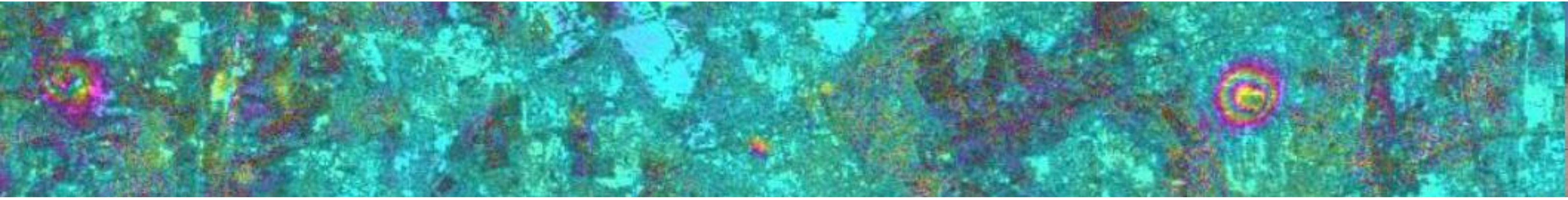
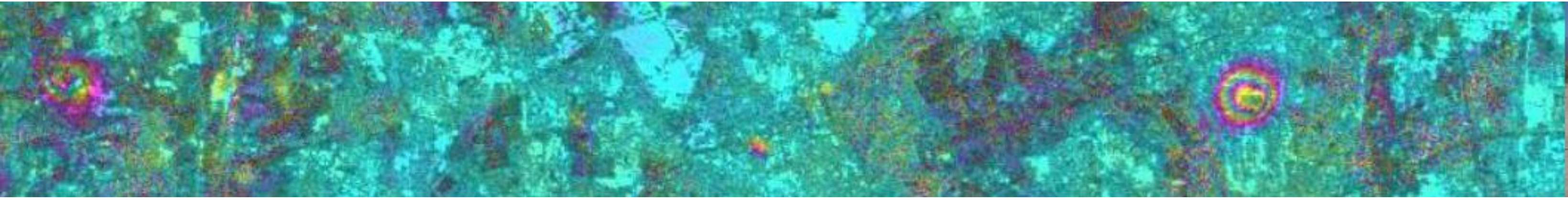


New trends in InSAR technologies and analyses for mining areas

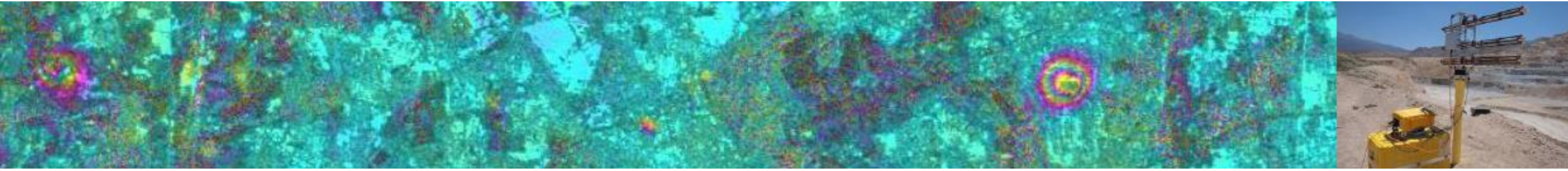
Urs Wegmüller, Christophe Magnard, Charles Werner
and Silvan Leinss
Gamma Remote Sensing AG
www.gamma-rs.ch

GAMMA REMOTE SENSING



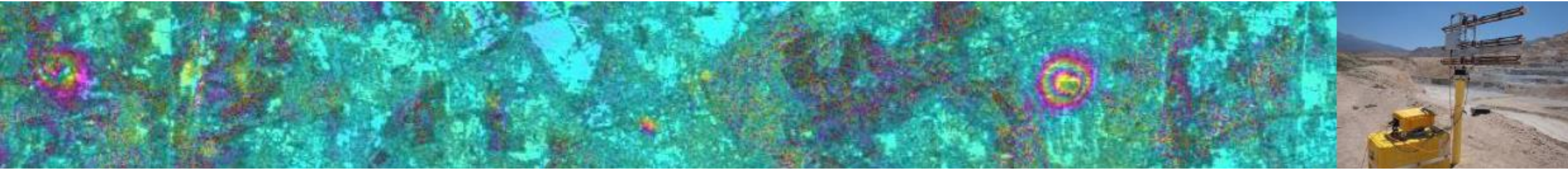
Gamma Remote Sensing

- Swiss company founded in 1995
- Focus on microwave remote sensing
- Main activities:
  - Research projects
  - Gamma SAR/InSAR/PSI processing software
  - Microwave instruments
  - Services and consulting
- Active in mining application since 1997

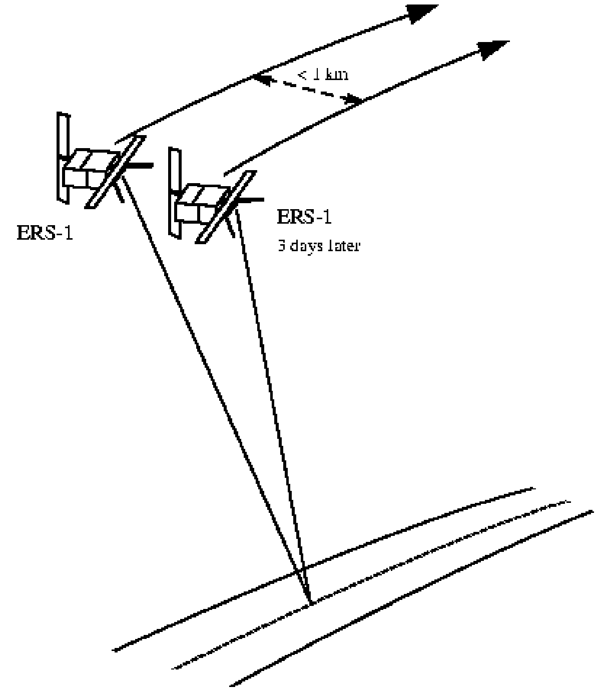


Contents

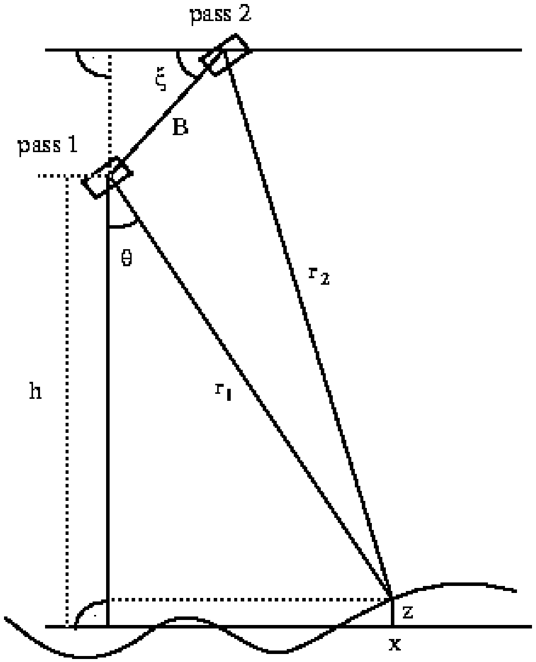
- Satellite InSAR Methodologies
  - Differential Interferometry (DInSAR)
  - InSAR time series analysis
- Main mining applications, potential and limitations
- Satellite SAR sensors
- Terrestrial radar sensors
- Summary and outlook



Satellite InSAR Methodologies

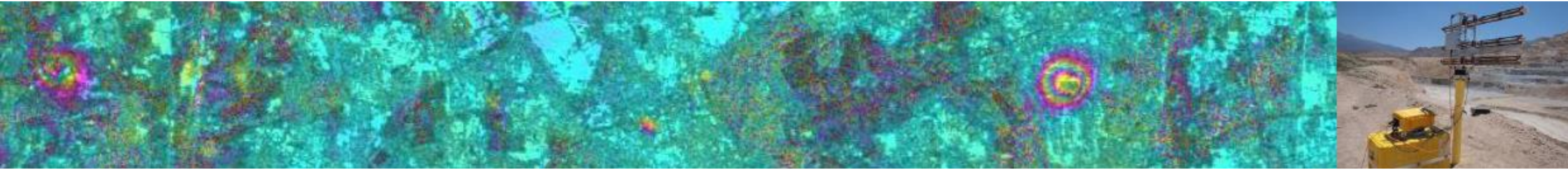


SAR satellite in repeat orbit.



InSAR phase corresponds to range difference

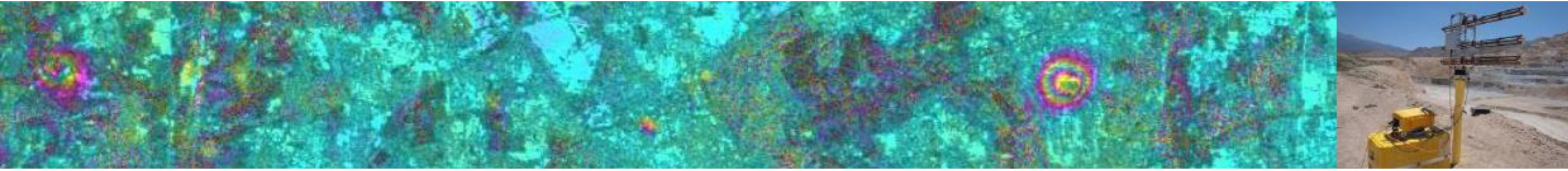
GAMMA REMOTE SENSING



InSAR phase terms

$$\phi_{unw} = \phi_{topo} + \phi_{def} + \phi_{atm} + \phi_{noise}$$

- Based on orbit data and DEM heights the topographic phase can be calculated.
- $\lambda/2$ line-of-sight displacement → 2π InSAR phase
- The main error sources are the atmospheric path delay variation and the phase noise (incl. decorrelation noise)



C-band DInSAR example

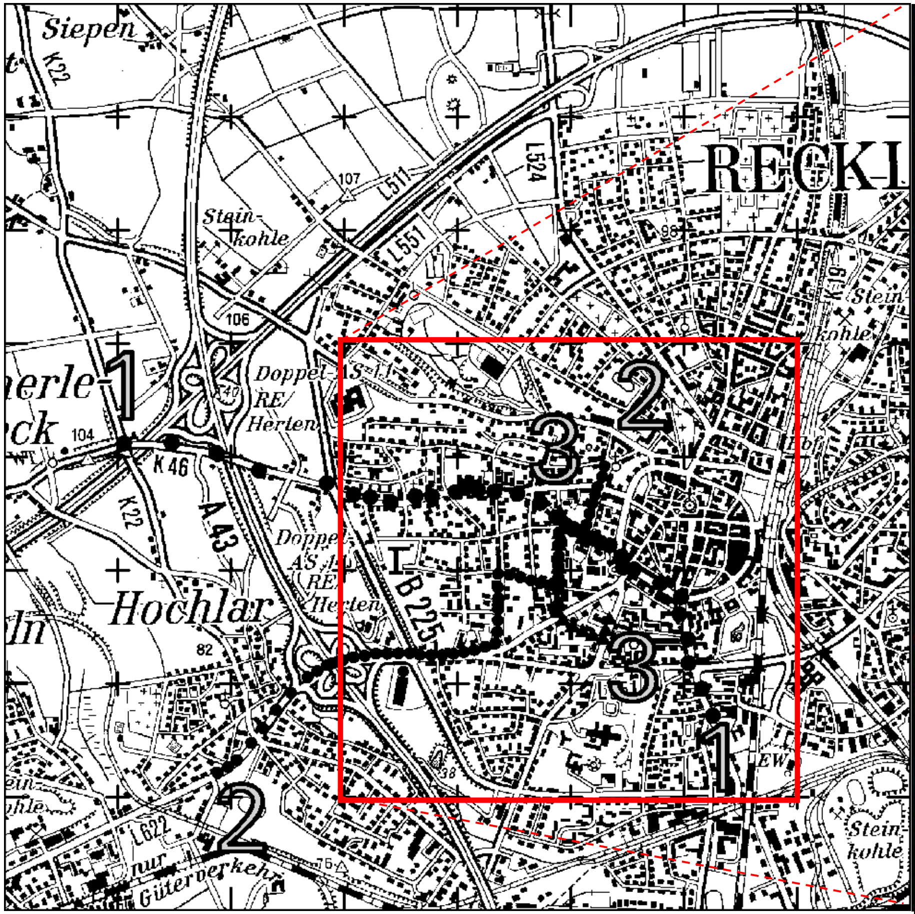
- Using ERS C-band data (35 day repeat intervals) over Ruhr area.

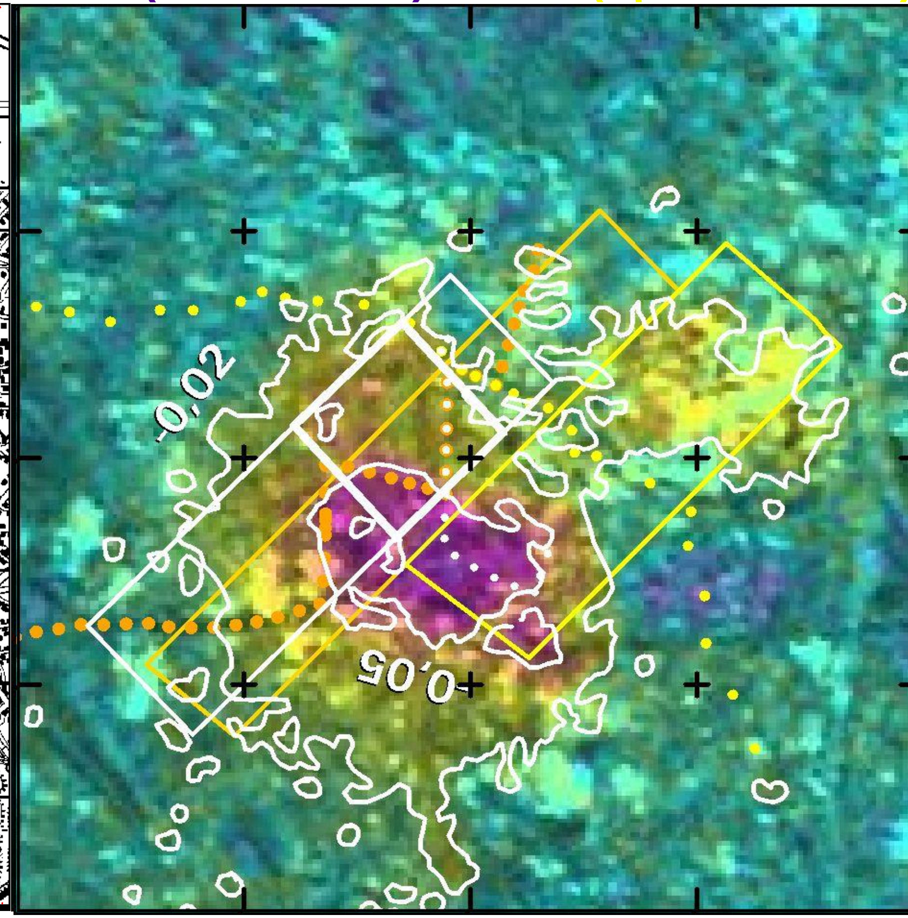
Investigation: Recklinghausen

Levelling Lines

Vertical Subsidence from ERS - dInSAR:

Production Panels: BH 484 (Jan 98–Dec 98) BH 408 (Jul 00-Jul 01) BH 485 (Apr 99–Nov 99)





Area: 4 km x 4 km **Area: 2 km x 2 km**

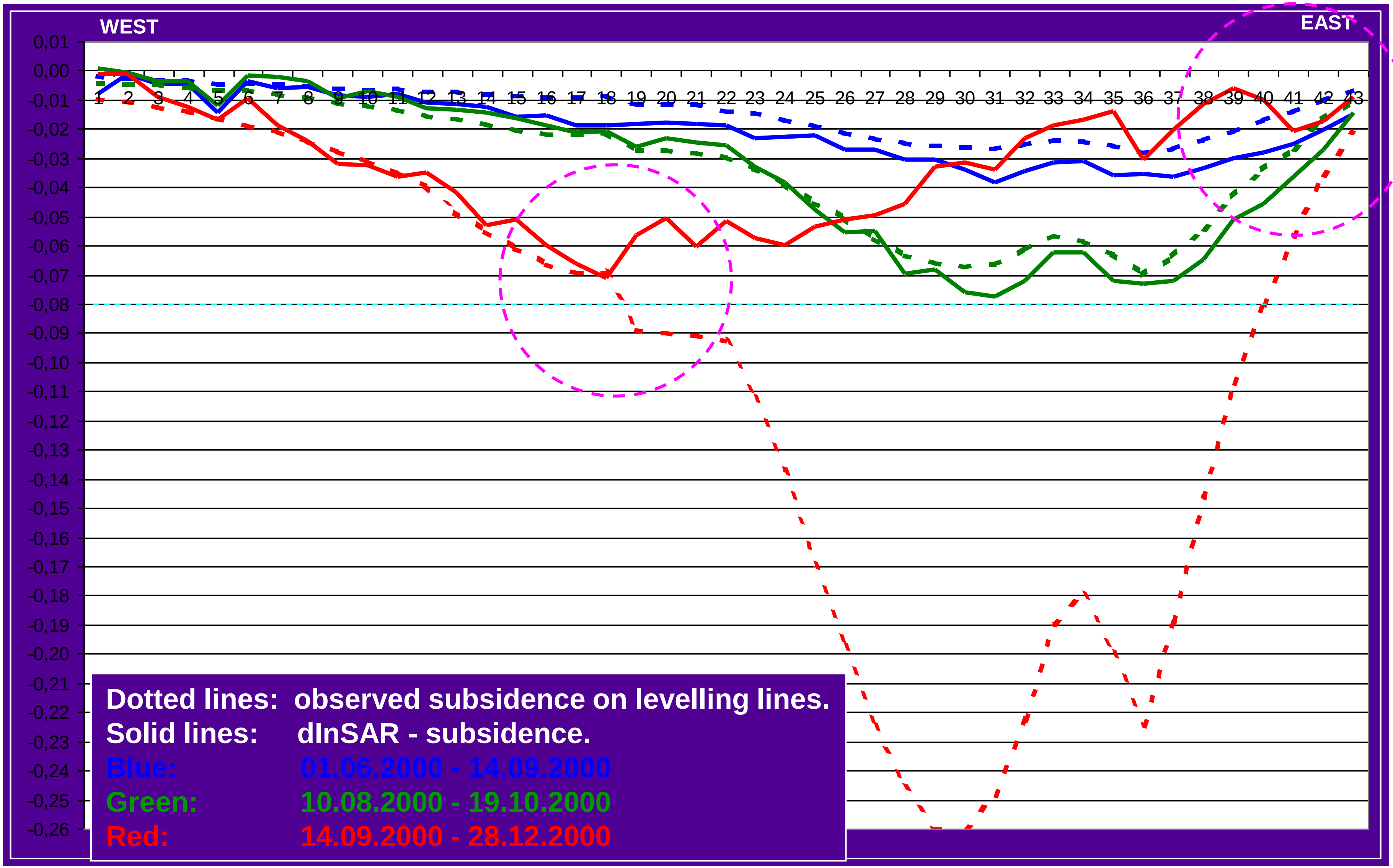
14.02.2000 - 18.10.2000

GAMMA REMOTE SENSING

From Spreckels et al., ISPRS, 2001

Investigation: Recklinghausen

Line 1



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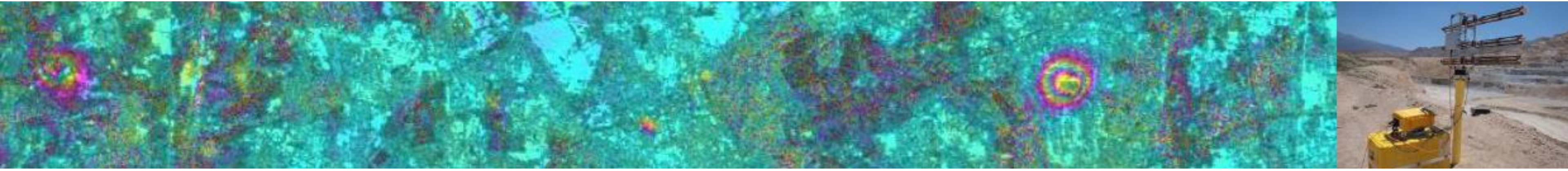


C-band DInSAR conclusions

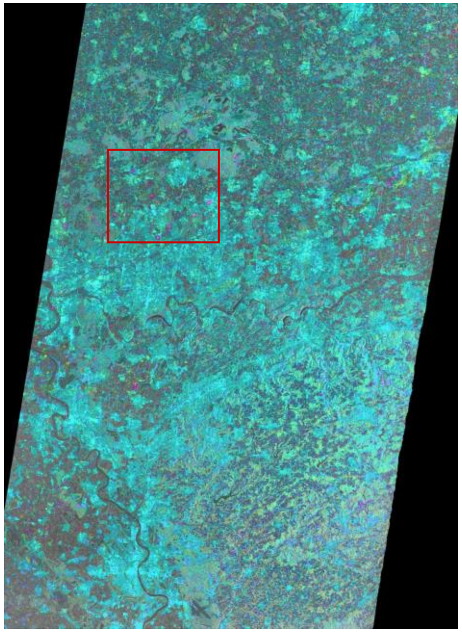
- Very good representation of subsidence movements up to an amount of ~ 10 cm per C-band observation interval.
- Detection of:
  - the zone of affected ground (0cm isoline),
  - the shape of the subsidence trough.
- Unwrapping is problematic for areas with fast movements (more than 5 cm per observation interval).
- In vegetated areas the signal decorrelates.

