Ground Displacement and Geotechnical Risk Monitoring Using Satellite Data

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Presentation outline

- When to implement risk monitoring?
- SAR fundamentals
  - SAR (Synthetic Aperture Radar)
  - InSAR techniques: time series analysis
  - Workflow of InSAR TS
  - Decomposition of Line-of-Sight InSAR measurements
- SAR application to monitoring
  - Subsidence monitoring
  - Case example
  - Slope stability and landslides
- Data integration & decision support
  - Integrated SAR remote sensing and ground monitoring
  - Case example
  - Takeaways

From millimeter scale ground motion to geotechnical risk decisions

Why ground displacement = geotechnical risk signal?

Surface displacement → Deformation patterns → Assessment And evaluation → Decision

Which satellite signals measure ground motion?

Small scale detection
Repeat observations
Weather independent
Day light independent
Wide area coverage

→ **Radar sensors (SAR)**
Primary tool

E.g., Sentinel-1 TerraSAR-X or COSMO-SkyMed
Ground-based InSAR: IBIS, SSR.

When to implement risk monitoring?

Geotechnical risks related to raw material utilization include:

Slope instability & landslide

Subsidence & ground deformation

Infrastructure failure

Underground excavation instability

Tailings failure

Liquefaction

Credit: RawMatCop Academy

We need early stage (mm-scale) ground movement detection over time.

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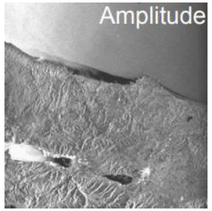
SAR fundamentals

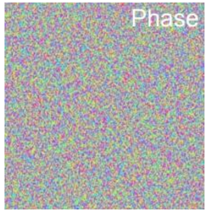
SAR (Synthetic Aperture Radar)

Active microwave remote sensing (wavelength of X - L band).

Transmits radar pulses & receives returned signal in phase and amplitude components.

SAR signal = **Phase** (sensor to target distance information) + **Amplitude** (target information)

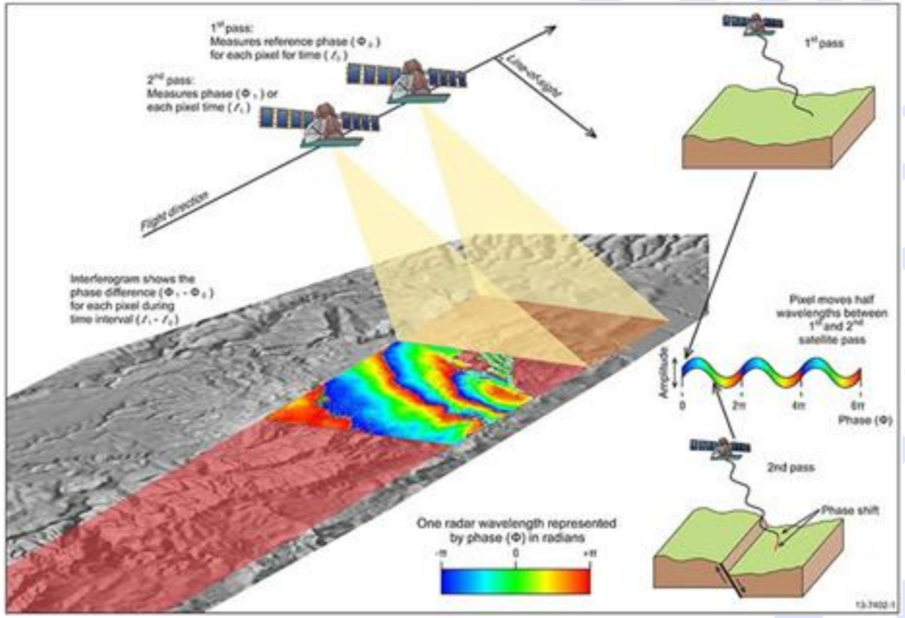




ESA, 2013

$$\phi = \frac{4\pi R}{\lambda}$$

ϕ = radar phase (radians)
ΔR = range (satellite to ground distance)
λ = radar wavelength



Geoscience Australia.

