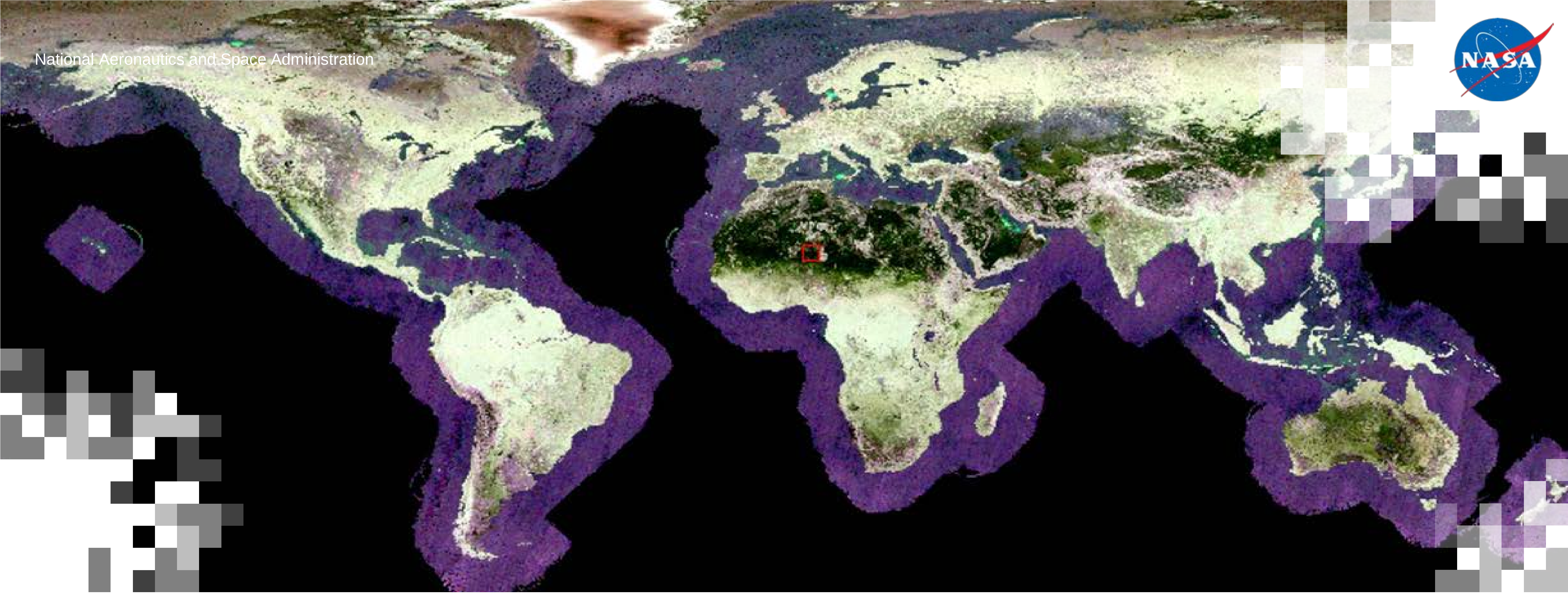
National Aeronautics and Space Administration



Introduction to SAR Interferometry – Generating a Digital Elevation Model (DEM)

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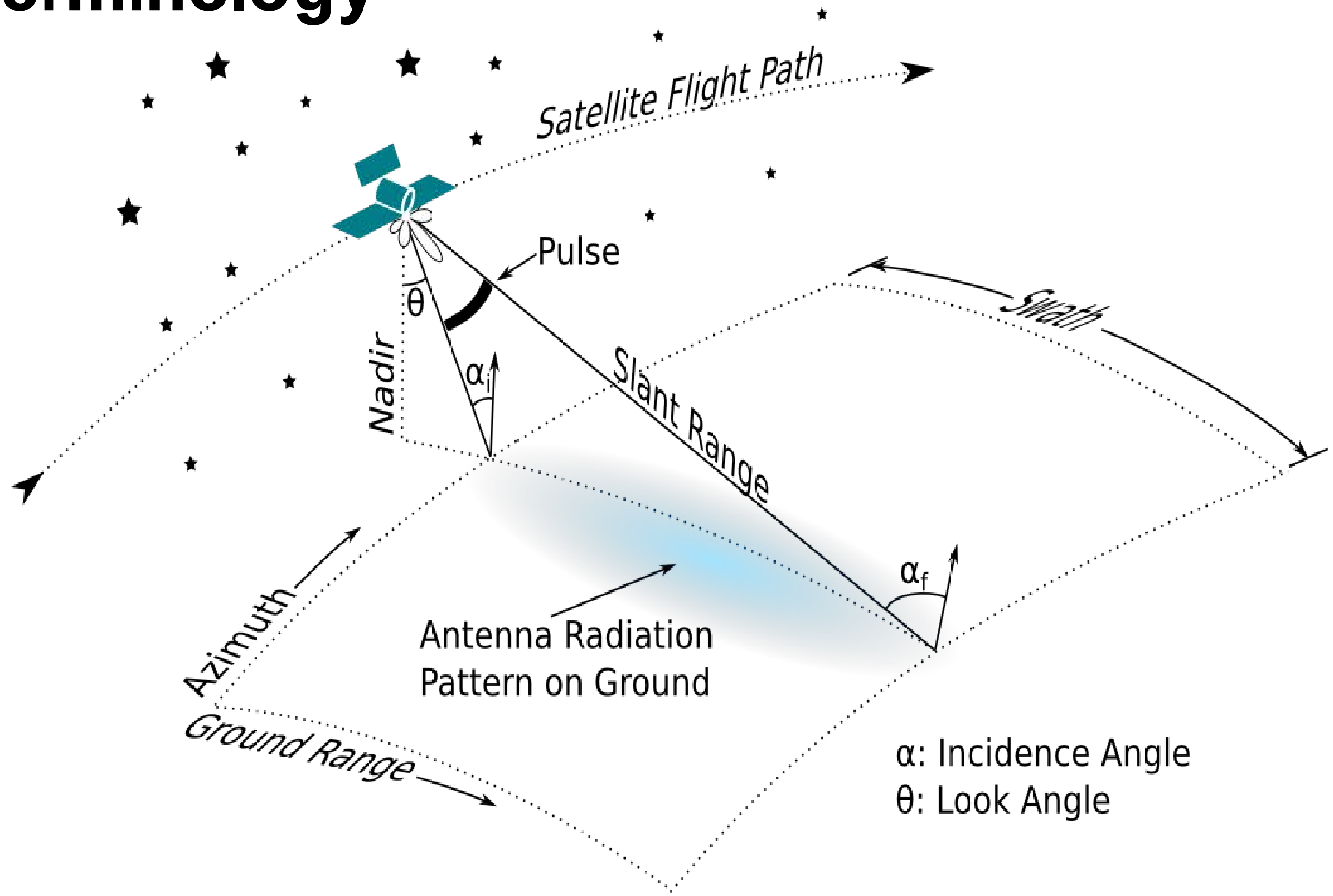
Argentine National Commission for Space Activities (CONAE)

Learning Objectives

- SAR Imaging:
    - Difference between amplitude and phase
    - Potential of phase

- SAR Interferometry:
    - Interferometric phase
    - Sensitivity to topography and deformation
    - InSAR / DInSAR
    - Factors that affect interferometric phase
    - Basic workflow for generating a DEM

Terminology



SAOCOM (L-band)

Frequency: 1.3 GHz

Wavelength: 23 cm

PRF: ~2000 Hz

Range sampling frequency: ~50 MHz

Bandwidth, range: ~50 MHz

Bandwidth, azimuth: ~1800 Hz

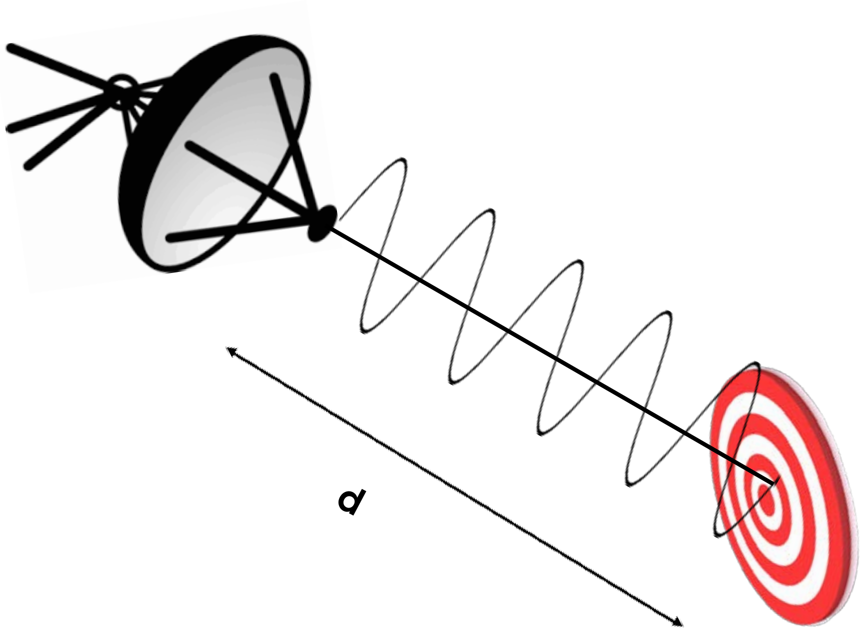
Amplitude vs Phase

Amplitude:

- Energy backscattered toward the sensor, dependent on the characteristics of the target (roughness, absorption, etc.)

Phase:

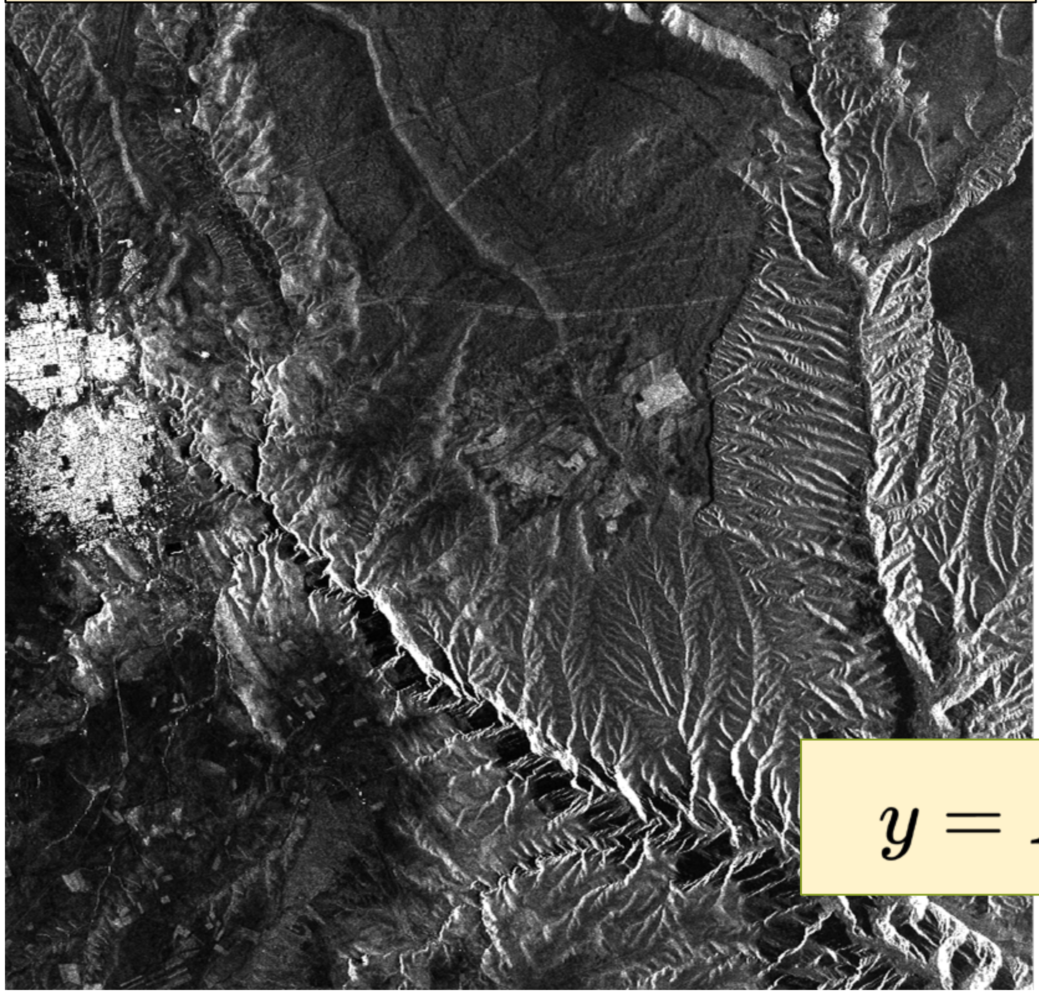
- The distance **d** between the sensor and the target
- The rotation of the phase caused by the structure of the target and its dielectric characteristics.



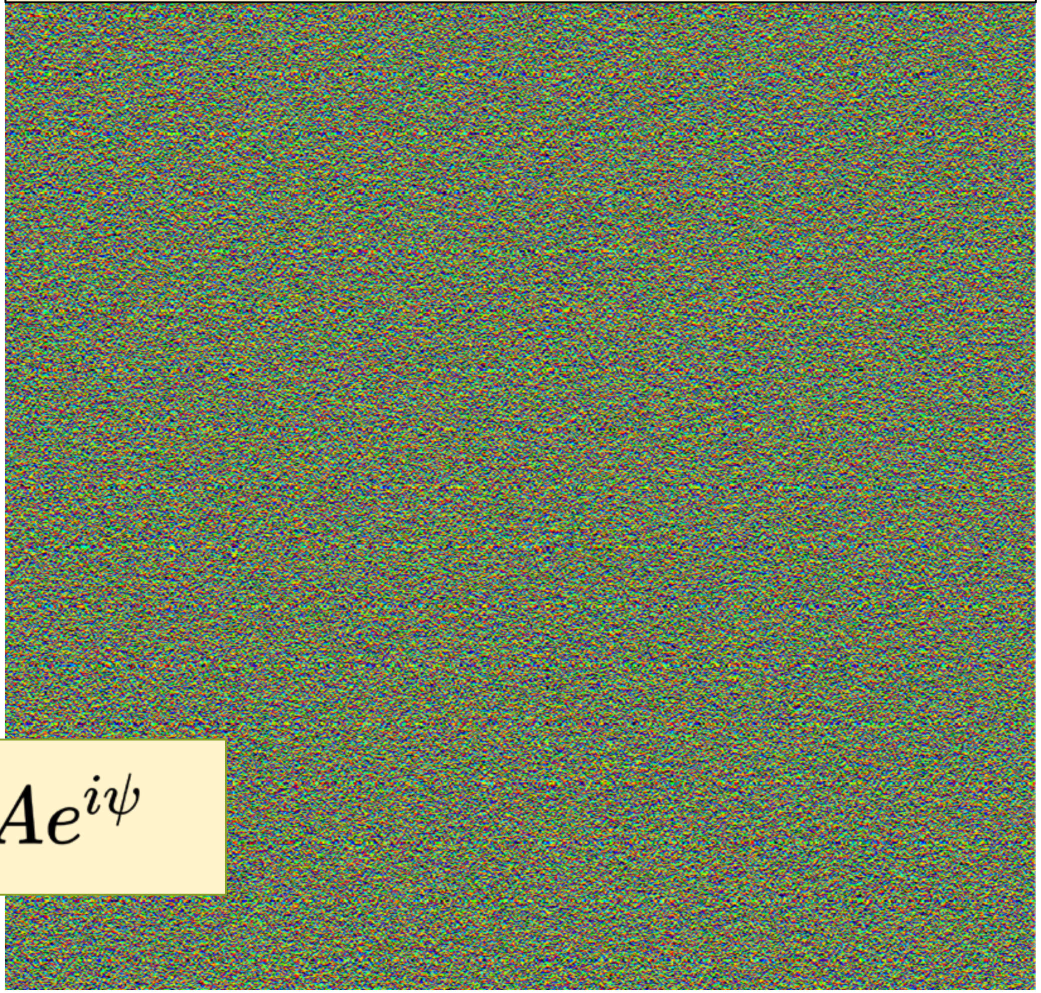
$$\psi = -\frac{4\pi d}{\lambda} + \psi_{target}$$

Amplitude vs Phase

Amplitude: energy backscattered toward the satellite



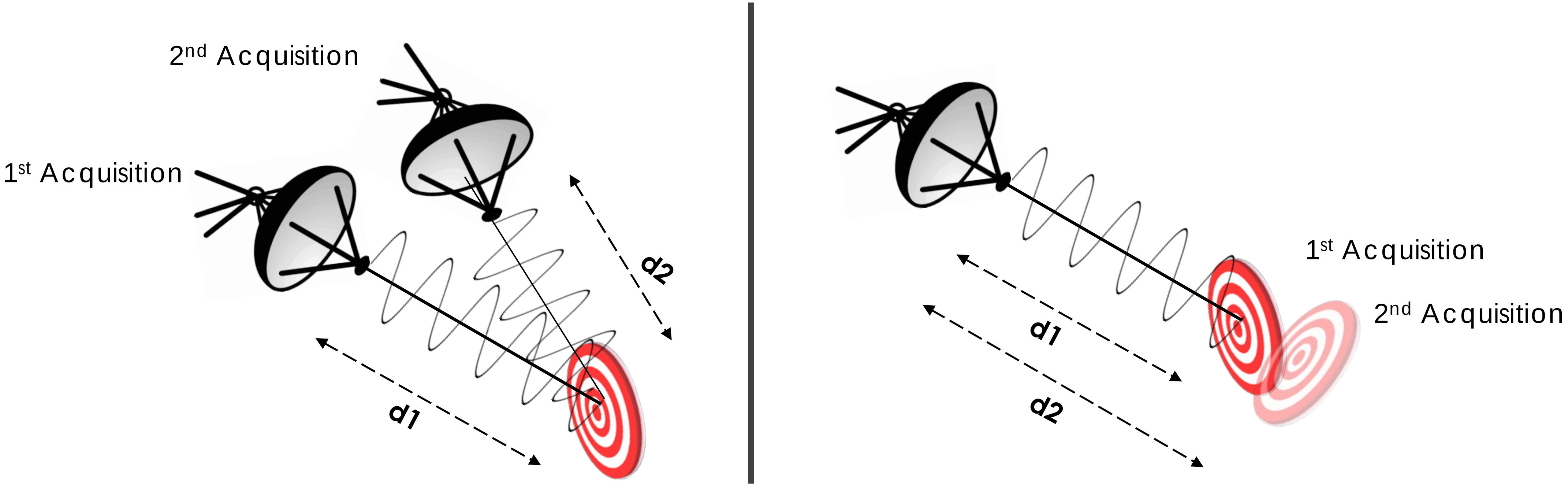
Phase: distance from target to satellite



$$y = Ae^{i\psi}$$

Interferometric Phase (Repeat Pass)

In order to create an interferogram, we need 2 SAR images illuminating the same target in the same way (similar angles of observation).



$$\phi = \psi_1 - \psi_2 = -\frac{4\pi(d_1 - d_2)}{\lambda} + \psi_{target} - \psi_{target} = -\frac{4\pi(d_1 - d_2)}{\lambda}$$

