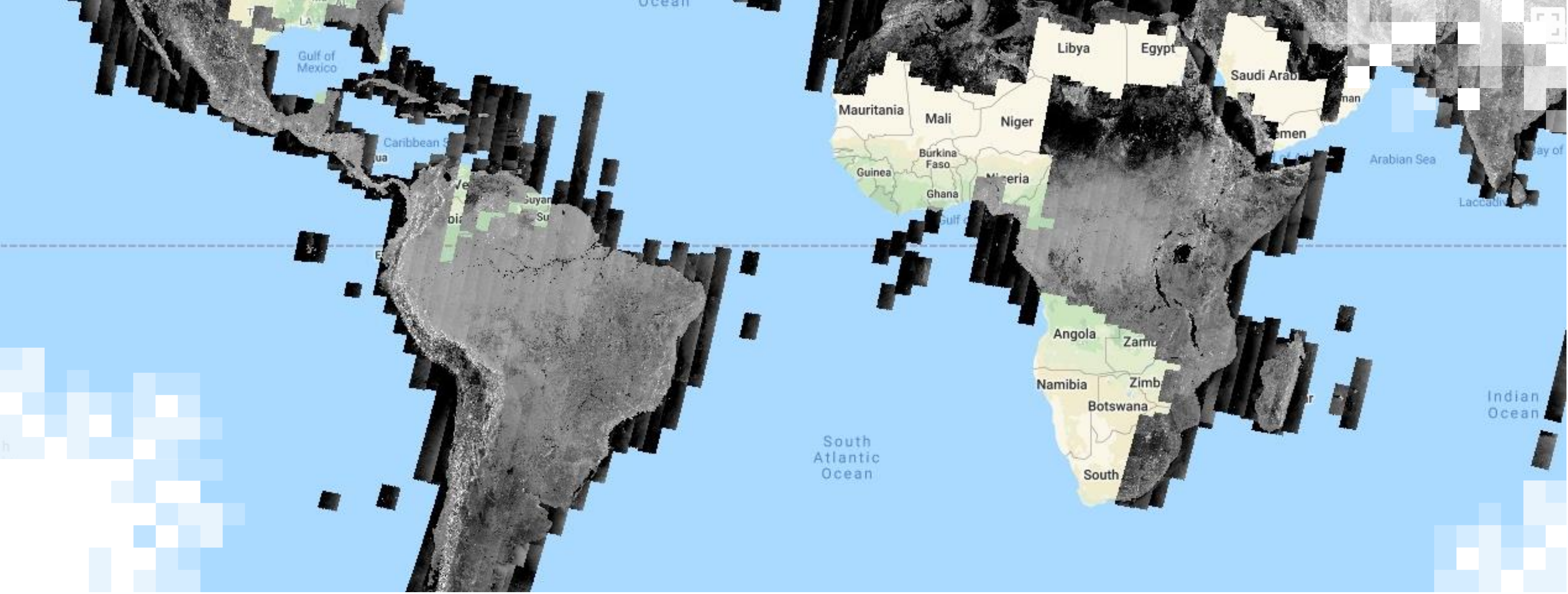
- Large displacements of surface, more than about 1/10 of the SAR pixel size, cause loss of InSAR coherence
- Landslides and earthquakes can involve large displacements
- Pixel offset tracking or image correlation can measure large displacements
- Can be used with optical or SAR images
- Similar to InSAR, measures displacements between two images
- SAR pixel offsets measure 2D deformation along the slant line-of-sight and horizontal flight directions
- Cross correlates SAR amplitude images with subpixel precision to measure changes

Pixel Offset Tracking with SAR

- **Advantages:**
- Provides 2D measurements
- No deformation rate limit (InSAR has a limit)
- measures a continuous deformation field
- No problem with clouds
- little or no atmospheric effects
- **Limitations:**
- cm- to m-scale sensitivity
- Vegetation
- Observational bias



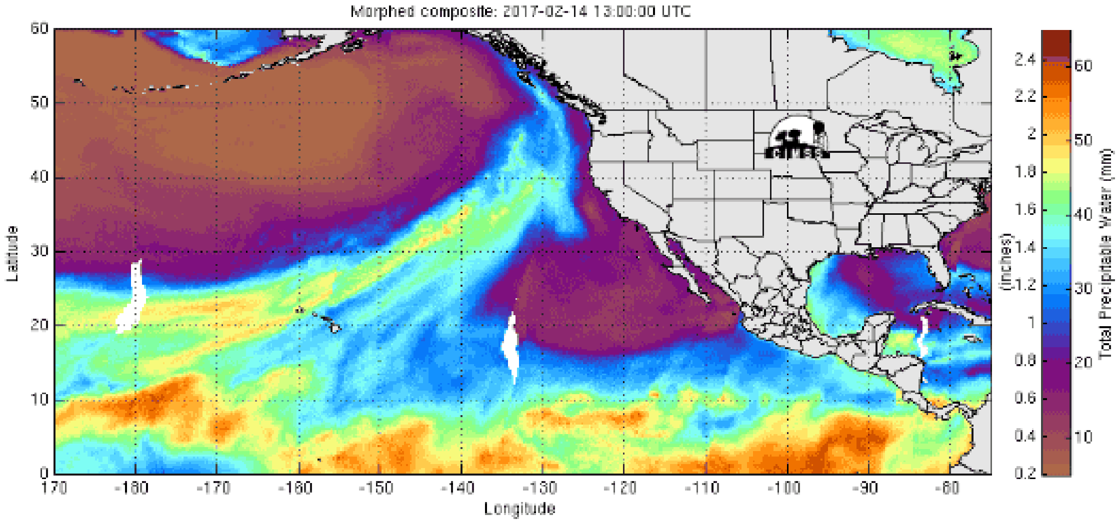
Leprince et al., 2007

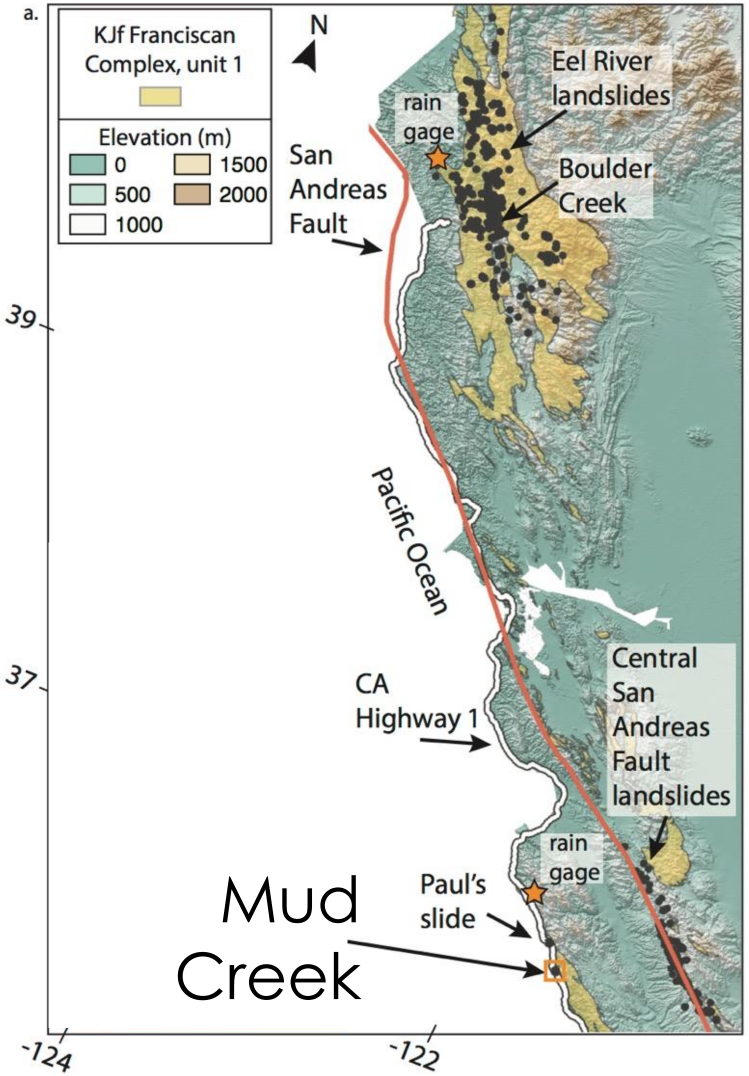


InSAR Examples:
Landslides in California, Oregon, and Colorado

California Landslides

- Landslides in the California Coast Ranges:
  - Franciscan Complex Lithologic Units are weak rocks that are prone to landslides
  - Active tectonics along plate boundary generates mountains
  - High seasonal rainfall





Credit (left): Credit: *Nature Geoscience* (2017). DOI: 10.1038/ngeo2894; (Right) Handwerger et al., *Scientific Reports* (2019)

NASA/JPL Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR)

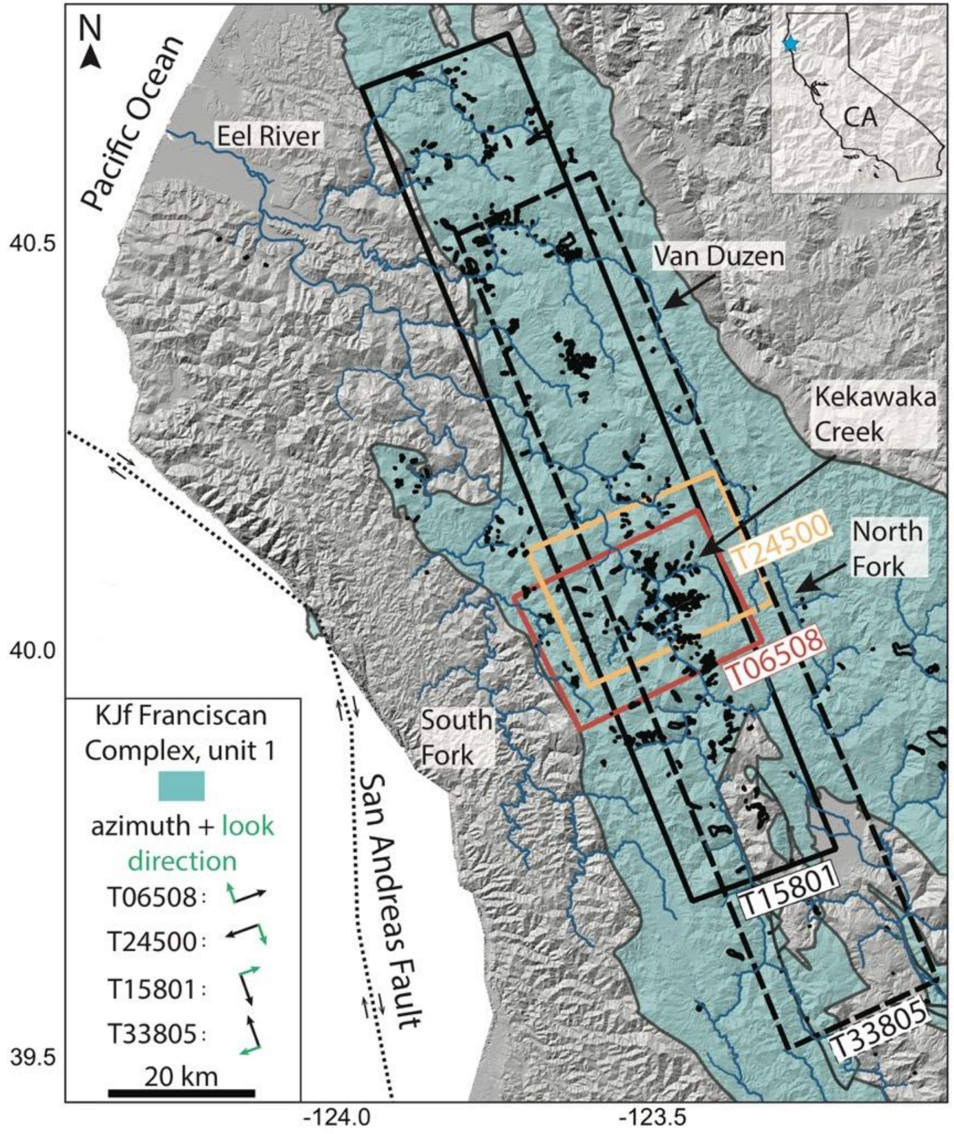
- NASA Gulfstream III
- High resolution SAR
  - (0.6 m along-flight direction, 1.6 m look direction)

SAR processing and time series inversion

- InSAR Scientific Computing Environment (ISCE) (Rosen et al., 2012)
- Generic InSAR Analysis Toolbox (GIAnT) (Agram et al., 2013)
  - Small Baseline Subset (SBAS) method (Schmidt and Bürgmann, 2003)

Northern California landslides

- Hundreds of active landslides in the Eel River catchment
- UAVSAR flights on 4 lines
- Perpendicular flight lines to get three-dimensional surface displacements
- 11 sets of flights April 2016 to May 2019



Handwerger, A. L., E. J. Fielding, M. H. Huang, G. L. Bennett, C. Liang, and W. H. Schulz (2019), Widespread Initiation, Reactivation, and Acceleration of Landslides in the Northern California Coast Ranges due to Extreme Rainfall, Journal of Geophysical Research: Earth Surface, 124(7), 1782-1797, doi:10.1029/2019jf005035.

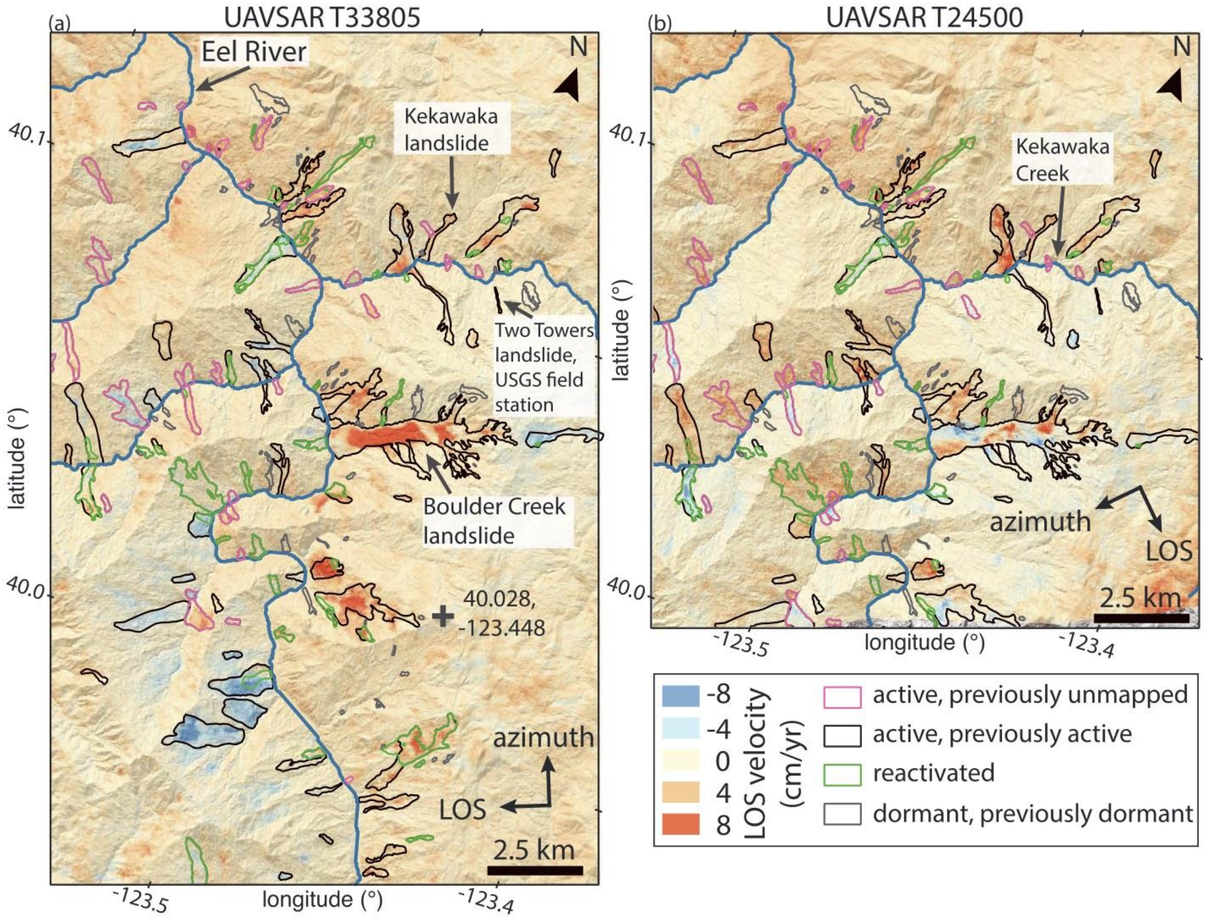
Eel River UAVSAR Results

Landslide identification

- Deformation signal
- Previously published inventories
- Landslide morphology (DEMs)
- Downslope motion
- Google Earth