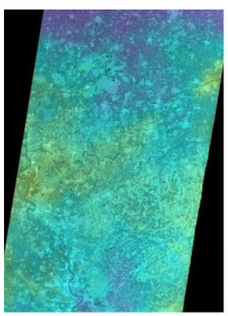
L-band DInSAR example

- Using JERS data (44 day repeat interval) over Ruhr area.

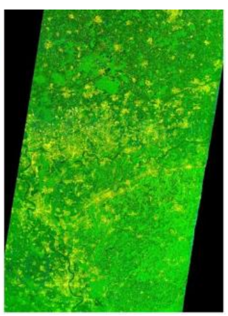
Ruhr area, JERS differential interferogram, 19980713_19980826, 44 days, B_p 352m

Overview (92 km x 127 km)

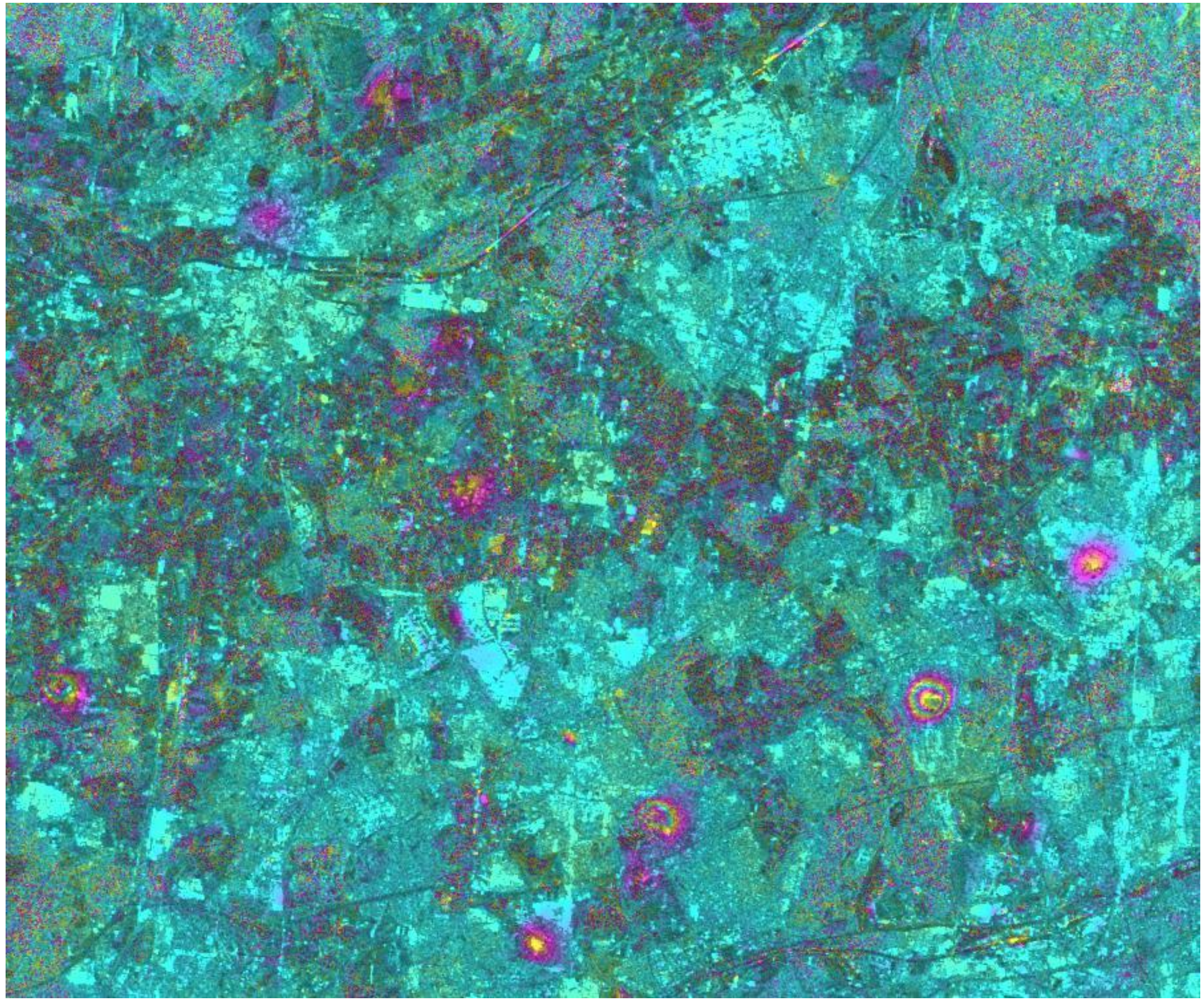




Atmospheric phase

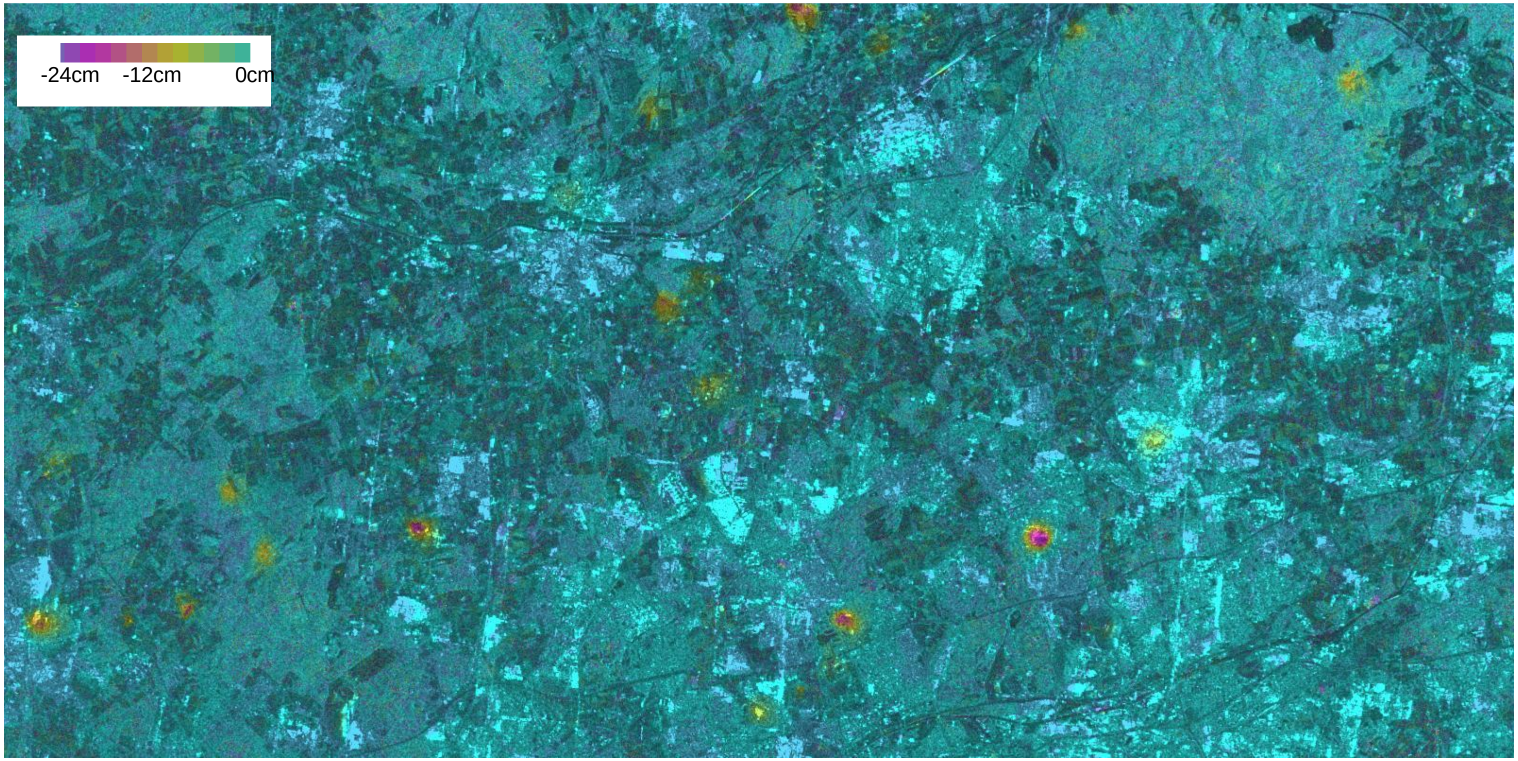


Coherence Product



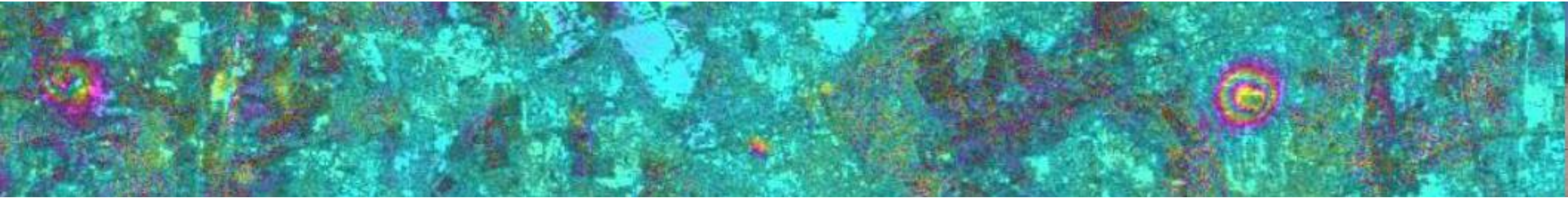
Detail view of 22.5 km x 18.75 km section, a color cycle corresponds to 11.8 cm line-of-sight or approximately 15.0 cm vertical displacement

L-band DINSAR subsidence map



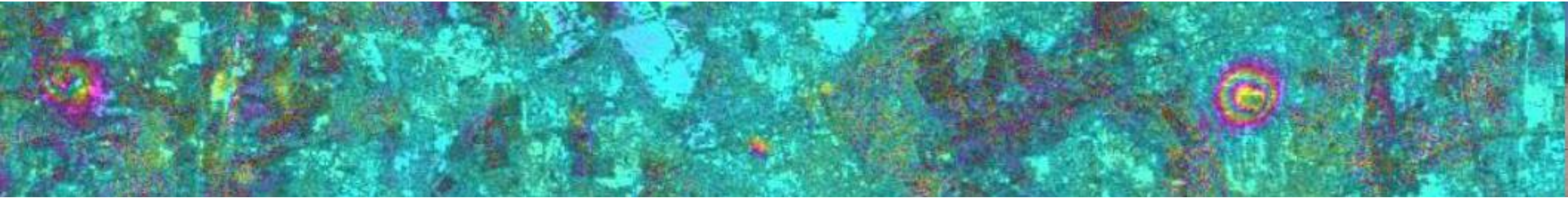
Ruhr area, JERS 19980713_19980826, 44 days, B_{perp} 352m, 32 km x 16 km (negative values corresponding to subsidence).

GAMMA REMOTE SENSING



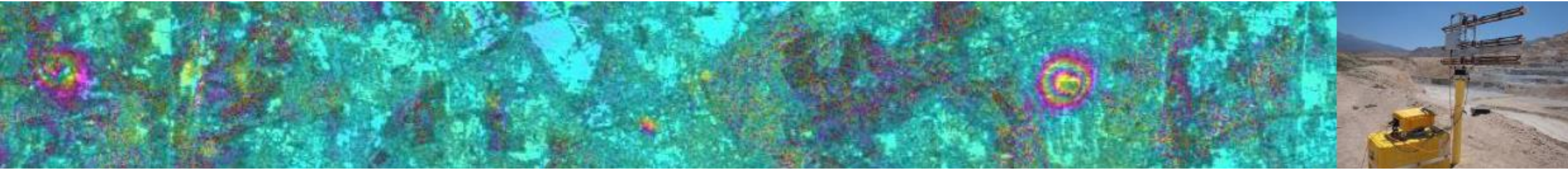

L-band DInSAR conclusions

- Better spatial coverage than at C-band (less decorrelation for vegetated areas).
- Better suited for fast movements (longer wavelength).
- Generally, more robust and better applicable.
- Similar atmospheric errors.
- Same phase noise level causes higher displacement error.



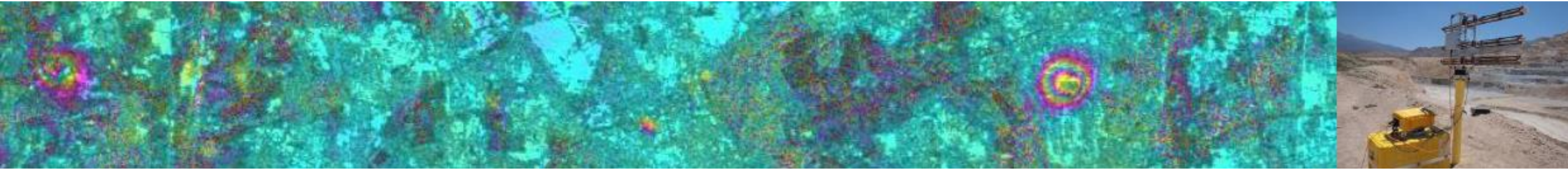

Interferogram stacking

- Combination of multiple interferograms (C- or L-band)
  Deformation rate = Σunw / Σdt
- Signal term (deformation phase) adds linearly,
  Error terms (atmosphere) are temporally uncorrelated
  → Reduced relative errors
- By combining sufficient observation time, it is possible to achieve mm/year accuracies for relatively slow uniform deformations, e.g., in urban areas.
- Restricted to spatial coverage of the individual results.



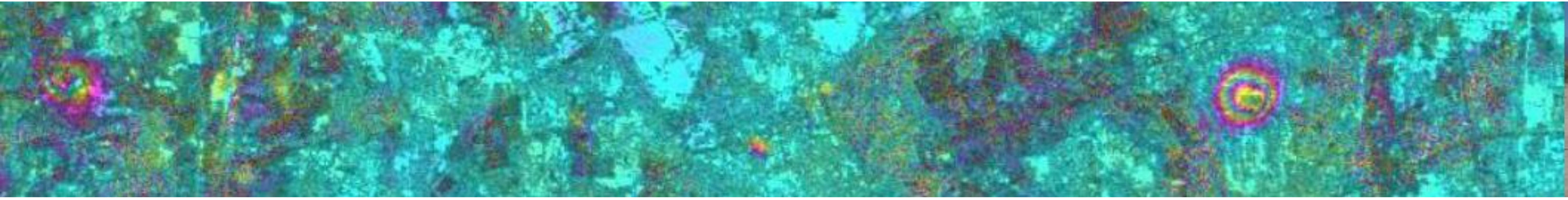
Interferometric time-series analysis

- Methods to exploit temporal and spatial characteristics of interferometric signatures collected from suited targets to accurately map surface deformation histories, terrain heights, and relative atmospheric path delays.
- Characteristics of the methods differ depending on the data and algorithms used.



Important characteristics

- “Point-like scatterers” versus “distributed scatterers”
- “Single pixel phases” versus “multi-look phases”
- “Single-reference stack” versus “multi-reference stack”
- “Spatial unwrapping” versus “temporal unwrapping”
- Atmospheric path delay estimation used
- “Deformation model” assumptions used
- Quality thresholds used
- Total period considered, time intervals, baselines, …

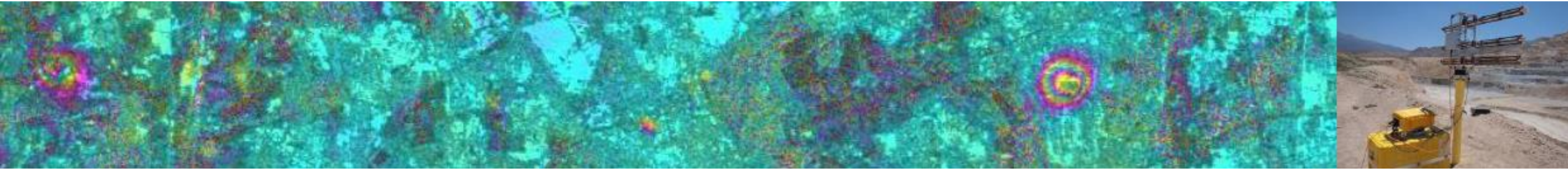


Approach 1

- C-band data, 50 scenes over 8 years, 20m x 4m resolution, long baselines.

Strategic decisions:
1) use “Point-like scatterers” → works for long baselines
2) use “Single-reference stack” → suited for slow, almost uniform movements

→ mm/year accuracy solution for buildings, infrastructure, and rocks with a slow, almost uniform movement.

