Basics of Synthetic Aperture Radar Remote Sensing

Interferometric Synthetic Aperture Radar (InSAR) Training Course

Economic Cooperation Organization (ECO)

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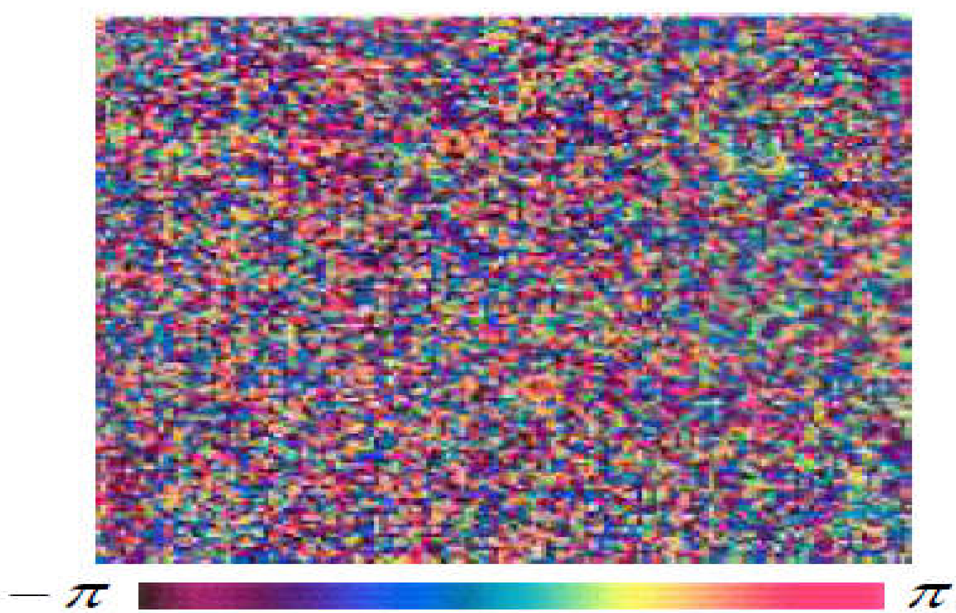
20-22 June, 2022

Tehran, Islamic Republic of Iran

Introduction

- Since the SAR resolution cell contains a large number of scatterers, the phase of pixels seems randomly distributed.



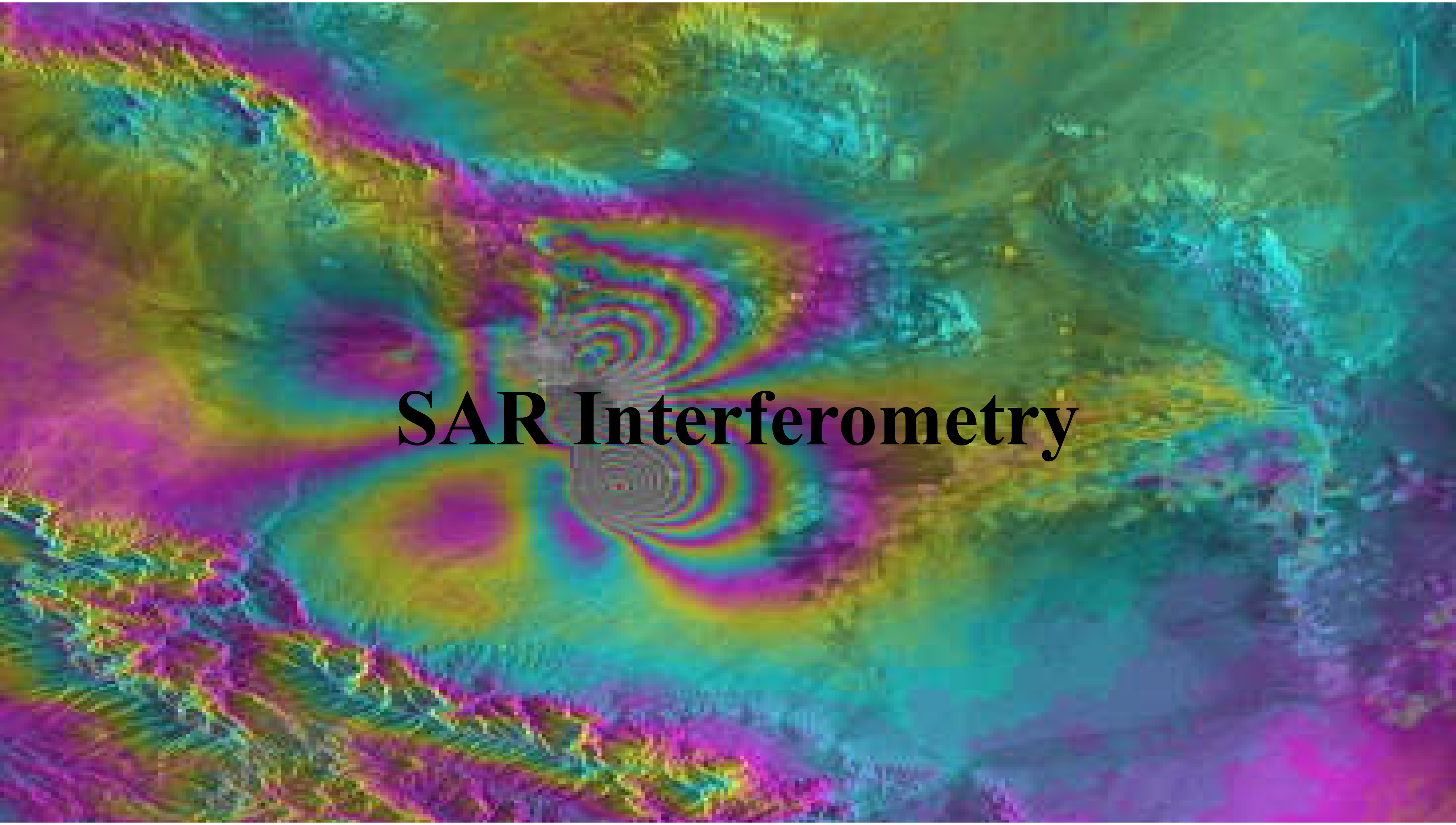
$$Ae^{i\phi} = \sum_{k=1}^{N} A_k e^{i\phi_k}$$

Introduction

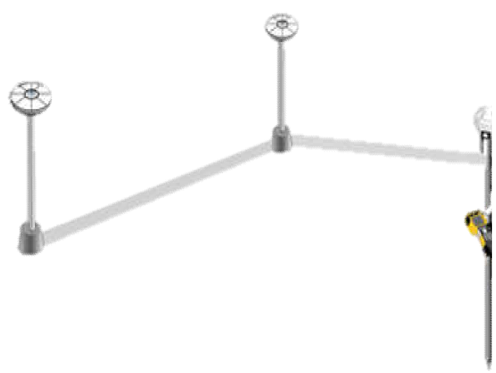
- If the scene is observed in 2 images, in which the scatterers remain unchanged in the resolution cell, the phase difference between pixels of the 2 images can be exploited.

  - SAR Polarimetry
  - SAR Interferometry

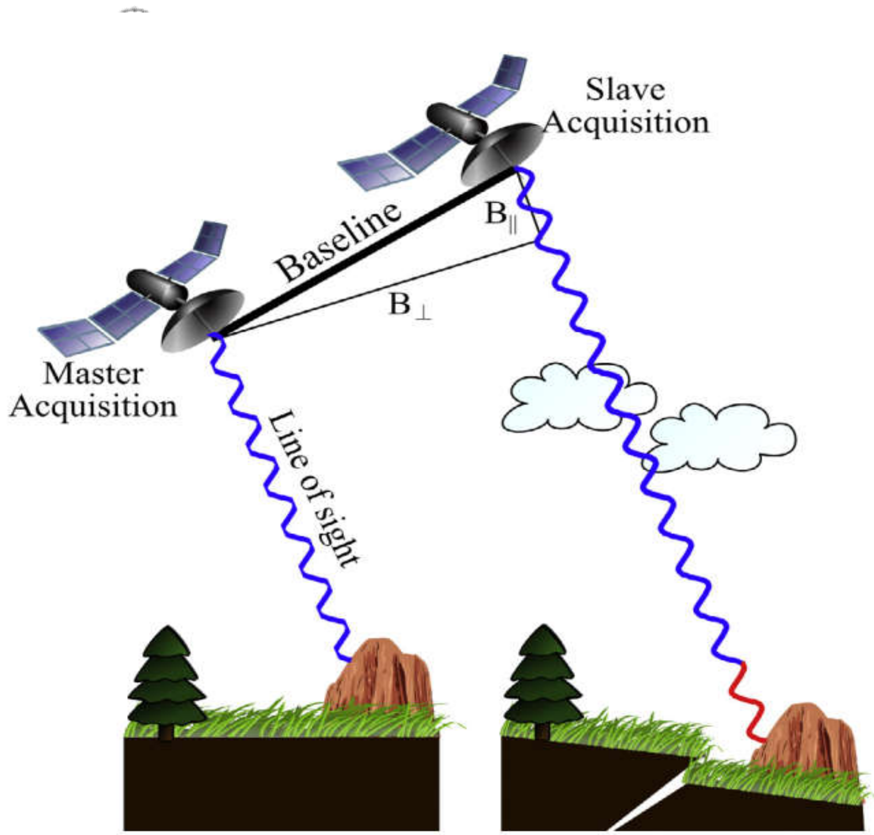
SAR Interferometry

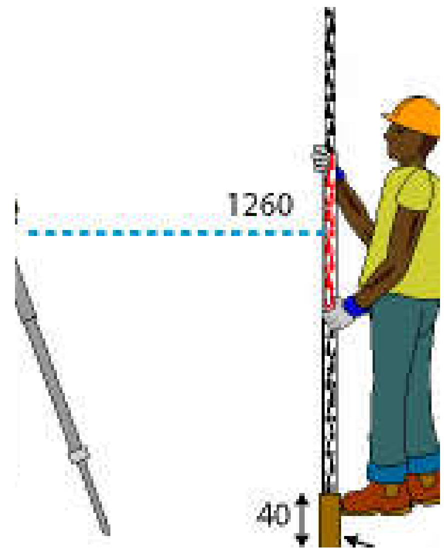


SAR interferometry (InSAR)



GPS





Levelling

SAR interferometry (InSAR)

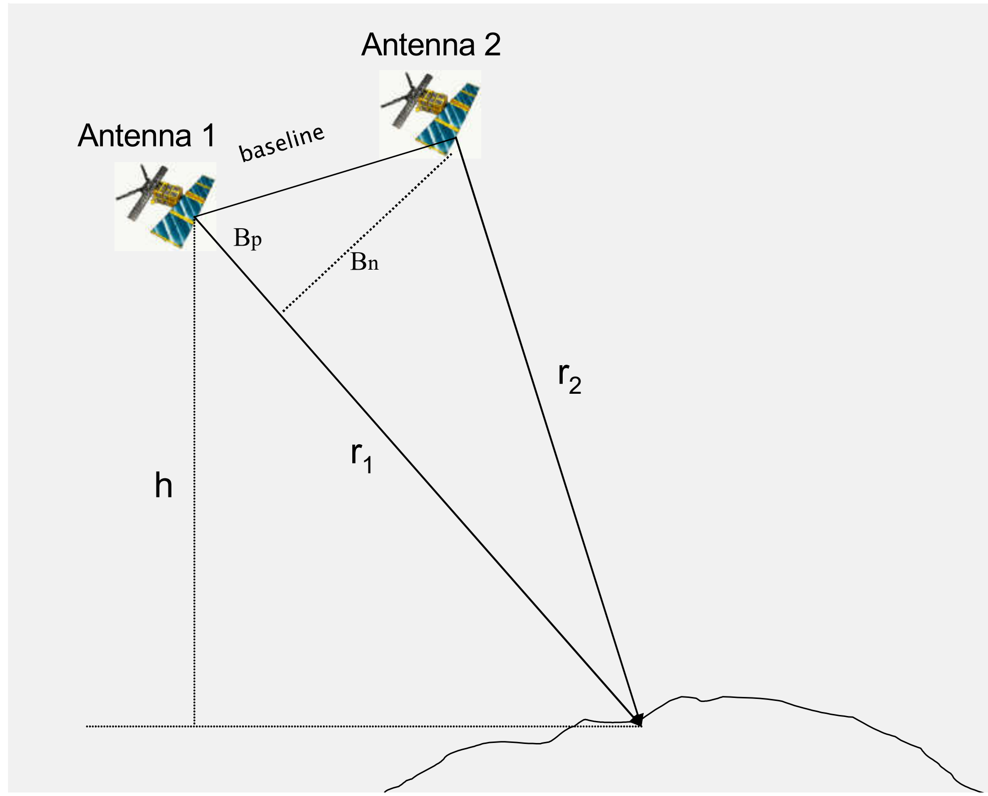
S_1 and S_2 are the received signals at two satellite positions:

$$S_1 = A_1 e^{-j\varphi_1} = A_1 e^{-j\frac{4\pi}{\lambda} r_1}$$

$$S_2 = A_2 e^{-j\varphi_2} = A_2 e^{-j\frac{4\pi}{\lambda} r_2}$$

The interferogram is the map of the pixel-to-pixel phase differences between S1 and S2:

$$S_1 S_2^{*} = A_1 A_2 e^{-j\frac{4\pi}{\lambda}(r_1 - r_2)}$$



SAR interferometry (InSAR)

Interferogram: the image of the pixel to pixel phase differences.

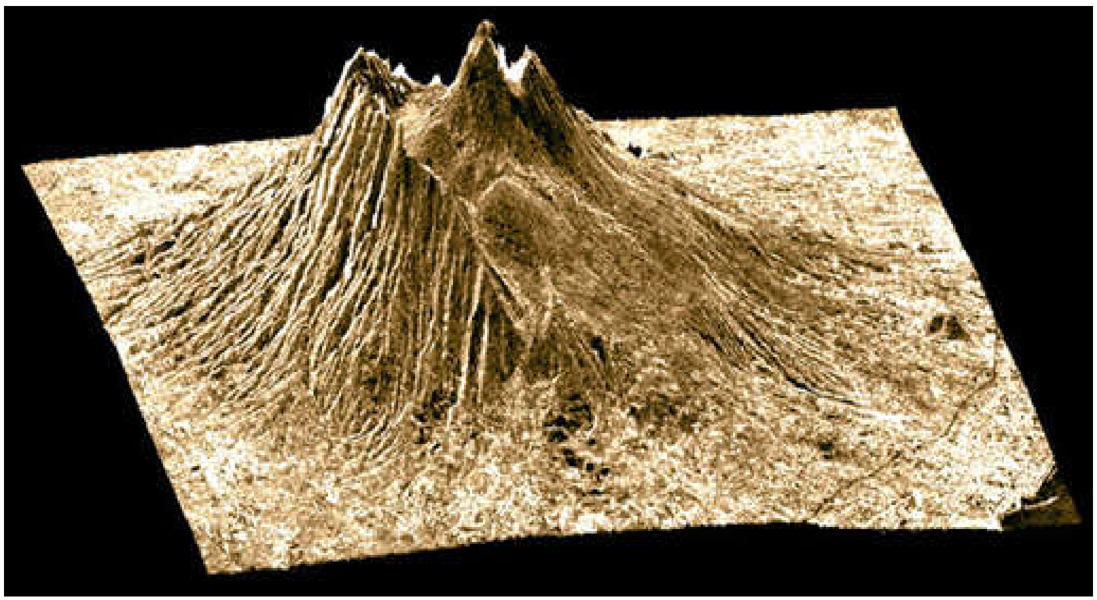
An interferogram is a complex image with (a) magnitude given by the product of the SAR amplitudes and (b) phase (the InSAR phase) given by the path length difference, as well as variations of the scattering properties and the medium conditions.

