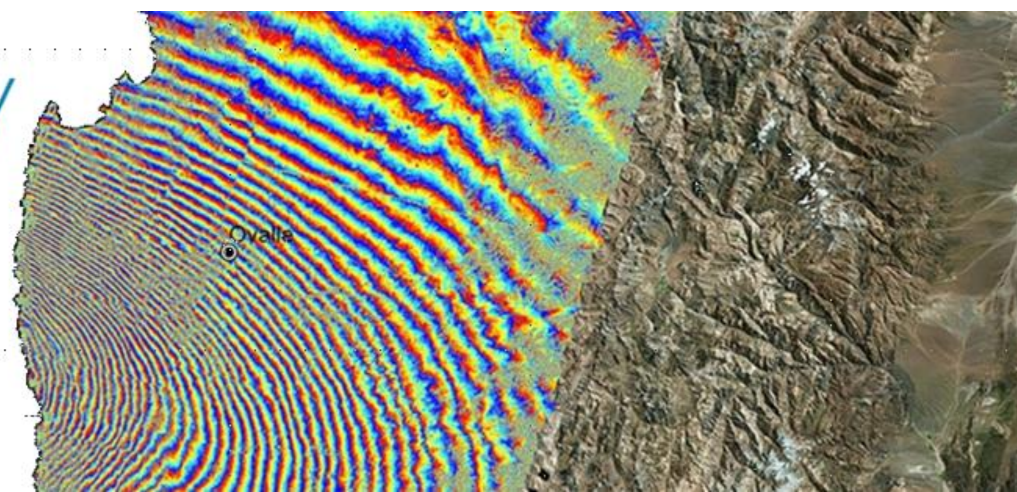
Big Satellite Data for Ground Deformation Assessment at Global Scale

Charalampos (Haris) Kontoes
Research Director
Institute of Astronomy, Astrophysics, Space Applications & Remote Sensing
National Observatory of Athens

geObservatory

IAASARS

BEYOND



Challenge

To efficiently process big volumes of satellite data provided from Copernicus Sentinel-1 SAR mission and third party missions of high to very high spatial resolution ranging from a few centimeters to up to 10-20 meters on the ground depending on the level of signal focus

Big Data: More than 110 TiB of satellite data are acquired only in one month, a volume that is equivalent to the entire 7-year archive of the Envisat mission

Building upon the efficient employment of High Performance Cloud Computing (HPC) resources, Datacubes/ Array Data Bases, and ML/AI new capabilities are available for the effective processing of big data to estimate with millimeter accuracy ground deformations over countries and continents

A Solution

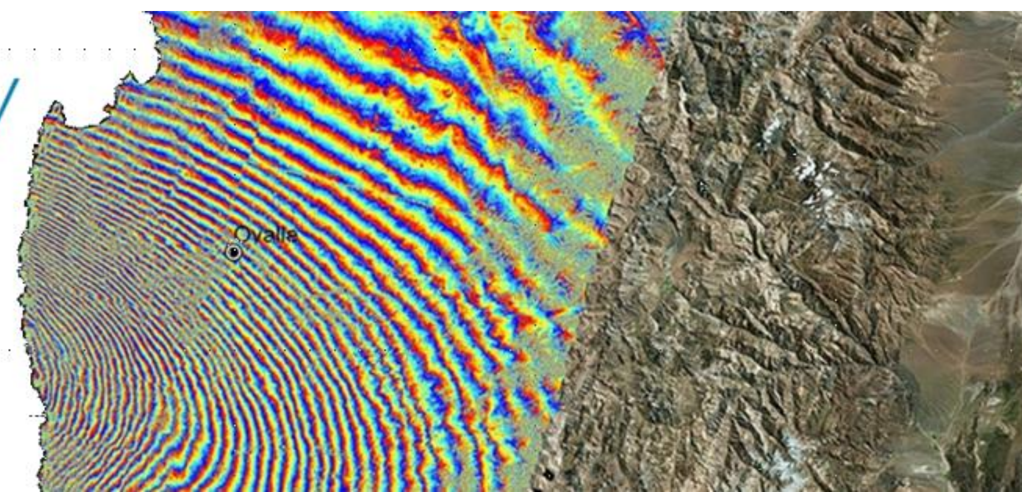
Our **Center of Exellence BEYOND/NOA**, that is hosted and operated at the premises of the National Observatory of Athens provides services to Copernicus EU Space program in the domains of natural disasters, and addresses these challenges through the **geObservatory service**

This **service offers to the communities of citizens and civil protection authorities a global observatory of ready-to-use differential interferograms**, and data analysis and data processing solutions on HPC cloud environment

geObservatory

IAASARS

BEYOND

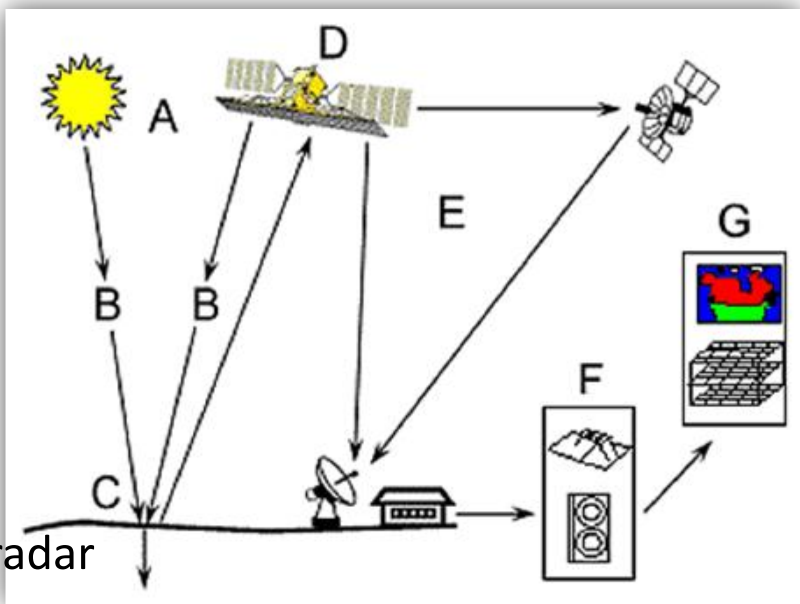


Outline

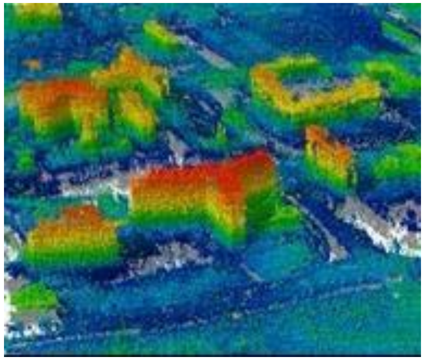
- Measuring deformation from space: basic SAR & InSAR theory
- Processing of big satellite SAR data and key examples
- geObservatory

Why Use Radar for Remote Sensing?

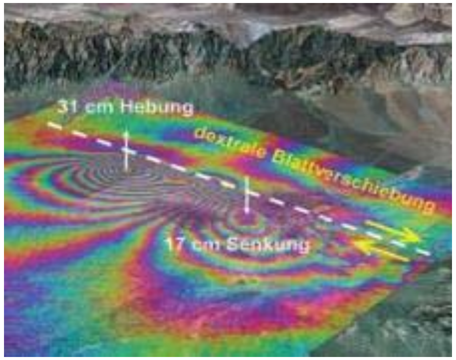
- Day-and-night imaging capability (not affected by clouds and not using sun light)
- Measure distances between sensor and ground
- Some surface features can be seen better in radar images:
  - ice, ocean waves
  - soil moisture, vegetation mass
  - man-made objects, *e.g*. buildings
  - geological structures
- New image products by coherent combination of radar images (i.e. using phase in the radar images)



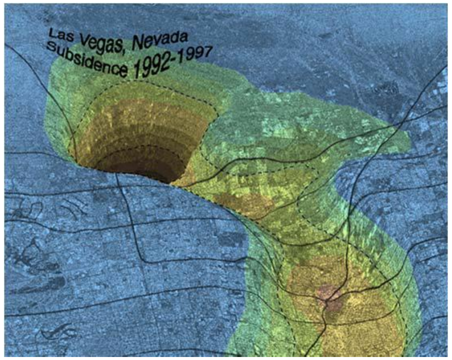
3D Mapping – DEM



Tomography – urban mapping

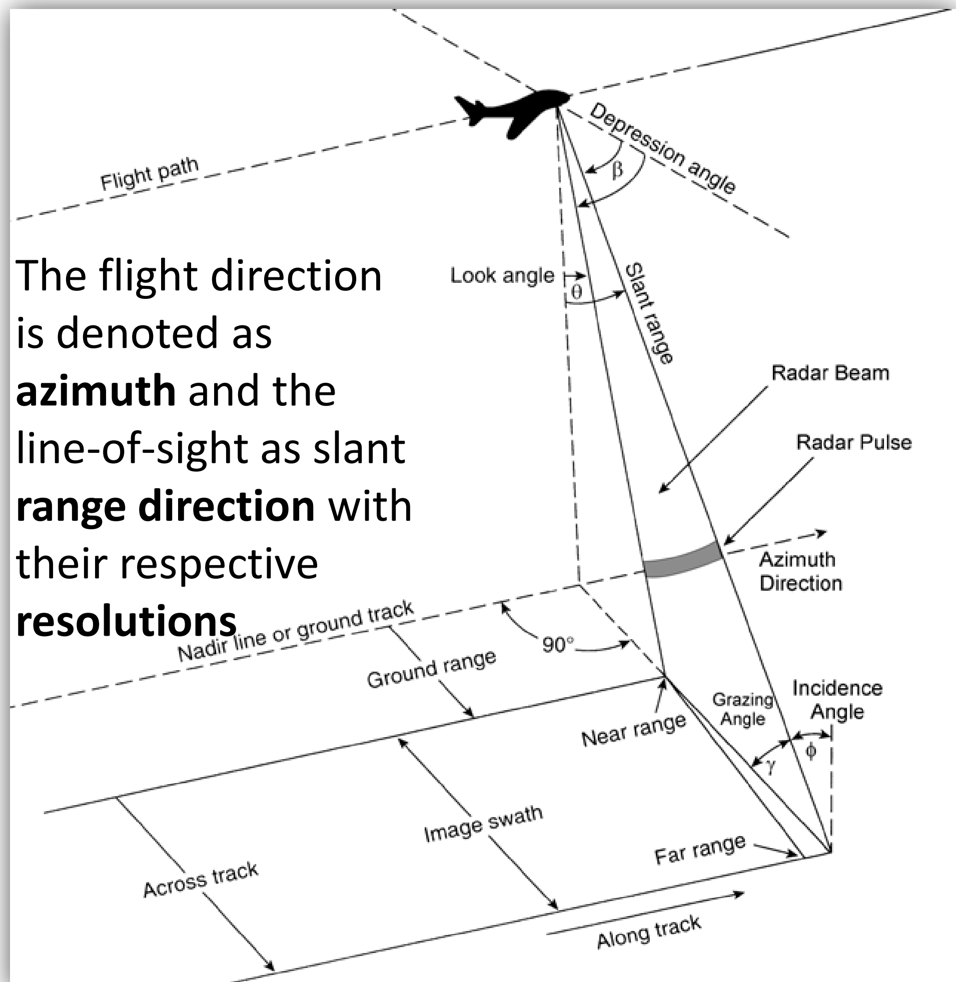


DInSAR Earthquake def.



DInSAR Subsidence

Radar jargon



The flight direction is denoted as **azimuth** and the line-of-sight as slant **range direction** with their respective **resolutions**

In the case of the first Side Looking Airborne Radar systems which are not using the principle of the SAR, a moderate azimuth resolution that deteriorates as the range distance increases is returned

In the case of X-band Radar system (wavelength λ=0,03μ) and a 3m antenna da, has a azimuth antenna beamwidth

$$\Theta_a = \frac{\lambda}{d_a} = \frac{0.03\,\mathrm{m}}{3\,\mathrm{m}} = 0.01\,\mathrm{rad},$$

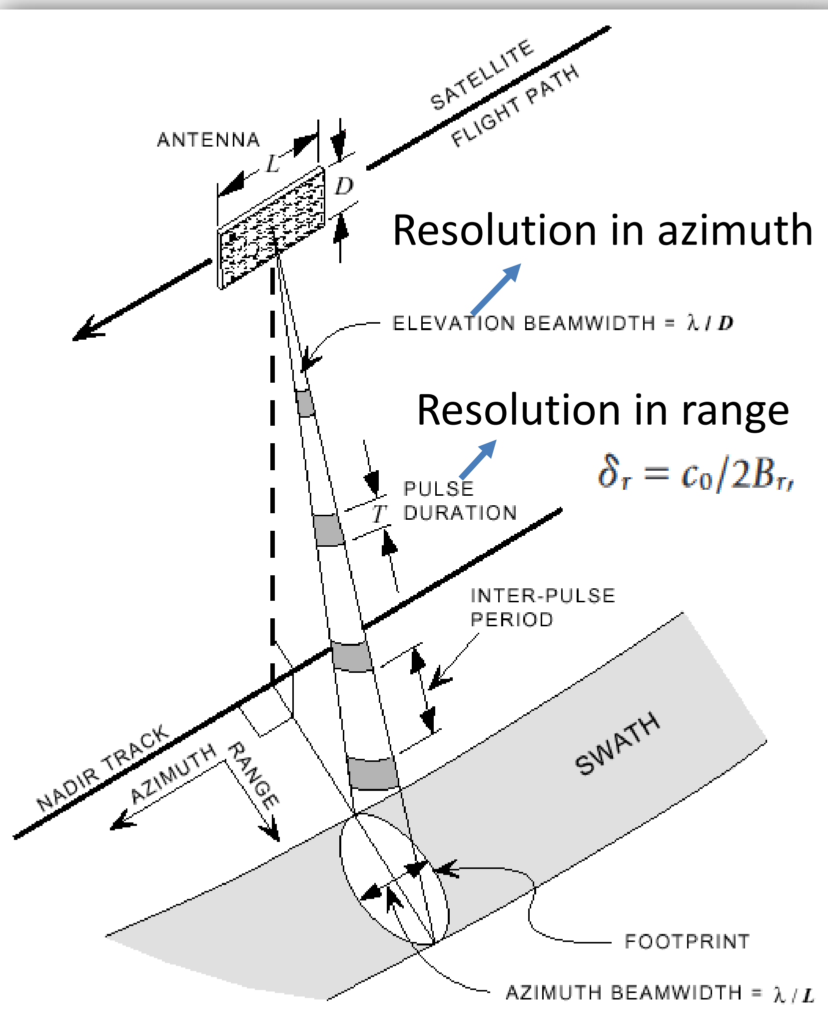
and assuming a slant range direction of 5km, **the corresponding azimuth resolution *δα***

$$\delta_a = \frac{\lambda}{d_a} \cdot r_0 = \Theta_a \cdot r_0 = 0.01 \cdot 5000\,\mathrm{m} = 50\,\mathrm{m}.$$