The Measured signal consists of multiple components that contribute to the total phase change.

Interferometric phase change:

$\Delta\varphi = \varphi_{geometry} + \varphi_{atmospheric} + \varphi_{topographic} + \varphi_{deformation} + \varphi_{noise}$

.

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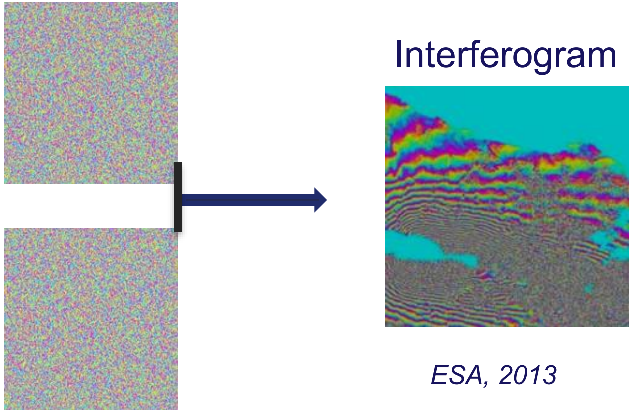
Phase change (difference between two SAR acquisitions of the same area at different times) used to construct interferogram.

Interferogram is a map of phase differences representing surface displacement along the line-of-sight (LOS).



ESA, 2013

Illustration of interferogram formation

This technique refers to **InSAR** (Interferometric Synthetic Aperture Radar).

$$\Delta d_{LOS} = \frac{\lambda}{4\pi} \Delta\varphi$$

Δd_{LOS} = LOS displacement
$\Delta\, \phi$ = phase difference

Decomposition of Line-of-Sight InSAR measurements

InSAR measurement captures motion only along the radar LOS.

Actual ground displacement is not always vertical (N–S).

Combining ascending and descending satellite orbits helps to understand the true ground movement.

Separation of InSAR LOS measurements into vertical and horizontal (E–W) displacement ⇒ Decomposition

Decomposition is required to estimate the true 2D or 3D surface motion.

$$\begin{pmatrix} d_{LOS}^{asc} \\ d_{LOS}^{dsc} \end{pmatrix} = \begin{pmatrix} \cos\theta_{\mathrm{asc}} & -\cos\alpha_{\mathrm{asc}}\sin\theta_{asc} \\ \cos\theta_{dsc} & -\cos\alpha_{\mathrm{dsc}}\sin\theta_{dsc} \end{pmatrix} \begin{pmatrix} d_{ver\ (Up-Down)} \\ d_{hor\ (East-West)} \end{pmatrix}$$

2D decomposition Equation

d_{LOS}^{asc}, d_{LOS}^{dsc} = *deformation of the descending satellite*

θ_{asc}, θ_{dsc} = *Incidence angles*

α_{asc}, α_{dsc} = *satellite heading angles*

d_{hor}, d_{ver} = *vertical and horizontal component*

Interferometric artifacts

A single Interferogram contains artifacts originating from atmospheric, topographic, and geometric phase contributions.

Atmospheric (Ion & trop)

- Caused by tropospheric and Ionospheric phase delays

Orbital artifacts

- Due to difference in satellite position

Topographic error

- Due to the slightly different antenna positions of the satellite during the two image acquisitions, a systematic phase difference over the whole scene can be observed. The presence of topography introduces an additional effect on top of the one observed over flat terrain

Coherence/ temporal

- Due to land cover change or presence of vegetation

Unwrapping (phase inconsistency)

- Due to noise, bad coherence, fast movements

Mitigation techniques

➡ Weather model; time analysis, complement with GNSS

➡ Precise orbit data, ramp removal through known Ground Control Point (GCP)

➡ High resolution DEM; residual DEM error estimation

➡ Short temporal, multilooking

➡ Good algorithm, discard bad interferogram

InSAR techniques: time series analysis

Time series (TS): Temporal evolution of ground displacement.

Separate deformation signal from noise.

