InSAR for Mining

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2 October 2024

TRE ALTAMIRA
A CLS Group Company

Outline

- Basic Principles of InSAR
- InSAR processing & data precision
- InSAR Capabilities, limitations and program design considerations
- What’s next

Outline

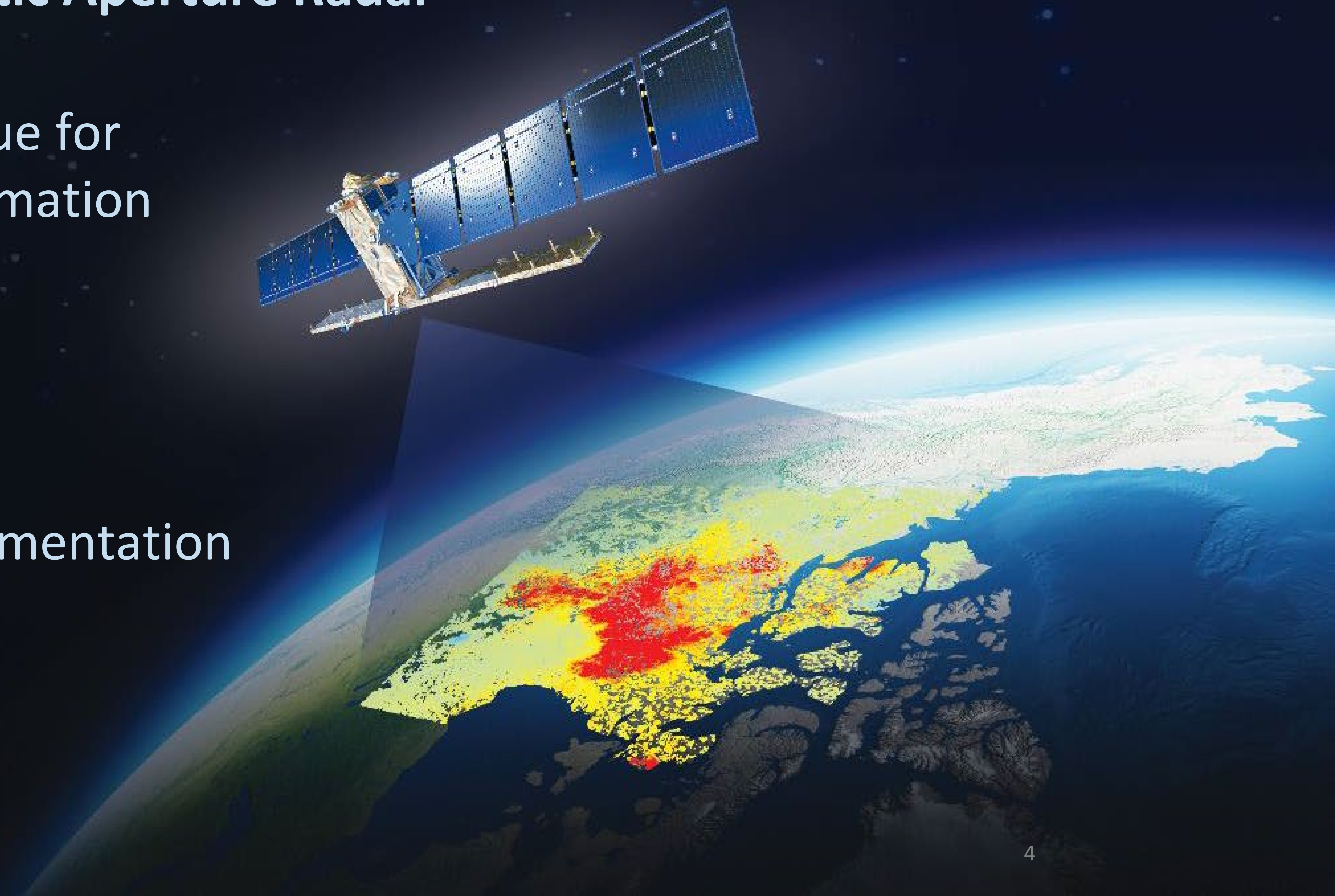
- ❑ **Basic Principles of InSAR**
  - **SAR satellites**
  - **InSAR fundamentals**
- ❑ InSAR processing & data precision
- ❑ InSAR Capabilities, limitations and program design considerations
- ❑ What’s next

What is InSAR?

Interferometric Synthetic Aperture Radar

Remote sensing technique for measuring ground deformation

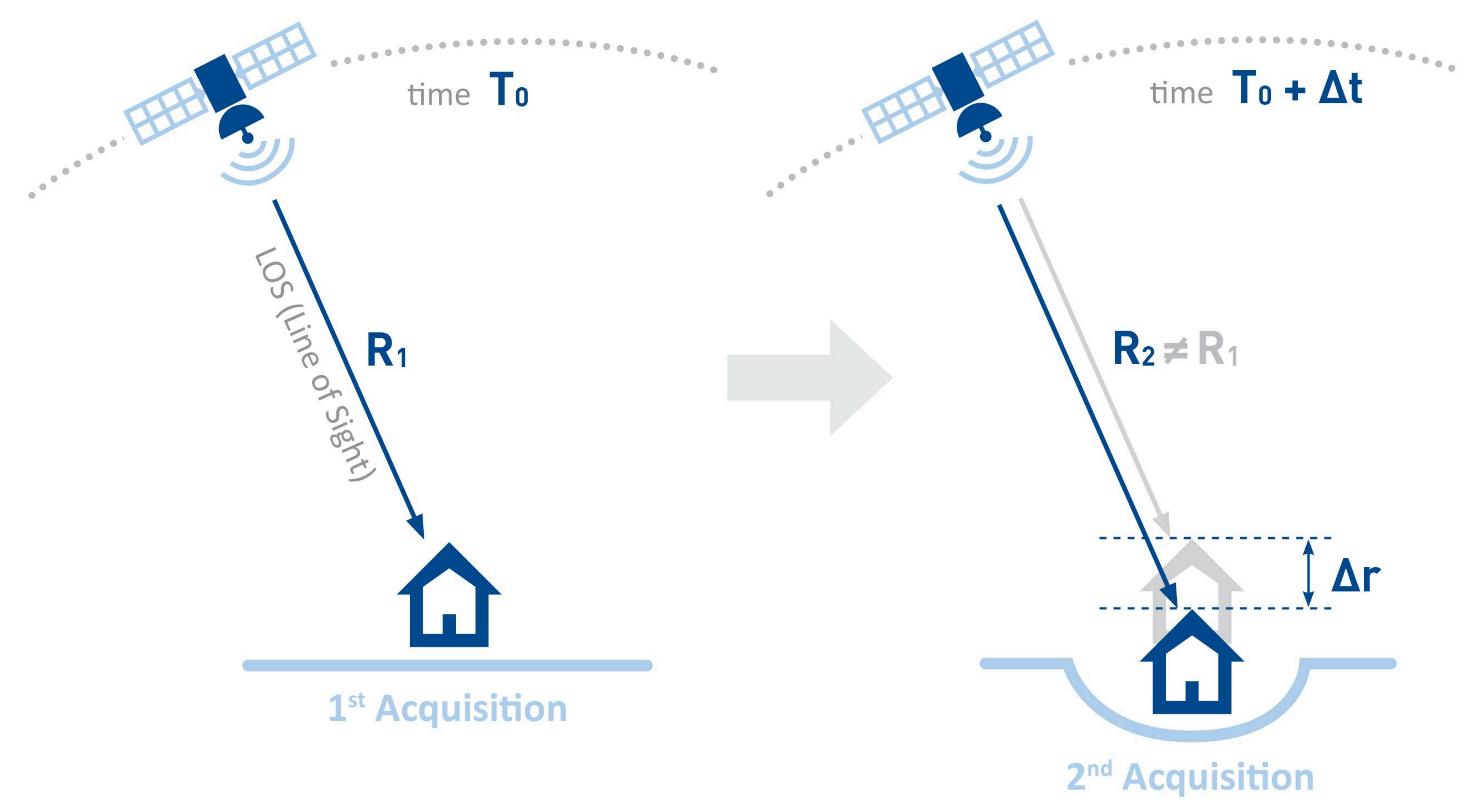
- using data from radar satellites
- advanced algorithms
- without ground instrumentation

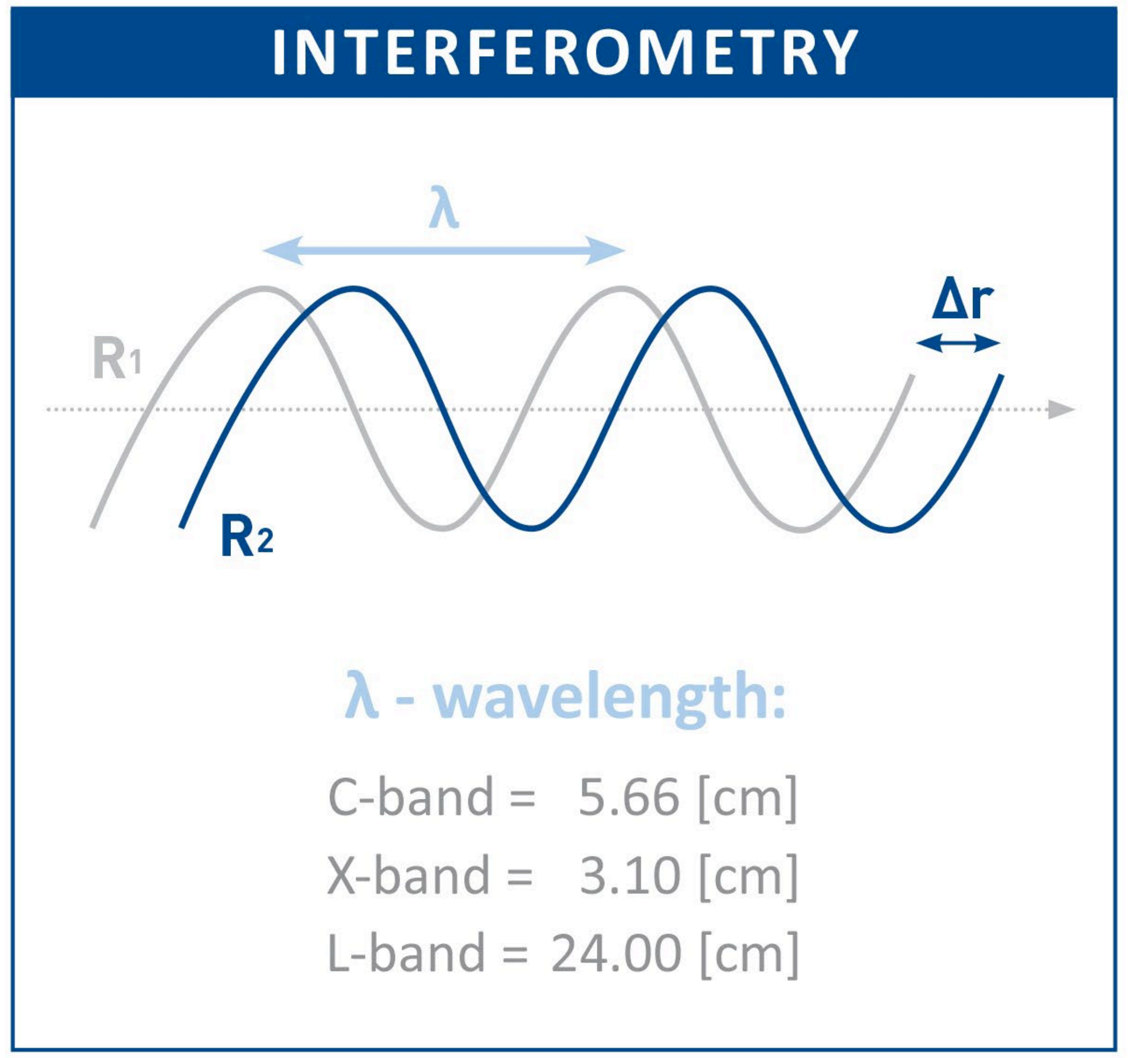


SAR Satellites

- Polar, sun synchronous orbits
- Active systems – don't require sunlight
- All-weather systems
- Fixed revisit frequency (4, 7, 11, 12 ... days)
- View the ground surface at an off-vertical angle
- First SAR satellite launched in 1992

InSAR – measuring phase differences





$\Delta\phi$ between two SAR images is proportional to the movement of the object on the ground

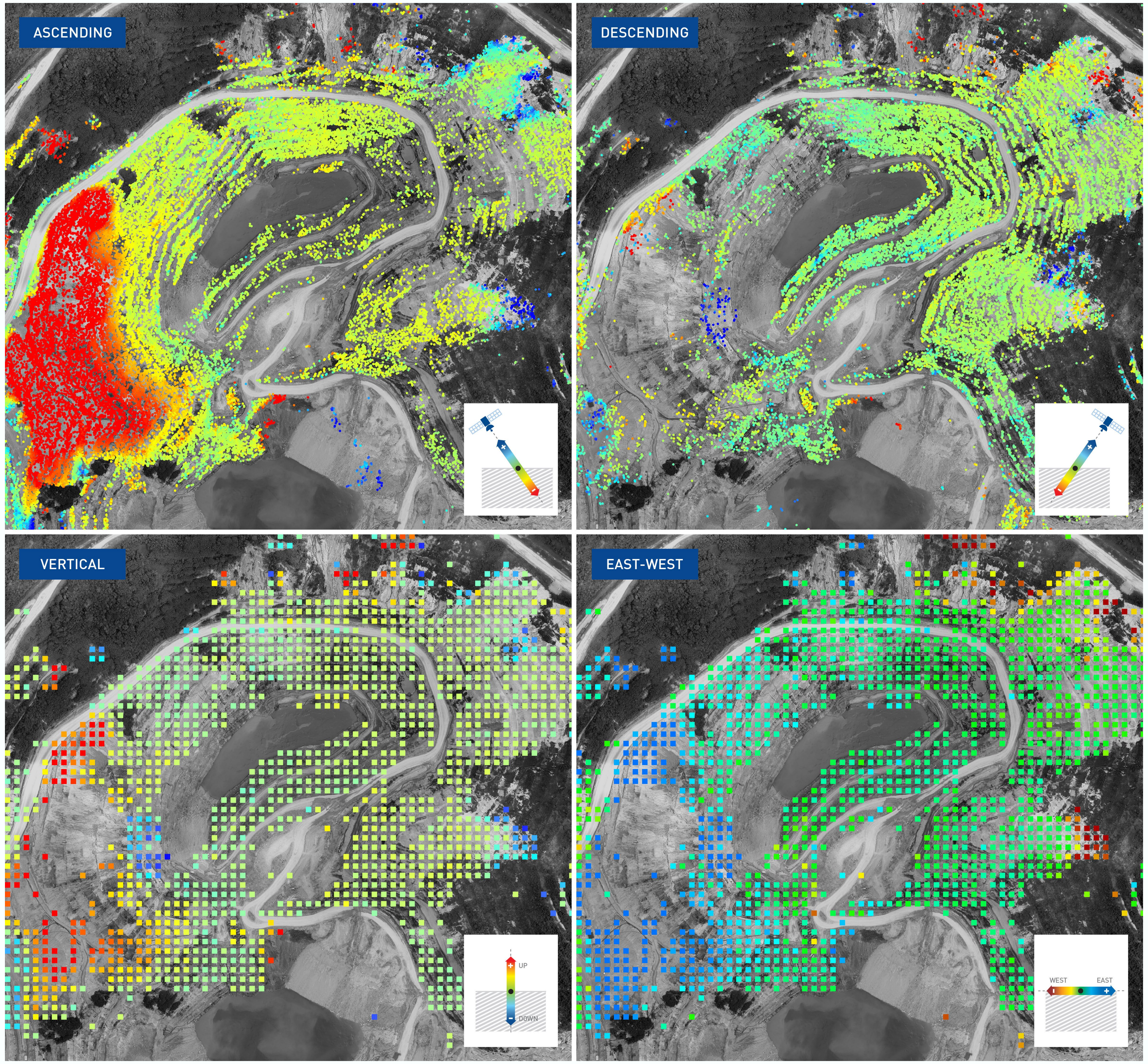
$$\Delta\varphi = \frac{4\pi}{\lambda}\Delta R + \alpha$$

InSAR geometry

- InSAR measurements are 1D along the satellite LOS
- Ascending and descending orbits observe the ground from different directions
  - East-looking orbit has best coverage of east-facing slopes
  - West-looking orbit has best coverage of west-facing slopes
- 2D measurements (Vertical and East-West) are generated by combining overlapping LOS data