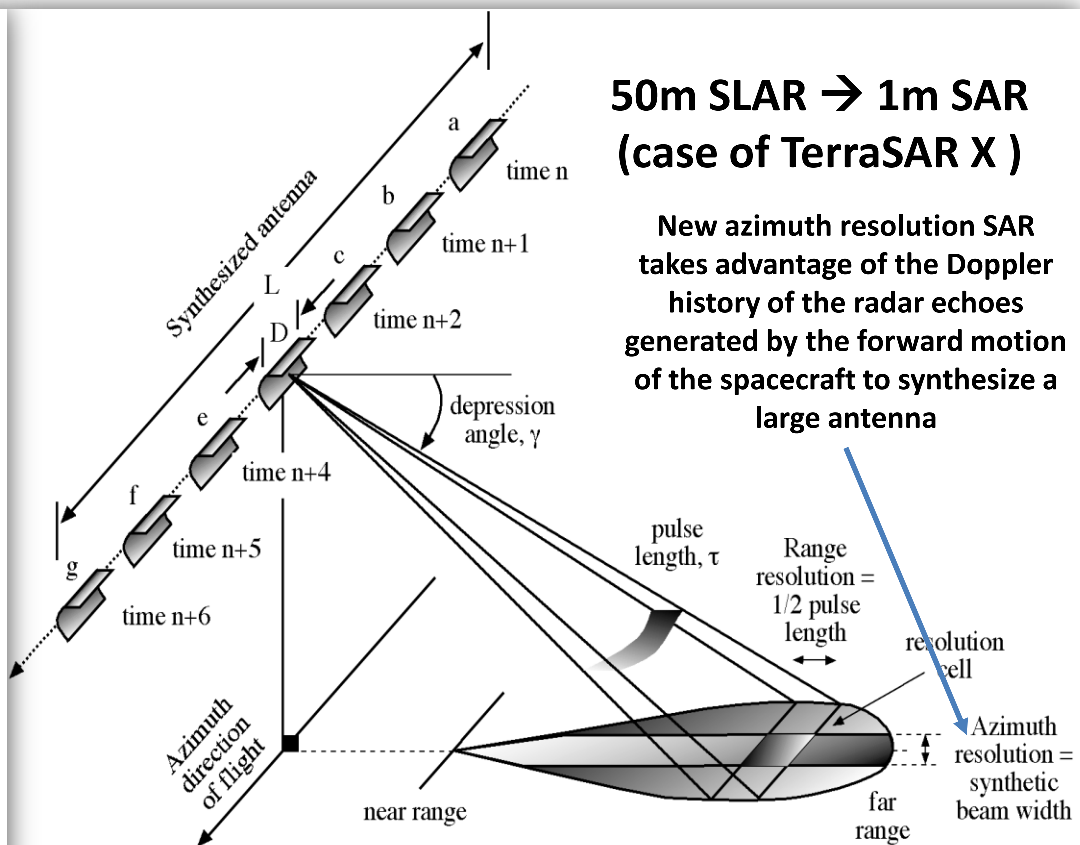
This rendered the technology inappropriate for space borne systems (500km-700km away) thus the invention of SAR imaging was introduced by Carl Wiley in 1951

From Real Aperture Radar to Synthetic Aperture Radar

Real Aperture Radar



Synthetic Aperture Radar



50m SLAR → 1m SAR (case of TerraSAR X)

New azimuth resolution SAR takes advantage of the Doppler history of the radar echoes generated by the forward motion of the spacecraft to synthesize a large antenna

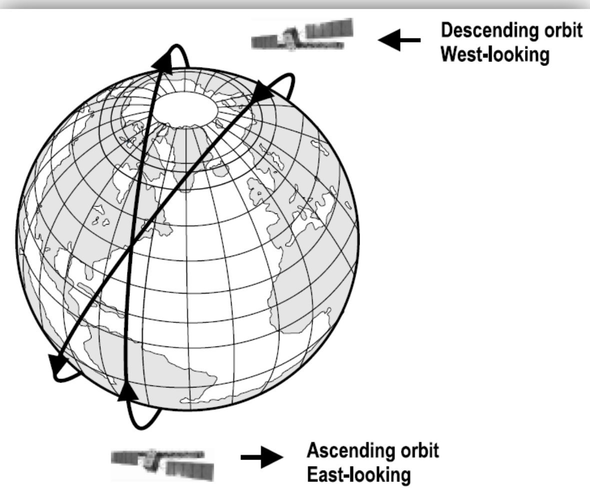
long synthetic aperture is favorable since it results in a narrow virtual beamwidth $\Theta_{sa} = \lambda/2L_{sa}$ (again, the factor 2 appears because of the two-way path from transmission to reception) :

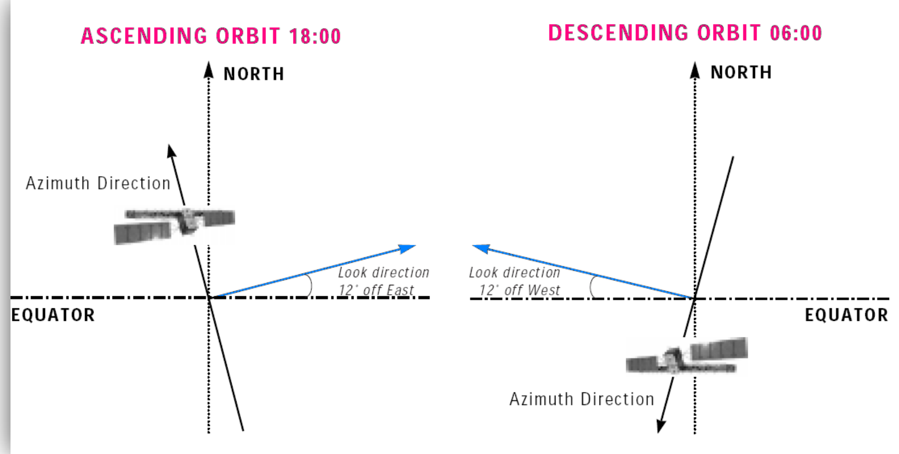
Radar jargon

Because of the great advantage in acquiring data during day and night the simultaneous use and combination of ascending and descending pass SAR data from various sensors allow to:

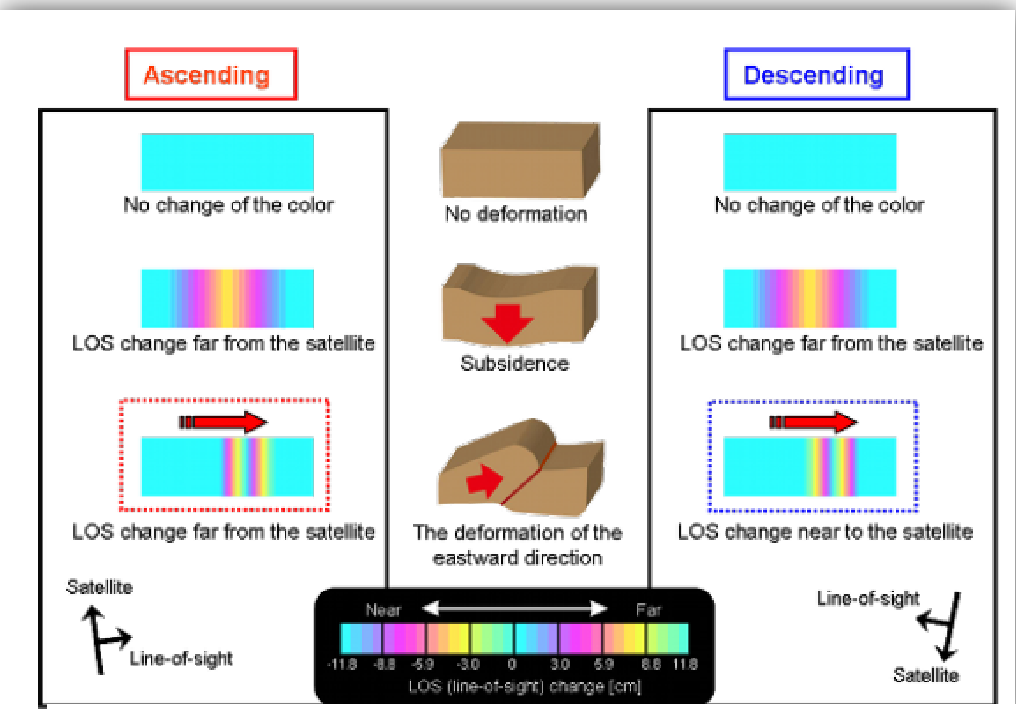
1. **Avoid the influence of layover and shadow effects and increase dramatically the:**
2. **Observational capability**
3. **Accuracy of the measured parameters**
4. **Temporal resolution**
5. **Full and timely coverage of the entire globe**

It favorites significantly the **InSAR** and **Multi-track InSAR methodologies,** which allow the **3-D decomposition of the deformation process and assesses its corresponding evolution in time**

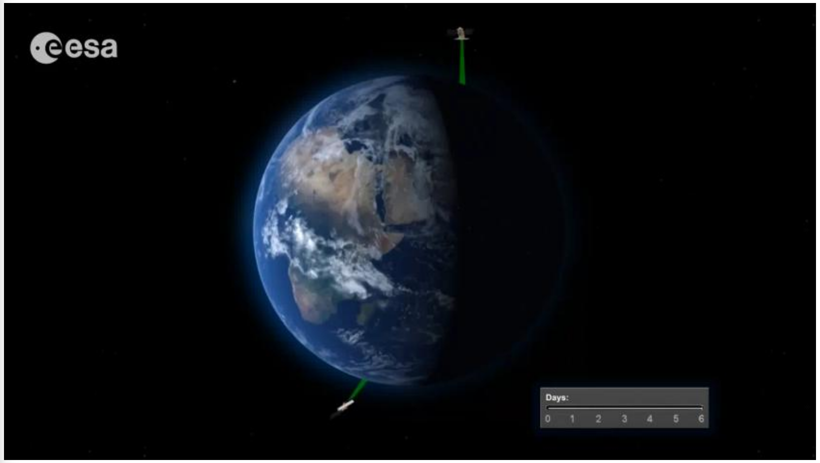




Combining descending & ascending data



Sentinel-1 coverage in 6 days



Hence, a synthetic Permanent Scatterer is generated, with associated ascending (V_A) and descending (V_D) velocity estimates. Using the synthetic values and taking into account the orientation of the employed LOS, the vertical (V_V) and east-west (V_E) ground velocity components were estimated, by solving—cell by cell—the following formulas [57]:

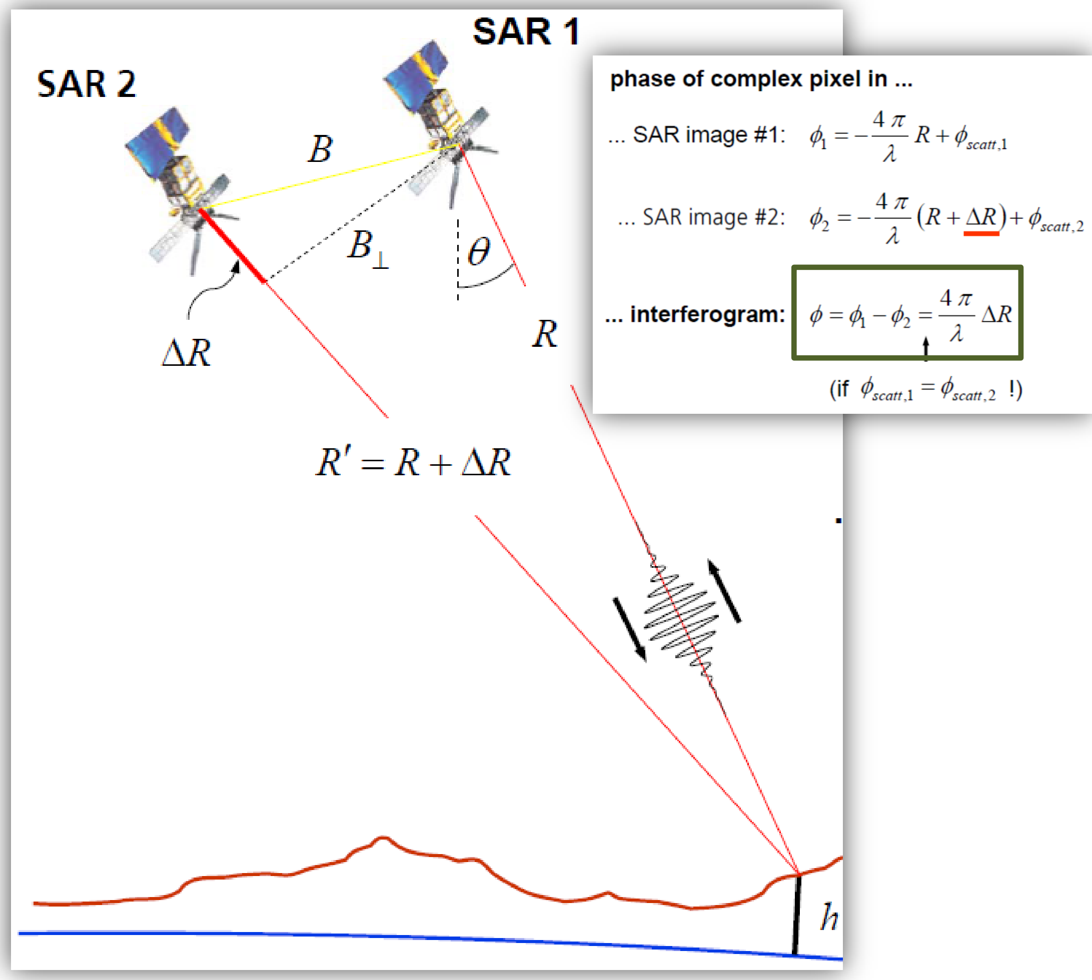
$$V_A = V_V \cos\theta_A + V_E \sin\theta_A \tag{1}$$

$$V_D = V_V \cos\theta_D + V_E \sin\theta_D \tag{2}$$

LOS of ERS1/2 and ENVISAT satellites have identical acquisition geometries and are characterized by incidence angle (θ), $\theta_A = \theta_D \sim 23°$.

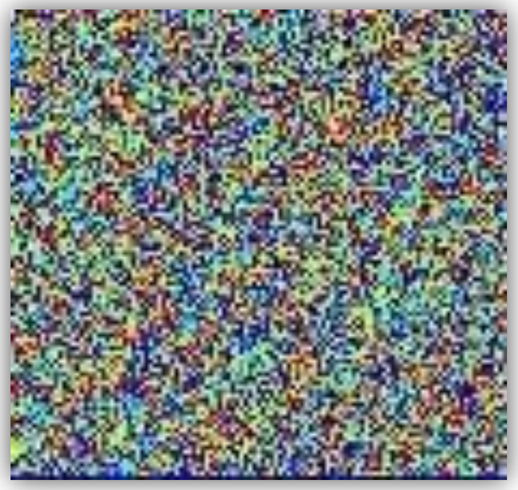
What is Radar Interferometry (InSAR)?

- **Radar interferometry** can be broadly defined by use of phase measurements to precisely measure the relative distance to an object when imaged by synthetic aperture radar from two or more observations separated either in time or space
  - ➢ Interferometric phase is simply another means of measuring (relative) distance
- **Repeat-pass interferometry**: when a single-antenna revisits the same position and images the same area on the ground after several days or weeks.
- **Interferogram**: the phase difference (ϕ) between two complex SAR images can be measured at the receiver. ϕ is a linear function of the ***LOS*** distance difference r1 minus r2.
- Fringes: the phase of the interferogram contains fringes that trace the topography and/or deformation like contour lines.