Images must differ in at least one aspect (= "baseline")

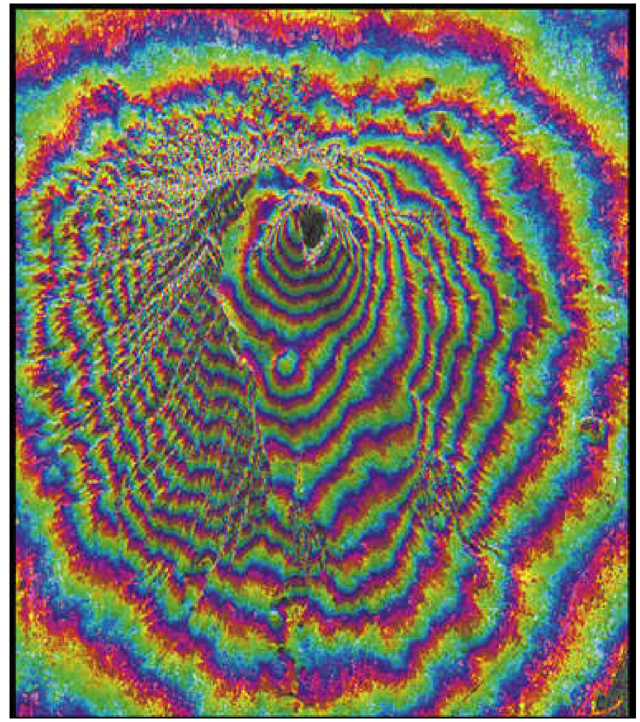
- Temporal baseline
- Spatial baseline

SAR interferometry (InSAR)

DEM

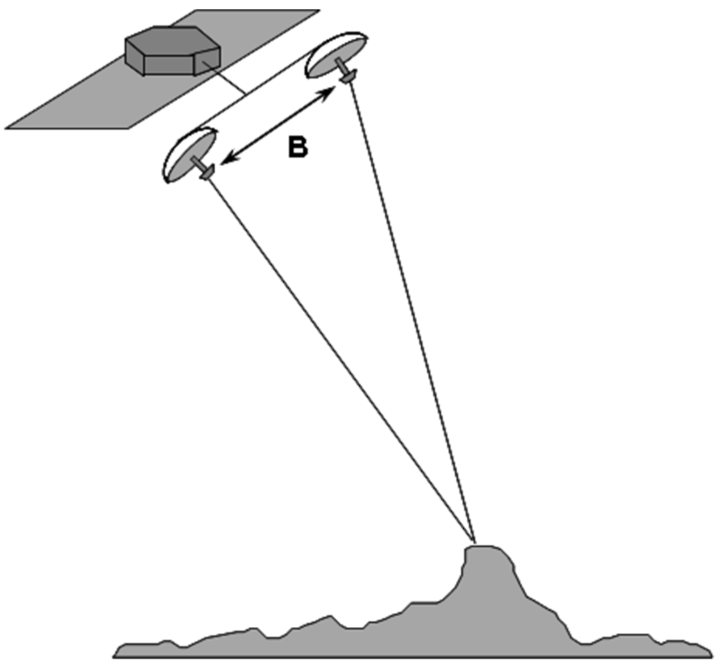


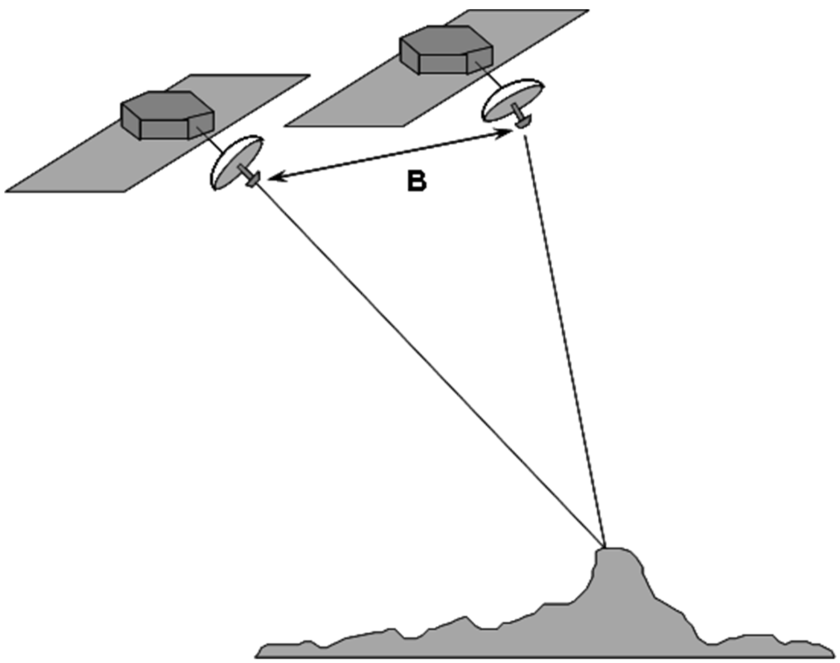
Interferogram



ERS-1, Vesuvius, Italy

SAR interferometry (InSAR)





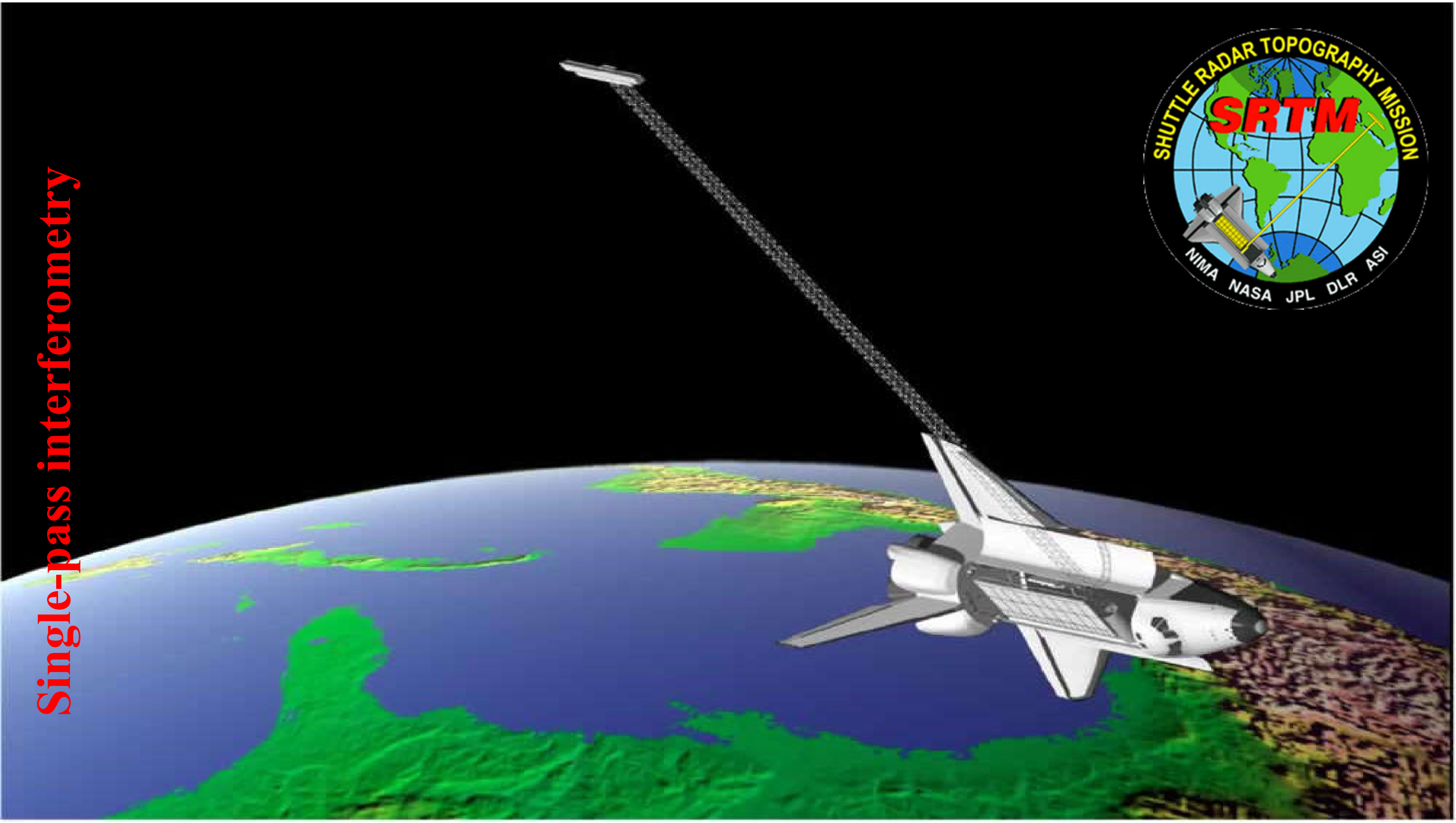
Single pass or simultaneous baseline:

Two radars acquire data from different vantage points at the same time.

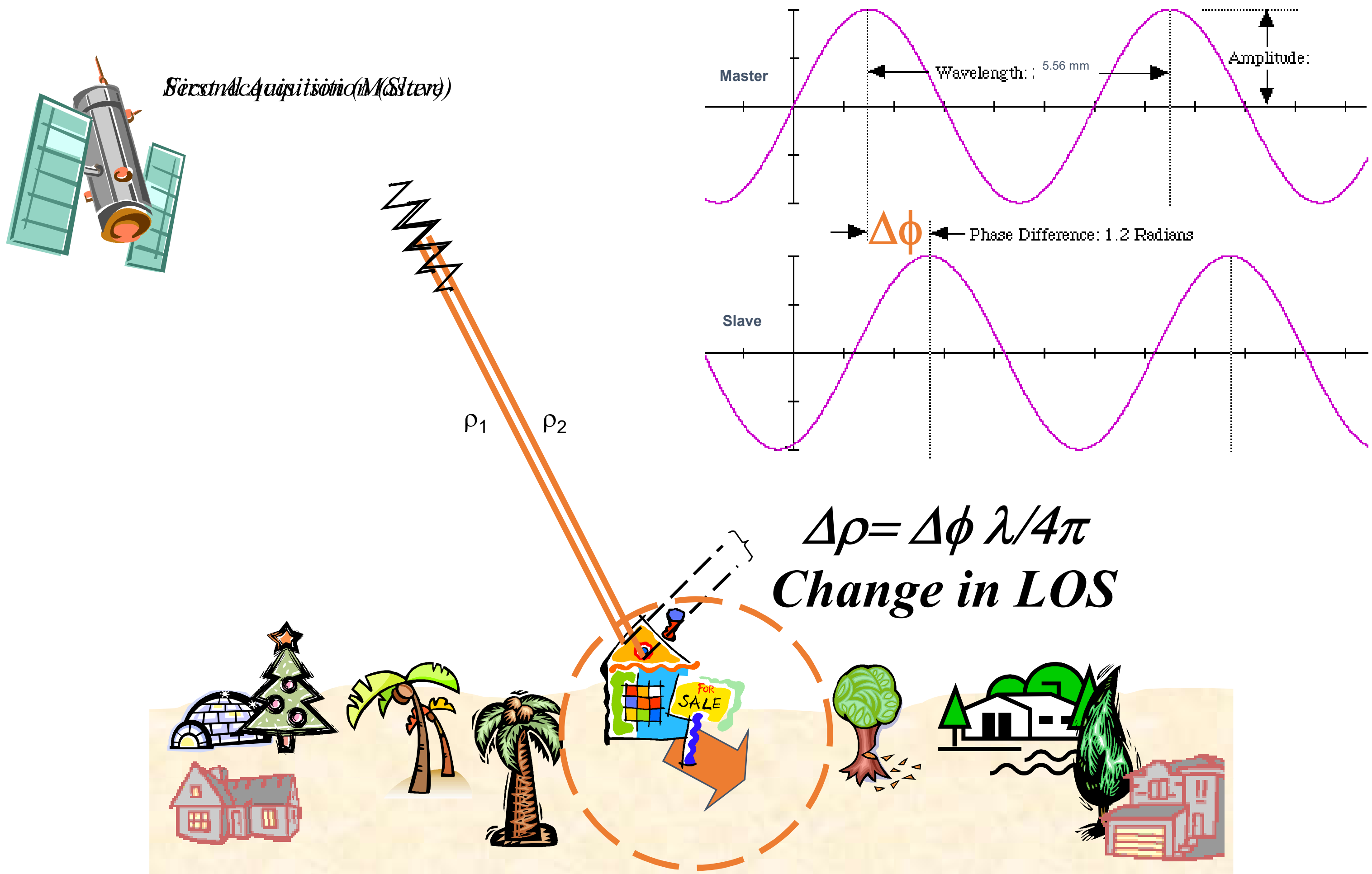
Repeat pass or repeat track:

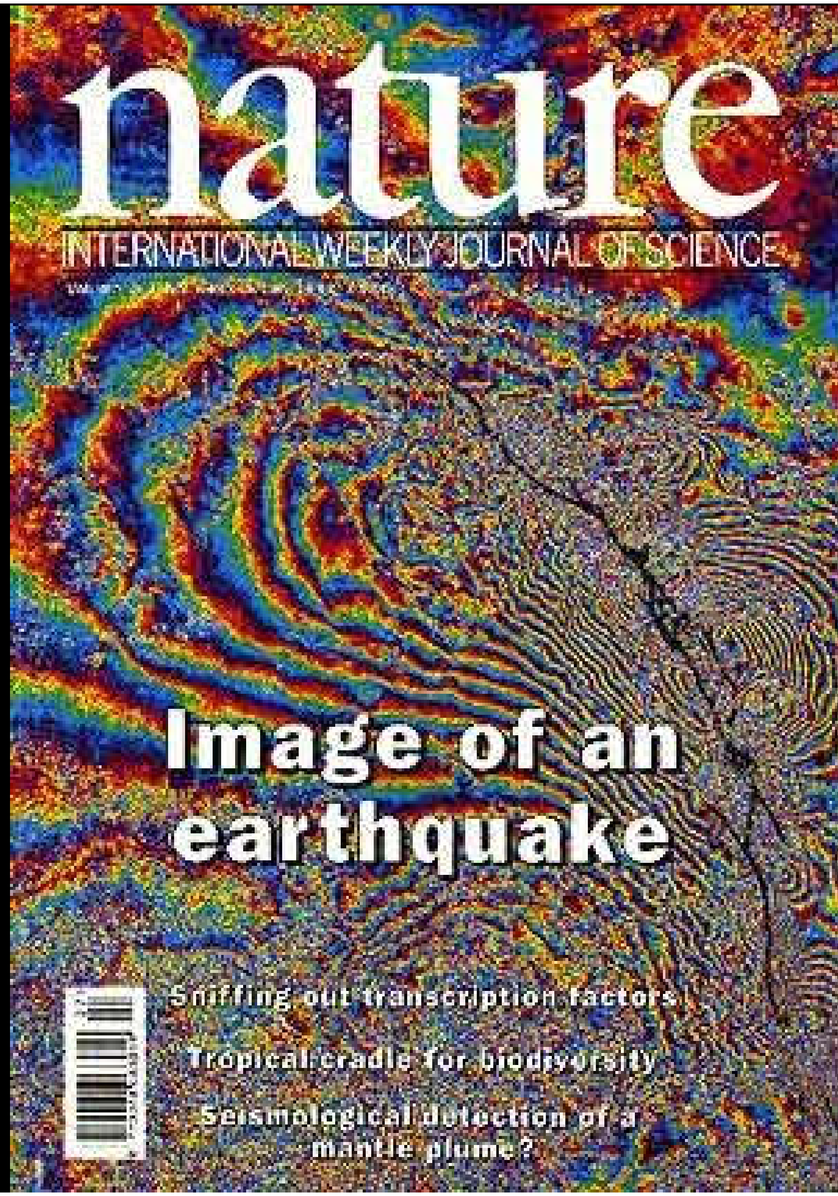
Two radars acquire data from different vantage points at different times.

Single-pass interferometry



Repeat pass interferometry




nature
INTERNATIONAL WEEKLY JOURNAL OF SCIENCE
Image of an earthquake
Sniffing out transcription factors
Tropical cradle for biodiversity
Seismological detection of a mantle plume?

SAR interferometry (InSAR)

If:

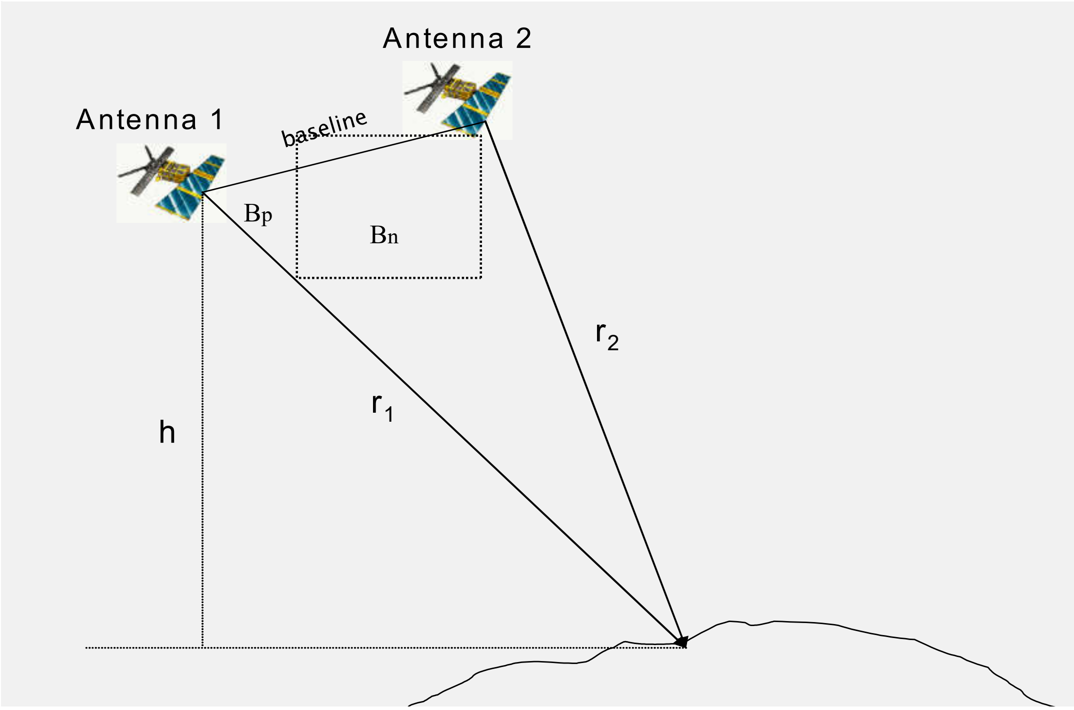
Earth was flat.
The satellite orbit was fixed.
No atmosphere.