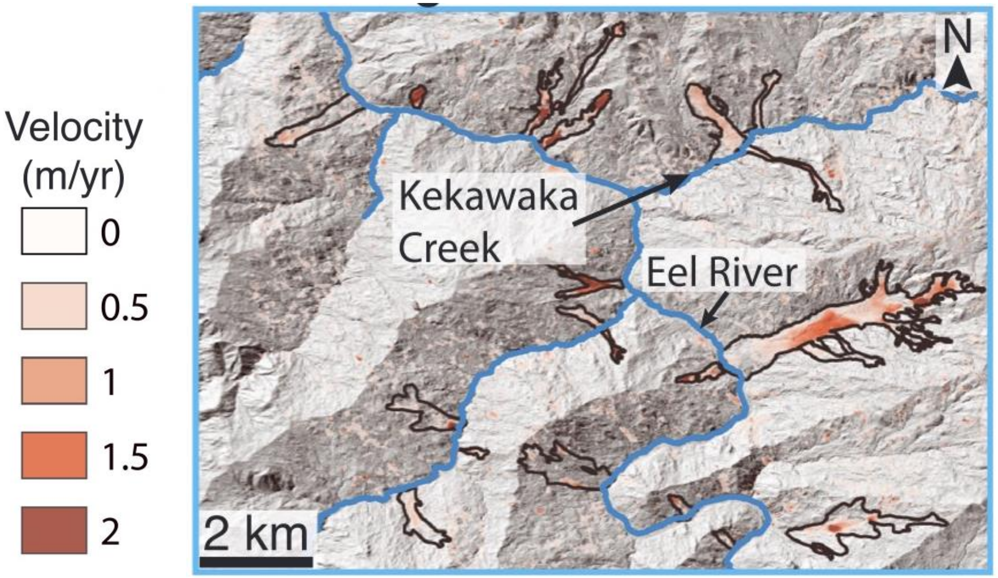
Landslide inventory

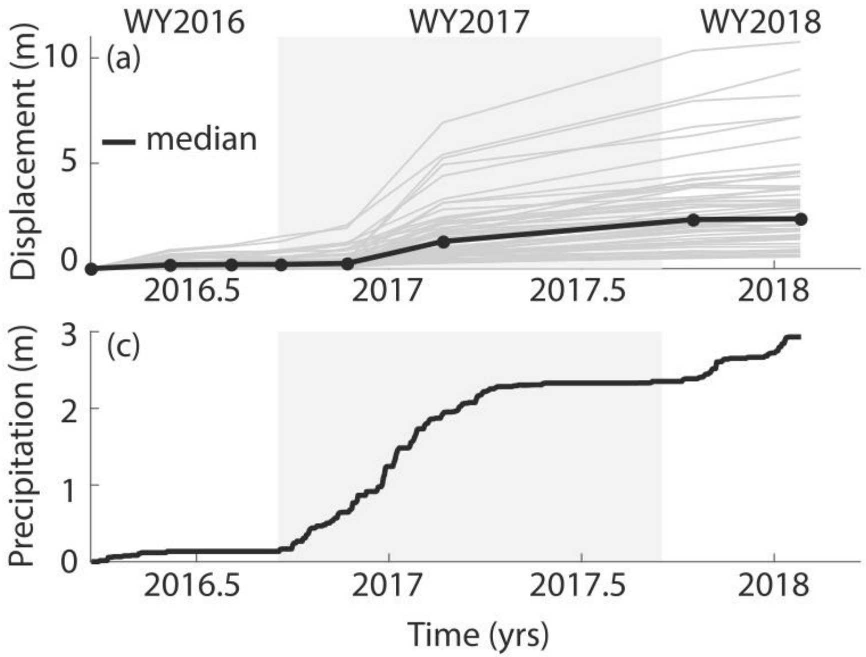
- 312 landslides between April 2016 and February 2018
- 102 previously unmapped landslides
- (i.e. new or reactivated)



Handwerger et al., JGR (2019)

Eel River UAVSAR Results





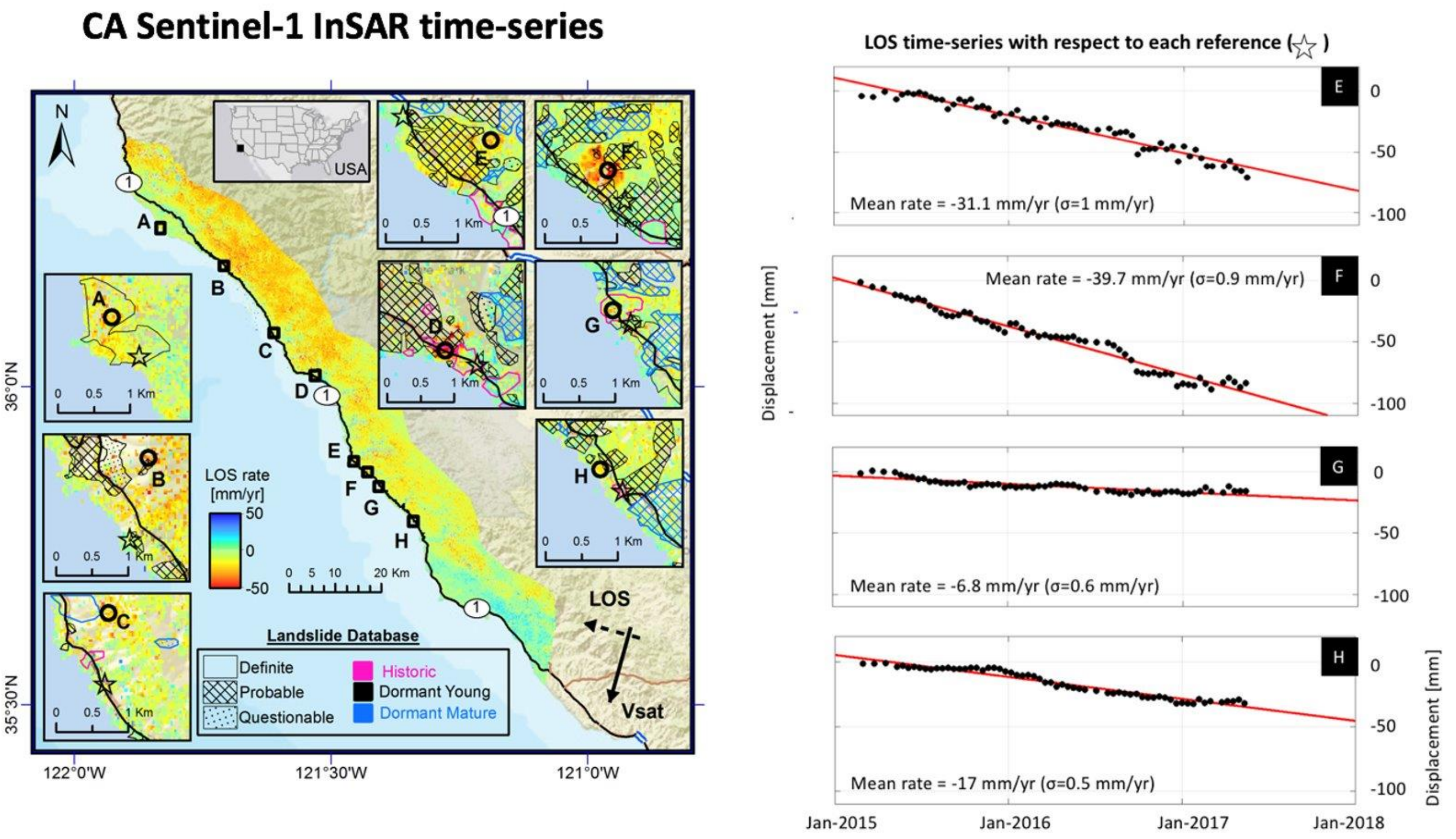
Pixel offset tracking

- Horizontal displacement measured from pixel offsets
- Displacement time series analyzed
- Seasonal displacement driven by rainfall

Handwerger et al., JGR (2019)

Central California landslides

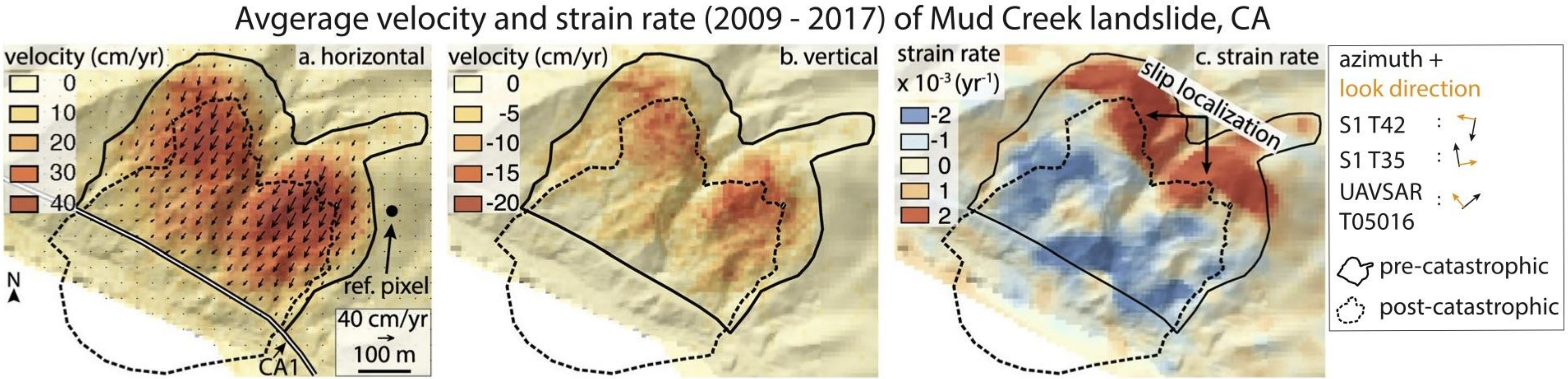
- Sentinel-1 A/B data
- Dozens of active landslides along the Central California Coast



Sentinel-1 available for free under Copernicus program

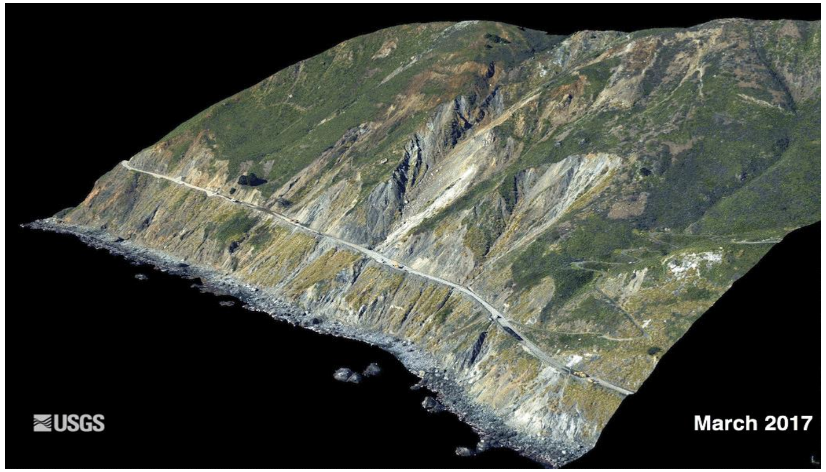
Slide from David Bekaert, P. Agram, H. Fattahi (JPL)

Central California Landslides



Mud Creek landslide

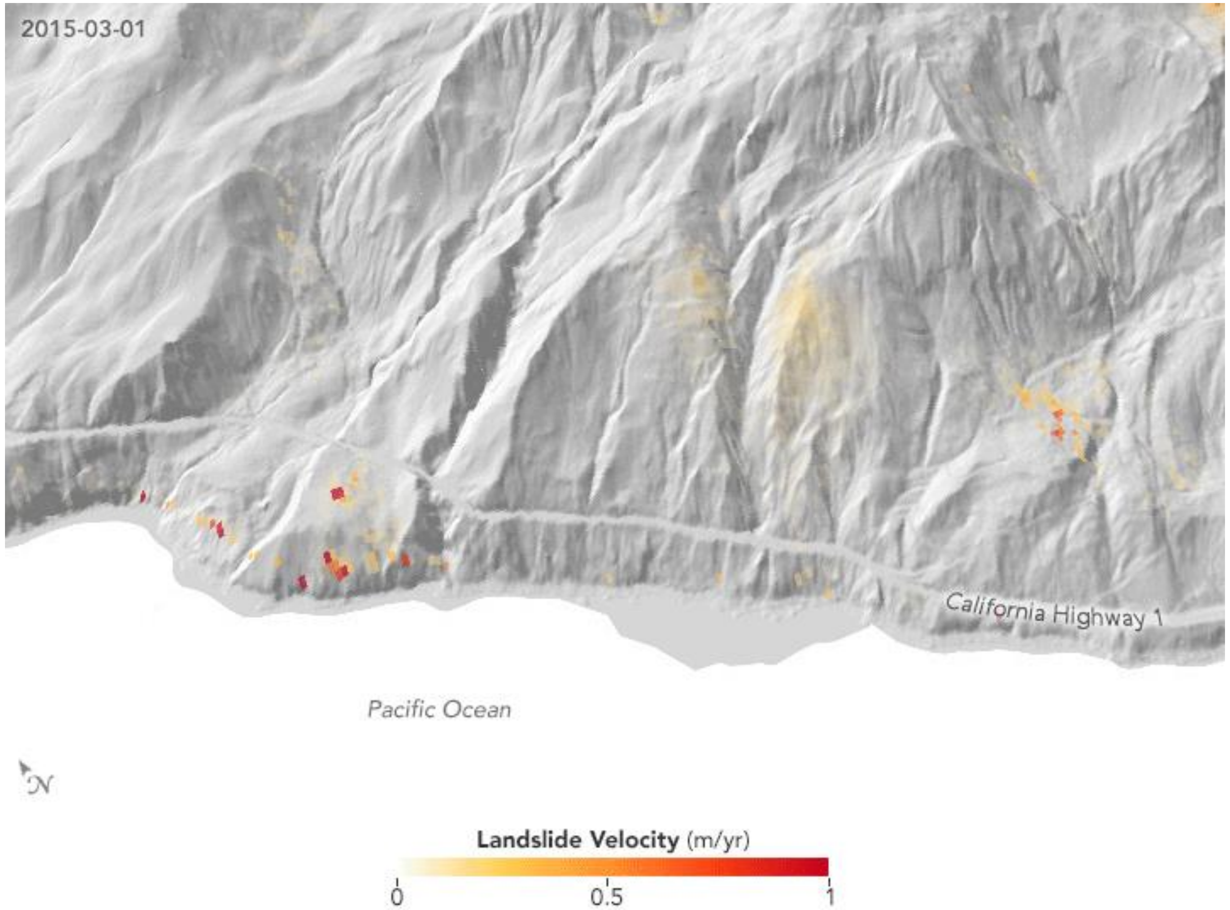
- Failed catastrophically on May 20, 2017
- Repair cost ~$54 million
- Sentinel-1 and UAVSAR data combined for 3D displacement

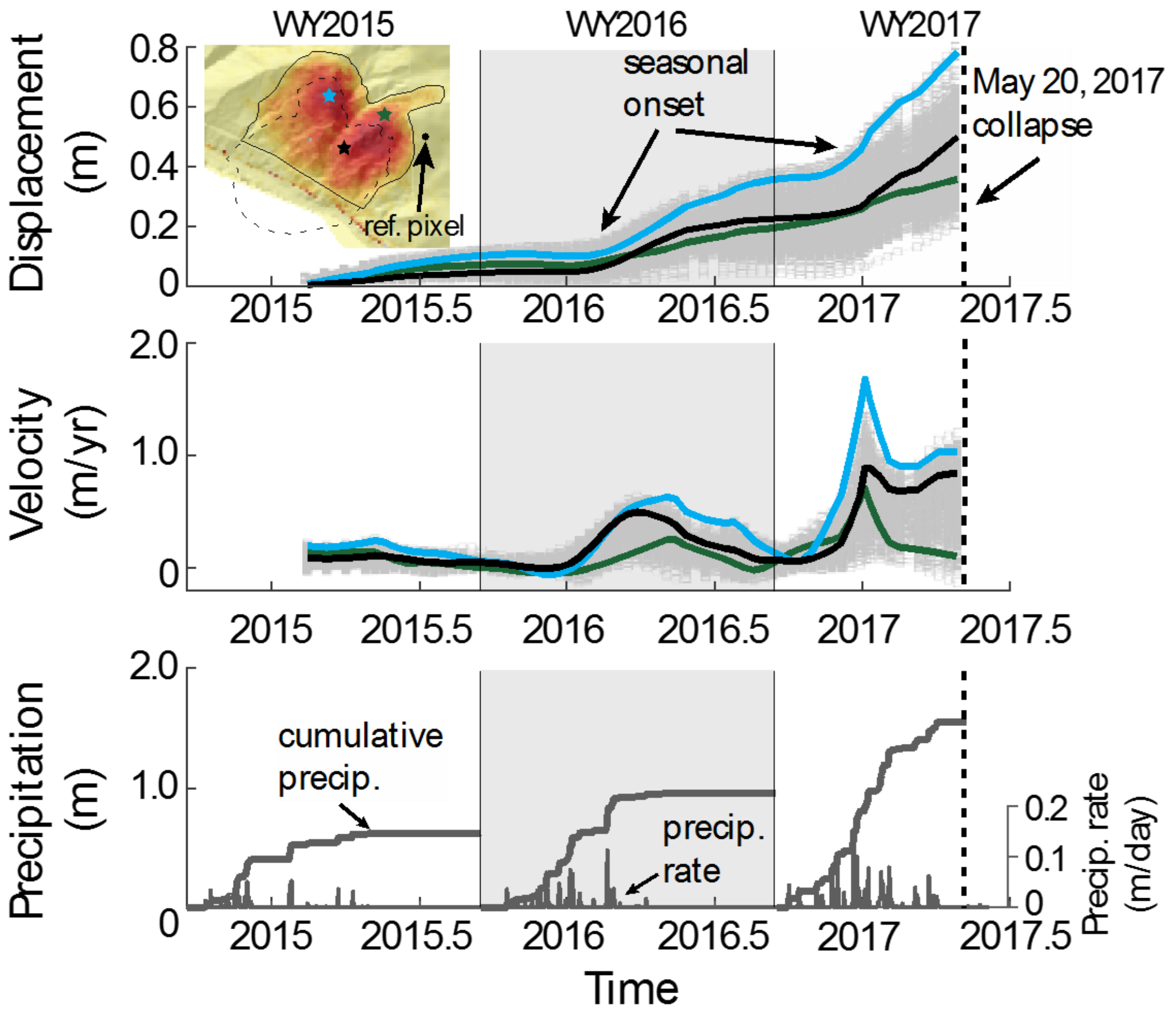


Top: Handwerger et al., Scientific Reports (2019); Bottom: Warrick et al. 2019, https://walrus.wr.usgs.gov/remote-sensing/