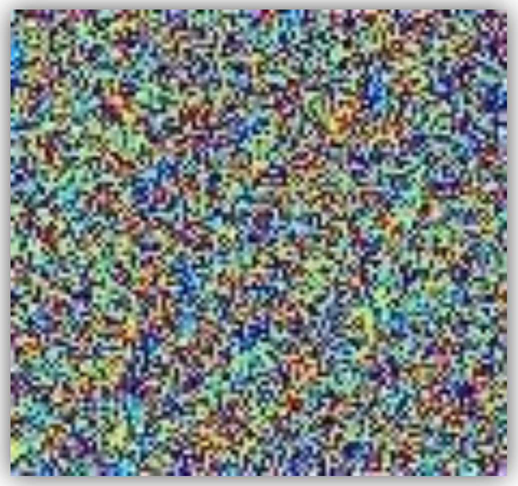
InSAR phase magic: from noise to information!

phase "master"



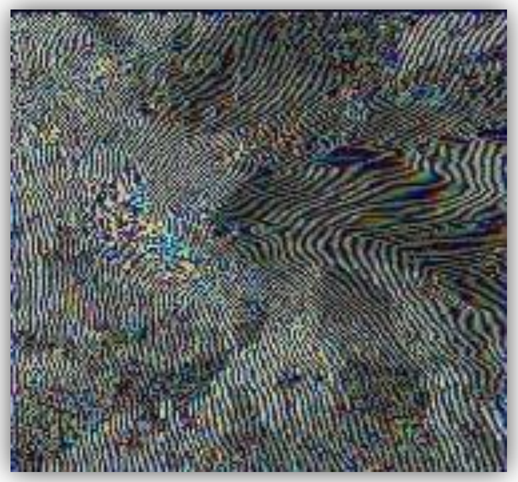
-

phase "slave"



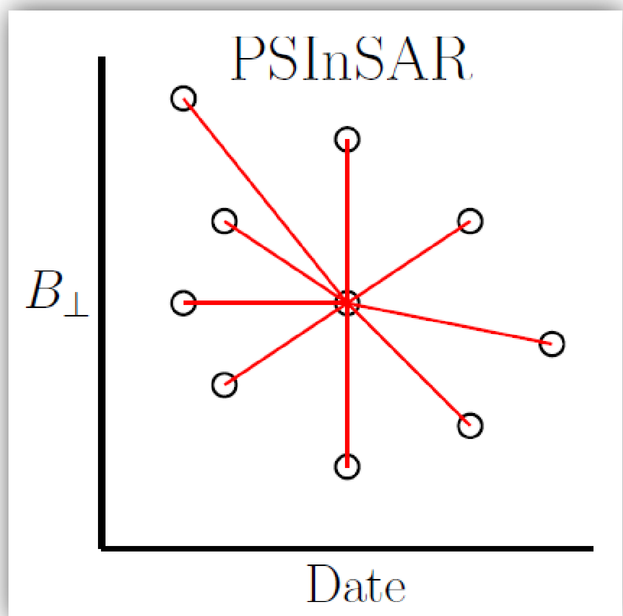
=

phase interferogram

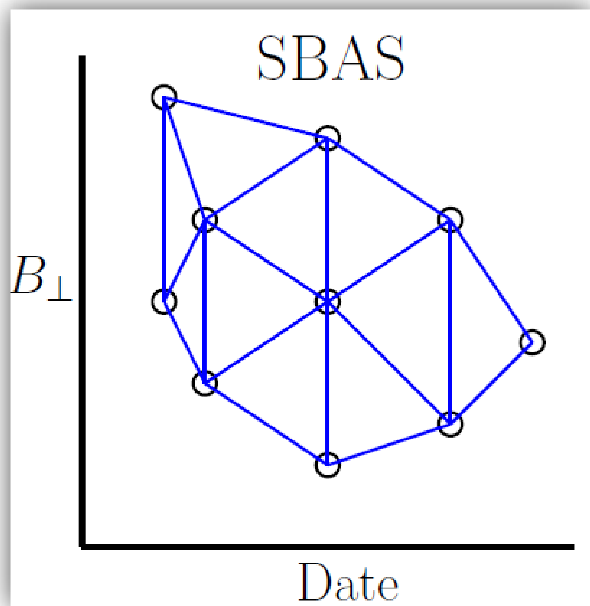


Time-series InSAR: PSI vs SBAS

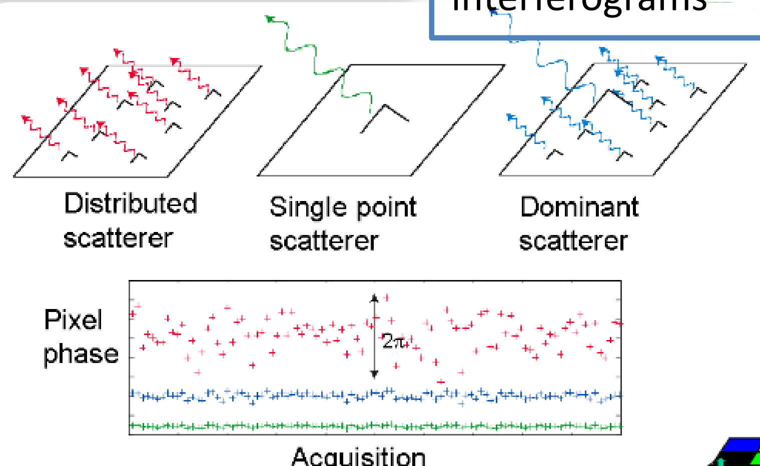
PS are corner reflector like resolution elements that are characterized by a dominant scatterer.



PS algorithms select interferometric data pairs about a single common master image, **without imposing any constraint on the temporal and spatial separation (baseline)** among the orbits



The SBAS techniques use differential SAR interferograms that are generated by **multiple-master images,** in order to have interferometric data pairs with **small temporal and spatial baselines**. Accordingly, **distributed targets can also be investigated** and the analysis may exploit both **single-look and multi-look** interferograms



Time-series InSAR: measuring diachronic ground deformation rates

Time-series techniques

Persistent Scatterers (PS) methods

- Popular with engineers
- Analysis at high resolution - single look pixel scale.
- Computationally intensive.
- Typically used for small area analysis and infrastructure monitoring

Short Baseline (SB) methods

- Popular with scientists
- Analysis at lower resolution - multi-look pixel scale.
- Typically used for large area analysis.

Hybrid methods

- Popular with engineers
- Best of both worlds – PS and SB
- Extension of PS techniques
- Newer approach and becoming more popular
- More robust approach

InSAR pros

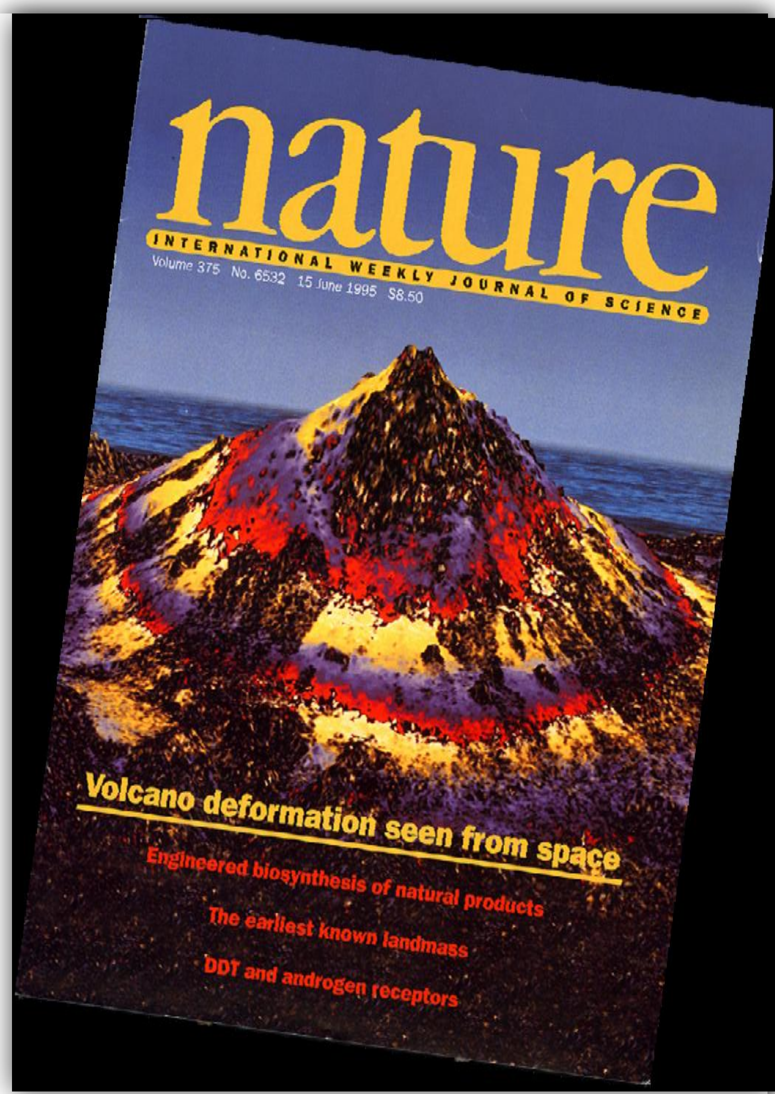
- Wide area coverage
- Centimeter/milmeter scale accuracy locally
- Geophysically useful even without other data sets
- Complementary to established geodetic (e.g. Satellite Geodesy and leveling)!

InSAR cons

- Not on demand processing, we have to stick with the satellite orbit and wait
- Not real-time processing
- Loss of coherence in non-urban areas
- Inherent SAR distortions due to topography
- Atmospheric variations affect measurement quality

Radar Interferometry (InSAR)

The routine monitoring over the years of the deformation status of all volcanoes from space based on big SAR data, is unique for feeding probabilistic and Machine Learning models that are increasingly inform hazard decisions and strategic development for resilient communities

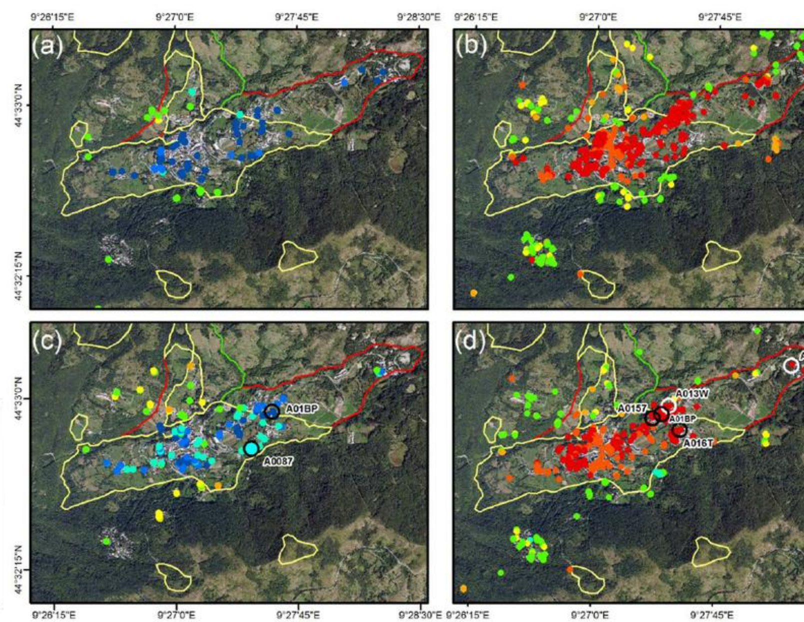


Radar Interferometry (InSAR)

SAR interferometry (InSAR) technique which has been developed to:

1. Detect, monitor and assess of the **dynamic of Earth's crust**
2. Monitor the surface extensions and assess with high precision **(mm→cm)** the deformations induced by:
   - **I. Extensive fractures** due to earthquakes **(of the order of cm→ a few meters)**
   - **II. Eruptions of active volcanoes** (of the order of cm→ a few meters)
   - **III. Pre-seismic tectonic** deformations (mm/year)
   - **IV. Slow-moving landslides** (mm/year)

Multi-interferograms SAR Interferometry (PSI) data available for the **Santo Stefano d'Aveto landslide**: (a) ERS1/2 ascending (1992 – 2000); (b) ERS1/2 descending (1992 – 2001); (c) ENVISAT ascending (2003 – 2008); (d) ENVISAT descending (2002 – 2008). PSI data overlapped onto Visual Earth imagery



Legend

Vel (mm/yr)		
-30.44 - -20.00	-9.99 - -5.00	1.51 - 3.25
-19.99 - -10.00	-4.99 - -3.00	3.26 - 5.00
	-2.99 - -1.50	5.01 - 11.46
	-1.49 - 1.50	

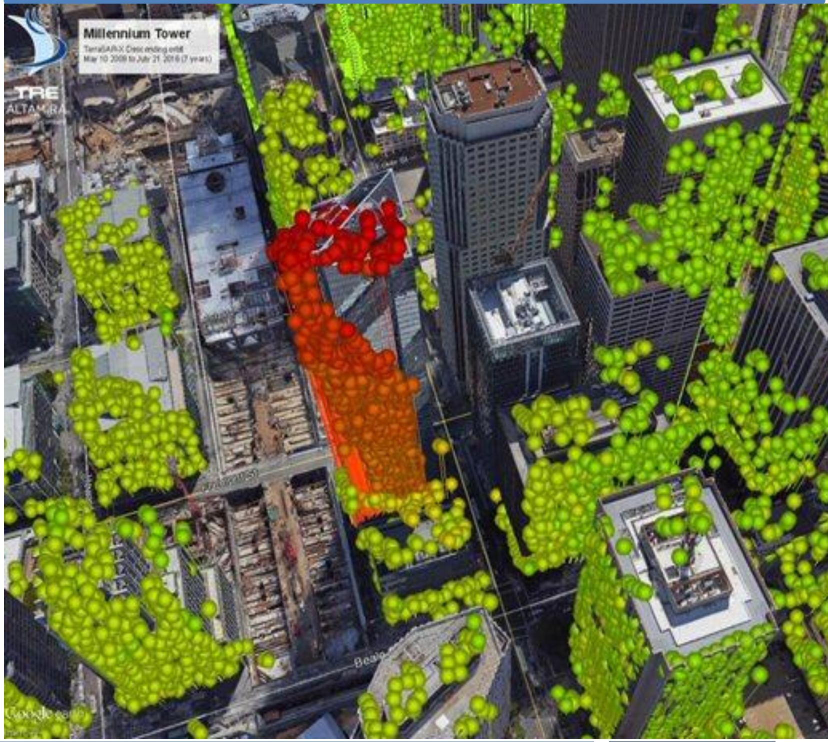
Tofani et al, **Persistent Scatterer Interferometry (PSI) Technique for Landslide Characterization and Monitoring**, Remote Sens. 2013, 5, 1045-1065; doi:10.3390/rs5031045

Radar Interferometry (InSAR)

SAR interferometry (InSAR) technique which has been developed to:

1. Detect, monitor and assess of the **dynamic of Earth's crust**
2. Monitor the surface extensions and assess with high precision **(mm→cm)** the deformations induced by:
   - **I. Extensive fractures** due to earthquakes **(of the order of cm→ a few meters)**
   - **II. Eruptions of active volcanoes** (of the order of cm→ a few meters)
   - **III. Pre-seismic tectonic** deformations (mm/year)
   - **IV. Slow-moving landslides** (mm/year)
3. Monitor changes in the environment due to **industrial and construction** activity
4. Monitor the **millmetric movement of buildings, facilities, and monuments** (mm/year)
5. Support the work of the city/site planners to **make cities resilient against the geophysical hazards**