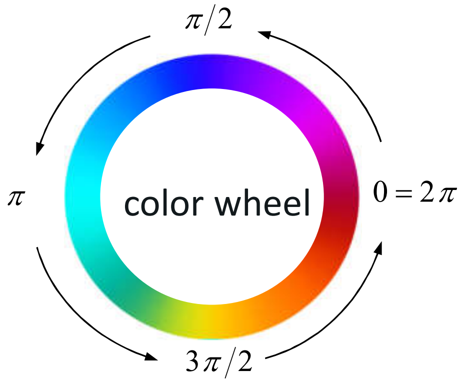
Then:

Things were simple, and the calculation of ground deformation would have been indeed an easy task.

SAR interferometry (InSAR)

The interferometric phase contains some distinct contributions:



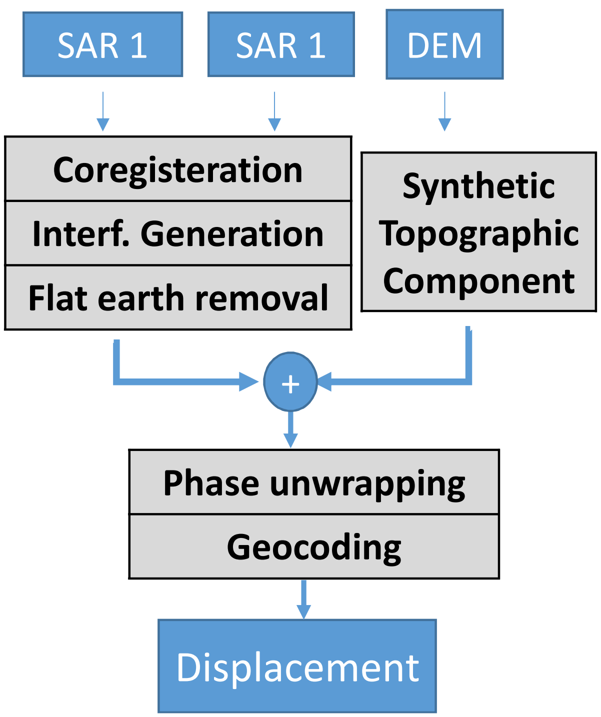


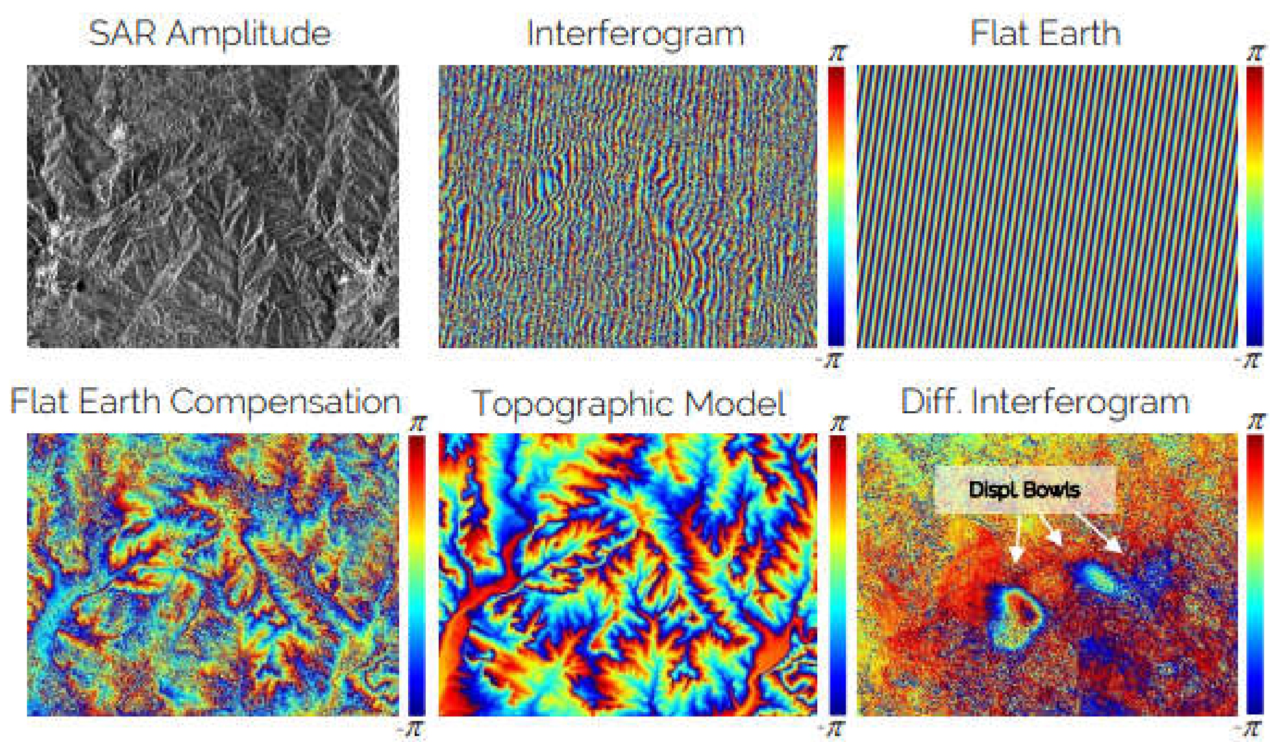
$$\varphi_{\text{int}} = \varphi_f + \varphi_{topo} + \varphi_{displ} + \varphi_{atm} + \varphi_{err}$$

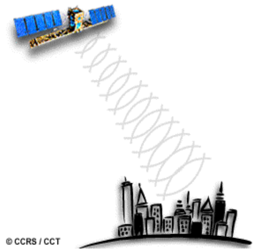
SAR interferometry (InSAR)

Displacement estimation

$$\varphi_{\text{int}} = \cancel{\varphi_f} + \cancel{\varphi_{topo}} + \varphi_{displ} + \cancel{\varphi_{atm}} + \cancel{\varphi_{err}}$$



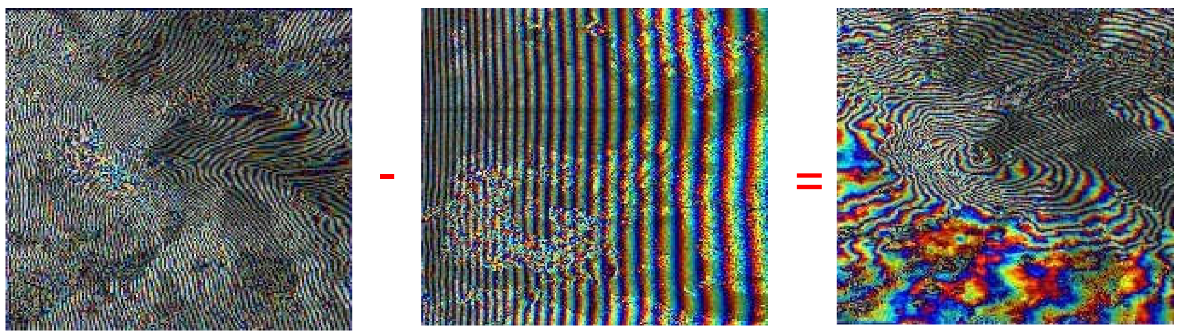




InSAR processing: Flat-earth removal

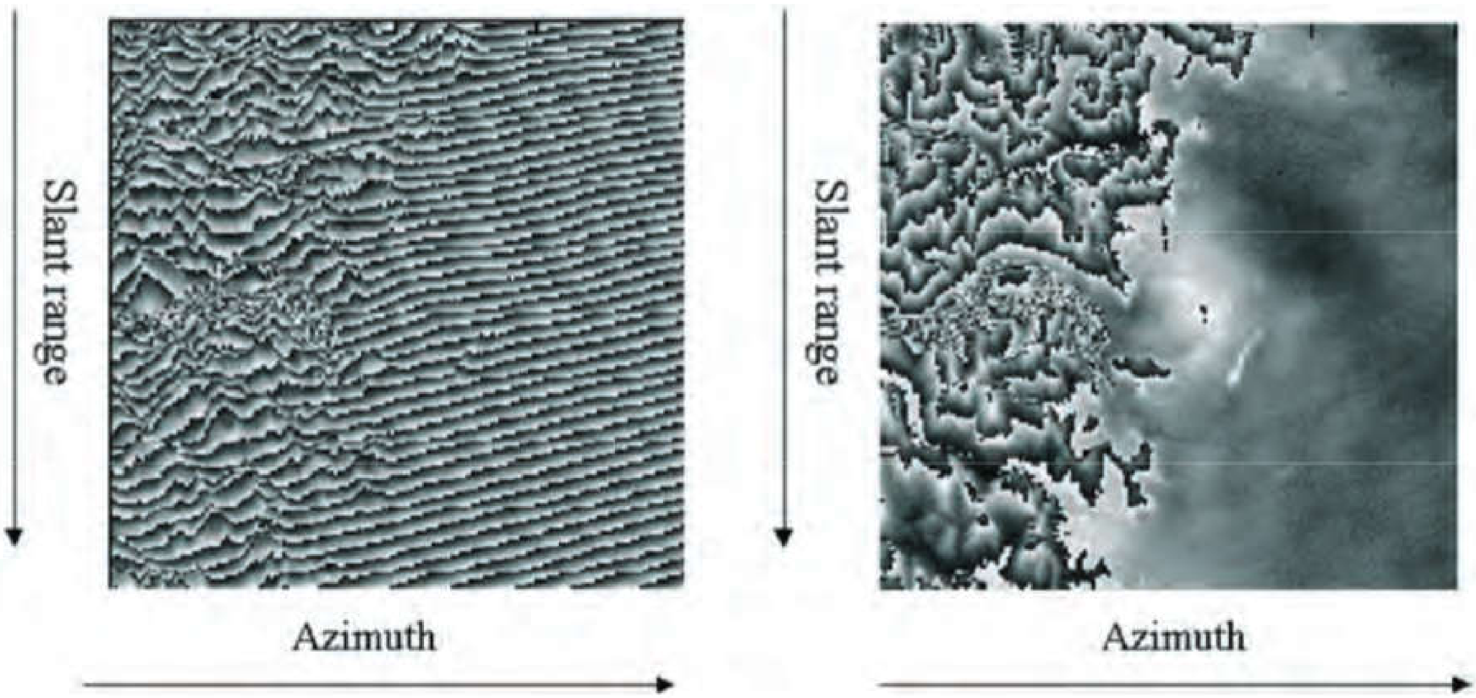
Next, we need to remove the phase interferogram that would result from a flat-earth.

φ_{int} φ_f



Removing the phase component due to the smooth Earth yields a "flattened interferogram"

InSAR processing:
Flat-earth removal

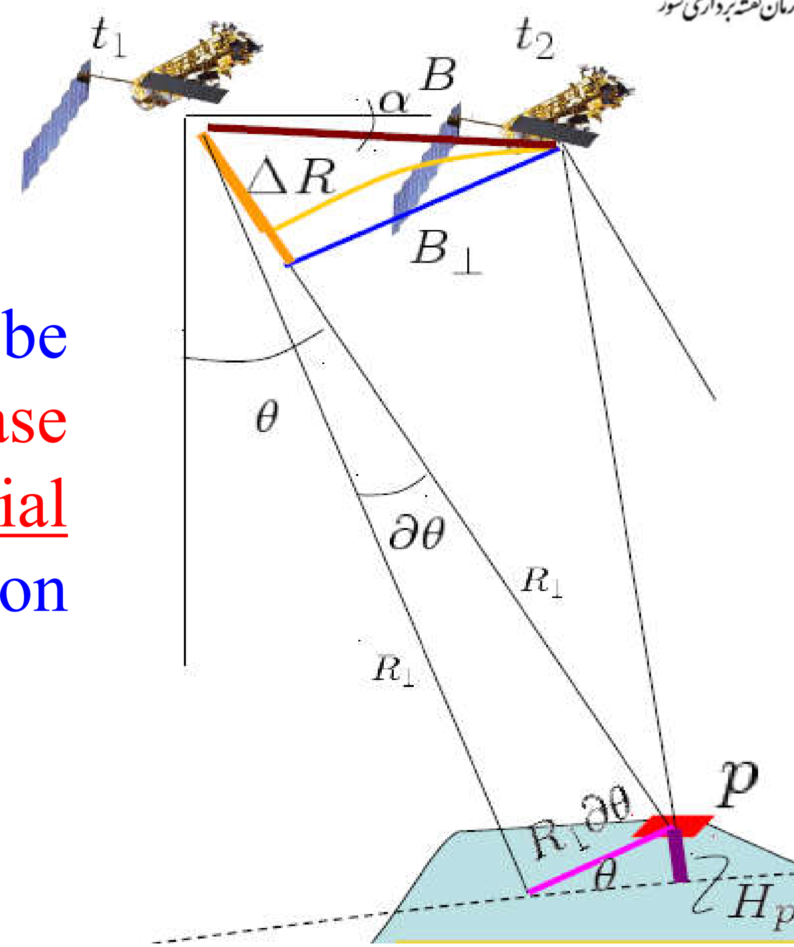


After removing the flat-earth effect we are left with an interferogram that contains **topography+deformation** between the two acquisitions and atmospheric effect.

InSAR processing:
Remove topographic phase

$$\varphi_{\text{int}} = \cancel{\varphi_f} + \varphi_{topo} + \varphi_{displ} + \varphi_{atm} + \varphi_{err}$$

The altitude contribution can be subtracted from the interferometric phase (generating the so-called <u>differential interferogram</u>) and the terrain motion component can be measured.



InSAR processing:
Remove topographic phase (cont.)

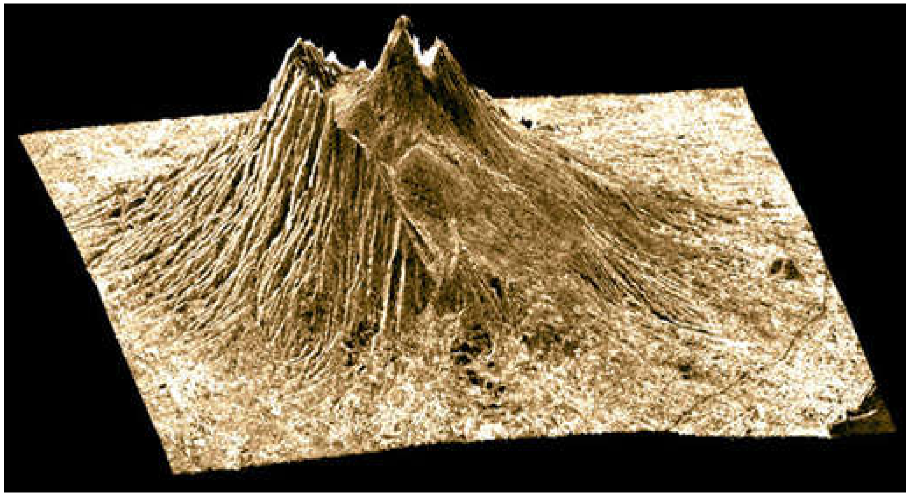
The topographic phase can be removed by one of the following methods:

- Two-pass: Simulate ϕ_{topo} based on existing DEM. High accuracy of DEM required.
- Three-pass: Derive ϕ_{topo} from independent interferogram, no existing DEM is required.