Various TS algorithms developed:

Permanent Scatterer InSAR (PSInSAR), Stanford Method for Persistent Scatterers (StaMPS), Persistent Scatterer Pairs (PSPQuasi Persistent Scatterers (QPS), Small Baseline Subset (SBAS), Coherent Pixels Technique (CPT), … .

Differential Scatterer InSAR

- Uses two SAR images to detect deformation.
- Suitable for sudden deformation.
- Useful in sparce persistent scatterers.
- Often integrated with PS/SBAS.

Persistent Scatterers (PS)

- Best when stable reflectors exist (e.g., buildings).
- High precision on points.
- Long time series.
- In mining & urban infrastructure.

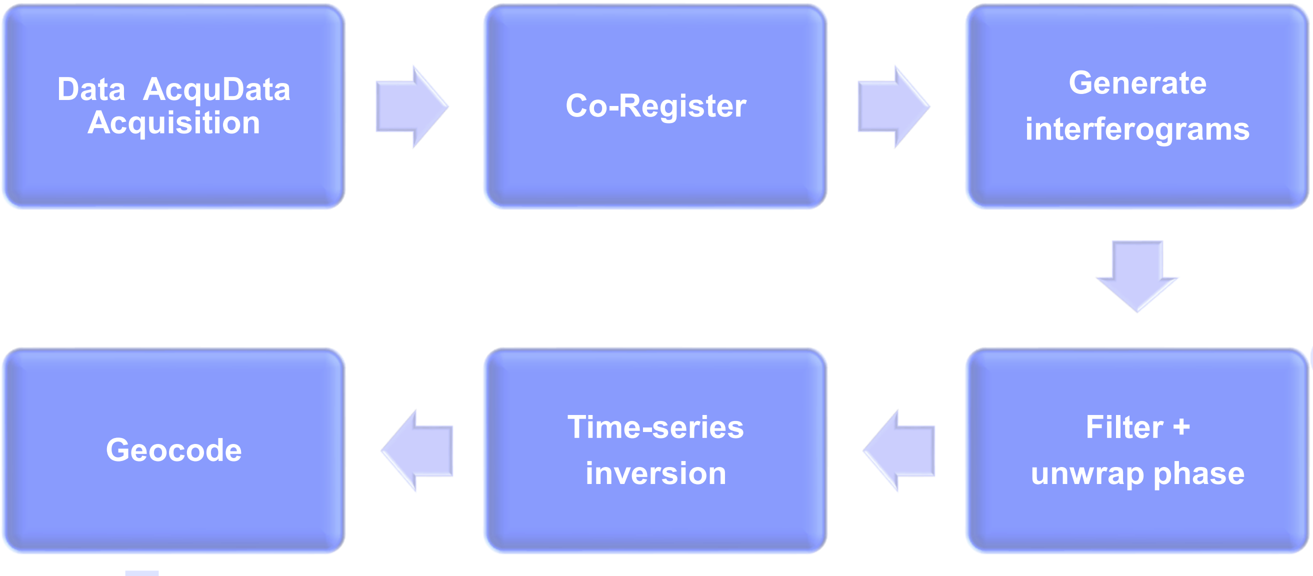
Small Baseline Subset (SBAS)

- Uses short temporal & spatial baseline networks = better coherence.
- Effective in mixed terrain.
- Long term slow deformation
- Good for regional and mining basin deformation.

E.g., Berardino et al., (2002); Osmanoglu et al., (2016)

Some InSAR data and TS processing tools: ISCE, SNAP, MintPy, LiCSAR

Workflow of InSAR TS



E.g., Simons, & Rosen (2007)

Velocity map (mm/yr)
Displacement time series measurement

\+

Uncertainty estimates

SAR application to monitoring

Subsidence monitoring

Subsidence is often slow and cause gradual damage.

Can be related to material removal (mining, groundwater), underground voids, or uneven/ poor backfill.