600 measurement points on the **San Francisco Millennium Tower** capture motion from the foot of the building to the top. Analysis shows that the tower is moving down and away from the satellite as measured along the line of sight from the satellite to the tower at an annual rate of **26 millimetres per year (by TRE ALTAMIRA)**

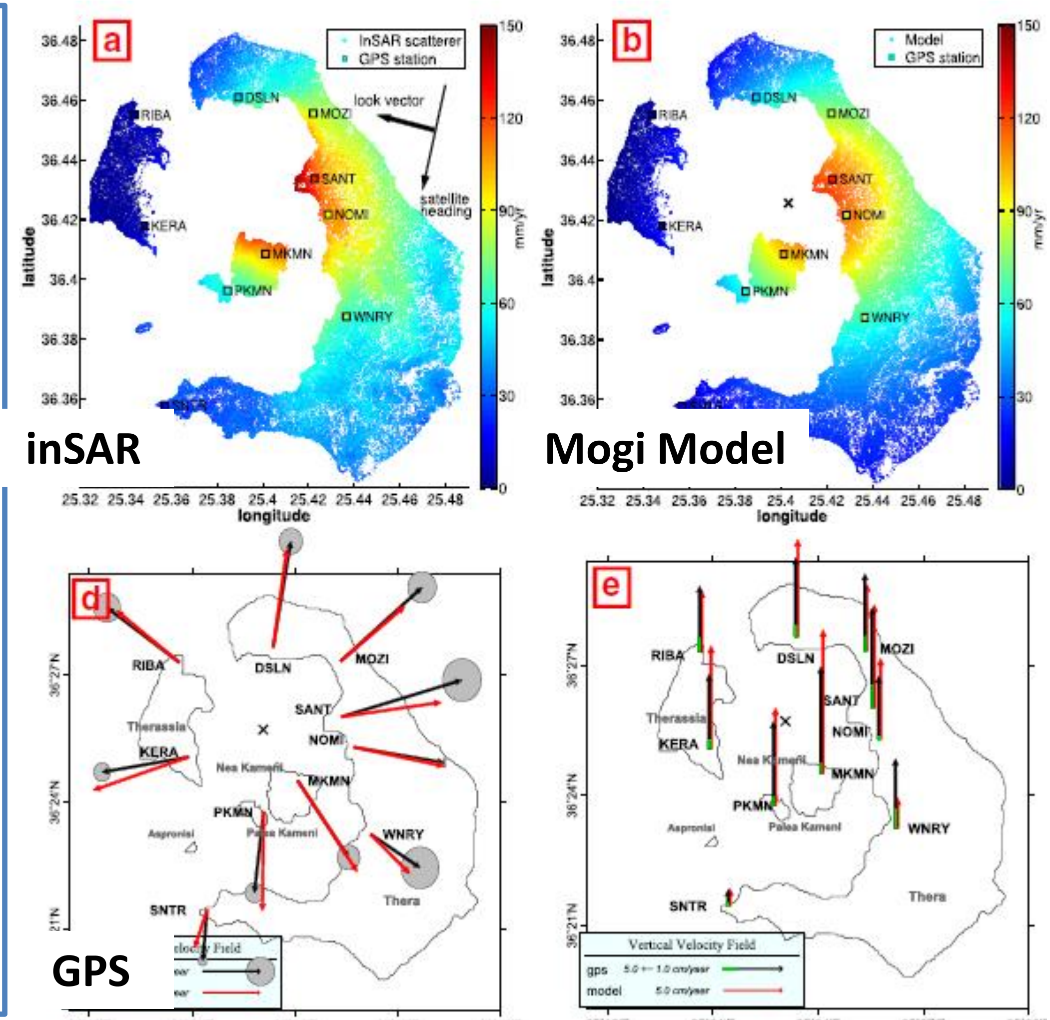


InSAR: The earth is breathing!

SAR & InSAR theory

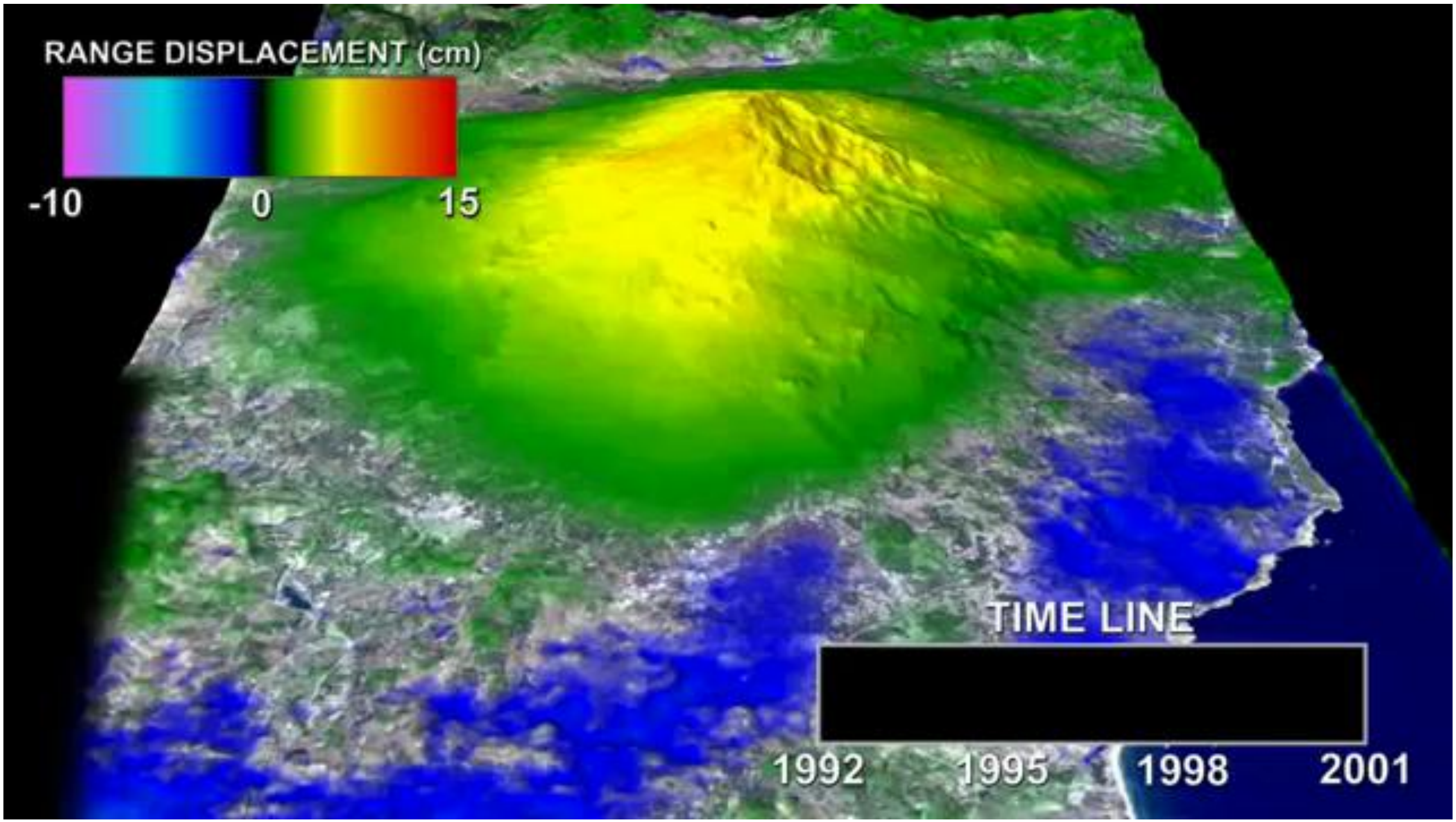
Interferometric Synthetic Aperture Radar

Mapping inflation of Santorini volcano, Greece, from 01/2011 to 02/2012 **using GPS and InSAR (ENVISAT Data processed with PSI&SBAS techniques).** A clear and large inflation signal, **up to 150mm/yr in the LOS direction**, with a radial pattern outward from the center of the caldera is observed. The deformation pattern was model using a Mogi source located north of the Nea Kameni island, at a depth **between 3.3km and 6.3km and with a volume change rate in the range of 12million m³ to 24 million m³ per year (by BEYOND GeObservatory)**



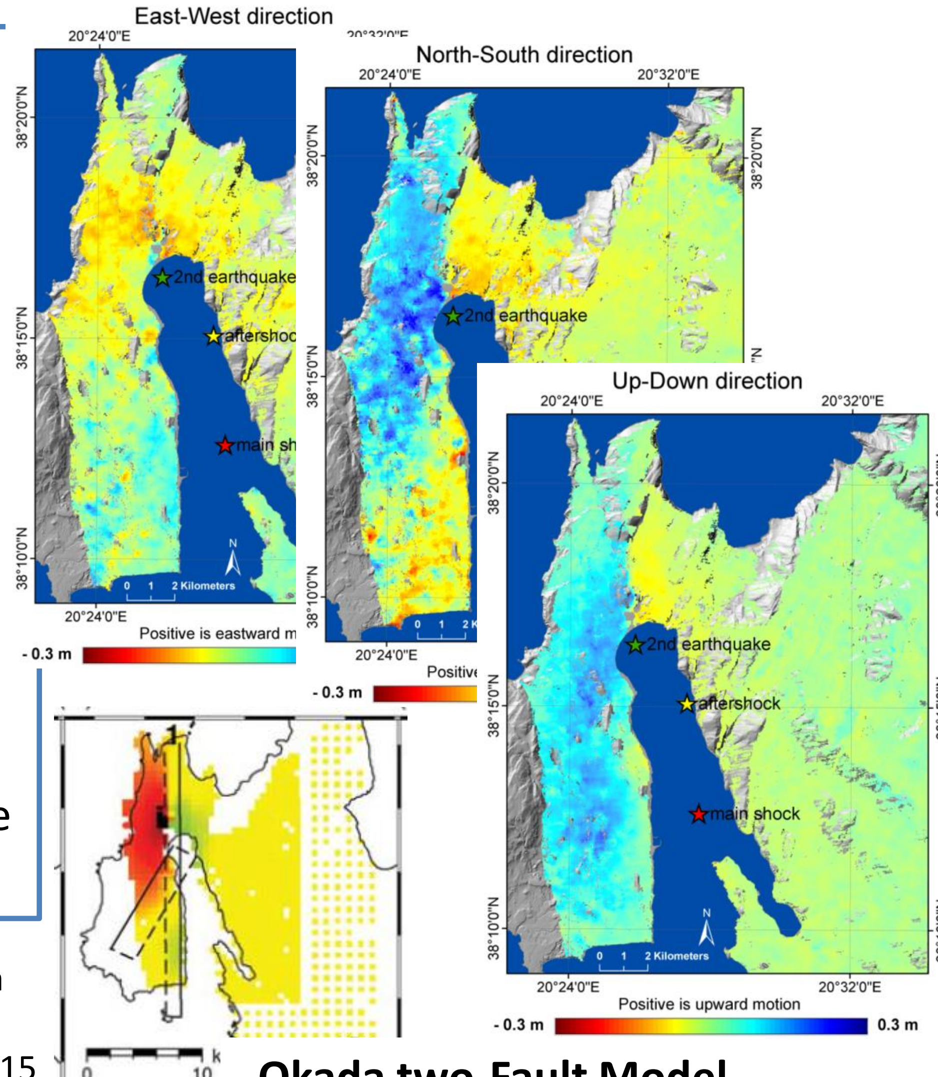
Papoutsis et al, Mapping inflation at Santorini volcano, Greece, using GPS and InSAR, GRL, Vol. 40, 267–272, doi:10.1029/2012GL054137, 2013

InSAR: The earth is breathing!



InSAR for measuring ground deformation after abrupt events

The complex sequence of EQs that struck the island of Cephalonia, Greece, started on 26 January 2014 at 13:55 UTC, Mw 6.0, and followed five hours later by an Mw 5.3 aftershock and by an Mw 5.9 event on 3 Feb 2014 at 03:08 UTC. SAR image pairs spanning the second mainshock were acquired on **descending and ascending passes**, by the **COSMO–SkyMed and TanDEM-X** satellite missions. **East, North, and Up displacement** components associated with the EQ, indicate a **strong horizontal and vertical displacement of up to 30 cm**. Using Okada model a two-fault model reproduced the observed DInSAR surface displacements **(by BEYOND GeObservatory)**

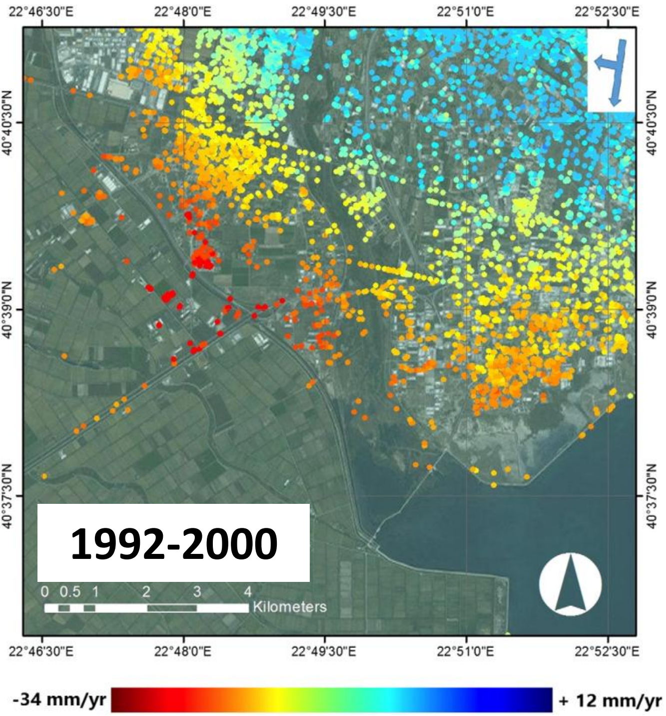


J.P. Merryman Boncori et al, The February 2014 Cephalonia Earthquake (Greece): 3D Deformation Field and Source Modeling from Multiple SAR Techniques, **SRL, Vol86, No 1,** 2015

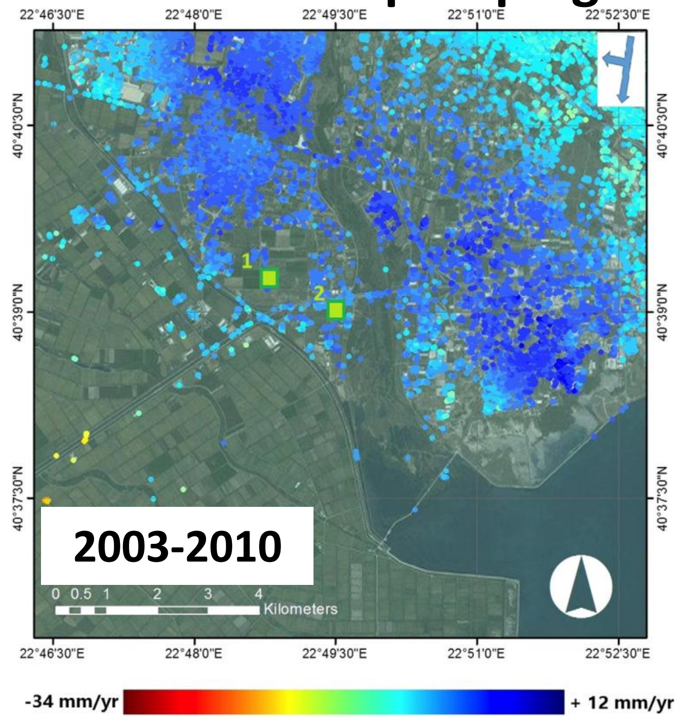
Okada two-Fault Model

InSAR for measuring land subsidence due to excessive water pumping

InSAR based land subsidence in the western side of Thessaloniki, recorded since the early 1960s and **reaching gradually up to 3–4 m** was assessed**. PSI and SBAS multi-temporal Interferometry** was applied to analyse the **20 year ERS 1, 2 and ENVISAT** data. The ERS dataset depicted **subsidence up to 35mm/year for the period 1992-2000**.