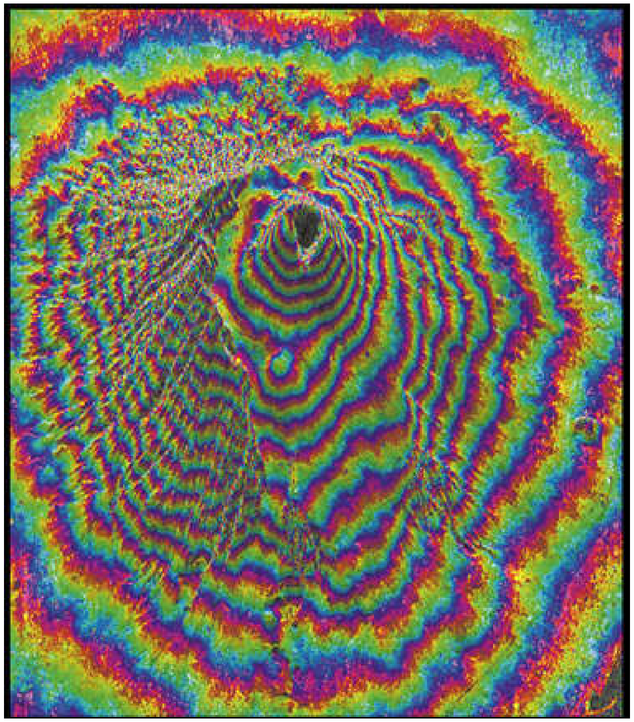
Differential Interferometry (DInSAR)

InSAR processing:
Remove topographic phase (cont.)

DEM



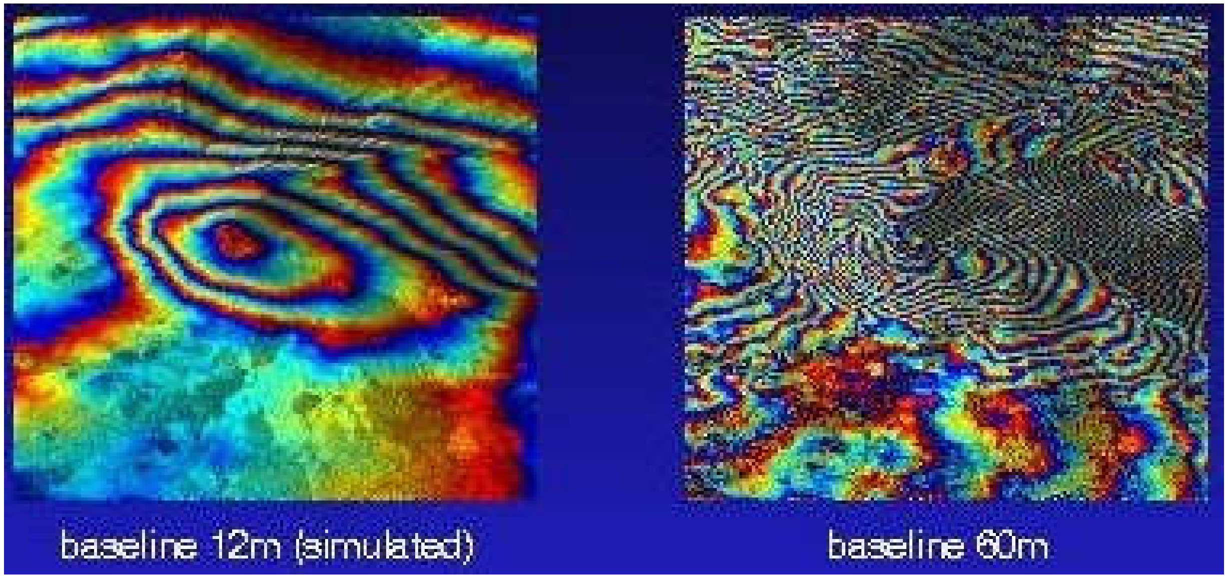
Interferogram



ERS-1, Vesuvius, Italy

InSAR processing: Remove topographic phase (cont.)

The longer the baseline, the smaller the topographic height needed to produce a fringe of phase change (or, the longer the baseline is the stronger the topographic imprint).

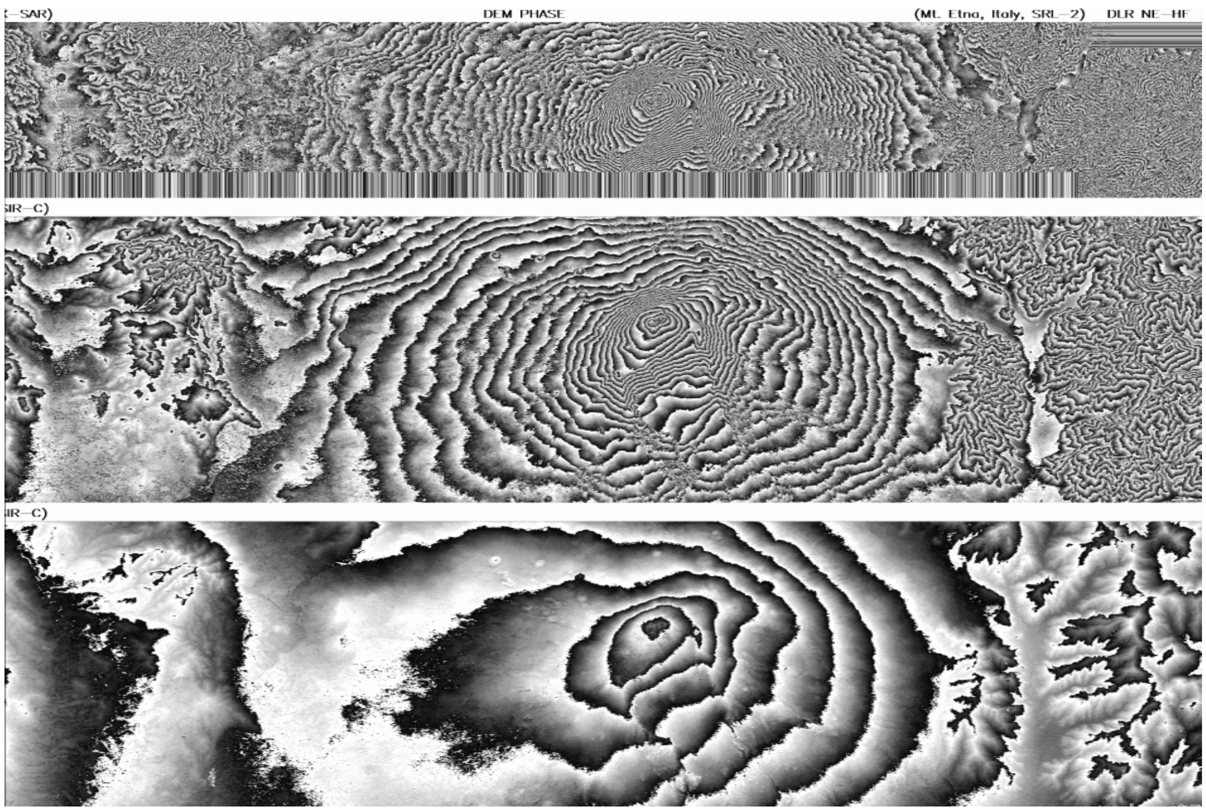


InSAR processing:
Remove topographic phase (cont.)

The higher the baseline the more accurate the altitude measurement.

There is an upper limit to the perpendicular baseline, over which the interferometric signals decorrelate and no fringes can be generated

InSAR processing:
Remove topographic phase (cont.)



X-band

C-band

L-band

In c-band the fringes are closer to each other than in L-band

InSAR processing:
Remove topographic phase (cont.)

Suppose that some of the point scatterers on the ground slightly change their relative position in the time interval between two SAR observations (as, for example, in the event of subsidence, landslide, earthquake, etc.). In such cases the following additive phase term, independent of the baseline, appears in the interferometric phase:

$$\Delta\phi_d = \frac{4\pi}{\lambda} d$$

where d is the relative scatterer displacement projected on the slant range direction.

This means that after interferogram flattening, the interferometric phase contains both altitude and motion contributions:

$$\Delta\phi = -\frac{4\pi}{\lambda}\frac{B_n q}{R\sin\theta} + \frac{4\pi}{\lambda} d$$

InSAR processing:
Remove topographic phase (cont.)

- If a DEM is available, the altitude contribution can be subtracted from the interferometric phase (generating the so-called differential interferogram) and the terrain motion component can be measured.
- In the ERS case with $\lambda = 5.6$ cm and assuming a perpendicular baseline of 150 m (a rather common value), the following expression holds:

$$\Delta\phi = -\frac{q}{10} + 225\, d$$

- From this example it can be seen that the sensitivity of SAR interferometry to terrain motion is much larger than that to the altitude difference.

A 2.8 cm motion component in the slant range direction would generate a 2π interferometric phase variation.

InSAR processing:
Remove topographic phase (cont.)

The **altitude of ambiguity** guide us how the topography affect the interferometric phase.

The altitude of ambiguity h_a is defined as the altitude difference that generates an **InSAR phase change** of 2π after interferogram flattening. The altitude of ambiguity is inversely proportional to the perpendicular baseline:

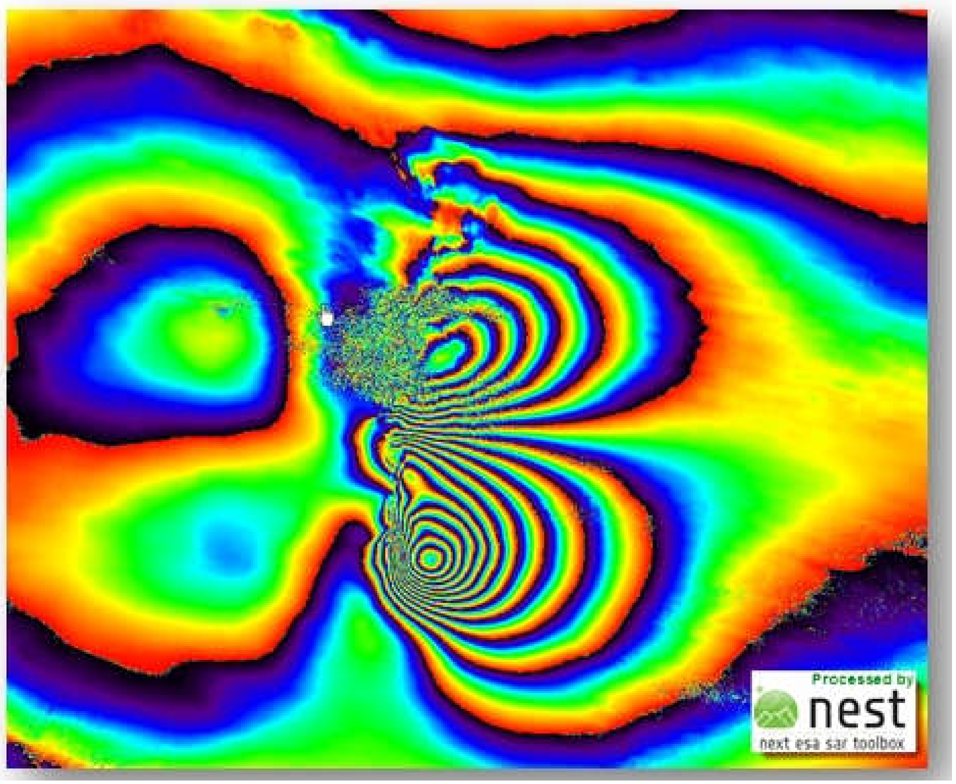
$$h_a = \frac{\lambda R \sin\theta}{2 B_n}$$

For the case of ERS: $\lambda = 5.6\ cm, \theta = 23^o$ and R=850 km

$$h_a \approx \frac{9300}{B_n}$$

InSAR processing:
Remove topographic phase (cont.)

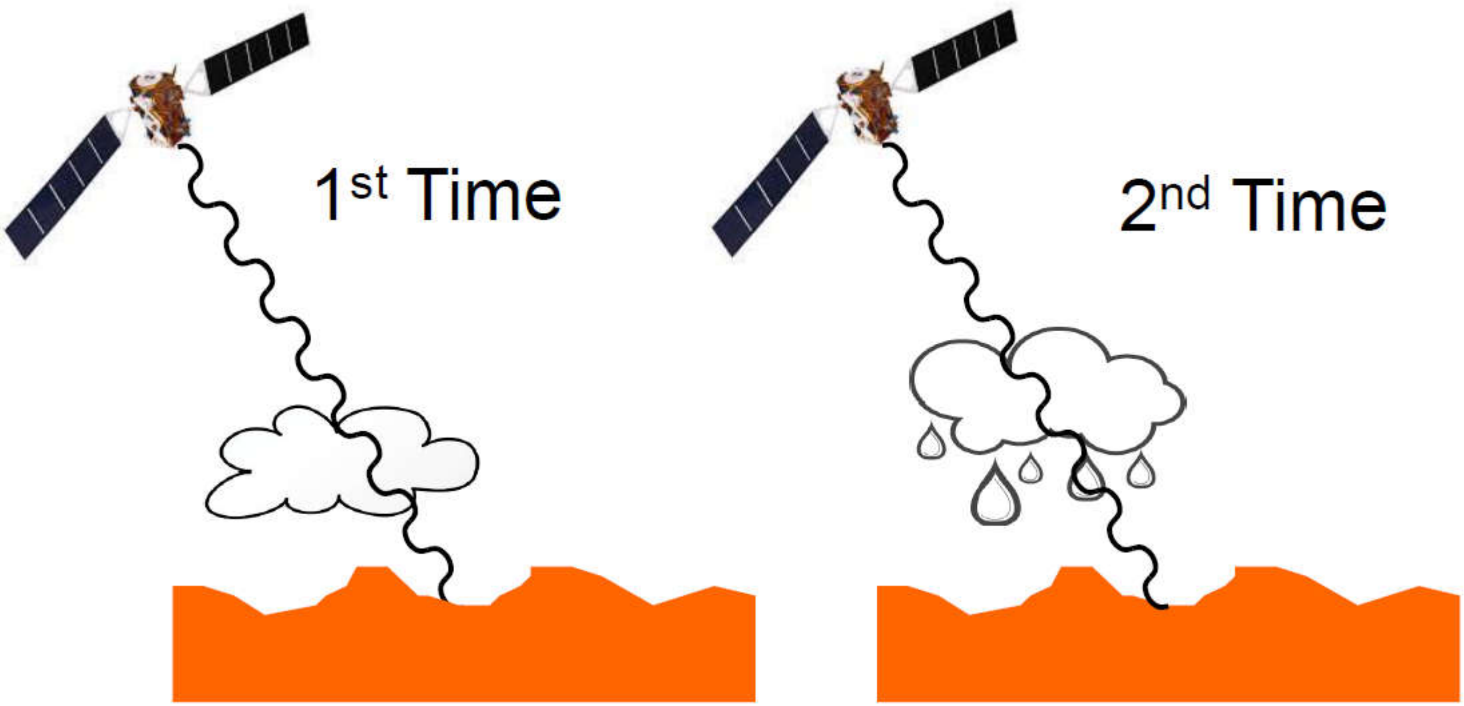
Differential Interferometry (DInSAR)



InSAR processing: Atmospheric phase

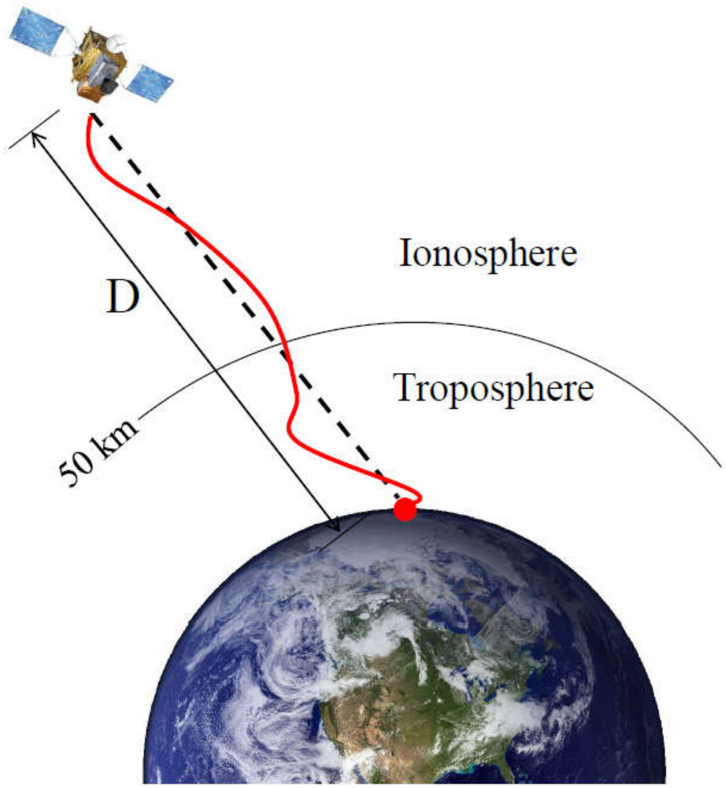
$$LOS_{ms} = LOS_{master} - LOS_{slave}$$

$$\varphi_{int} = \varphi + \varphi_{topo} + \varphi_{disp} + \varphi_{atm} + \varphi$$



InSAR processing: Atmospheric phase

What is Atmospheric delay ?