Central California Landslides

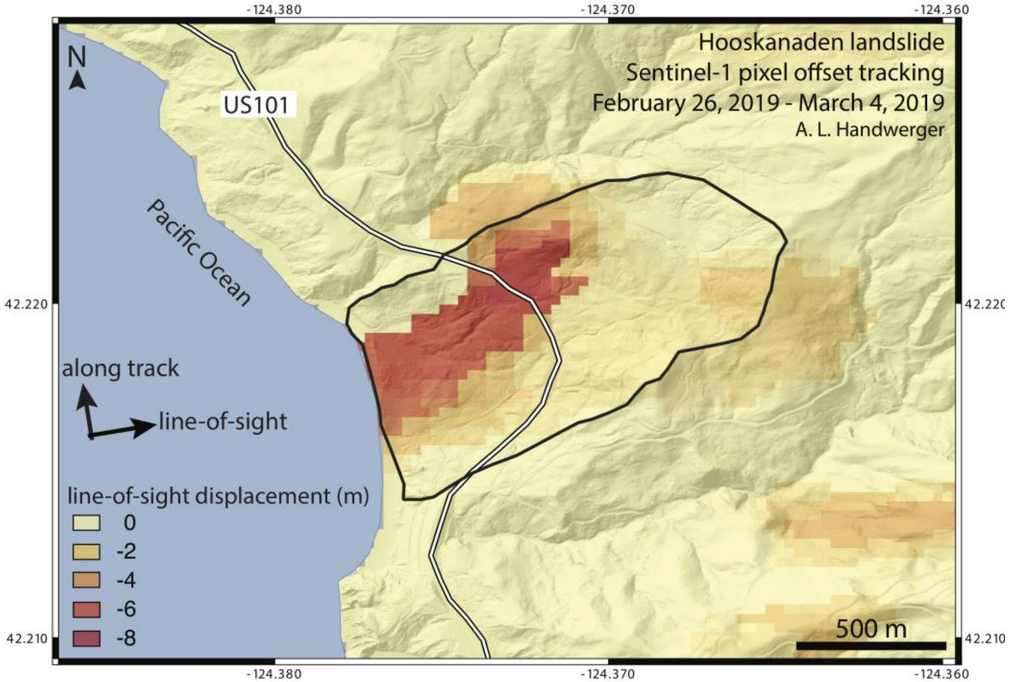
Mud Creek Landslide





(Left) InSAR Time Series from Sentinel 1; (Right) Handwerger et al., Scientific Reports (2019)

Oregon Coast Landslides



Hooskanaden landslide

- Destroyed US101 near Brookings, OR
- Pixel tracking with Sentinel-1 SAR data
- ~6 meters of displacement in the LOS direction between Feb 26 and Mar 4, 2019

(Left) Tidewater photo via ODOT from March 3, 2019

Slumgullion Landslide, Colorado

- The active Slumgullion Landslide:
- Peak velocity:1-2 cm/day
- Average Slope: 8 degrees
- Length: 3.9 km
- Width: ~300 m
- Depth: ~14 m
- Volume: 20x10^{6} m

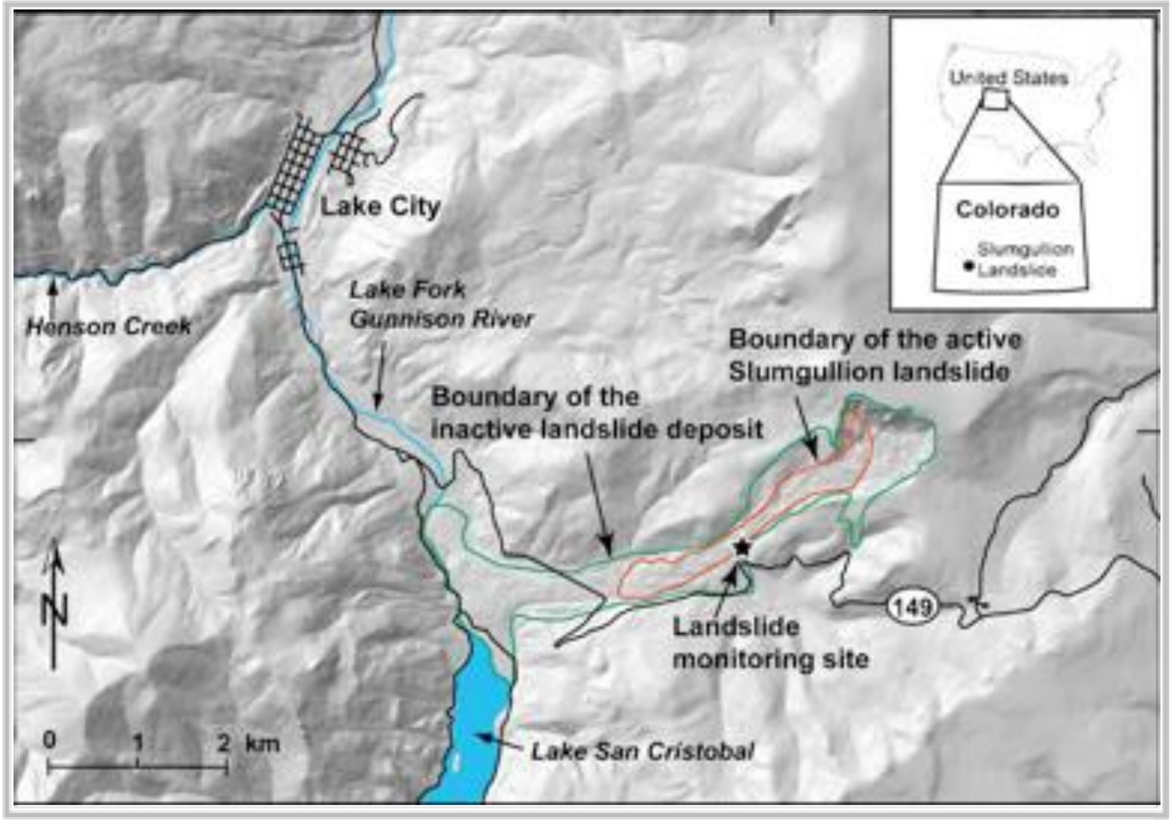
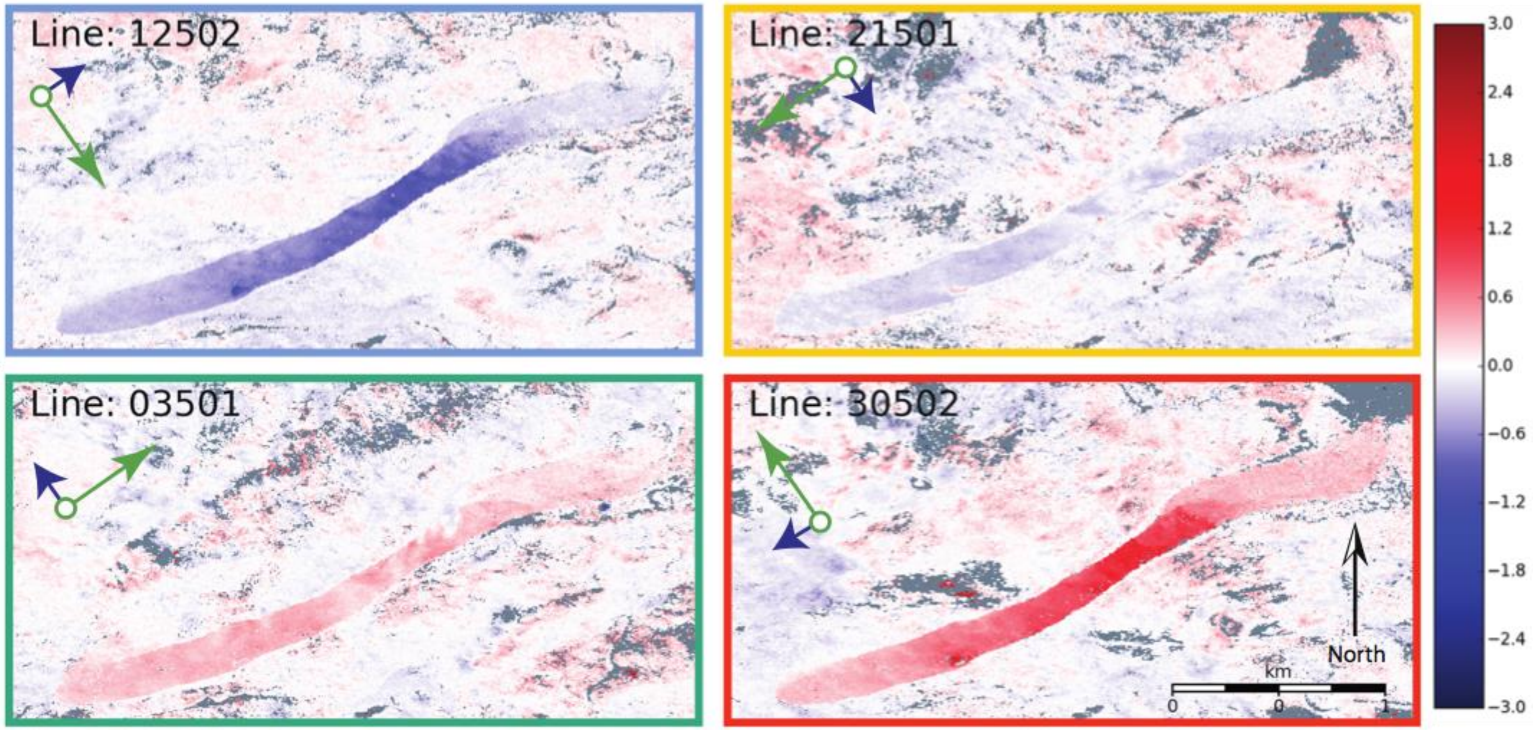


Figure From Schulz et al 2009

Slumgullion UAVSAR L-band interferograms

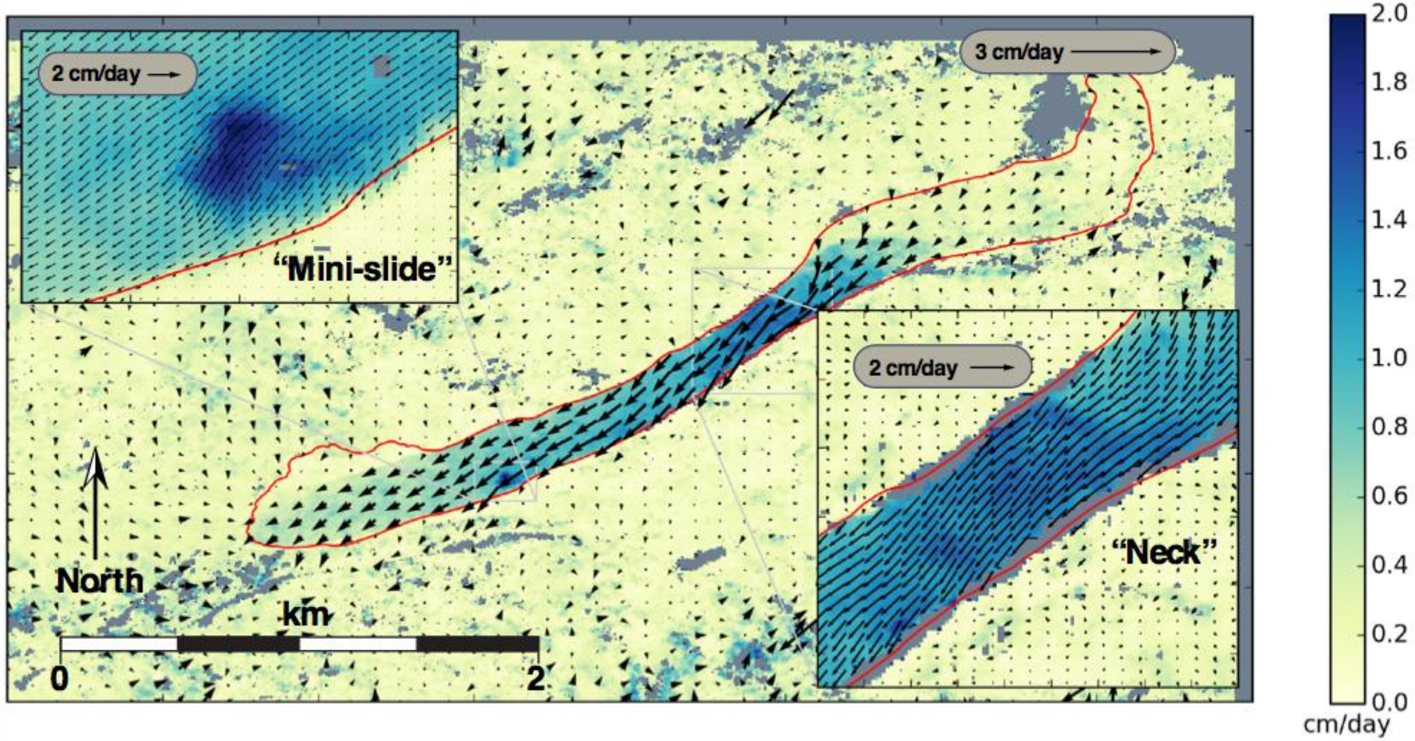
- Four flight directions (green arrows)
- Four lines of sight (blue arrows)
- April 16th and 23rd 2012
- Velocity in centimeters per day



B. Delbridge, UC Berkely

Slumgullion 3-D displacements

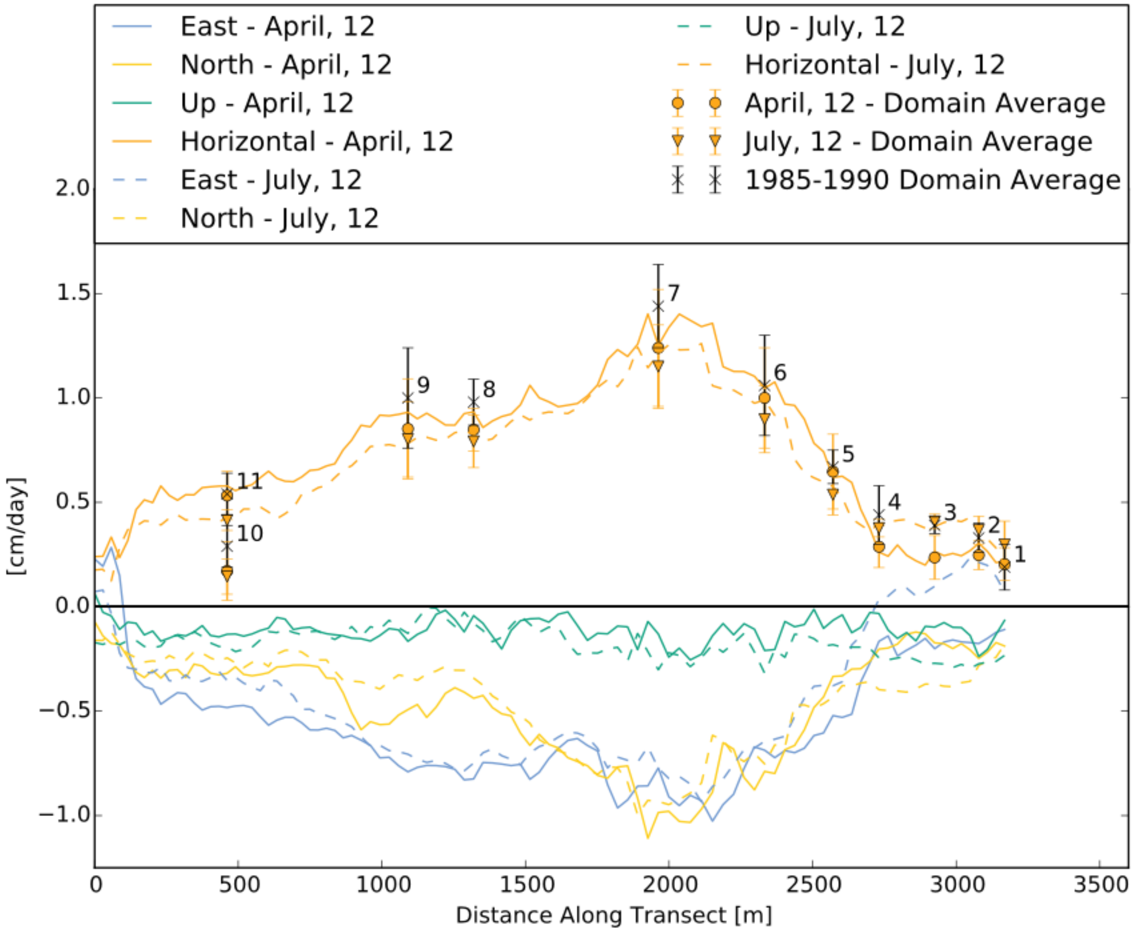
- Four UAVSAR 7-day interferograms combined
- Full 3-D displacement of surface
- Converted to velocity in cm/day
- Horizontal component shown with color and vectors
- Largely parallel to sides except mini-slide on top