Svigkas Nikos et al, Land subsidence rebound detected viamulti-temporal InSAR in Kalochori and Sindos regions, Northern Greece, **Engineering Geology 209 (2016) 175–186**

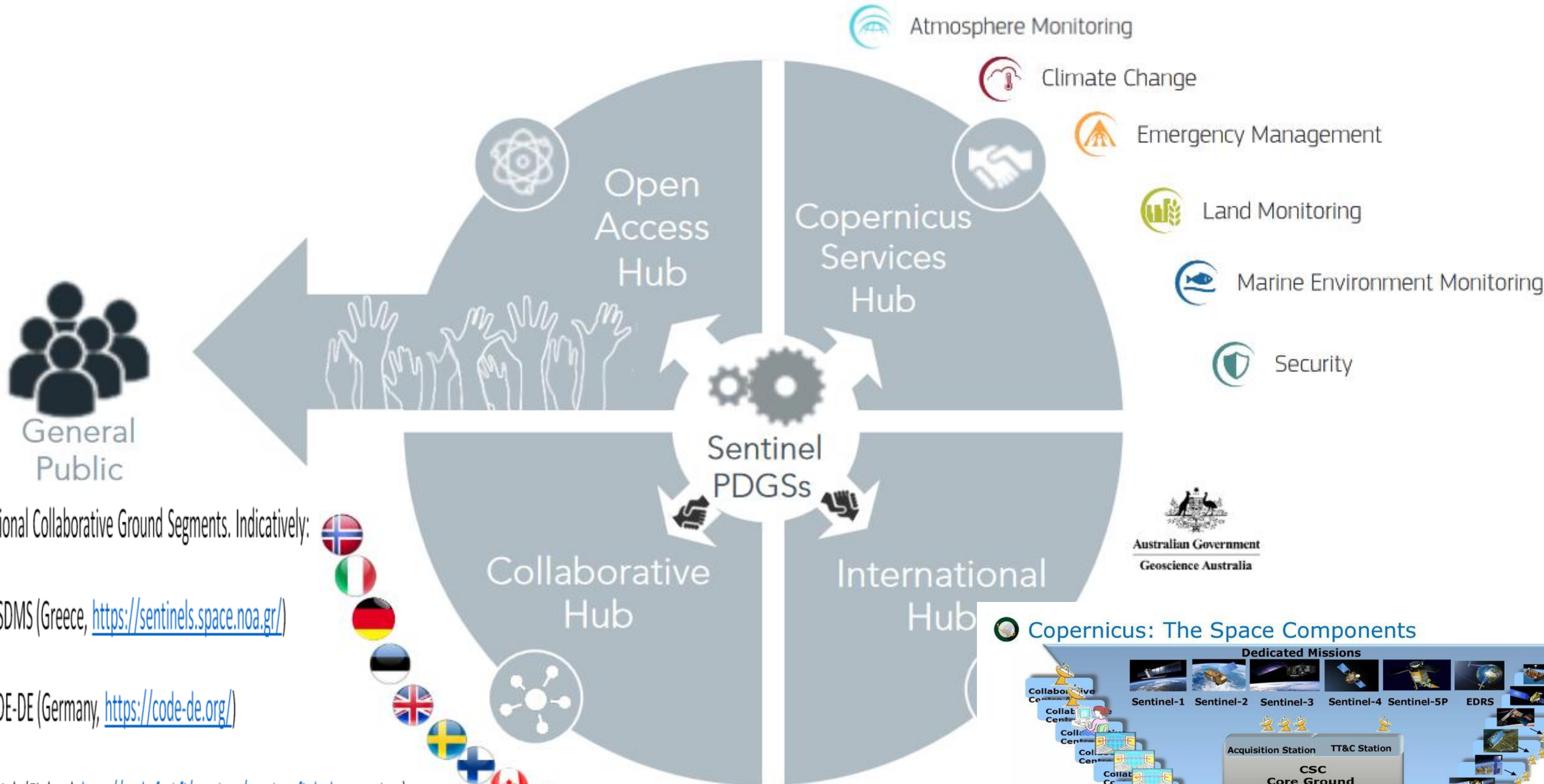


The ENVISAT data (2003–2010) showed that there was a change **from subsidence to uplift, a motion that is well correlated with hydrogeological data that showed a synchronous rise of the aquifer level**. The dominating driver of the human factor concerning the land subsidence phenomena for the last 55 years is obvious

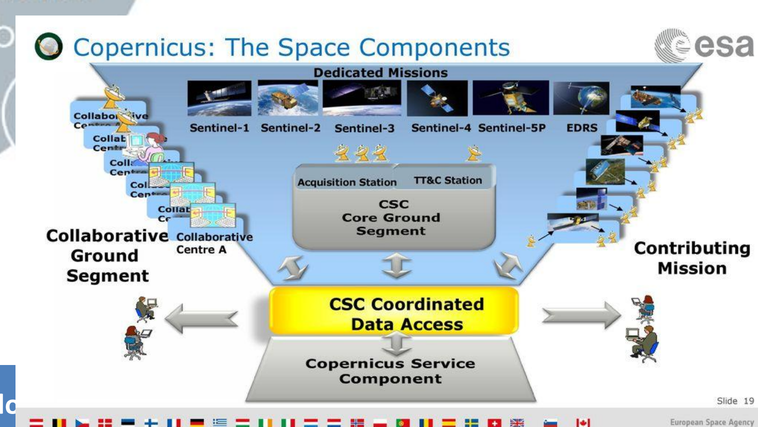
IN THE ERA OF BIG SATELLITE DATA THE GEOBSERVATORY SEARCH ENGINE FOR FEDERATED ACCESS TO DATA

Leveraging different Copernicus access Hubs
and National Mirror Sites
for large scale interferometric processors
to monitor geohazards

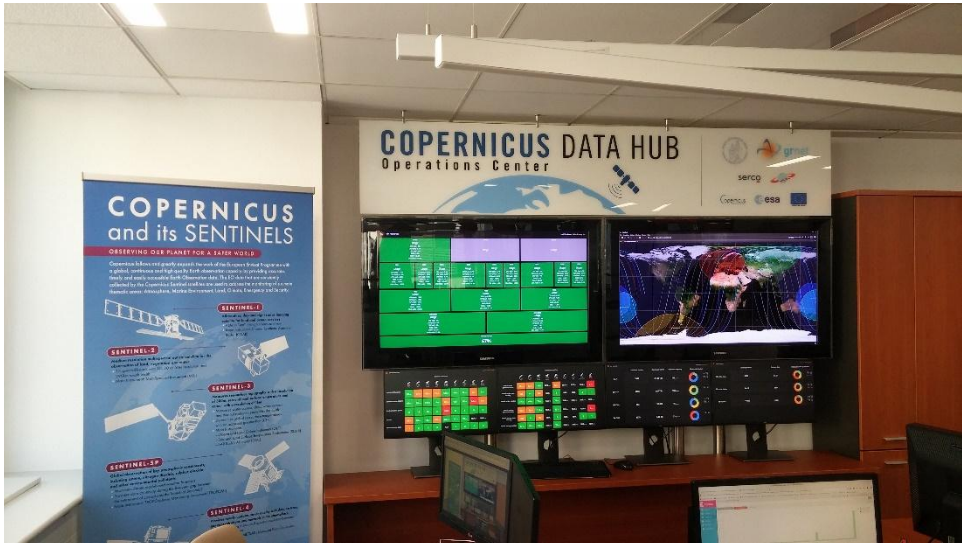
Copernicus Sentinel Data Access



- 23 National Collaborative Ground Segments. Indicatively:
  - ✓ HNSDMS (Greece, https://sentinels.space.noa.gr/)
  - ✓ CODE-DE (Germany, https://code-de.org/)
  - ✓ FinHub (Finland, http://nsdc.fmi.fi/services/service_finhub_overview)
  - ✓ Peps (France, https://peps.cnes.fr/rocket/)



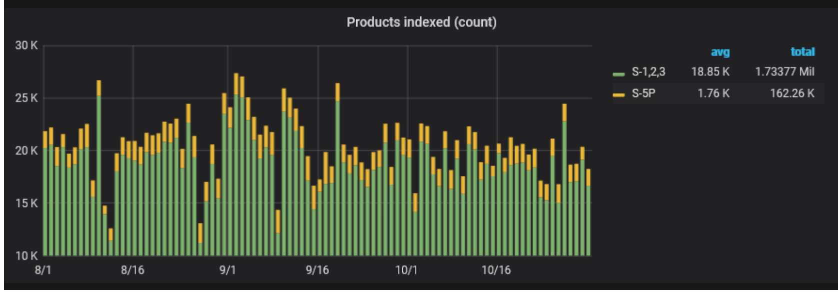
Sentinels Greek Hub | Operations bridge

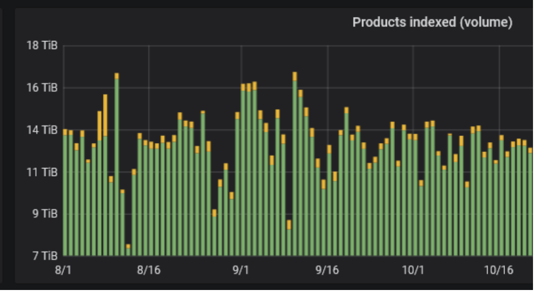


Sentinels Greek Hub | Some numbers!

What's coming in

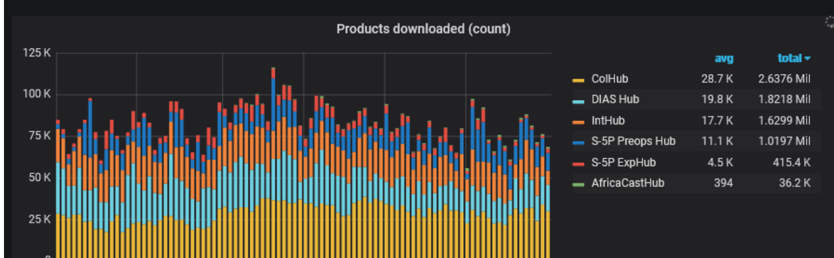
On average:
~20K products (13TiB) / day or
~600K products (390TiB) / month
~2 Gbps

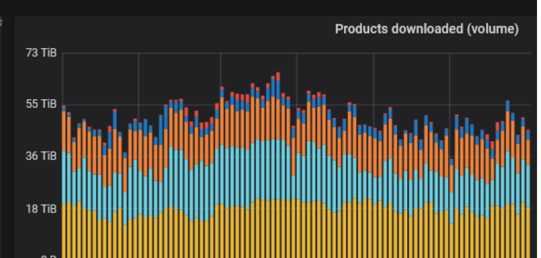




What's going out

On average:
~80K products (50TiB) / day or
~2.5M products (1.5PiB) / month
~6 Gbps





SENTINELS GREEK HUB

- ❑ INTHUB #1
- ❑ COLHUB #3
- ❑ DIASHUB #3
- ❑ AfricaCastHub
- ❑ S-5p PreOps Hub
- ❑ S-5p Expert Users Hub
- ❑ TMPHUB #1
- ❑ HNSDMS

58 Virtual Machines:

- **~1 TB RAM**
- **~530 virtual CPUs**
- ~4.5 TB disk storage

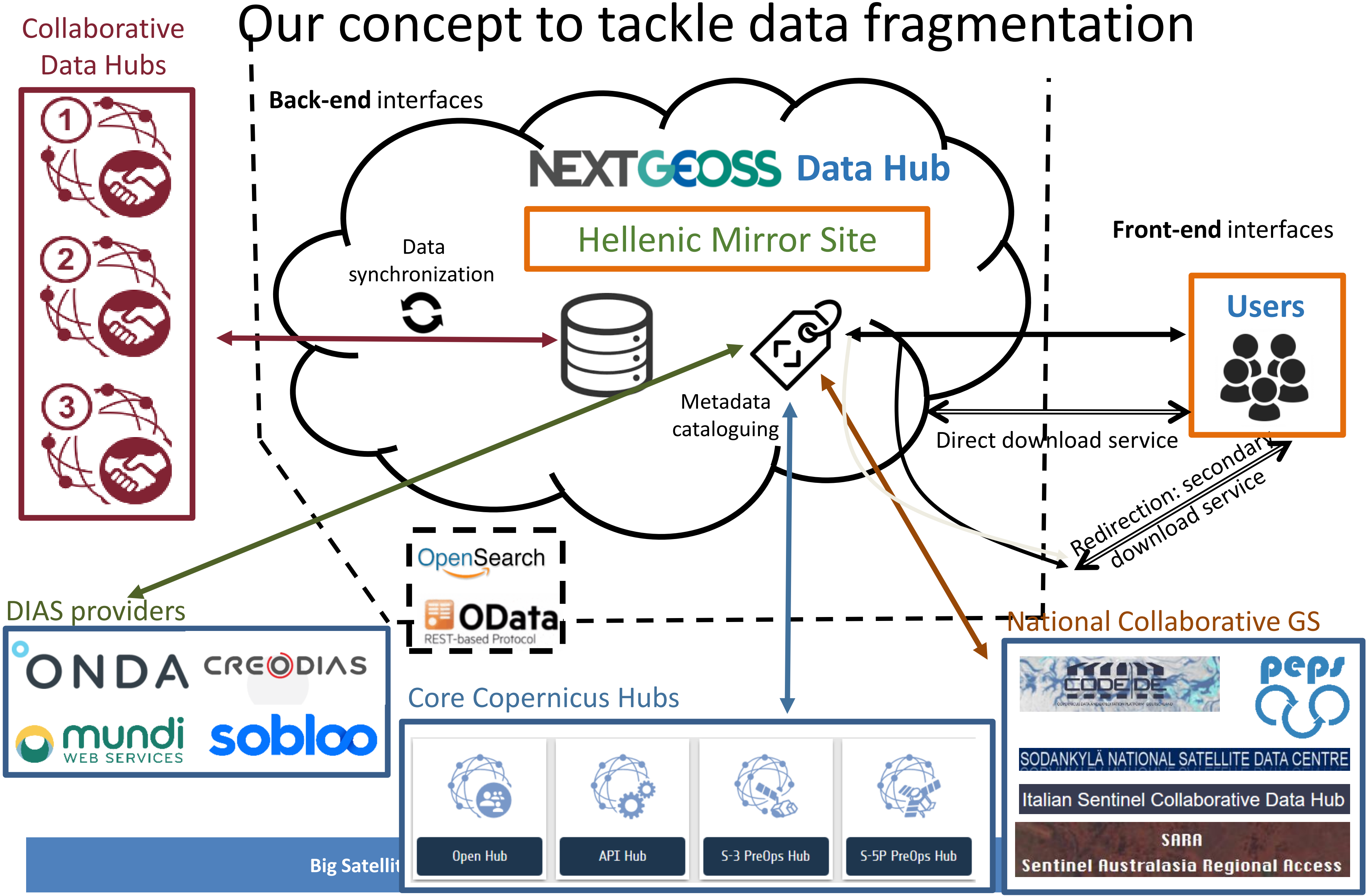
A **550 TB** network filesystem for storing > **500 thousand** Sentinel products at any time

Fragmented access to Sentinel data

- The hubs have different data offer
  - Availability of different missions and different products per sensor
  - Geographic coverage within which Sentinel products are available (e.g. see the Greek Collaborative Ground Segment AOI
  - Maximum concurrent downloads allowed
  - Data rolling policy (even SciHub has adopted a rolling policy)
  - Serve different user types
- The hubs experience different performances
  - Downloading speed
  - Integrity
  - Number of published products
  - Response times
  - Availability
  - Product latency
- Even for the same hub there is intra-day, and intra-product variability in terms of KPIs

Distribution of SAR data

Our concept to tackle data fragmentation



Advantages

- Linking federated Copernicus Sentinels Hubs
- Access to a single hub instead of looking across several Sentinel Hubs to find the appropriate products for your application
- Access to all Sentinel mission data, no geographic restrictions
- Better timeliness and reduced lead times for accessing Sentinel products ------> more important for disaster management applications
- Less performance variability by exploiting Hub diversity

THE GEOBSERVATORY SOLUTION FOR BIG SATELLITE DATA PROCESSING ON THE CLOUD

Why Cloud services

Requirements

- InSAR and time series InSAR applications take as input but also produce massive volume of data and have extreme power processing needs. (Processing results can often reach a size scale of TBs for an area of few degrees.)
- The new SAR sensors increase further the requirement of "Big Data" (Sentinel-1's C-SAR SLC products size 4-5 GB each!).
- ESA provides open web access to many sensor's data including C-SAR through Copernicus hubs

Cloud Services could offer

- Accessing high quantity of remote resources for storage and processing.
- Ease of scale up for processing and storage requirements
- Fast and secure data networks through internet and VPNs.
- Input data collection, data processing and presentation of results could be entirely handled by the Cloud service.