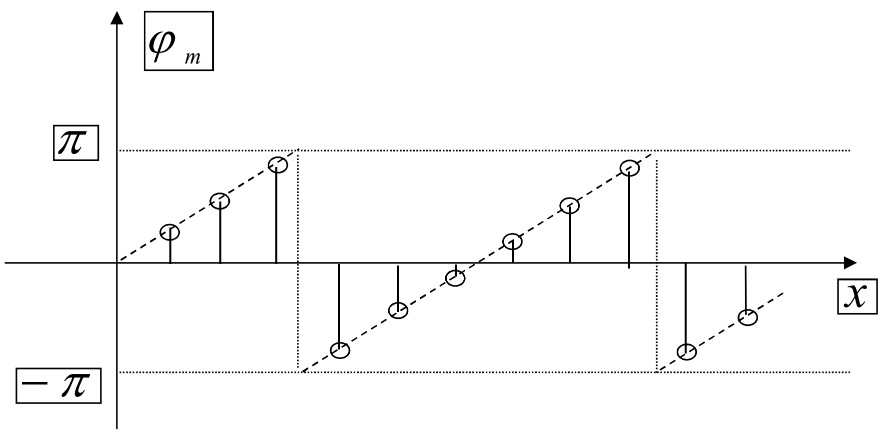


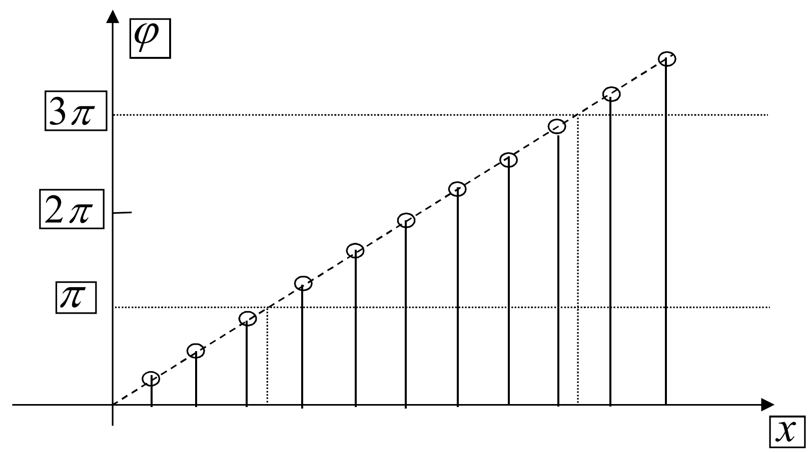
Atmospheric delays include:

- **Ionospheric delay**
- **Tropospheric delay**
  - **Temperature and pressure**
  - **Wet delay (water vapor instability)**

InSAR processing: unwrapping

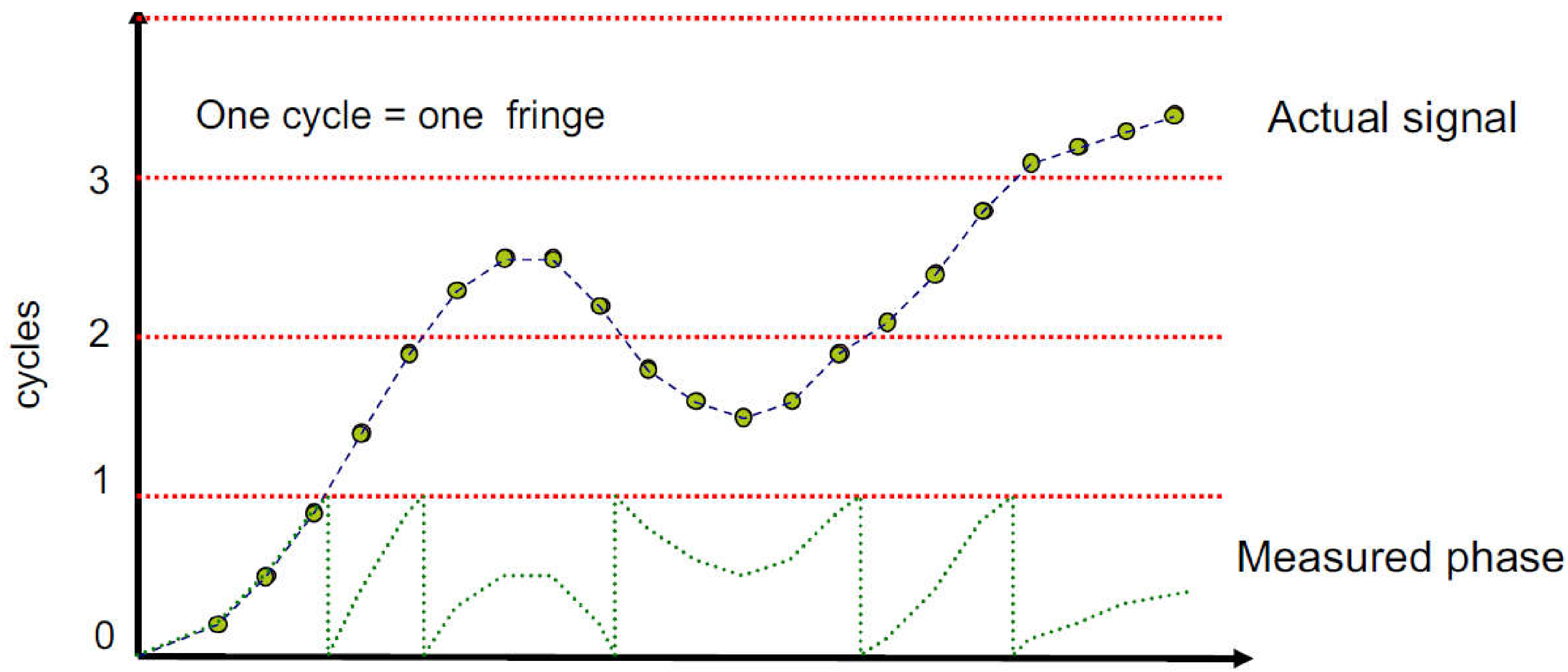
The interferogram is a map of an ambiguous phase offset between -π and +π. In order to recover the absolute unambiguous phase offset, one needs to unwrap the data.





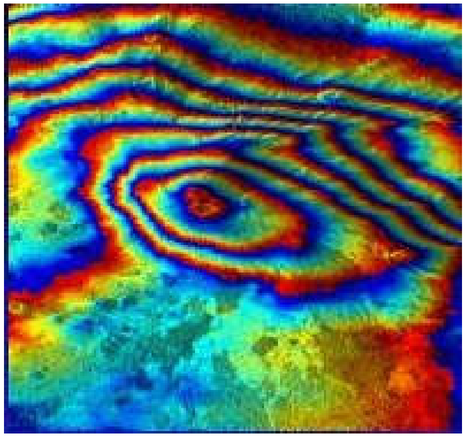
InSAR processing: unwrapping

Phase unwrapping is the reverse-finding the integer shift values for each point.

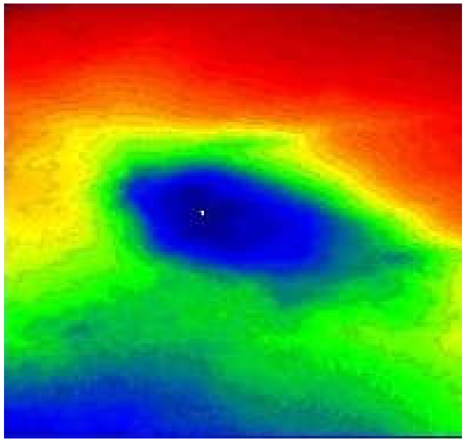


InSAR processing: unwrapping

While the wrapped phase looks like this:

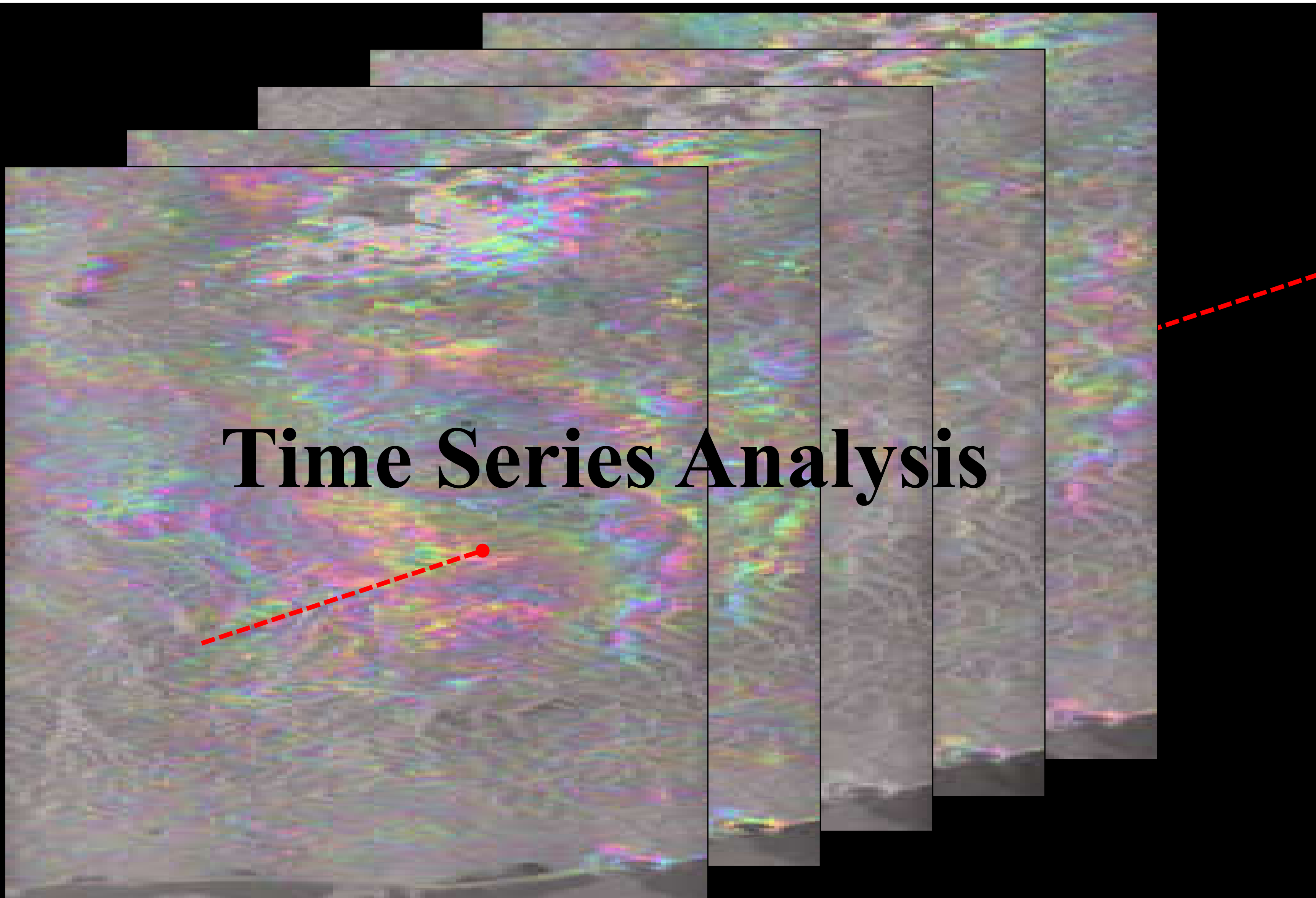


The unwrapped phase looks like this:



* Note that in this specific example the topographic effect has not been removed, thus the unwrapped phase map correspond mainly to topographic height.

Time Series Analysis

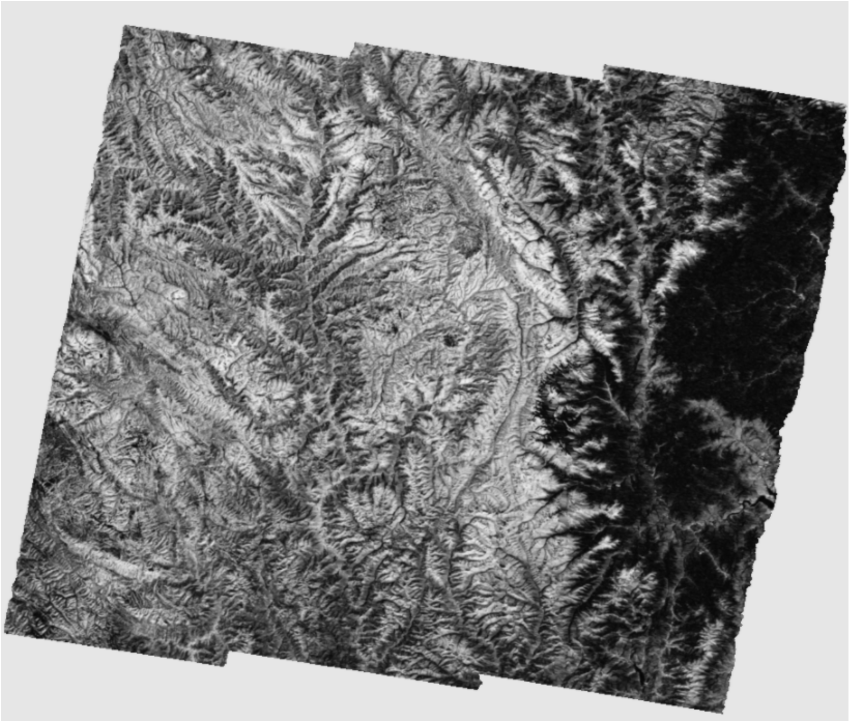


Decorrelation

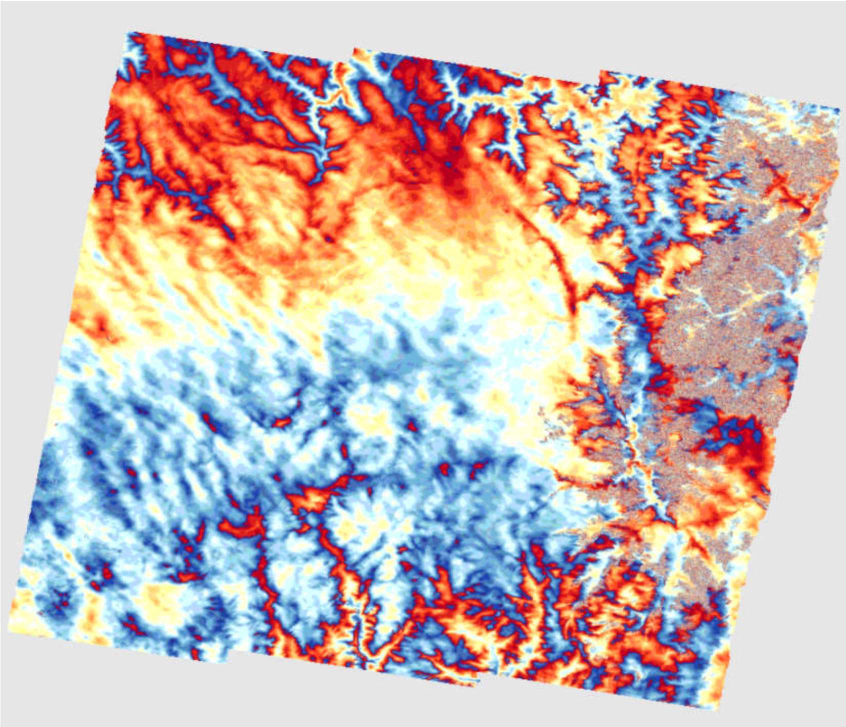
- **Temporal decorrelation**: makes InSAR measurements unfeasible over vegetated areas and where the electromagnetic profiles and/or the positions of the scatterers change with time within the resolution cell.

- **Geometrical decorrelation**: limits the number of image pairs suitable for interferometric applications and prevents one from fully exploiting the data set available.