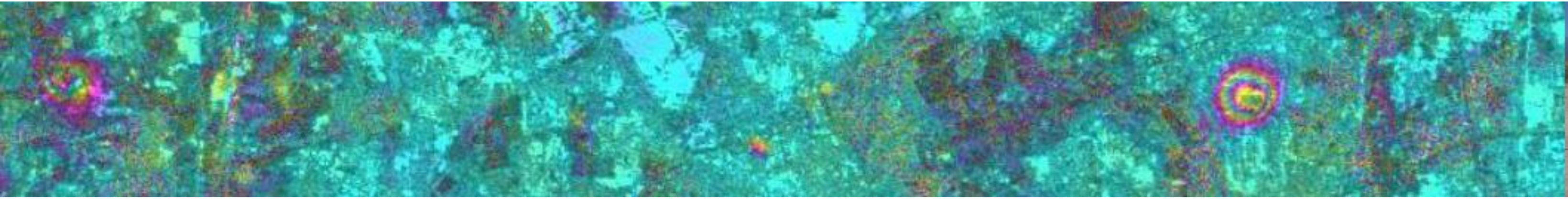


Implementation approach

- Build upon conventional DInSAR phase model:

$$\phi_{unw} = \phi_{topo} + \phi_{def} + \phi_{atm} + \phi_{noise}$$

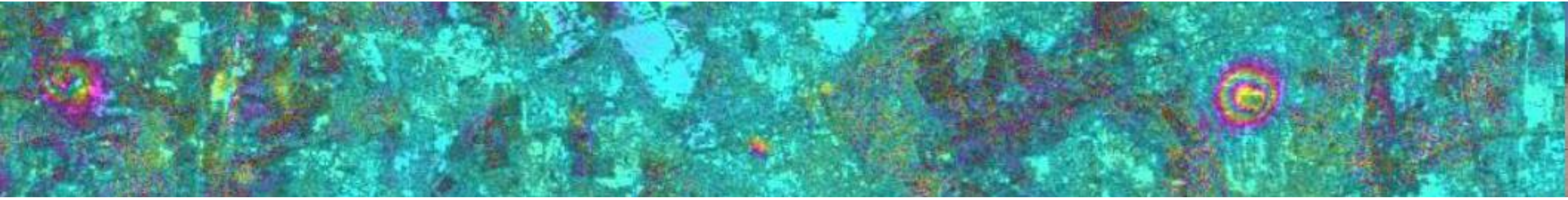
- Adapt data base model
  - Use of point lists and vector data stacks (35 Gbyte → 70 MByte for 100’000 points in 70 SLCs)
  - Table listing interferometric pairs



Main processing steps

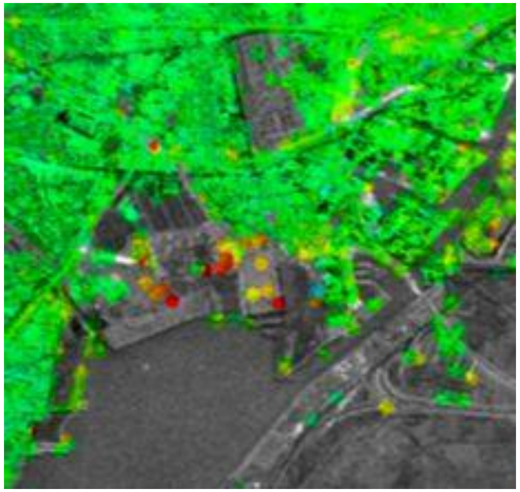
1) Point target candidate identification
2) Get interpretable interferometric phases
   (Phase unwrapping)
3) Interpret interferometric phases
4) Quality control

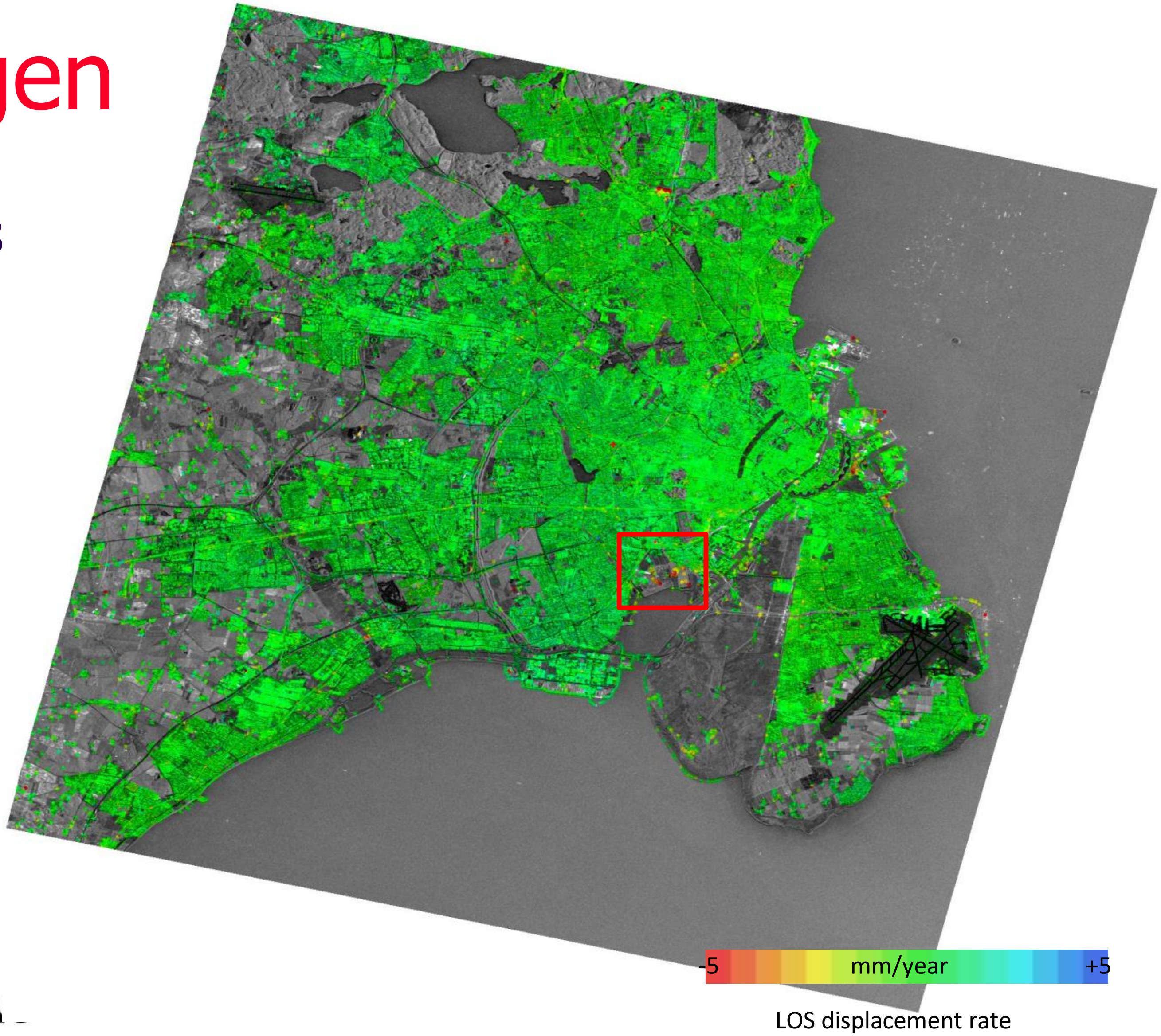
→ mm/year accuracy solution for buildings, infrastructure, and rocks with a slow, almost uniform movement.



Copenhagen

70 ERS scenes
1992-2000





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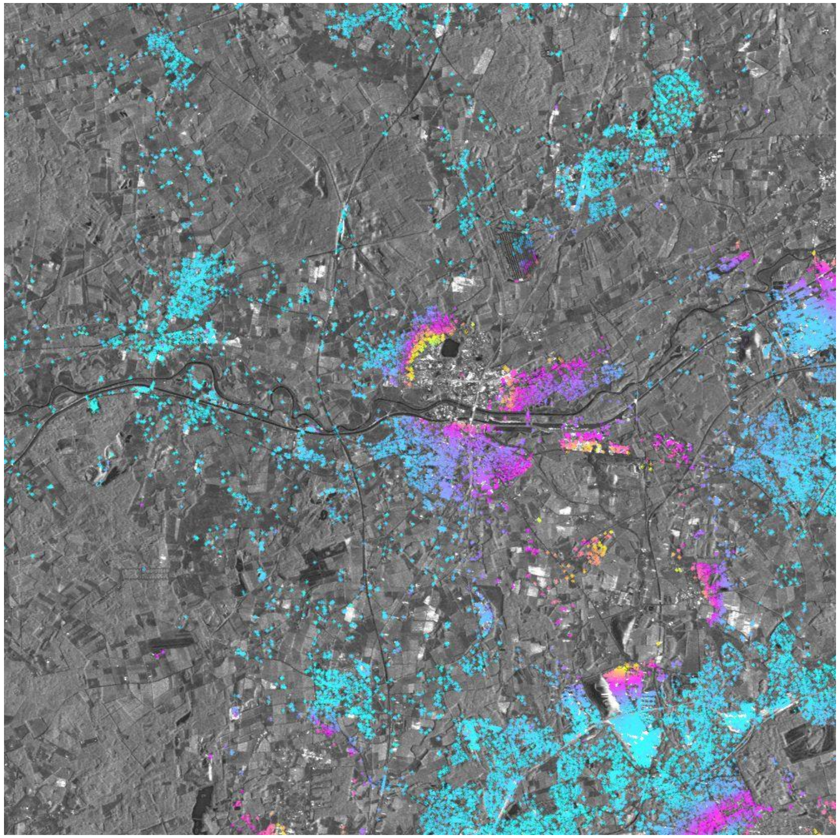
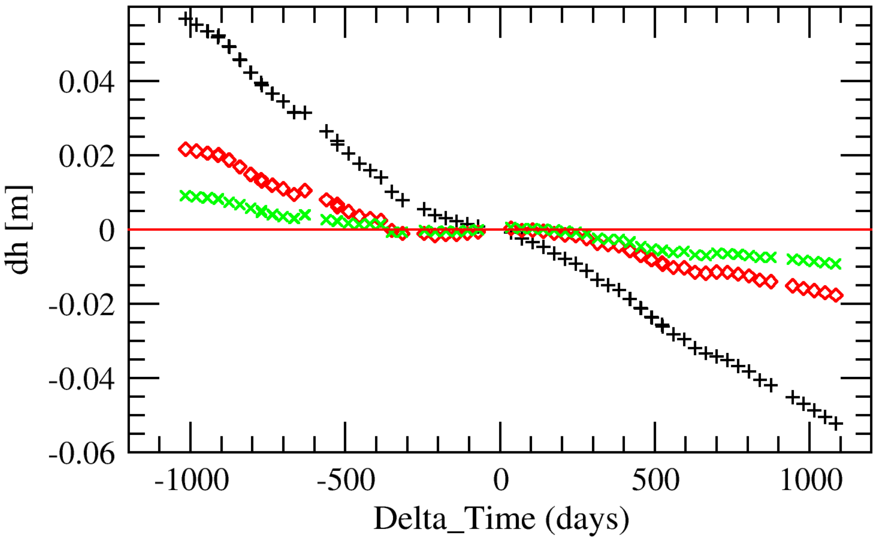
Ruhr ERS C-band



Deformation, 25-Mar-1995 to 18-Jan-1998 derived from an ERS stack using IPTA



Deformation histories relative to 18-Jan-1998 for 3 points near the subsidence cone located near the center

→ Spatial gaps related to faster and non-uniform motion and related to vegetation.

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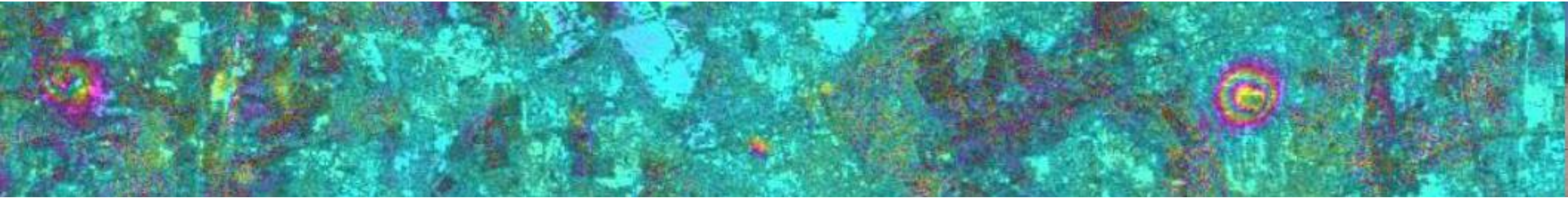
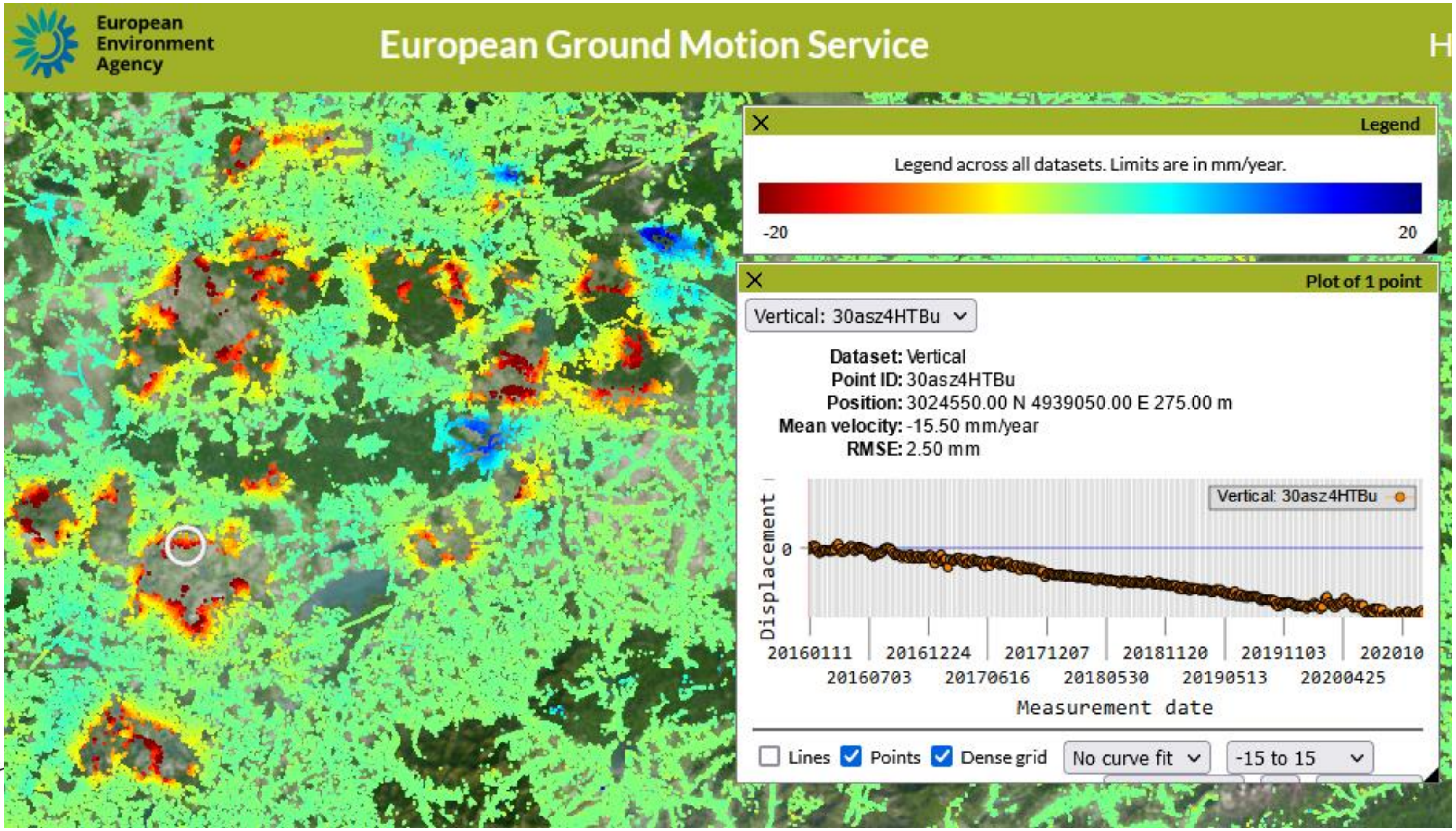


The European Ground Motion Service

provides similar results at European scale using Sentinel-1.

See https://egms.land.copernicus.eu



Approach 2

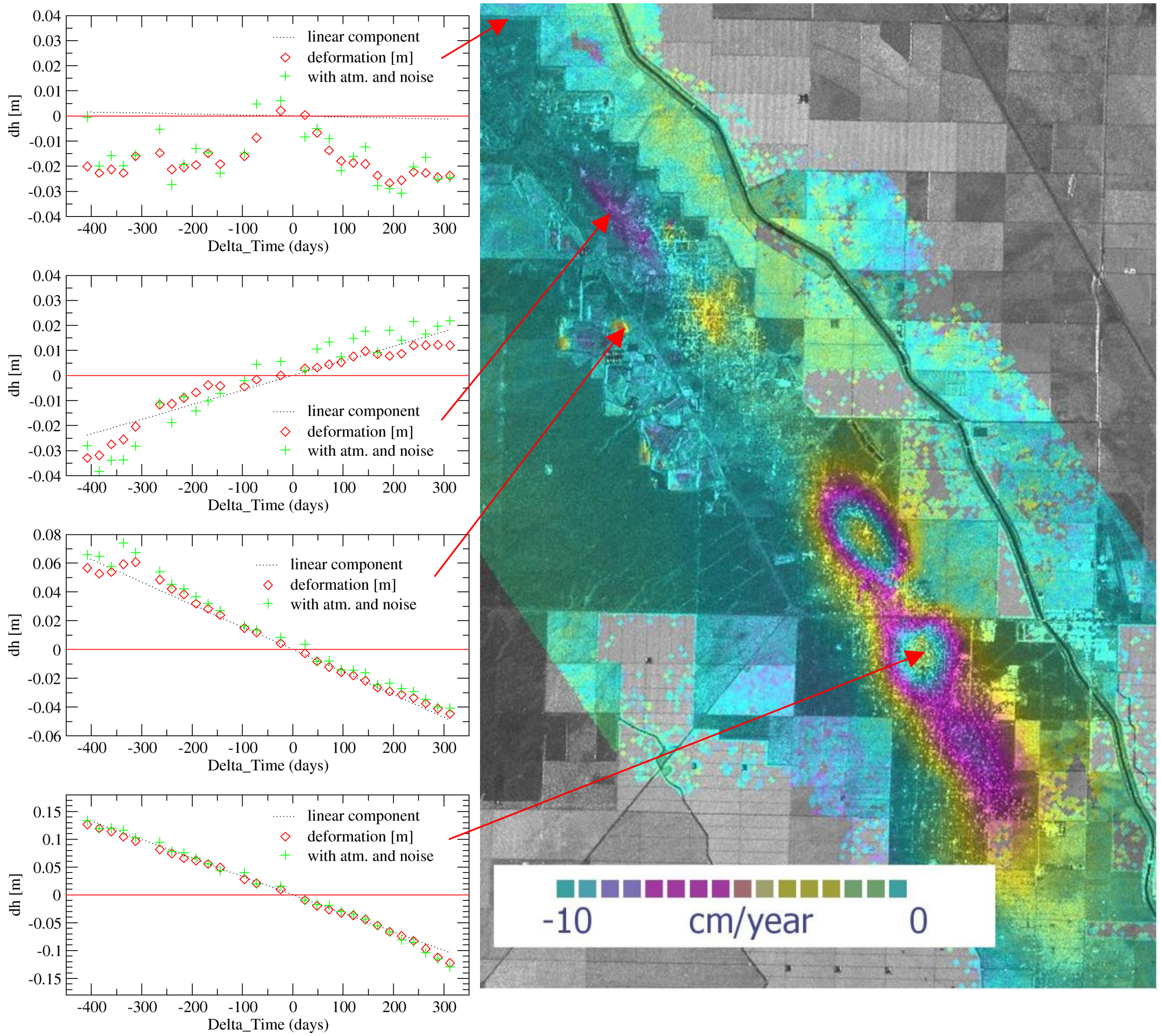
- Radarsat C-band data at higher spatial resolution
- Baselines are generally rather short (<< critical baseline)
- Area is quite arid (low vegetation cover)