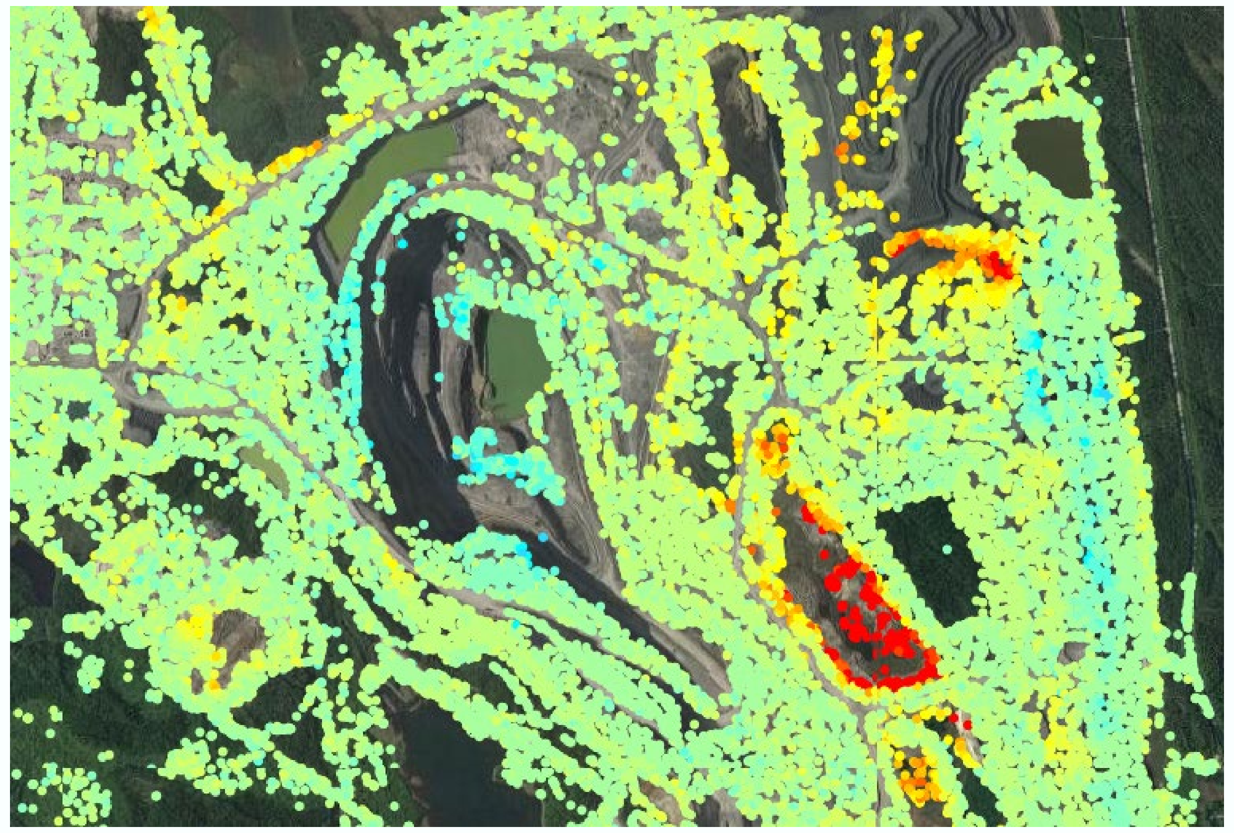
1-D LOS data
Max spatial resolution

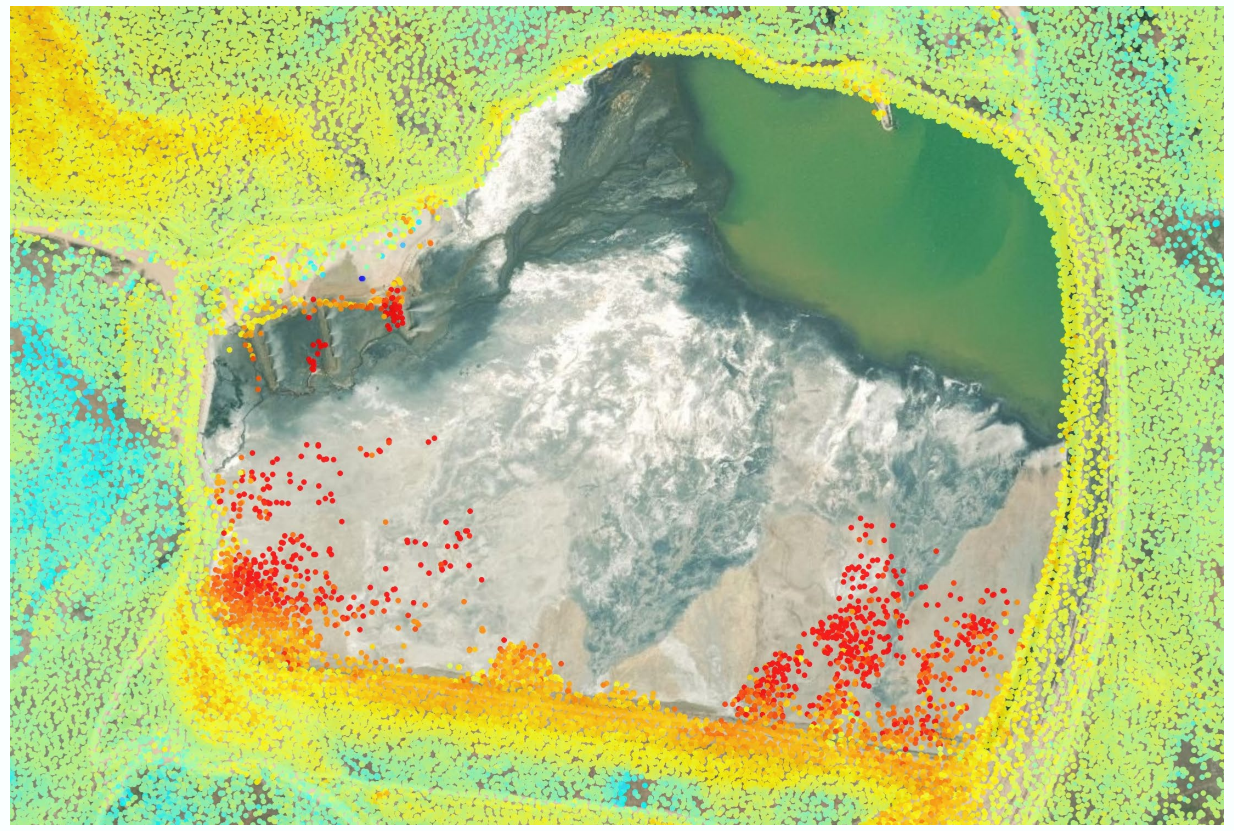
2-D data
Regular grid of points

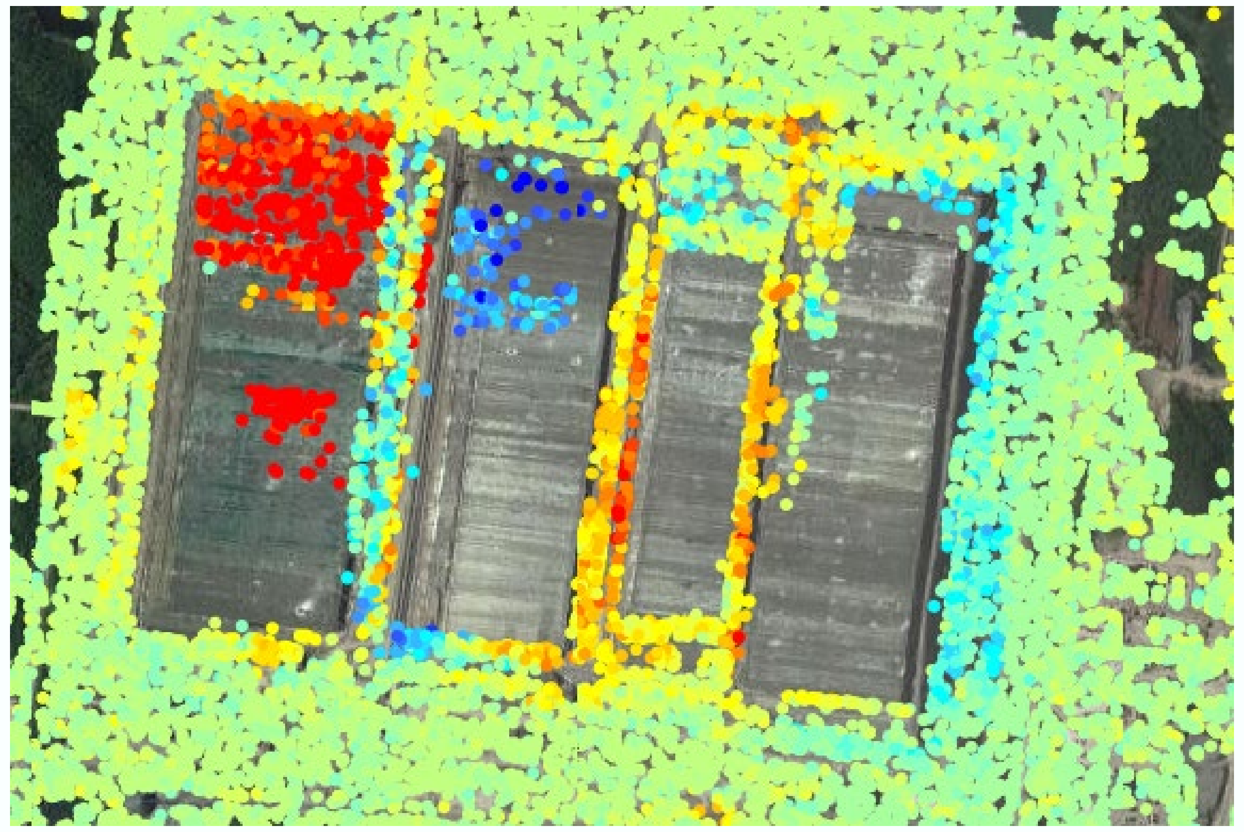


When is InSAR Used?

- Remote sensing of areas hard to reach/no instrumentation
- Long-term, strategic monitoring of entire mine
- Verifying design performance, prioritizing inspections, surveys and deploying ground-based sensors
- Assessing historical ground displacement
- Low impact and low-cost monitoring for legacy assets







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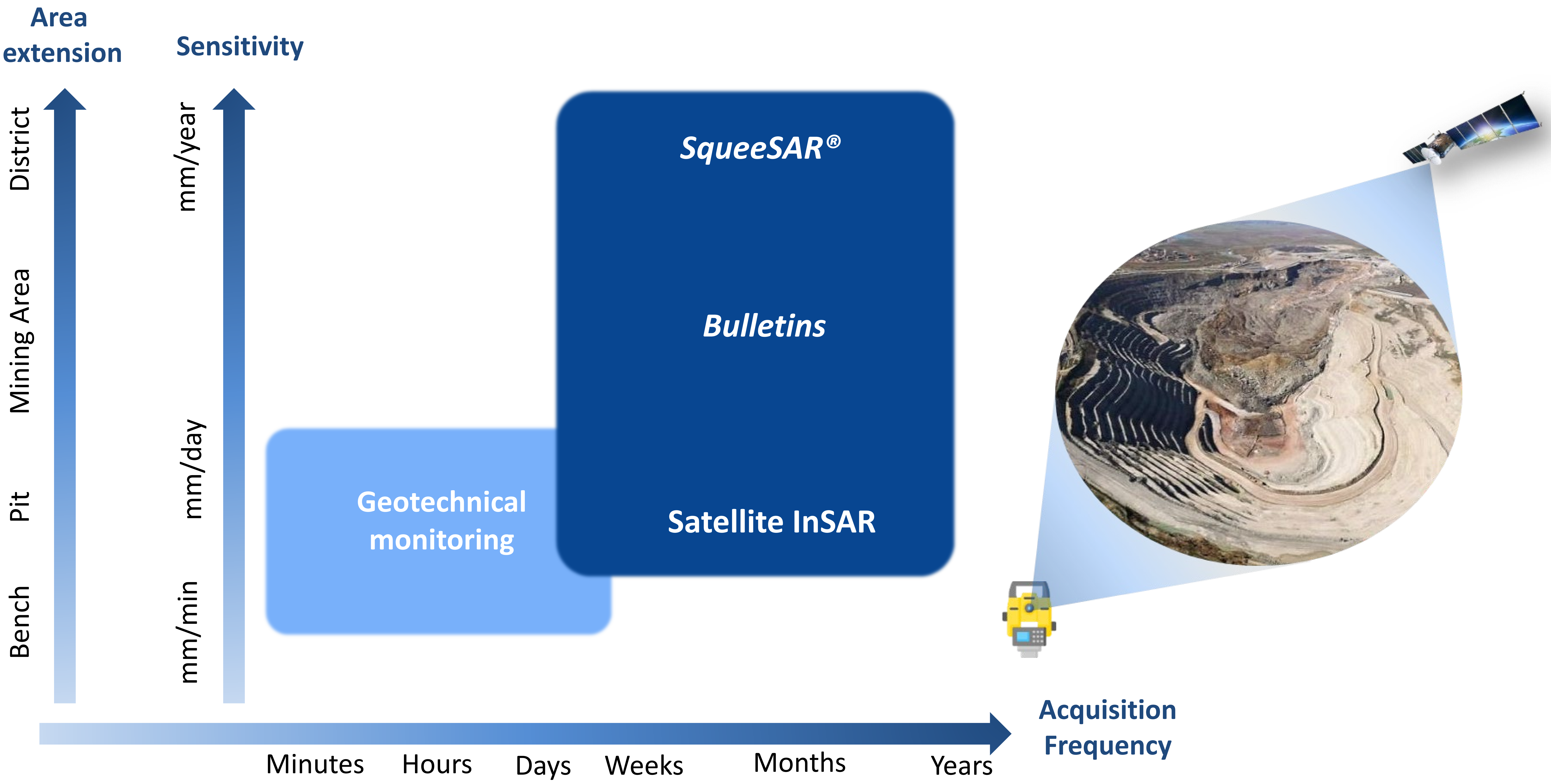
→

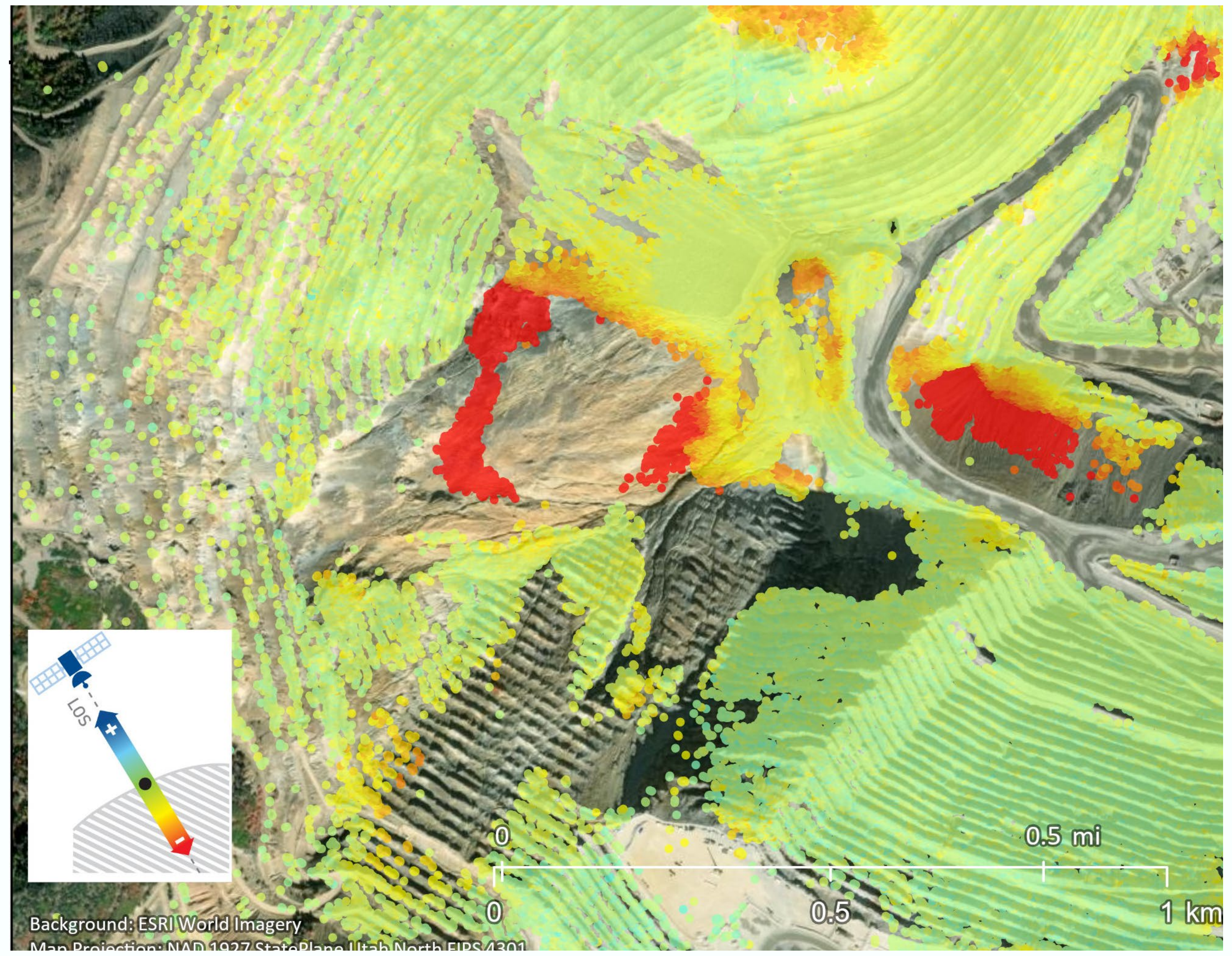
- **Processing techniques**
- **Sources of noise**
- **Data precision**

InSAR and Geotechnical Monitoring



Processing Techniques

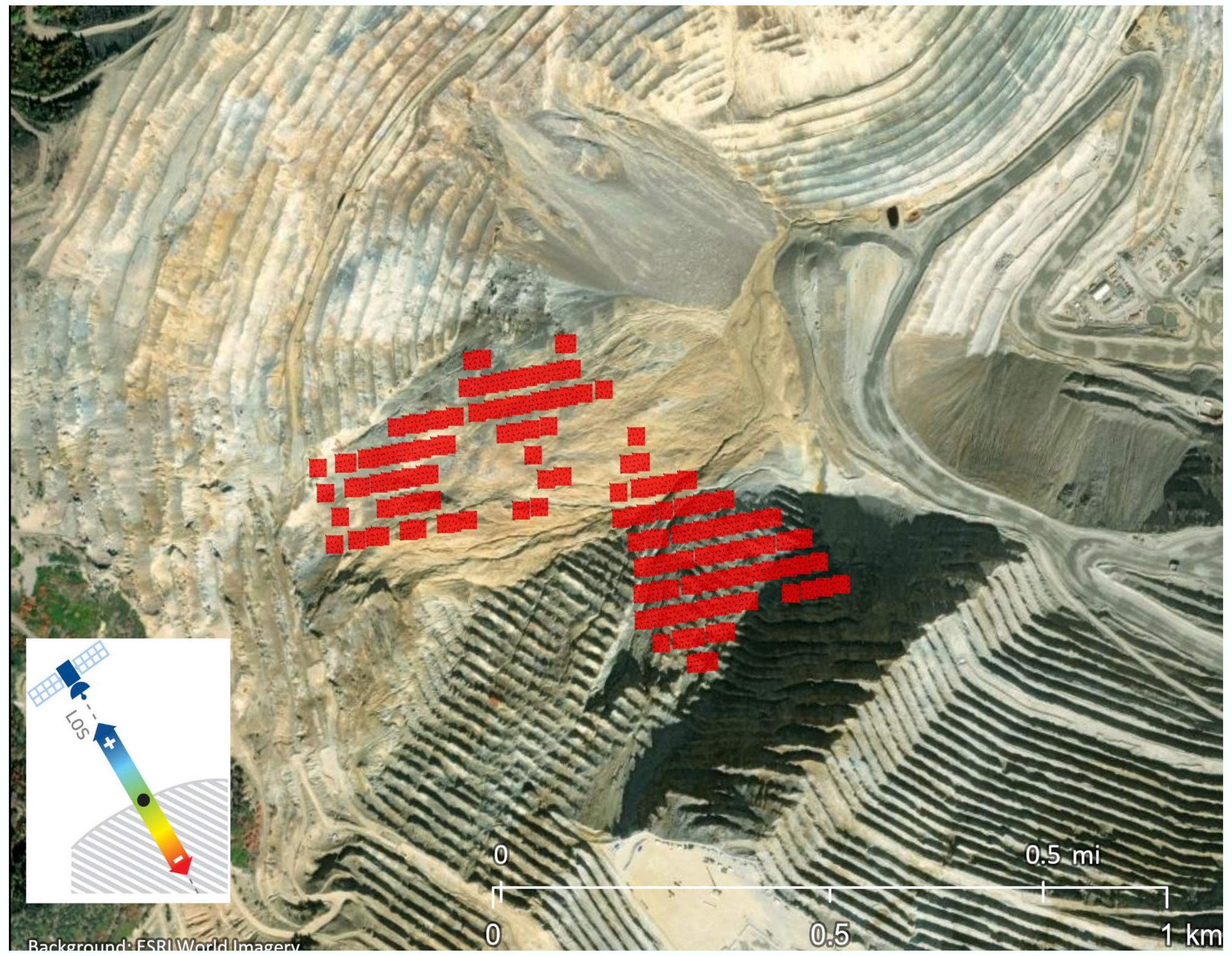
Multi-temporal - SqueeSAR



Strategic areas/low surface variations

- Frequent updates every 11 days/monthly
- 1-D and 2-D displacement
- ± 1 mm/yr precision
- ± 2 mm sensitivity
- Full-resolution

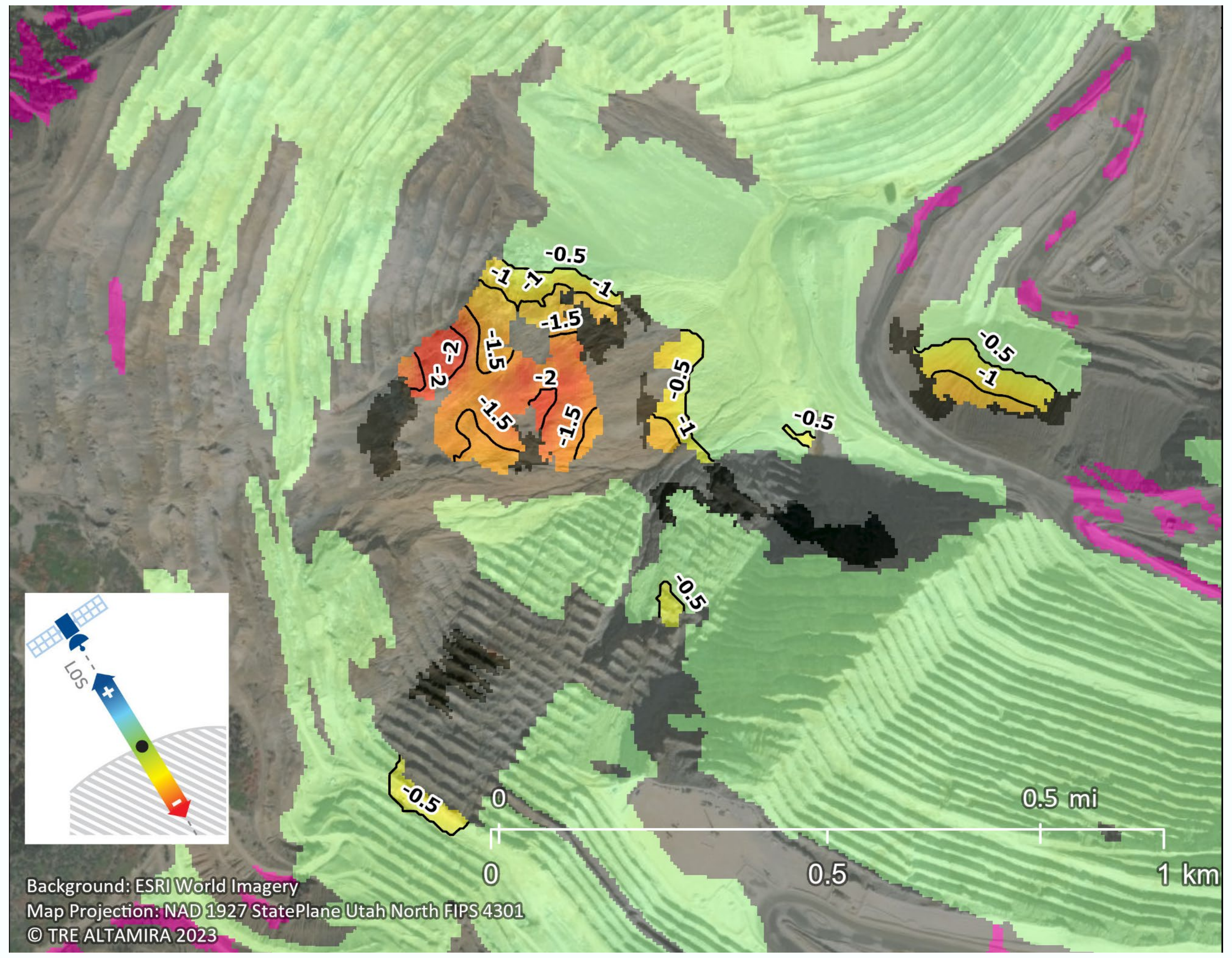
Rapid Motion Tracking



Areas of fast movement

- Frequent updates every 11 days/monthly
- 2-D (LOS, Azimuth) or 3-D (with two orbits)
- ± 10-15 cm/yr precision
- Rapid movement (>50 cm/yr)
- Coarse resolution (100x100 pixels)