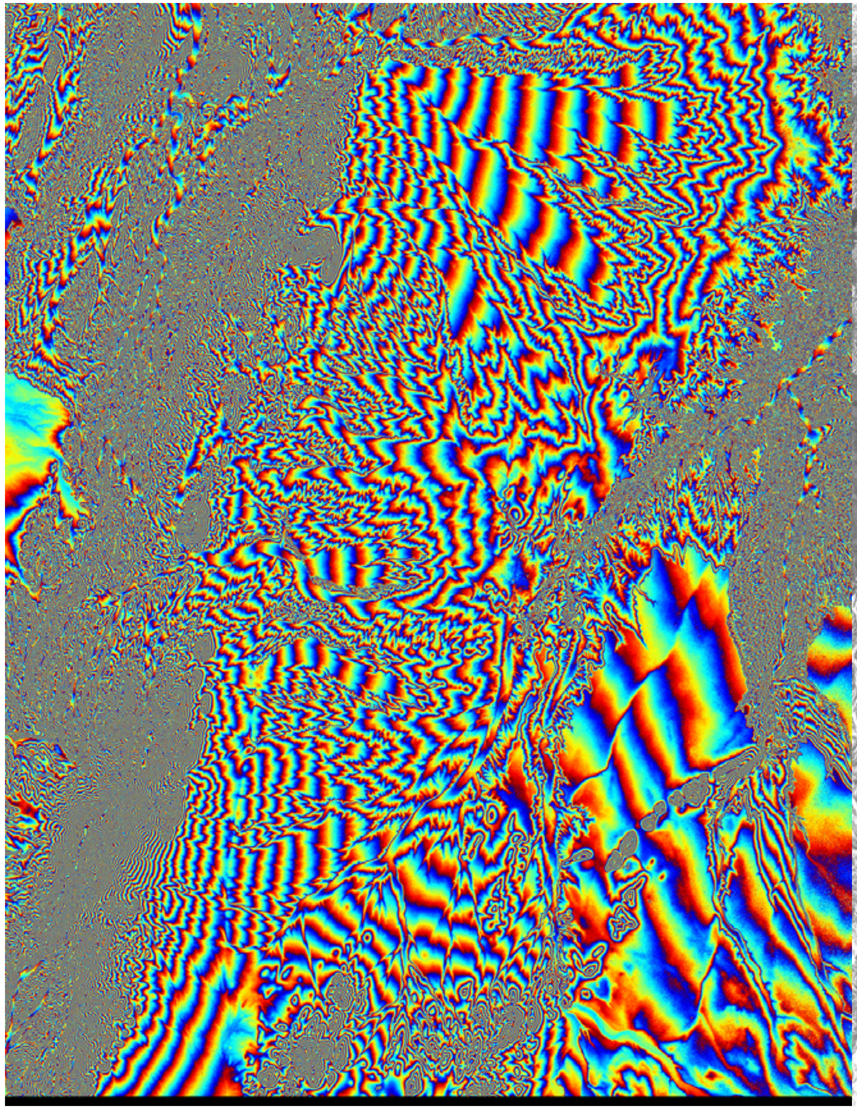
Speckle

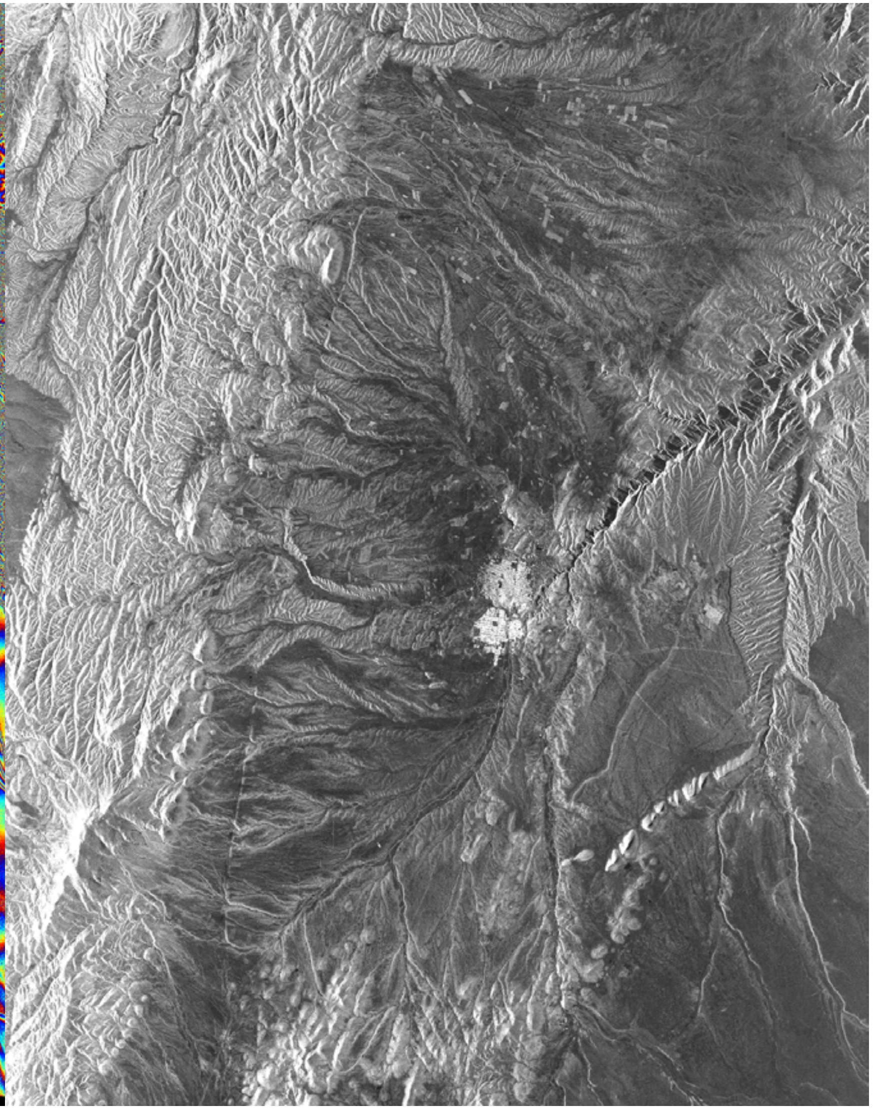
- Many sub-scatterers contribute to the response inside a resolution cell. SAR measures the coherent sum of all these sub-targets for each resolution cell
- For SAOCOM each pixel is ~ 5m x 10 m
- If the sub-scatterers change between the two images, the term corresponding to the *target* in the interferometric phase doesn't cancel out (coherence)

A Closer Look at Phase

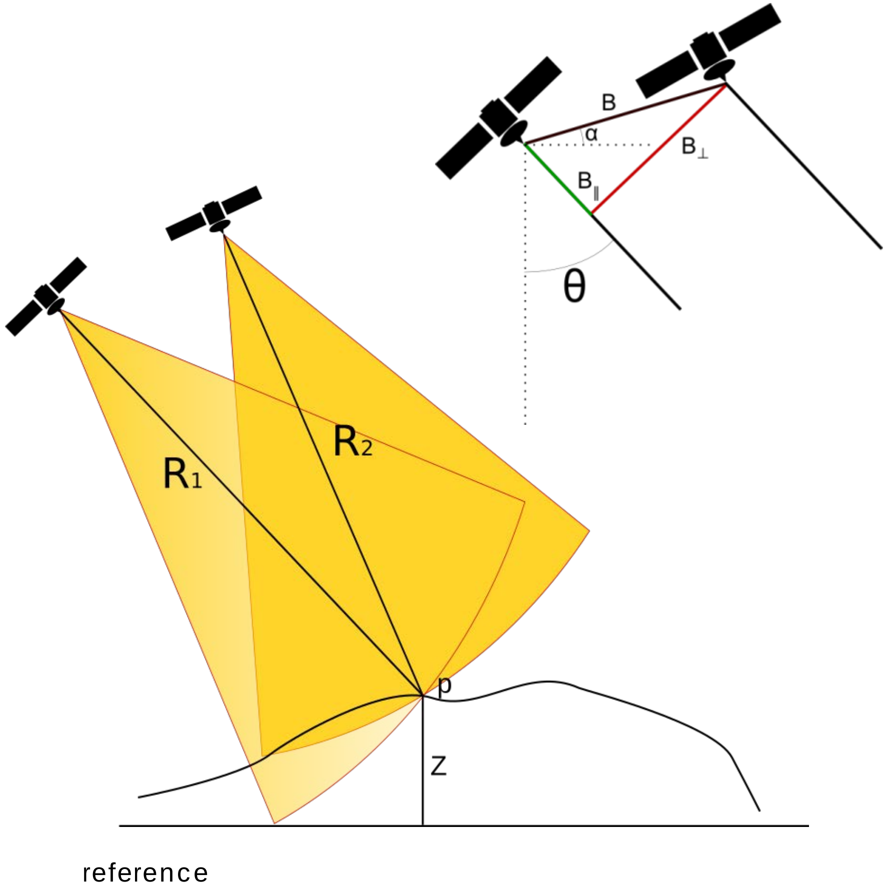
Case Study No. 1 – Interferometric Phase
Topographic Sensitivity
(InSAR)

Sensitivity to Topography





Sensitivity to Topography

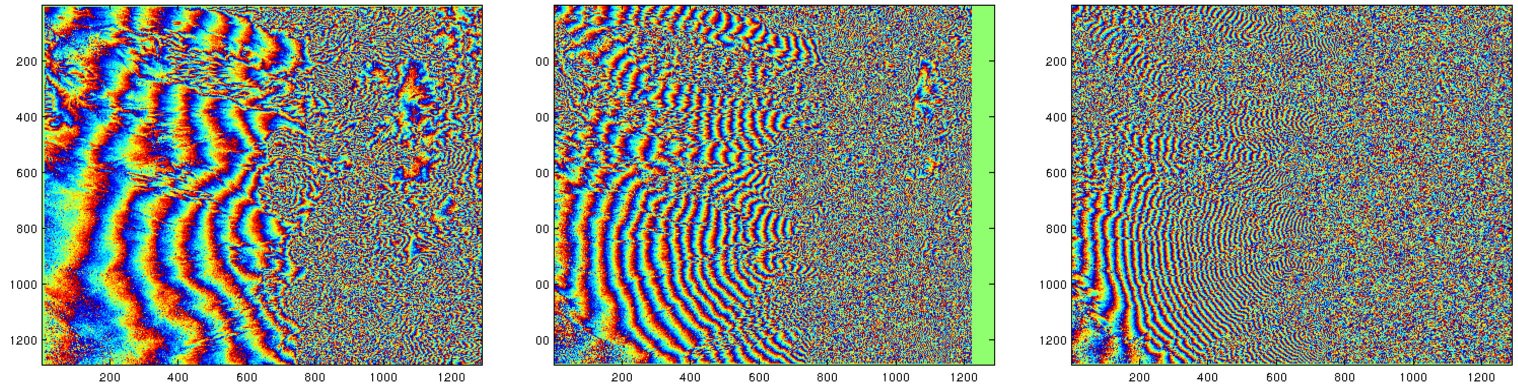


When the same target is observed from two different locations, we can link the interferometric phase to the height **z** of the illuminated target (assuming that the phase of the targets is the same in both images).

$$\phi = -\frac{4\pi B_{\perp}}{\lambda R_1 \sin\theta} z + \phi_{reference}$$

Sensitivity to Topography

$$\frac{d\phi}{dz} = -\frac{4\pi B_\perp}{\lambda R_1 \sin\theta}$$



$B_\perp = 80m$, $z_{2\pi} = 63.5m$

$B_\perp = 156m$, $z_{2\pi} = 32.5m$

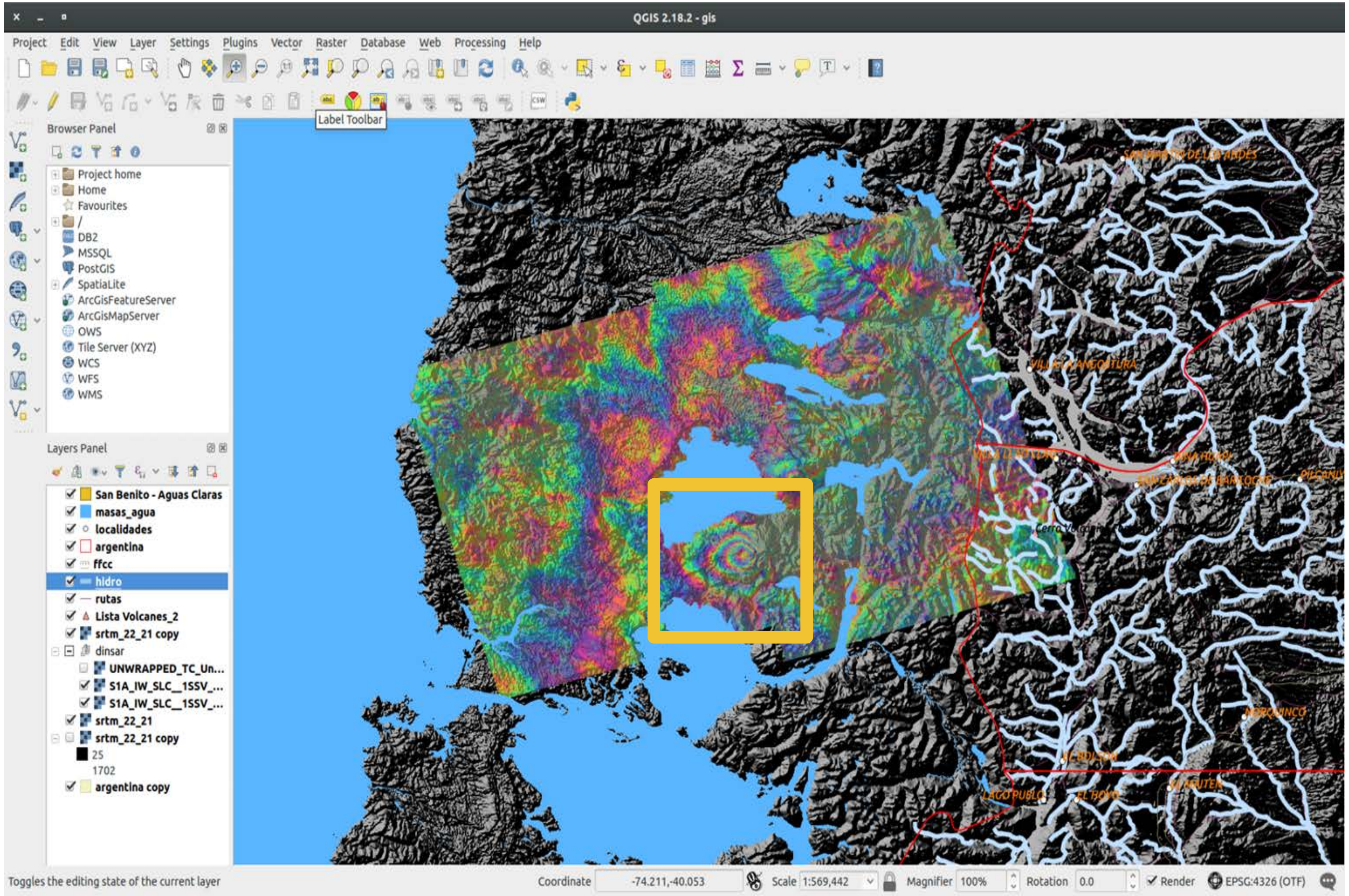
$B_\perp = 364m$, $z_{2\pi} = 13.9m$

The greater the perpendicular baseline, the greater the number of fringes for any given difference in height

A Closer Look at Phase

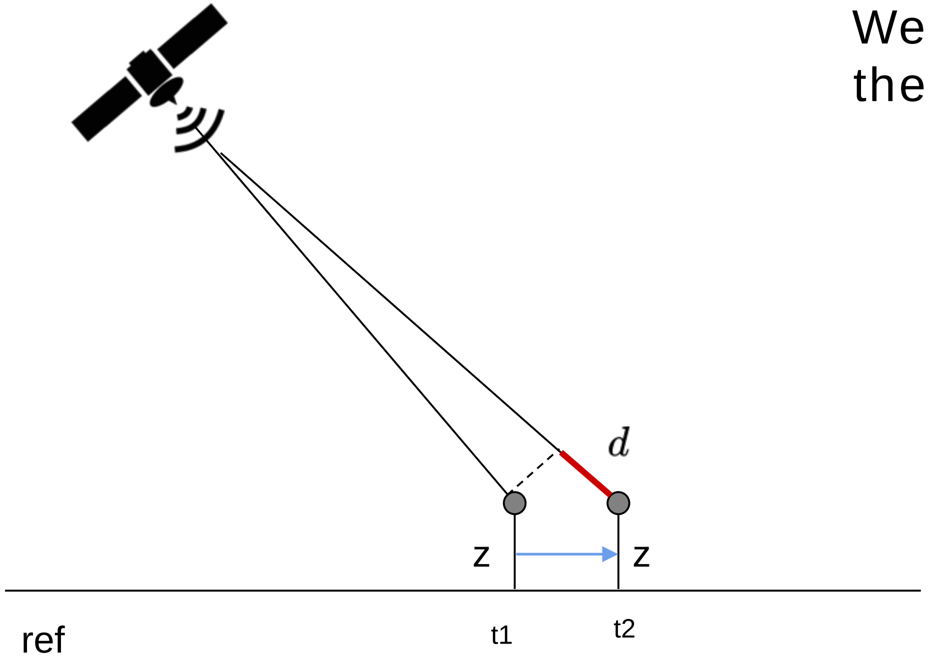
Case Study No. 2 – Interferometric Phase Sensitivity to Displacement (DInSAR)

Sensitivity to Displacement



Sensitivity to Displacement

Let's suppose that we're observing a target at **two different times,** t1 and t2 from **exactly the same position**. And, let's suppose that this target experiences some horizontal displacement as shown in the following figure



We can measure the displacement *d* (in the direction of the radar's line of sight) using the interferometric phase.

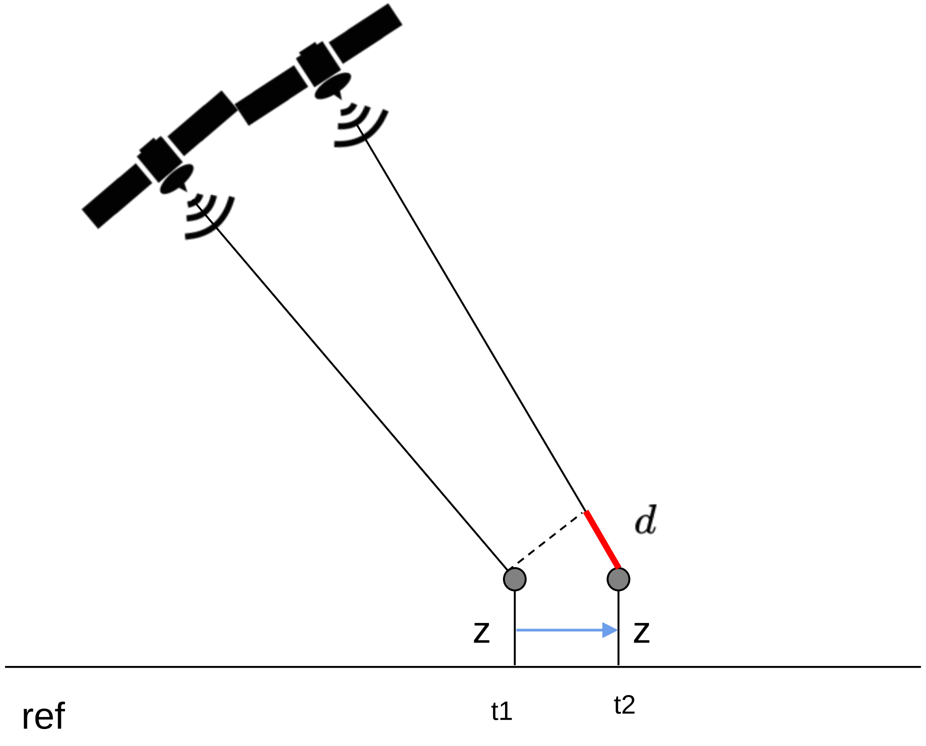
$$\phi = -\frac{4\pi}{\lambda} d + \phi_{ref}$$

Why didn't we include the term for the phase that corresponds to topography?

We observed the target from **exactly the same position**. The sensitivity to topography is null (the perpendicular baseline is zero)

Sensitivity to Displacement

In practice, it's impossible to measure the target from the same position at two different times



$$\phi = -\frac{4\pi}{\lambda} d - \frac{4\pi B_{\perp}}{\lambda R_1 \sin\theta} z + \phi_{ref}$$

In order to measure the displacement ***d*** we need to subtract the contribution to the phase due to topography (we need a DEM) and the contribution of the phase of reference (for example ellipsoid WGS84)

Nota: the displacement that we can measure with DInSAR is in the look direction of the radar. If we want to decompose the displacement into horizontal and vertical components, we need two differential interferograms with different geometries (e.g. one ascending and the other descending)

Summary

$$\phi = -\frac{4\pi B_{\perp}}{\lambda R_1 \sin\theta} z - \frac{4\pi}{\lambda} d$$

InSAR	DInSAR
Digital elevation maps (DEM)	Displacement maps
Preferably simultaneous acquisitions	Acquisitions that contain the event to be studied
Accuracy of ~m	Accuracy of ~mm
Bperp must be large*	Bperp should be small
Sensitivity: $k_z = -\frac{4\pi B_{\perp}}{\lambda R_1 \sin\theta}$	Sensitivity: $k_d = -\frac{4\pi}{\lambda}$ $k_v = -\frac{4\pi}{\lambda}\Delta t$

With differential interferometry we can measure displacement on the order of millimeters given that sensitivity to deformation is much greater than sensitivity to topography.