Coherence Maps



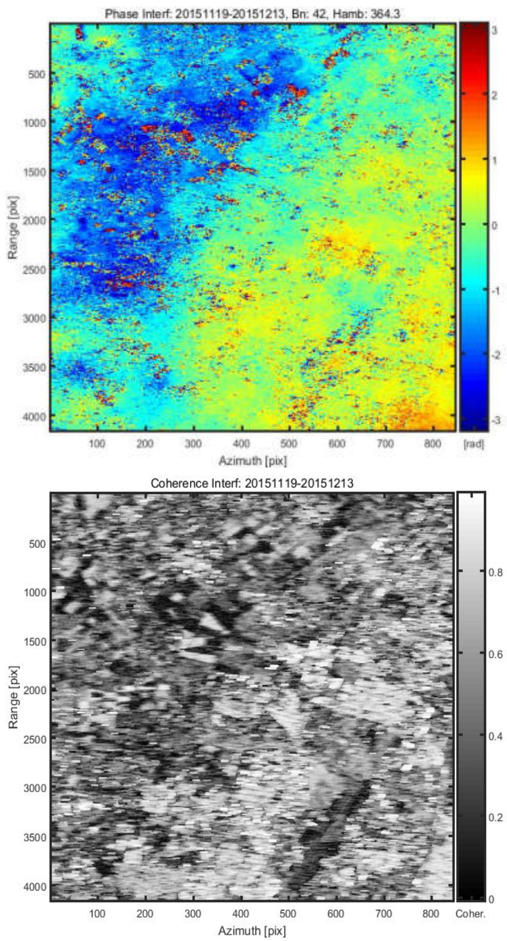
Coherence



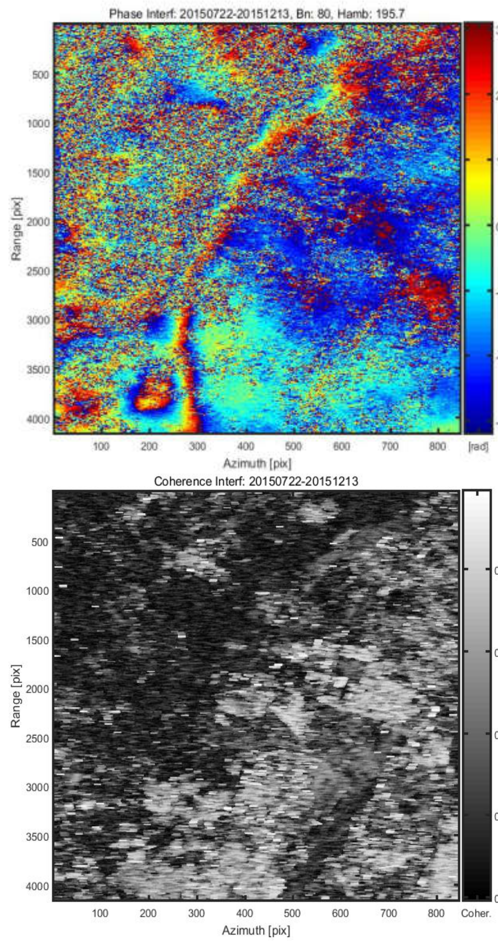
interferogram

Temporal & Geometrical Decorrelation

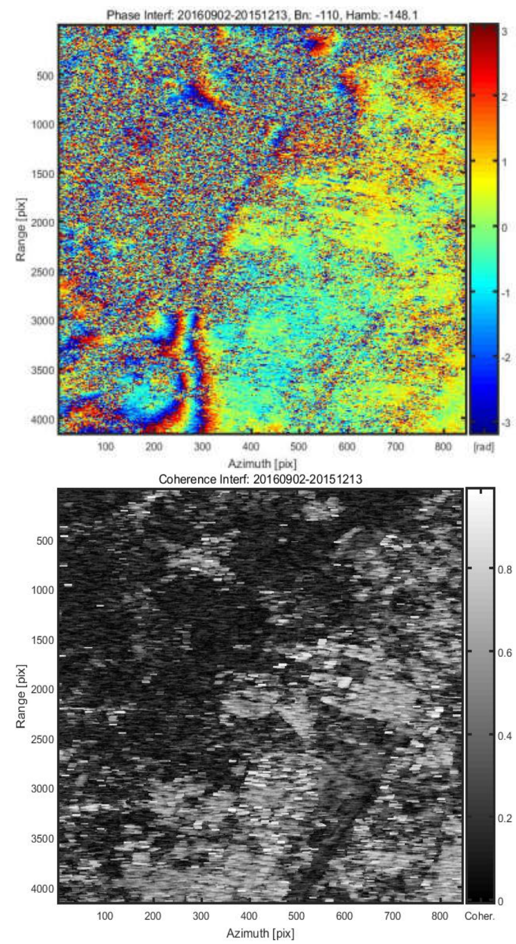
B_n=42m , B_t=24 days



B_n=80m , B_t=142 days



B_n=110m , B_t=287 days



Time Series InSAR

Motivation!

- Allows better selection of coherent pixels (in high temporally/ geometrically decorrelated areas)
- Atmosphere errors can be reduced by filtering in space and time
- DEM error estimation possible
- More reliable phase unwrapping possible (3-D)

Overcoming the limitations of D-InSAR


Multi-Temporal InSAR
Infrastructure Monitoring Service

Multi-Temporal InSAR Infrastructure Monitoring Service

The Monitoring platform is currently capable of providing autonomous Multi-temporal InSAR (MT-InSAR) processing and generation of regularly updated displacement maps to find the risk area in the case of the collapse in Tehran.


Sentinel-1

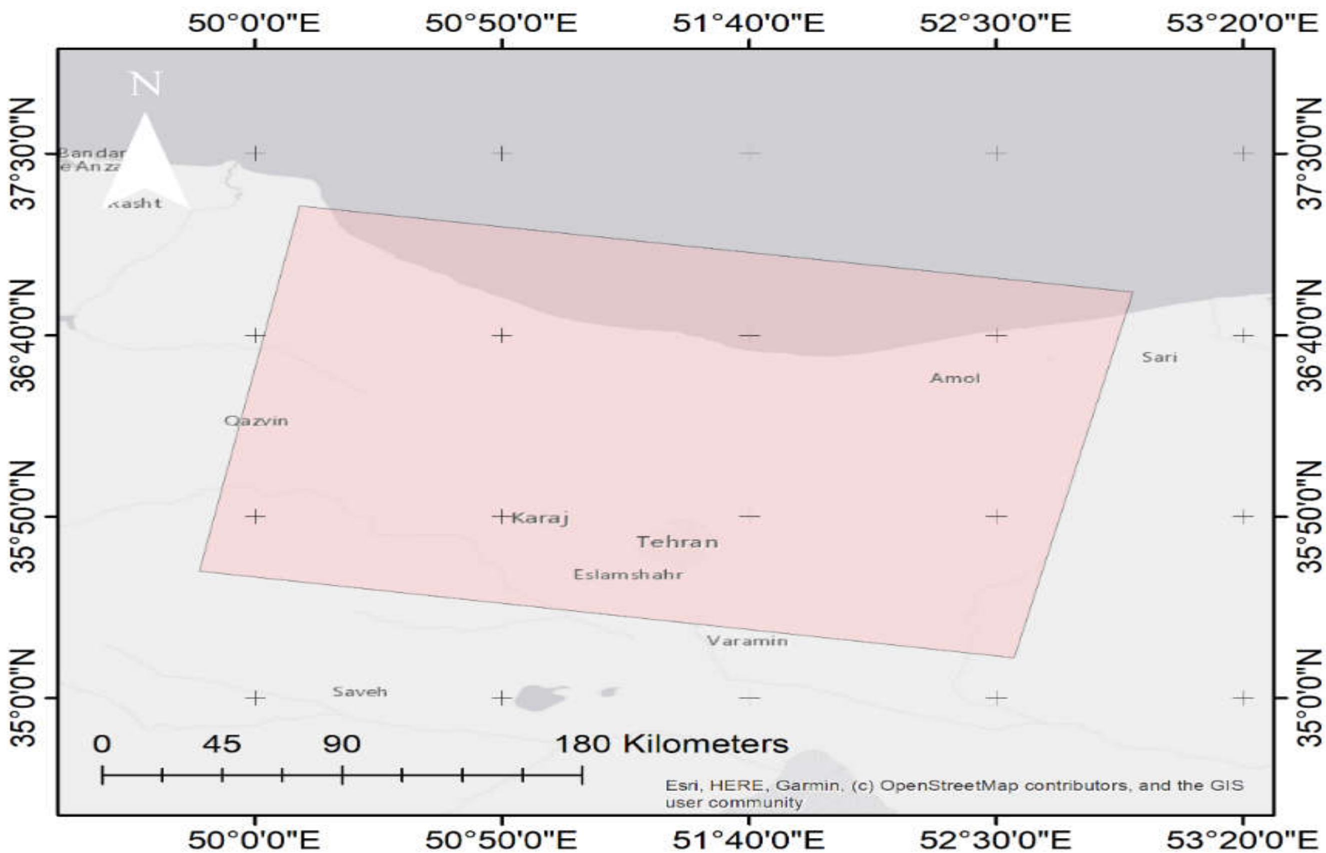
Multi-Temporal InSAR Infrastructure Monitoring Service
Sentinel-1

- C-band
- Revisit time, 6/12 days
- Dual polarization in Iran
- Spatial resolution in IW mode: 20(Azimuth)×5(range) meters

  - https://scihub.copernicus.eu/dhus/#/home
  - http://step.esa.int/main/download/snap-download/

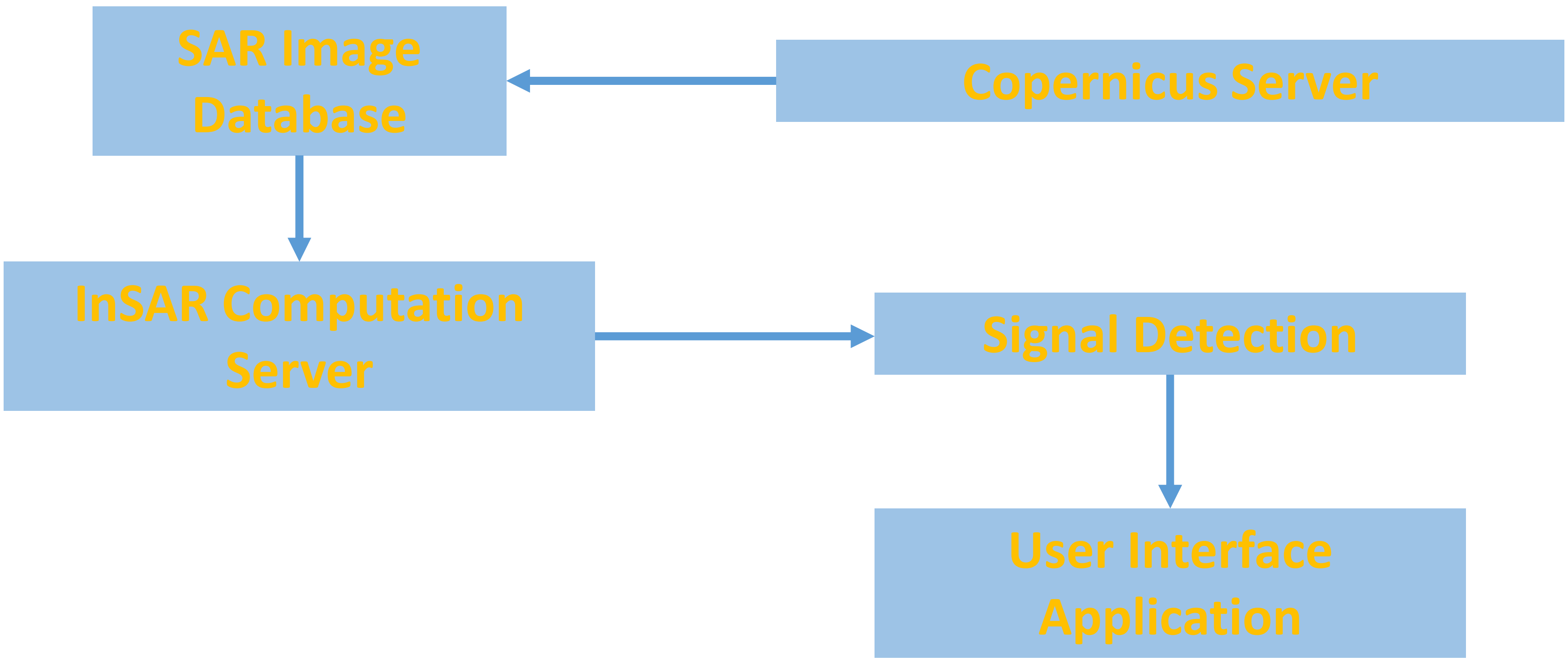
Multi-Temporal InSAR Infrastructure Monitoring Service

Track 35 over Tehran



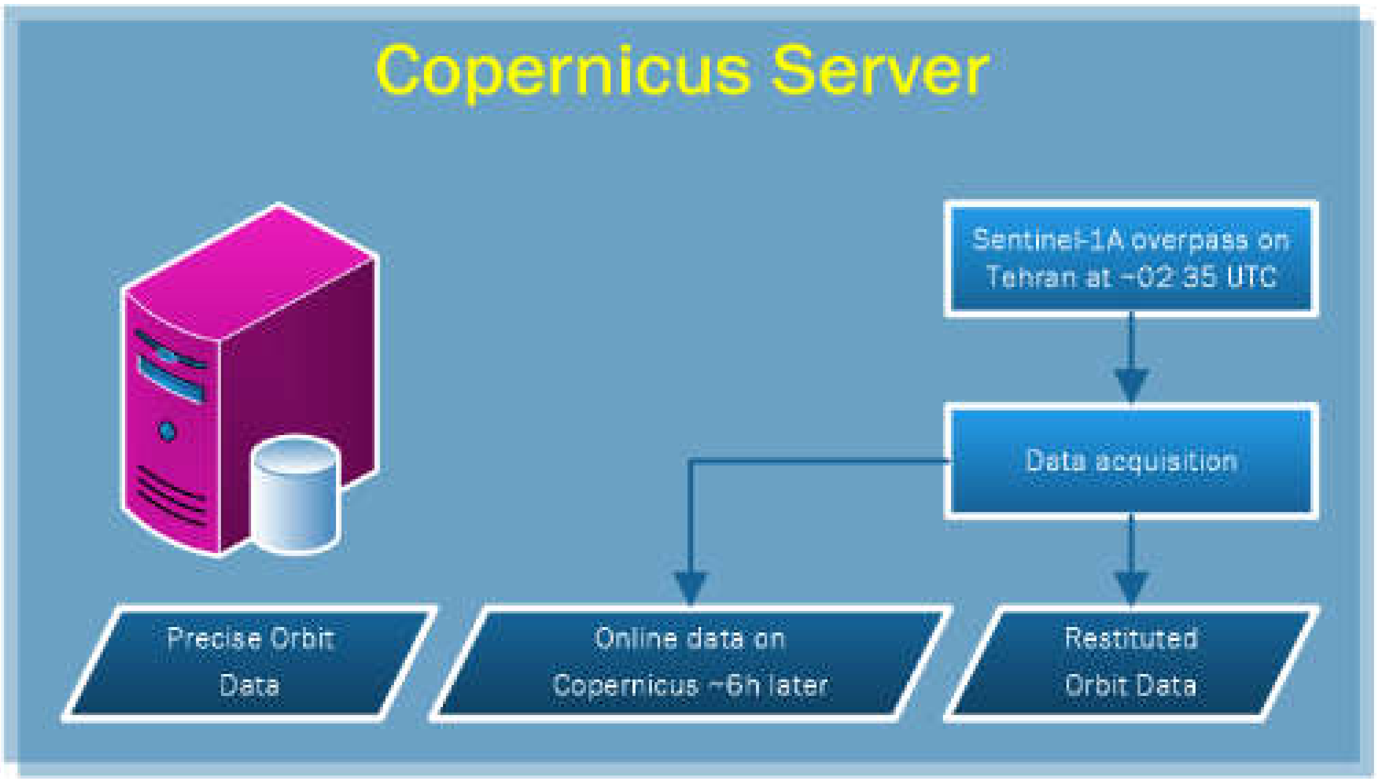
Multi-Temporal InSAR Infrastructure Monitoring Service

System Architecture



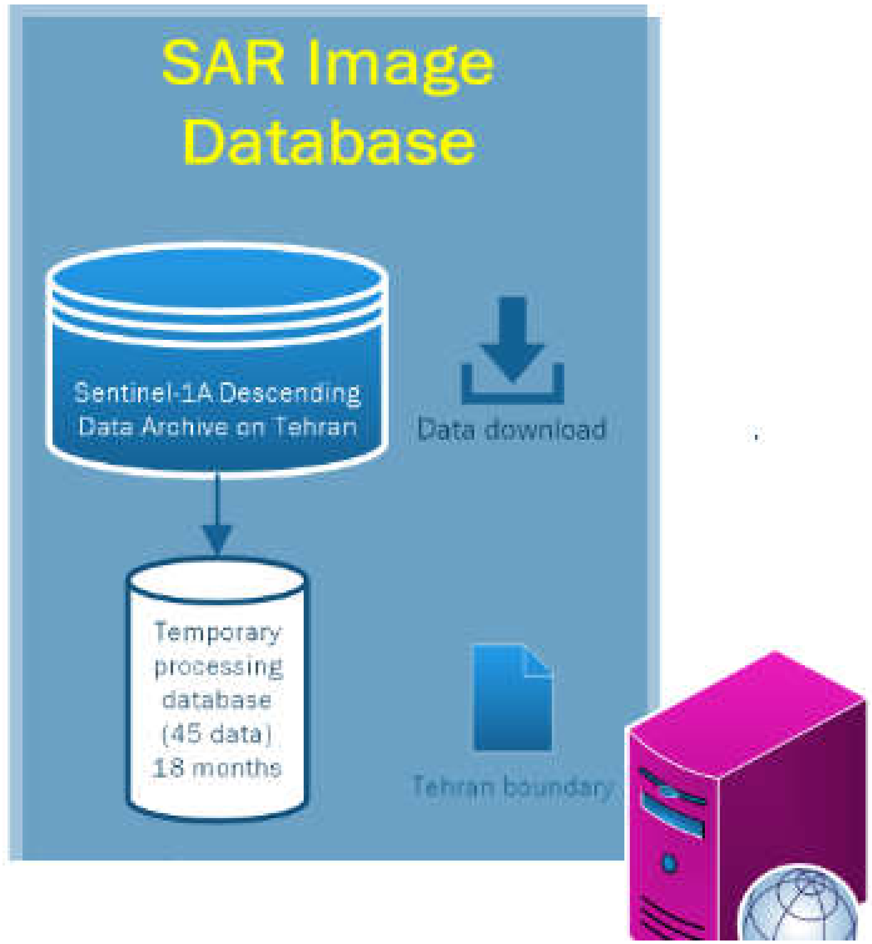
Multi-Temporal InSAR Infrastructure Monitoring Service