Bulletins

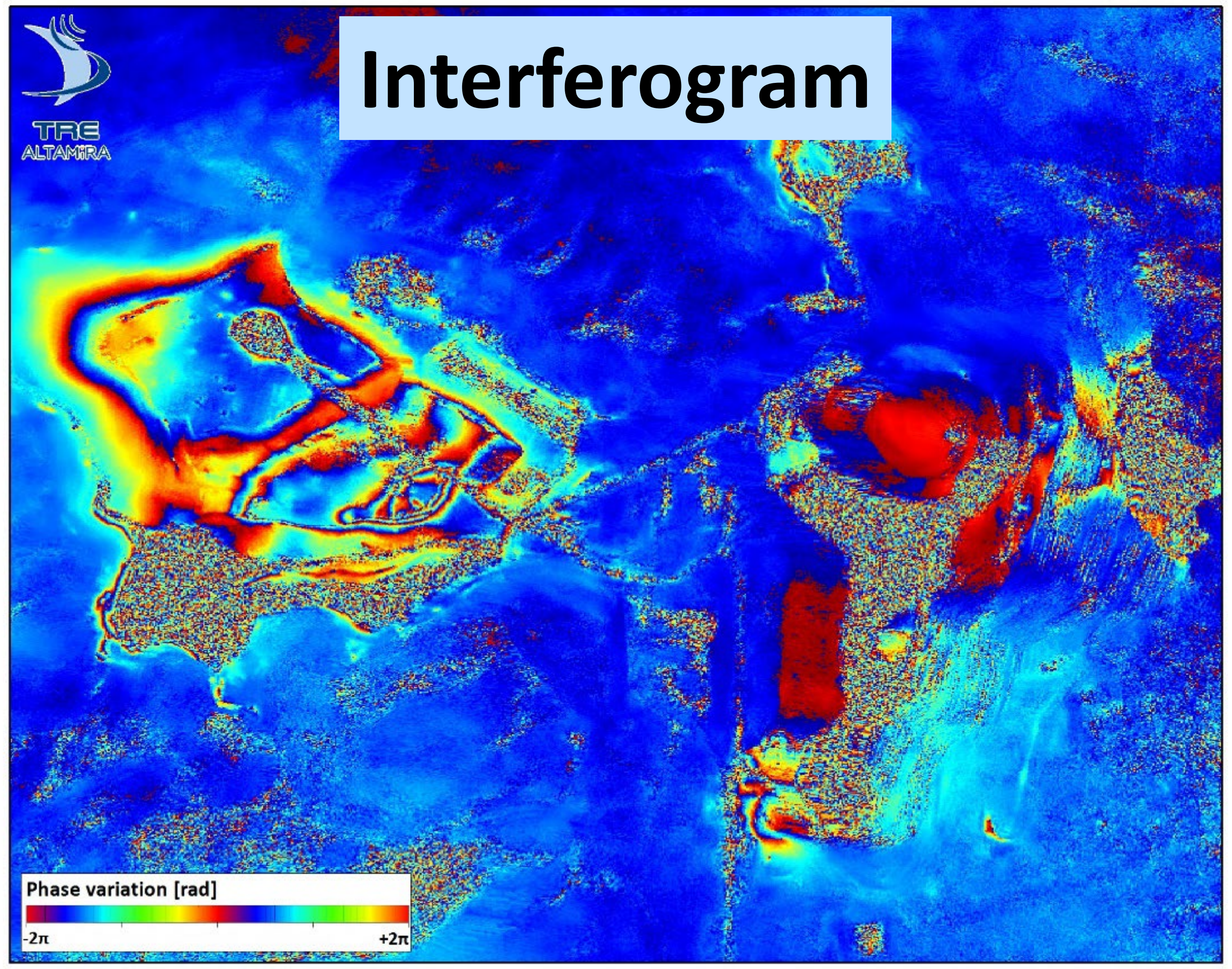


Operational/changing areas

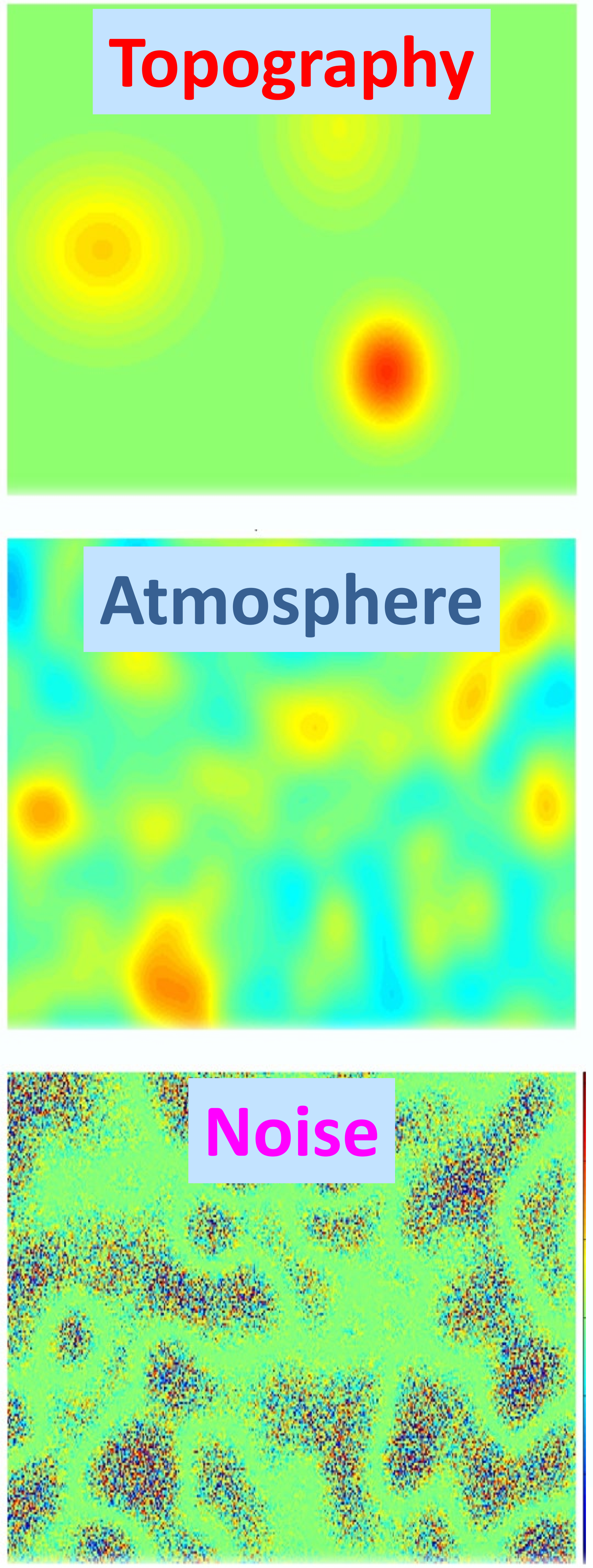
- Updates every 11 days
- 1-D (LOS) displacement and visibility maps
- 0.5-1cm precision
- 0.5-1 cm/11 days sensitivity
- Medium-resolution (5-10 pixels)

Factors affecting Precision

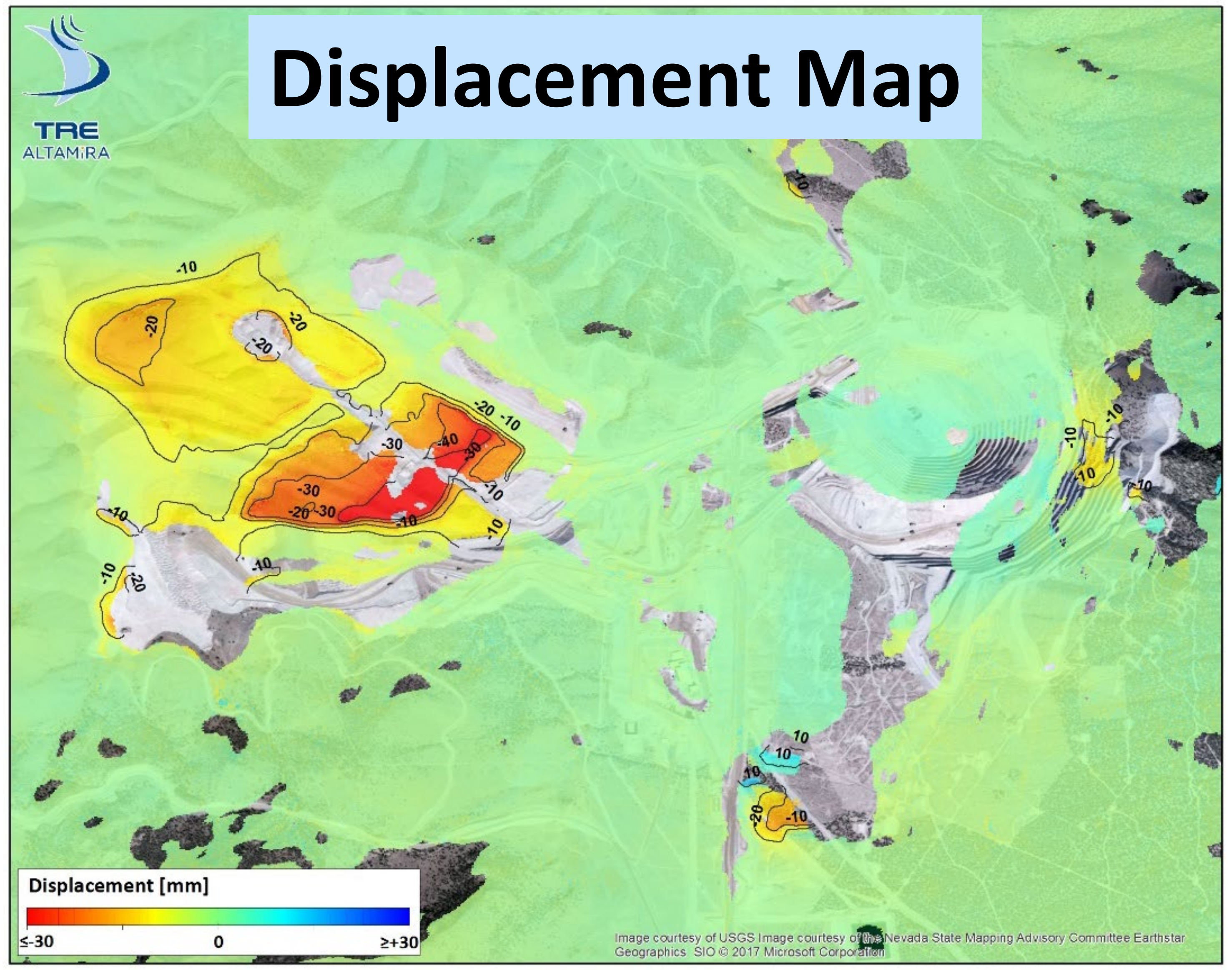
From phase...



$\Delta\phi$ = displacement
+ topography effects
+ atmospheric noise
+ decorrelation noise



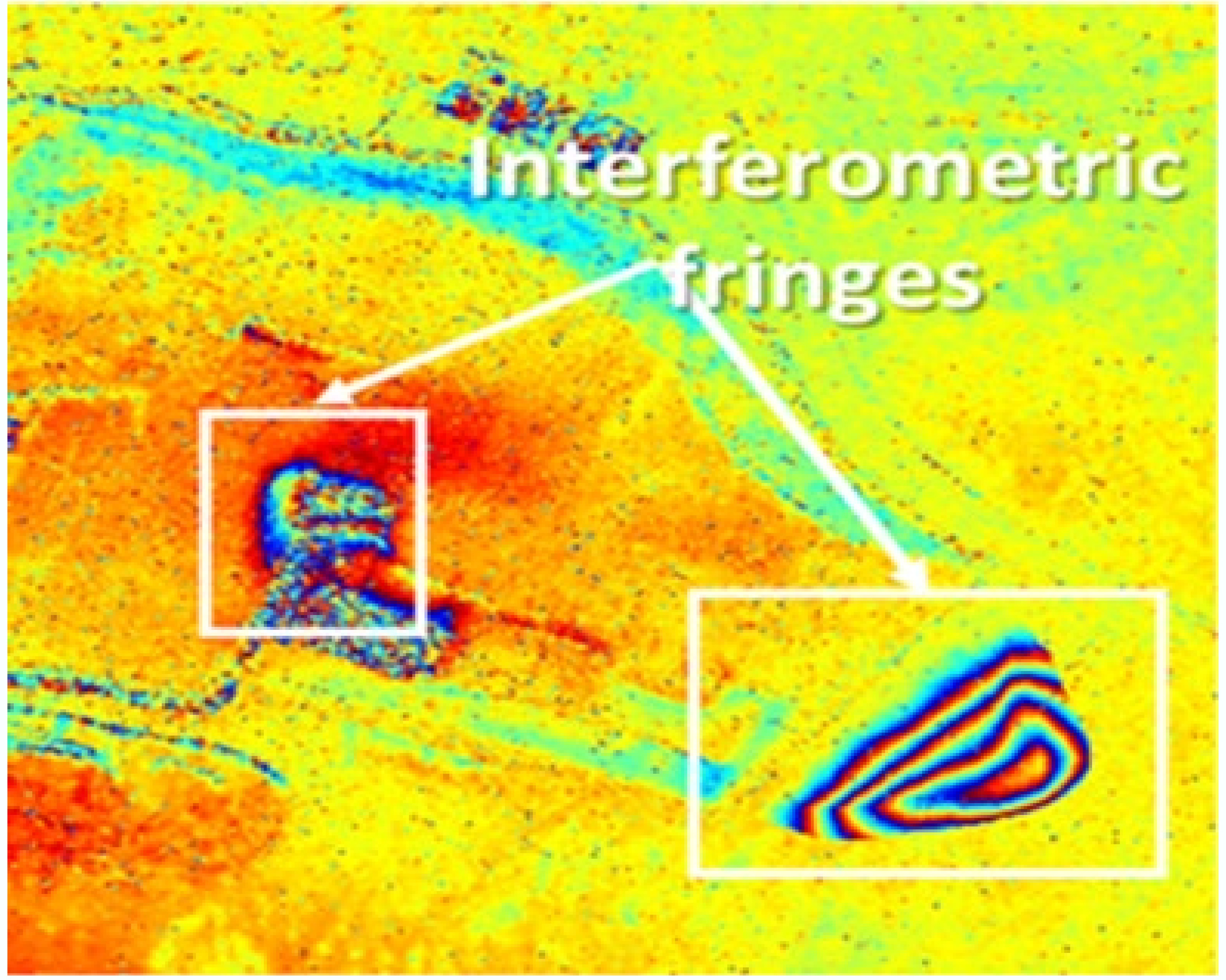
...to displacement.



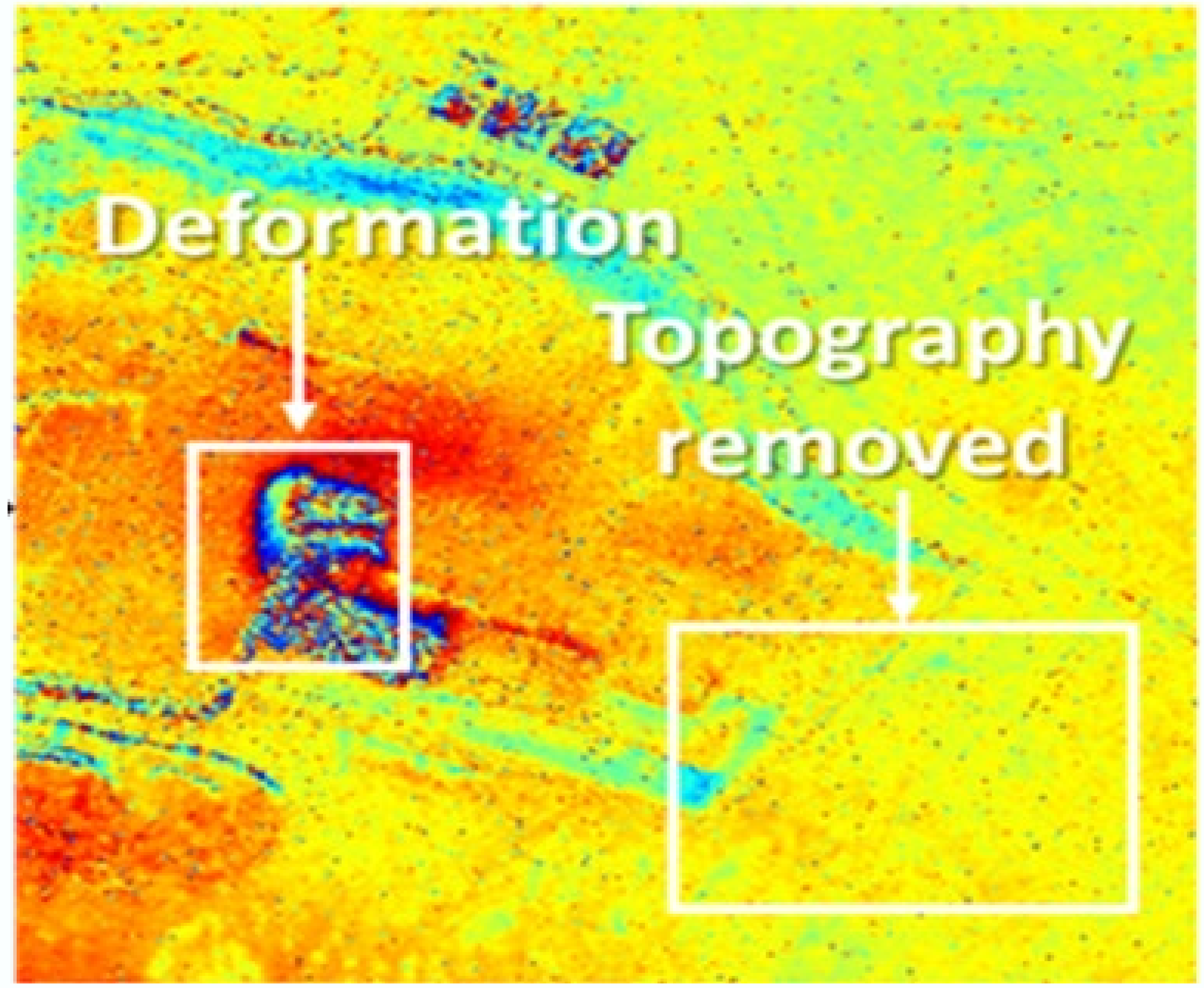
What Affects Precision - Topography

- ❑ Used at project set-up
- ❑ Very important for monitoring programs of active mines