Mitigation:

✓ Velocity (mm/yr) → ascending orbit + descending orbit ⇒ **2D displacement.**

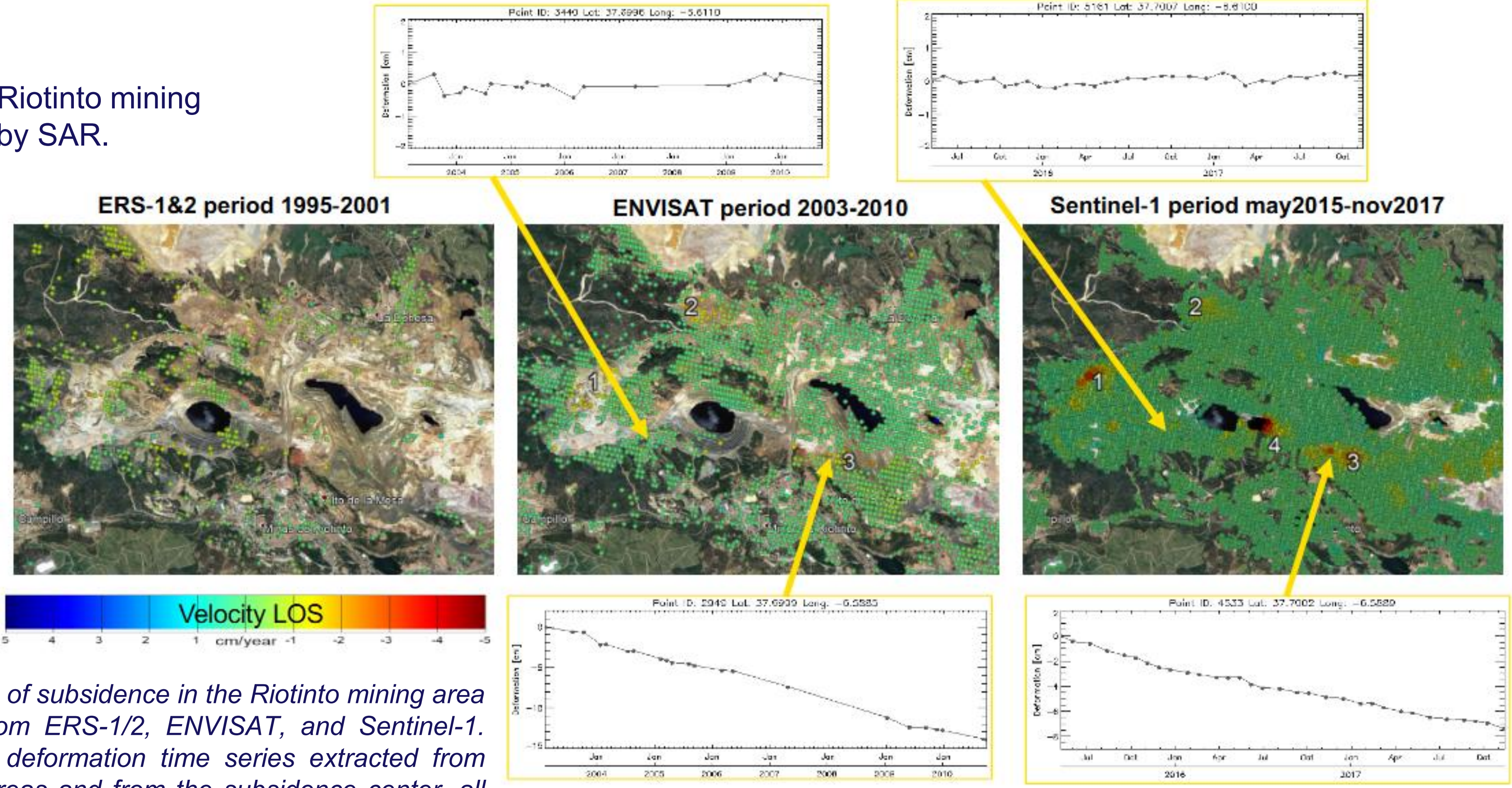
✓ Cumulative displacement over time.

- Differential settlement.
- Deformation gradient/strain proxy.
- Track time series for trend changes… (historical review).

Validation ⇒ integrate with other technique (e.g., GNSS, levelling).

Case example

Subsidence in Riotinto mining area analysed by SAR.