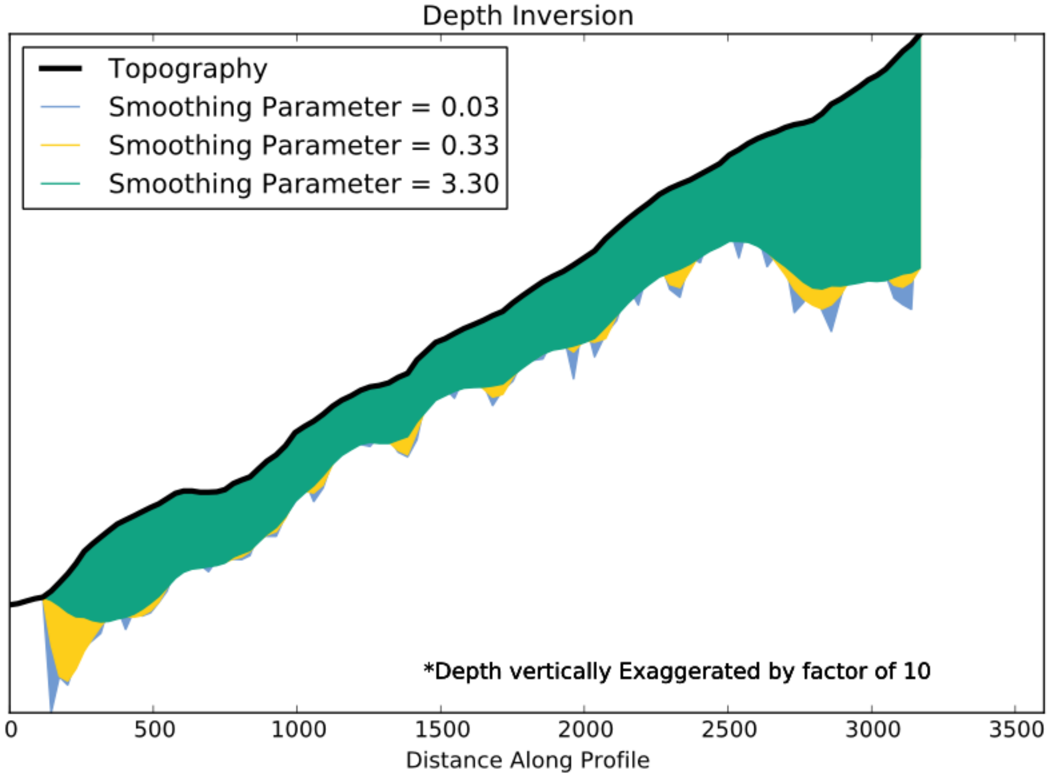
Delbridge, B. G., R. Bürgmann, E. Fielding, S. Hensley, and W. H. Schulz (2016), 3D surface deformation derived from airborne interferometric UAVSAR: Application to the Slumgullion Landslide, *Journal of Geophysical Research*, *121*(5), 3951-3977, doi:10.1002/2015JB012559.

Slumgullion thickness inversion

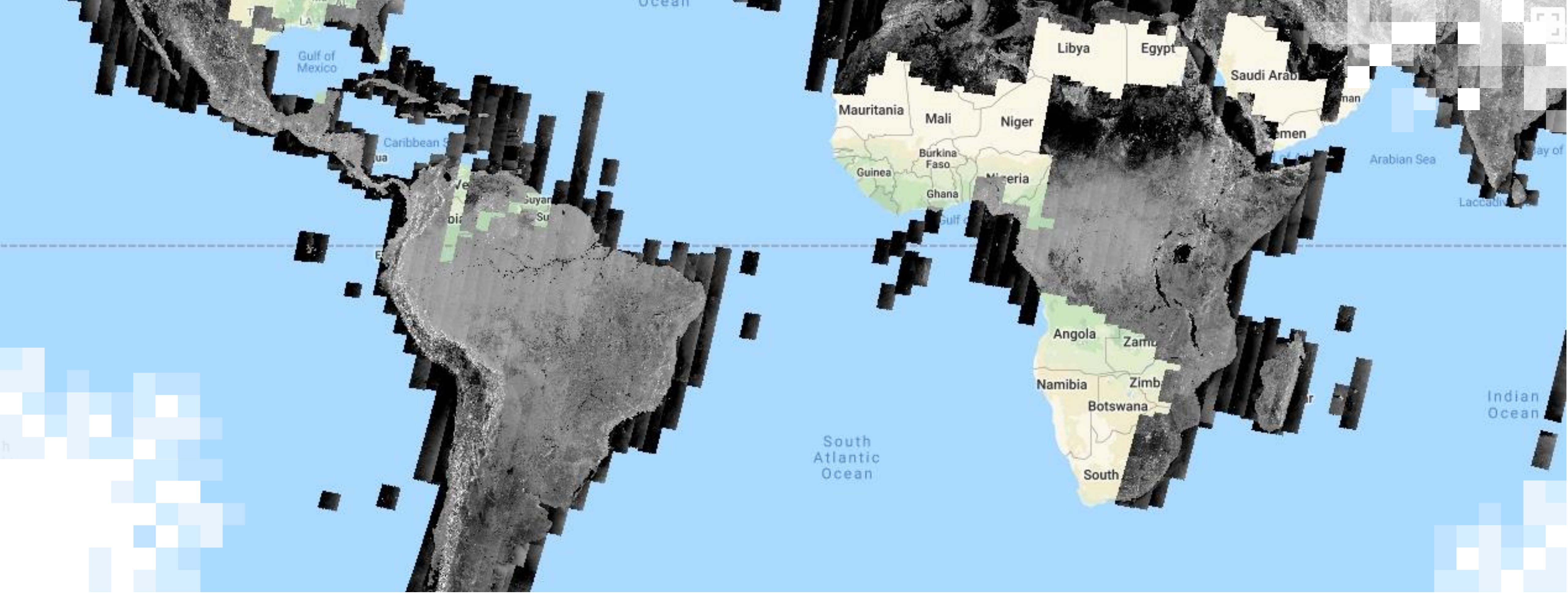
Along-slide Velocity Profiles



Resulting Basal Geometry



Delbridge et al. (2016)



SAR Data for Landslides

SAR Satellites

SAR Satellites	Operational	Repeat Cycle (days)	Wavelength (cm)
European ERS-1 ERS-2	1992 – 2000 1995–2001 (–2011 limited)	35 (1, 3, 183)	6
Canadian Radarsat-1	1995-2013	24	6
European Envisat	2003 – Sep 2010 Oct 2010 – Apr 2012	35 30	6
Japanese ALOS	Jan 2006 – Apr 2011	46	24
German Terra SAR-X TanDEM-X	2007 – present 2010 – present	11	3
Italian COSMO-SkyMed constellation	2007 – present	16 (1, 4, 7, 8)	3
Canadian Radarsat-2	Dec 2007 - present	24	6

New SAR Spacecraft

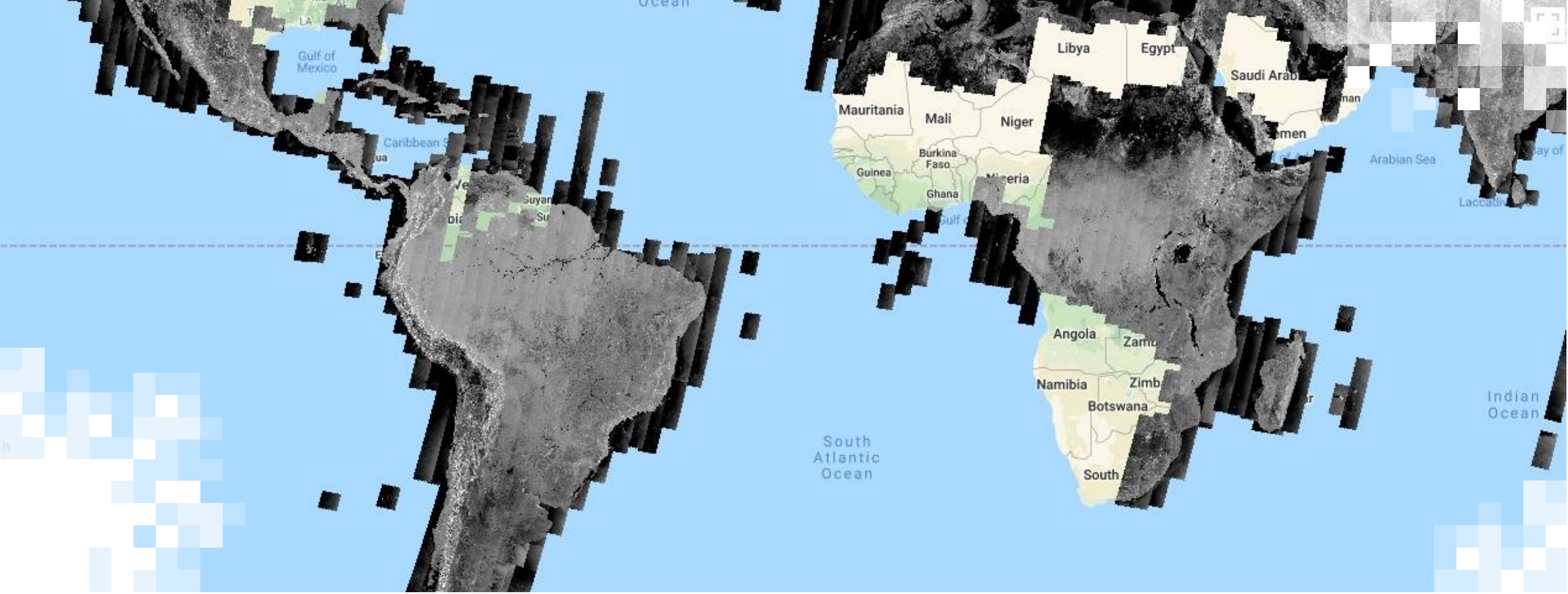
Satellites (launched or planned)	Repeat Cycle (days)	Wavelength (cm)
European Sentinel-1 (A: Apr 2014, B: May 2015)	A: 12, B: 6	6
Japanese ALOS-2 (May 2014)	14	24
Indian RISAT-1 (Apr 2012)	25	6
NASA-ISRO SAR (NISAR) Mission (Jan 2022)	12	12, 24

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

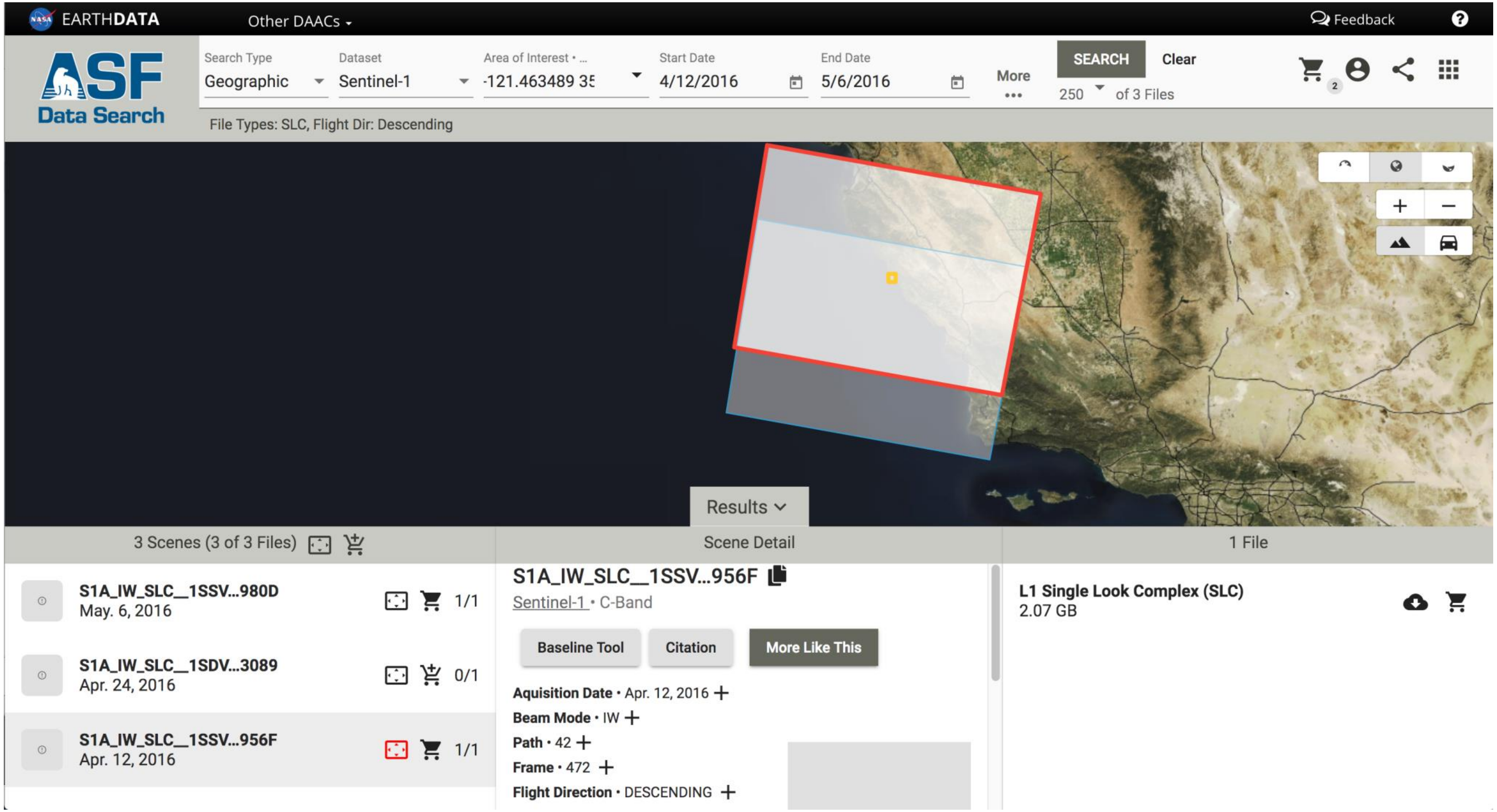
Accessing Sentinel-1 Data for Interferometry

1. **Go to the Alaska Satellite Facility Sentinel Data Portal:** https://search.asf.alaska.edu/

- **Identify the area** (-121.463489 35.88952, -121.388017 35.88952, -121.388017 35.821763, -121.463489 35.821763) **and dates** (2016-04-12, 2016-05-6) of interest (Mud Creek landslide, California, USA)

1. Identify images of interest (Sentinel-1 A/B)
2. Click More>Additional Filters>File Type> "L1 Single Look Complex (SLC)"
3. Click More>Additional Filters>Direction> "Descending"
4. Click **Search**
5. Select Granule: S1A_IW_SLC__1SSV_20160412T140755_20160412T140823_010789_0101FE_956F-SLC
6. Download the L1 Single Look Complex (SLC) (2.01 GB) Product
7. Similarly download SLC for Granule: S1A_IW_SLC__1SSV_20160506T140756_20160506T140824_011139_010CD3_980D-SLC

Accessing Sentinel-1 Data for Interferometry



Opening the Data with the Sentinel Toolbox

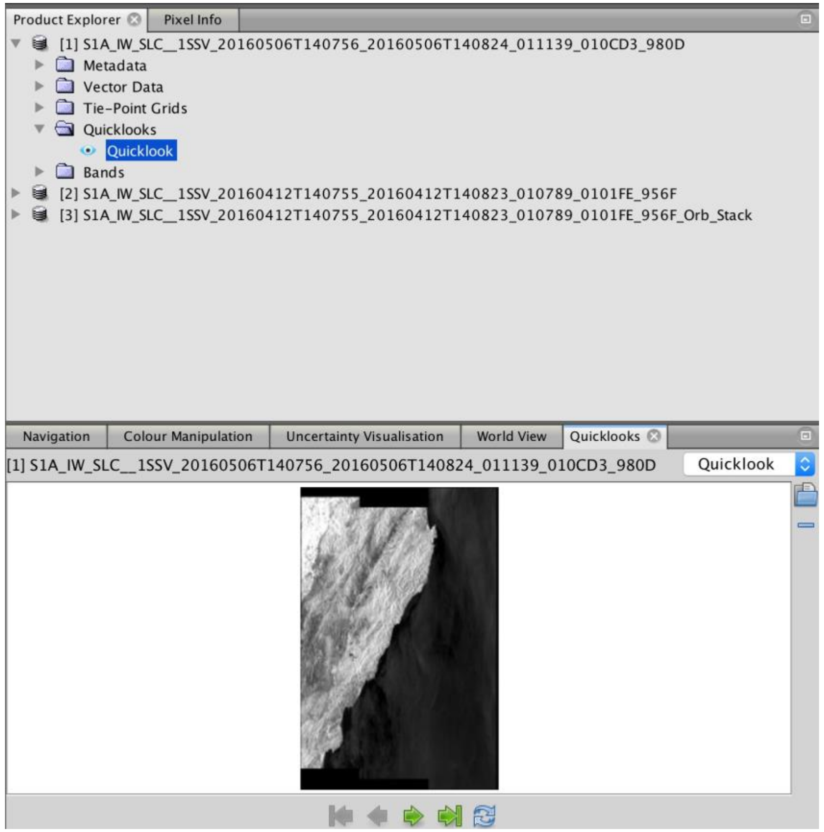
- Initiate the Sentinel Toolbox (SNAP) by clicking on its desktop icon
- In the Sentinel Toolbox interface, go to the File menu and select Open Product
- Select the folder containing your Sentinel-1 SLC file, and double click on the .zip file (do not unzip the file; the program will do it for you)

Opening the Data with the Sentinel Toolbox

SLC Data Has a Different Format Than GRDH

- The Product Explorer window of the Sentinel Toolbox contains your file.