System Architecture



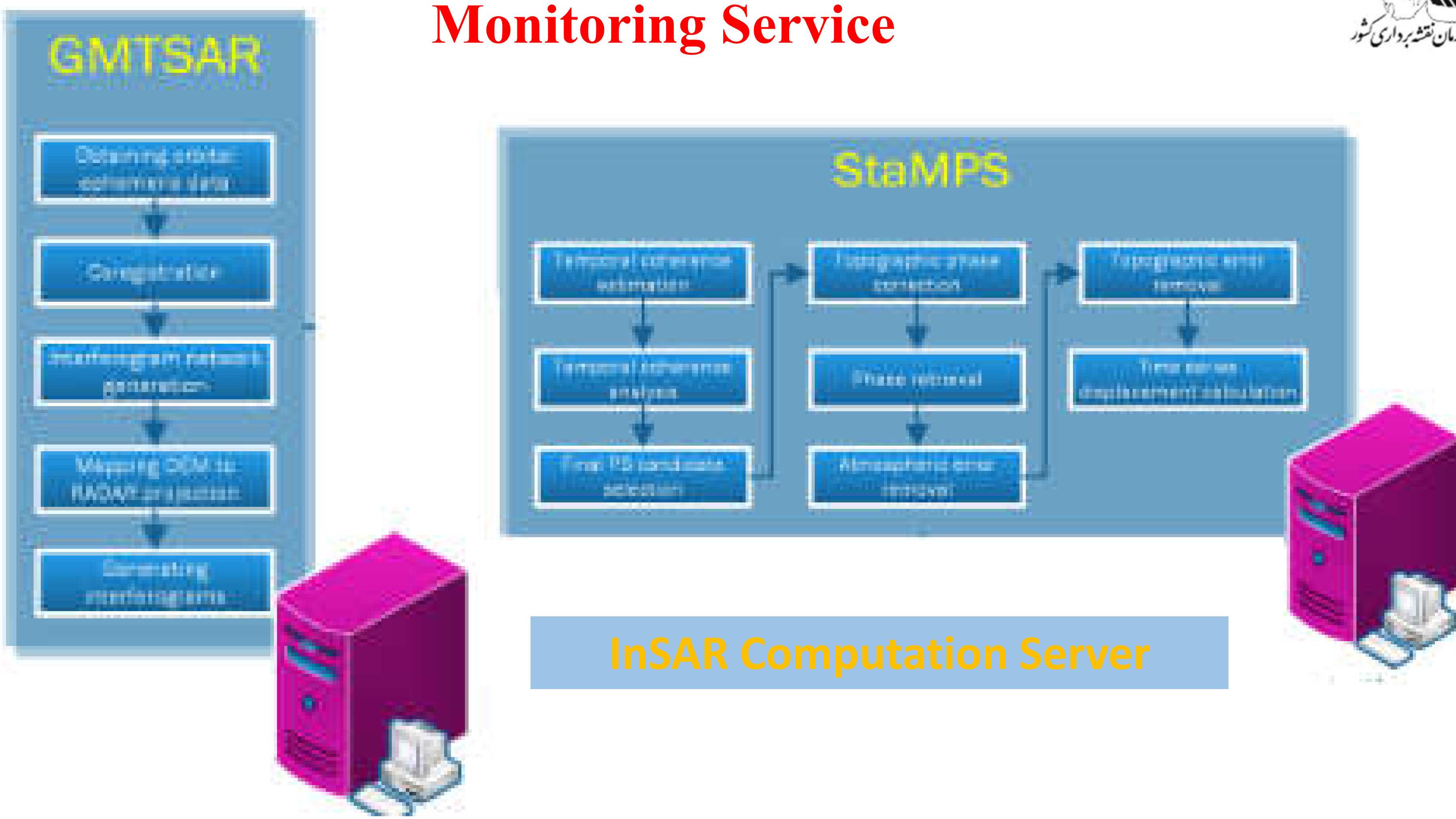
Multi-Temporal InSAR Infrastructure Monitoring Service

System Architecture



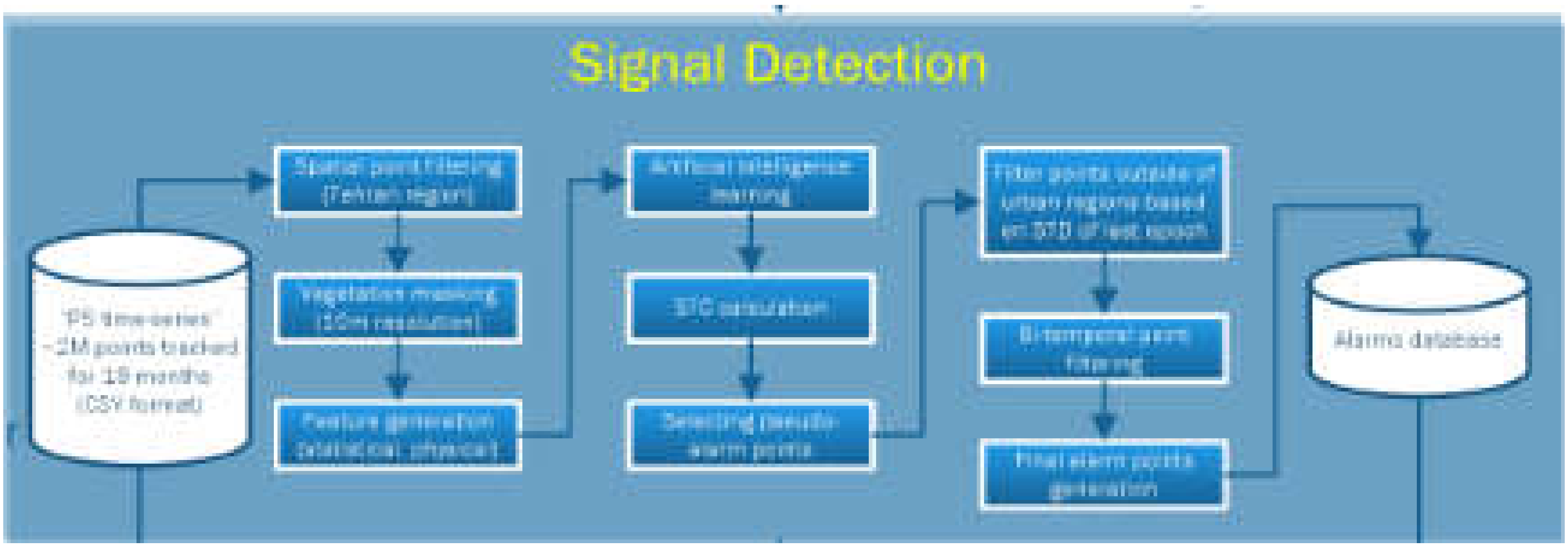
Multi-Temporal InSAR Infrastructure Monitoring Service

System Architecture



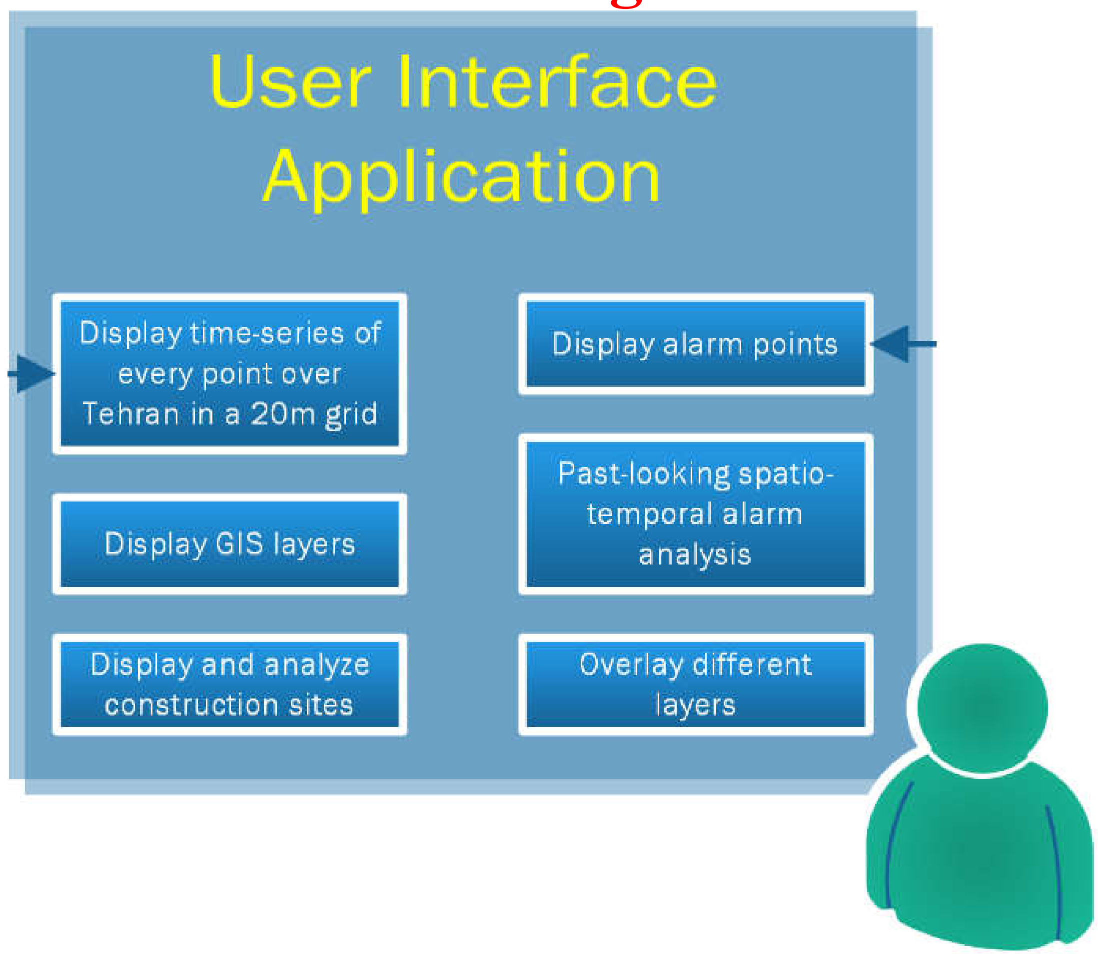
Multi-Temporal InSAR Infrastructure Monitoring Service