Interferogram without updated DEM

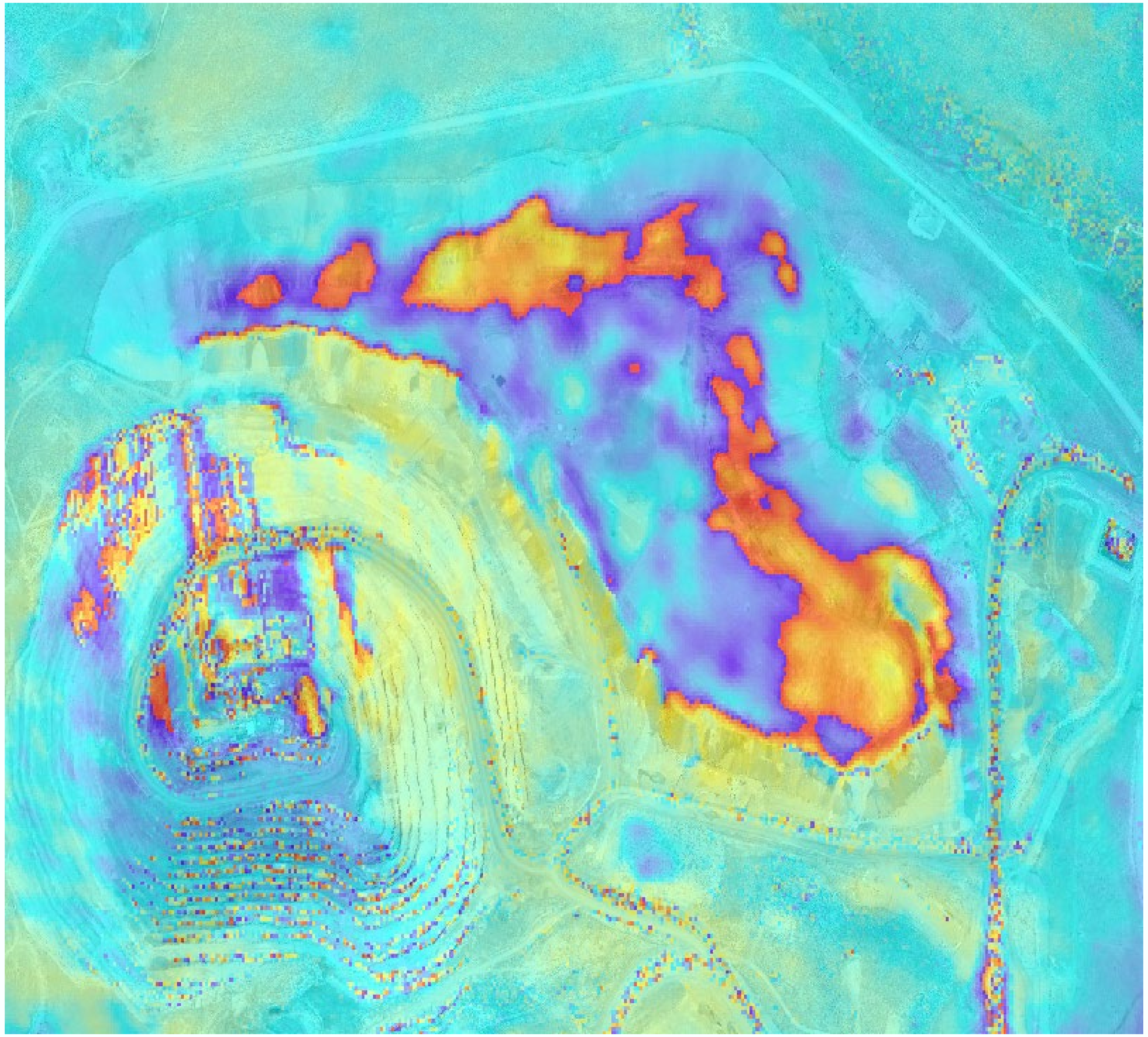


Interferogram with updated DEM



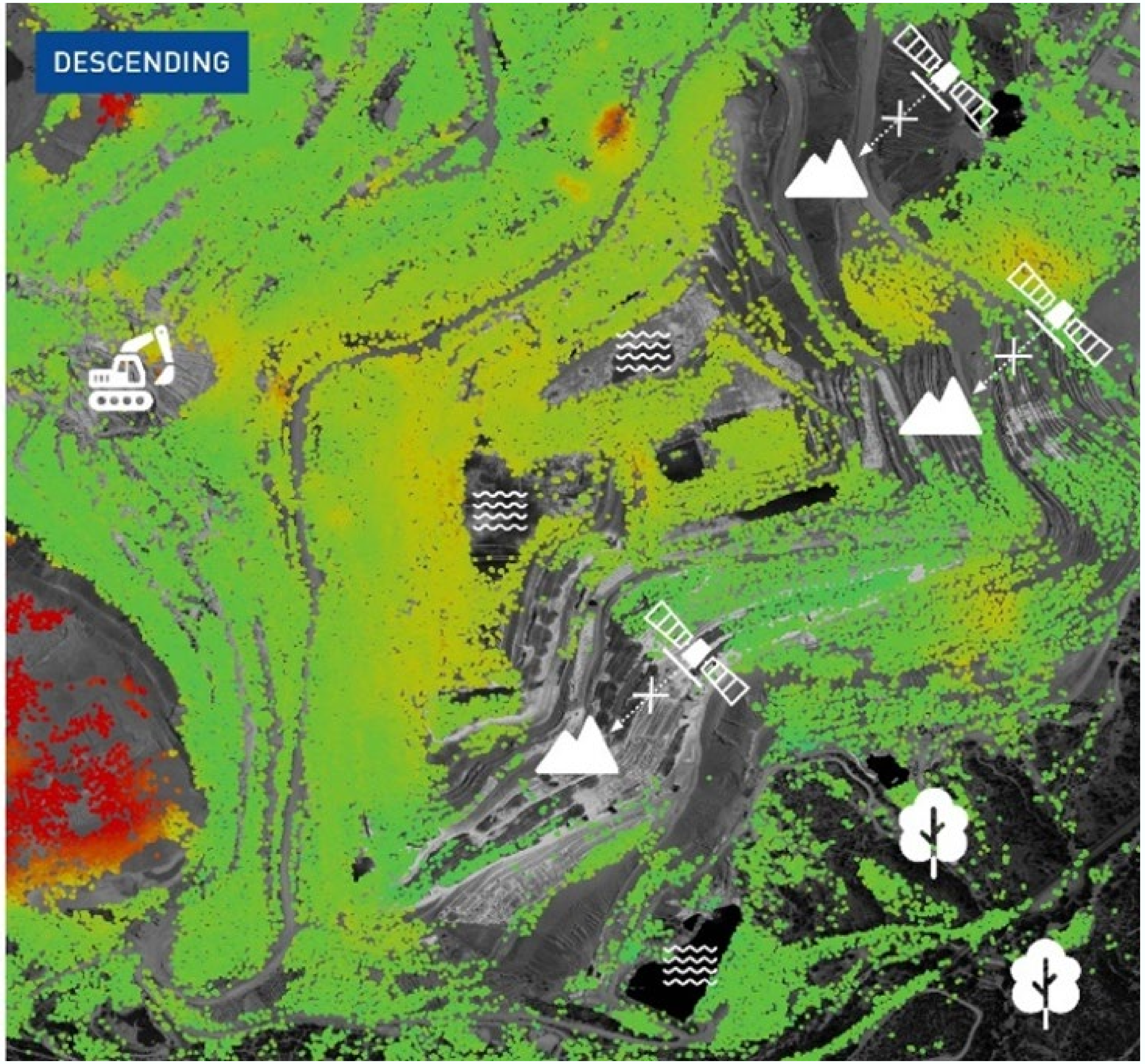
What Affects Precision - Atmosphere

- Time of acquisition
  - Greater atmospheric noise during day time
- Acquisition geometry
  - Higher angles off of vertical means signal travels longer distance
- Distance from the reference point



What Affects Precision - Decorrelation

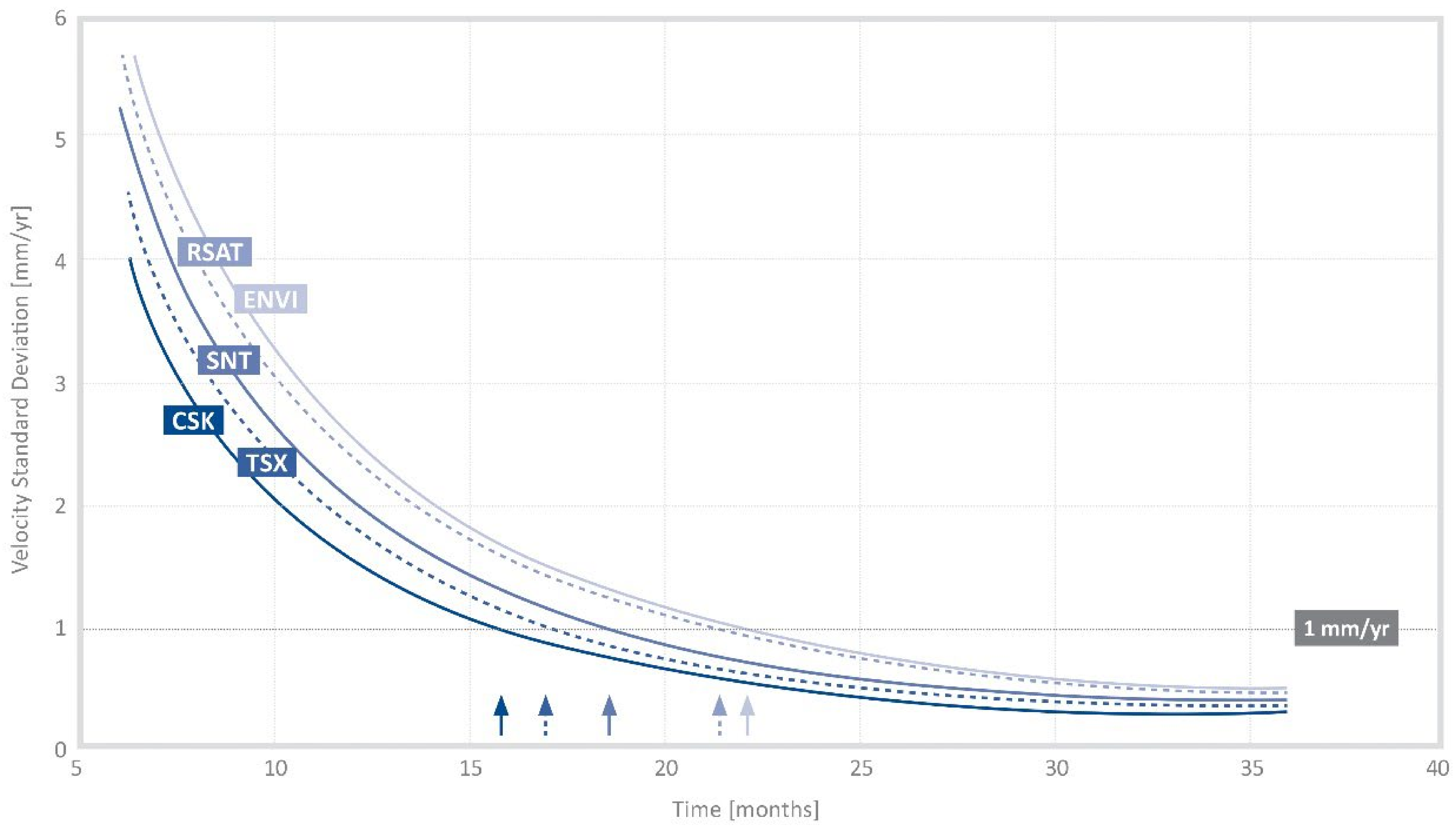
- Areas affected by temporal decorrelation
  - radar signal is not coherent over time
- Surface changes in the period of the analysis
- Seasonal surface changes



What Affects Precision – Other Factors

- ❑ Number of processed images
- ❑ Length of the interval analysed
- ❑ Temporal continuity of acquisitions

Multi-temporal InSAR



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- Basic Principles of InSAR
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- **What InSAR can/cannot do**
- **Choosing the right approach**
- **Data visualization**

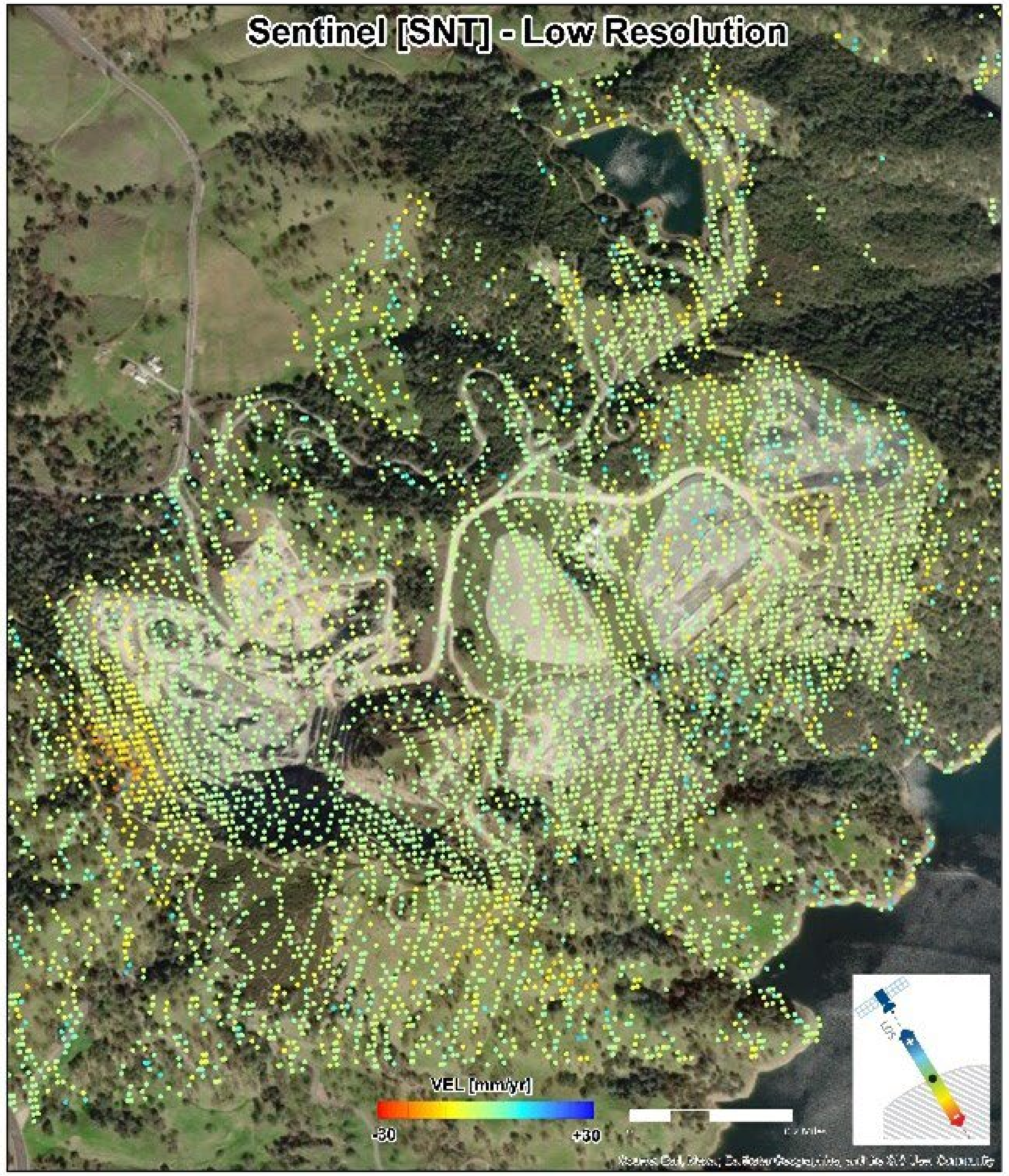
What InSAR Can & Cannot Do

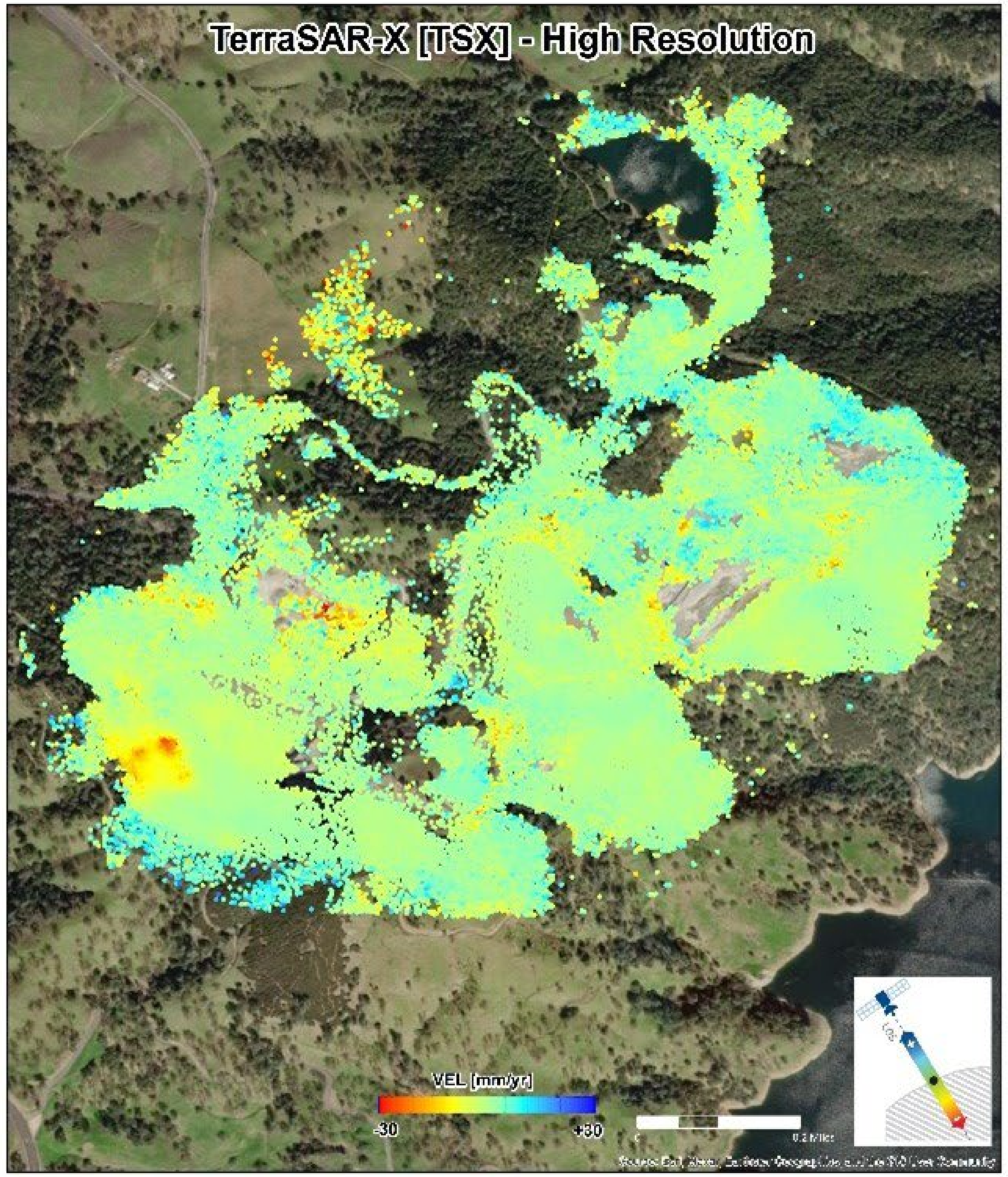
- ✓ Long-term, strategic monitoring of entire mines
- ✓ High-frequency monitoring of rates from mm to m/year
- ✓ Prioritization of inspections, surveys and ground-sensor deployment
- ✓ Forensic analysis of ground displacement