StaMPS impementation to Terradue (Sentinel-1 input)

Open Web

Copernicus Hub

Orbit Data repository

DEM repository

Sentinel -1 SLCs

Process: Create SLC stack
Software: ISCE (topsStack)

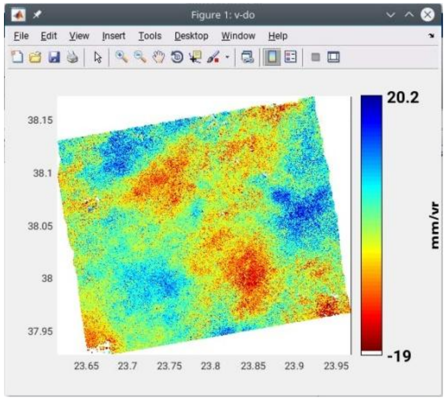
Process: Divide area of interest to sections called "Patches"
Software: StaMPS

Process: Parallel processing of area divided "Patches"
Software: StaMPS, Terradue Hadoop workflow

Process: Aggregation of "Patches and final calculations
Software: StaMPS, Terradue workflow

Process: Publish Results
Software: Terradue workflow

StaMPS sample plot



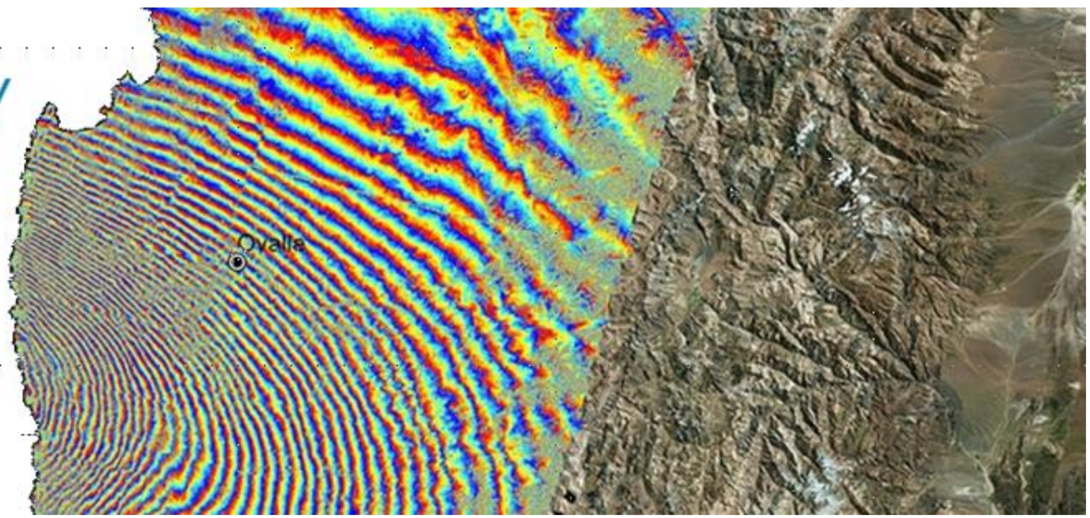
GEOBSERVATORY OPERATIONAL APPLICATION IMPLEMENTED BY BEYOND

geObservatory

geObservatory

IAASARS

BEYOND



geObservatory | In a nutshell

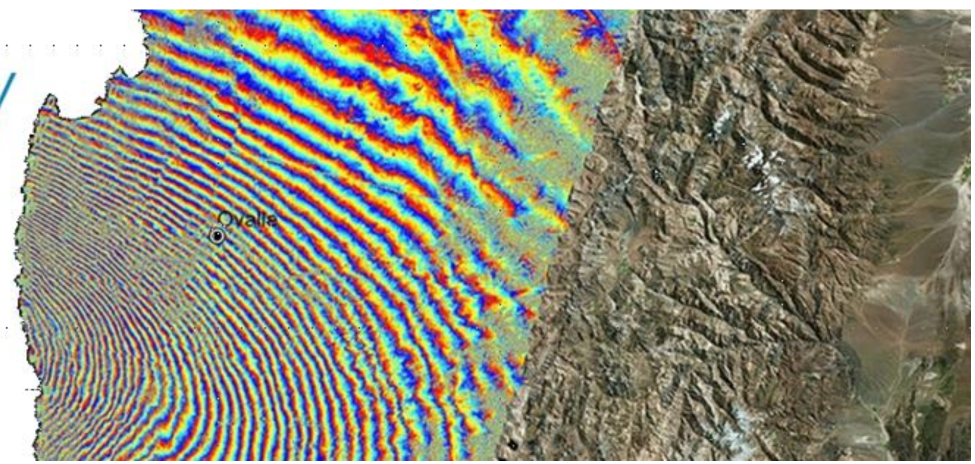
GeObservatory is activated automatically in major geohazard events (earthquakes, volcanic activity, landslides,etc.) and automatically produces a series of Sentinel-1 based co-event interferograms (DInSAR) to map the surface deformation associated with the event.

http://beyond-eocenter.eu/index.php/web-services/geohub

geObservatory

IAASARS

BEYOND



geObservatory | Activation

- Manual activation. An authorized user provides to the application a json file delineating the Area of Interest and registering the timestamp of the event.

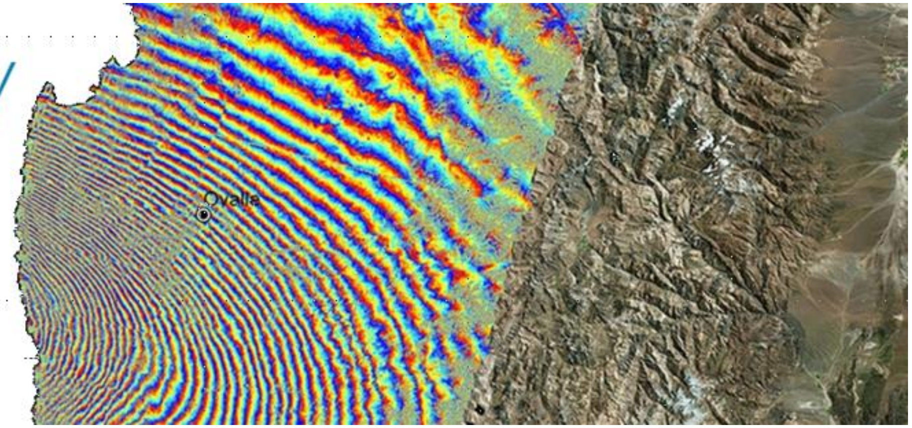
- Automatic activation. GeObservatory connects to EMSC and is activated when a major earthquake occurs. Criteria for the activation of GeObservatory is the magnitude of the earthquake and its depth.

http://beyond-eocenter.eu/index.php/web-services/geohub

geObservatory

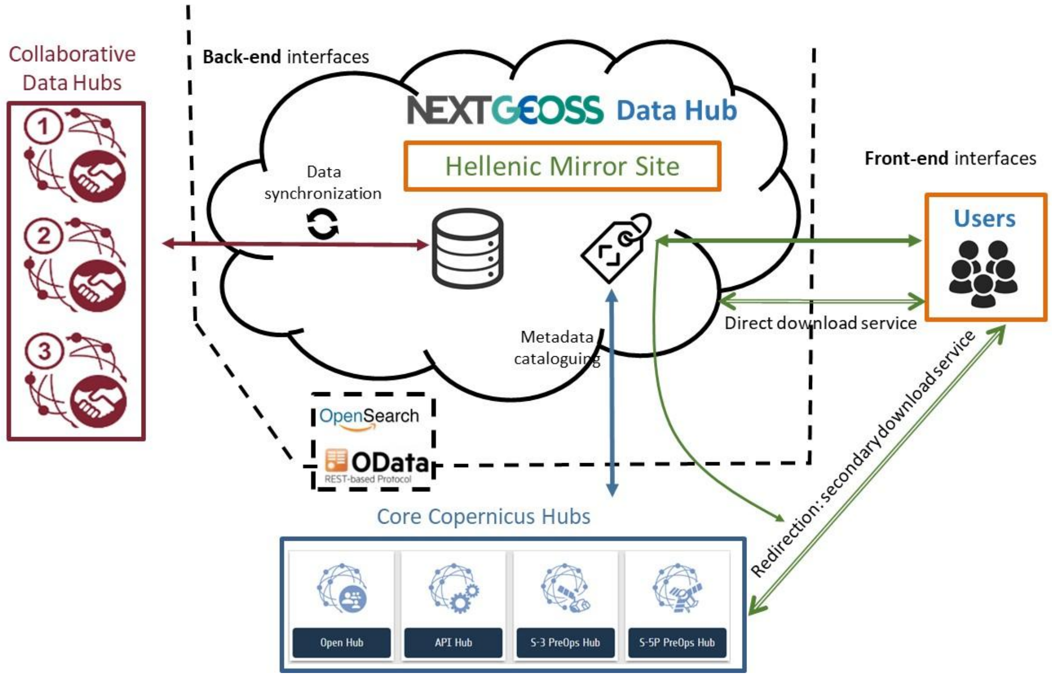
IAASARS

BEYOND

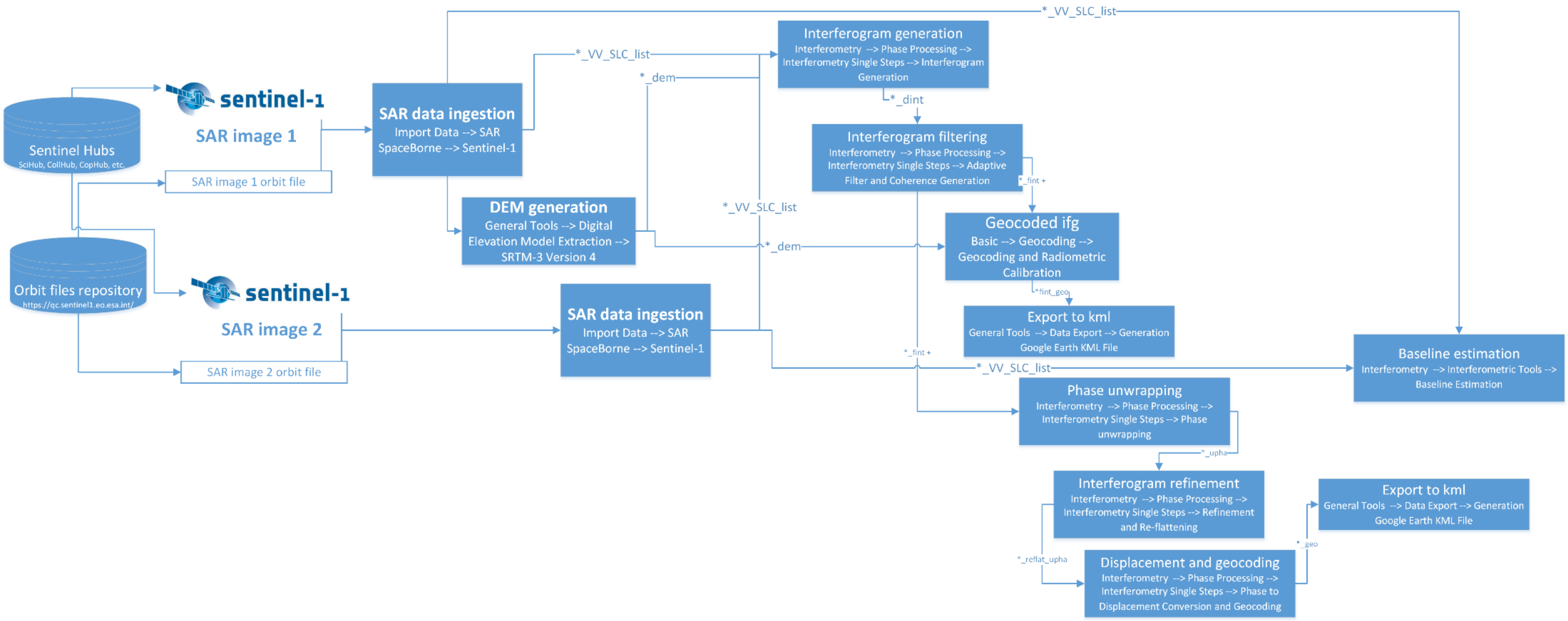


geObservatory | Input data

After the system is triggered, the application automatically scans different Copernicus hubs, including the Greek Collaborative Ground Segment, to find the appropriate Sentinel-1 satellite data for interferometry.