*There is a critical perpendicular baseline beyond which there is a loss in **coherence**.

Factors that Affect the Interferometric Phase

- Orbital errors
- Atmosphere
- Noise

$$\phi_{ifg} = k_z z + k_v v + \phi_{orb} + \alpha + \eta$$

Orbital errors

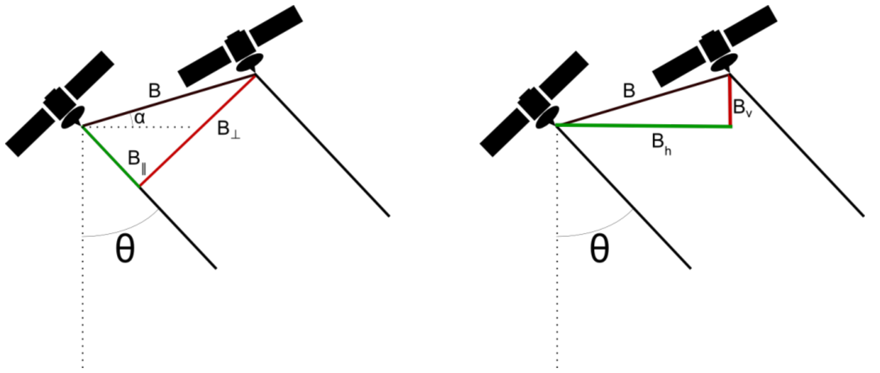
$$\phi_{ifg} = k_z z + k_v v + \boxed{\phi_{orb}} + \alpha + \eta$$

Orbital Errors

Decomposition of Bperp and Bpar

$$B_{\parallel} = B_h \sin(\theta) - B_v \cos(\theta)$$

$$B_{\perp} = B_h \cos(\theta) + B_v \sin(\theta)$$

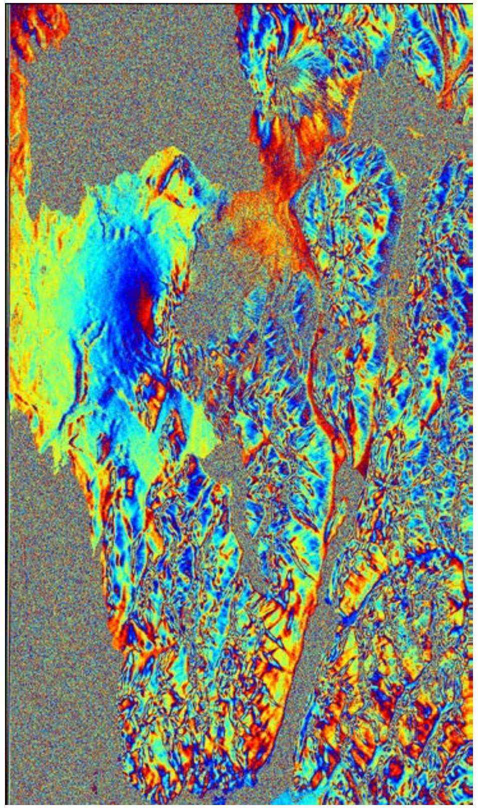


Interferometric Phase: $\phi = \frac{4\pi}{\lambda} B_{\parallel}$

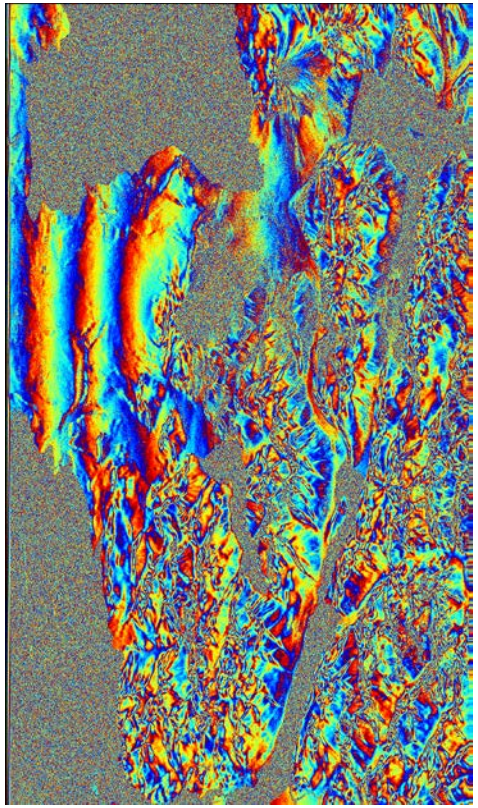
If we take the derivative of azimuth and range: $\Delta\phi = \frac{4\pi}{\lambda}\frac{\partial B_{\parallel}(\theta,t)}{\partial t}\Delta t + \frac{4\pi}{\lambda}\frac{\partial B_{\parallel}(\theta,t)}{\partial \theta}\Delta\theta = \frac{4\pi}{\lambda}\dot{B}_{\parallel}\Delta t + \frac{4\pi}{\lambda}B_{\perp}\Delta\theta$

- An error in the Bpar generates a phase offset (this is not a problem) $\sigma\phi = \frac{4\pi}{\lambda}\sigma_{B_{\parallel}}$
- An error in the Bperp generates a phase ramp in the range $\sigma_{\Delta\phi} = (\frac{4\pi}{\lambda}\Delta\theta)\sigma_{B_{\perp}}$
- An error in variation of the Bpar in time generates a phase ramp in the azimuth (for example, non-parallel orbits) $\sigma_{\Delta\phi} = (\frac{4\pi}{\lambda}\Delta t)\sigma_{\dot{B}_{\parallel}}$

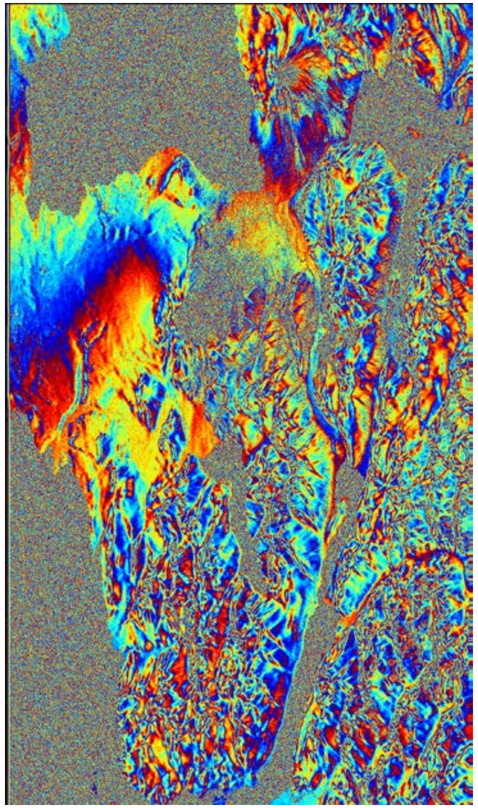
Orbital Errors



Original Interferogram

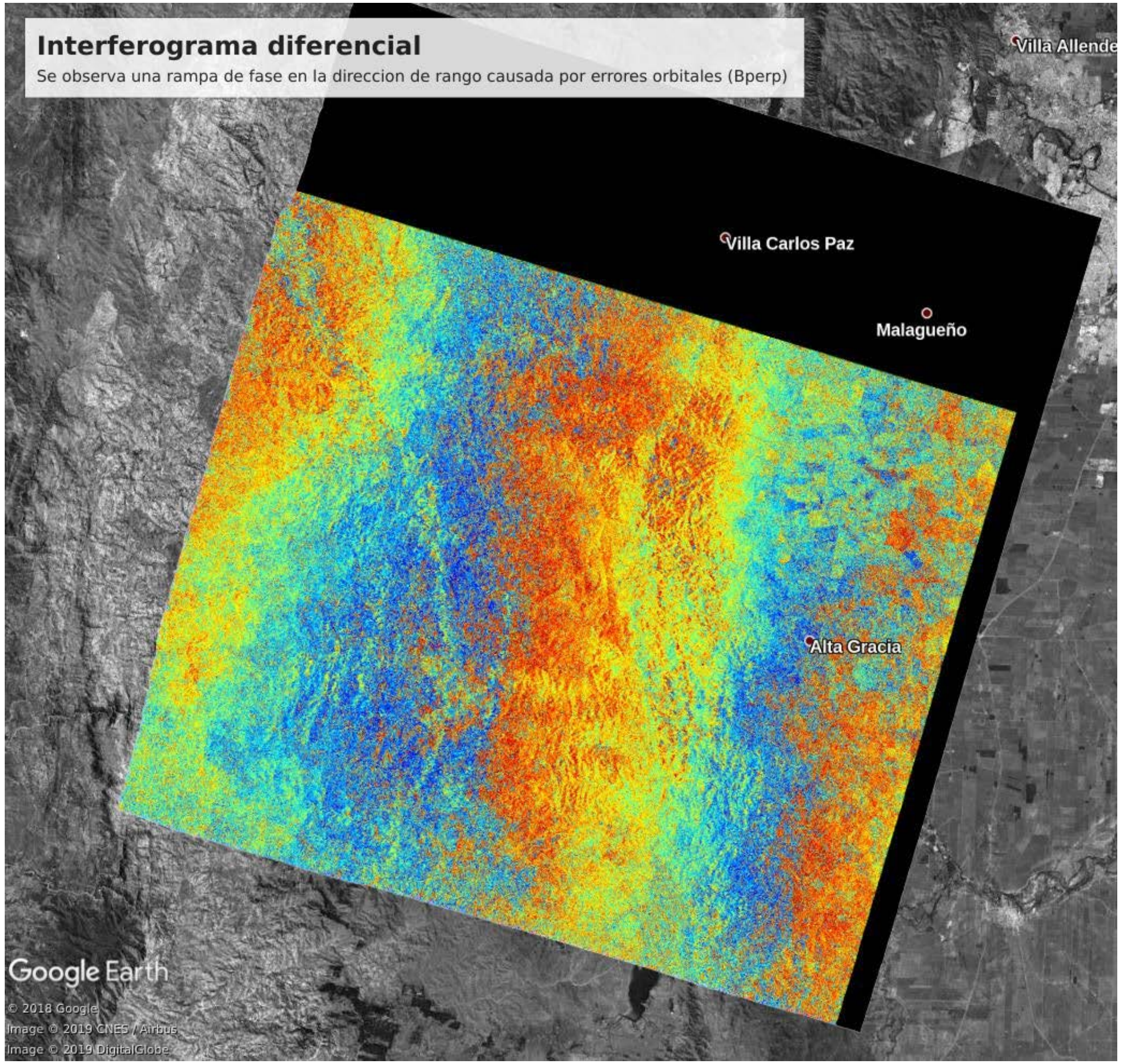


Interferogram with error in Bperp = 10m



Interferogram with error in Bpar_rate = 0.0325m/s

Orbital Errors



Atmosphere

$$\phi_{ifg} = k_z z + k_v v + \phi_{orb} + \boxed{\alpha} + \eta$$

Atmosphere

Non-simultaneous acquisitions ⇒ there may be different atmospheric conditions affecting the path followed by a wave (the phase)

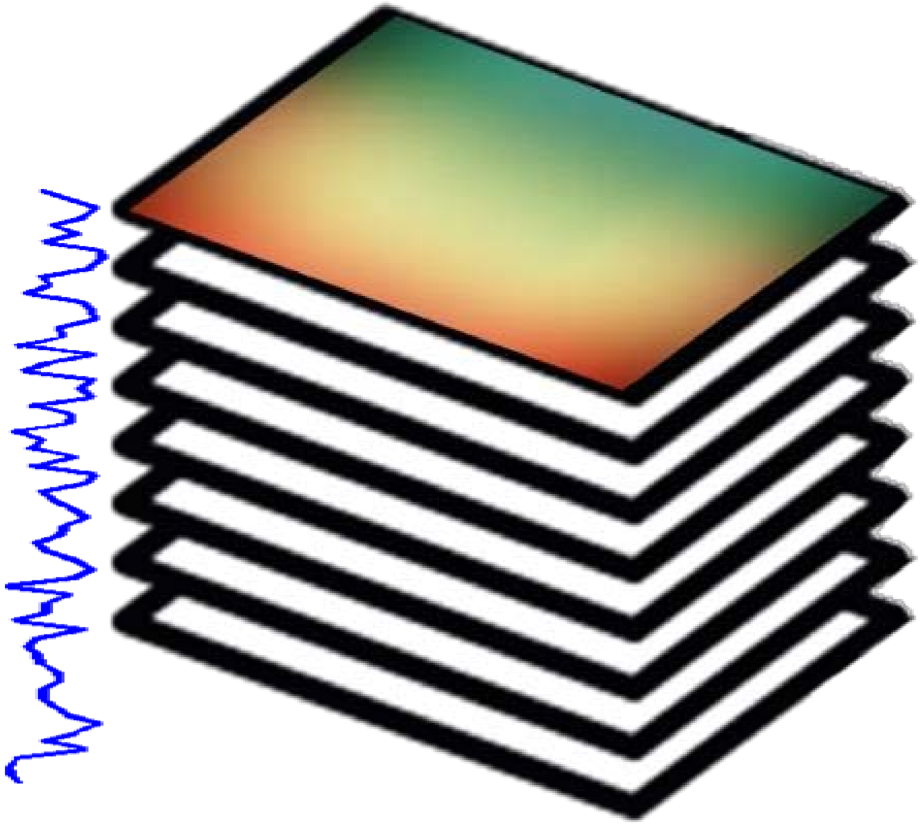
- Humidity
- Temperature
- Pressure

Atmospheric Phase Screen (APS)

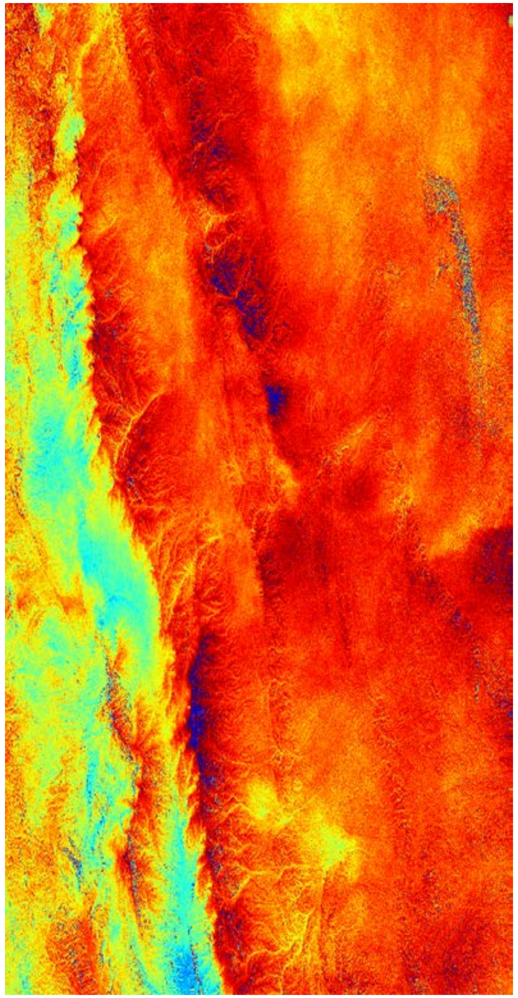
- Slight changes in space
- Abrupt changes in time

Affects:

- Height measurement (especially small Bperp)
- Measurement of deformation



Example of Stratospheric Stratification



Example of the atmospheric effects on the interferometric phase due to tropospheric stratification

Differential interferogram generated using SAOCOM data in San Juan (near Leoncito)

Typical effect of tropospheric stratification, as we can see, there is a correlation between phase and topography

When we generate the interferogram, we assume that the wave travels in a vacuum at a speed of c. But upon entering the atmosphere, it encounters a stratified dielectric medium which causes its speed to reduce. The interferometric phase generated by the changes in the speed of propagation should be counterbalanced so that it doesn’t mix with the terms of deformation and topography.

Noise

$$\phi_{ifg} = k_z z + k_v v + \phi_{orb} + \alpha + \boxed{\eta}$$

Coherence

If the target undergoes changes between the two acquisitions that make up the interferometric pair, the images lose coherence, and the interferometric phase is degraded. The phase term corresponding to the target doesn't cancel out.

$$\phi = \psi_1 - \psi_2 = -\frac{4\pi(d_1 - d_2)}{\lambda} + \psi_{target1} - \psi_{target2} = -\frac{4\pi(d_1 - {}_2)}{\lambda} + \eta$$

It's possible to quantify the change that occurred in the target between acquisitions by calculating the **interferometric coherence**.

$$\gamma = \frac{\mathbb{E}\{y_1 y_2^*\}}{\sqrt{\mathbb{E}\{|y_1|^2\}\mathbb{E}\{|y_2|^2\}}} \quad \Longrightarrow \quad \hat{\gamma} = \frac{\sum_{n=1}^{N} y_1 y_2^*}{\sqrt{\sum_{n=1}^{N} |y_1|^2 \sum_{n=1}^{N} |y_2|^2}}$$

Values for modules near 0 indicate a low correlation;
Values for modules near 1 indicate a high correlation.

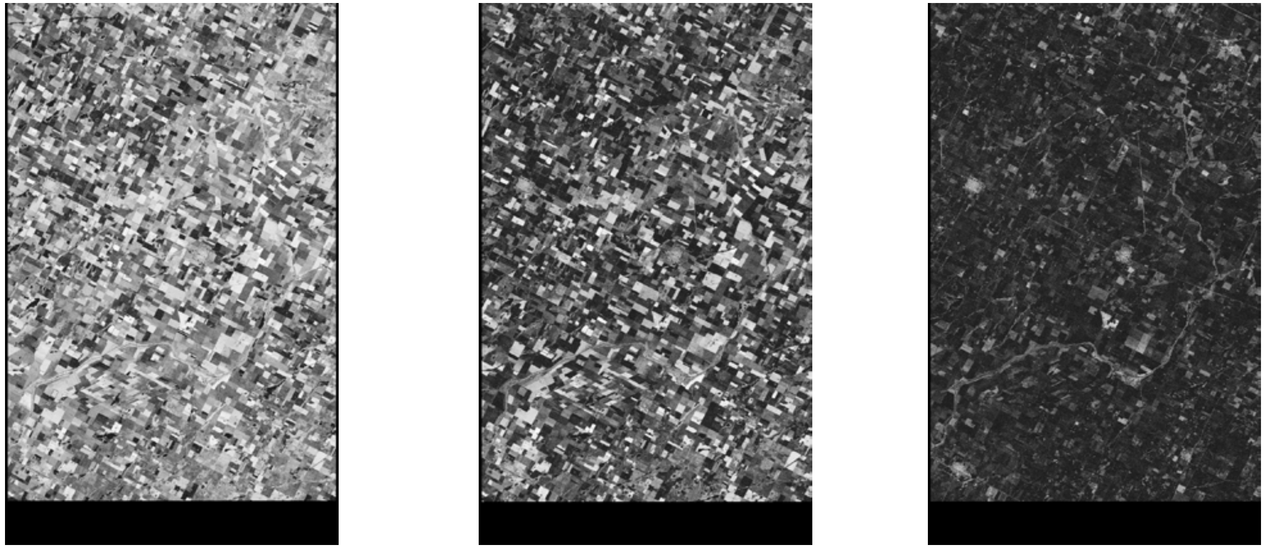
Sources of Decorrelation

- **Geometric**: caused by the difference in incidence angles between acquisitions (critical Bperp)
- **Doppler**: caused by the difference in Doppler centroids between acquisitions
- **Thermal**: inherent to the system (e.g. antennas)
- **Volumetric**: caused by penetration of the wave into a scattering medium (band dependent)
- **Temporal**: caused by physical changes in the terrain that affect the scattering characteristics (band dependent)
- **Processing**: coregistration, interpolation, etc...