Historical evolution of subsidence in the Riotinto mining area (Spain) derived from ERS-1/2, ENVISAT, and Sentinel-1. The figure shows deformation time series extracted from stable reference areas and from the subsidence center, all generated from a single satellite orbit (Escayo et al., (2022).

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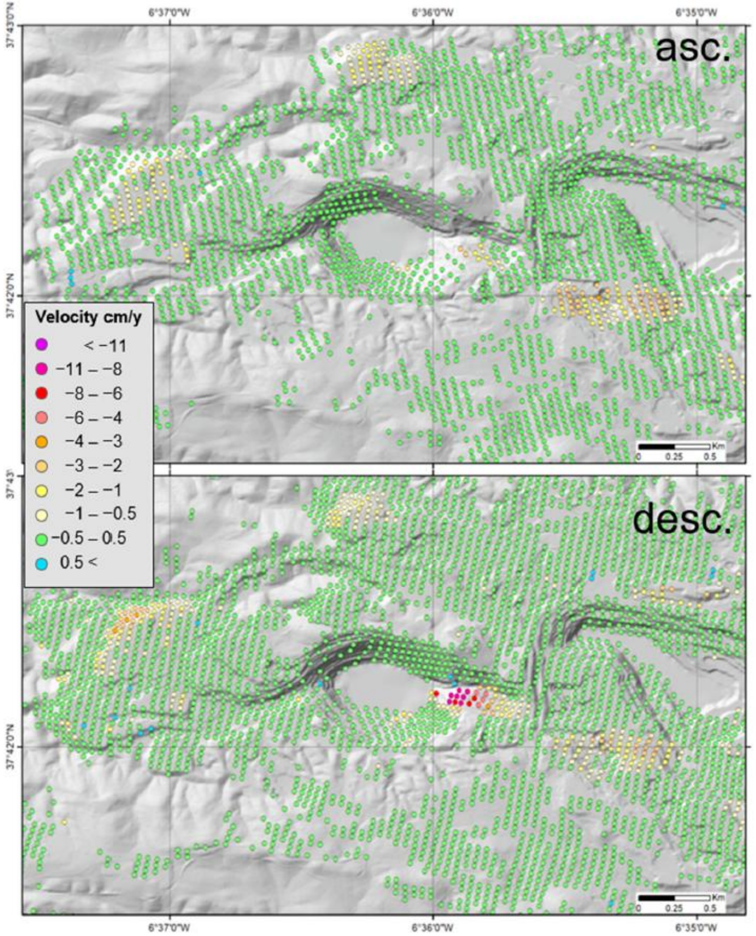
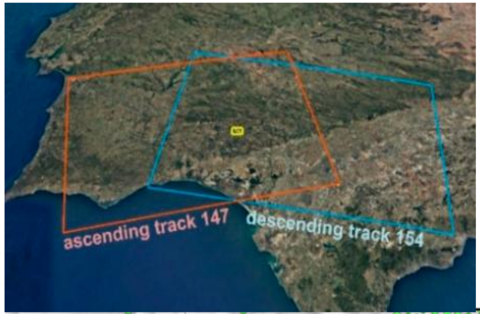
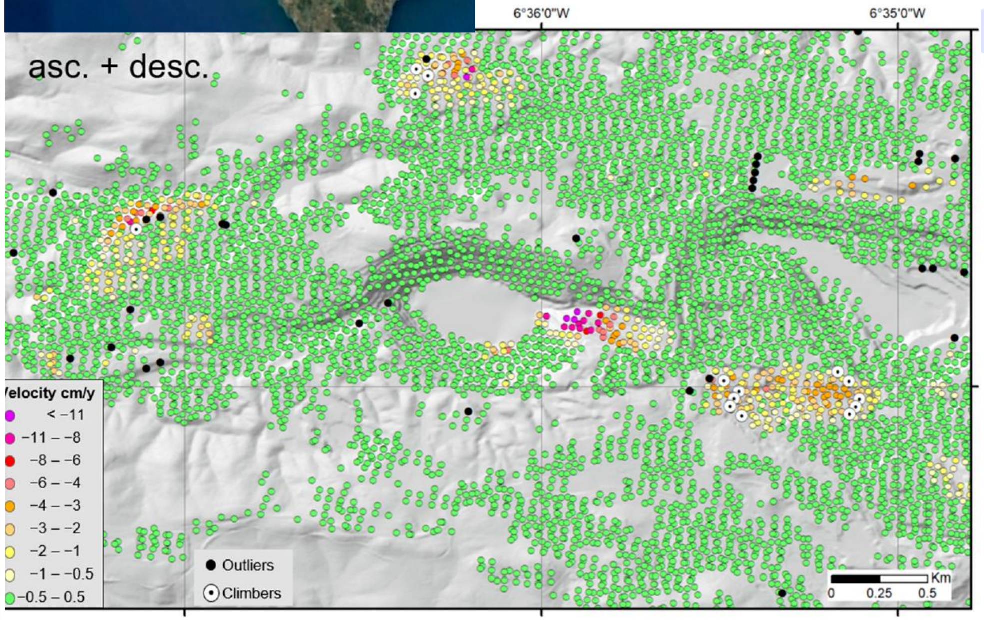