Strategic decisions:

1) use "Point-like scatterers" and "distributed scatterers" (considering single pixel and multi-look phases)

2) use "Multi-reference stack" → better suited for fast and non-uniform motion

Lost Hills Radarsat C-band result



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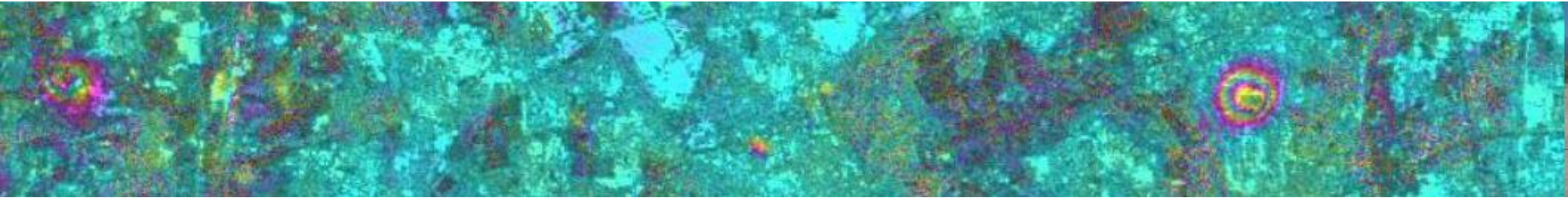


Approach 3

- TerraSAR X-band data stack over coal mining site
- High spatial resolution (< 2m sampling)
- 11-day interval
- Strong (> 30cm in 253 days), non-uniform motion

Strategic decisions:

1) use “Point-like scatterers” (single pixel phases)

2) use “Multi-reference stack” with short time intervals

3) use spatial unwrapping

Result

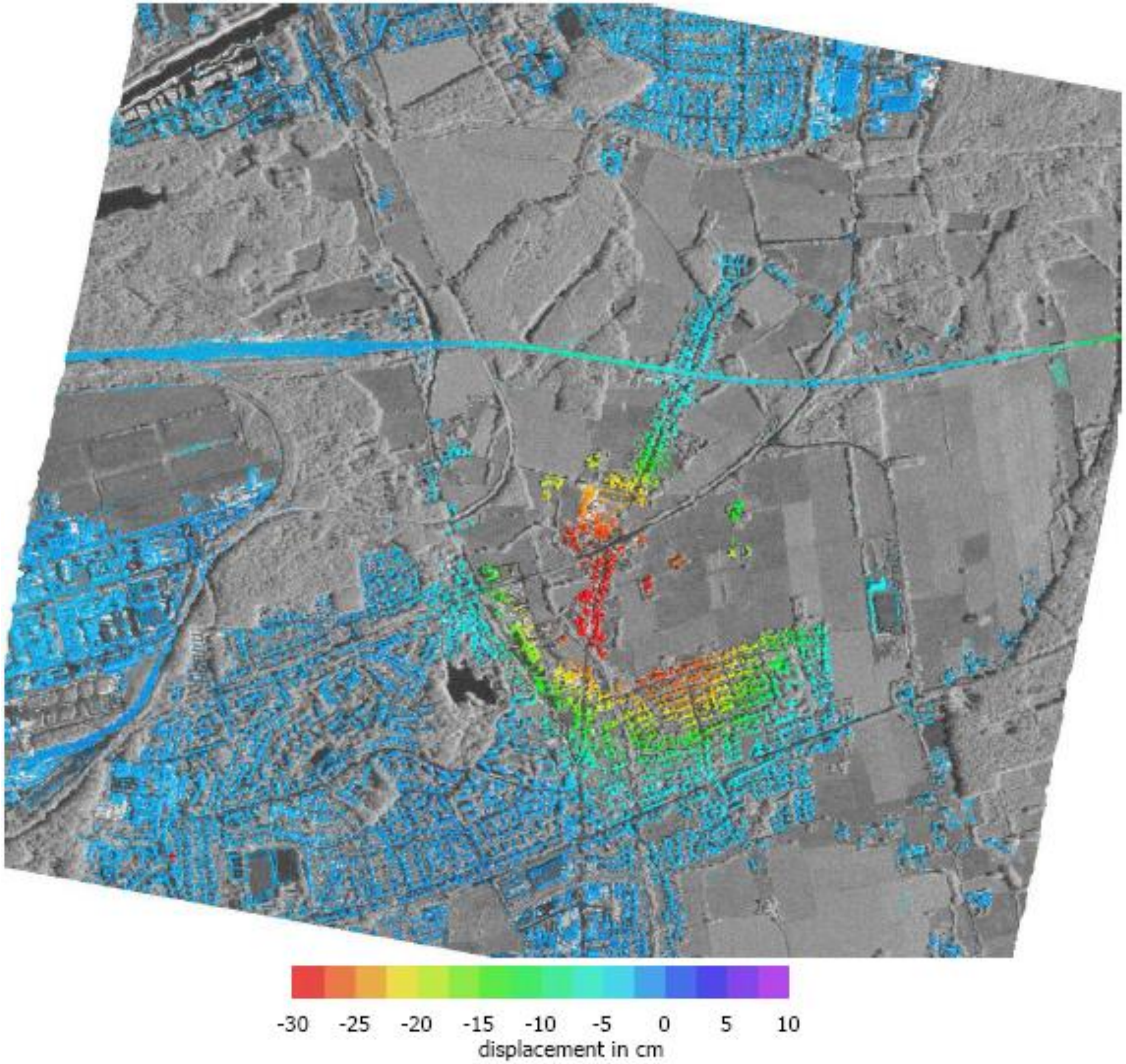
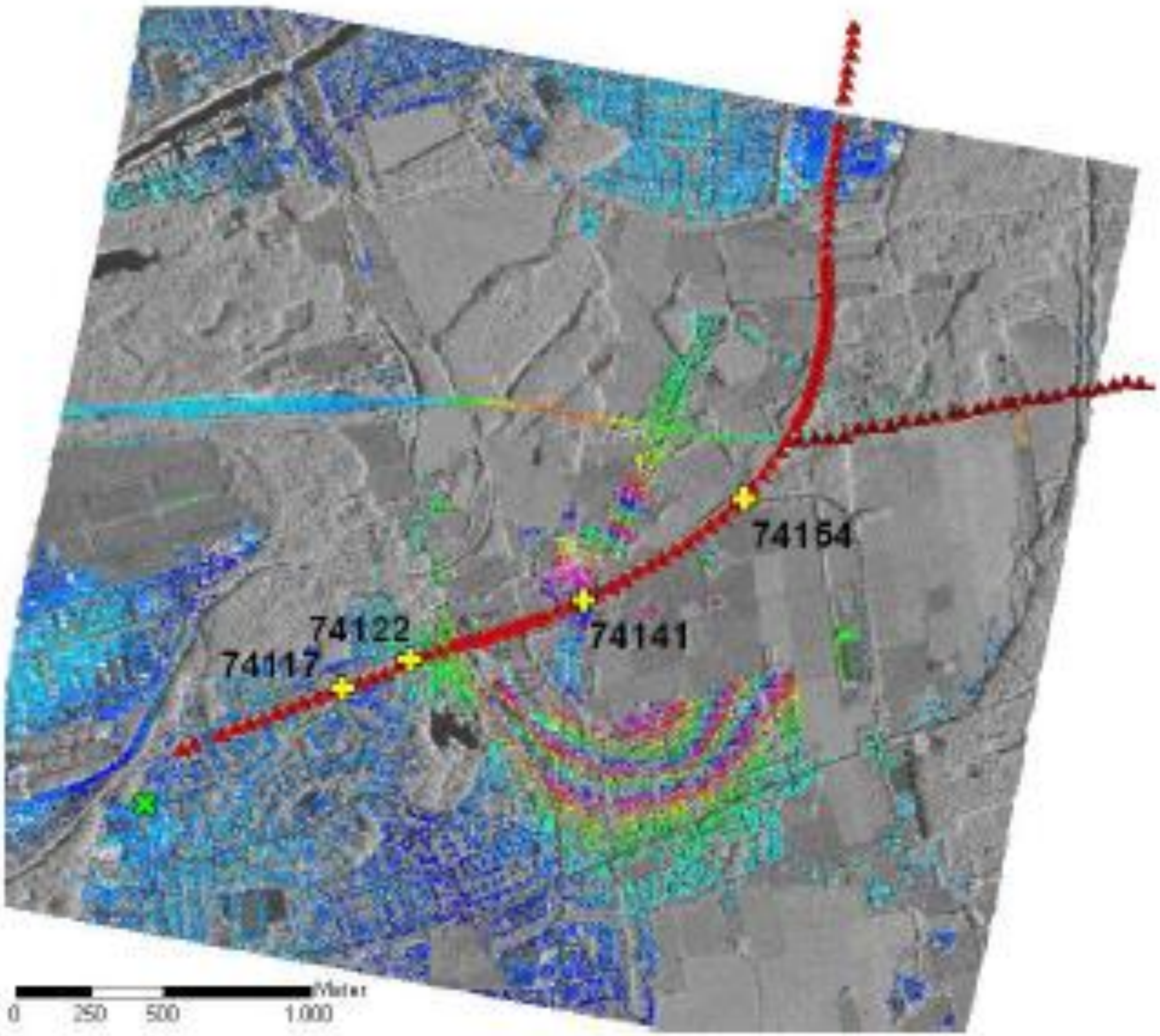


Figure 2 Line-of-sight surface deformation between 11-Feb-2008 and 21-Oct-2008 derived from TerraSAR-X data series in an IPTA processing over an active mining area in Germany.

See Wegmüller U., et al., TGRS Vol. 48, 2, 2010.

Validation

- Leveling
- GPS



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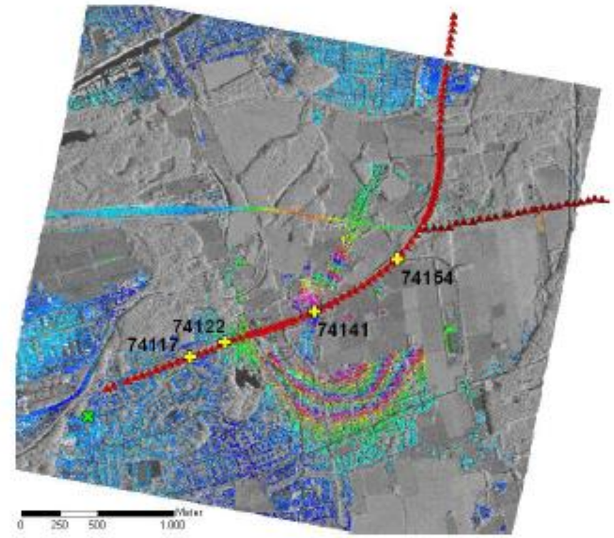
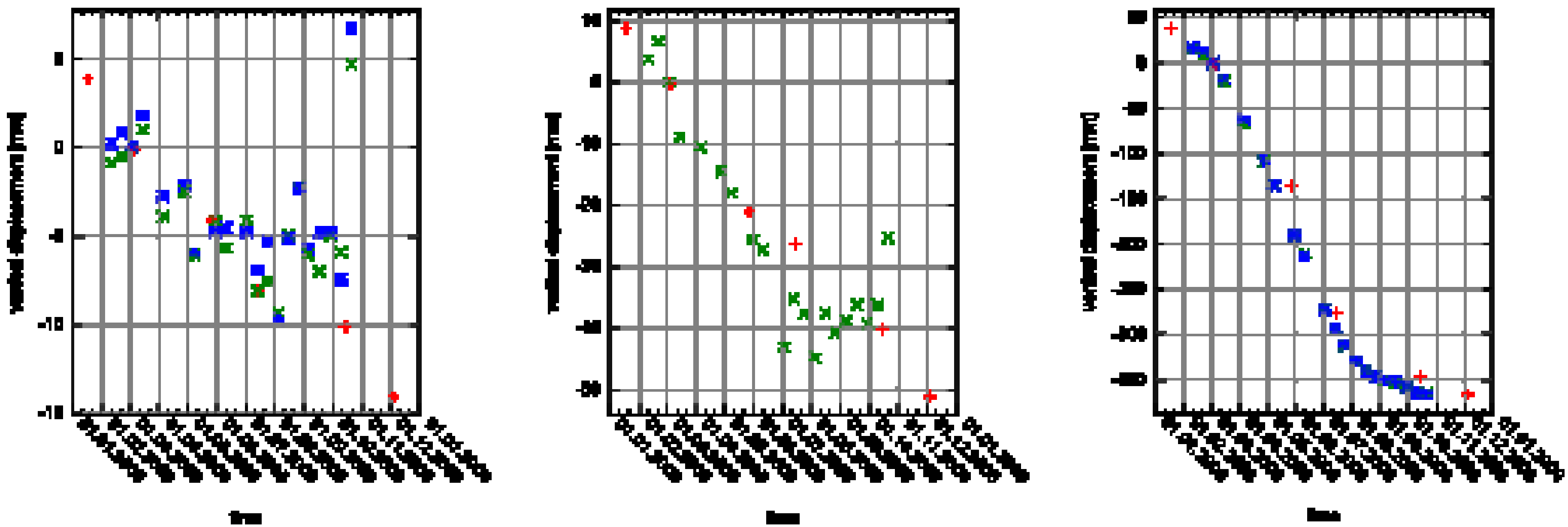
Validation





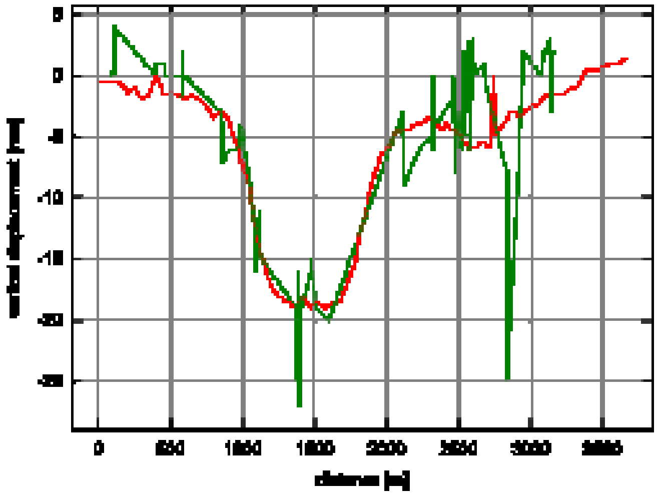
Leveling at point 74117 (+) and 2 IPTA points (x,x)

Leveling at point 74154 (+) and an IPTA point (x)

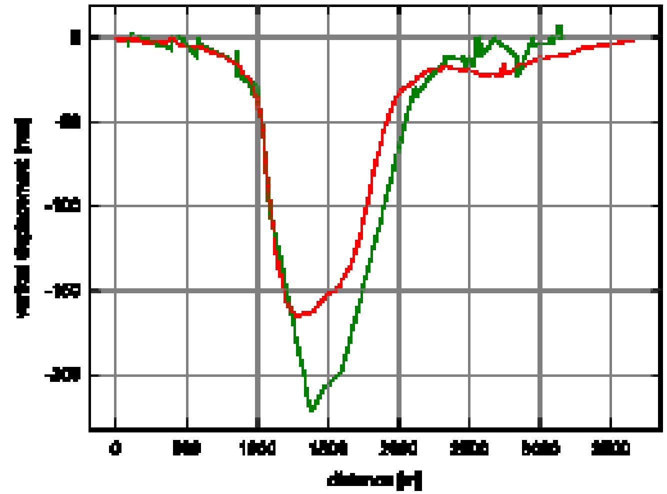
Leveling at point 74141 (+) and 2 IPTA points (x,x)

Figure 5 Comparison of leveling and PSI vertical deformation time series for selected locations.

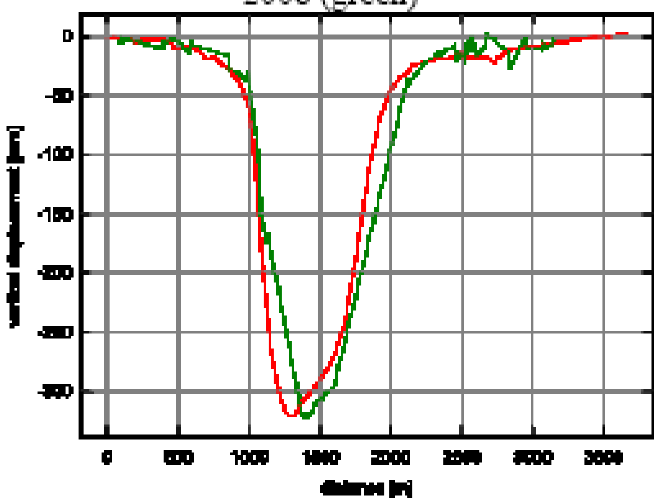
Validation (cont.)



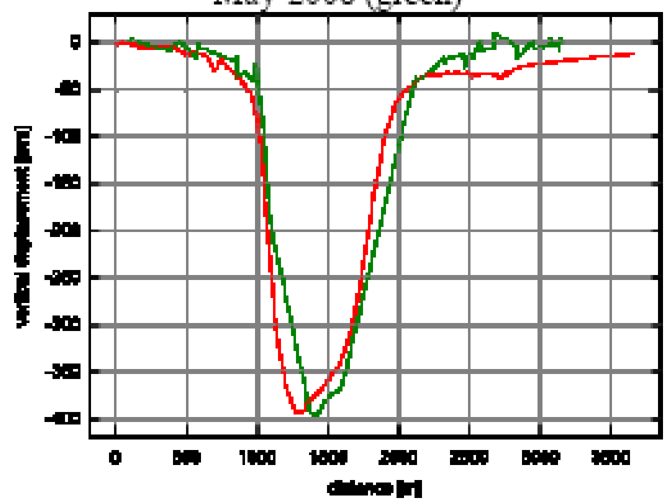
Leveling 05-Mar-2008 (red) and PSI result 04-Mar-2008 (green)



Leveling 28-May-2008 (red) and PSI result 31-May-2008 (green)



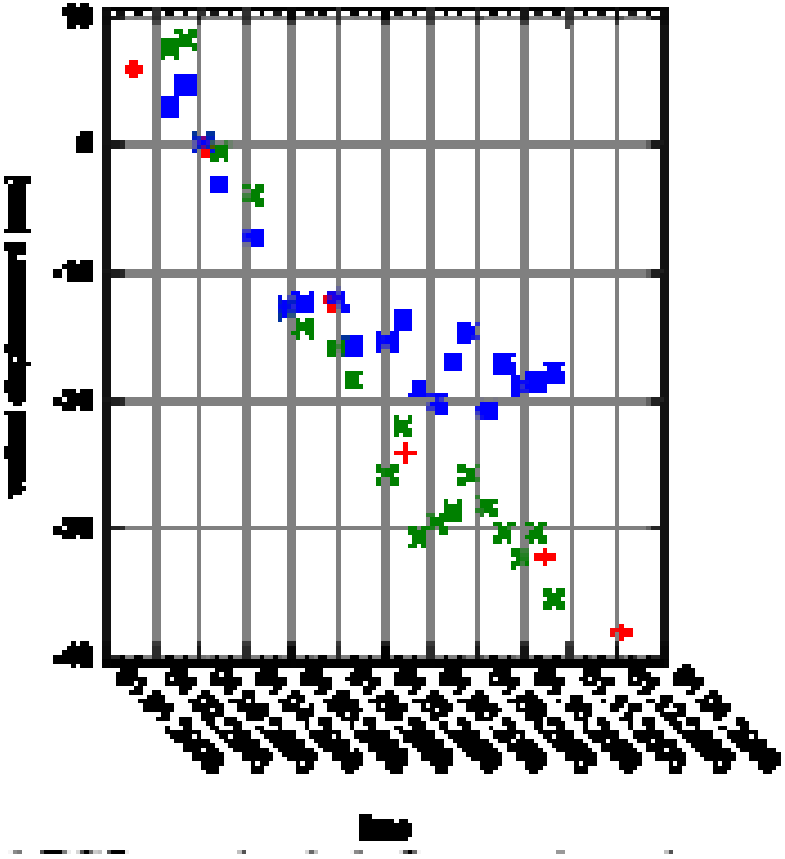
Leveling 16-Jul-2008 (red) and PSI result 14-Jul-2008 (green)



Leveling 15-Oct-2008 (red) and PSI result 10-Oct-2008 (green)

Figure 6 Comparison of leveling and PSI vertical deformation profiles along the leveling line (see Figure 4) from southwest to north relative to 11-Feb-2008. The indicated distances are measured along the profile.