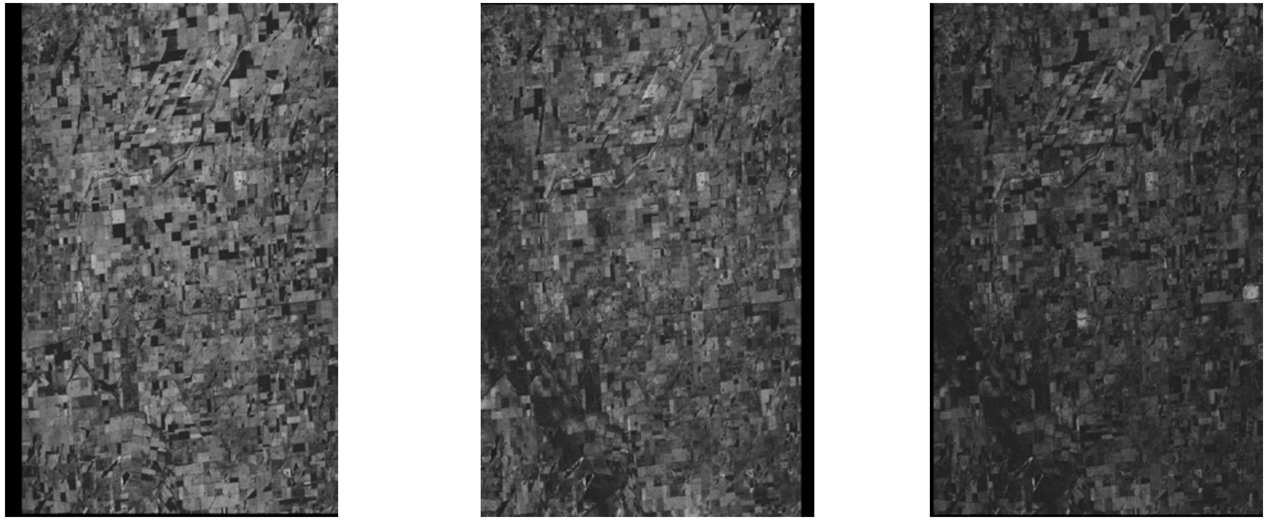
$$\gamma = \gamma_{geom}\gamma_{dc}\gamma_{vol}\gamma_{thermal}\gamma_{temporal}\gamma_{processing}$$

Coherence- X-Band vs L-Band

ALOS-2 (L-Band)
Btemp: 14, 28, 98 days
Bperp: 400, 30, 50 m

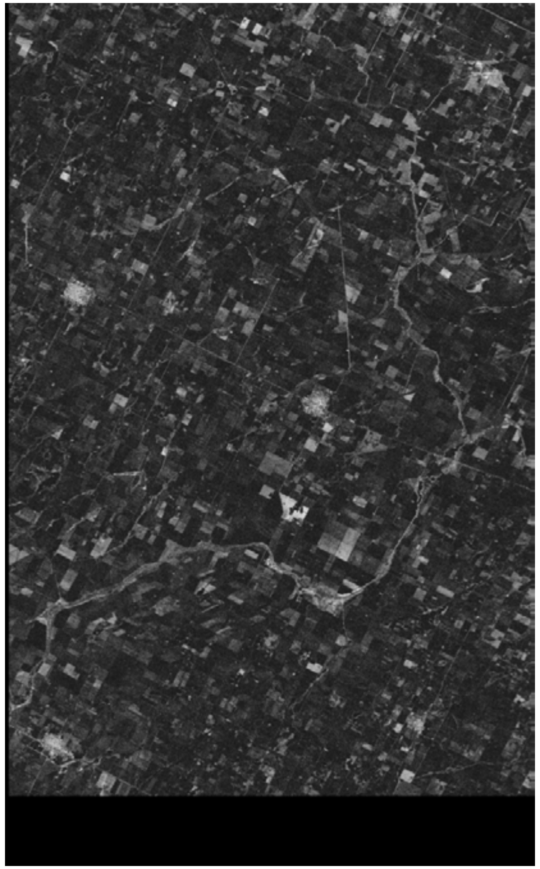


COSMO (X-Band)
Btemp: 8, 12, 20 days
Bperp: 1500, 1170, 420 m



Coherence- X-Band vs L-Band

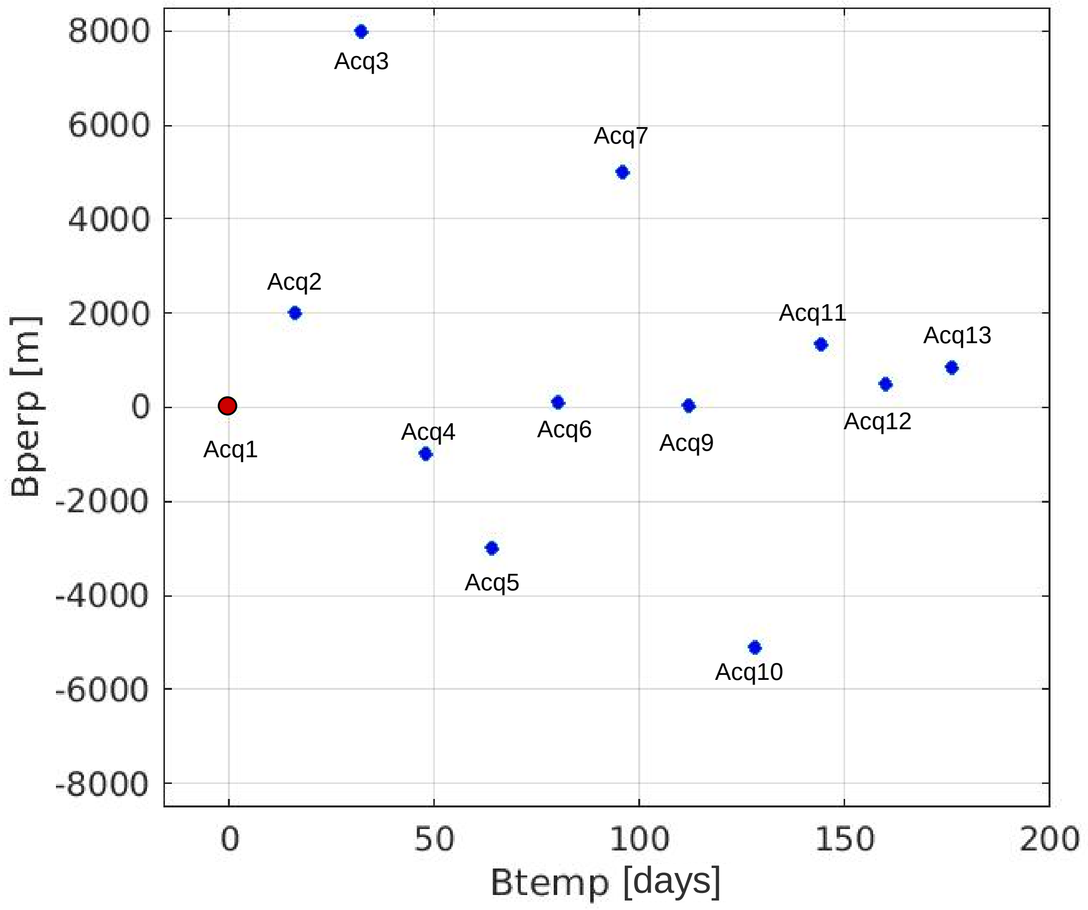
Btemp 14 days
Bperp 400m
L-Band (ALOS2)



Btemp 20 days
Bperp 420m
X-Band (COSMO)

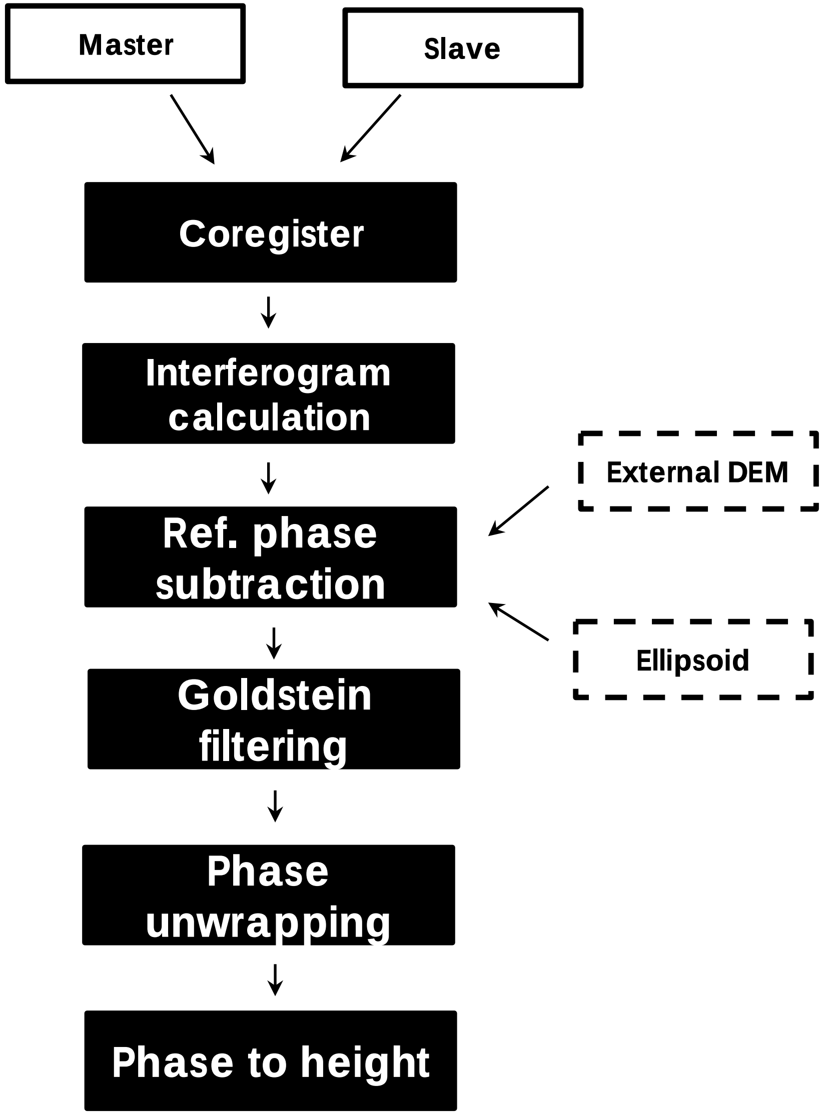
Exercise

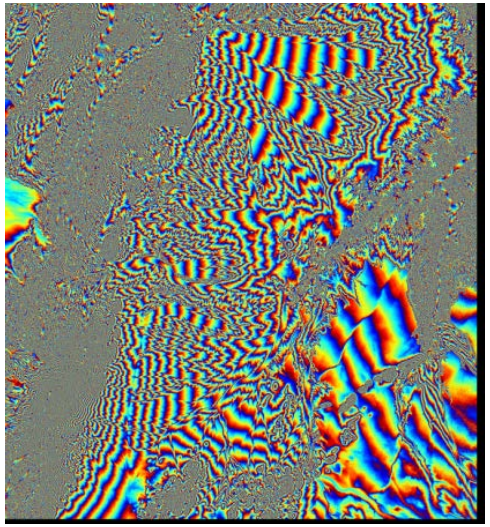
Let's take the following plane which graphs the perpendicular baseline as a function of the temporal baseline for 13 acquisitions over the same region.
Which three pairs would you select to make a DEM? (note: assume critical Bperp of ~5Km)



Basic Workflow for Generating a DEM

Basic Workflow for Generating a DEM





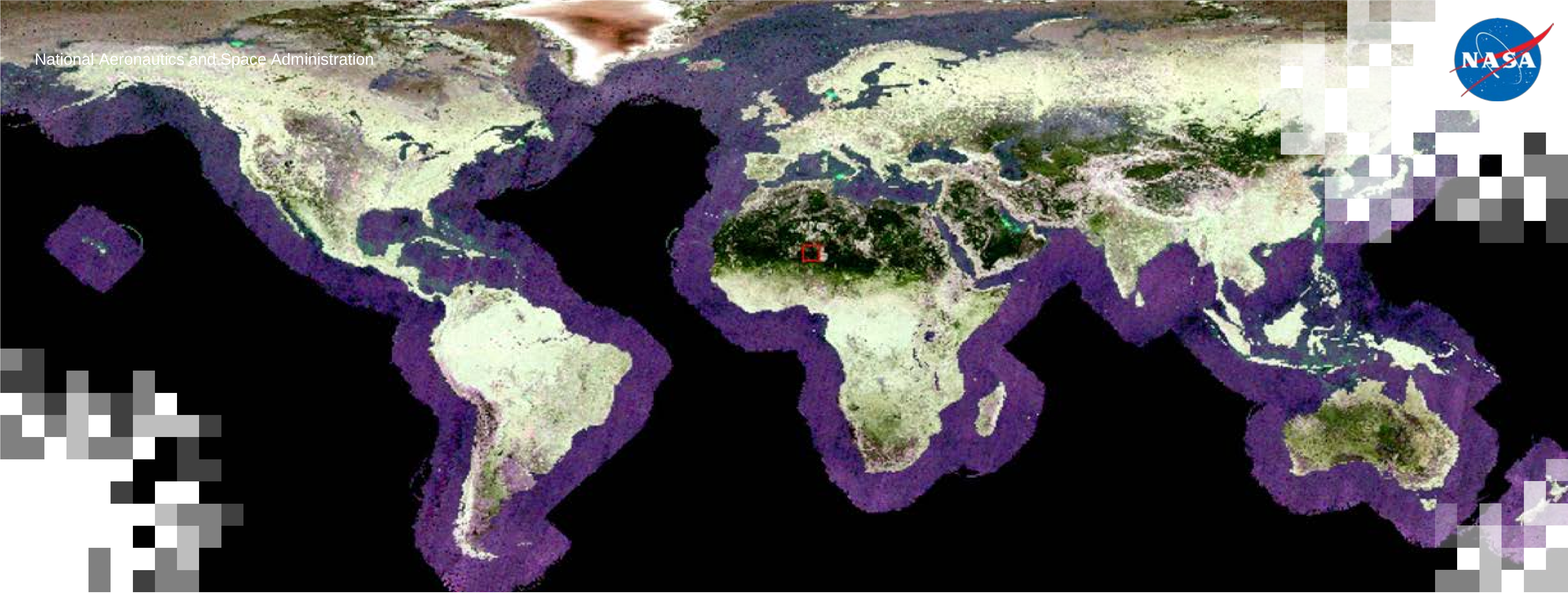
Bibliography and Software

Bibliography

- *Radar Interferometry, Data Interpretation and Error Analysis. Ramon F. Hanssen.*
- *InSAR Principles, Guidelines for SAR Interferometry Processing and Interpretation. ESA.*

Software

- SNAP 7.0 http://step.esa.int/main/download/snap-download/
- Sentinel 1 Toolbox: https://github.com/senbox-org/s1tbx
- Doris: https://github.com/TUDelftGeodesy/Doris
- Snaphu: https://step.esa.int/main/third-party-plugins-2/snaphu/



Basic Workflow for Generating a DEM

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Argentine National Commission for Space Activities (CONAE)

Requirements

- A computer with at least 8GB of RAM

- Software:
  - SNAP 7.0 with Sentinel Toolboxes http://step.esa.int/main/new-release-of-snap-7-0-public-beta-is-available/
  - Snaphu v2.0.1 https://web.stanford.edu/group/radar/softwareandlinks/sw/snaphu/

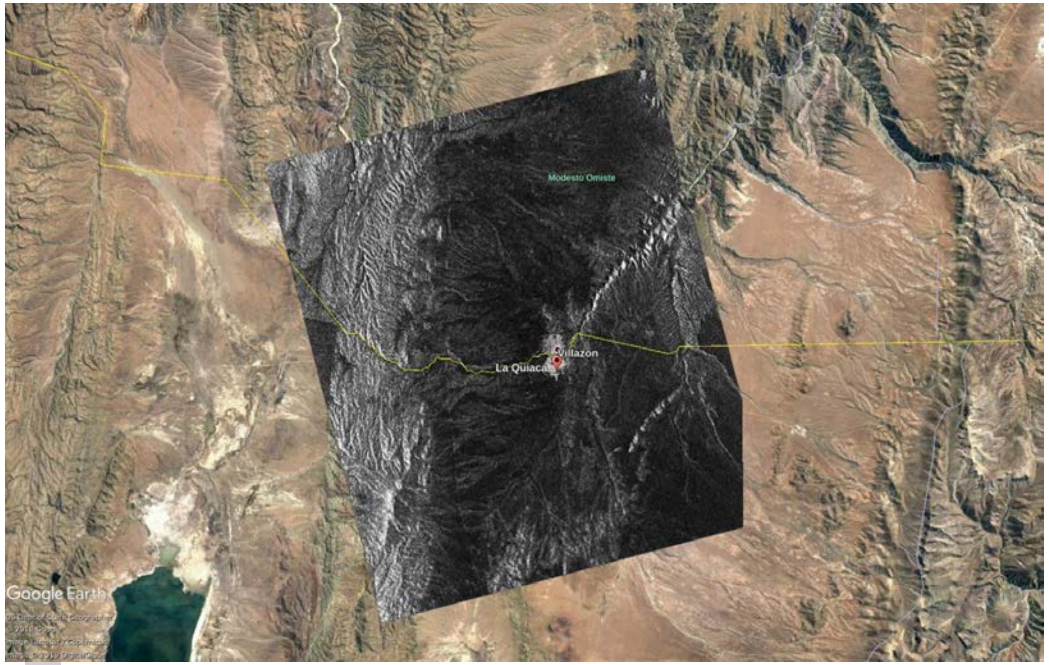
Jujuy - La Quiaca

Semi-arid climate

~80% of precipitation occurs in summer

Winters are very dry and cold. It barely rains

https://www.weather-arg.com/en/argentina/la-quiaca-climate



What's the best what time of year to you capture images to generate a DEM?

Jujuy - La Quiaca

Semi-arid climate

~80% of precipitation occurs in summer

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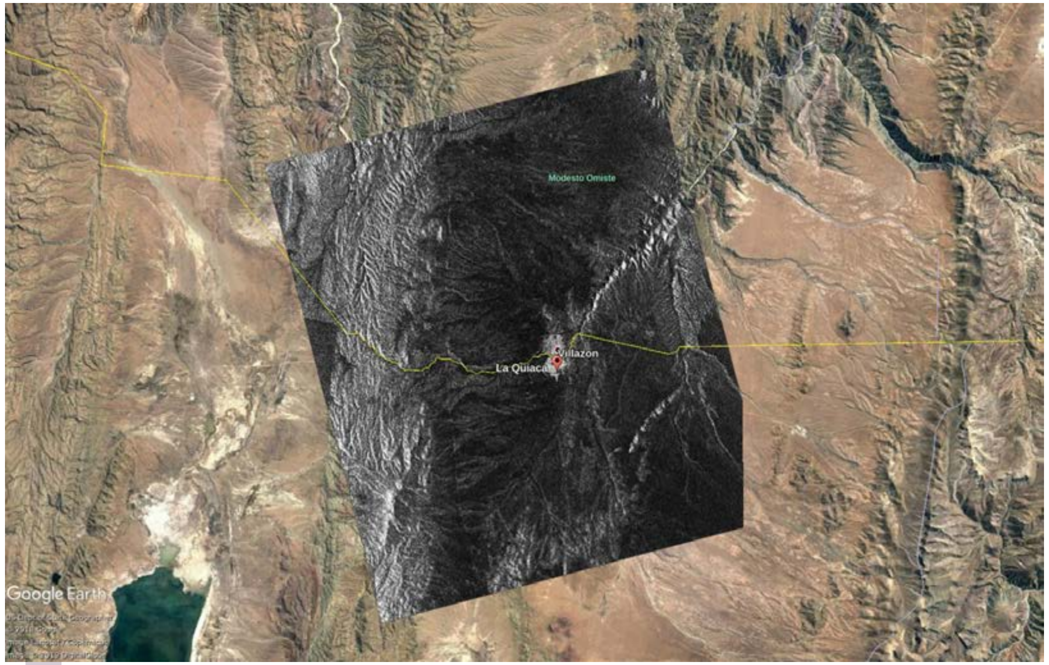
https://www.weather-arg.com/en/argentina/la-quiaca-climate



What's the best what time of year to you capture images to generate a DEM?

Interferograms would probably be least affected by atmospheric conditions during winter.