LOS displacement maps of Riotinto mining area derived from ascending (top) and descending (bottom) geometries are shown on the left; their integration enhances spatial resolution and deformation detail, as illustrated in the combined displacement map on the right (Escayo et al., 2022).



Slope stability and landslides

Keep in mind:

- Can be caused by heavy rainfall, earthquakes, and human activities
- Precursors of ground deformation can precede the slope failure.
- Slow moving slides (mm–cm/year) can be detected.

Limitations

- Dense vegetation & land cover change ⇒ decorrelation
- Fast motion ⇒ phase unwrapping issue.
- LOS-only sensitivity;
- Blind to displacement occurring along the N–S direction.

Mitigation

✓ Wide area screening ⇒ helps identify potential instability.

✓ Target coherent surfaces ⇒ important for the InSAR analysis.

✓ Use longer wavelength (L-band) to increase the coverage over vegetated areas

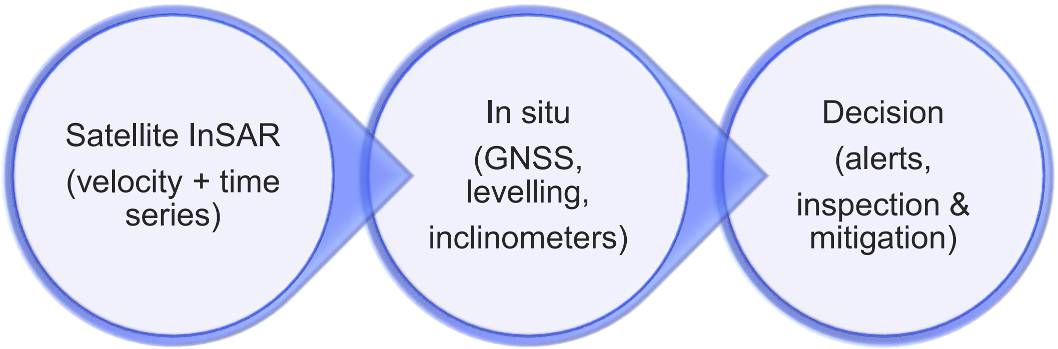
✓ Combine Ascending + Descending geometries to derive 2D displacement (E-W and vertical components)

✓ Conduct field check.