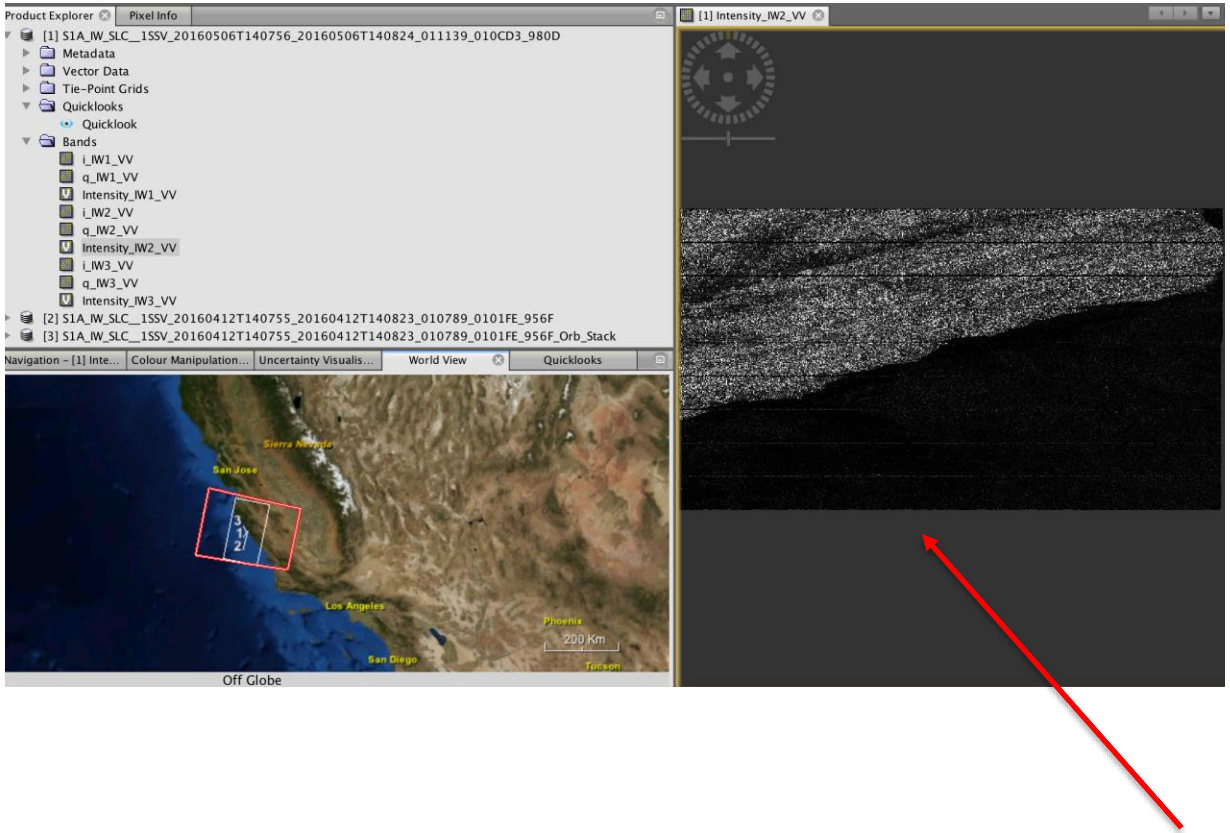
1. Double click on the file to view the directories within the file, which contain information relevant to the image, including:
   - Metadata: parameters related to orbit and data
   - Tie Point Grids: interpolation of latitude/longitude, incidence angle, etc.
   - Quicklooks: viewable image of whole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

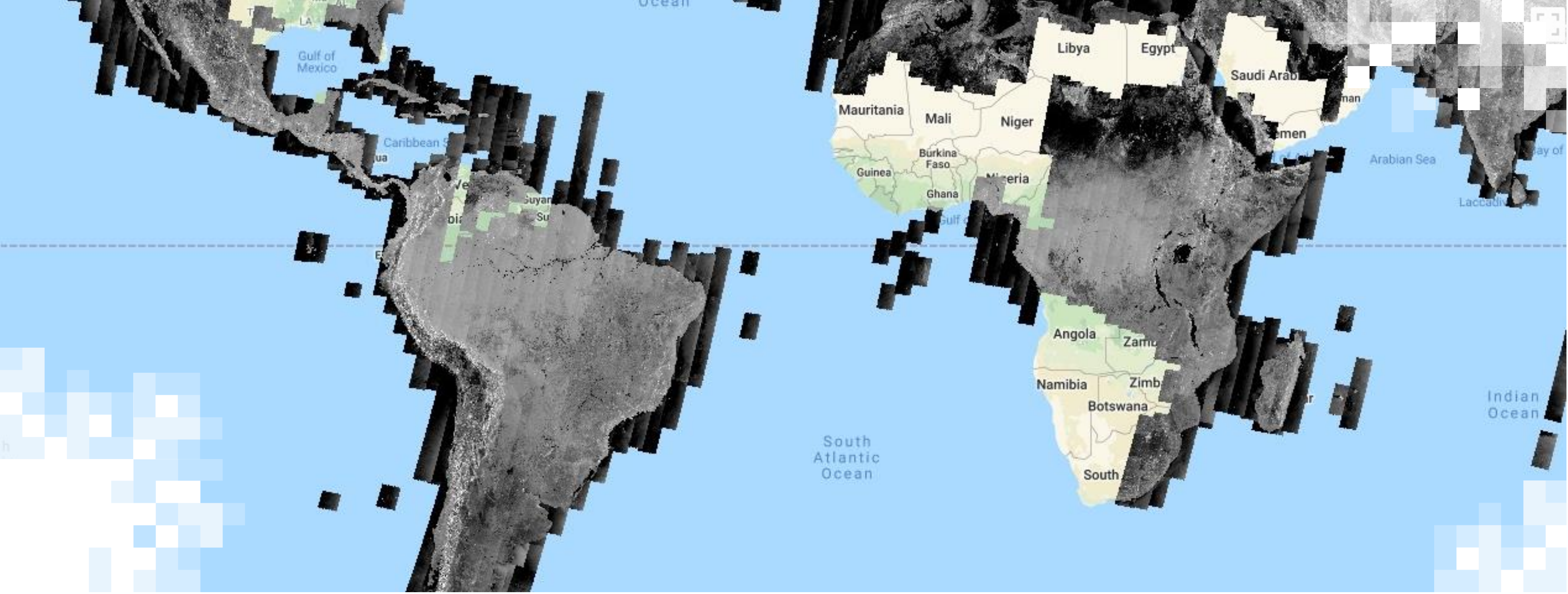


Opening the Data with the Sentinel Toolbox

Viewing Subswath Images

2. The Worldview image (lower left) shows the footprint of the whole image selected
3. Select intensity image for swath IW2 VV
   - **Note**: Each SAR image is flipped east–west because it is oriented the same way it was acquired with side closest to satellite on the left (descending track in this case)



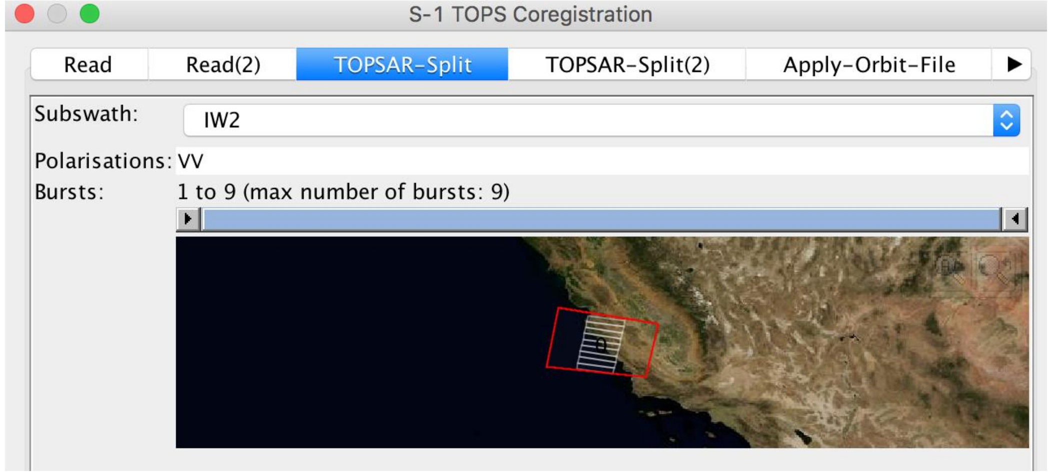


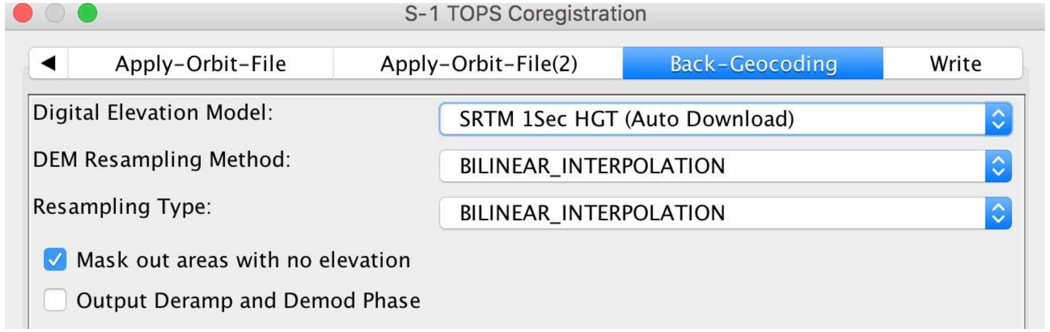
InSAR Processing

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 > Coregistration > S1 TOPS Coregistration** > **S1 TOPS Coregistration** again

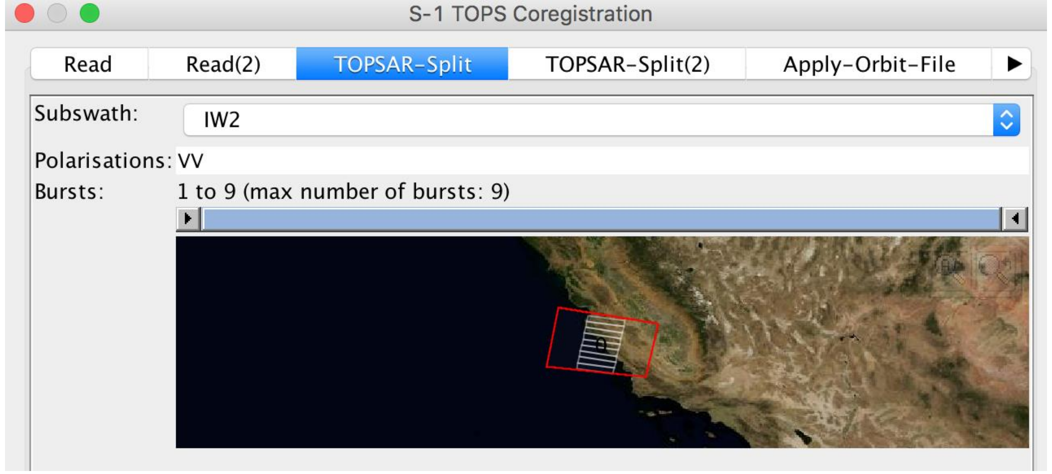


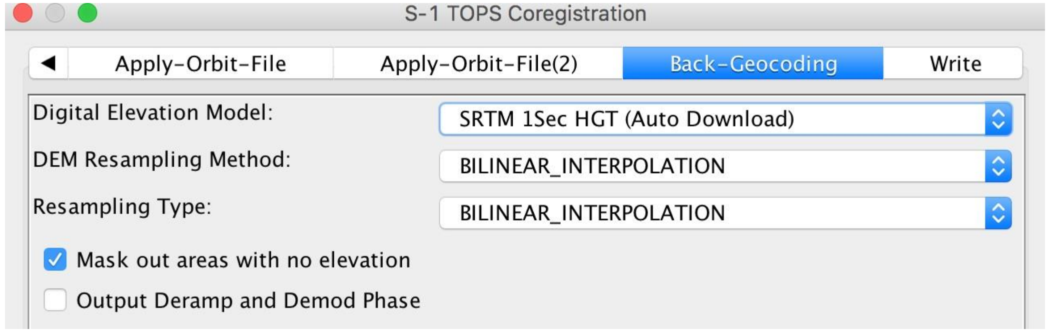


Interferometry Data Preparation

Coregistering the Scenes

3. In the Read tab, select the 20160412 SLC and in the Read(2) tab select the 20160506 SLC
4. In TOPSAR-Split and TOPSAR-Split(2) tabs, select Subswath: IW2 Polarisations: VV
5. Back-Geocoding tab- SRTM 1sec HGT (auto download)
6. In the Write tab, select the directory where you want to save your processing results

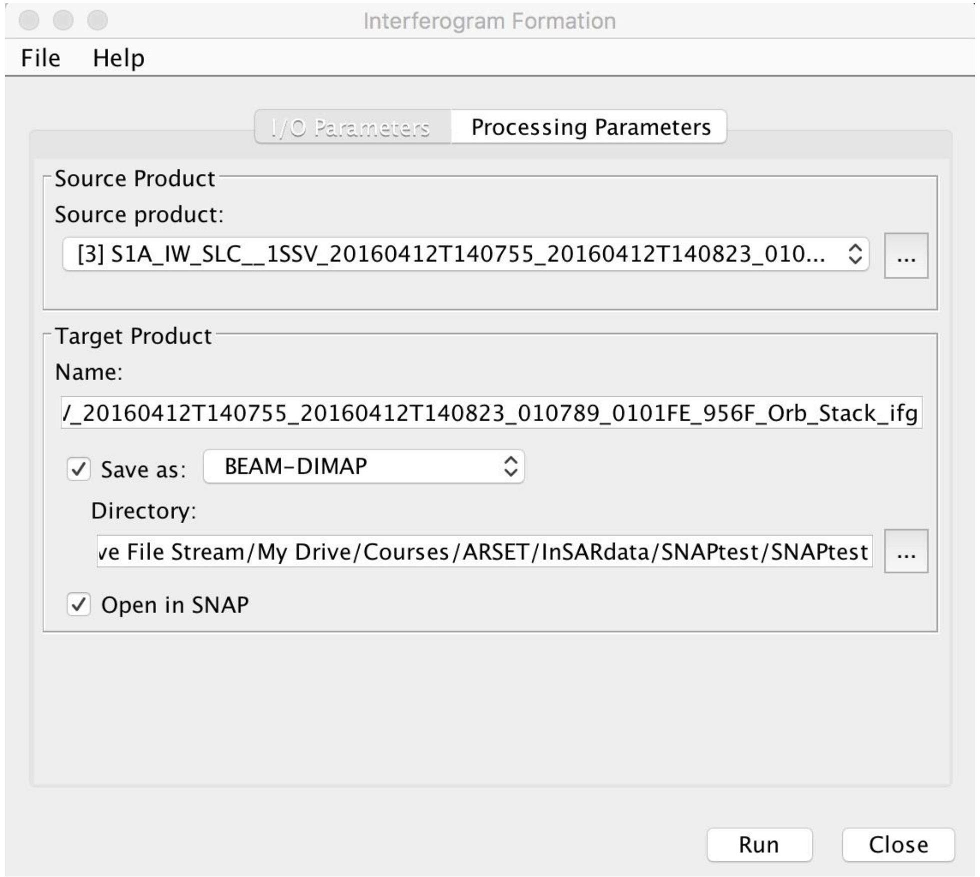




Interferometric Processing

Forming a Raw Interferogram

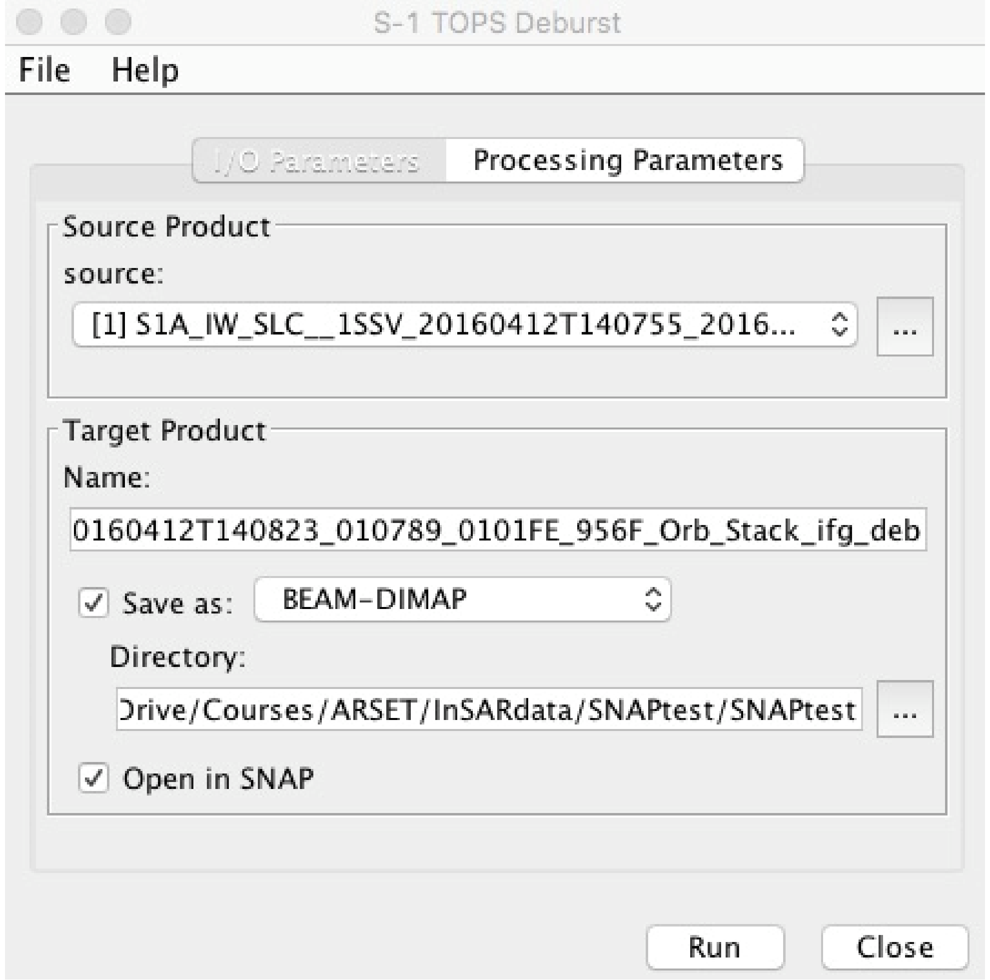
1. Second step of interferometry is to make an interferogram out of the coregistered SLC images
2. From the top main menu bar, select **Radar**, then **Interferometric**, then **Products**, and then **Interferogram Formation**
3. In **I/O Parameters** tab, select the "Orb_Stack" product created by the 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