Consequence of undetected unwrapping error in multi-reference stack analysis

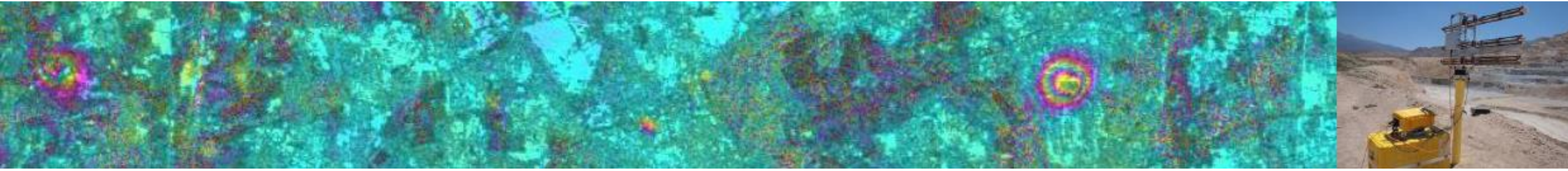


Leveling (red) shows more or less linear subsidence

Nearby green IPTA point corresponds well to the leveling

Nearby blue IPTA point shows approximately a 1.5 cm offset relative to the leveling of relative to the green IPTA point (→ this is likely a unwrapping error

Such unwrapping errors can be identified through checks of the spatial consistence of the IPTA solution and can be corrected by modification of the unwrapped phase.

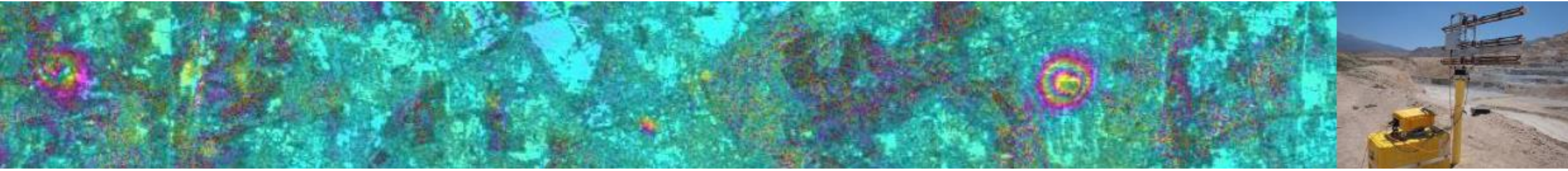


Approach 4

- PALSAR-2 L-band data stack over European Alps
- Longer time intervals (14 summer scenes in 6 years)
- Alpine terrain, area includes fast landslides

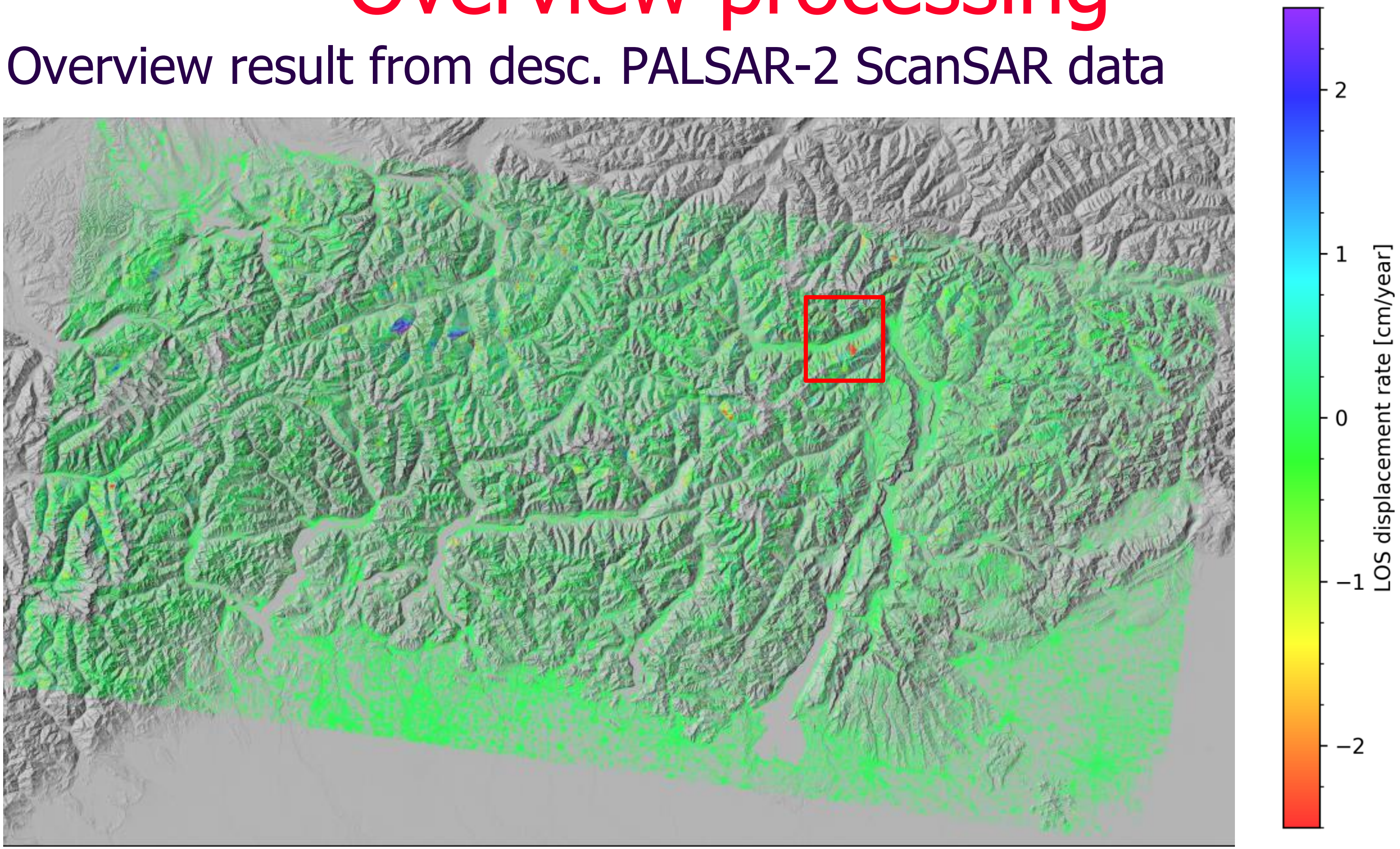
Strategic decisions:

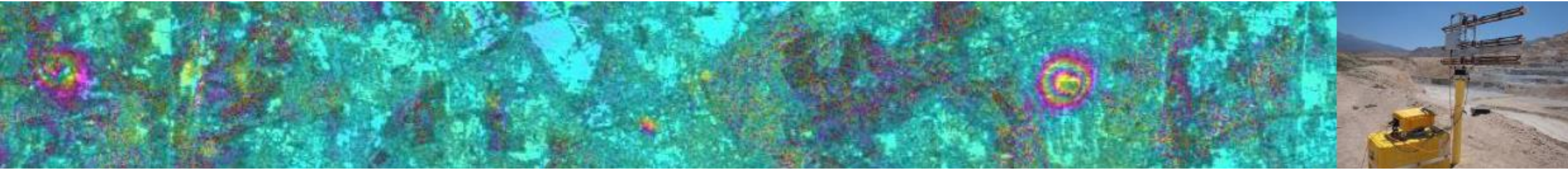
1) use “Point-like scatterers” (single pixel phases)
2) use “Single reference stack”
3) use spatial unwrapping for the estimation of the atmospheric path delay



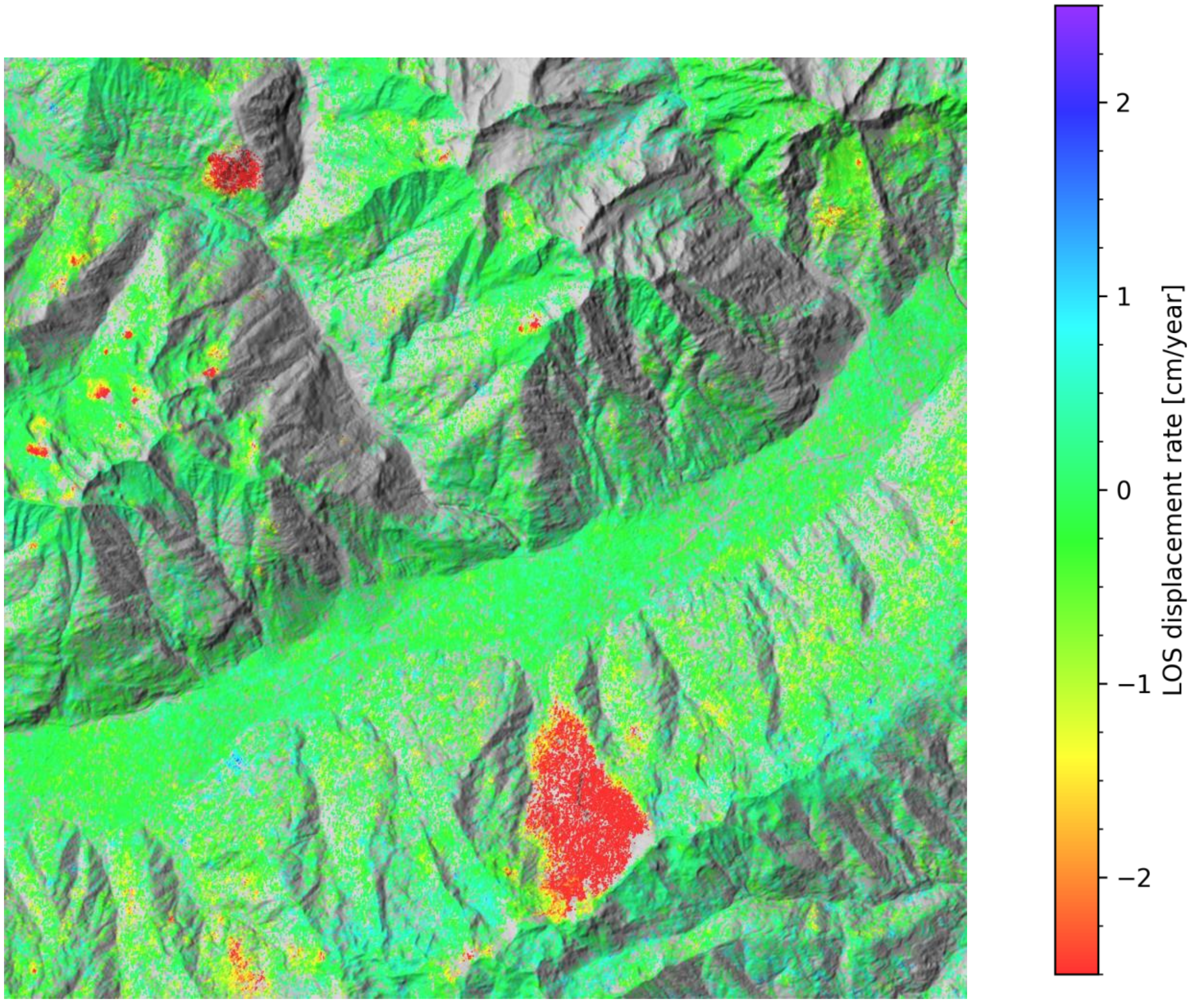
Overview processing

Overview result from desc. PALSAR-2 ScanSAR data





PALSAR-2 local processing for Naturns



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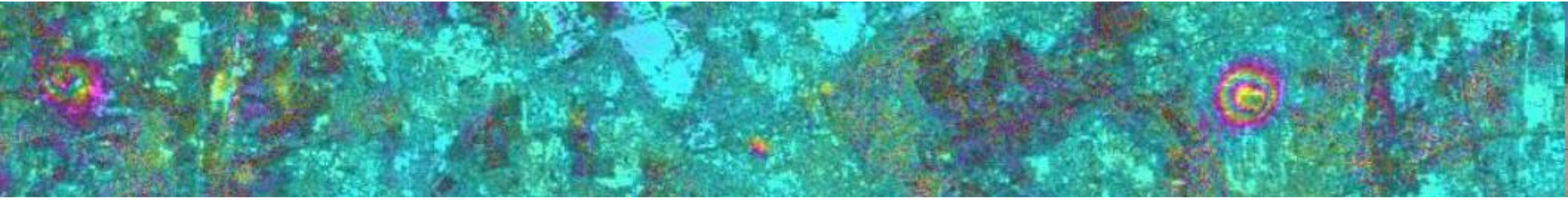
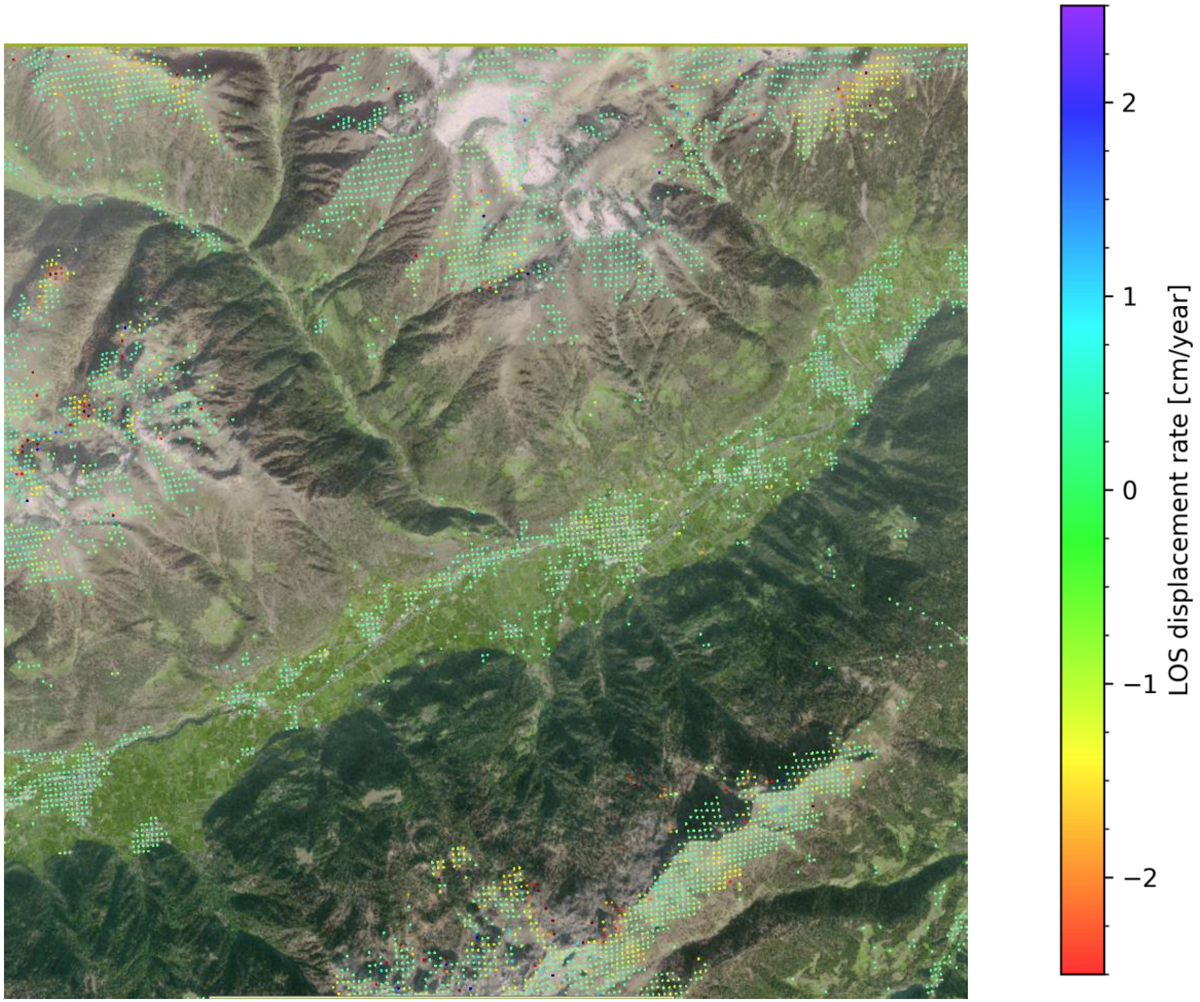


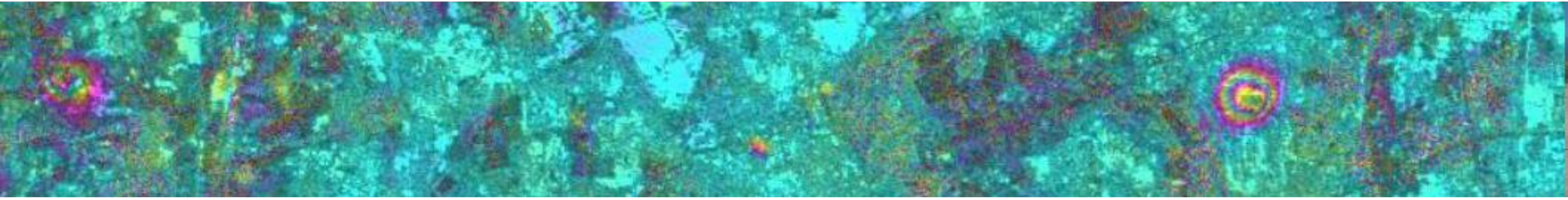

Sentinel-1 result (EGMS) for Naturns

→

Gaps for vegetation

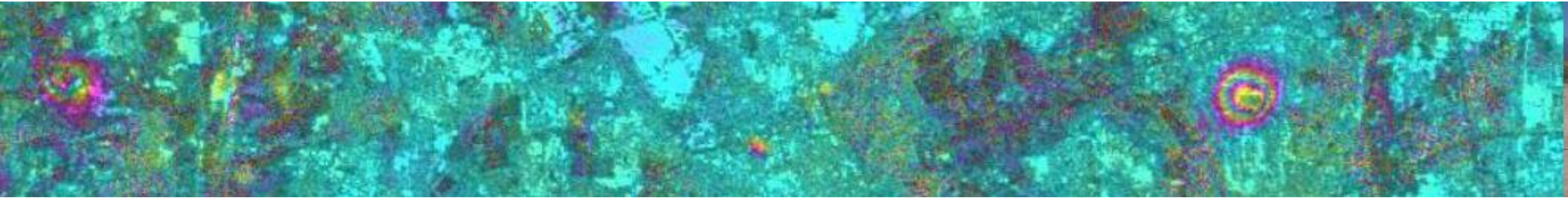
Gaps for faster movements





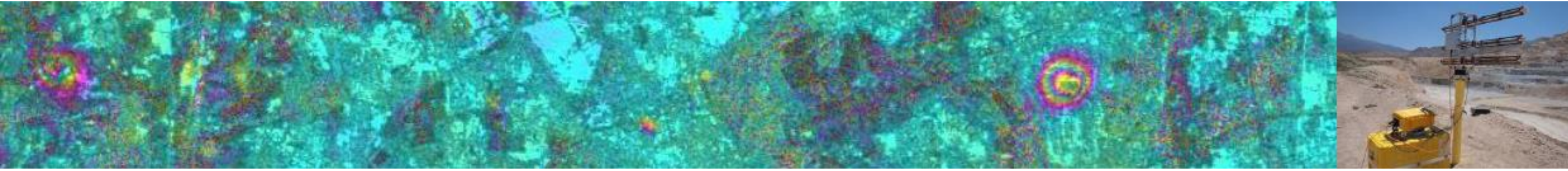
Main mining applications

- Identification and mapping of ground displacements.
- Estimation of displacement rates.
- Displacement / ground stability monitoring.
- Well suited to determine deforming area (zero disp. line).
- Monitoring for the post mining period.