Dataset

We have a tandem pair of STRIPMAP Cosmo-Skymed*, X-Band (3cm) images

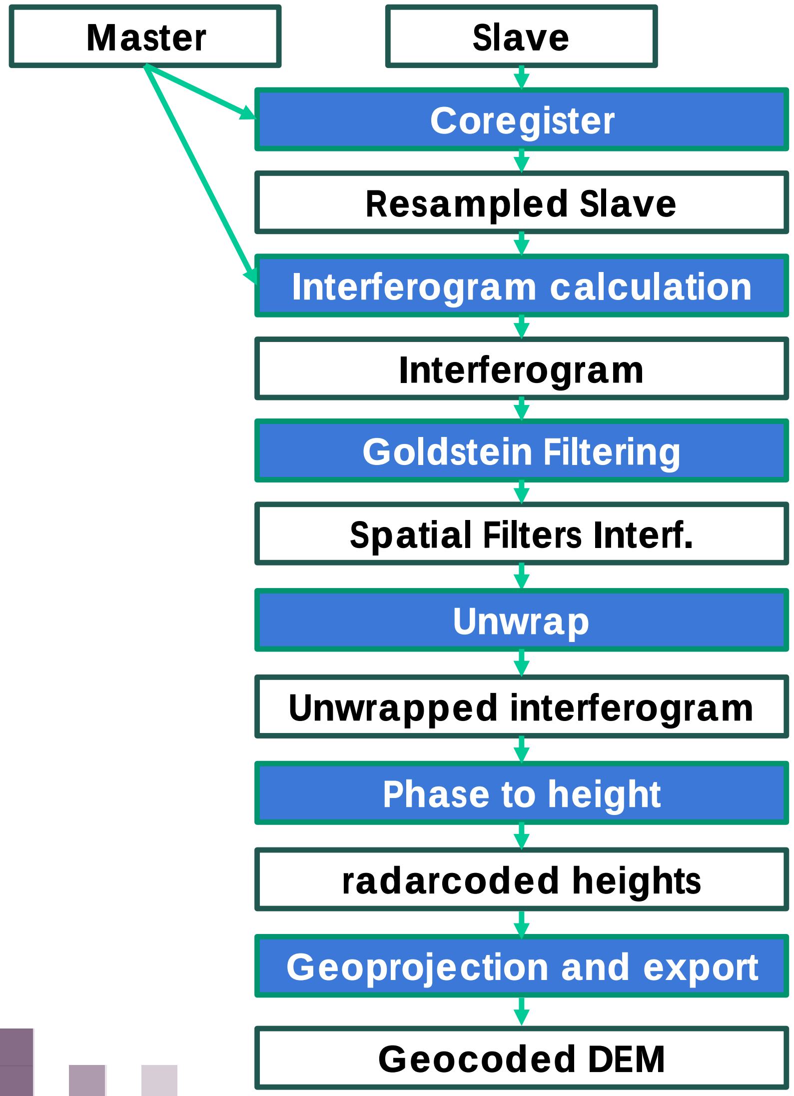
- Master: 2017-05-14
- Slave: 2017-05-15

Parameters:

- Temporal baseline: 1 day
- Perpendicular Baseline: 500 m
- Height of ambiguity: 22 m
- Delta centroids Doppler: 22 Hz
- Bandwidth, range: 73.5 MHz
- Bandwidth, azimuth: 2590 Hz
- Incidence angle: 40 º
- Slant range: 884 Km

*The images used herein were obtained by the COSMO SkyMed satellite and CONAE uses them per the Memorandum of Understanding signed by ASI and CONAE in the framework of cooperation defined by SIASGE (Italo-Argentine Satellite Emergency Management System). These images are for academic use and for the sole purpose of conducting the training exercises.

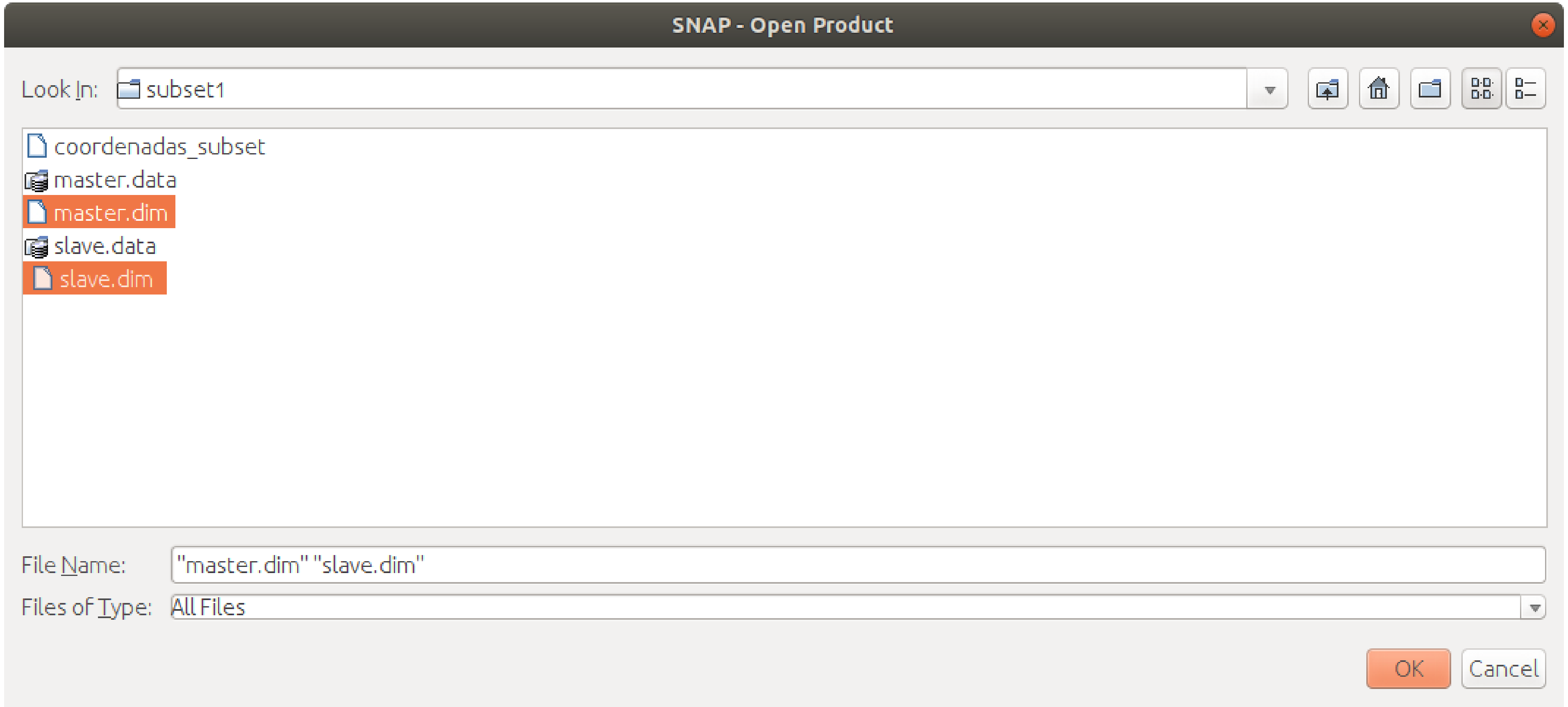
Basic Workflow



1. Master and Slave
2. Coregistration (subpixel) and Slave-to-Master re-sampling
3. Creation of an interferogram by subtracting the phase from the pixels. The flat-ground phase of reference is subtracted to obtain the interferogram with the topographic phase
4. Noise reduction via Goldstein Filtering
5. Phase unwrapping
6. The topographic phase is converted to height with respect to the reference (heights in slant range)
7. Projection of heights on lat-lon
8. We obtain a DEM that we can open with GIS

Step 1 – Read Images

- We open the images with SNAP, *File > Open Product* and we look for master.dim and slave.dim



Step 1 – Read Images

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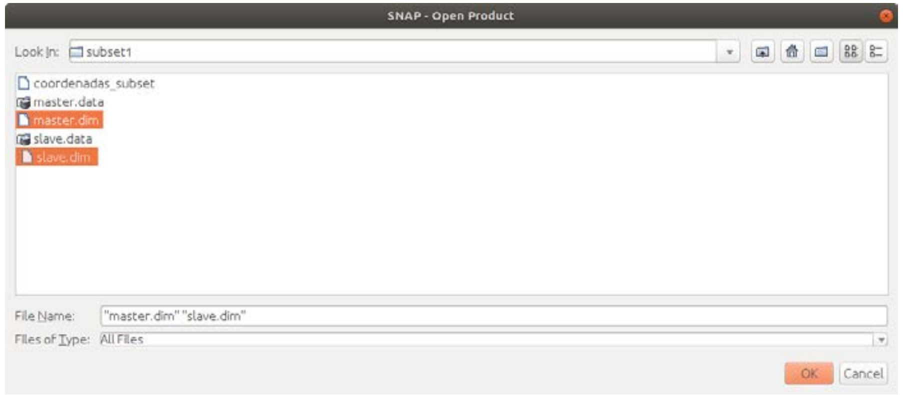
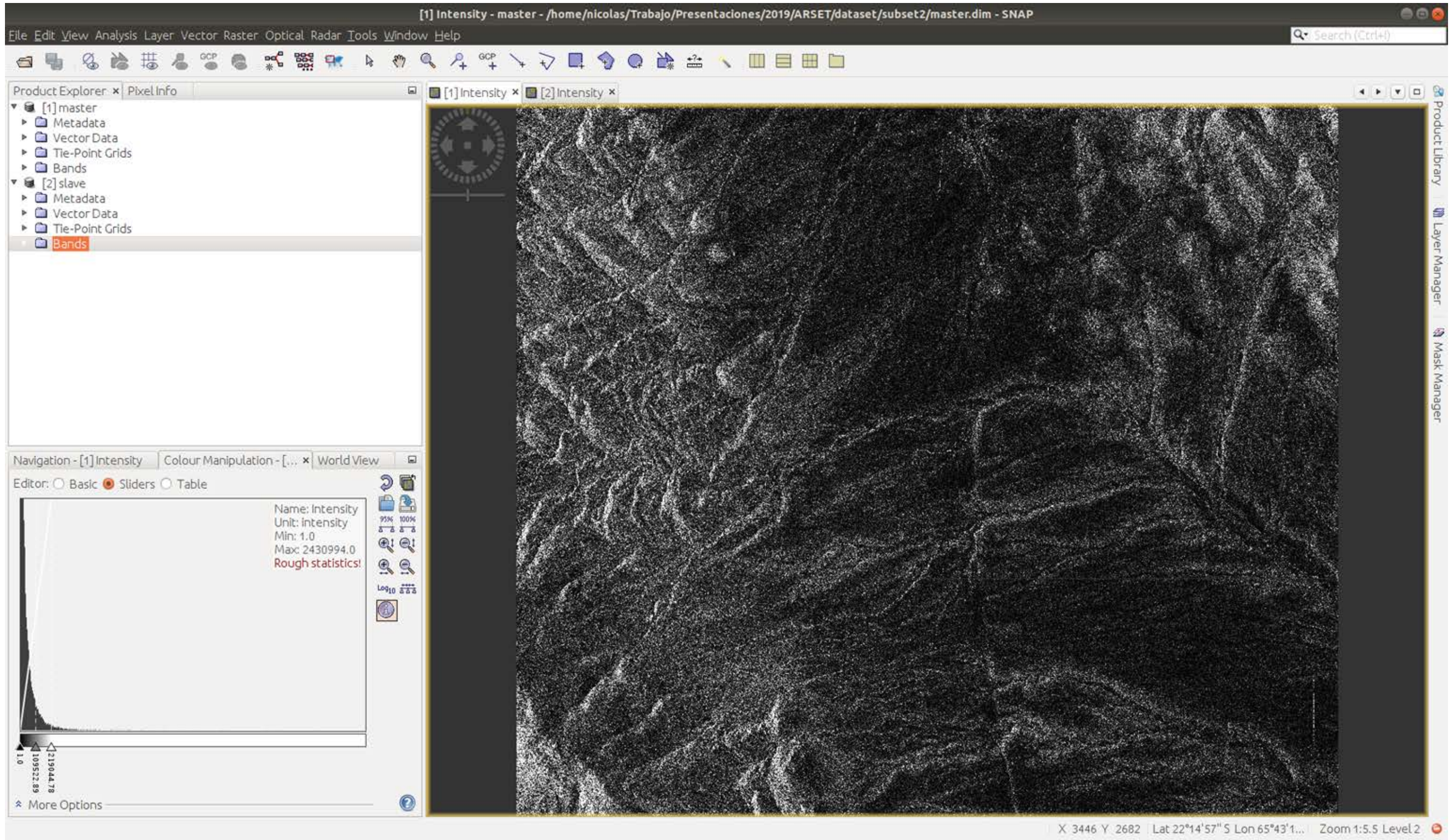


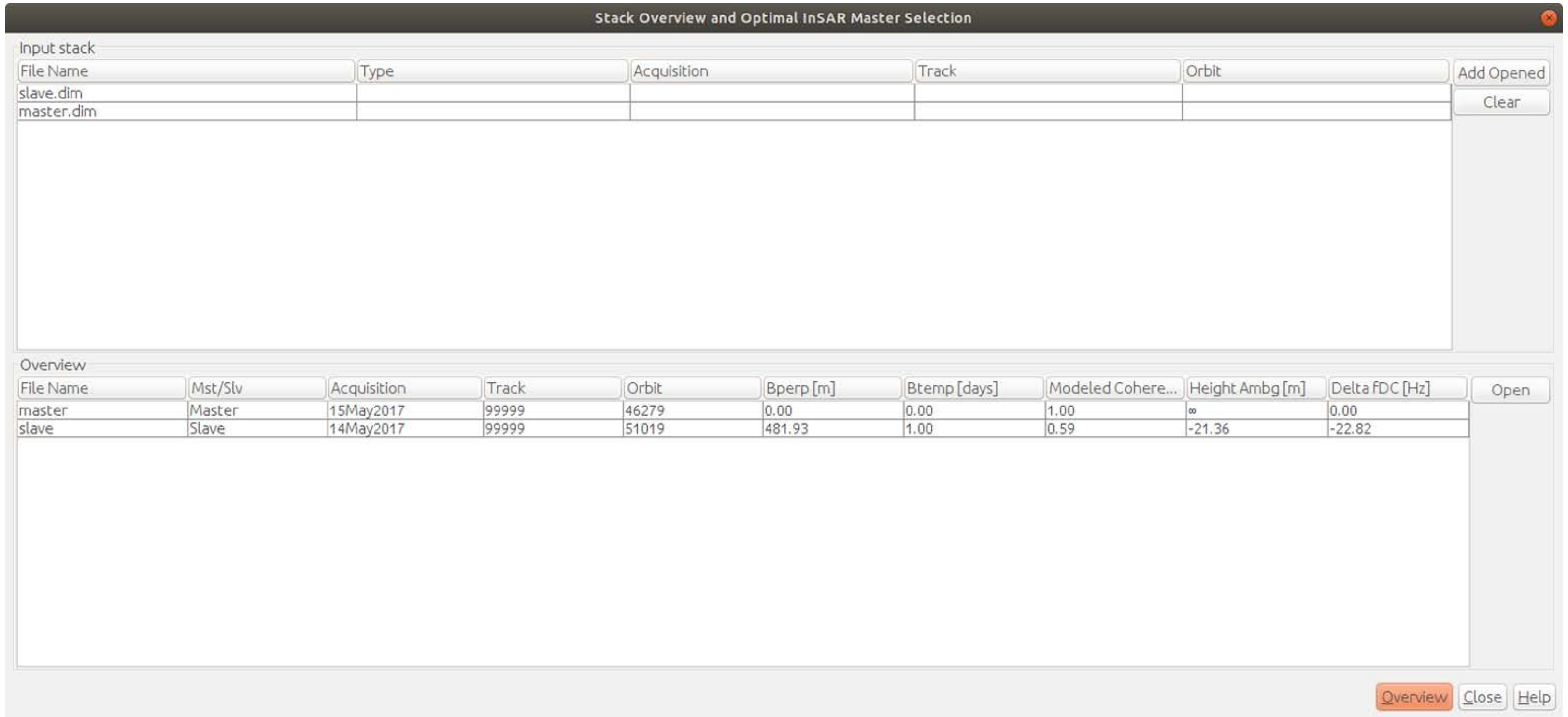


The images are made up of bands **I** (real part) and **Q** (imaginary part)

We can view the intensity of both images by opening the **Intensity** band

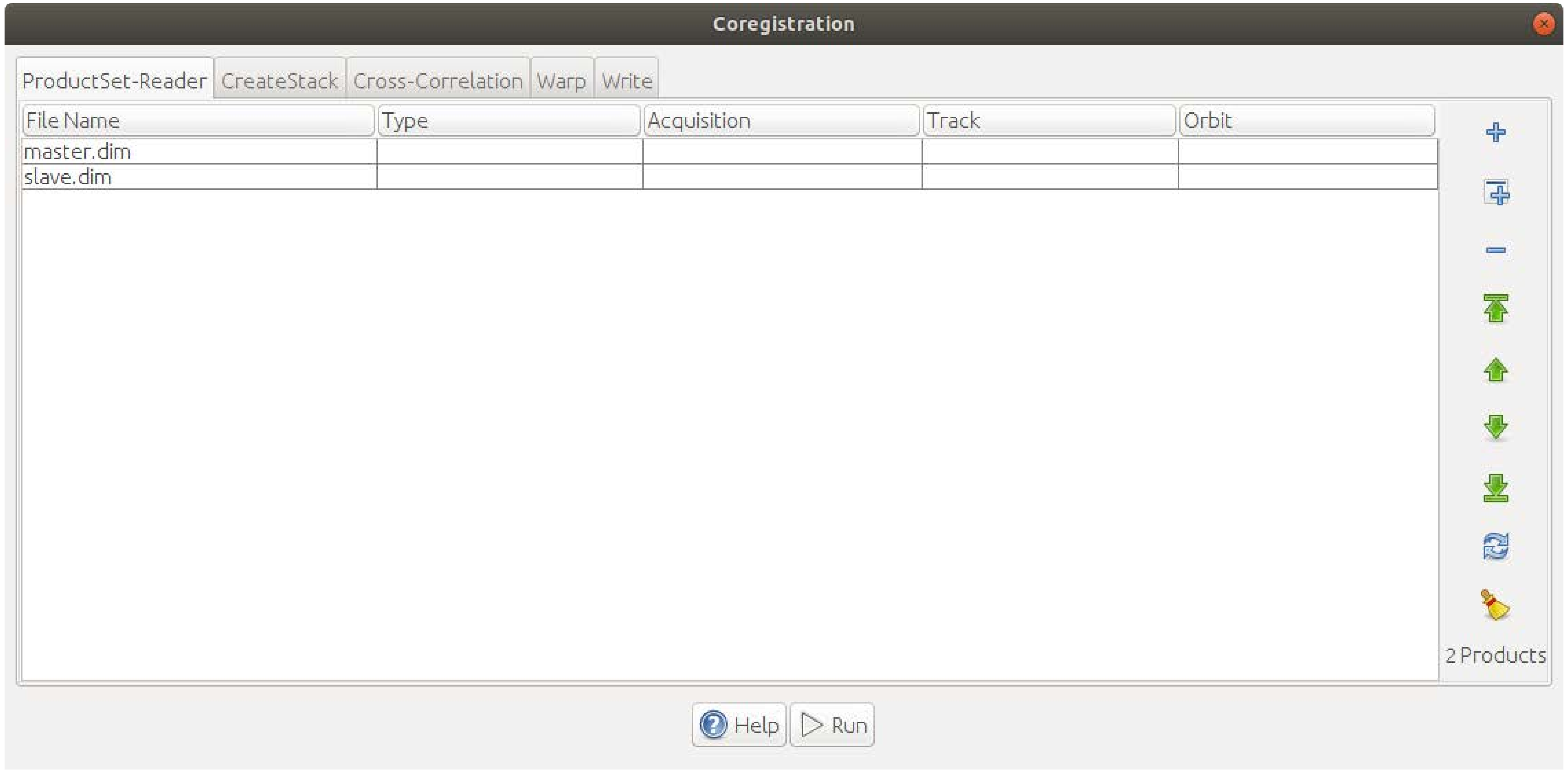
Step 1.1 – General Information about the Pair