- ✗ Real-time tactical monitoring
- ✗ See through water, snow & dense vegetation
- ✗ Replace ground-based radars
- ✗ See all areas of the mine with a single orbit
- ✗ Predict ground displacement

Choosing the Right InSAR Approach: Satellite

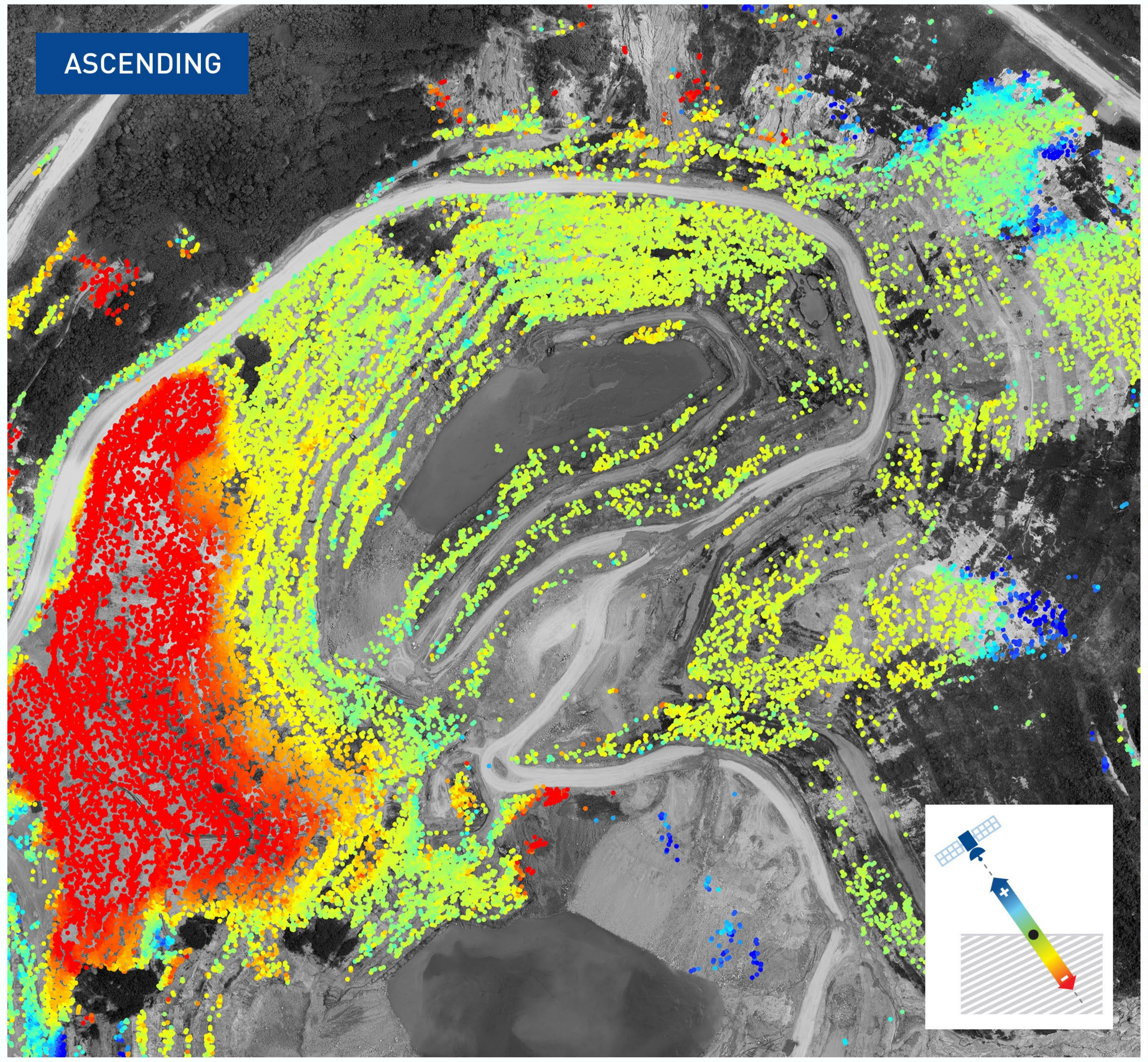
- Image resolution
- Revisit frequency
- Temporal continuity
- Wavelength
- Cost

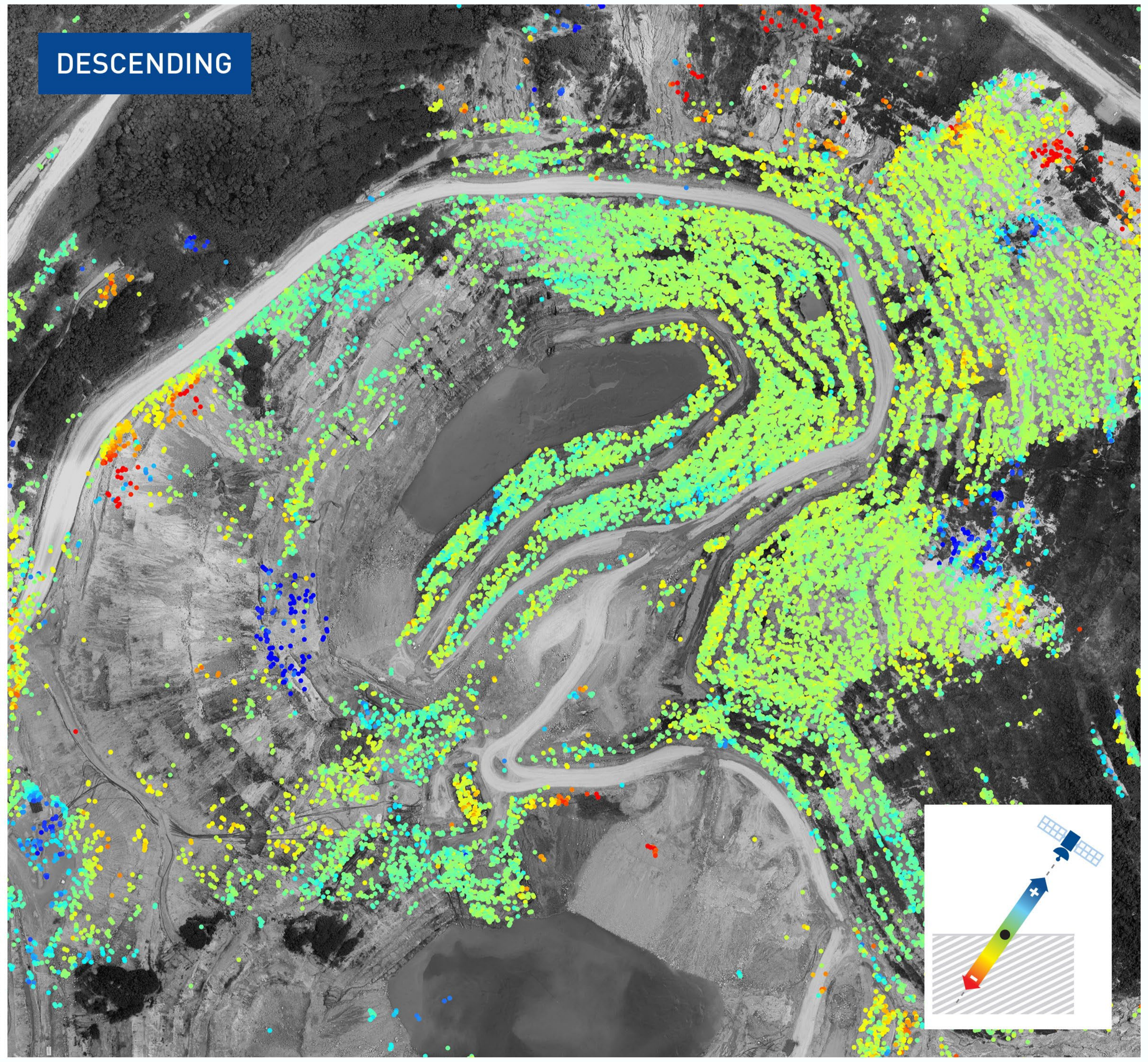




Satellite orbit and viewing angle

- Ascending and descending orbits observe the ground from different directions
  - East-looking orbit has best coverage of east-facing slopes
  - West-looking orbit has best coverage of west-facing slopes





Active Operations & Rate Variations

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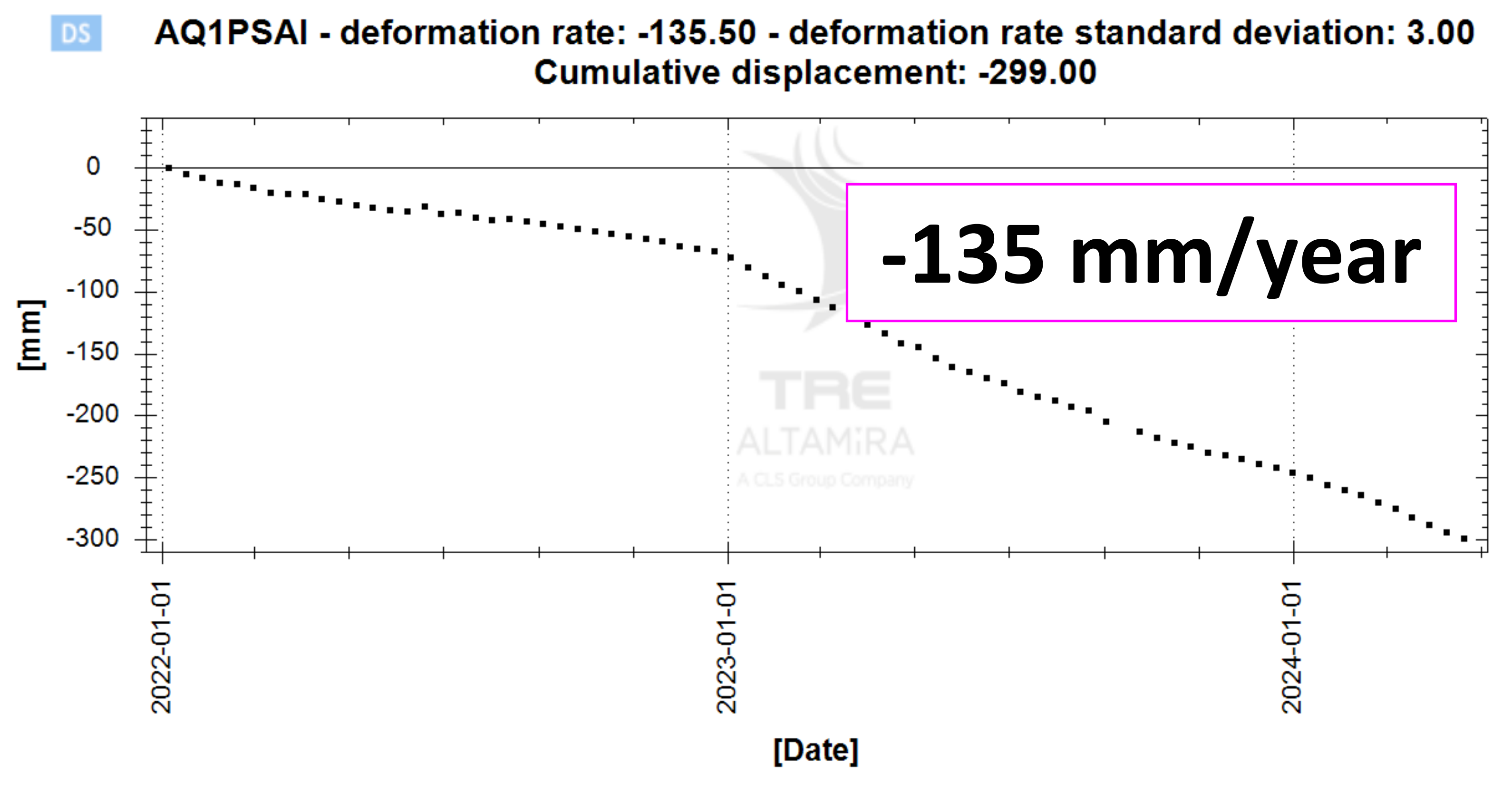
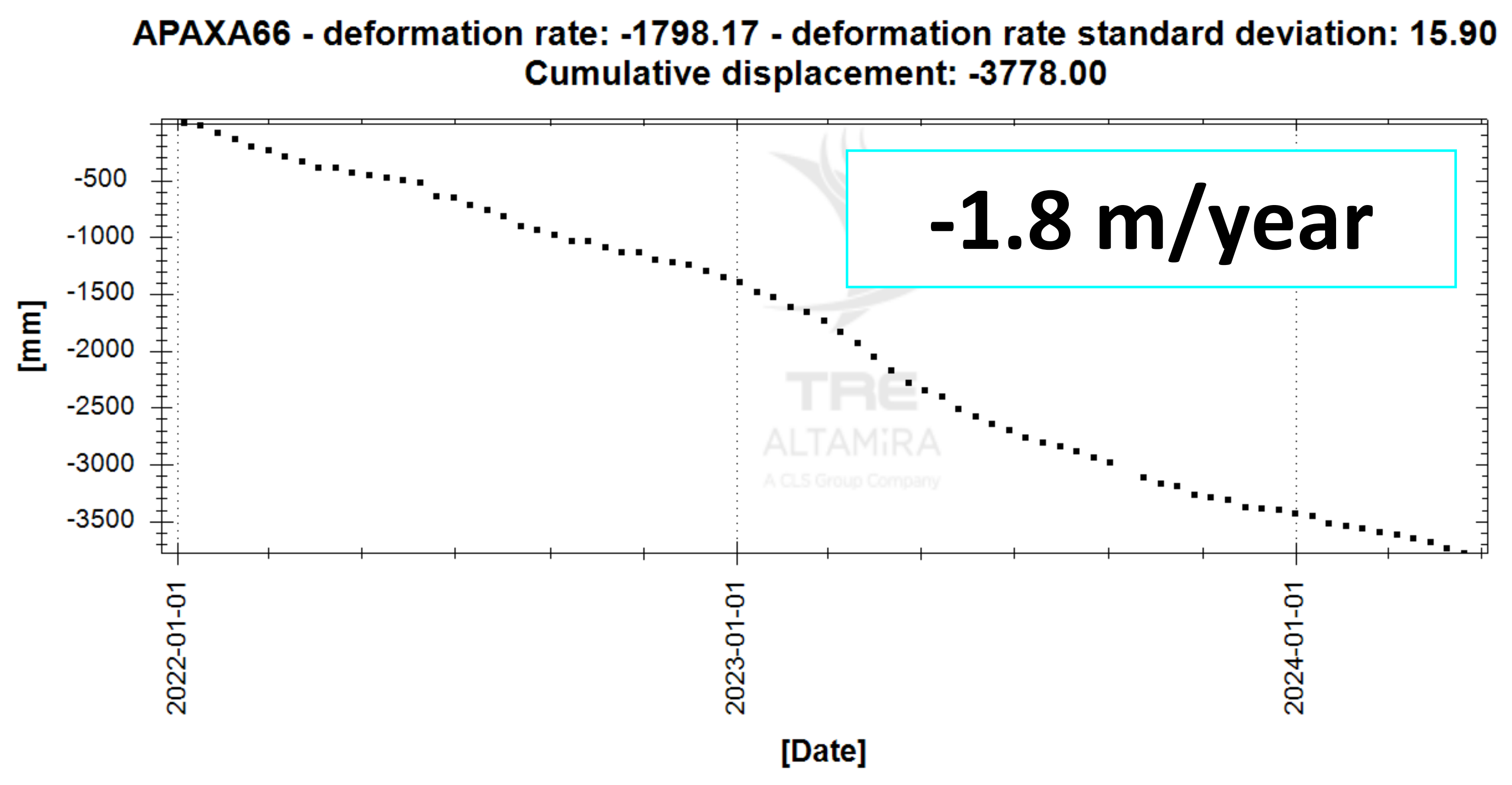
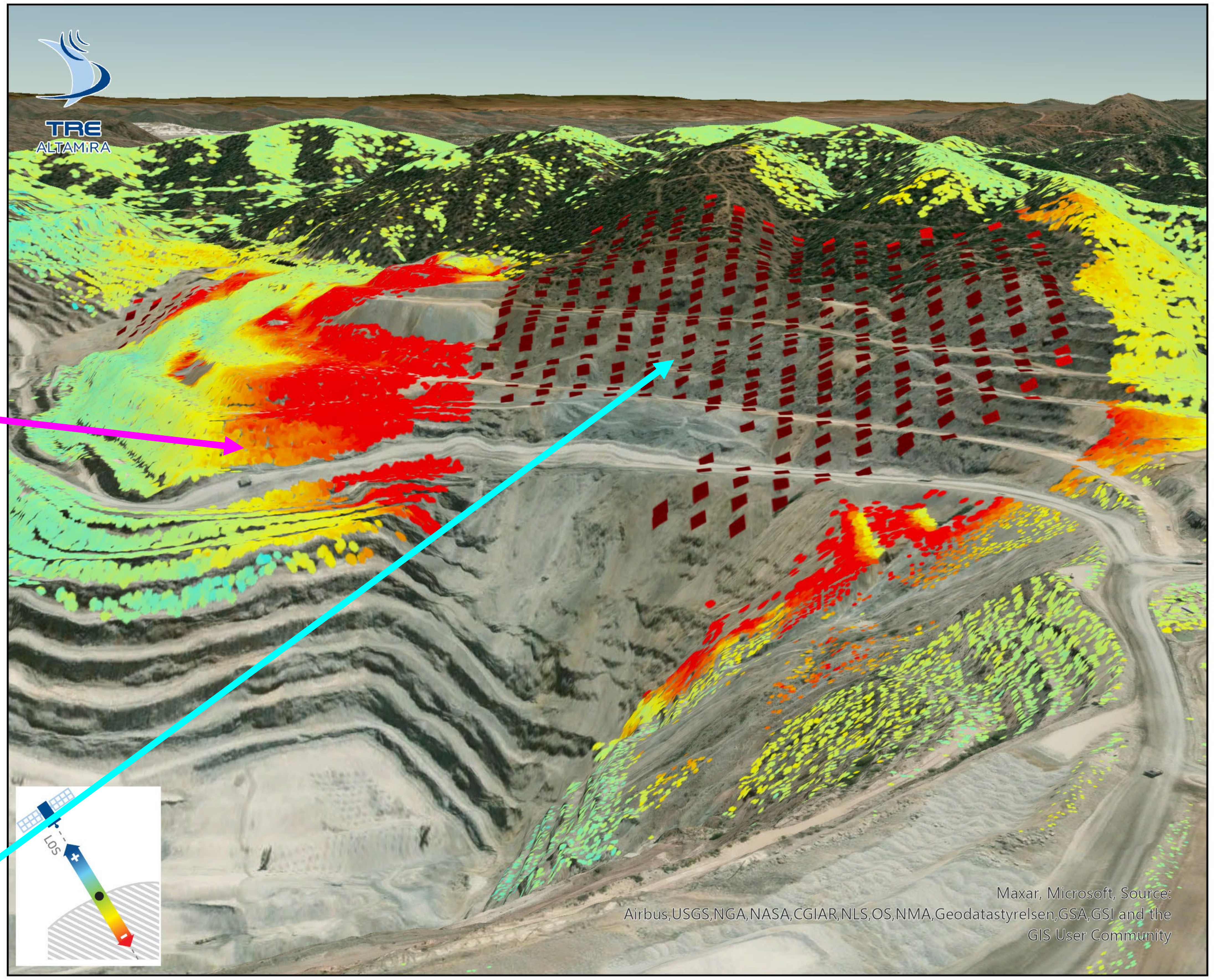
Varied rates of displacement







PROCESSING DATA

Satellite	TSX
Orbit (angle)	Ascending (Θ = 27.3º)
Date Range	Jan 2022 - Apr 2024

LOS Displacement Rate [mm/yr]