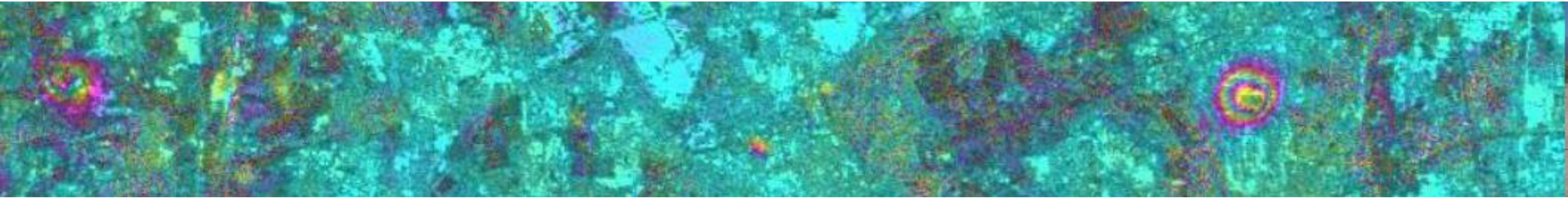

Main potential identified

- Differential interferograms have a good potential to identify and map ground displacements.
- Suited data stacks permit an accurate measurement of slow uniform displacements in built-up and arid areas.
- Availability of useful data archives (since 1992).
- Some potential also for faster and non-uniform motion.
- Some potential also for vegetated areas (L-band).



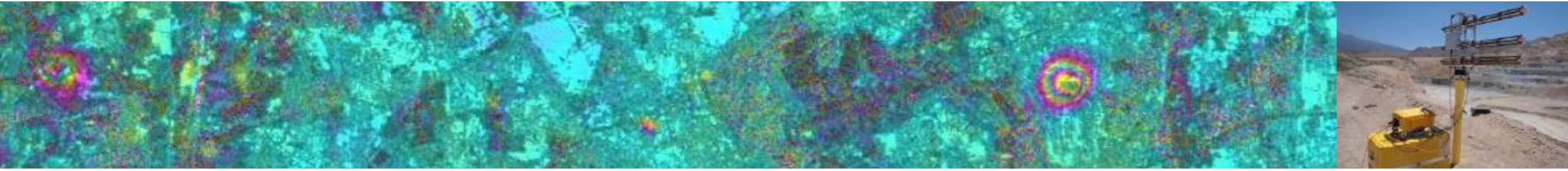
Main limitations identified

- Spatial information gaps.
- Less reliable / applicable for fast and non-uniform motion.
- Limited applicability for vegetated areas.
- Dependences on satellite operation, data provider, …



Satellite SAR sensors

Year	Sensors
1995	ERS-1/2, JERS, Radarsat-1
2005	ENVISAT, PALSAR, Radarsat-1
2015	Sentinel-1a/1b, PALSAR-2, Radarsat-2, TerraSAR-X, Cosmo-Skymed
2025	~ 100 SAR satellites incl. Sentinel-1, NISAR, PALSAR-3, … and many commercial and national sensors / constellations (e.g. ICEYE, Capella, Synspective, Novasat, …)



Satellite SAR sensors

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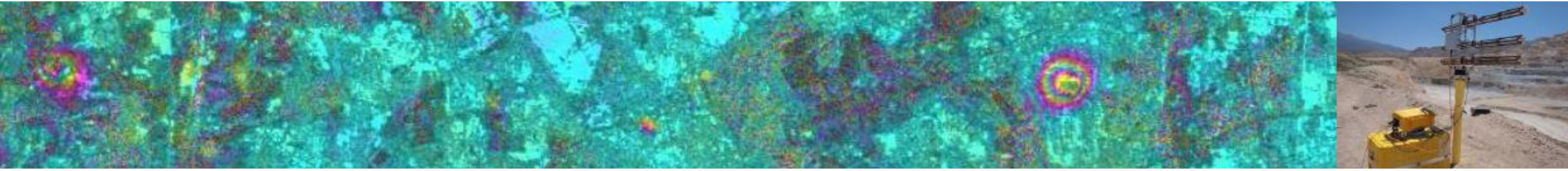
Red: Systematic acquisition of InSAR time series

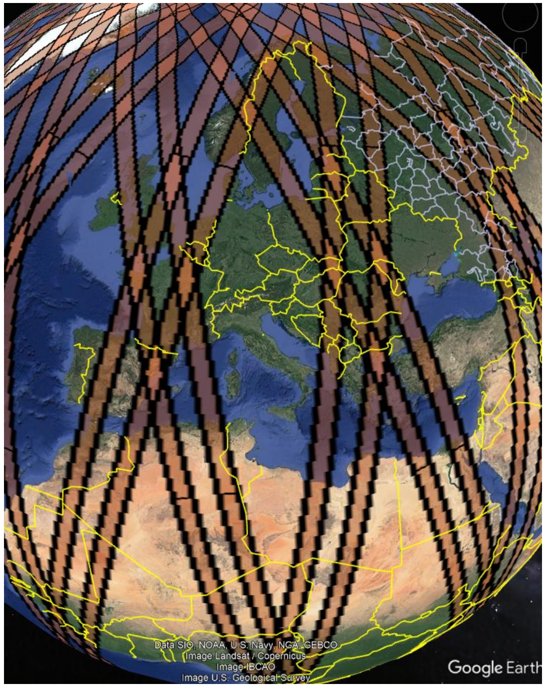


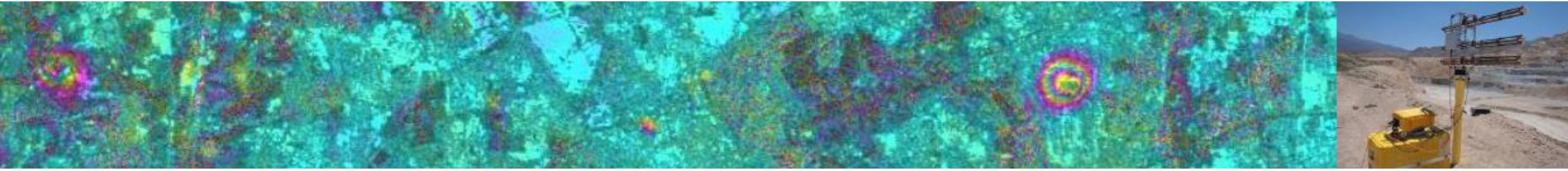
ICEYE Example

- About 20 satellites launched since 2018
- Orbits are drifting, so only the 1-day orbit satellites are well suited for InSAR, e.g. X6
- Resolution is high
- Swaths are narrow and so X6 coverage has large gaps

→ Limitations to applicability

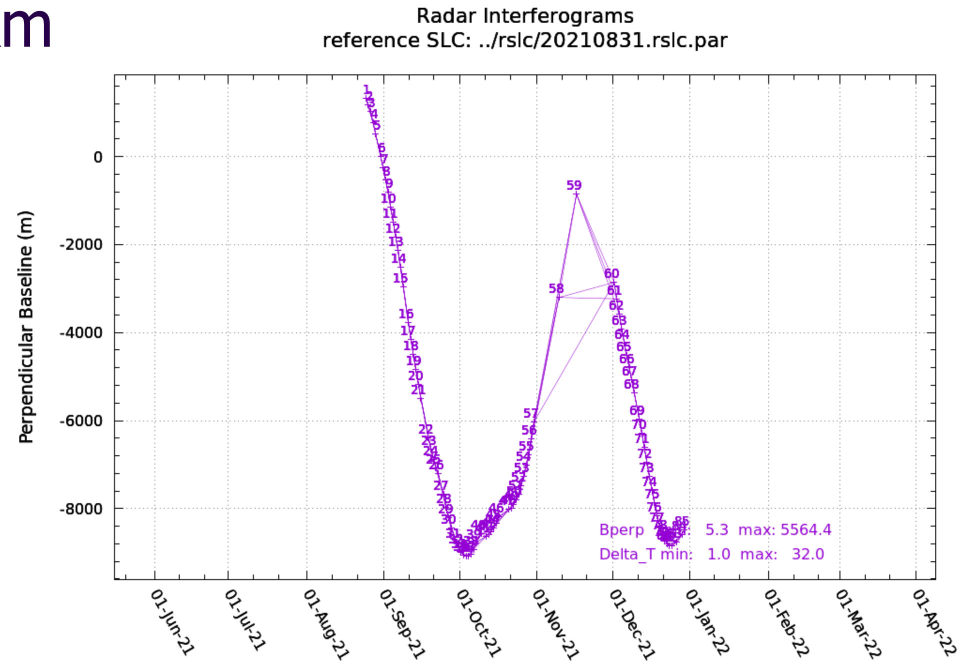
→ Limitations to archive building



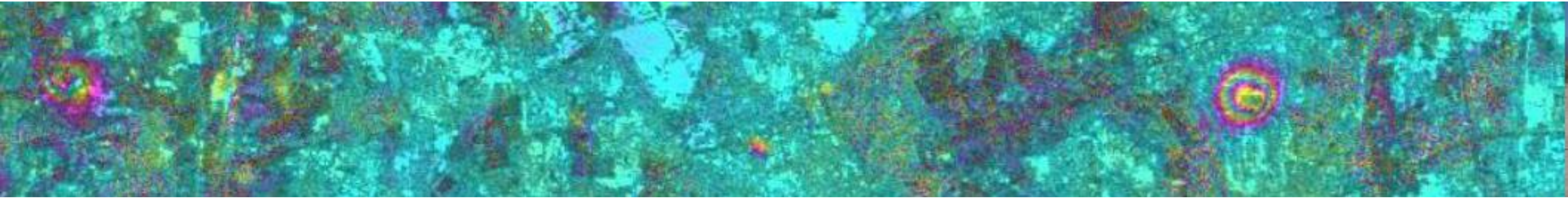


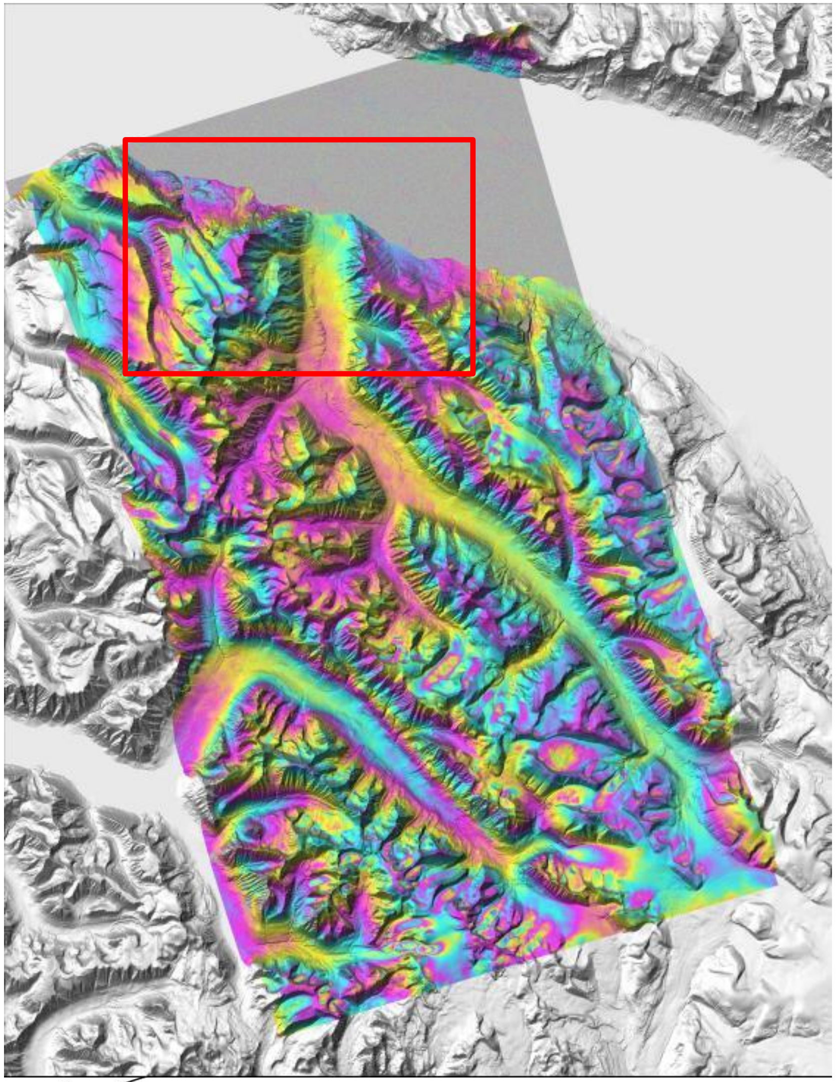
ICEYE Disko Island data

- ICEYE-X6 acquisitions Sep-Dec 2021
- High resolution: range_pixel_spacing: 0.43m
  azimuth_pixel_spacing: 1.37m
- Swath width ~ 35km
- Orbit drift
  (~ 200m per day)