In *Radar > Interferometric > InSAR Stack Overview* we can see general information regarding the interferometric pair: date of acquisition, sensor, mode, perpendicular baseline, temporal baseline, modeled coherence, height of ambiguity, etc…



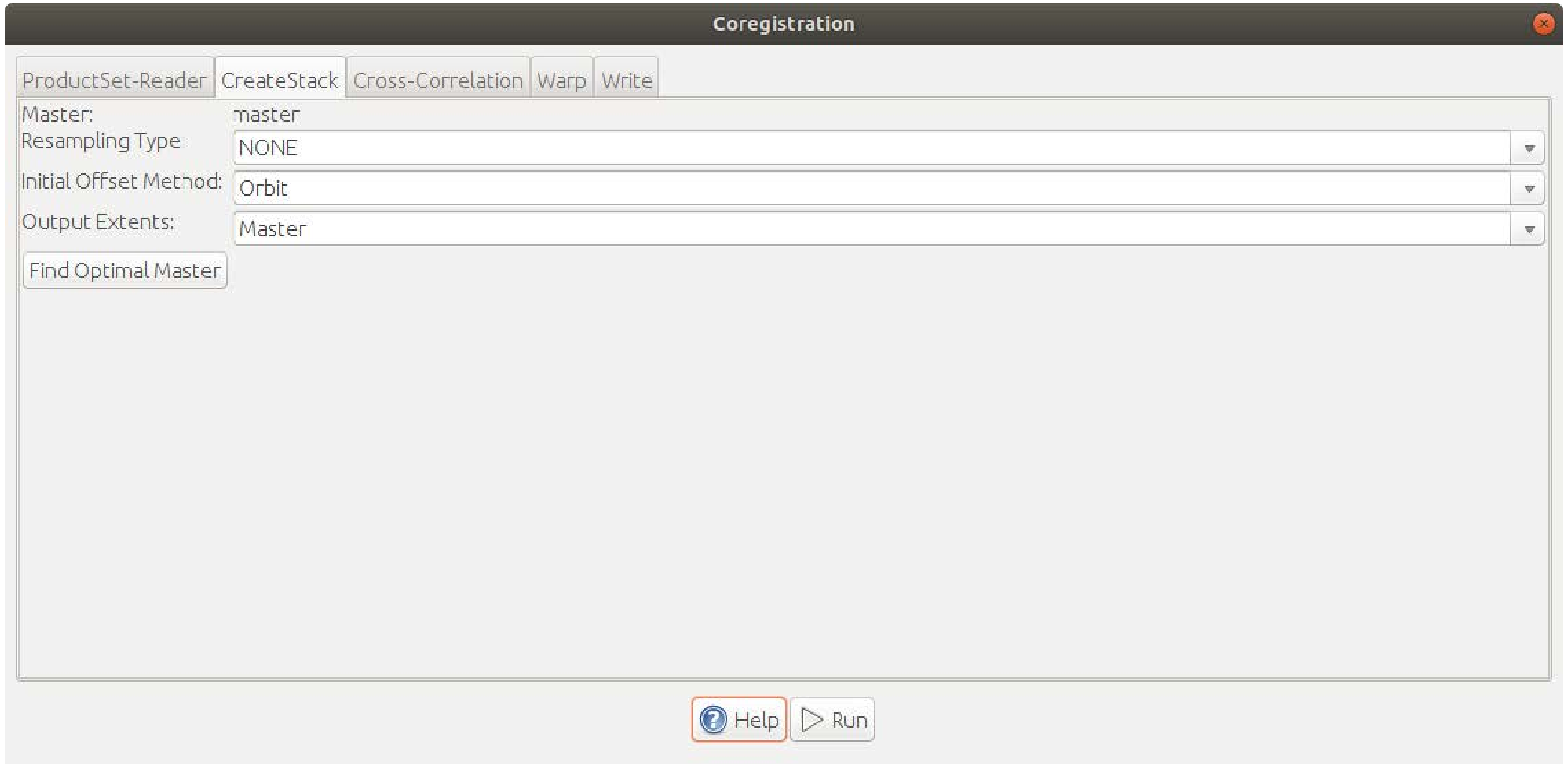
Step 2 - Coregistration

- *Radar > Coregistration > Coregistration*
- We select the images by clicking on Add Opened



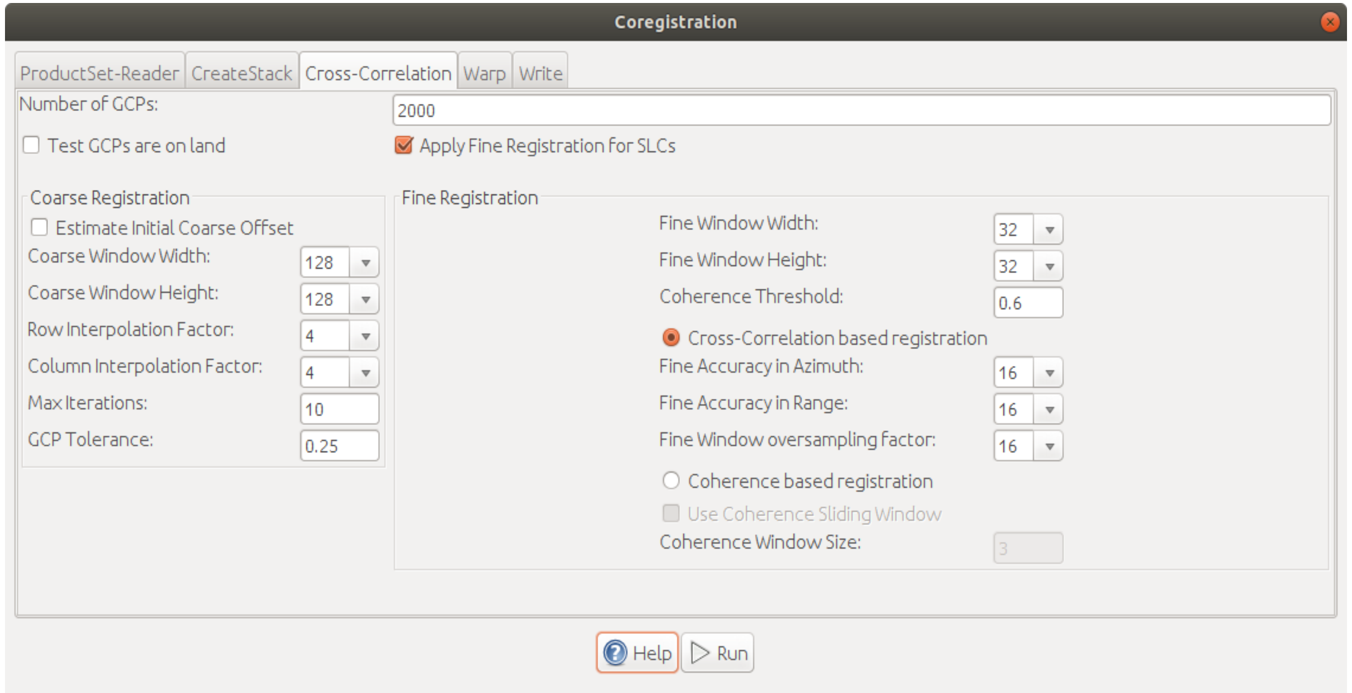
Step 2 – Coregistration and Re-sampling

CreateStack: Creates a coregistration between master and slave using orbital information. This orbital coregistration will later be used as a starting point for the coarse coregistration



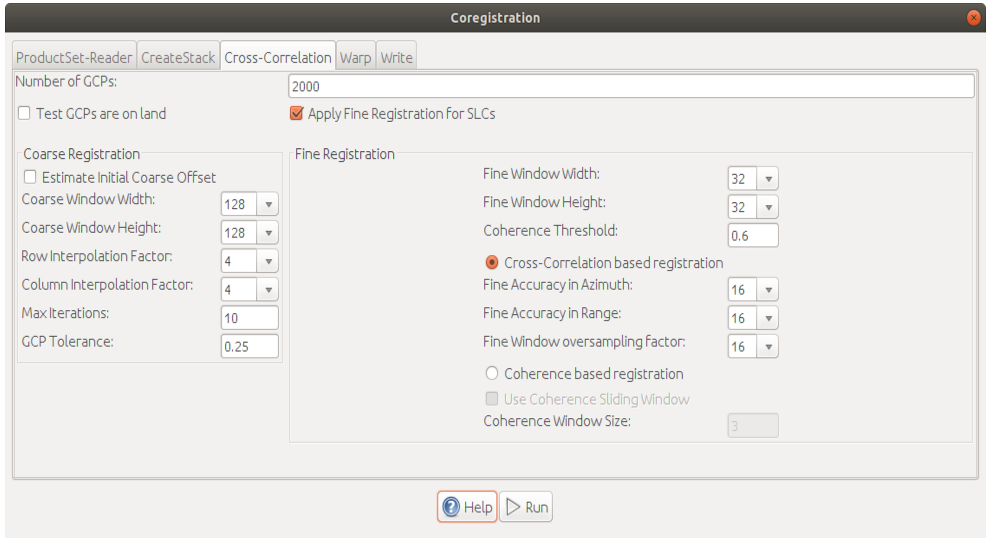
Step 2 – Coregistration and Re-sampling

- Cross-Correlation: used to set the parameters to perform both coarse and fine coregistration
- Calculates for a set of GCP (Ground Control Points) uniformly distributed in the master image as well as the corresponding GCP in the slave image



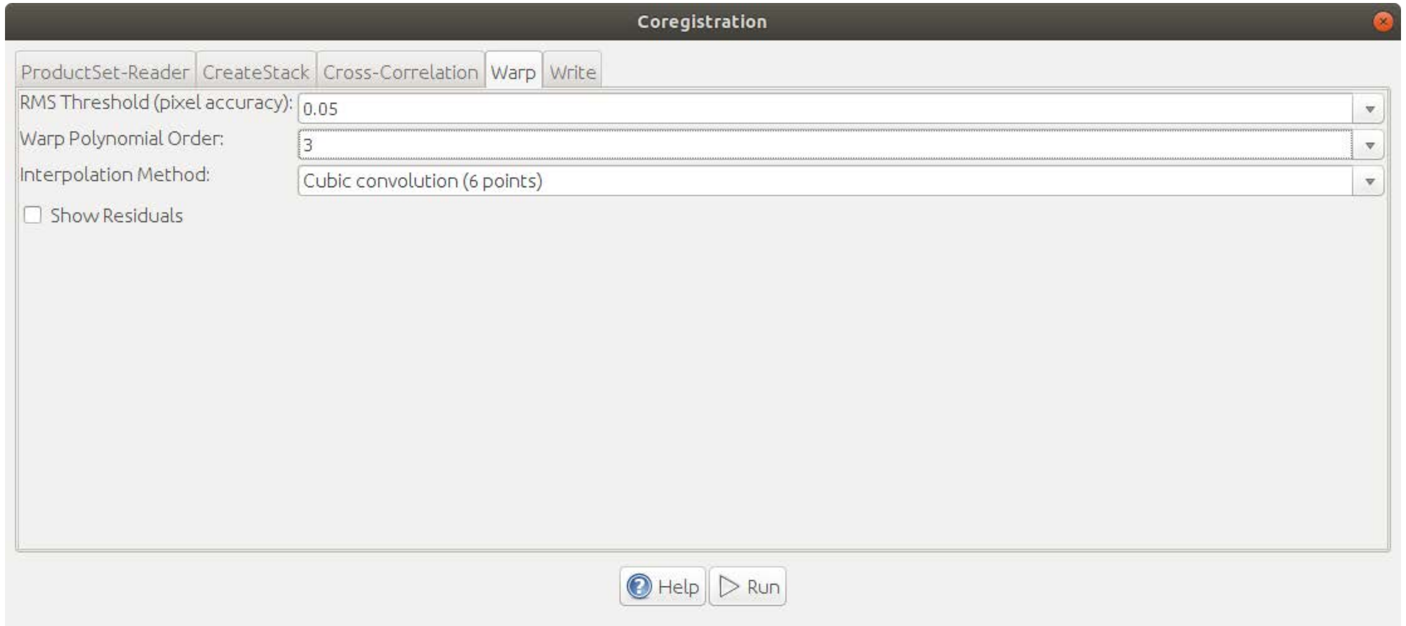
Step 2 – Coregistration and Re-sampling

- Coarse Registration: for each GCP in the master and slave images, this calculates the correlation in a window whose size you can define using the parameters Coarse Window Width/Height. The peak correlation shows us how far the slave GCP needs to travel in order to match the master GCP. Repeat this until you reach the maximum number of iterations or the shift is smaller than the specified tolerance
- Fine Registration:
  - Option 1: look for the greatest correlation between images by oversampling to gain sub-pixel precision
  - Option 2: Maximize the coherence between images by doing sub-pixel offsets in each of the GCPs



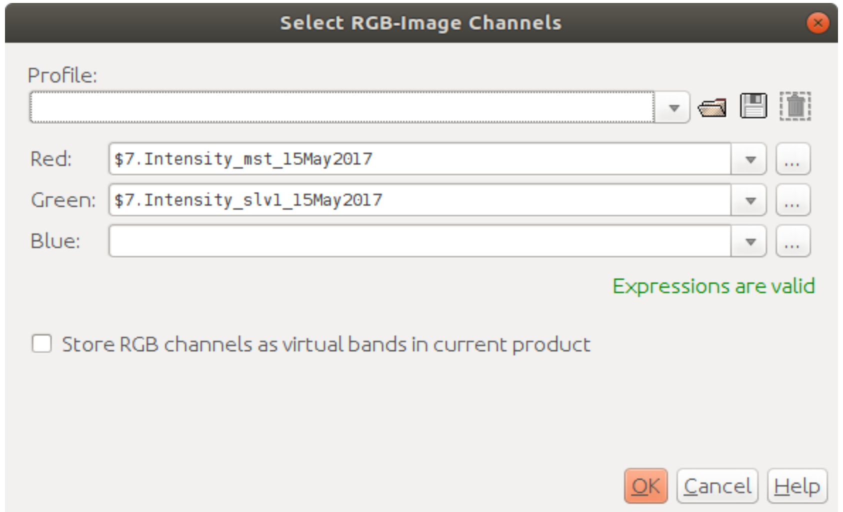
Step 2 – Coregistration and Re-sampling

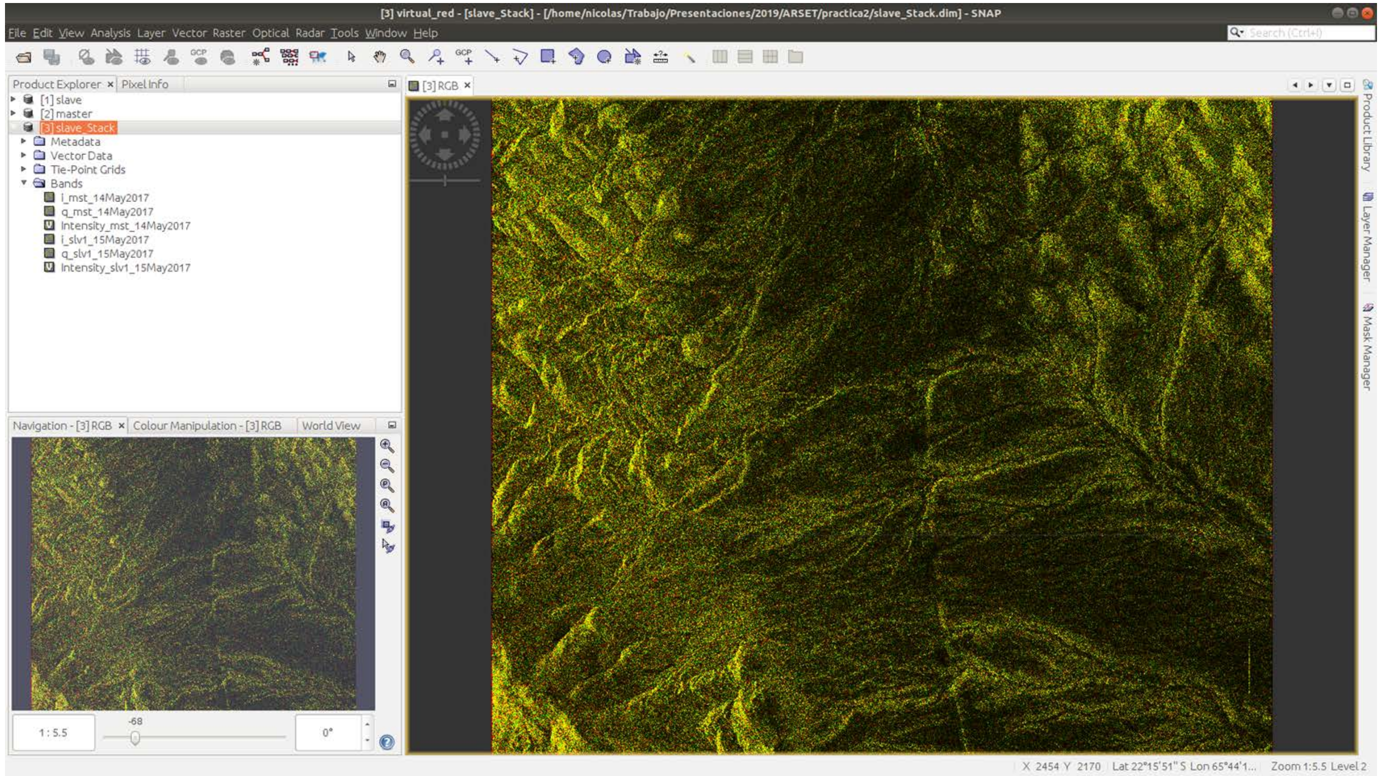
- Warp: Calculates the area of deformation to coregister the slave with the master based on the map of displacements obtained with the coarse and fine coregistration from the previous step
- The Wrap Polynomial Order depends on the shape of the deformation map. Usually it works well with an order of 2
- In this step we also choose the method of interpolation to re-sample the slave image to the master



Step 2.2 – Viewing the Coregistration

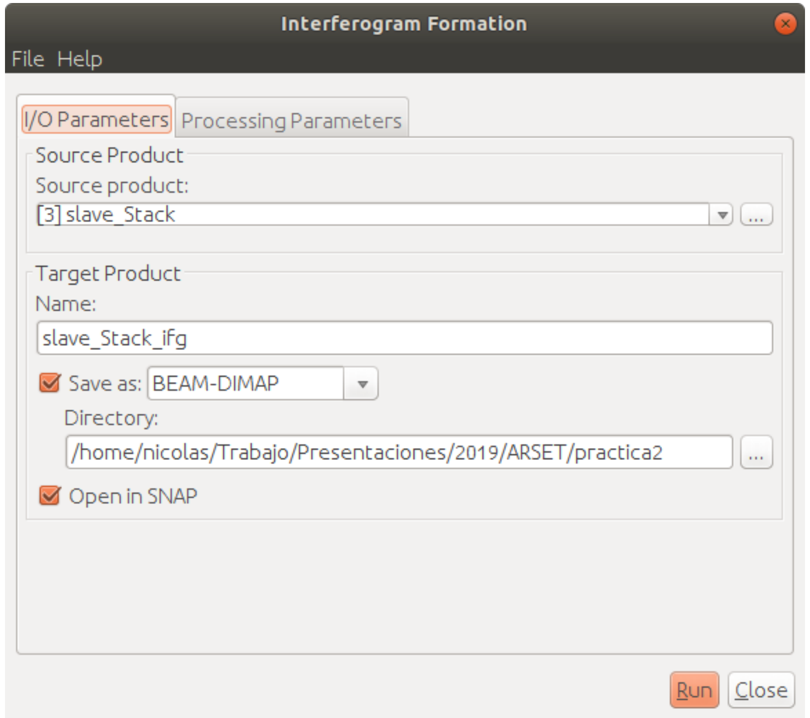
- If the operation was successful, a third file should appear in the Product Explorer. Right click on it and select Open RGB Image Window. Use the Master image for the red channel and the Slave image for the green channel
- It should be mostly yellow if the coregistration went well