≤-50 0 ≥+50

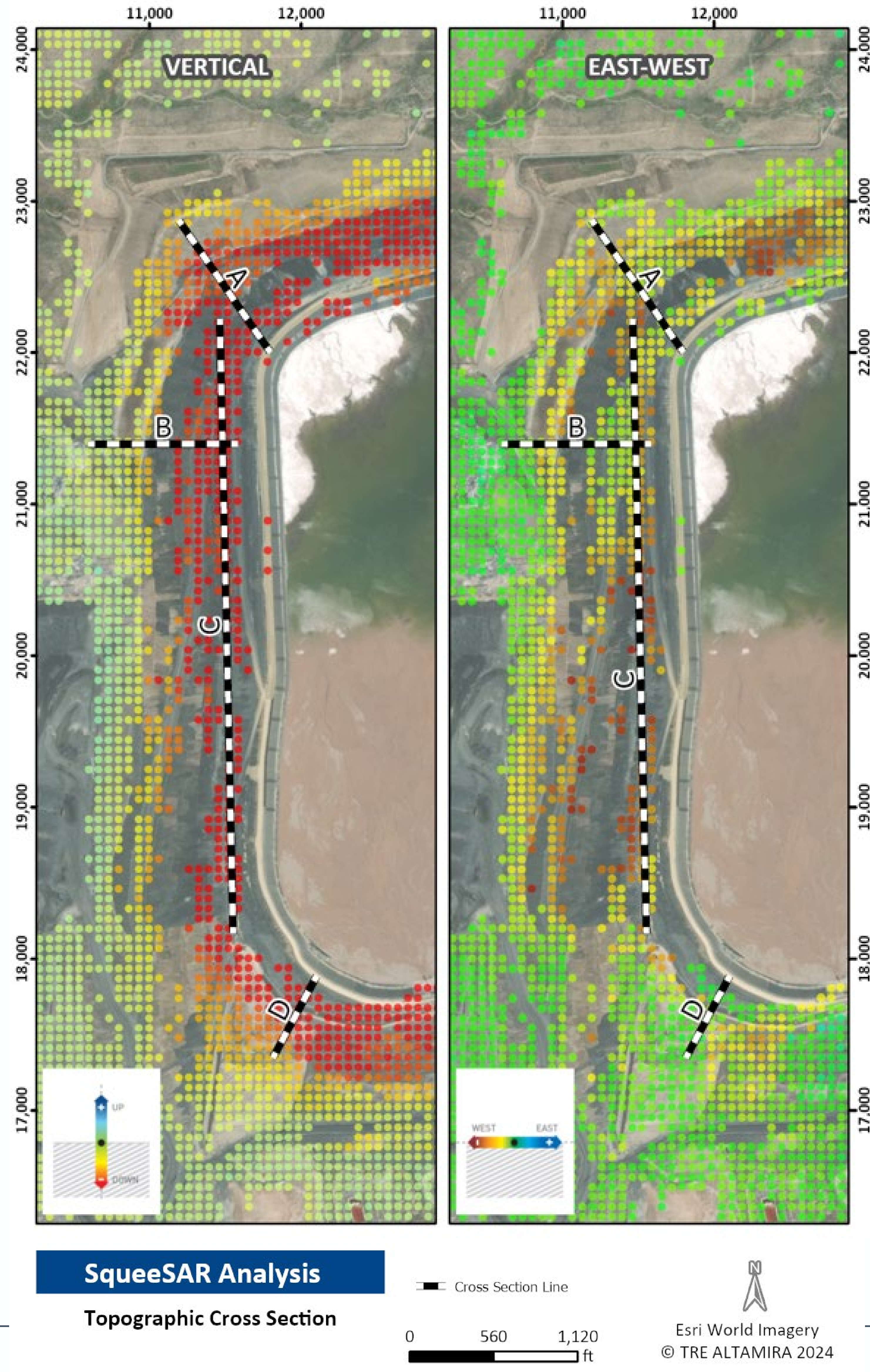
RMT LOS Displacement Rate [mm/yr]

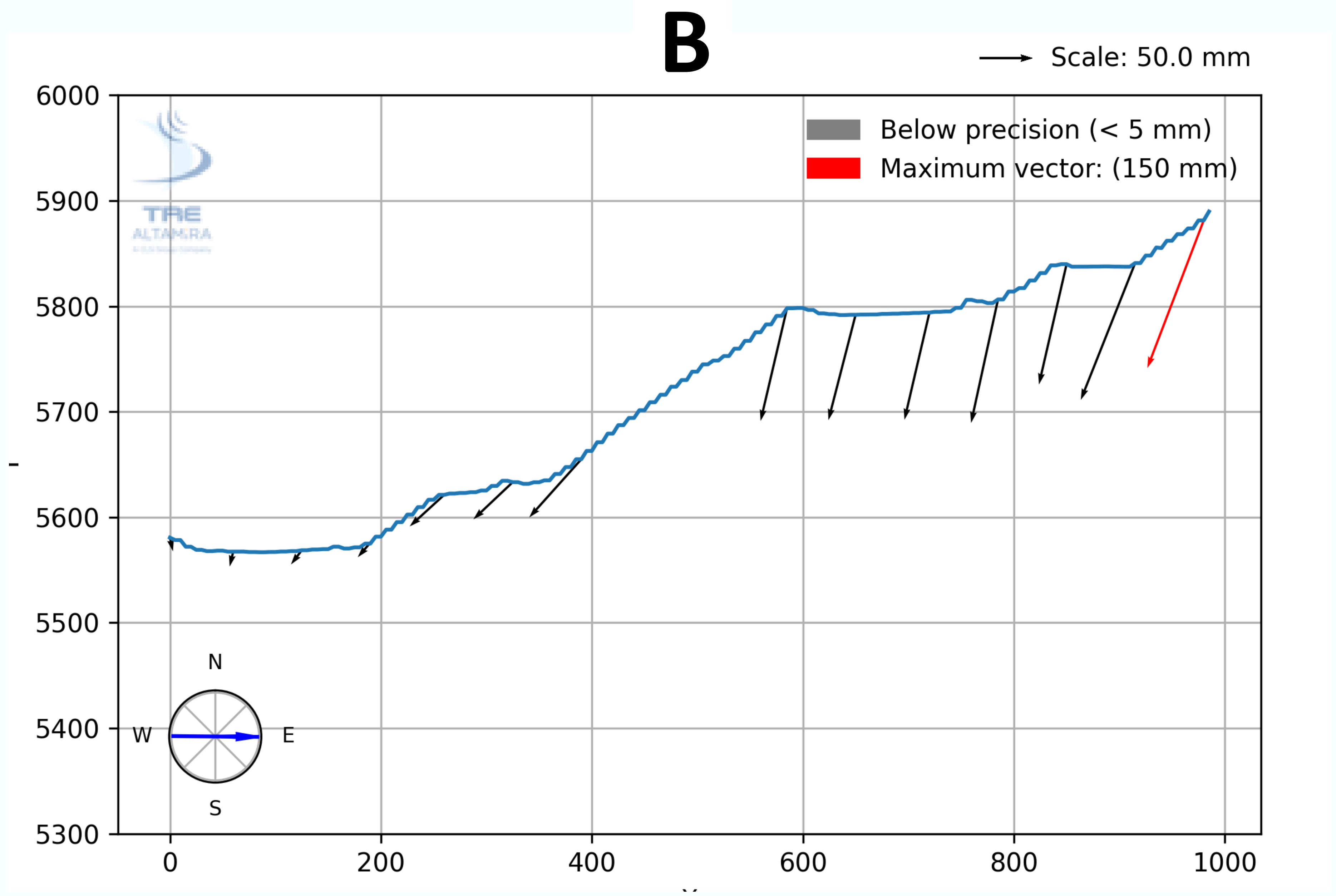
≤-500 0 ≥+500

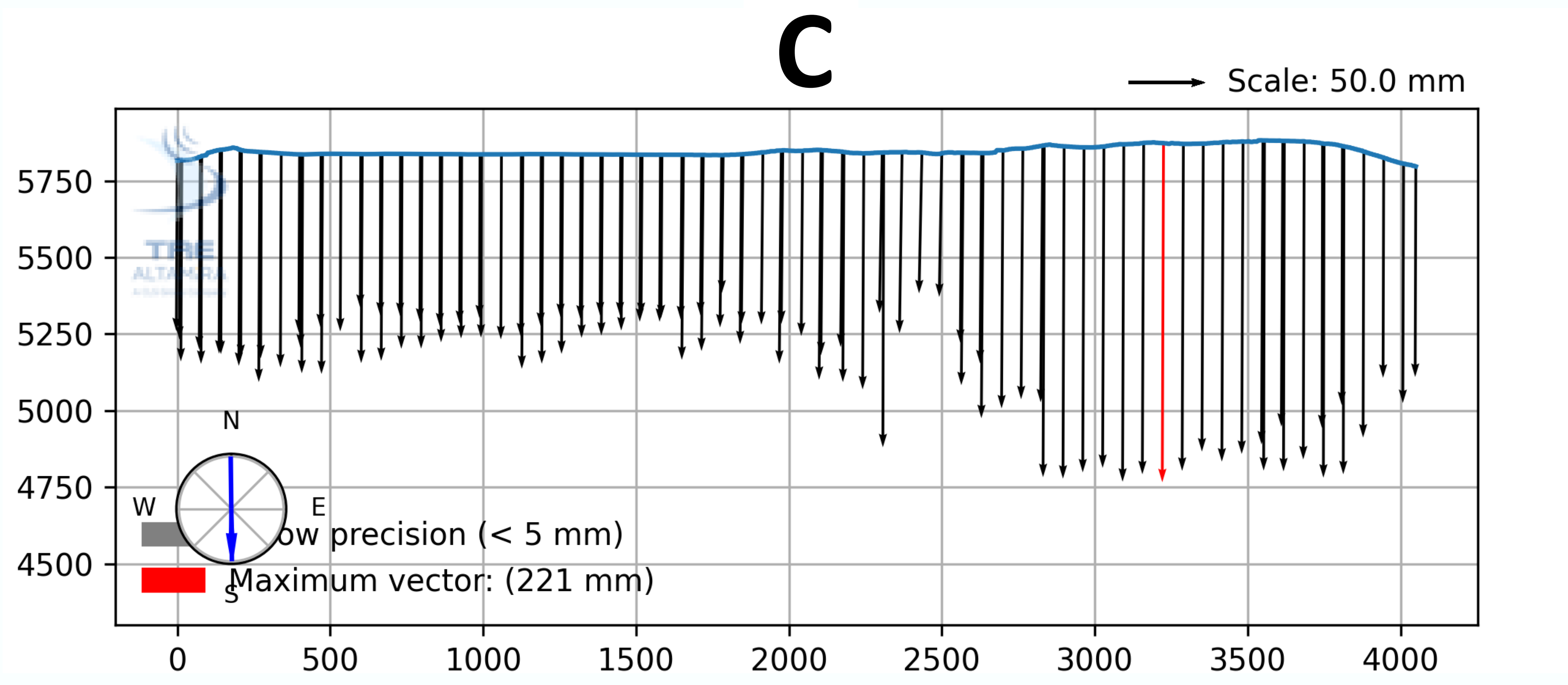
Background: Esri World Imagery
Map Projection: WGS 1984

Technical Considerations – Tailings Facilities

- ❑ Varied rates of displacement
- ❑ Buttress raises
- ❑ Vegetation
- ❑ Water



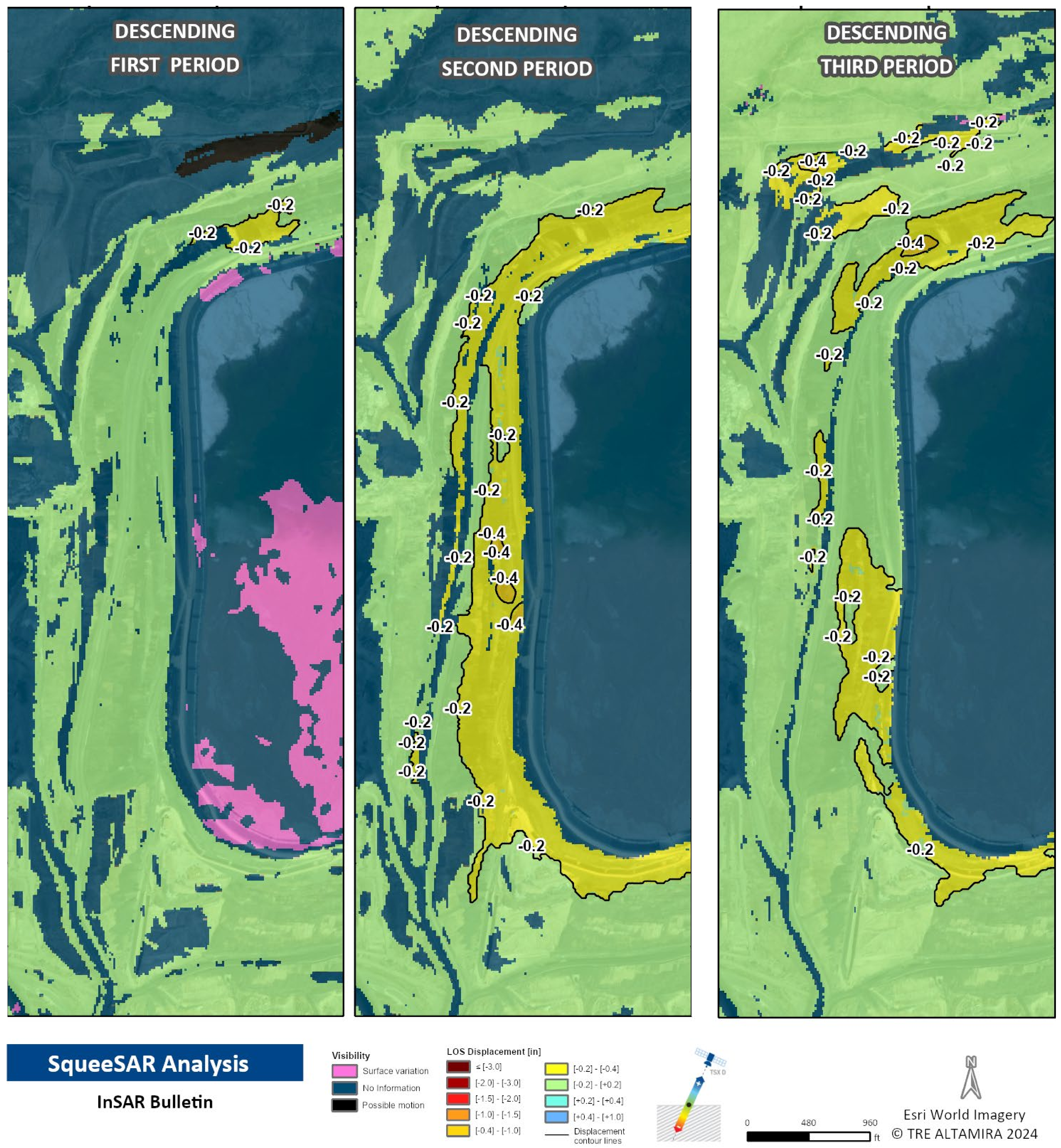




Active Operations - Tailings

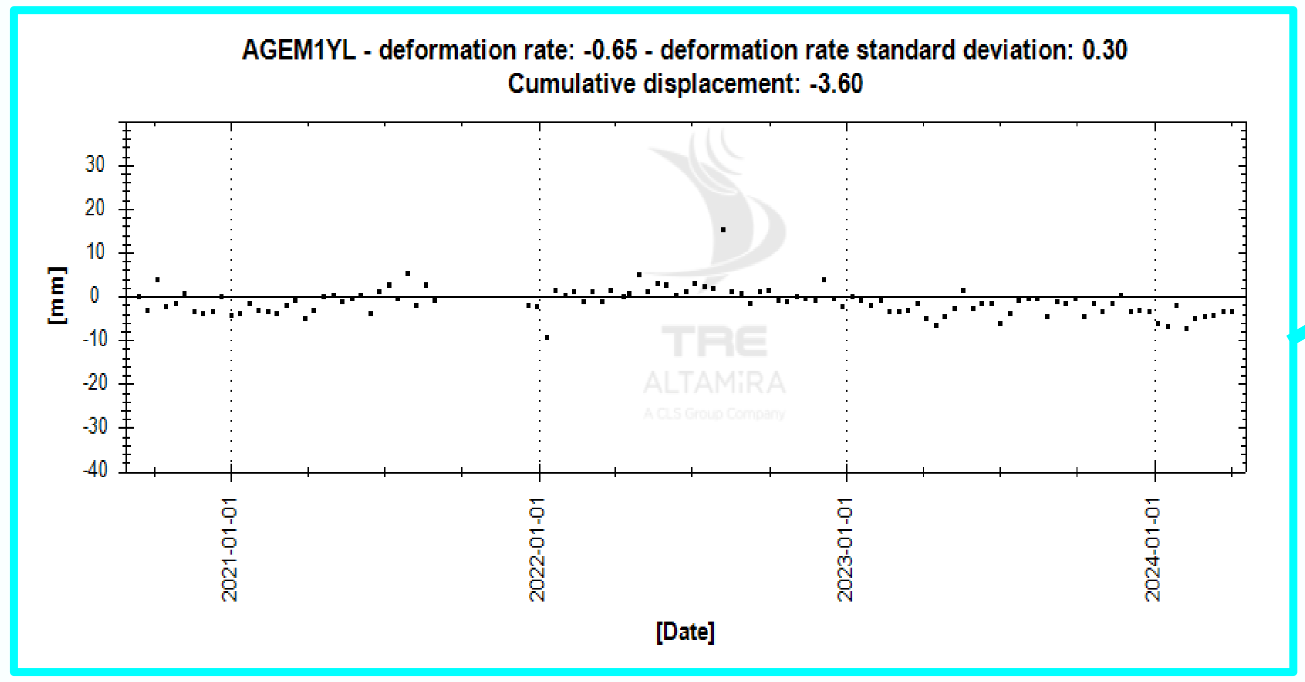
- Frequent changes to the ground surface
  - Impact coherence
  - Combination of processing approaches needed

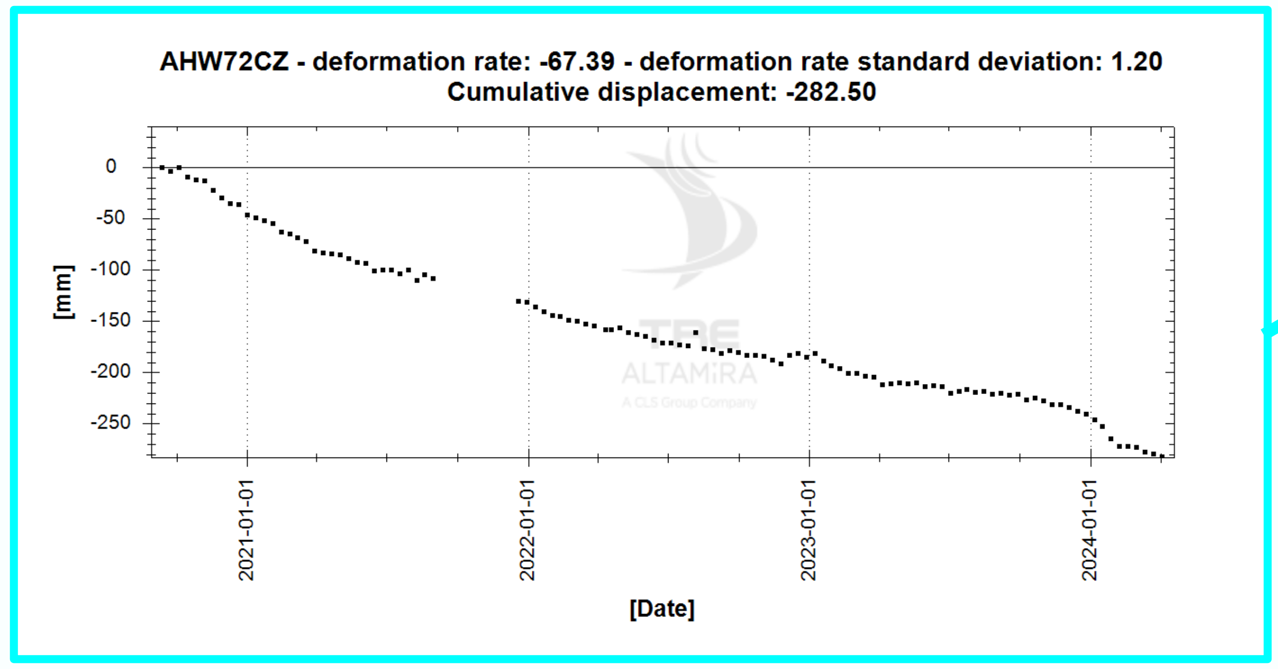
- Bulletins show displacement over 11 days