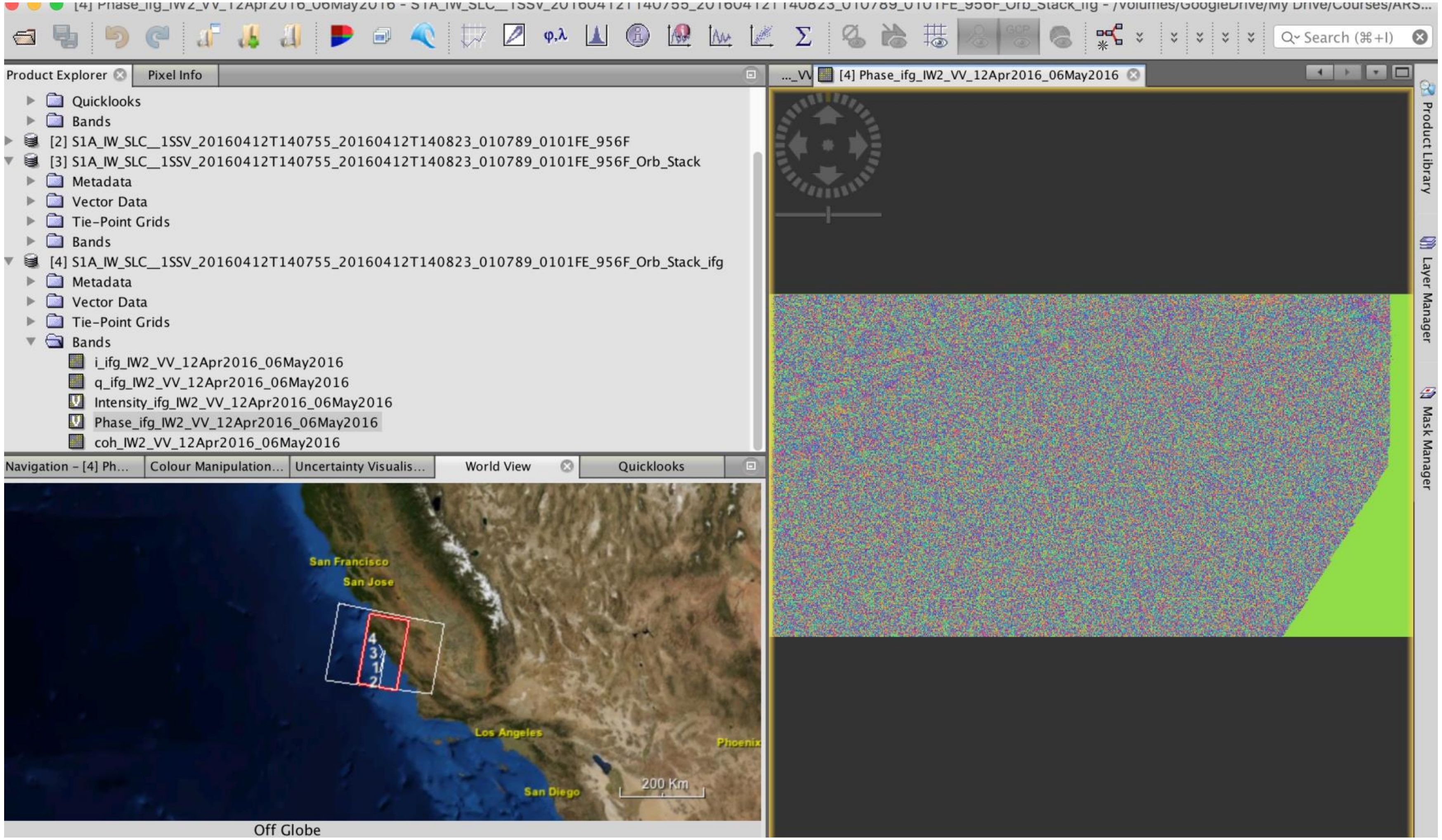
TOPS Deburst

1. Merge all burst data into a single image, apply the TOPS Deburst operator from the Sentinel-1 TOPS menu.
2. From the top main menu bar, select **Radar**, then **Sentinel-1 TOPS**, then **S1 Tops Deburst**,
3. In **I/O Parameters** tab, select the “ifg”



Interferometric Processing

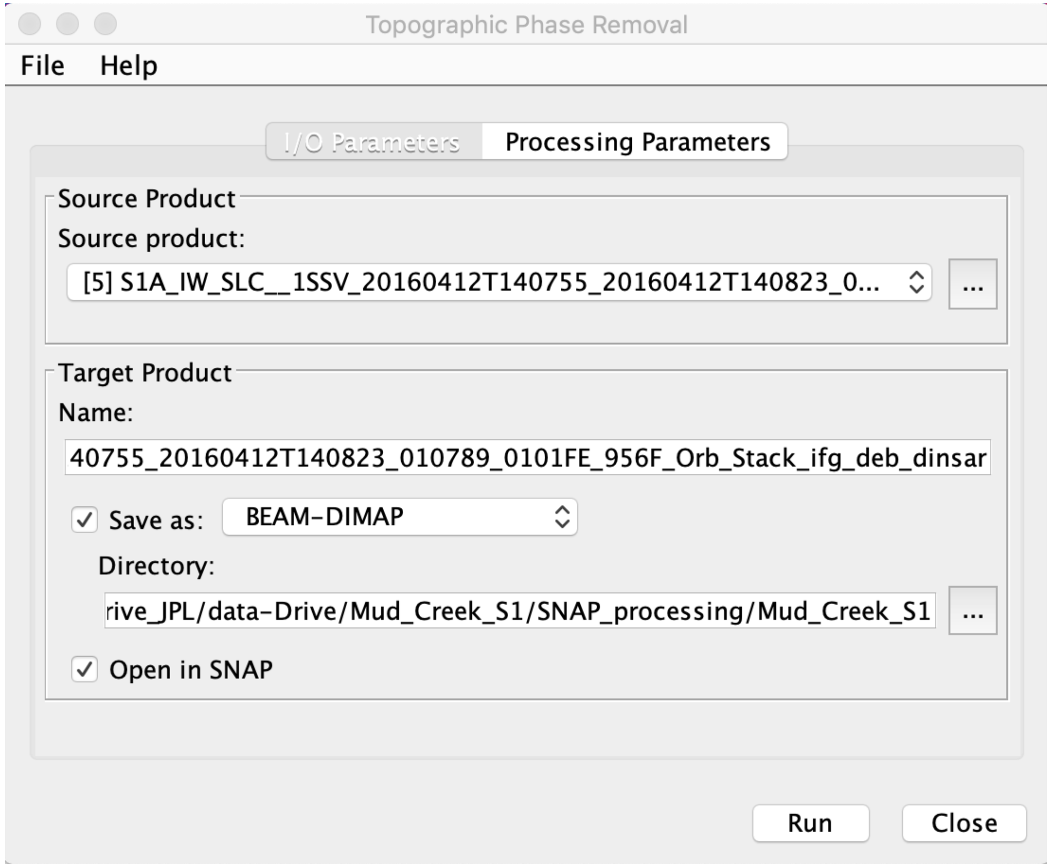
Viewing Differential Interferogram — Phase Image



Interferometric Processing

Topographic Phase Removal

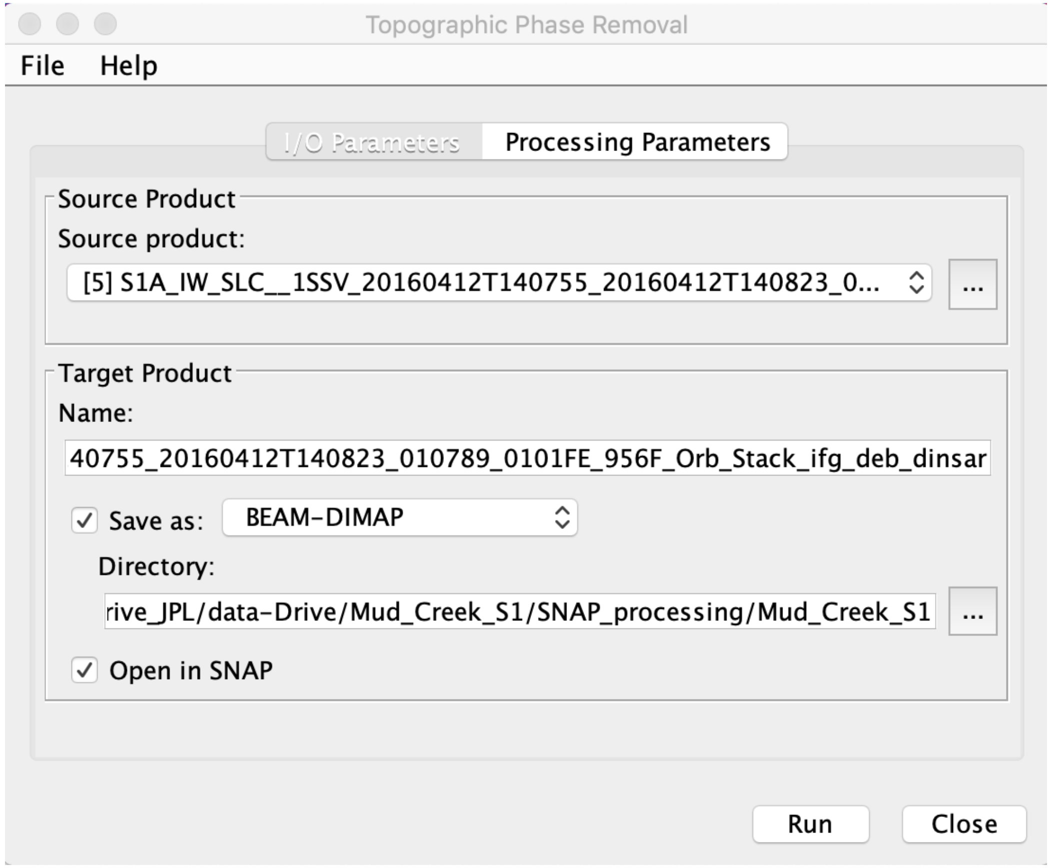
1. Next step for all interferometry is to remove the topographic phase using a DEM.
2. From the top main menu bar, select **Radar > Interferometric > Products > Topographic Phase Removal**



Interferometric Processing

Topographic Phase Removal

5. 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 landslides may require SRTM 1-arcsecond DEM to get better resolution



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 "ifg_deb" product created by the previous step
   - By default, the output target adds "flt" to the name
   - For landslide processing, it is better to change defaults in **Processing Parameters** tab

Interferometric Processing

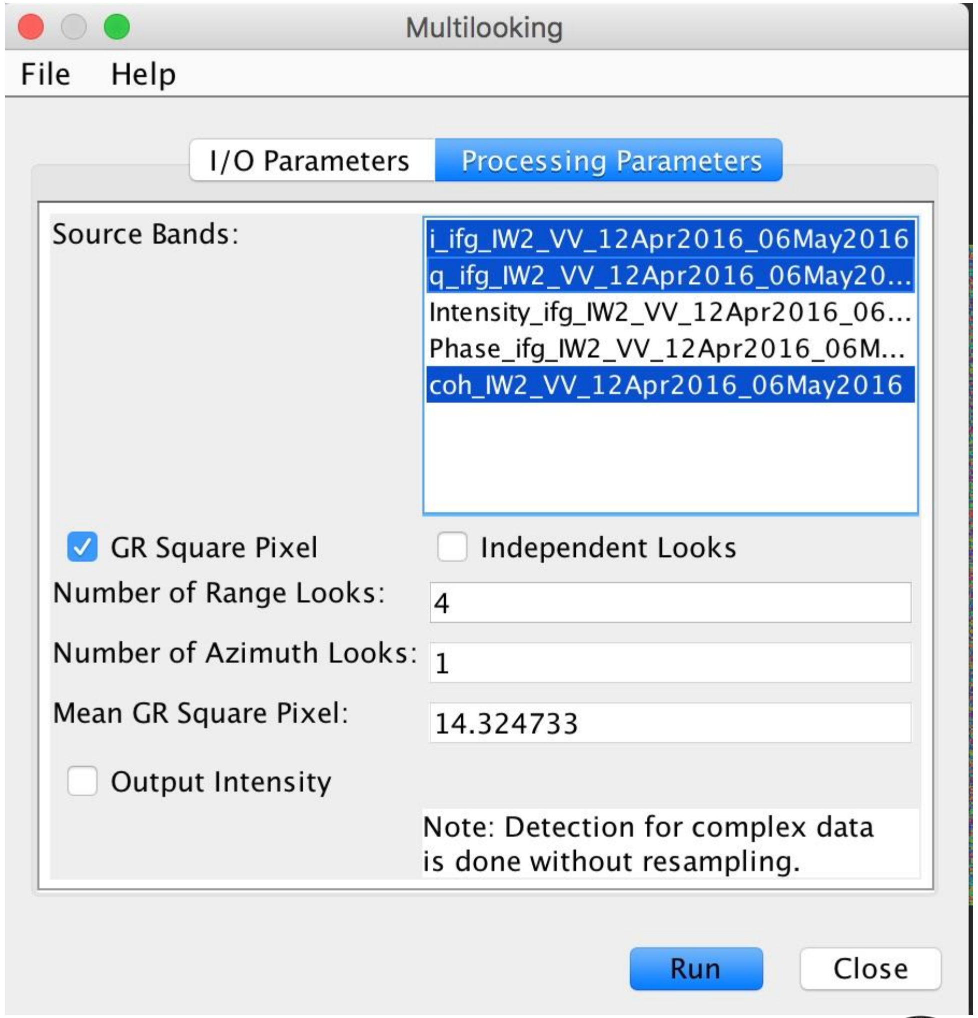
Filtering and Multi-Looking Interferogram

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
   - Landslides are generally small compared to Sentinel-1 resolution, so do less multilooking than for other InSAR targets

Interferometric Processing

Multi-Looking Interferogram

1. The Mud Creek landslide is ~500 m long and ~500 m wide
2. From the top main menu bar, select **Radar** then **SAR Utilities** then **Multilooking**
   - In **I/O Parameters** tab, select the "ifg_deb_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 4 range looks and 1 azimuth looks to give ~14 m output pixels
   - **Don't choose "Phase" or "Intensity" bands!**