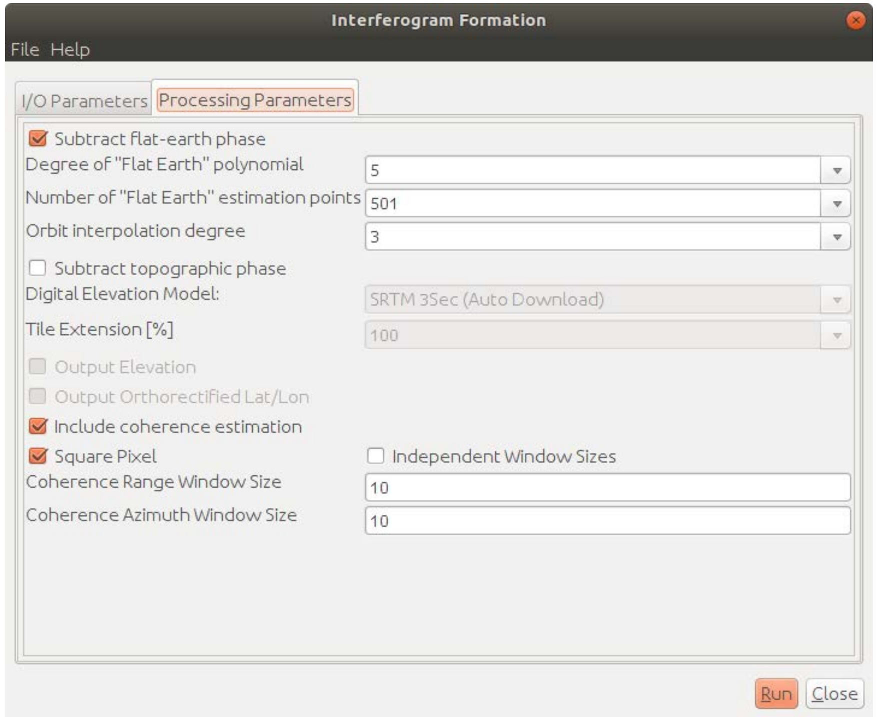




Step 3 – Interferogram Calculation

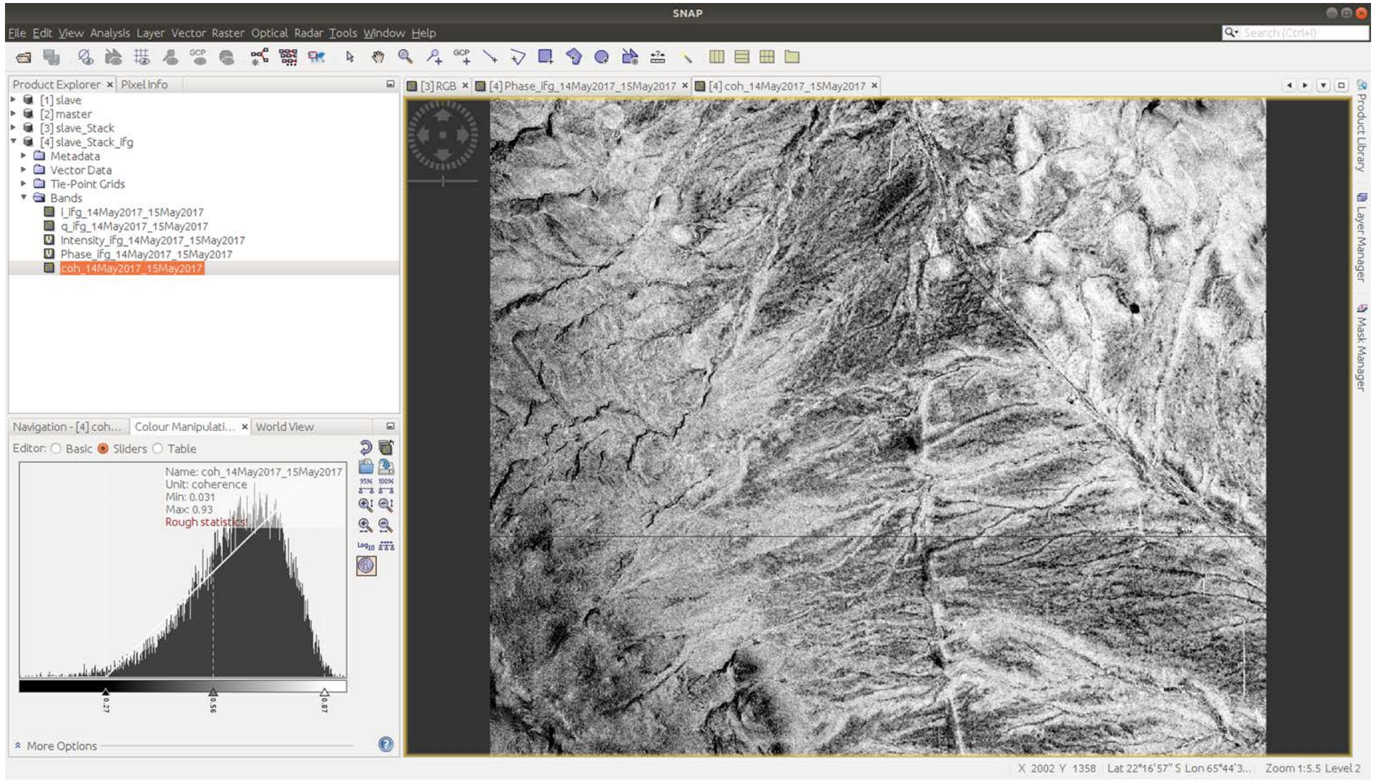
- *Radar > Interferometric > Products > Interferogram Formation*
- In this step we calculate the interferogram by subtracting the pixel-to-pixel phase between the coregistered images, the reference phase (flat earth) is removed and the coherence map is calculated



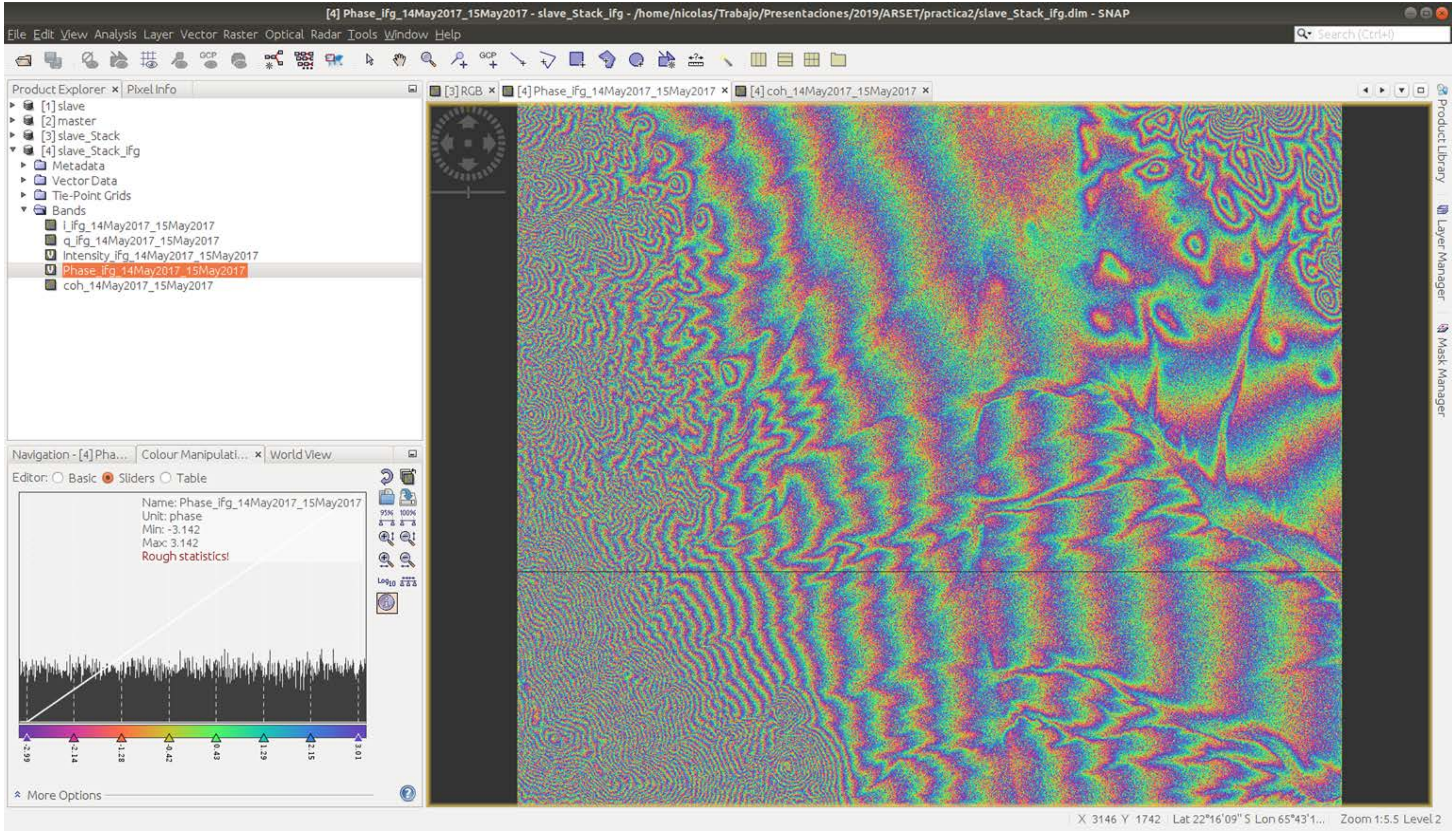


Step 3 – Viewing the Coherence Map

- The resulting coherence image…can be interpreted as a quality index for the interferogram. The lighter areas are the ones where the target changed the least and therefore the interferometric data would be more reliable



Step 3 – Viewing the Interferogram



Step 4 – Multi-looking Filter

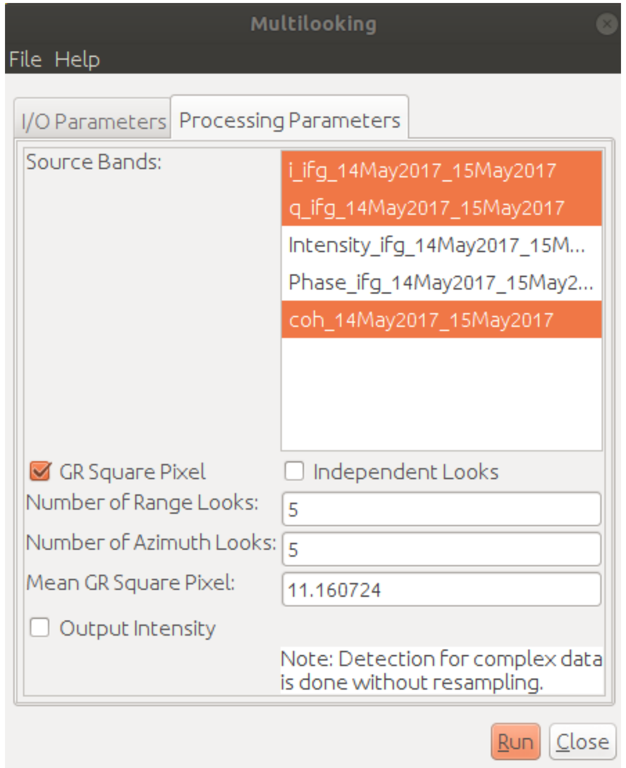
- We apply a 5x5 (~11m pixel) multilook filter to reduce noise
  Radar > SAR Utilities > Multilooking > Goldstein Phase Filtering

IMPORTANT

In the Processing Parameters tab

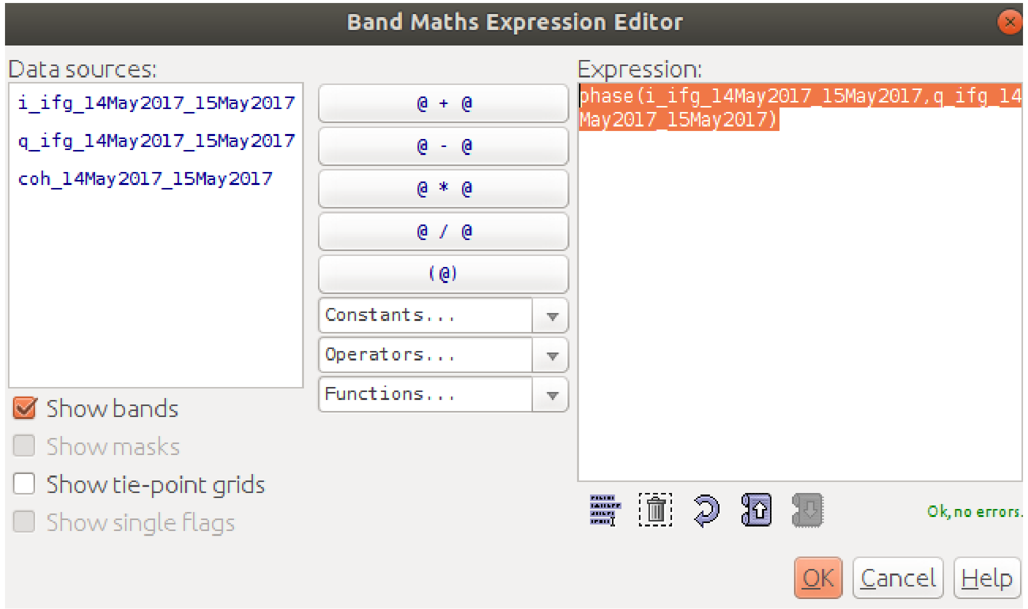
Select

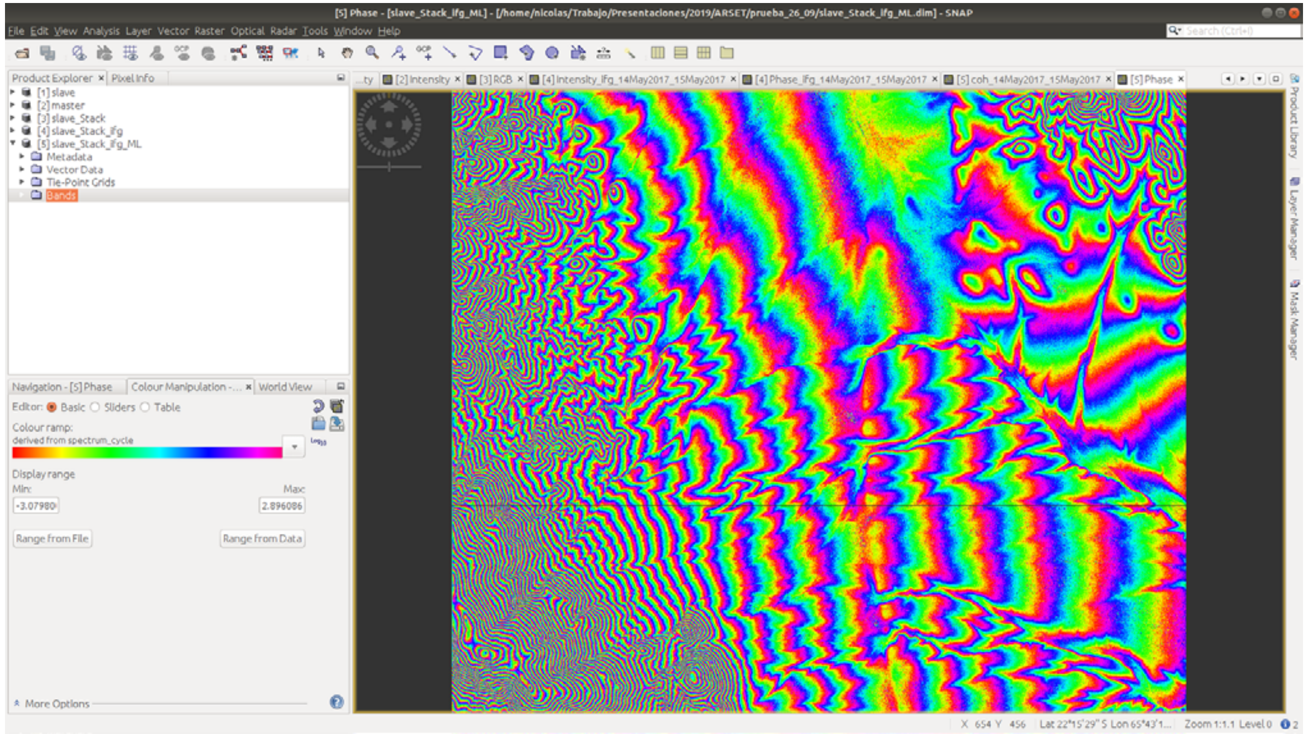
- *I Band*
- *Q Band*
- *Coherence*



Step 4 – Multilook Filter

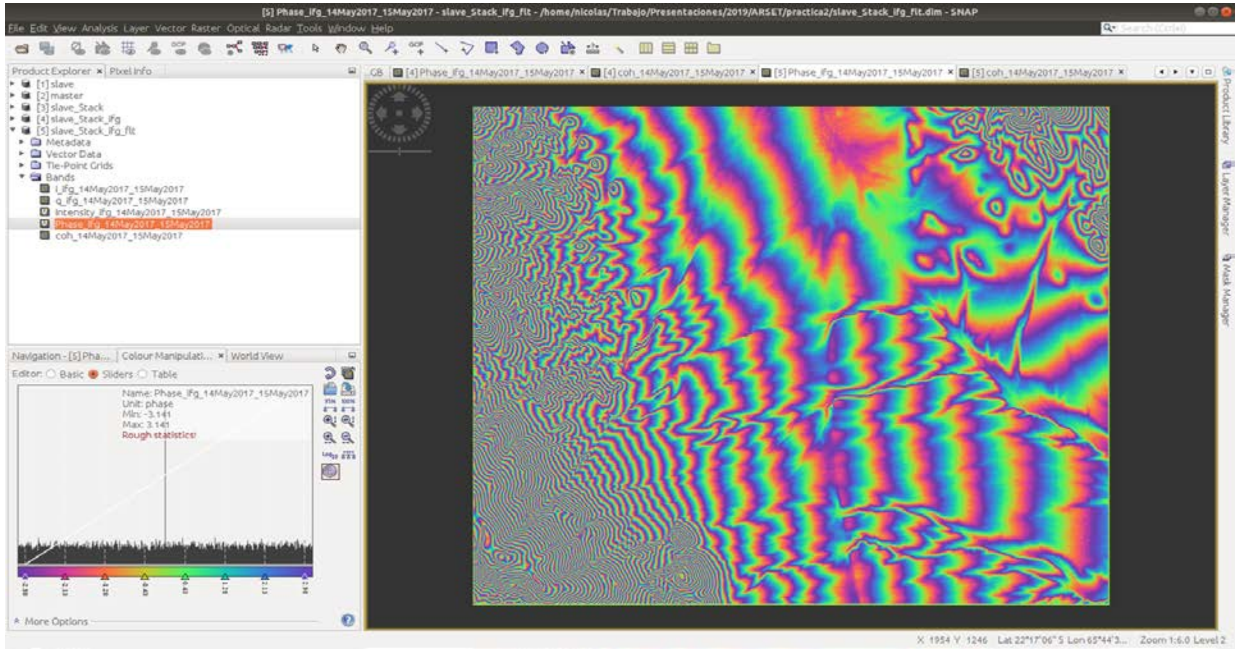
- To visualize the multi-look interferogram we right click on slave_Stack_ifg_ML and then on Band Math > Edit Expression