GAMMA REMOTE SENSING

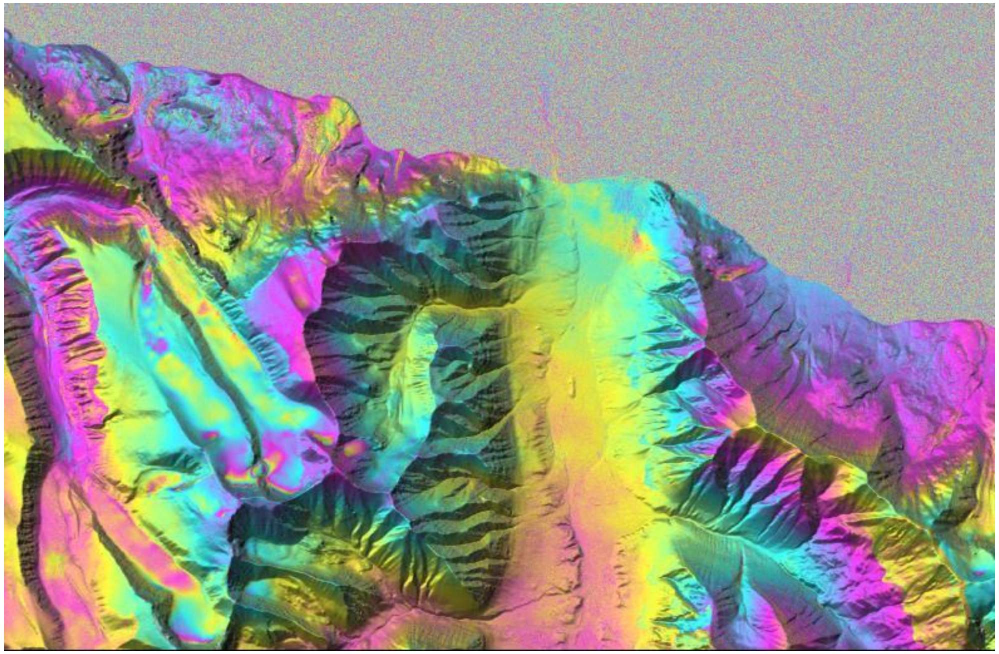




ICEYE DINSAR

20211004 - 20211005

$B_{\perp}$ 6.7m, dt 1 day



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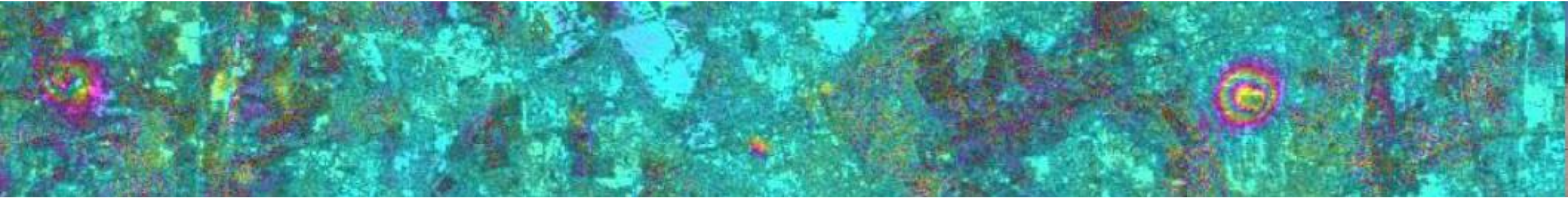
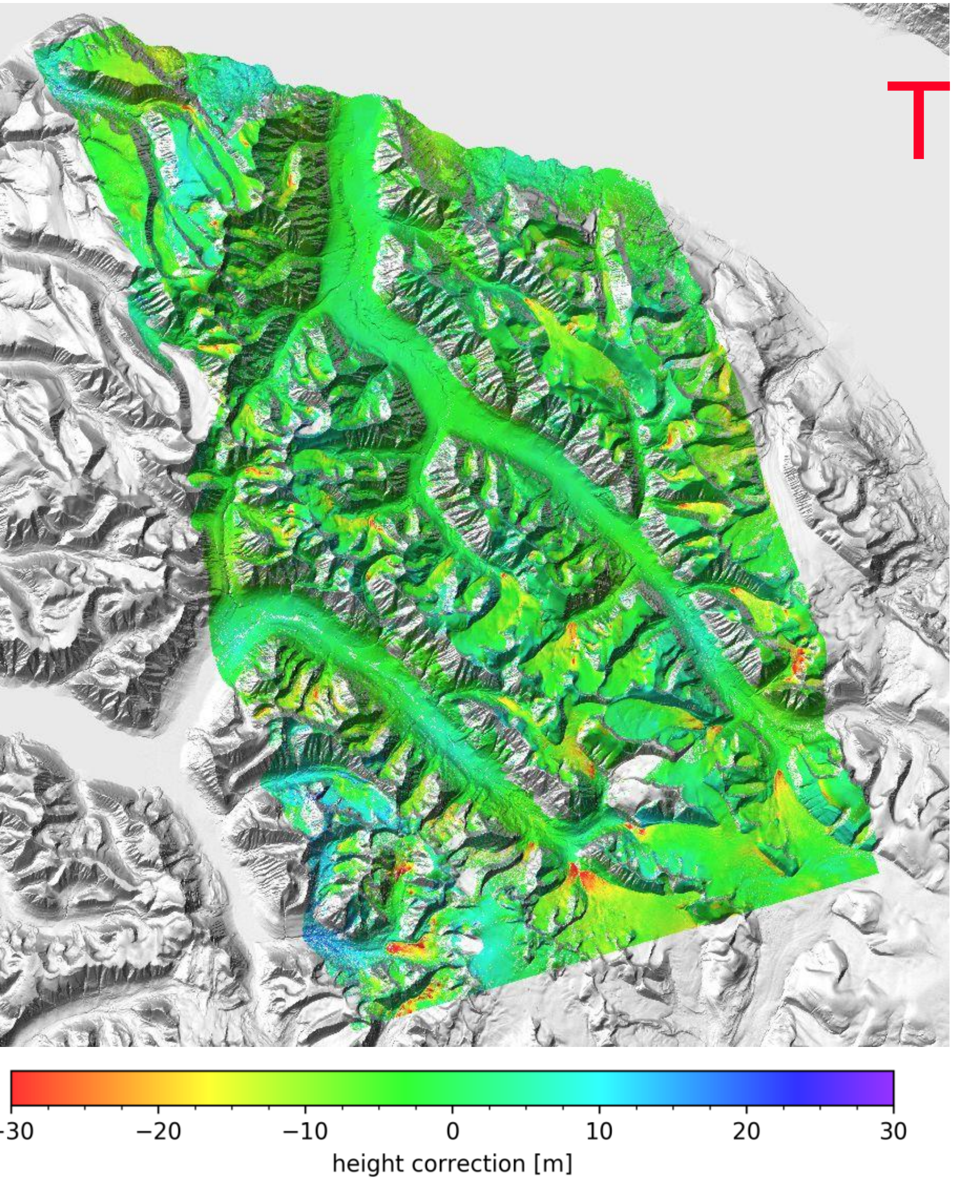
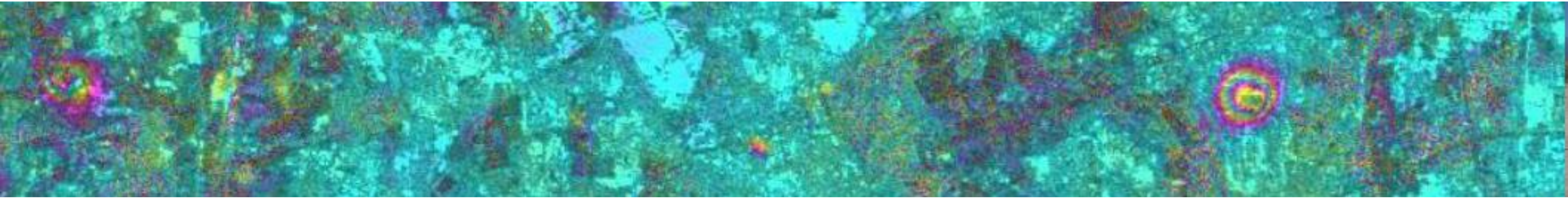


Time-series analysis

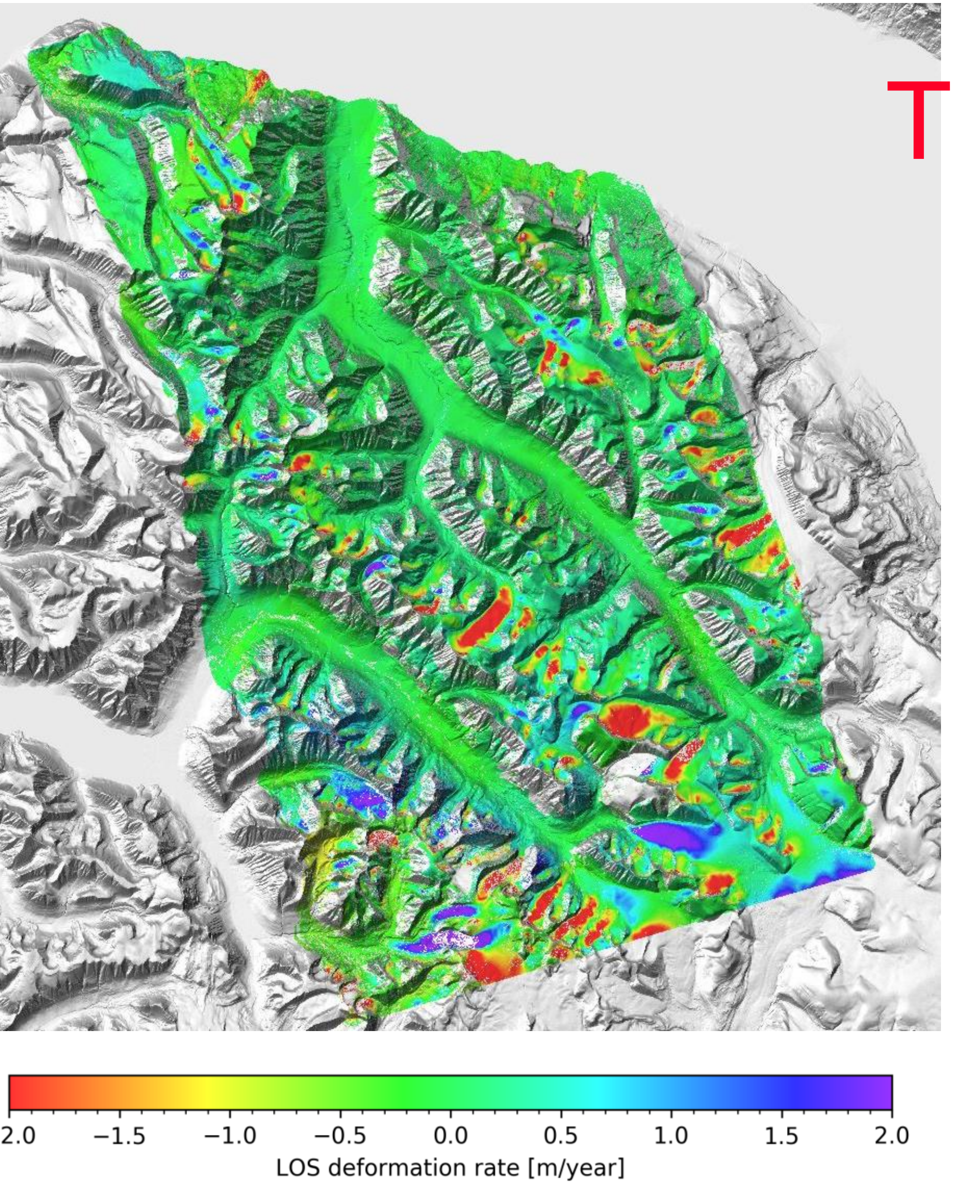


Result 1: Terrain height correction relative to the Copernicus DEM height.

→ Elevation changes over glaciers / snowfields

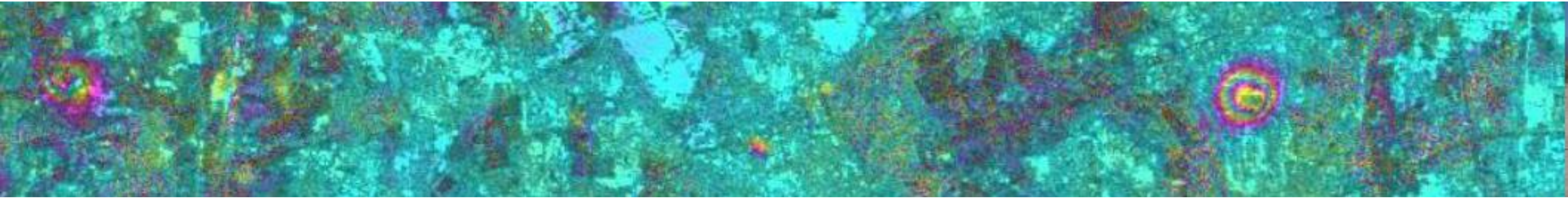


Time-series analysis



Result 2:
LOS displacement rates

→ glaciers, rock glaciers, landslides



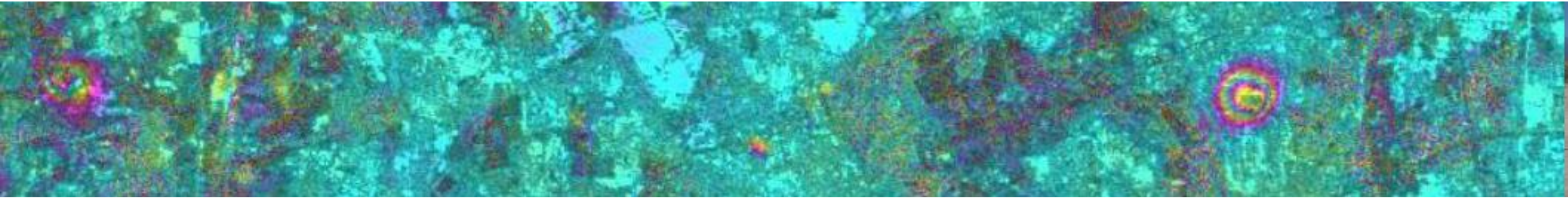
Conclusions for mining sector

- Monitoring of “cm per repeat interval” rates is possible

But:

- data need to be programmed
- data have a relevant price
- data access within hours to days after acquisition
- imaging of steep slopes may be limited

→ Terrestrial radar may be an interesting alternative




Potential of a terrestrial radar

- Flexible selection of look direction
- Flexible selection of time interval (e.g. every minute)
- KU-band (17.2 GHz) → high sensitivity
- Fast access to results
- No dependence on satellites, agencies, data providers
- Well suited for continued monitoring with short intervals
- Alarm system capability

Concepts

Synthetic Aperture
Radar concept

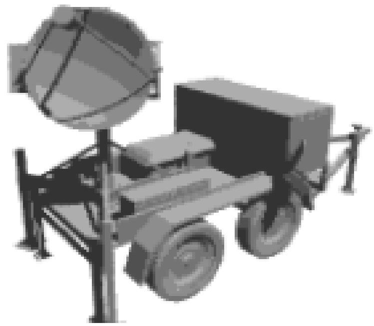
LiSALab

IDS INGEGNERIA DEI SISTEMI

Frequency: 17.2 GHz
Rail length L: 2 m
Azimuth resolution
0.2 deg., 4 m @ 1km

GAMMA REMOTE SENSING

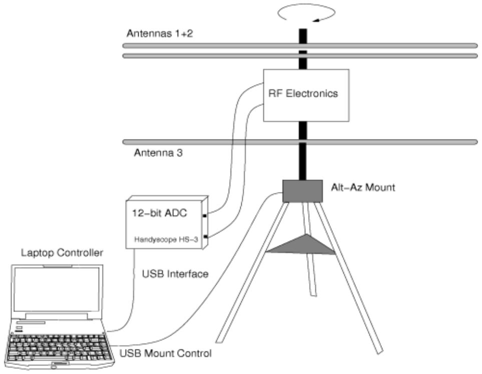
Real Aperture
Radar concept 1



GroundProbe
Unique Measurement Systems

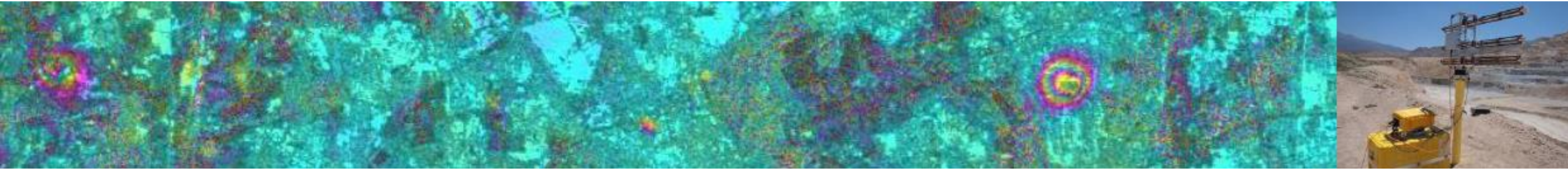
Frequency: 9.45 GHz
Dish diameter : 0.9 m
Azimuth resolution:
2 deg., 4 m@100m

Real Aperture
Radar concept 2

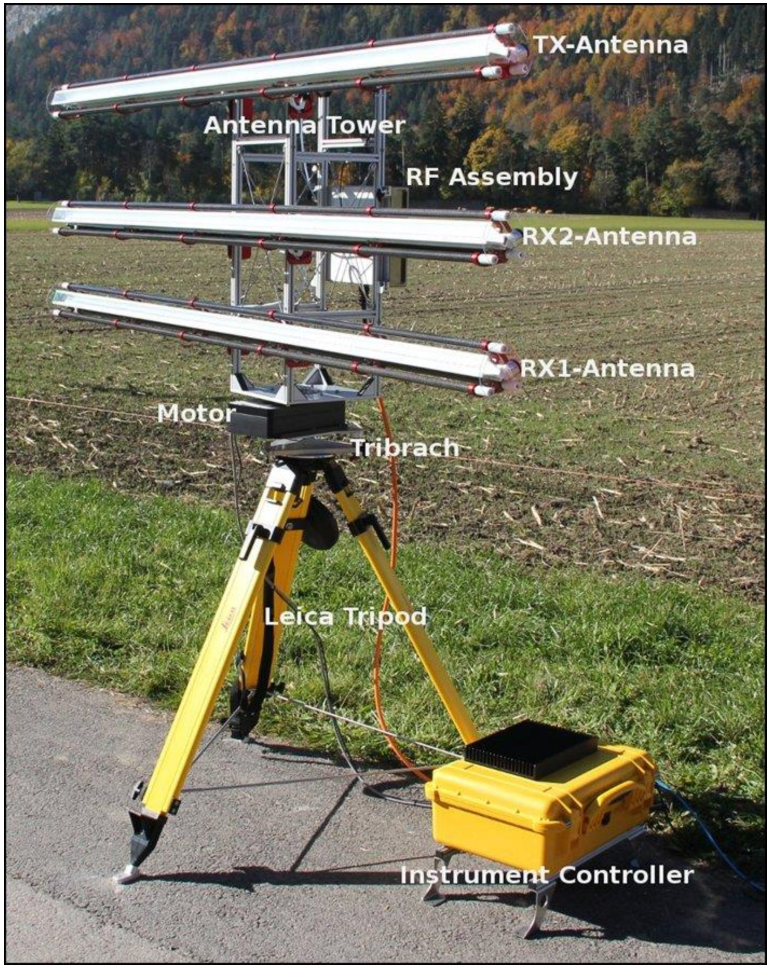


GAMMA REMOTE SENSING

Frequency: 17.2 GHz
Antenna length L: 2.1 m
Azimuth resolution
0.4 deg., 8 m @ 1km



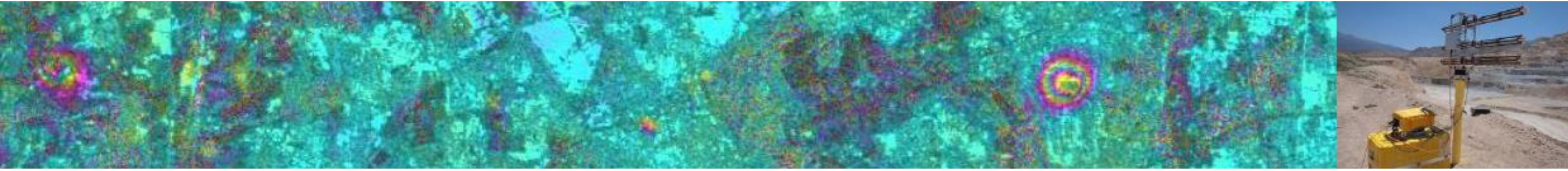
Gamma Portable Radar Interferometer (GPRI)



- KU-band (17.2 GHz)
- Portable, fast installation
- GAMMA Software
- High SNR
- Measurements up to 10 km
- 360 deg. view (@ 10 deg./s)
- Sensitivity < 1mm

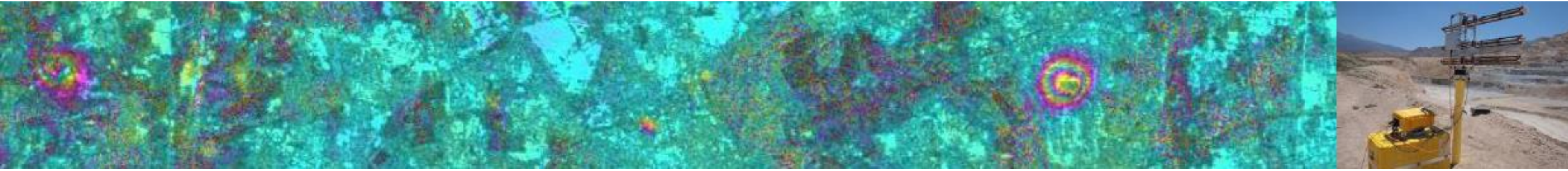
https://gamma-rs.ch/instruments

GAMMA REMOTE SENSING



Round Mountain - Fairview Pit

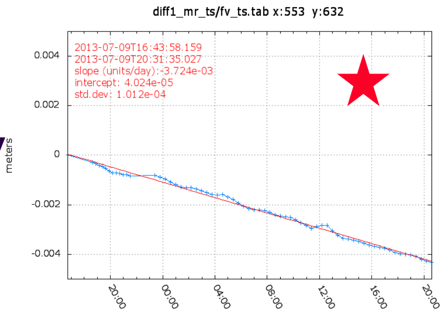
- 450 observations at 2 minute intervals

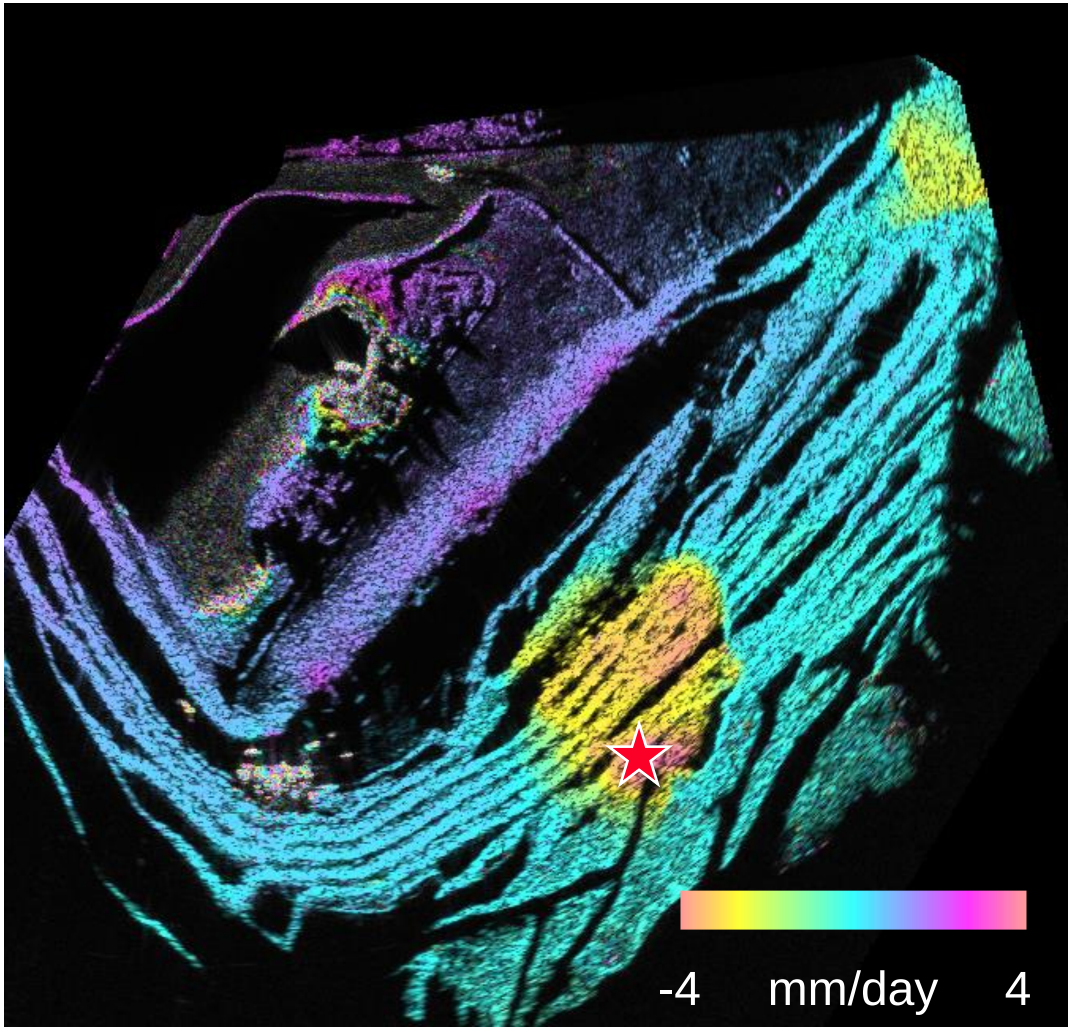


Deformation Time-Series at Fairview

Processing:
DInSAR series AB, BC, ...
Unwrapping
Summing of phases
Convert to displacements
(time series, average rate)
Quality control
Geocoding