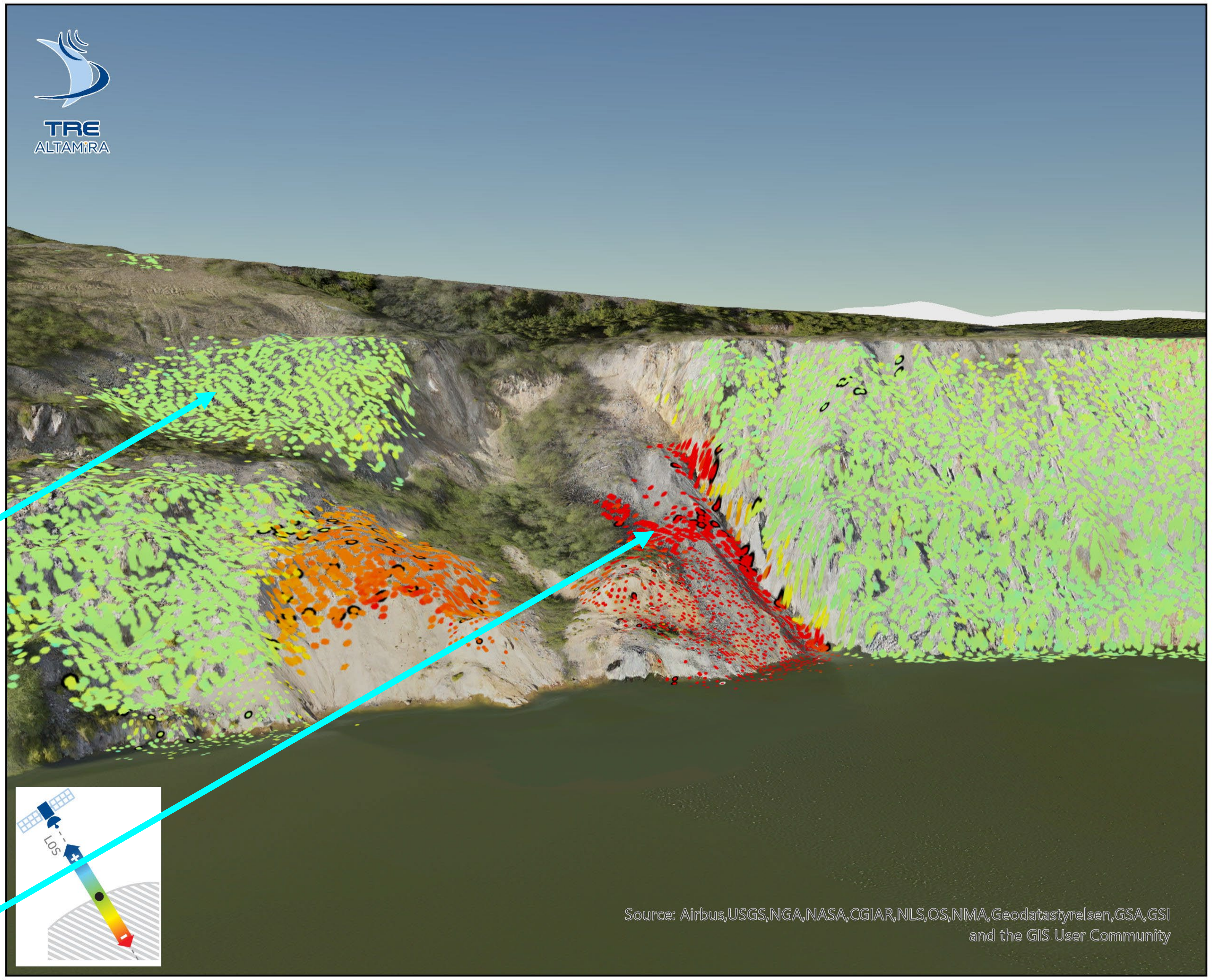


Monitoring Legacy Assets

- ❑ Little or no displacement in most areas
- ❑ Possible long-term slope movement
- ❑ Vegetation
- ❑ Water
- ❑ Cost







PROCESSING DATA

Satellite	Sentinel
Orbit (angle)	Ascending (ϴ = 35.97º)
Date Range	Sep 2020 - Apr 2024

LOS Displacement Rate [mm/yr]

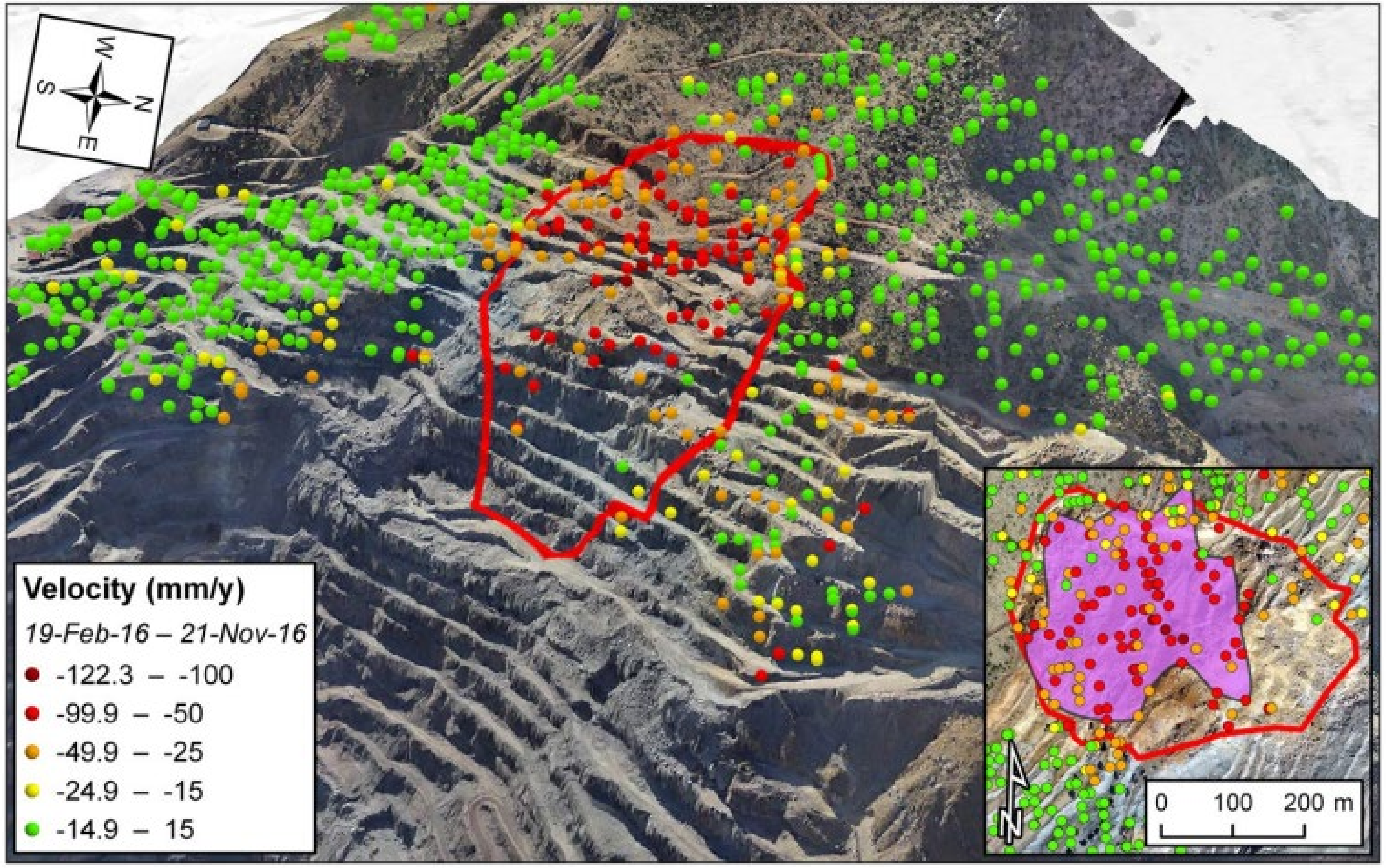
≤-100 0 ≥+100

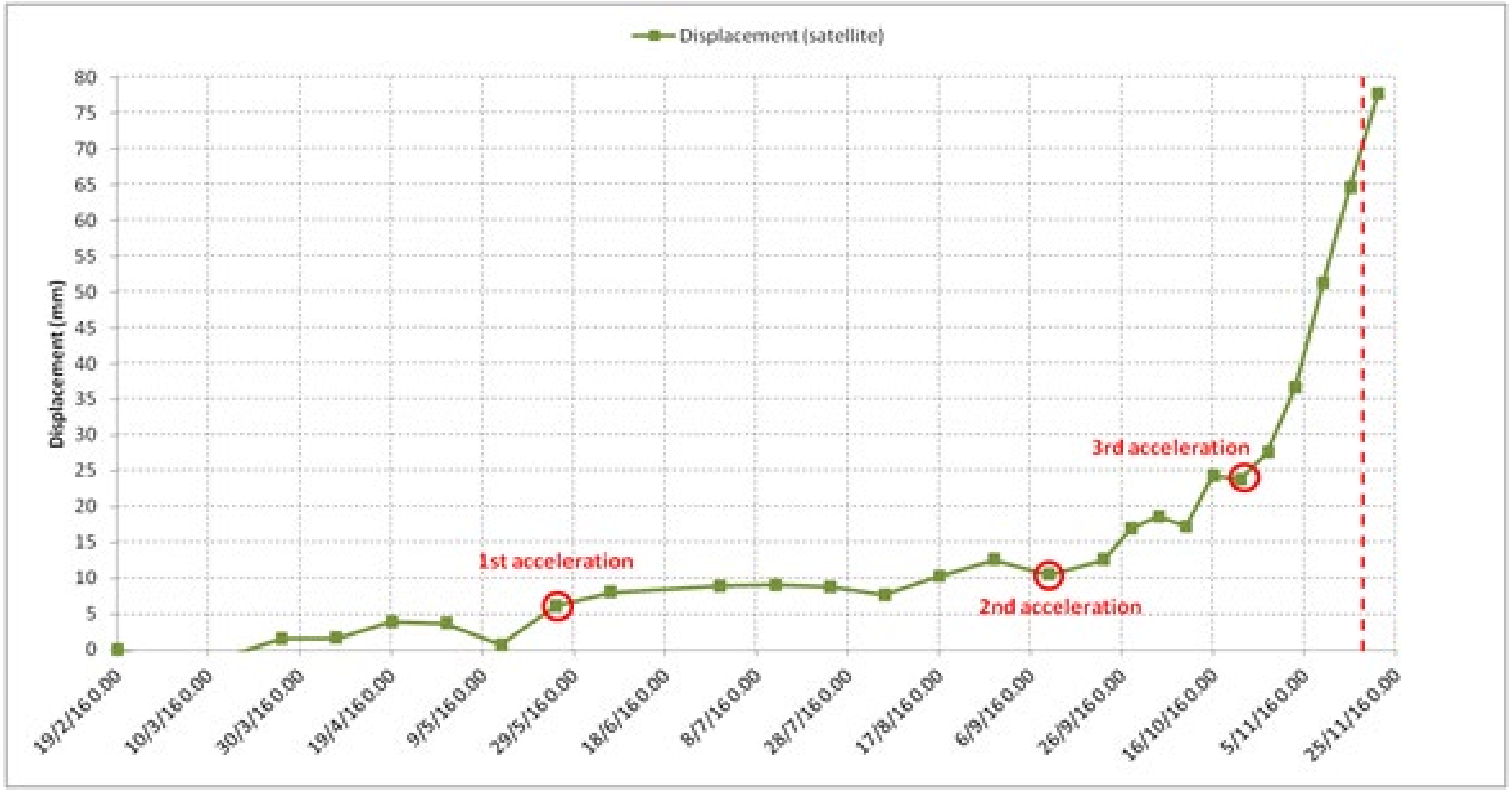
- ● Point with LOS rate decrease
- ○ Point with LOS rate increase

Data Visualization & Delivery

- ❑ Map rate or cumulative displacement
- ❑ Highlight changes in trend and differential displacement
- ❑ Time-slice data
- ❑ Filter by rate, acceleration & quality
- ❑ Overlay polygons & pins
- ❑ High-resolution optical base images

Early detection with SqueeSAR

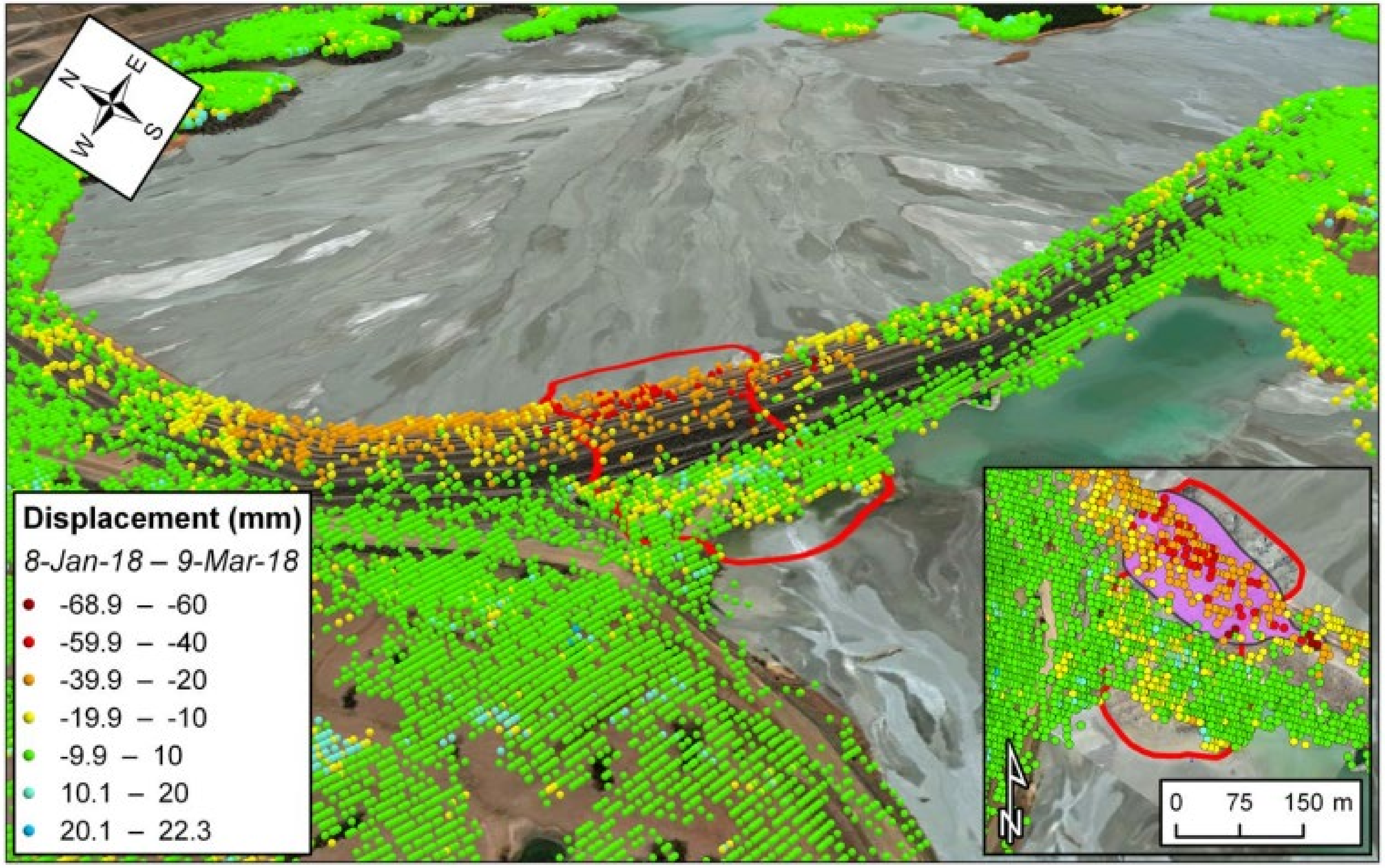


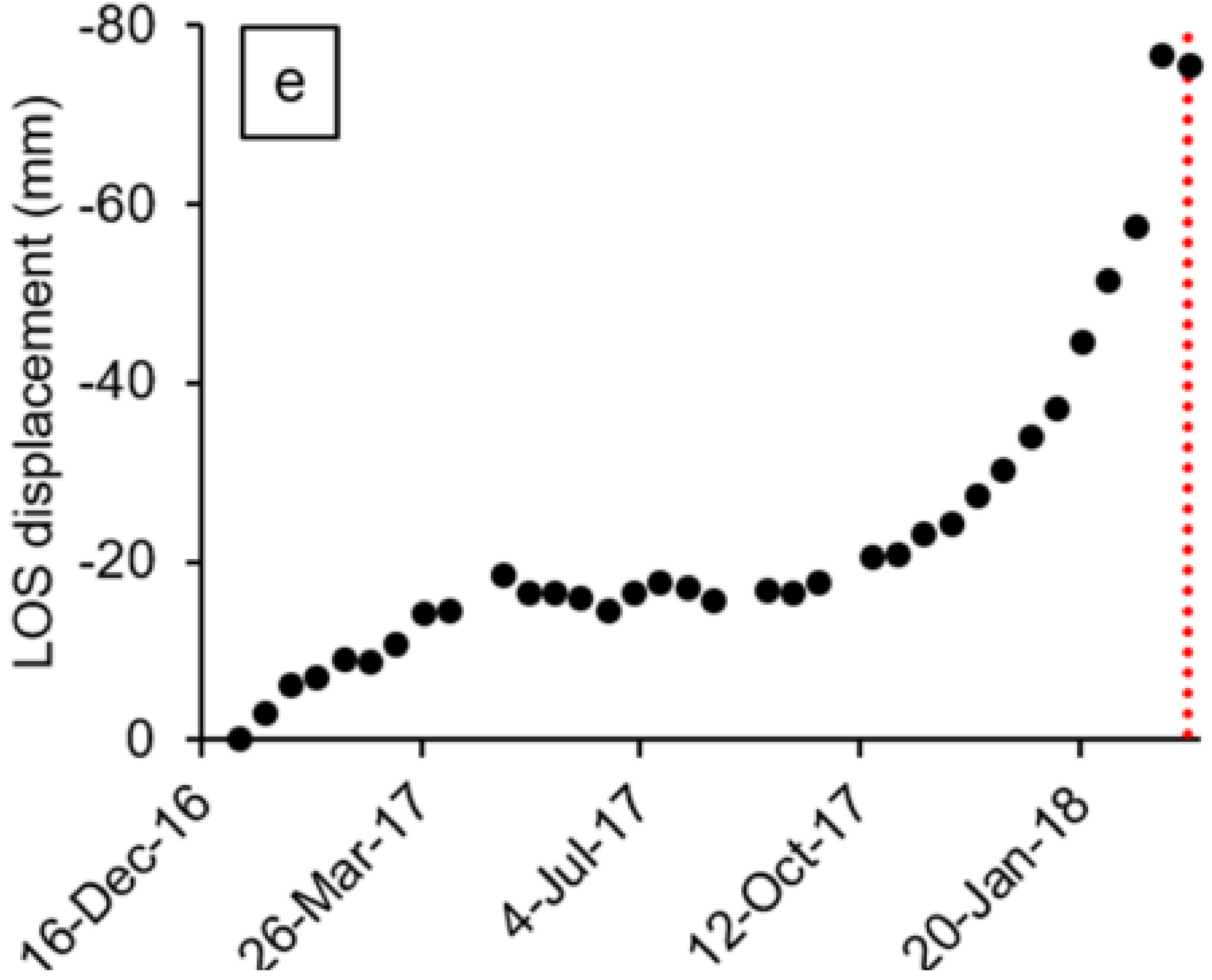


Carlà, T., Intrieri, E., Raspini, F. *et al.* Perspectives on the prediction of catastrophic slope failures from satellite InSAR. *Sci Rep* 9, 14137 (2019).

- **17 November 2016 slope failure** in a copper open-pit mine
- **Imagery**: 12-day revisit SNT imagery.
- Accelerations outside of the geotechnical monitoring area observable **starting from May 2017** in the **SqueeSAR time series**

Early detection with SqueeSAR





Carlà, T., Intrieri, E., Raspini, F. *et al.* Perspectives on the prediction of catastrophic slope failures from satellite InSAR. *Sci Rep* 9, 14137 (2019).