Data integration & decision support

Integrated SAR remote sensing and ground monitoring

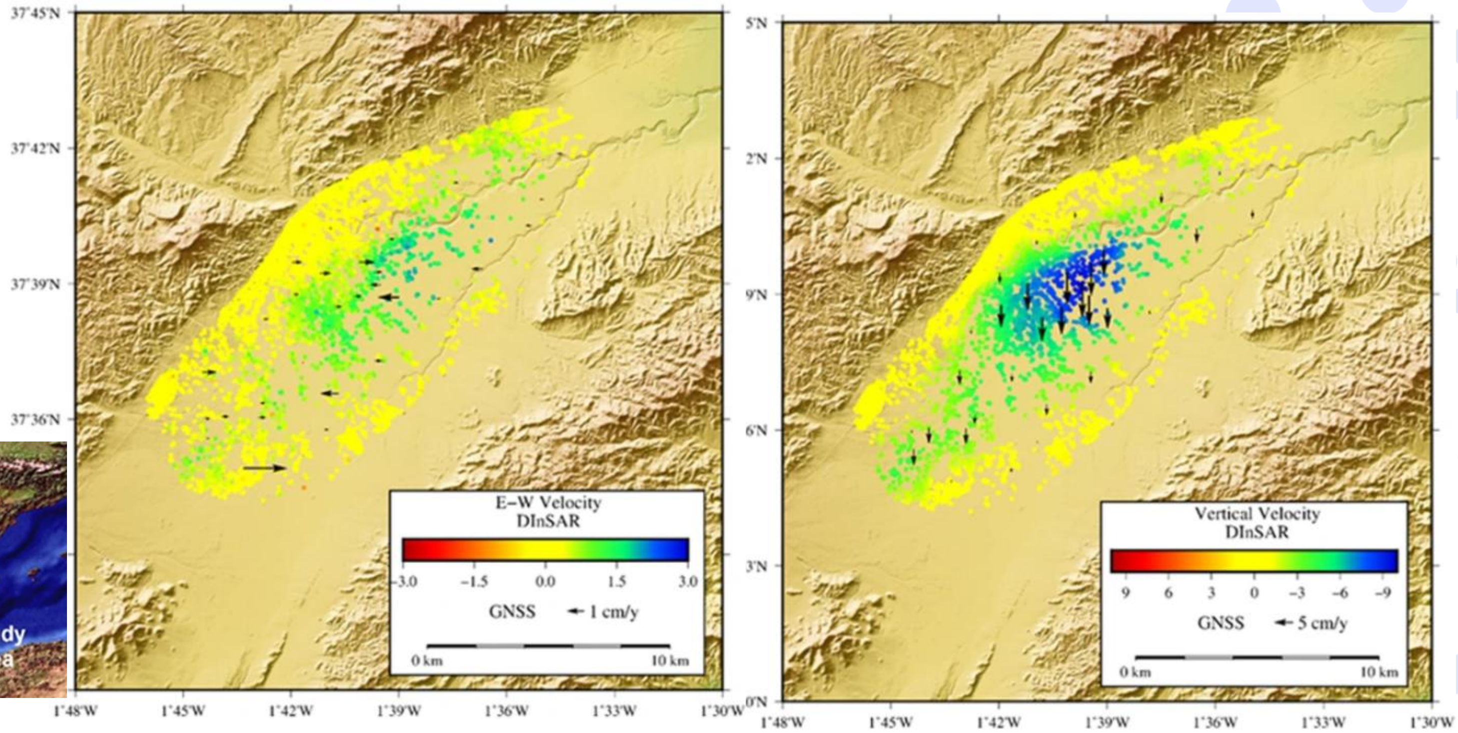
- ✓ Geometrical integration of InSAR (ascending & descending)
- ✓ Other geodetic data
- ✓ Geological & geotechnical maps
- ✓ Historical data review



Monitoring …… Integration …… Risk assessment …… Decision

Case example

Sentinel-1 SAR data analysis
(Ascending + descending)
(East-West and Vertical displacements)
+
In situ GNSS



Advanced Differential InSAR (A-DInSAR)–derived deformation maps showing land subsidence associated with aquifer overexploitation during the 2015–2017. Horizontal (East–West) and vertical (Up–Down) displacement rate fields were obtained through decomposition of LOS velocities using ascending and descending geometries. GNSS-derived displacement vectors are superimposed to assess consistency between spaceborne and in-situ observations (Fernandez et al., 2018).

Takeaways

InSAR is critical for geotechnical risk monitoring.

Continuous monitoring improves safety.

Time-series analysis (PSI / SBAS) improves reliability and trend identification.

Deformation signals must be interpreted considering error sources and uncertainty.

Integration with other geodetic and field inspections strengthens validation.

When properly integrated, InSAR becomes a powerful tool for geotechnical risk assessment and early warning.

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Questions & Answers

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