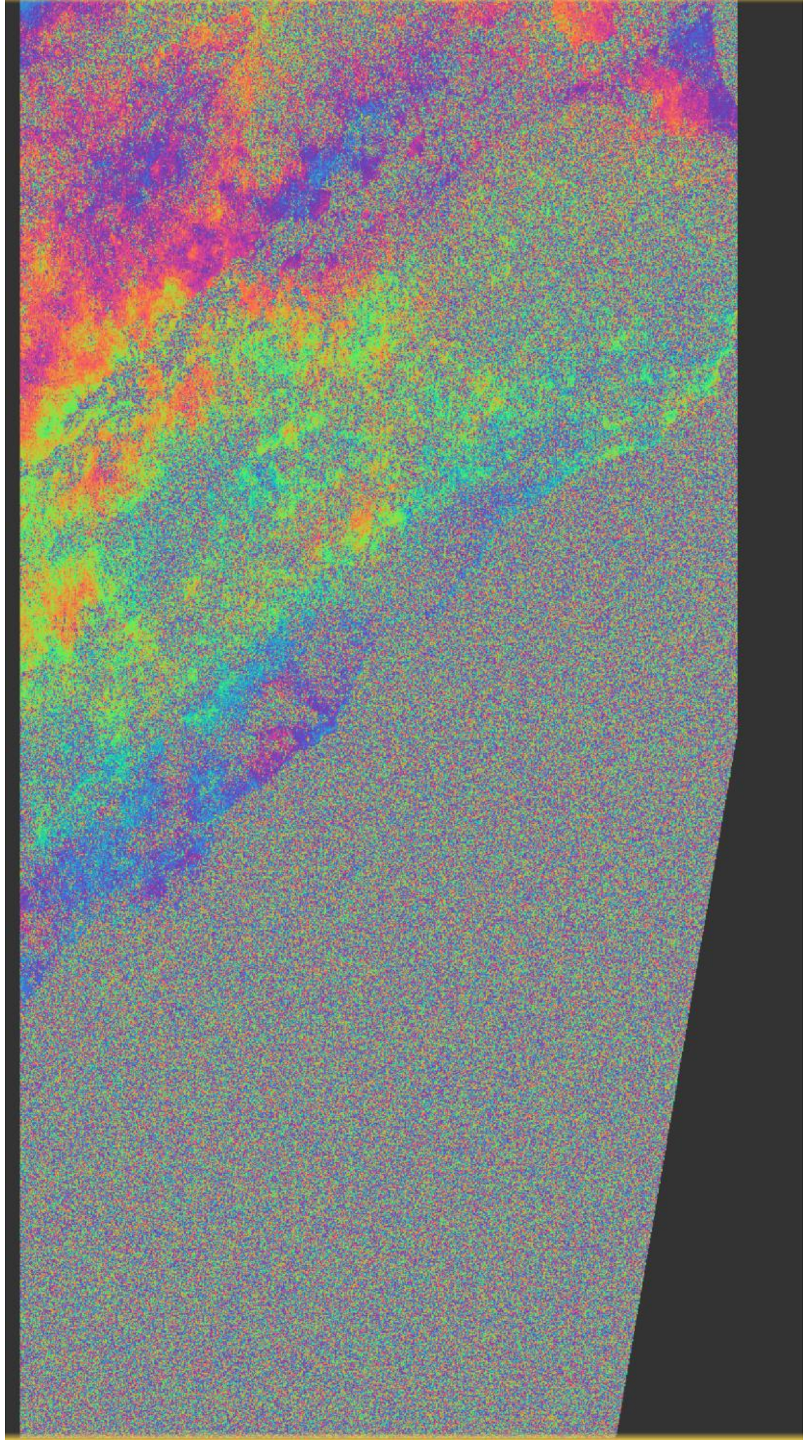


Interferometric Processing

Viewing Multi-Looked Interferograms

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

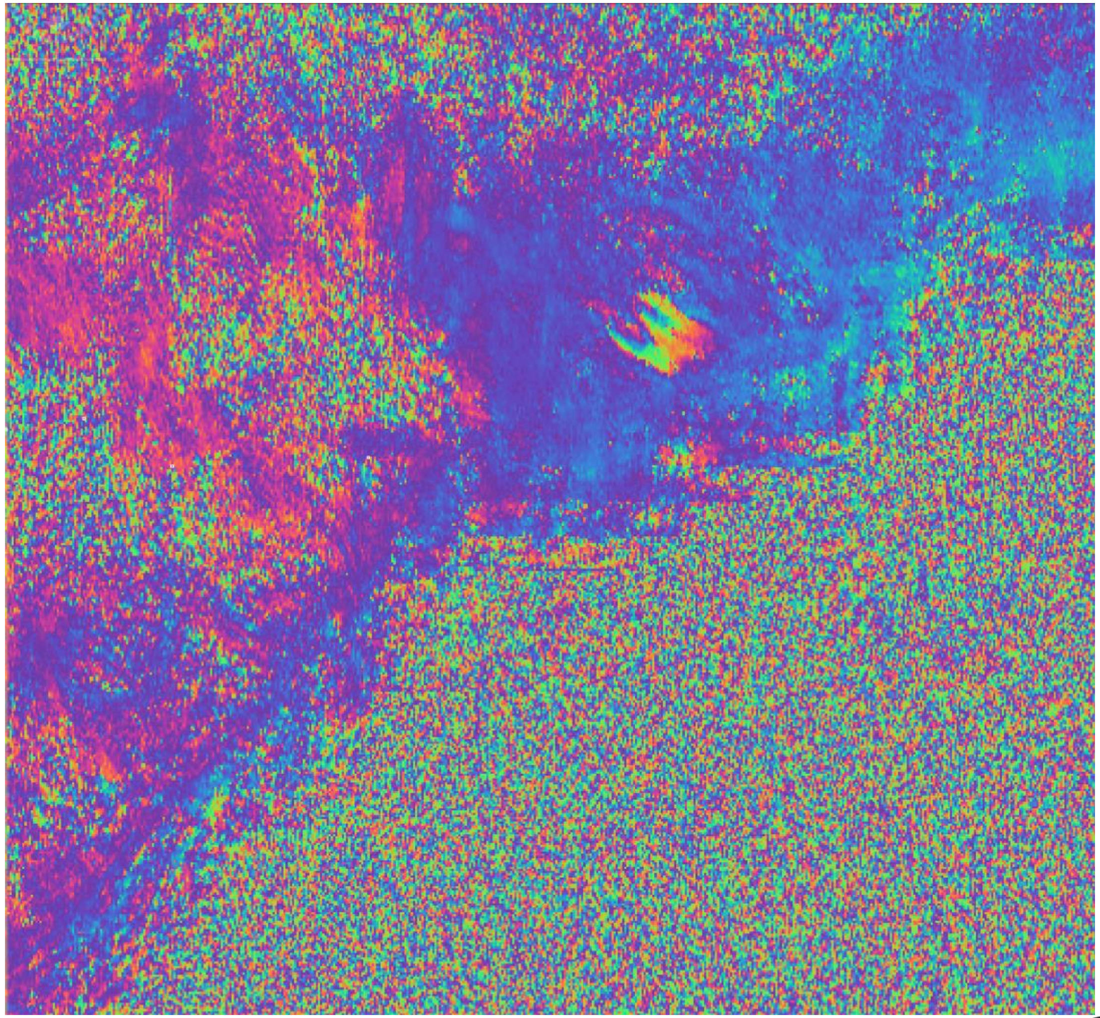
- The fringes are much less noisy
- Aspect ratio has changed so the pixels are roughly square on the ground



Interferometry Data Preparation

Creating a Subset

1. To analyze a single landslide you can create a subset around the area of interest. This will save unwrapping and later processing time.
2. Click **Raster** > **Subset** > **Geo Coordinates** > enter "North: 35.89, South: 35.82, West: -121.46, East: -121.39"



Interferometric Processing

Phase Unwrapping: SNAPHU plugin for SNAP 7.0

- Installation and usage instructions:
  - This plugin is now available under SNAP plugins. The SNAPHU Unwrapping plugin can be installed from **Tools > Plugins > Available Plugins**.
- Choose the plugin, click "**Install**" and follow the installation procedure. Restart SNAP when SNAPHU Unwrapping installation is finished.
- Once installed the plugin will be available under **Radar > Interferometric > Unwrapping > Snaphu-unwrapping***
  - * When running SNAPHU Unwrapping tool for the first time the user will be notified about the need to set up working path for the plugin
  - Click OK and proceed with bundle download/installation
  - After these steps the plugin will be ready use. On Linux, after the plugin installation, make sure to add the execute permission on snaphu script under $HOME/.snap/auxdata/snaphu-v1.4.2_linux/bin before starting to use the plugin.

Interferometric Processing

Phase Unwrapping

- Before unwrapping a product has to be exported using Snaphu Export
  - **Radar > Interferometric > Unwrapping >Snaphu Export**
- When the export is done, the Snaphu Unwrapping can be executed
  - **Radar > Interferometric > Unwrapping > Snaphu-unwrapping**

Interferometric Processing

Phase Unwrapping

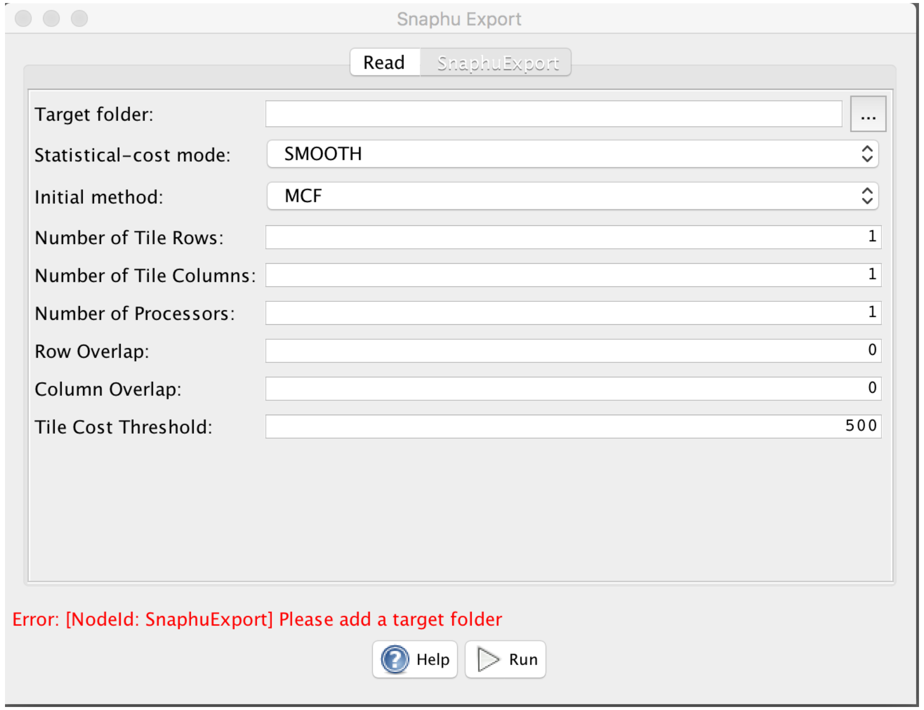
- On the first tab, select the product previously exported with Snaphu Export (e.g. Phase.hdr)
- On the parameters tab select the output folder
  – In order to be able to open the unwrapped product, it is mandatory to select as an output folder the same folder where your exported files (e.g. phase.img, snaphu.conf etc.) are located
  – You can also check "**Display execution output**" in order to be able to view the log and the unwrapping execution progress.
- Then click "Run"
- After the phase is unwrapped it can be imported to SNAP for further analysis using **Radar > Interferometric > Unwrapping > SNAPHU Import** (for using the unwrapped output product in SNAPHU Import, make sure to previously save it)

Interferometric Processing

Phase Unwrapping

- Older SNAP 6.0 does not include phase unwrapping plugin. 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.

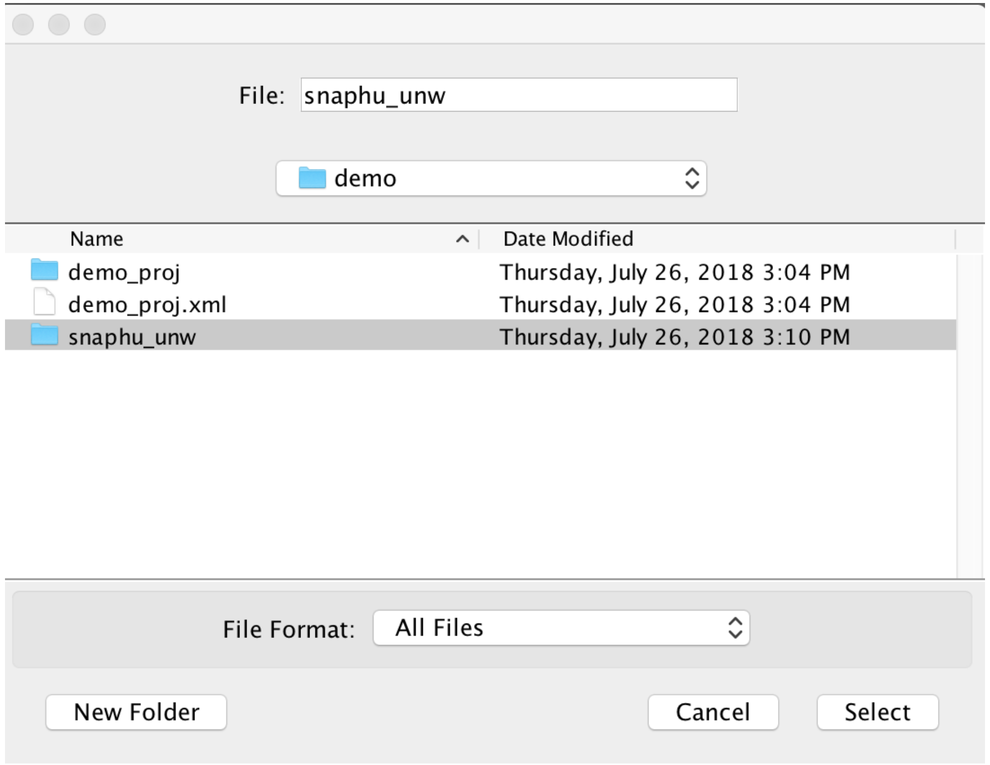
1. From the top main menu bar, select **Radar > Interferometric > Unwrapping > Snaphu Export.**
2. In the **Read** tab, select the "ML" product created by the multilooking step
3. In **Snaphu Export** tab, change the Statistical-cost mode to "SMOOTH"
4. Also change the number of tile rows and columns and number of processors to "1" because we don't need multiple tiles after multilooking and subsetting



Interferometric Processing

Phase Unwrapping

5. 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.
6. The **Snaphu Export** pop-up dialog does not work quite right in SNAP 7.0 on MacOS. 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



Interferometric Processing

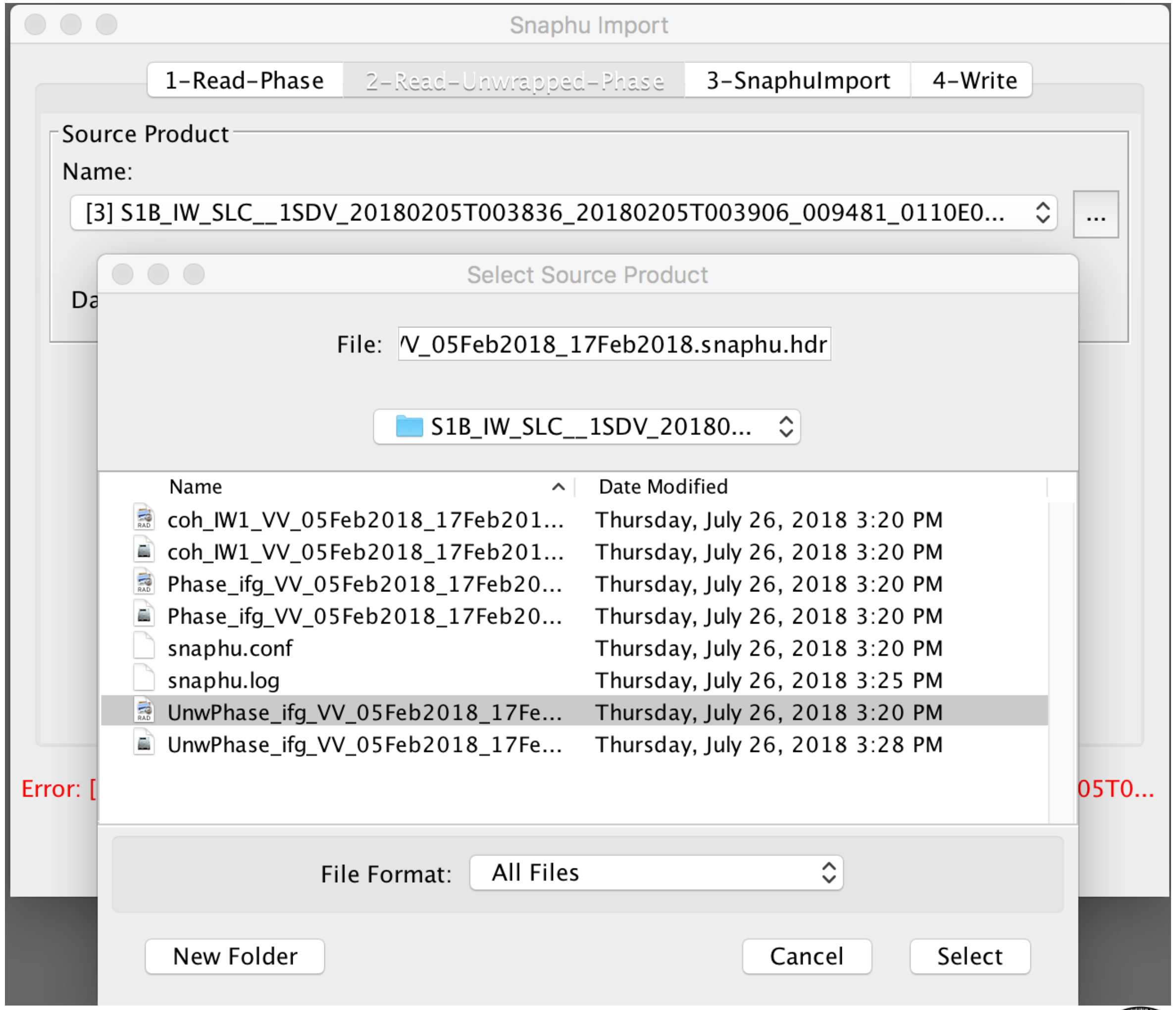
Phase Unwrapping

7. Now you can press **Run** button and SNAP exports the interferogram phase and coherence with a "`snaphu.conf`" file
8. Now, we import the unwrapped phase. From the top main menu bar, select **Radar**, then **Interferometric**, then **Unwrapping**, and then **Snaphu Import.**
9. The **Read-Phase** tab should be set to the wrapped product that you exported.