~4mm/day

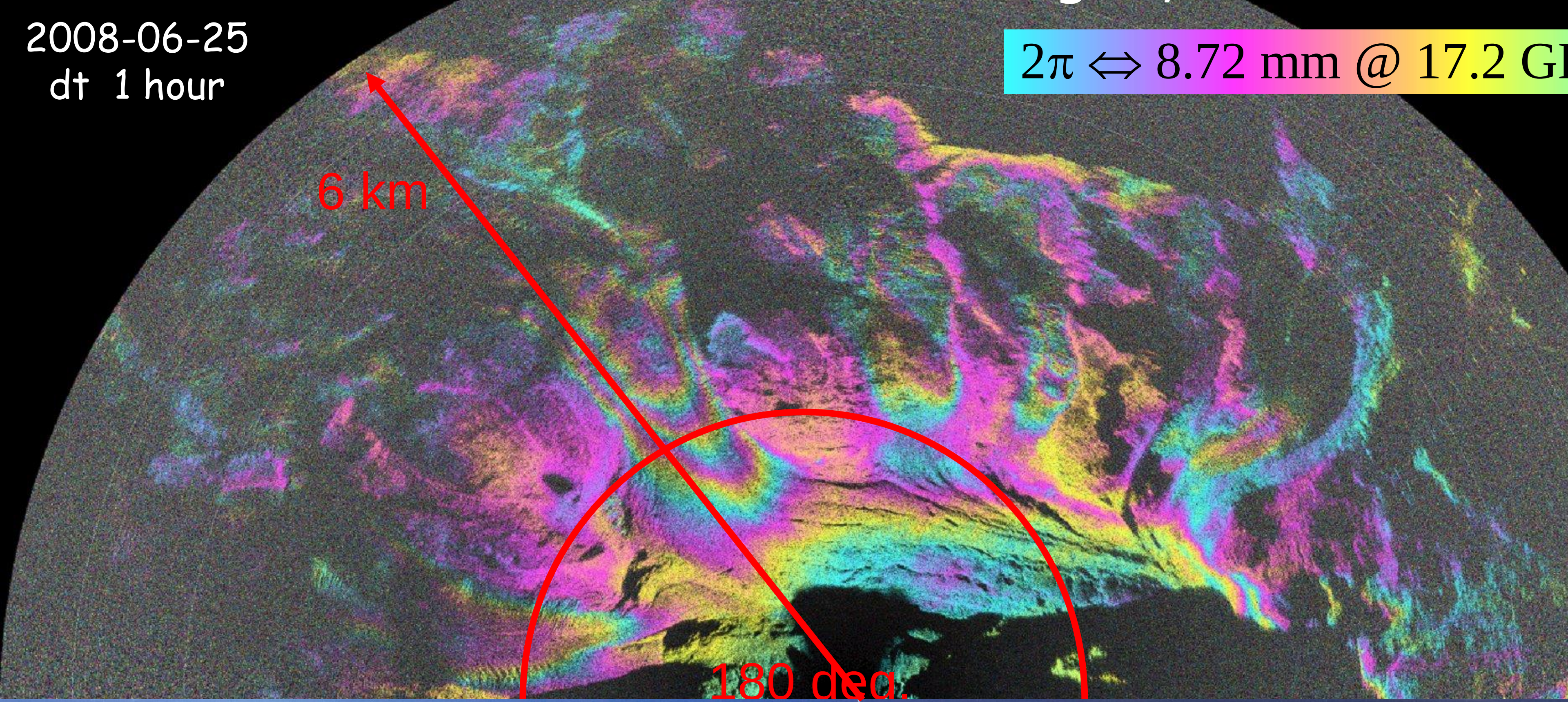


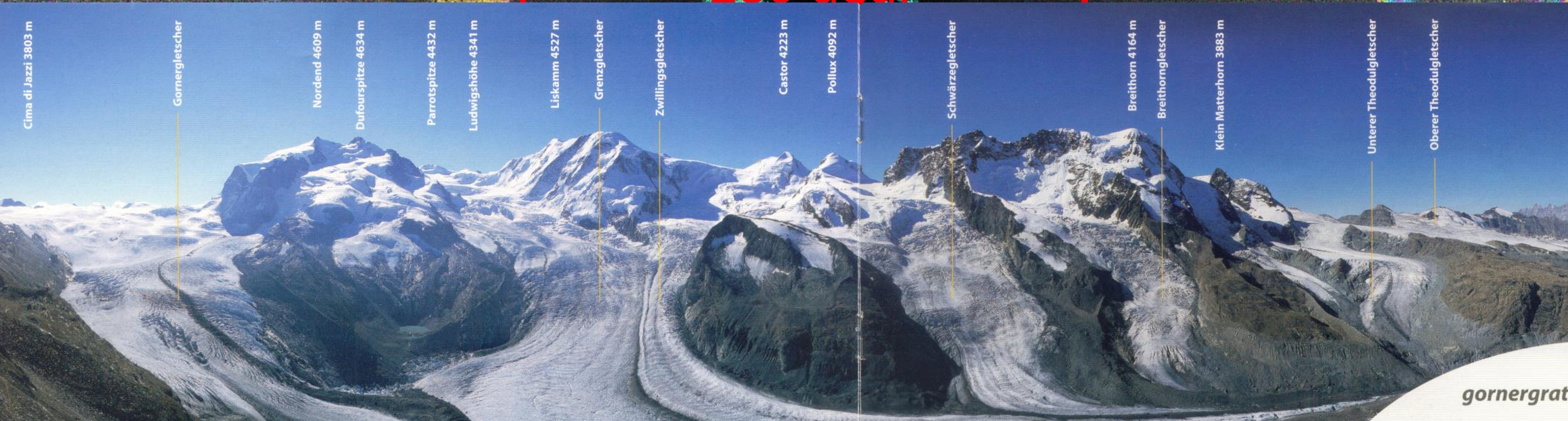


GAMMA REMOTE SENSING

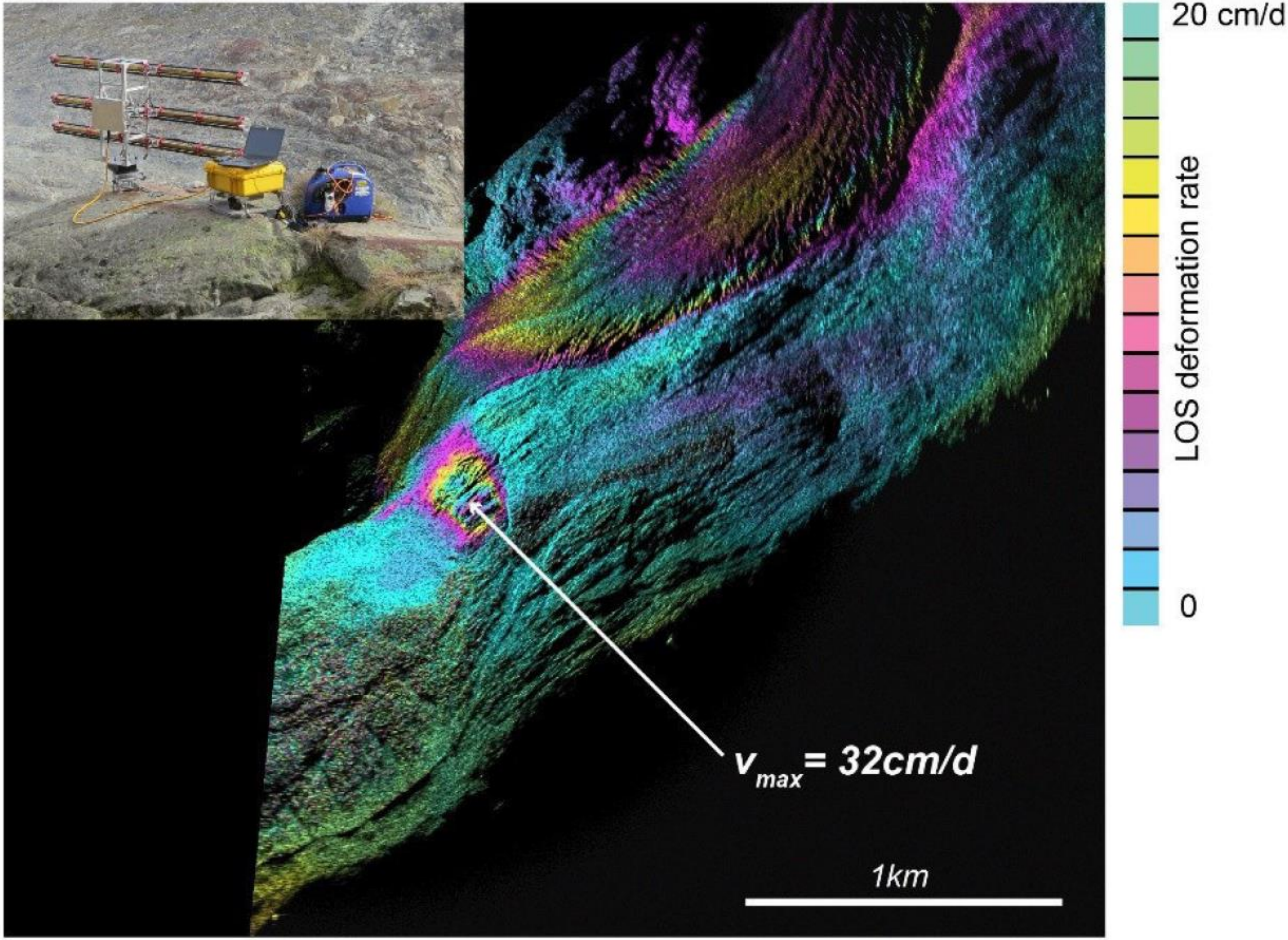
GPRI Measurement from Gornergrat, Switzerland

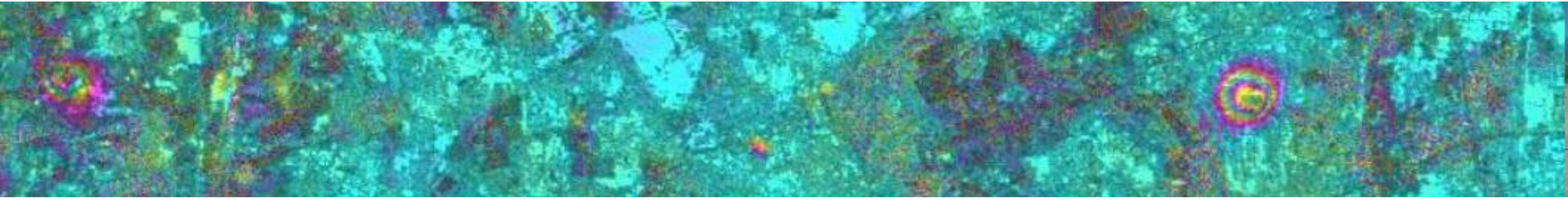
2008-06-25
dt 1 hour



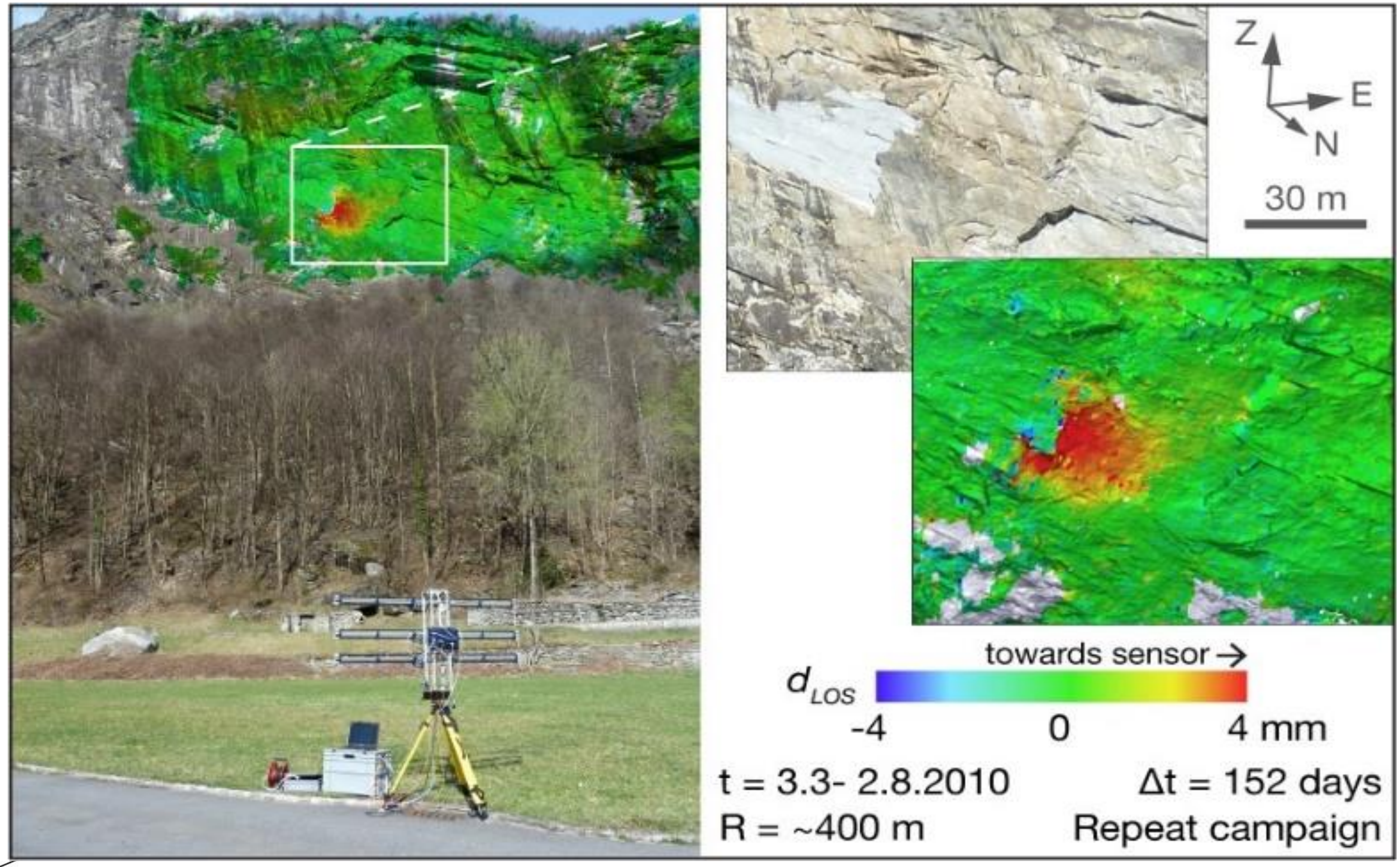


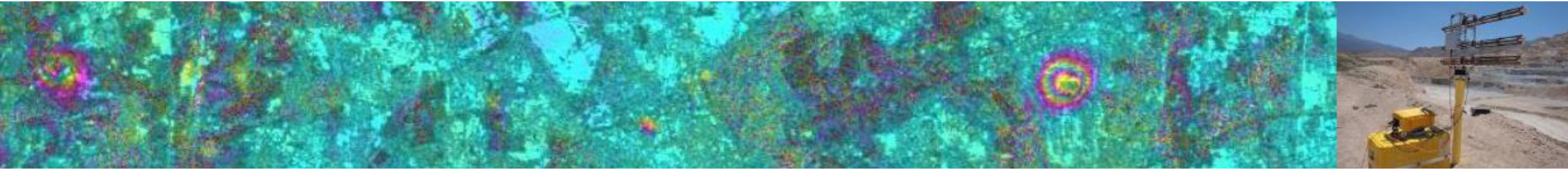
GPRI DInSAR phase over 30 minutes





Monitoring of rock instability (mm/year)

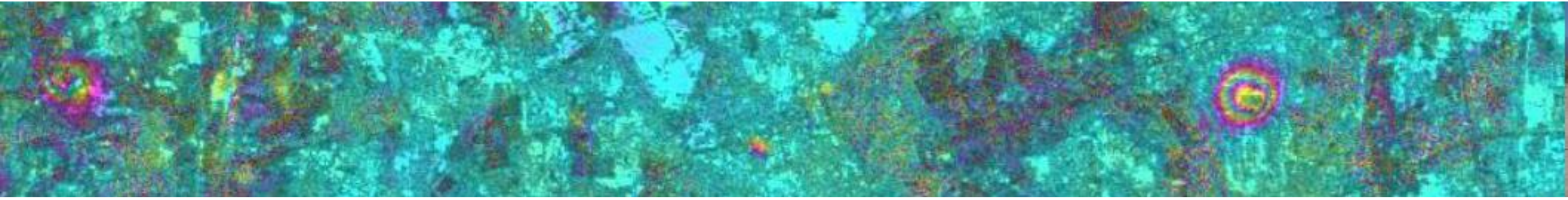




GPRI Interferometric Acquisition Modes

1) Monitoring of very rapid deformation (m/s) such as over bridges with the radar fixed on a defined position (m/s, … cm/s);
2) Rapidly deforming features such as glaciers where deformation occurs on minute time-scales (cm/min, … mm/day);
3) Observation of slowly moving features such as landslides where deformation occurs on monthly or yearly time-scales and reinstallation of the radar is required (cm/month, … mm/year);
4) Elevation model derivation and volume estimations (using separate receive channels with spatial baseline).


Recently, we also developed an interferometric L-band SAR operated on a drone, on the roof of a car, or on a 12m rail.




Summary and outlook

- Considering the available and planned SAR satellites it clearly looks like we are entering the SAR era …
- There are and will be institutional missions with consistent interferometric data acquisition strategies.
- This is complimented by (many) national and private SAR missions.
- InSAR techniques are quite mature but the applicability, accuracy etc. depend on the sensor and target characteristics.
- For operational more local applications, such as the monitoring of slopes in open-pit mines, terrestrial radars offer an excellent solution.

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