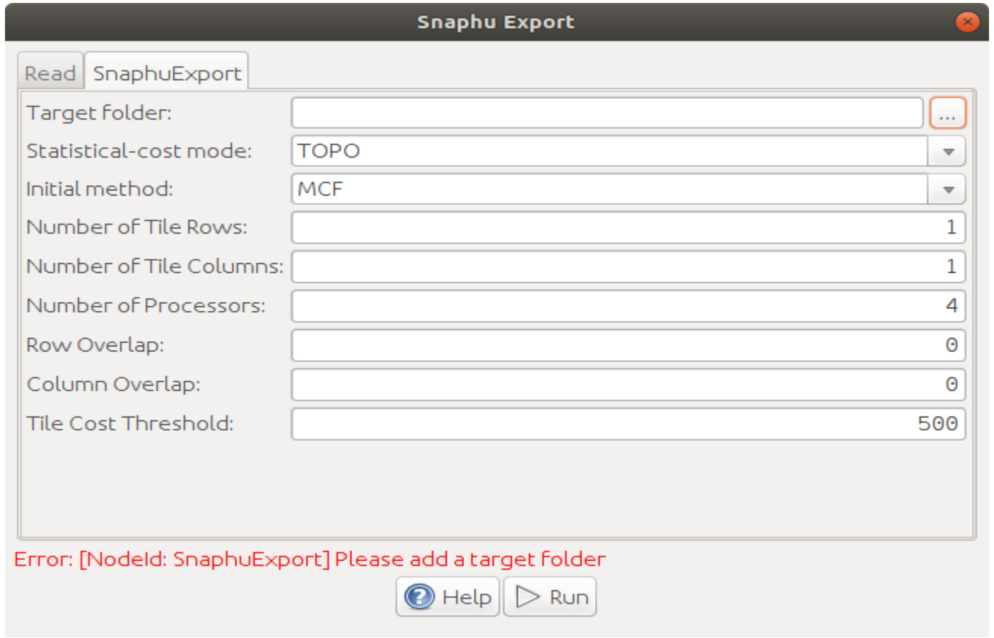
Step 4 – Goldstein Filter

- Our interferogram is almost ready now, but we can improve it by filtering out some of the noise. For this, we will use the Goldstein filter.
- The Goldstein filter is an adaptive filter that works in the space of frequencies, keeping the predominant frequencies of the interferometric phase and removing the noise
- To apply the filter, go to *Radar > Interferometric > Filtering > Goldstein Phase Filtering*

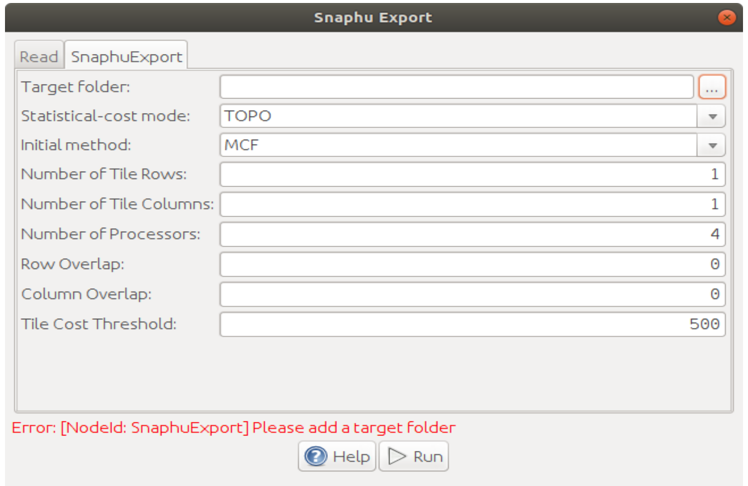


Step 5 – Phase Unwrapping

- We almost have the DEM, the next step is to unwrap the phase to remove the 2pi ambiguity
- For this we use the open-source software Snaphu: https://step.esa.int/main/third-party-plugins-2/snaphu/
- Note: this software works on Linux, so we recommend Windows users have a Virtual Machine with Ubuntu 18.04 to be able to install Snaphu
- To export the interferogram from SNAP to Snaphu, proceed as follows:
- *Radar > Interferometric > Unwrapping > Snaphu Export*



Step 5 – Phase Unwrapping



- The previous step created the configuration file to run *Snaphu* and find the unwrapped phase
- Open the Ubuntu VM with Snaphu installed and go the directory where you specified your exported files be saved
- Then open the file **snaphu.conf** and in the comments in the first lines you'll find the command that we need to run in order to unwrap.
- In my case , it's

```
snaphu -f snaphu.conf Phase_ifg_14May2017_15May2017.snaphu.img 5783
```

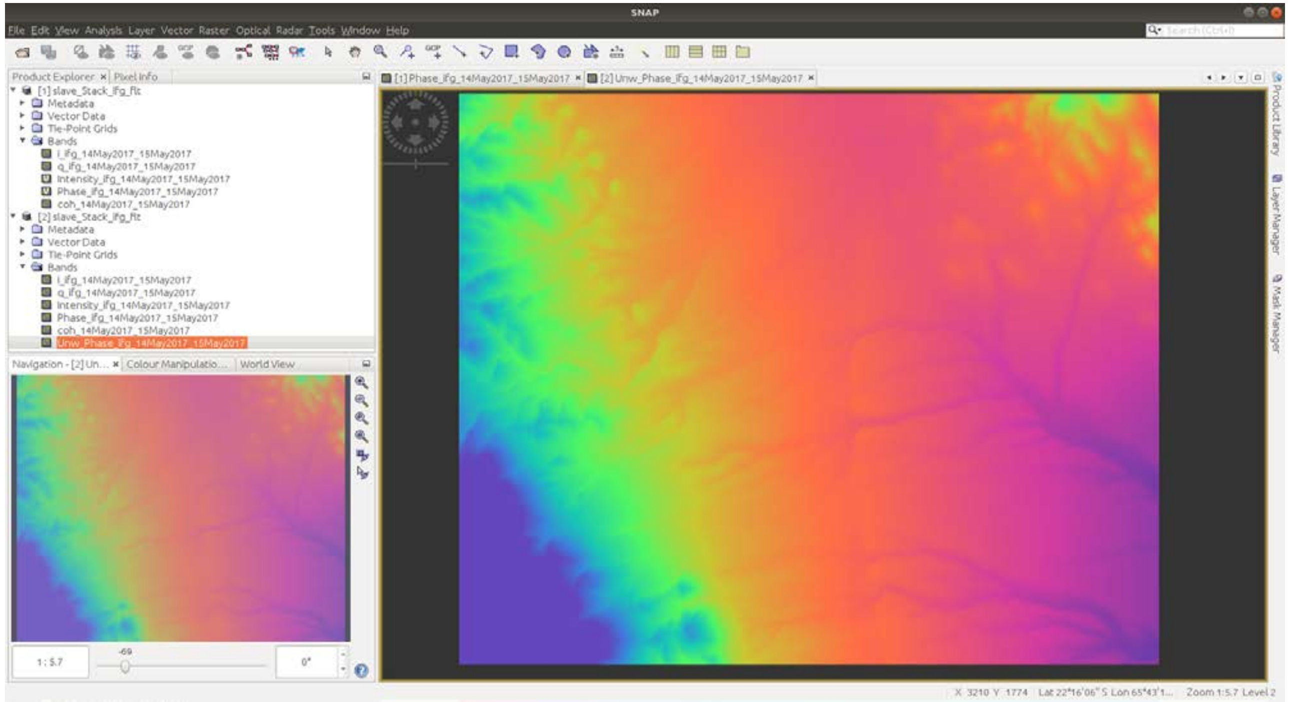
- Open the terminal and run the command
- Note: It's recommended that you close SNAP before running this command because it consumes a lot of RAM

Step 5 – Phase Unwrapping

- Once Snaphu finishes unwrapping we need to import the result into SNAP in order to continue with the processing workflow

  Radar > Interferometric > Unwrapping > Snaphu Import

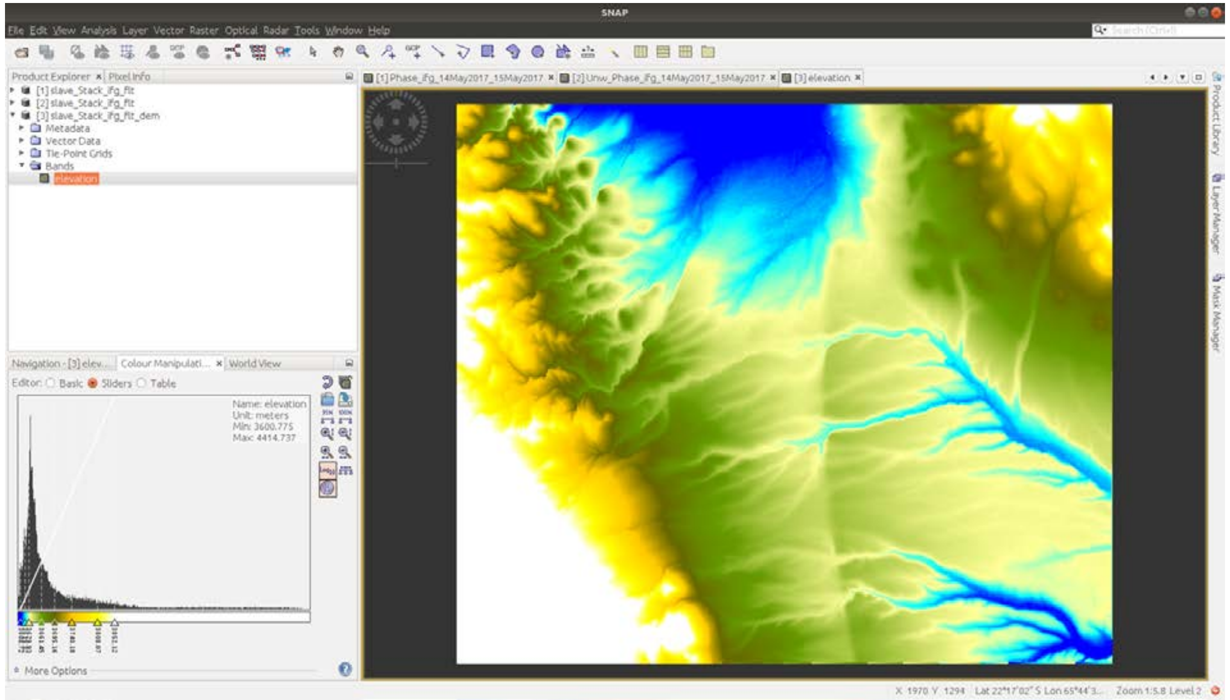
- And find the file generated with the UnwPhase*.hdr extension



Step 6 – Phase-to-Height Conversion

- The next step involves converting the interferometric phase to height. Remembering the equation that links phase and height in case there is no deformation, atmospheric, or orbital errors:

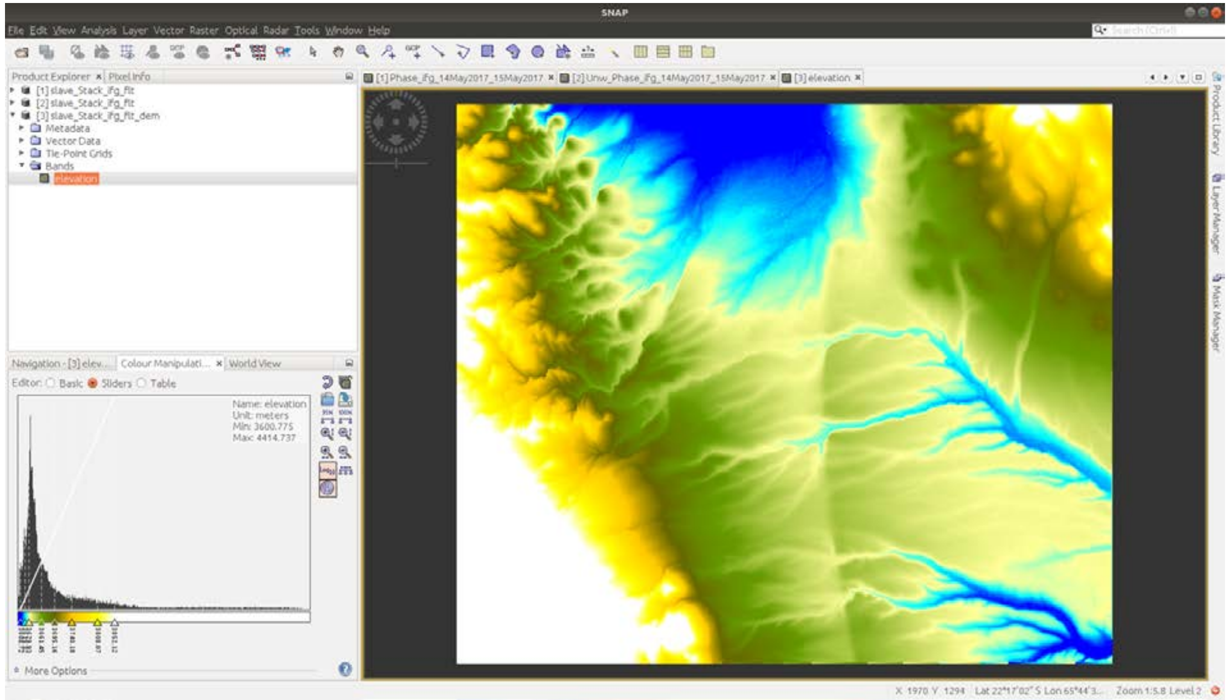
$$\phi = -\frac{4\pi B_{\perp}}{\lambda R_1 \sin\theta} z$$



Step 6 – Phase-to-Height Conversion

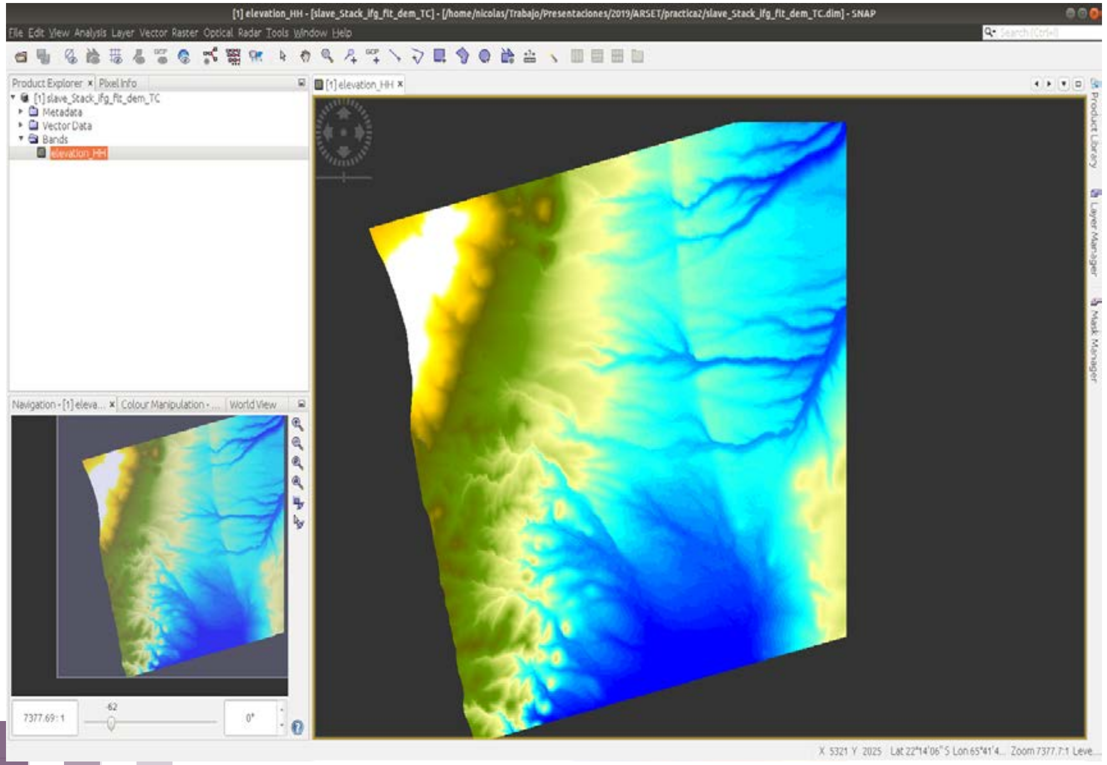
$$\phi = -\frac{4\pi B_{\perp}}{\lambda R_1 \sin\theta} z$$

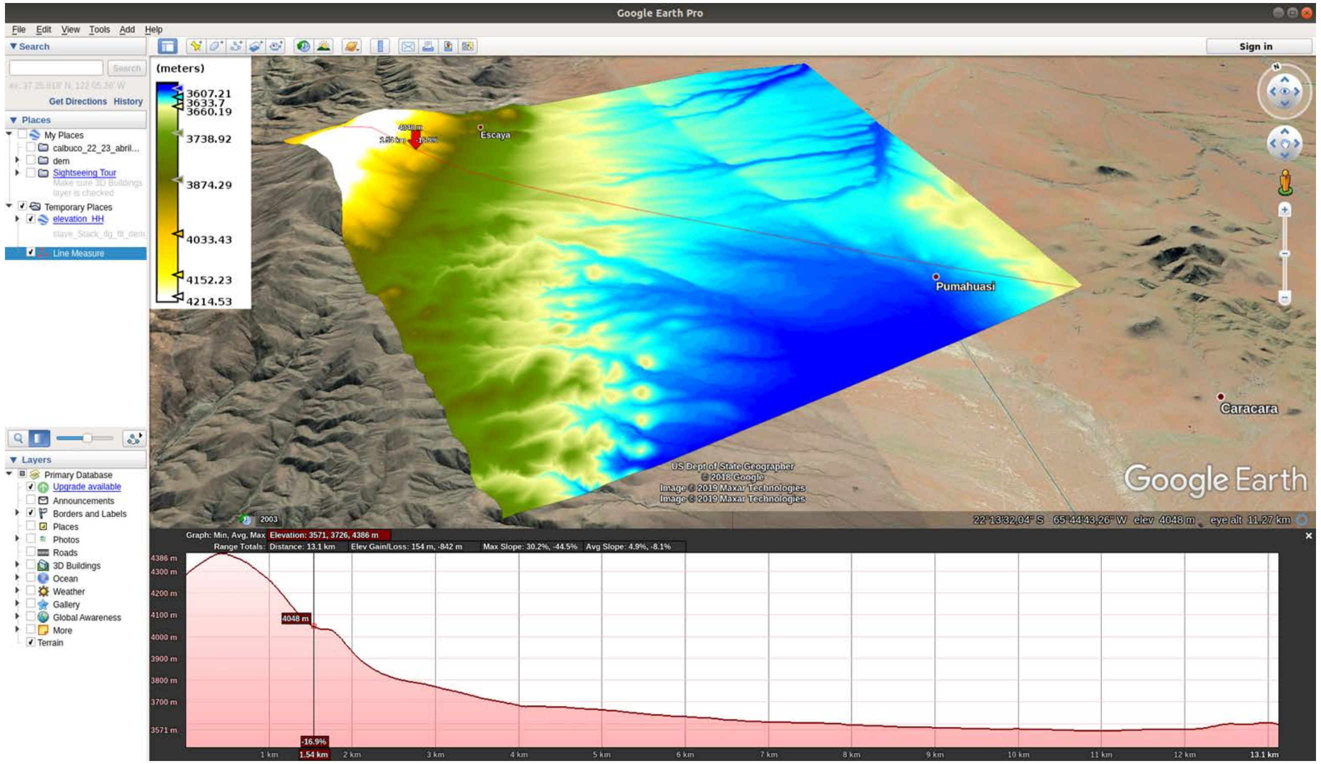
- The equation that links phase to height doesn't tell us about an absolute height but rather about the relative heights between pixels in the image. It's like the DEM is "floating". As a result, we need to use an outside source (in our case the SRTM 3 arc-sec DEM SRTM) to cut through these heights and refer to an absolute height
- *Radar > Interferometric > Products > Phase to Elevation*



Step 7 – Geoprojection

- One last step we can undertake is geocoding the image to send the radar coordinates to a mapping system
- *Radar > Geometric > Terrain Correction > Range-Doppler Terrain Correction*





Keep in Mind

Interferometric phase can be expressed as: $\phi = k_z z + k_v v + \phi_{orb} + \alpha + \eta$

- Phase due to orbital errors:
  - Perpendicular baseline errors ⇒ Ramp in the direction of the range
  - Parallel baseline variation errors (non-parallel orbits) ⇒ Ramp in the direction of the azimuth
- Phase due to atmospheric factors:
  - Spatially small
  - Greatly vary in time

Keep in Mind

- In this exercise we've assumed that the measured interferometric phase is a result of the topography + noise (which we reduced by filtering), considering the rest of the terms null. The pair we used was a tandem pair (a one-day difference between acquisitions)
- We assumed that:
  - ❑ There was no event that might have caused displacement between acquisitions
  - ❑ There were no appreciable orbital errors (no odd ramps were seen in the range or azimuth)
  - ❑ There were no atmospheric factors (the climate in that region is very dry and there is a difference of one day)
- If we wanted to make a more rigorous DEM we would need to control for these effects.
- This is usually done by analyzing a **stack of images**, with advanced techniques such as SBAS/PSI

Thank you very much!!

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