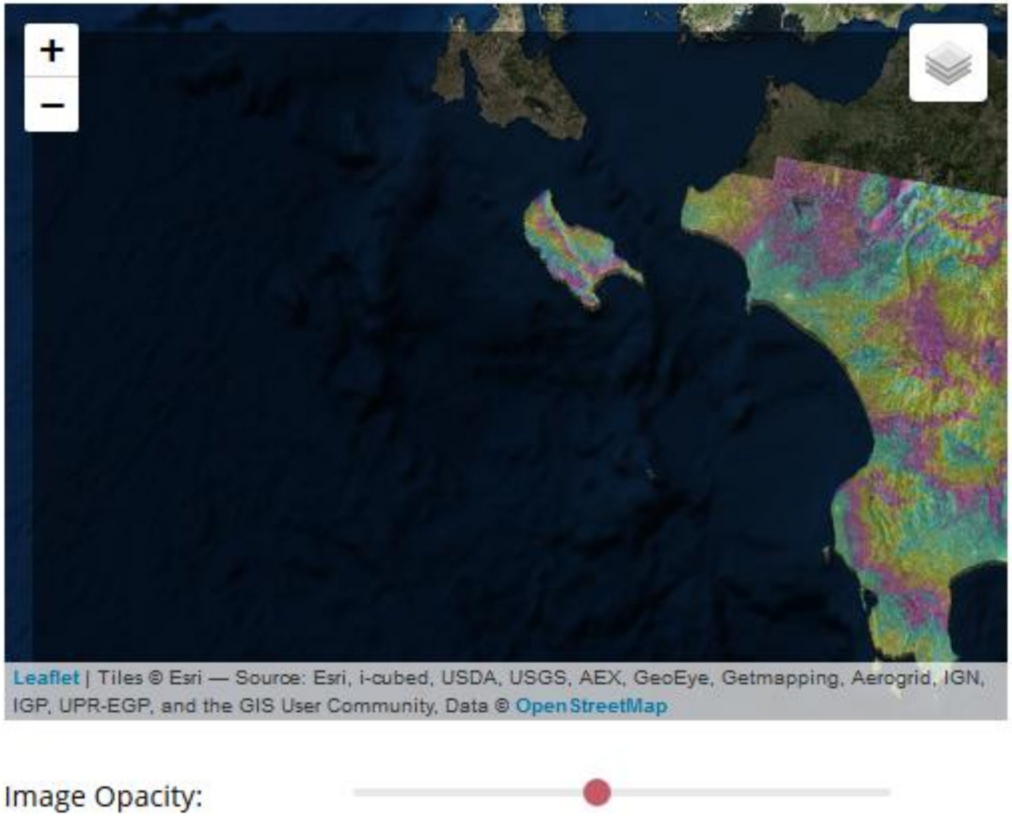


geObservatory | Interferometric processing



geObservatory | Interferograms

- High resolution tiff available for download
- Quicklook interferogram in PNG
- Online viewing using Leaflet technology

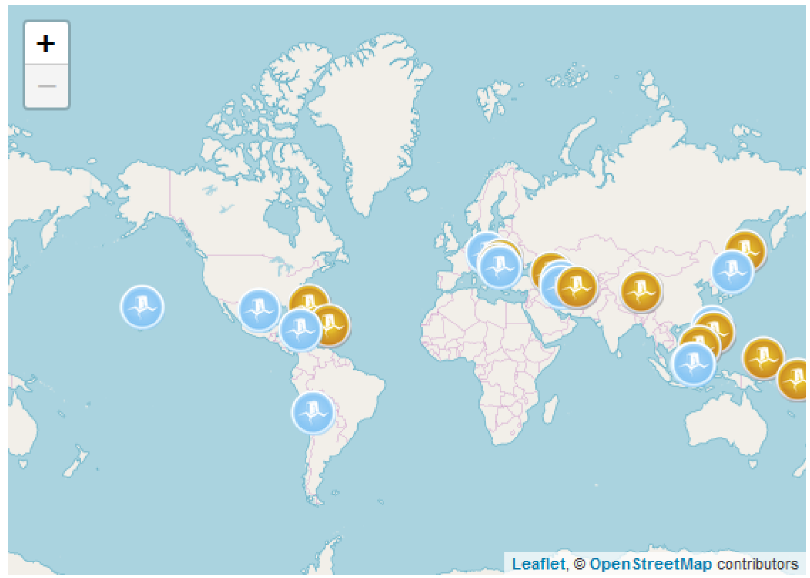


geObservatory | Front-end

HOME | HOW DOES IT WORK? | SENTINEL DATA | DISCLAIMER

Recent Events

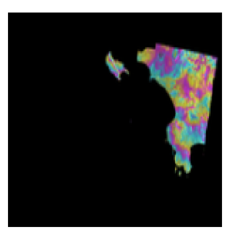
Historic Events



Recent event (Last 90 days)

Historic event

Last 5 events

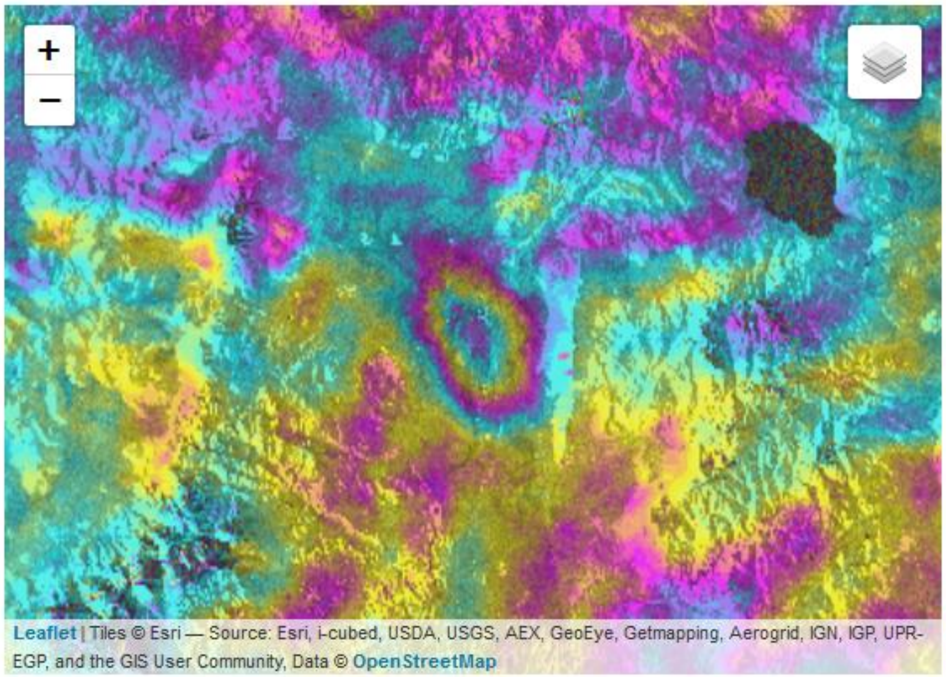


[IONIAN SEA (2018-10-25 22:54:51)]

WESTERN TURKEY (2019-03-20 06:34:27)

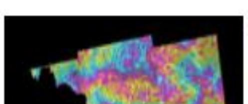
Earthquake location: WESTERN TURKEY

Magnitude: 6.4



Ascending

Interferograms



Type: co-seismic

Master: 2019-03-16 16:06:08

IONIAN SEA (2018-10-25 22:54:51)

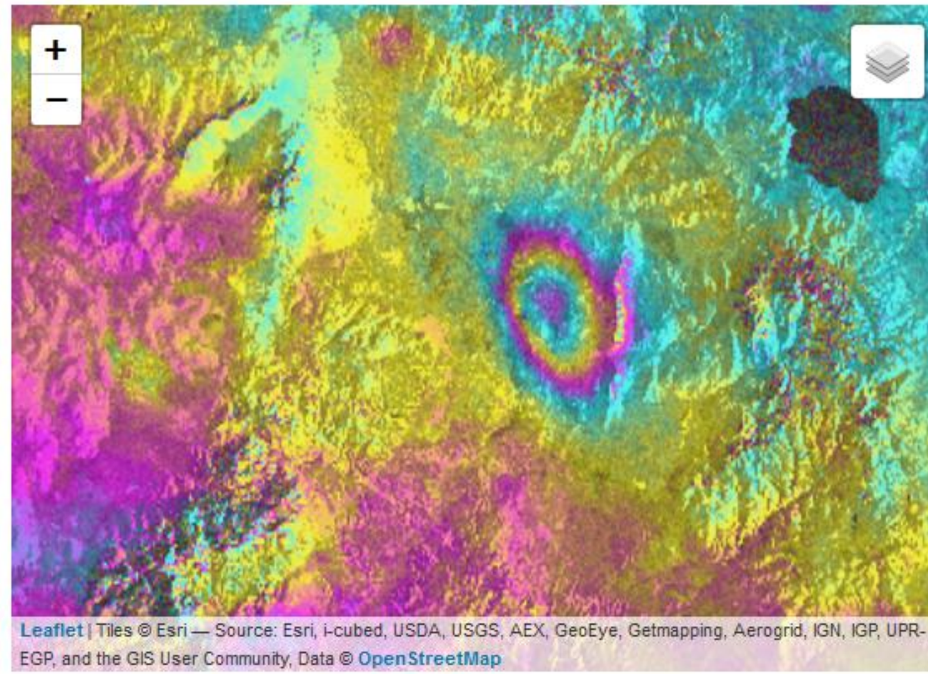
Earthquake location: IONIAN SEA

Magnitude: 6.6

Depth: 10 km

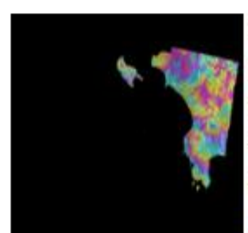
Time: 2018-10-25 22:54:51

Coordinates: 37.52 , 20.57



Interferograms

Descending



Type: co-seismic

Master: 2018-10-20 04:39:26

Slave: 2018-10-26 04:40:08

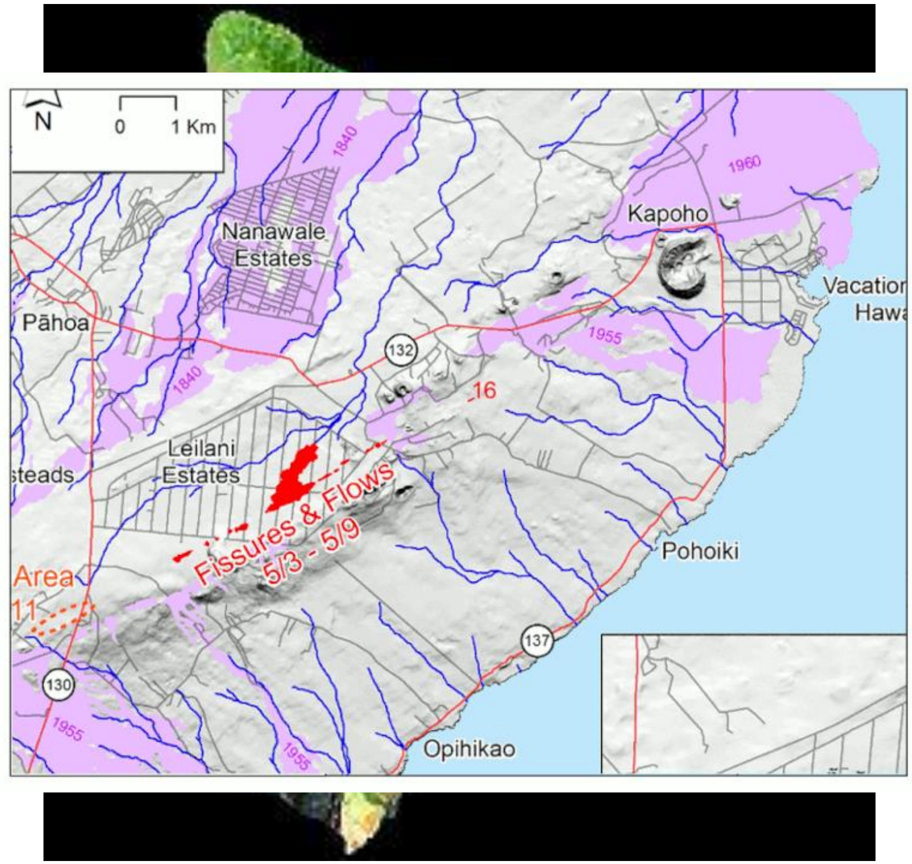
Orbit Number: 80

Mode: DESCENDING

Download (TIF) Download (Low Resolution) Preview

geObservatory | Kīlauea volcano, Hawaii

- ✓ Intense micro-seismic activity in the wider area of the Kīlauea volcano in Hawaii occurred during 26/4-2/5/2018.
- ✓ Suddenly, on Thursday 3/5 a volcanic crack appeared near the road network in lower Puna region, from which lava and hot steam appeared. The Civil Protection instructed residents of the Puna community (~10,000) to leave their homes immediately.
- ✓ On Friday, May 4, 2018, a powerful 6.9 earthquake hit Puna, the largest in the past 43 years.
- ✓ By May 27, 2018, 24 fissures had erupted lava in or near the Leilani Estates and Lanipuna Gardens subdivisions.
- ✓ The Puna Geothermal Venture, which provided one-quarter of the island's electricity, was forced to shut down and was later damaged by lava.
- ✓ By August 7, 35 km^2 of land had been covered by lava flows. The eruption had almost completely subsided, and on December 5, it was declared to have ended after three months of inactivity.
- ✓ Recovery efforts would cost more than $800 million



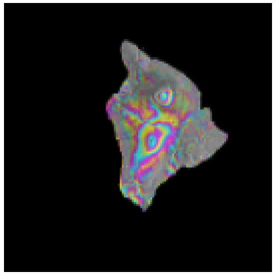
Source: USGS

geObservatory | Kīlauea volcano, Hawaii

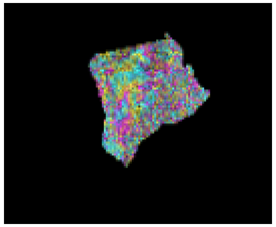
✓ BEYOND responded immediately and activated the geObservatory

ISLAND OF HAWAII, HAWAII (2018-05-04 22:32:57)

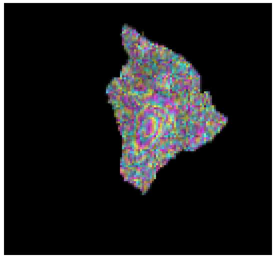
Earthquake location: ISLAND OF HAWAII, HAWAII
Magnitude: 6.5
Depth: 30 km
Time: 2018-05-04 22:32:57
Coordinates: 19.39 , -155.41



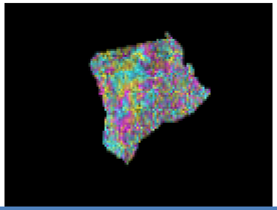
Type: co-seismic
Master: 2018-04-23 16:15:24
Slave: 2018-05-05 16:15:25
Orbit Number: 87
Mode: DESCENDING
Download (TIF) Download (Low Resolution) Preview



Type: co-seismic
Master: 2018-05-02 04:30:26
Slave: 2018-05-08 04:29:48
Orbit Number: 124
Mode: ASCENDING

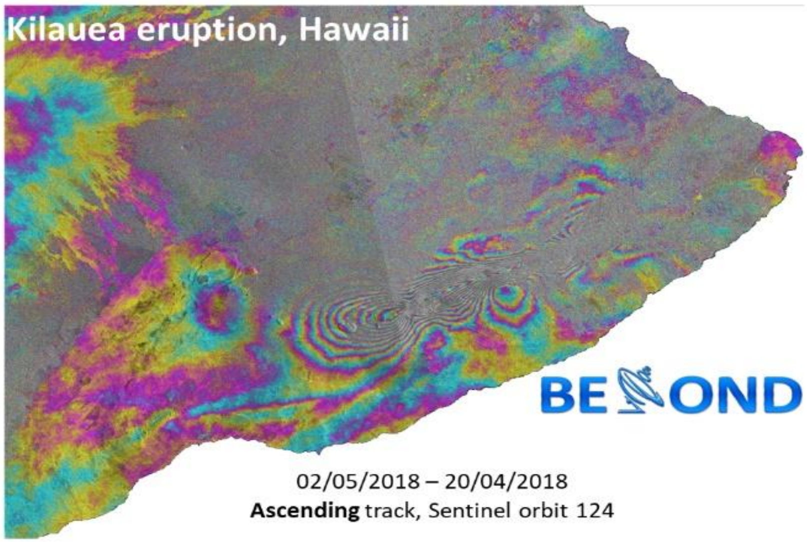


Type: pre-seismic
Master: 2018-04-23 16:15:24
Slave: 2018-04-11 16:15:24
Orbit Number: 87
Mode: DESCENDING
Download (TIF) Download (Low Resolution) Preview