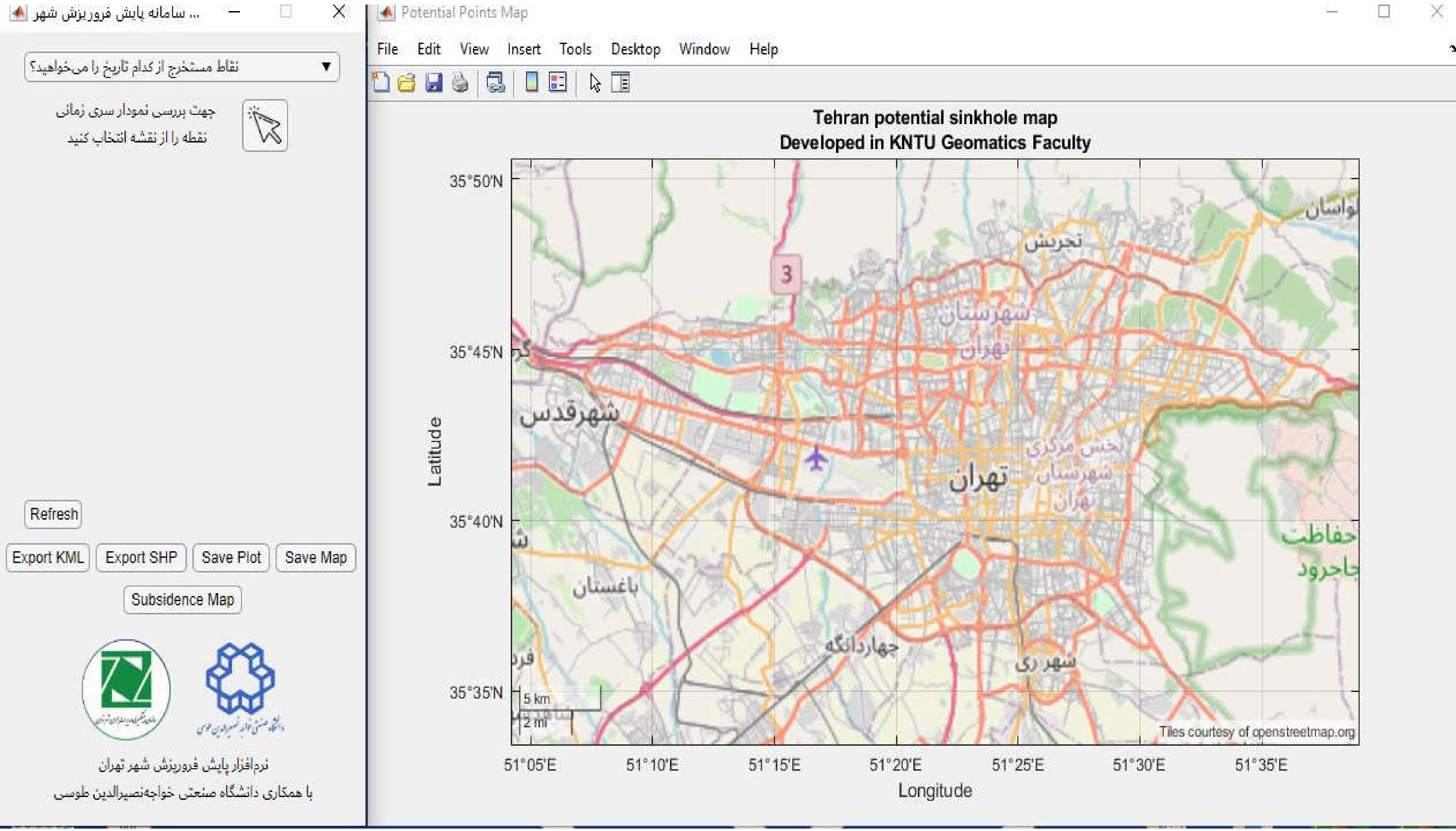
System Architecture



Multi-Temporal InSAR Infrastructure Monitoring Service

System Architecture




سامانه پایش فروریزش شهر ...
نقاط مستخرج از کدام تاریخ را می‌خواهید؟
جهت بررسی نمودار سری زمانی
نقطه را از نقشه انتخاب کنید
Refresh
Export KML
Export SHP
Save Plot
Save Map
Subsidence Map
نرم‌افزار پایش فروریزش شهر تهران
با همکاری دانشگاه صنعتی خواجه‌نصیرالدین طوسی
Potential Points Map
File
Edit
View
Insert
Tools
Desktop
Window
Help
Tehran potential sinkhole map
Developed in KNTU Geomatics Faculty
35°50'N
35°45'N
35°40'N
35°35'N
Latitude
51°05'E
51°10'E
51°15'E
51°20'E
51°25'E
51°30'E
51°35'E
Longitude
تجریش
شهرستان
تهران
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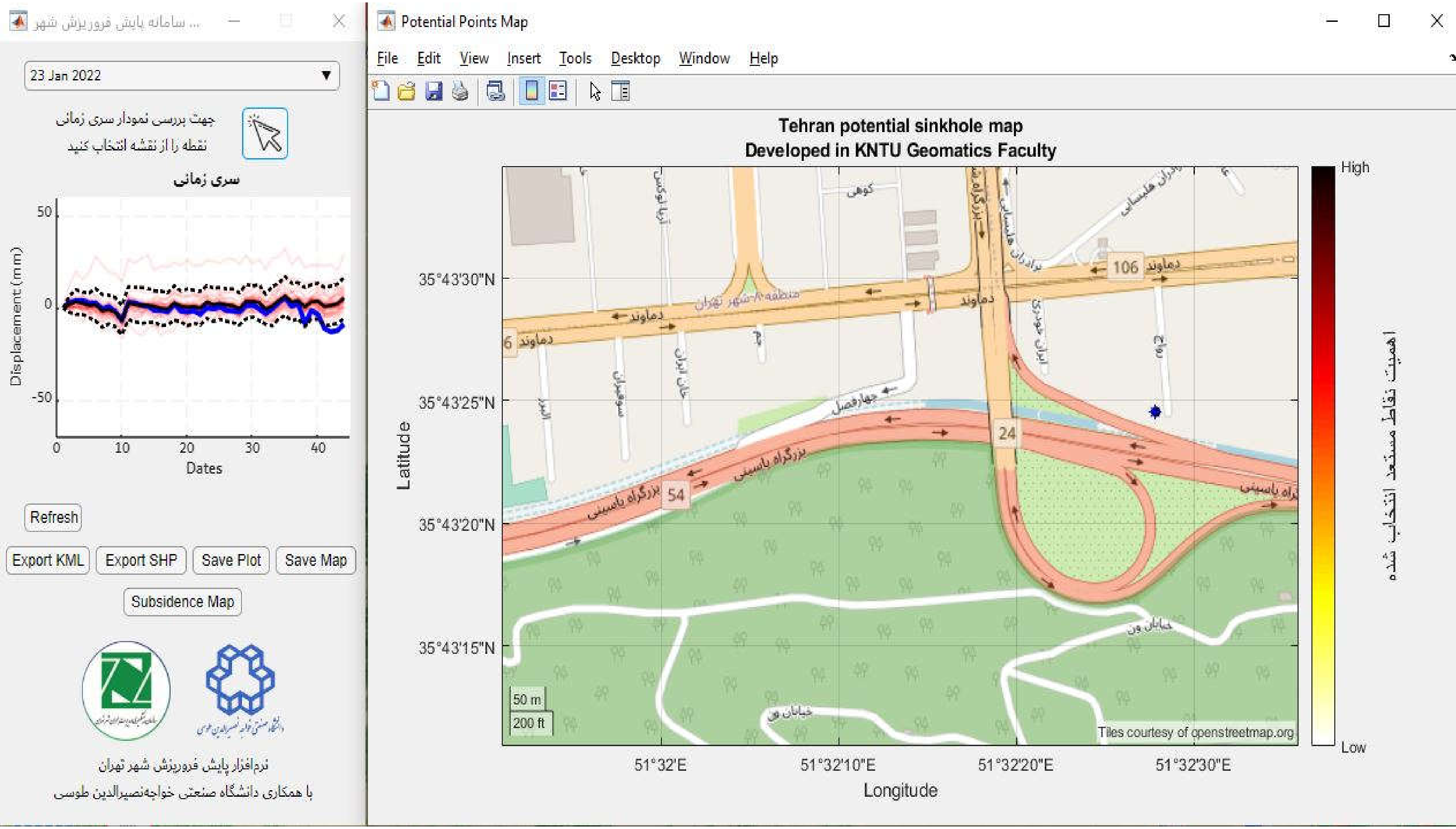

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23 Jan 2022
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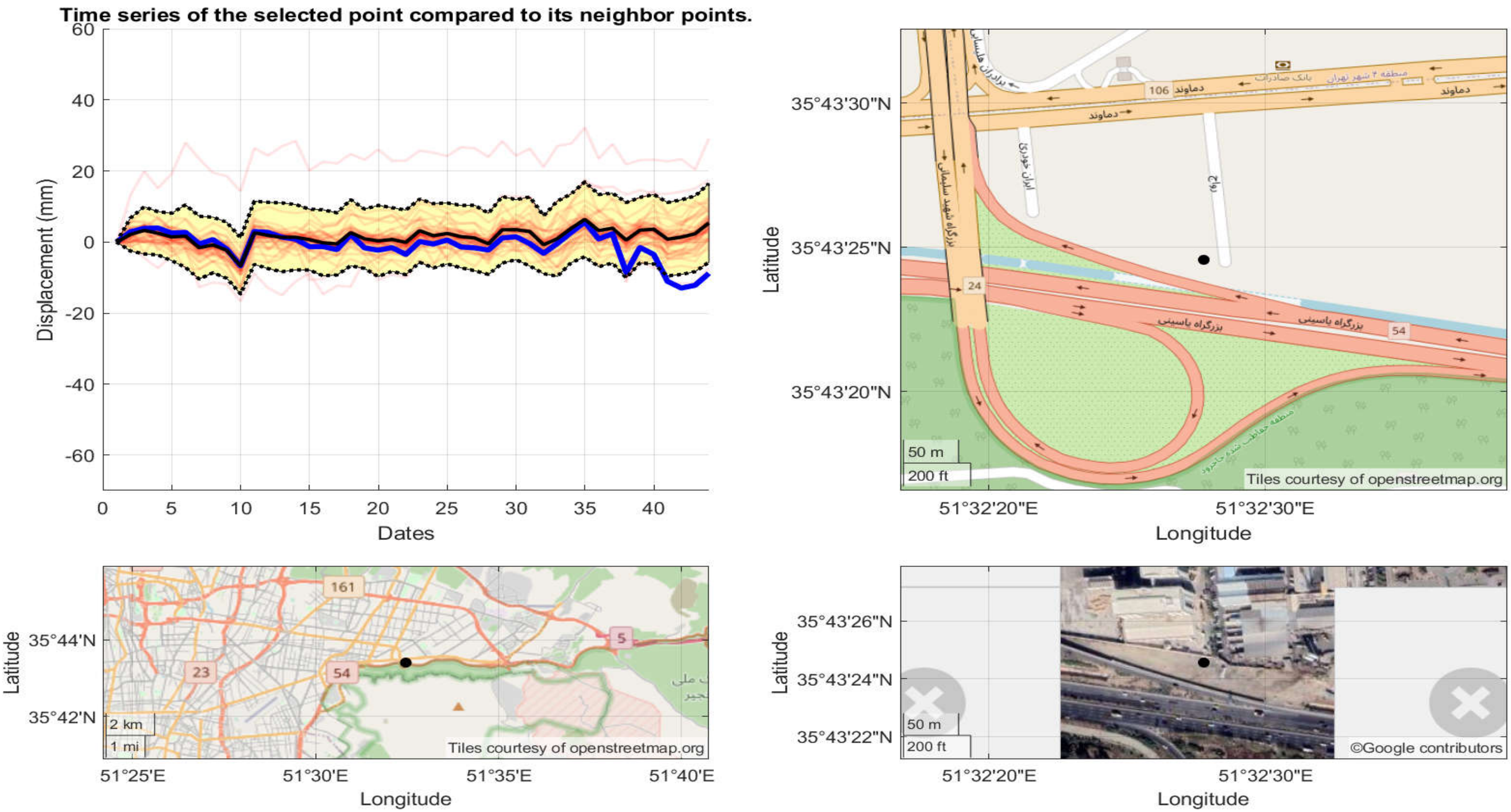
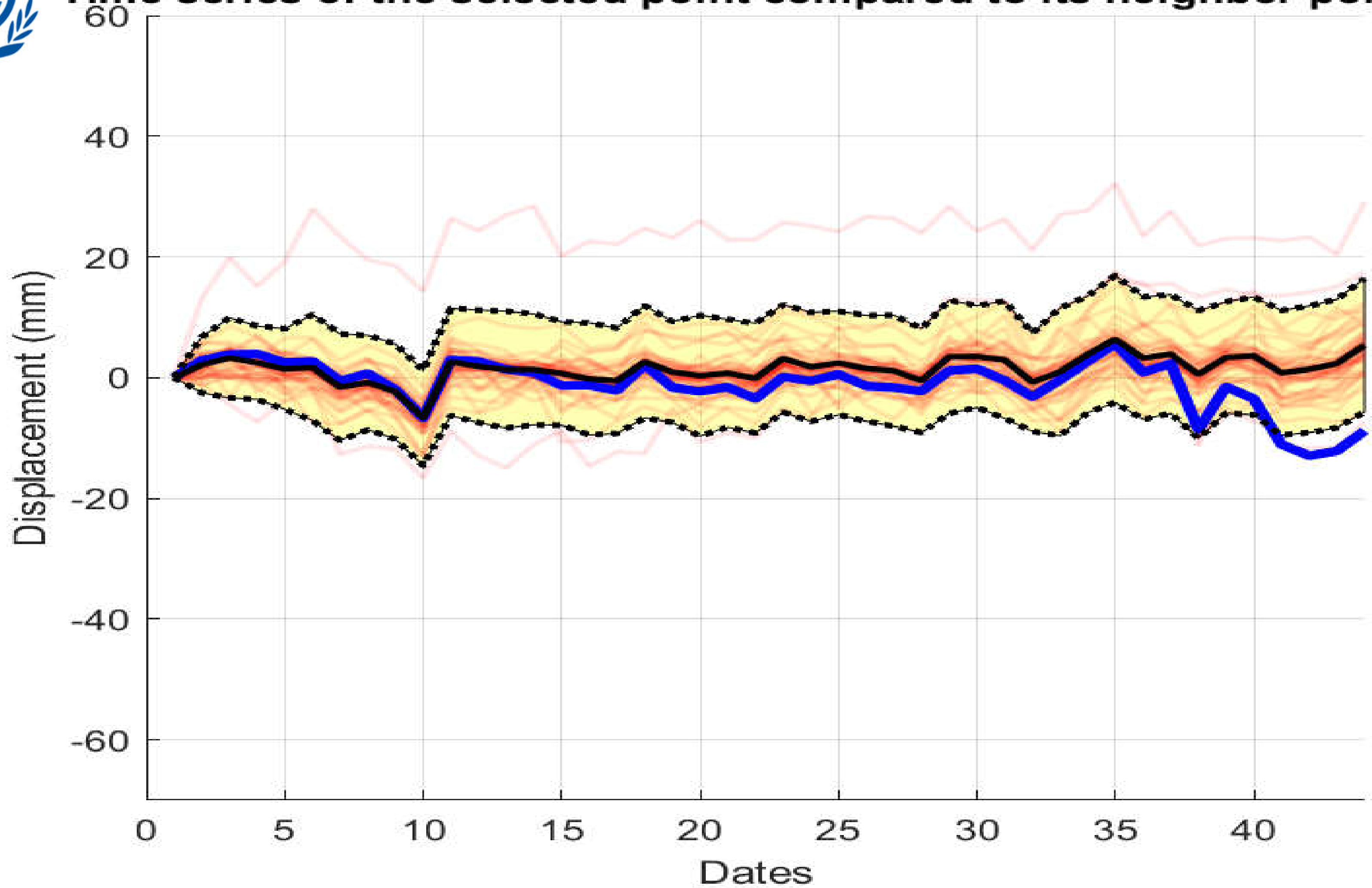
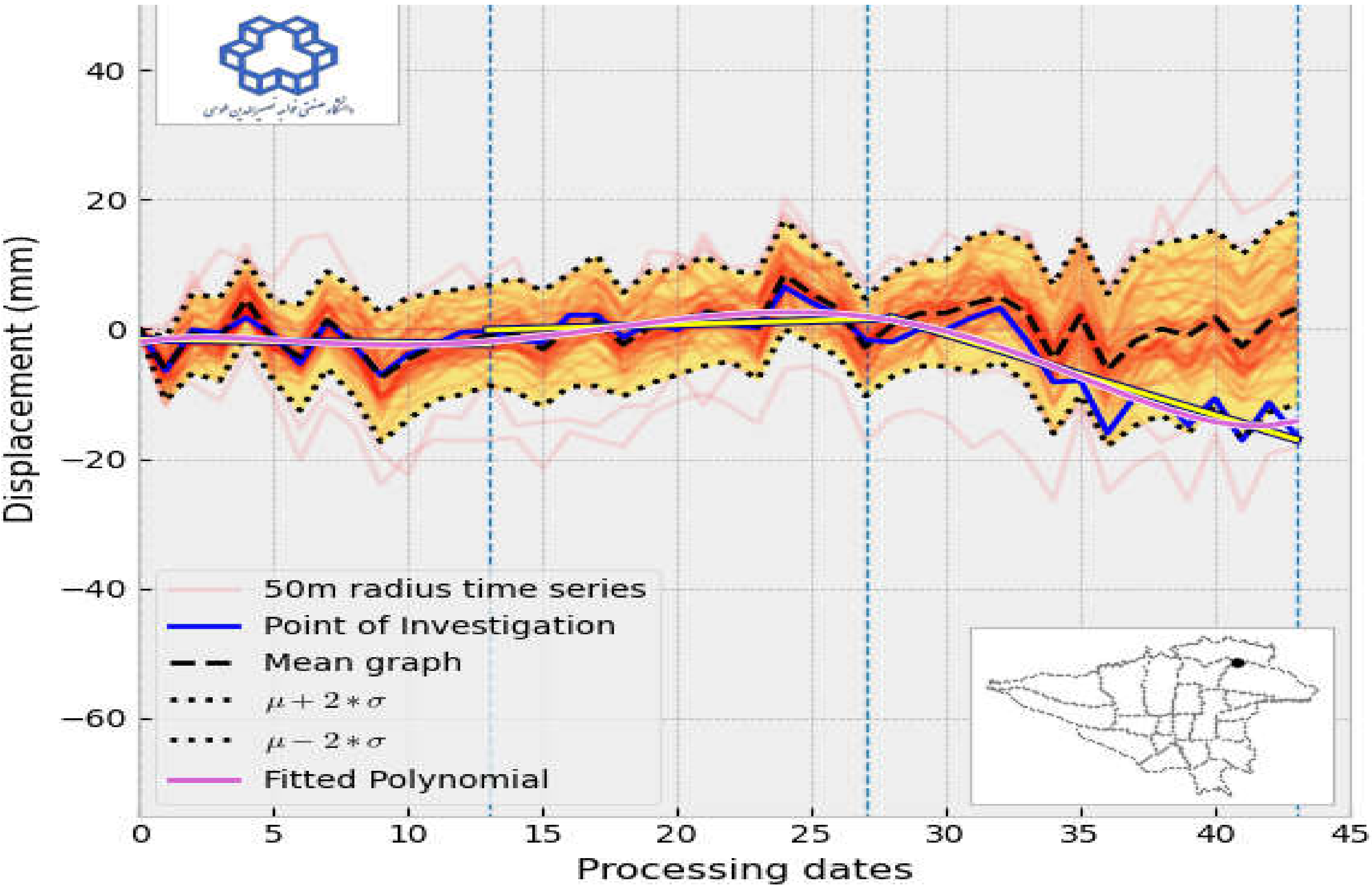
نقطه را از نقشه انتخاب کنید
سری زمانی
Displacement (mm)
50
0
-50
0
10
20
30
40
Dates
Refresh
Export KML
Export SHP
Save Plot
Save Map
Subsidence Map
نرم‌افزار پایش فروریزش شهر تهران
با همکاری دانشگاه صنعتی خواجه‌نصیرالدین طوسی
Potential Points Map
File
Edit
View
Insert
Tools
Desktop
Window
Help
Tehran potential sinkhole map
Developed in KNTU Geomatics Faculty
Latitude
35°43'30"N
35°43'25"N
35°43'20"N
35°43'15"N
51°32'E
51°32'10"E
51°32'20"E
51°32'30"E
Longitude
50 m
200 ft
Tiles courtesy of openstreetmap.org
High
Low
اهمیت نقاط مستعد انتخاب شده



Time series of the selected point compared to its neighbor points.
Displacement (mm)
60
40
20
0
-20
-40
-60
0
5
10
15
20
25
30
35
40
Dates
35°43'30"N
35°43'25"N
35°43'20"N
Latitude
106
24
54
50 m
200 ft
Tiles courtesy of openstreetmap.org
51°32'20"E
51°32'30"E
Longitude
161
5
23
54
35°44'N
35°42'N
Latitude
2 km
1 mi
Tiles courtesy of openstreetmap.org
51°25'E
51°30'E
51°35'E
51°40'E
Longitude
35°43'26"N
35°43'24"N
35°43'22"N
Latitude
50 m
200 ft
©Google contributors
51°32'20"E
51°32'30"E
Longitude

Time series of the selected point compared to its neighbor points.





Displacement (mm)
Processing dates
50m radius time series
Point of Investigation
Mean graph
$\mu + 2 * \sigma$
$\mu - 2 * \sigma$
Fitted Polynomial


• InSAR is a powerful, low-cost tool for monitoring Earth deformation
• Capability improving continuously (smaller rates, bigger areas…)
• Future missions and method development will ensure InSAR is a standard technique