Interferometric Processing

Phase Unwrapping

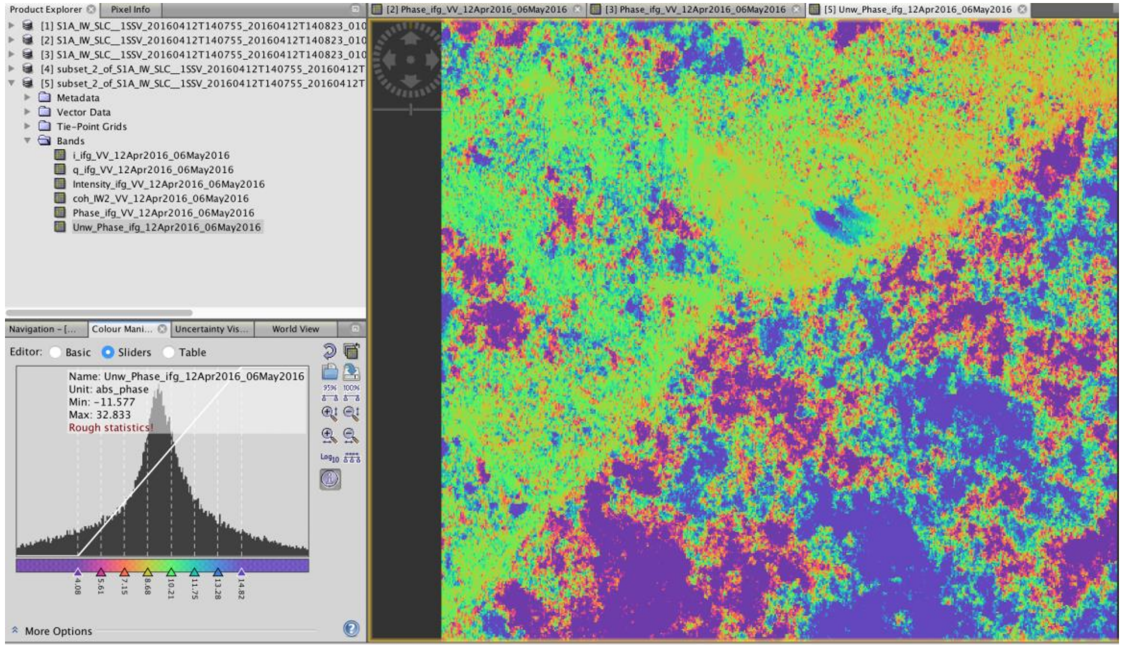
10. In the **Read-Unwrapped-Phase** tab, select the unwrapped source product:
    - Navigate to folder where you exported for Snaphu
    - Select the "`UnwPhase_ifg*.snaphu.hdr`" file
11. Go to **Write** tab and check product output name (I add "_unw" to wrapped product name, so I get a new product)



Interferometric Processing

Phase Unwrapping

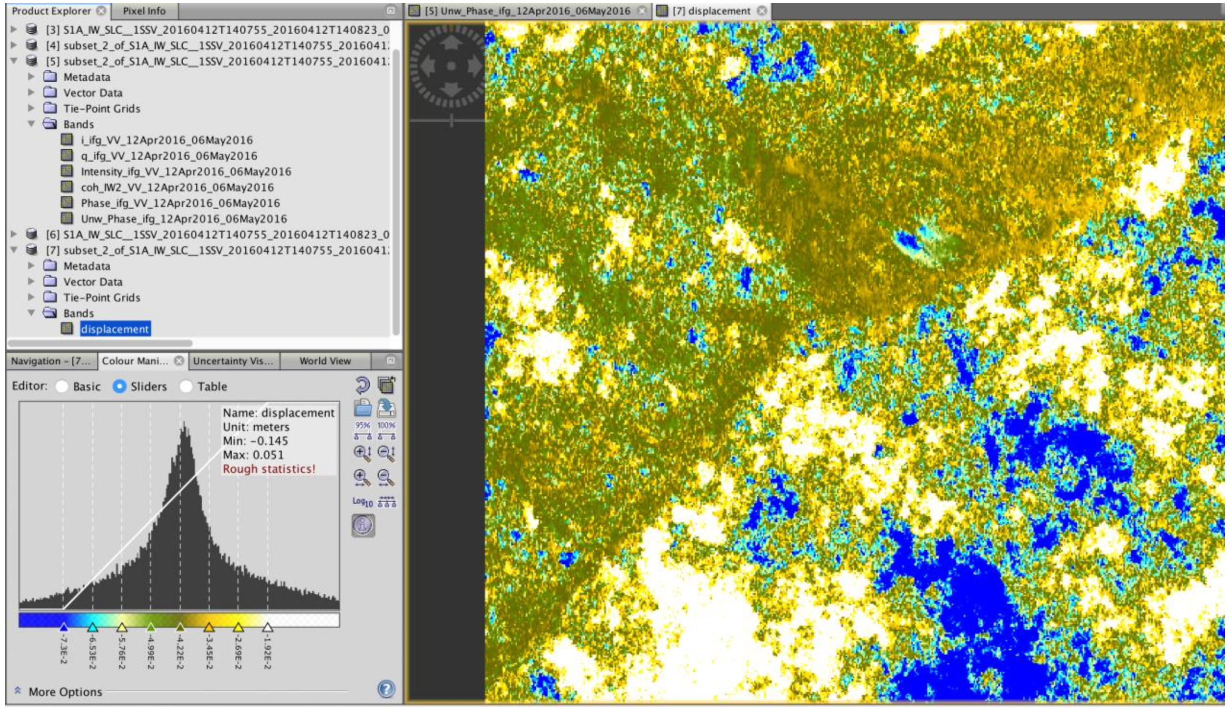
12. Finally, we can display the unwrapped phase
13. Select the Unw_Phase_ifg band
14. Go to the Colour Manipulation tab and select “95%” to stretch color scale, then adjust sliders to best show landslide
    – Unwrapped phase is still in radians
    – Phase is reference image minus coregistered image. If reference image is earlier, then negative phase is land moving toward satellite (negative range change)



Interferometric Processing

Phase to Displacement

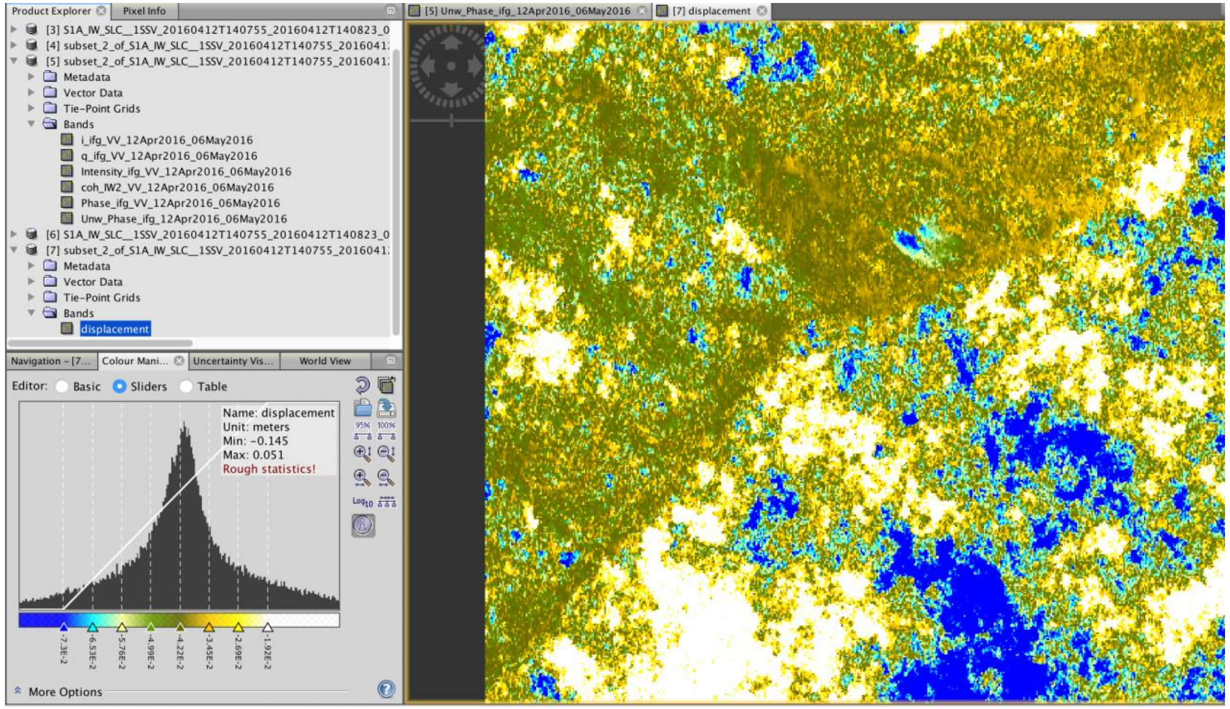
1. We can convert the unwrapped phase to displacements. From the top main menu bar, select **Radar,** then **Interferometric**, then **Products**, and then **Phase to Displacement.**
   - The **I/O Parameters** tab should be set to the unwrapped product that you imported.
   - default for target product name is to add "_dsp" to the name



Interferometric Processing

Phase to Displacement

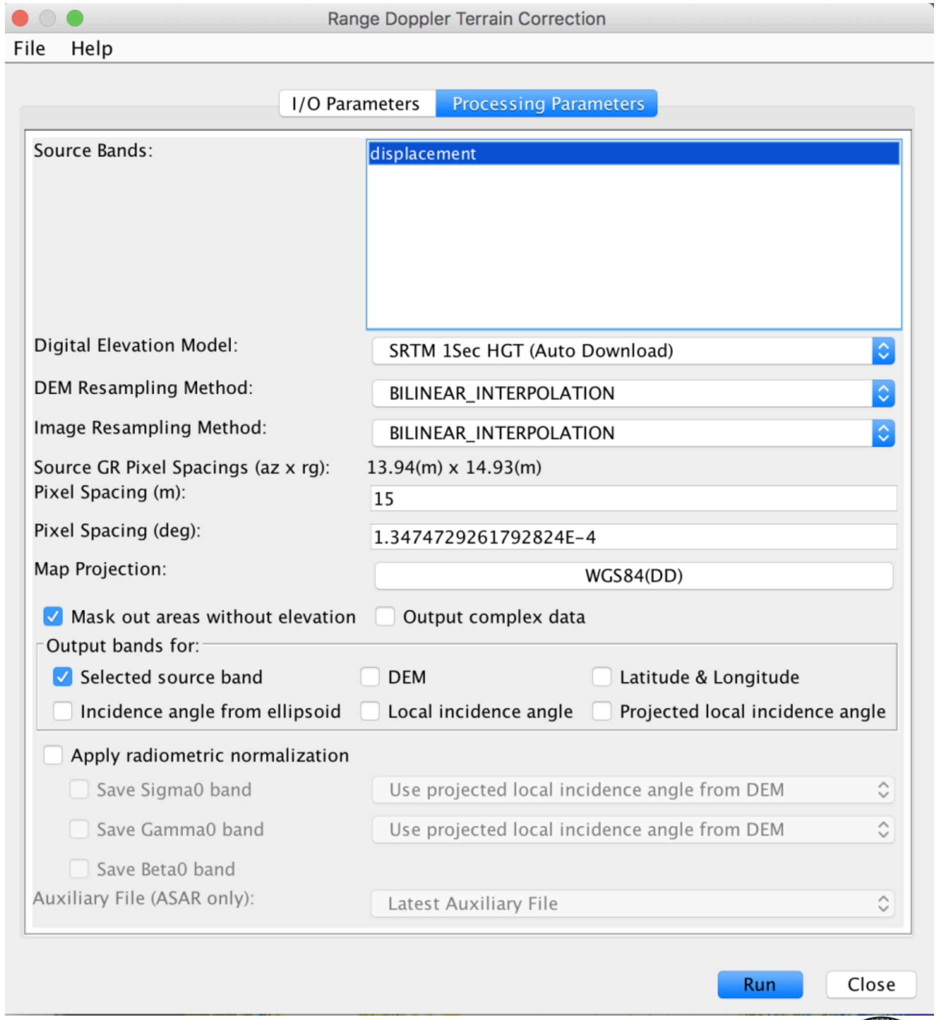
2. Now, we can display **displacement** band of result. Again, better to stretch colors.
   - Displacements now in meters.
   - Sign was changed so positive displacement is towards satellite (up or east on this track)



Interferometric Processing

Geocoding results—Terrain Correction

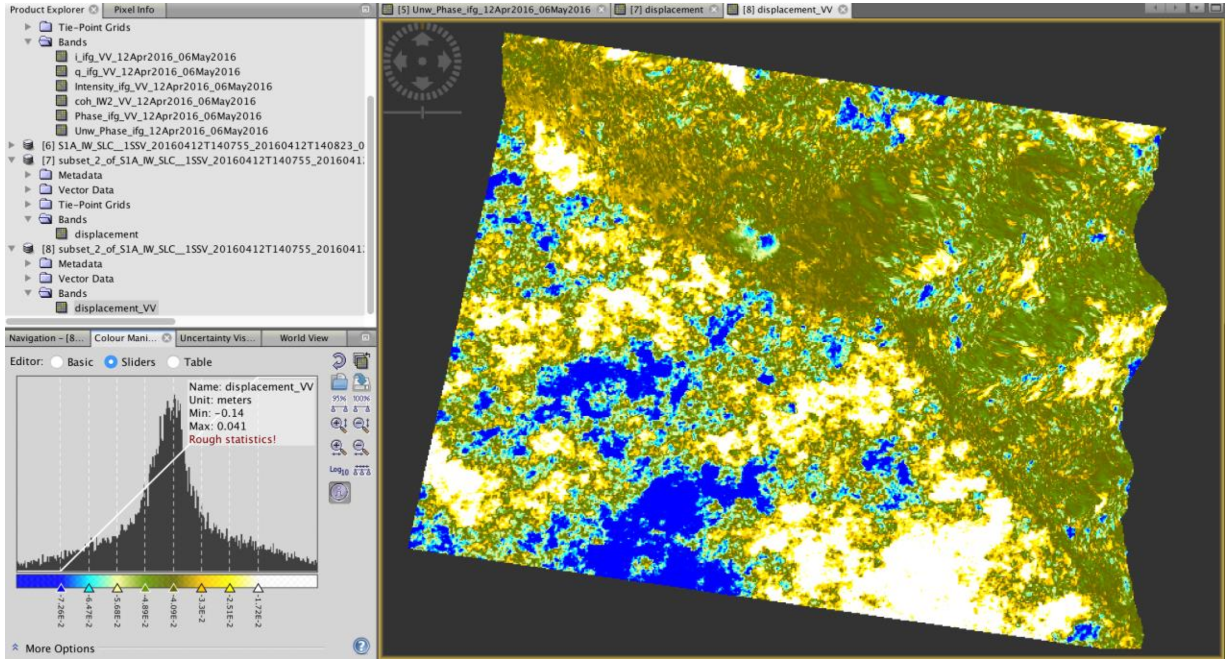
1. SNAP calls geocoding with topography "Terrain Correction." From the top main menu bar, select **Radar**, then **Geometric**, then **Terrain Correction**, and then **Range-Doppler Terrain Correction.**
   - The **I/O Parameters** tab should be set to the displacement product that you imported (or one of the other ML products).
   - default for target product name is to add "_TC" to the name
   - Under **Processing Parameters** tab, select **Source Bands** and any additional **Output Bands**. You can choose DEM (**SRTM 1Sec HGT** is actually 1-arcsecond or 30 m), output spacing (**15 m**), and map projection.

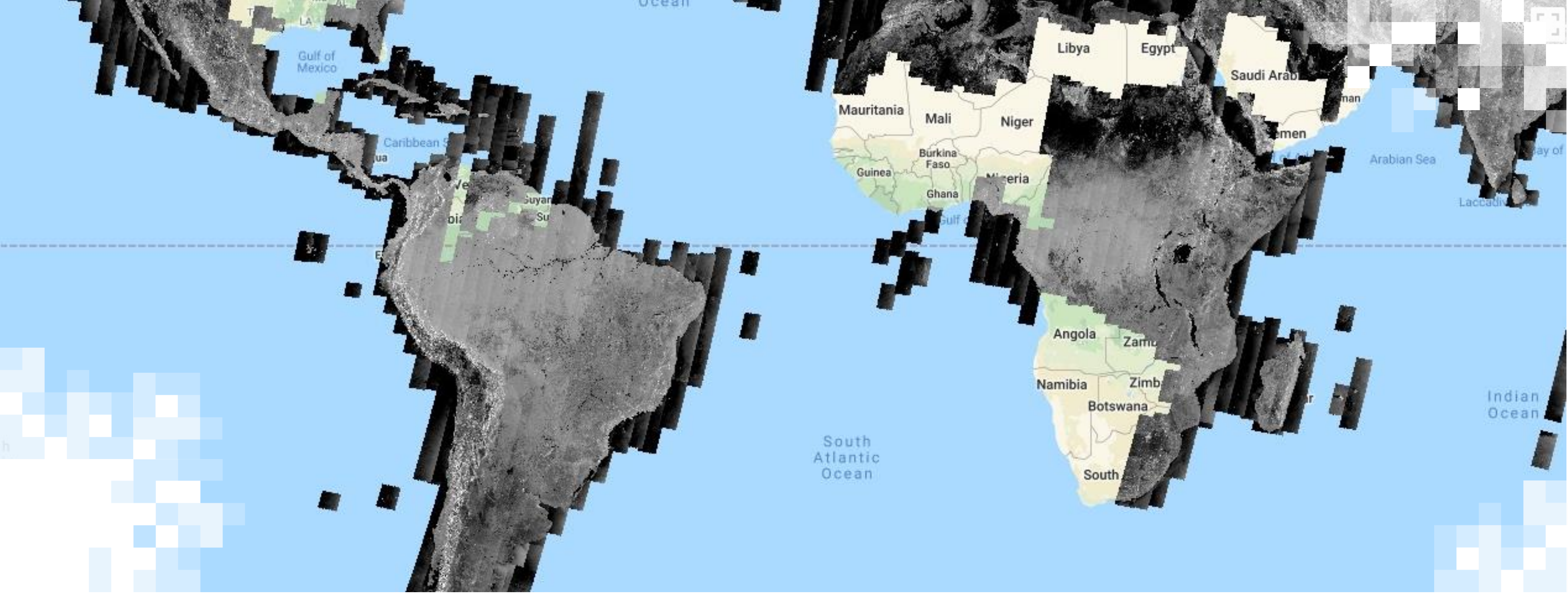


Interferometric Processing

Geocoding results—Terrain Correction

2. Now, we can display **displacement_vv** band of geocoded result. Again, better to stretch colors.
   - Displacements in meters with positive values towards satellite in Line-of-Sight direction (up or east).
   - Product is now evenly spaced in latitude and longitude at roughly 15 meter spacing (1.35×10^{-4} degrees).





InSAR Analysis for Landslides