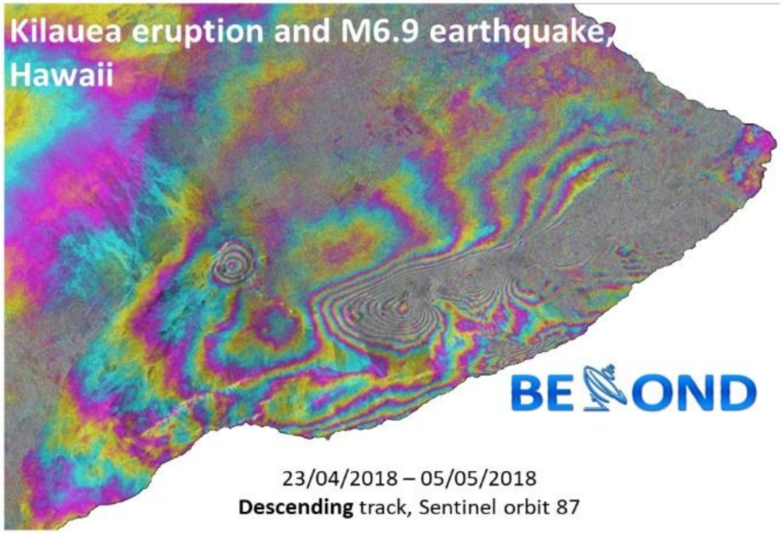


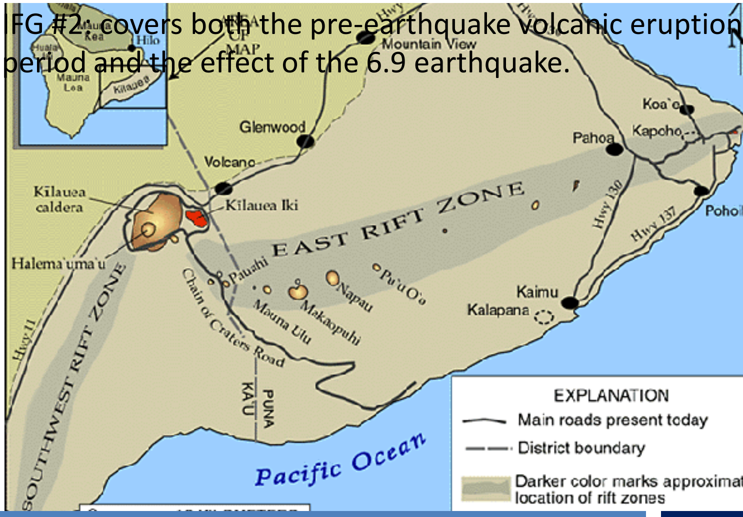
Type: pre-seismic
Master: 2018-05-02 04:30:26
Slave: 2018-04-20 04:30:26
Orbit Number: 124
Mode: ASCENDING

geObservatory | Kīlauea volcano, Hawaii



IFG #1: Covers only the pre-earthquake volcanic eruption period.

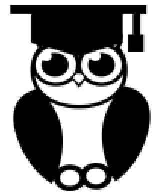




IFG #2: covers both the pre-earthquake volcanic eruption period and the effect of the 6.9 earthquake.

→ Intense subsidence at the top of the volcano as magma material moves along the East Rift Zone and escapes to the eastern edge of the fault. The maximum deformation along this zone, located between the top of the volcano and the area where the lava was firstly observed, is approximately 60-70 cm.

Source: USGS



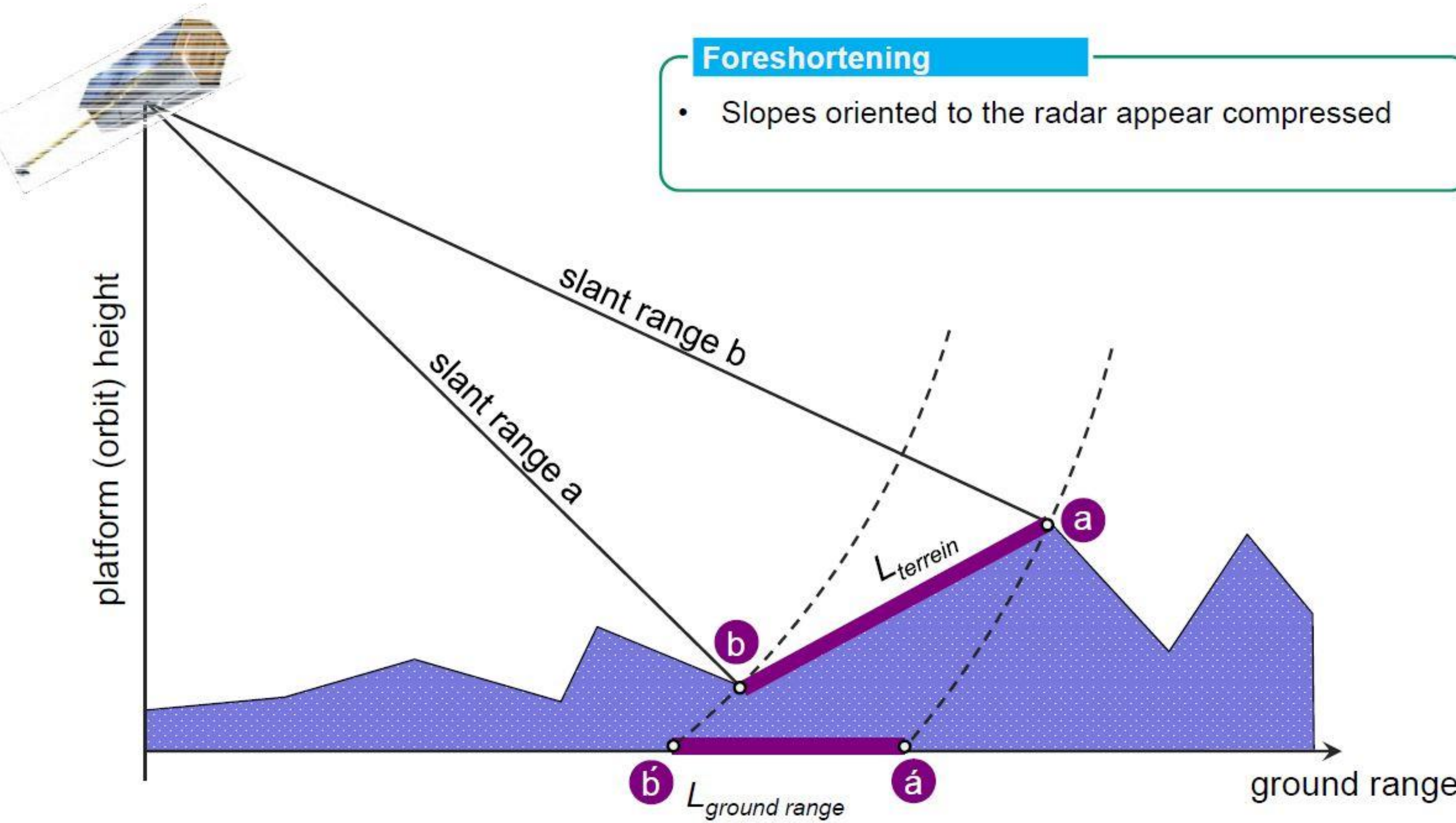
THANK YOU FOR YOUR ATTENTION!

ANY QUESTIONS?

Geometry

Foreshortening

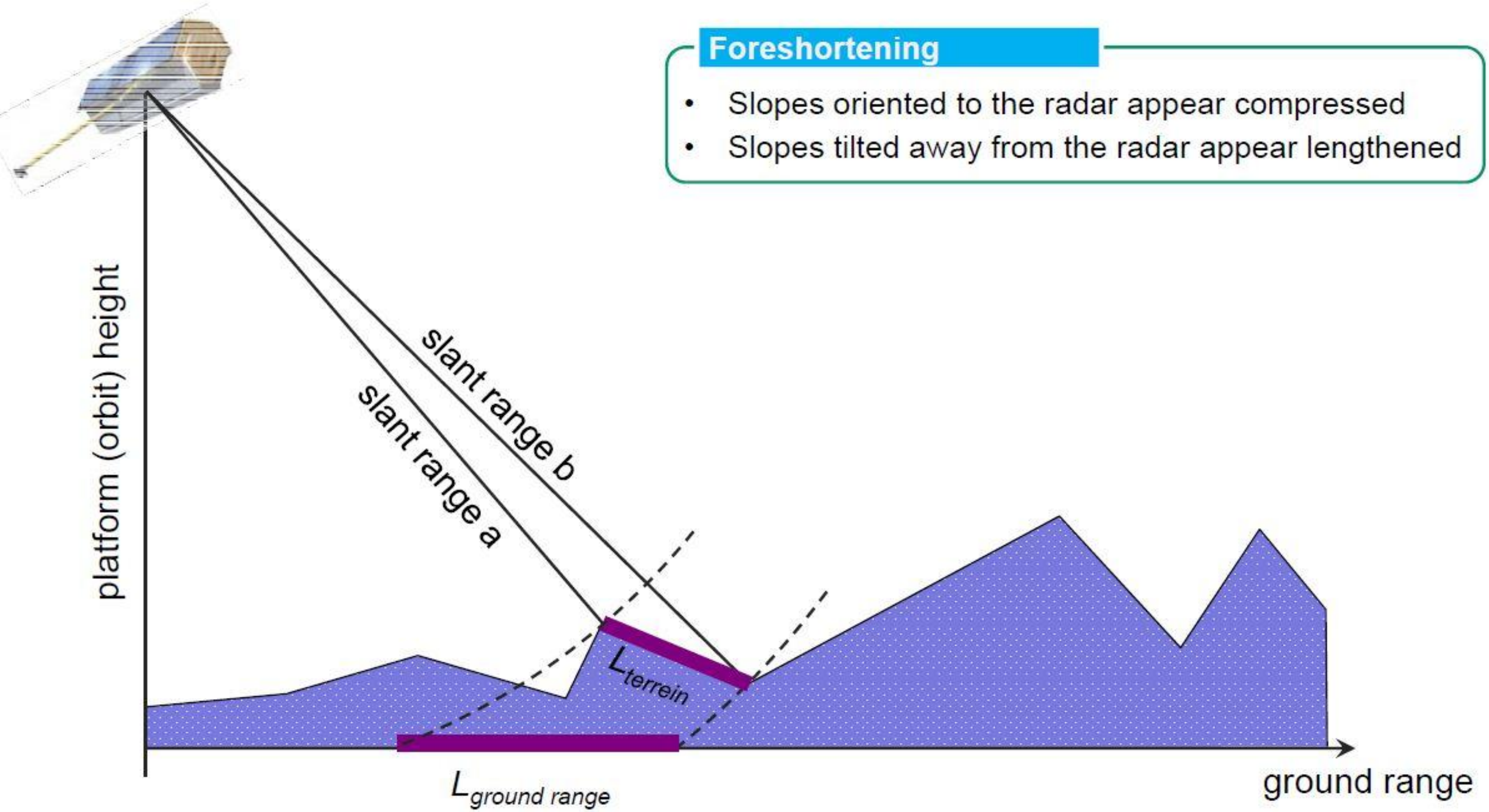
- Slopes oriented to the radar appear compressed



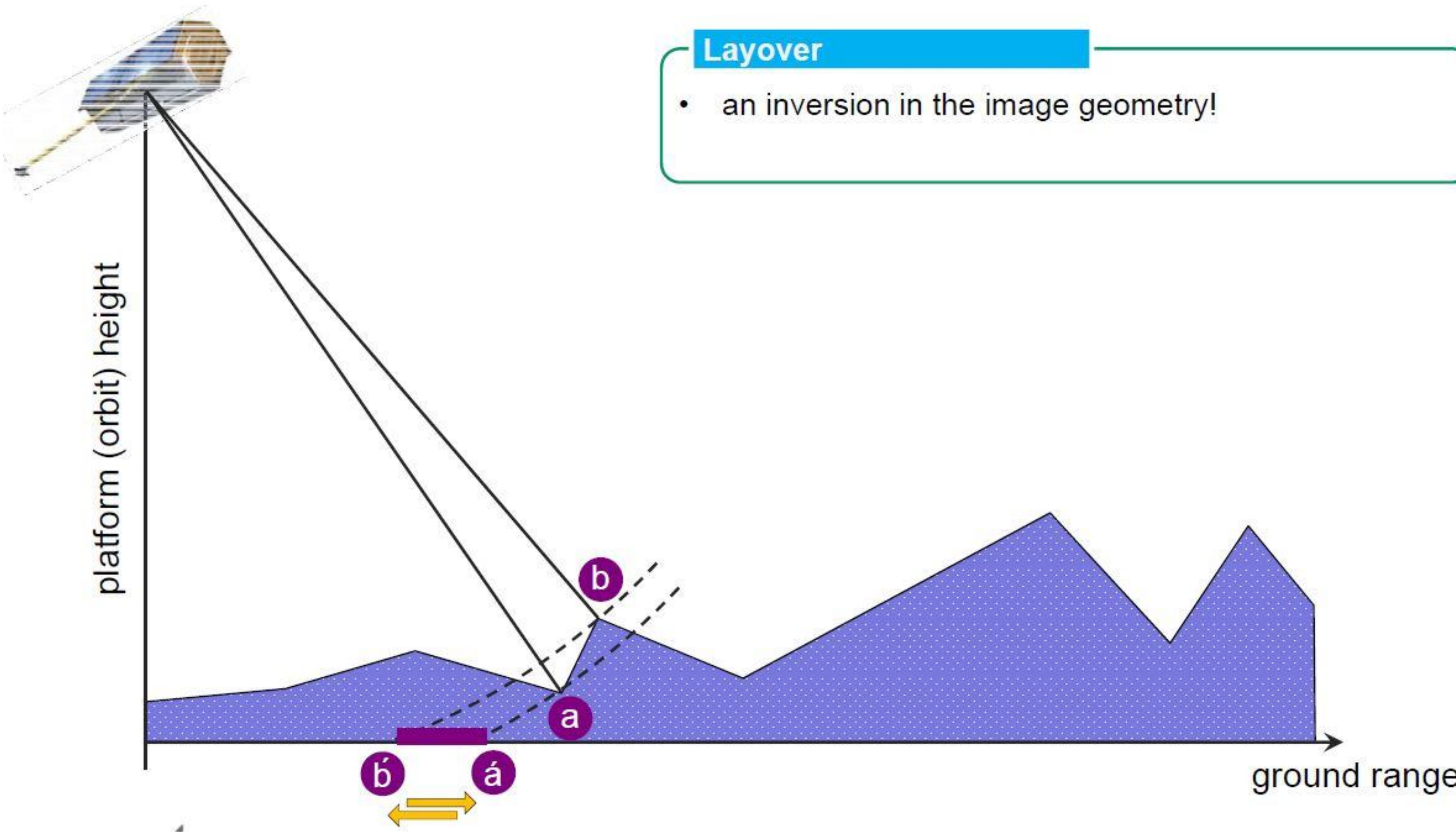
Geometry

Foreshortening

- Slopes oriented to the radar appear compressed
- Slopes tilted away from the radar appear lengthened



Geometry



Layover

- an inversion in the image geometry!

Geometry

Shadow

- Steep slopes oriented away from the radar return no signal