- **TSF Dam failure** occurred on **09 March 2018**
- **Imagery**: 11-day revisit TSX imagery.
- First acceleration observable in **late 2017** from the **SqueeSAR time series**

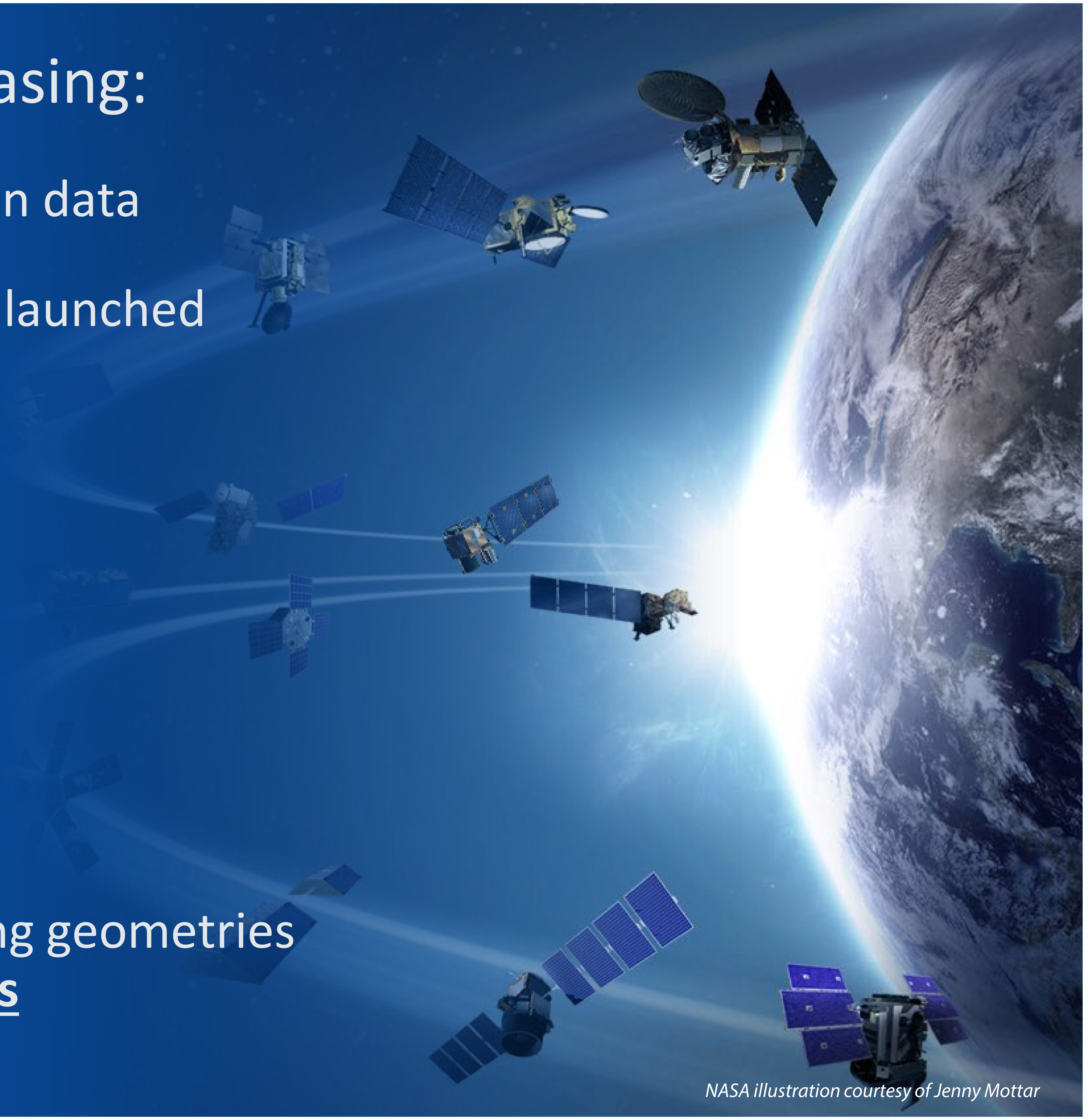
New Developments

- Satellites
  - 3D measurements
- Data Fusion
- Error Bars
- Reappearing targets
- Machine Learning
- Water pond/saturation mapping

SAR Satellites: Future

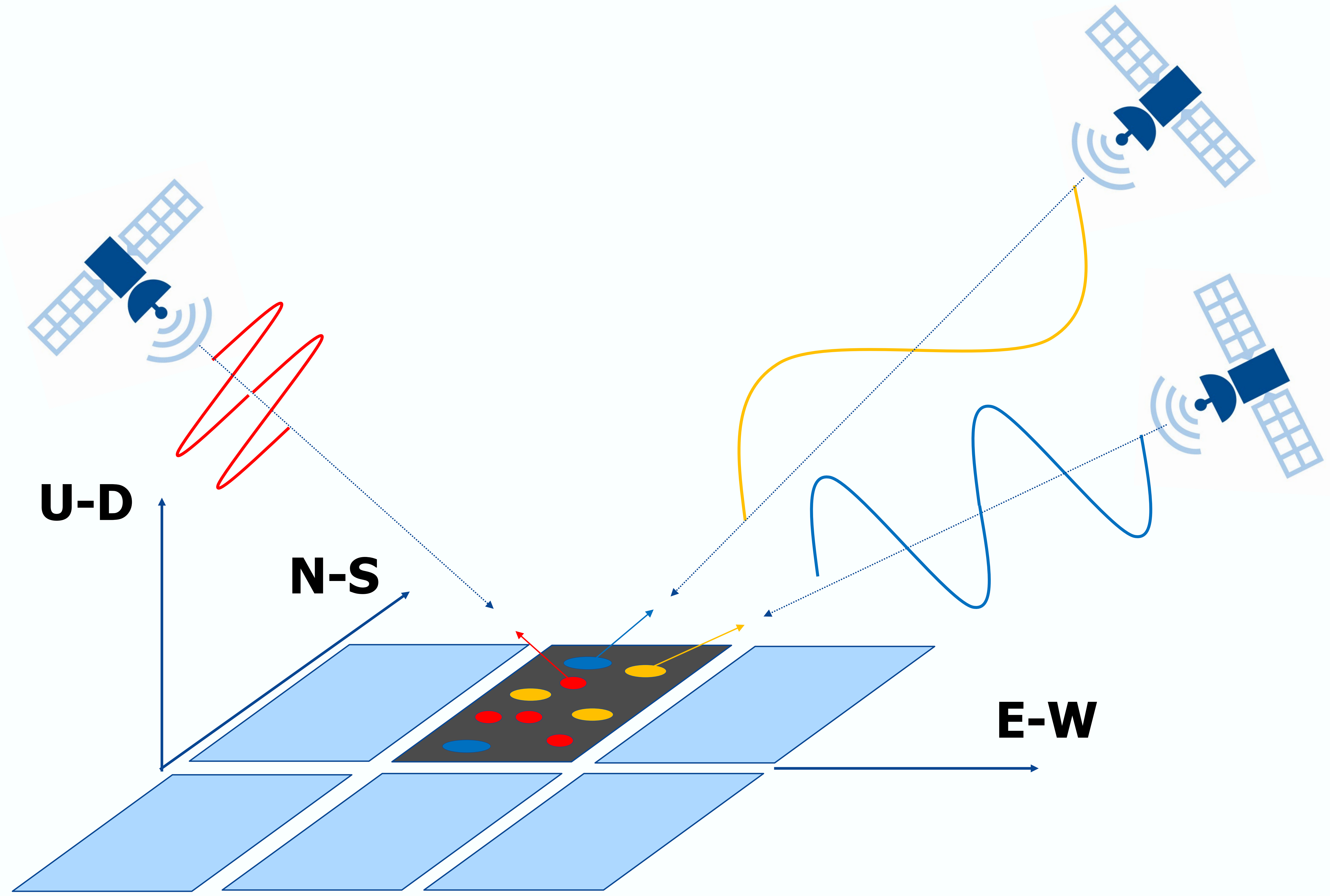
Number of SAR satellites is increasing:

- ❑ Growing demand for earth observation data
- ❑ First NASA SAR satellite, NISAR, being launched in ~~2024~~ 2025
- ❑ Several new constellations of SAR satellites operated by private companies planned:
  - Numerous small satellites in same orbit
  - Daily/hourly revisits
  - Non-polar orbits and new viewing geometries will allow **full 3-D measurements**



NASA illustration courtesy of Jenny Mottar

Data Fusion

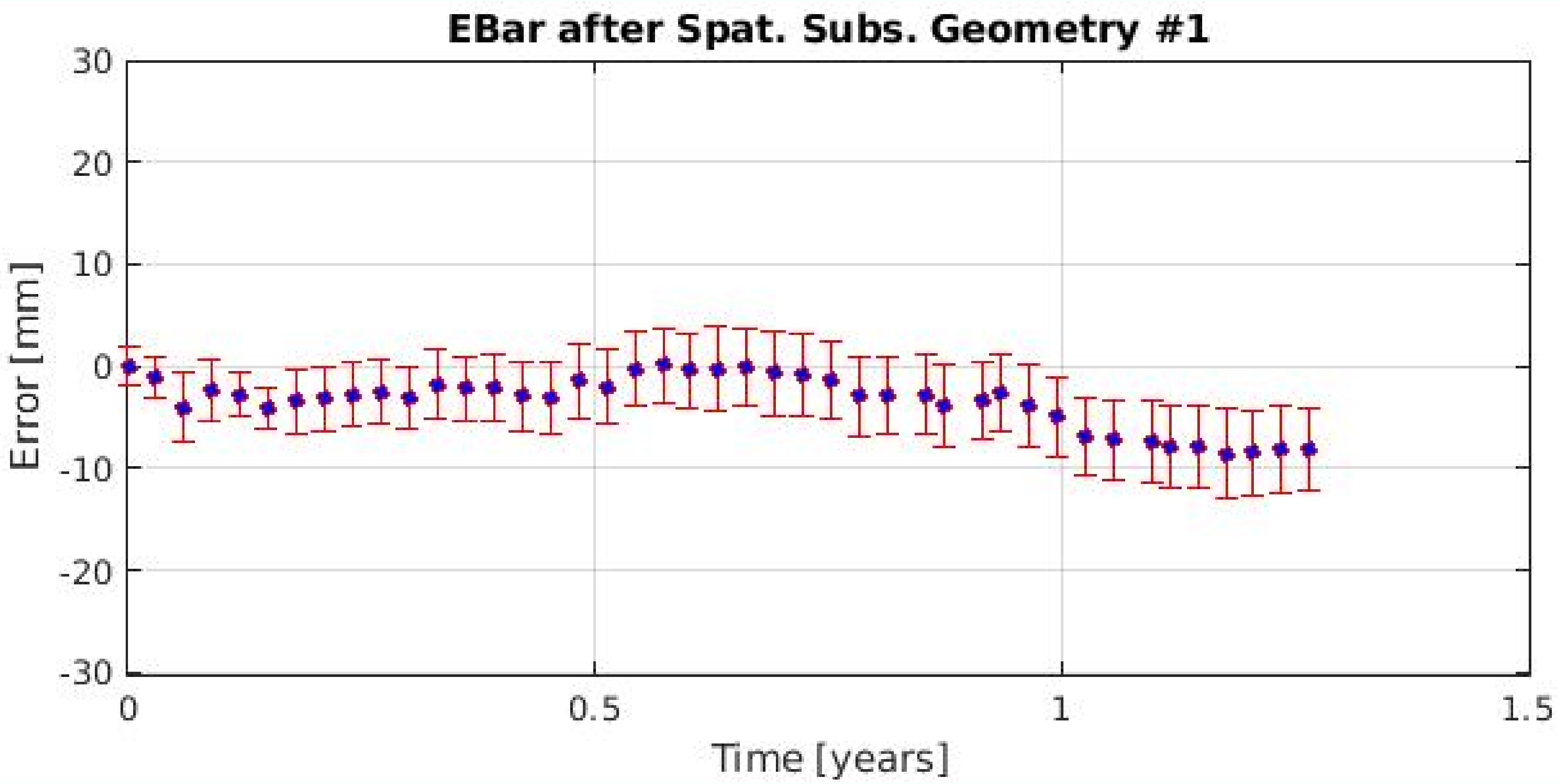


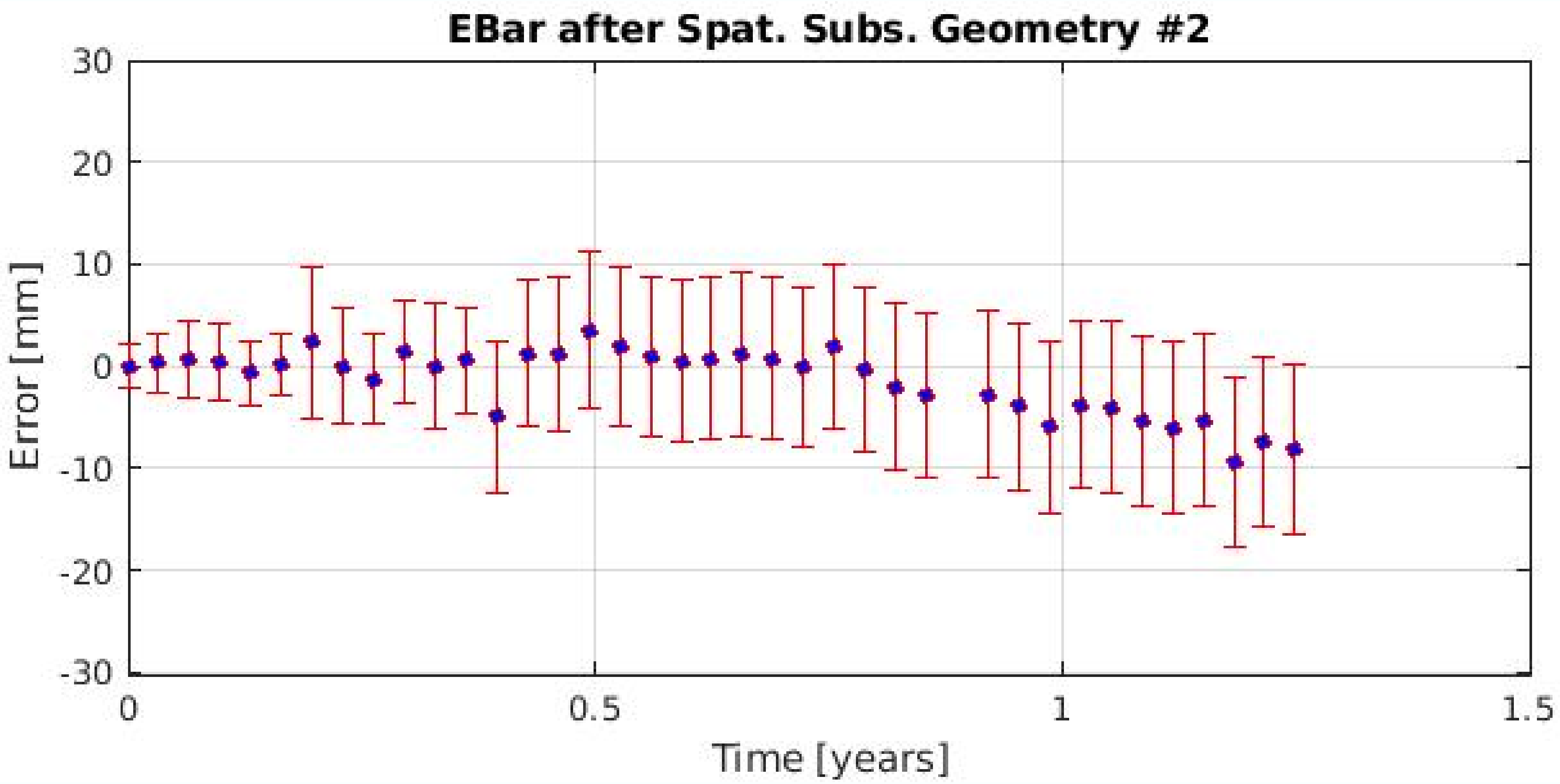
Combine InSAR measurements from different missions/sensors with diverse:

- wavelengths
- resolutions (MP density)
- geometry (A/D, look direction)
- revisit time

to obtain an advanced merged deformation product no longer related to mission design parameters and extracting and collating as much info as possible from each one

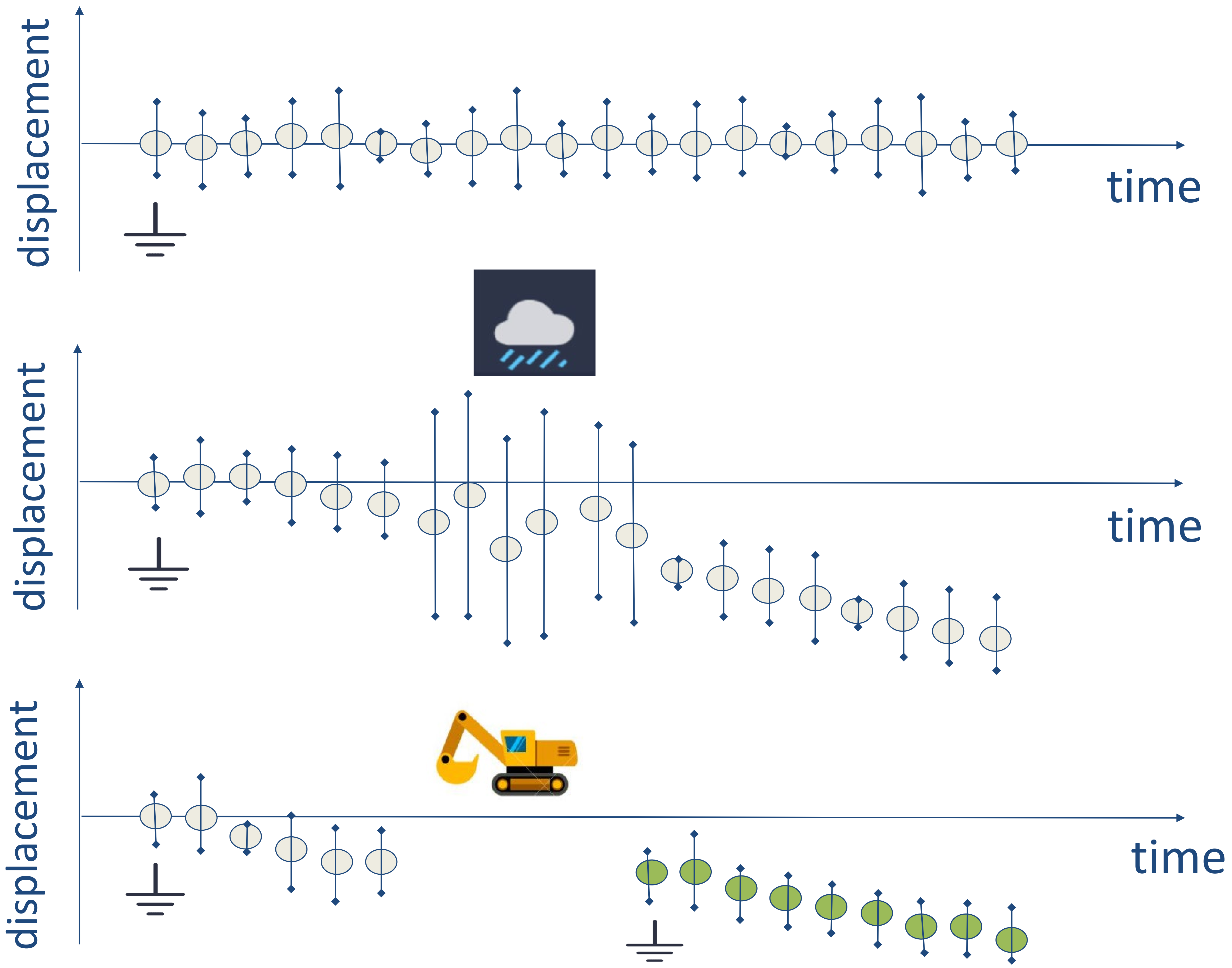
Error Bars – characterizing uncertainty





Overcoming loss of coherence

Surface changes or severe weather conditions introduce noise in the time series



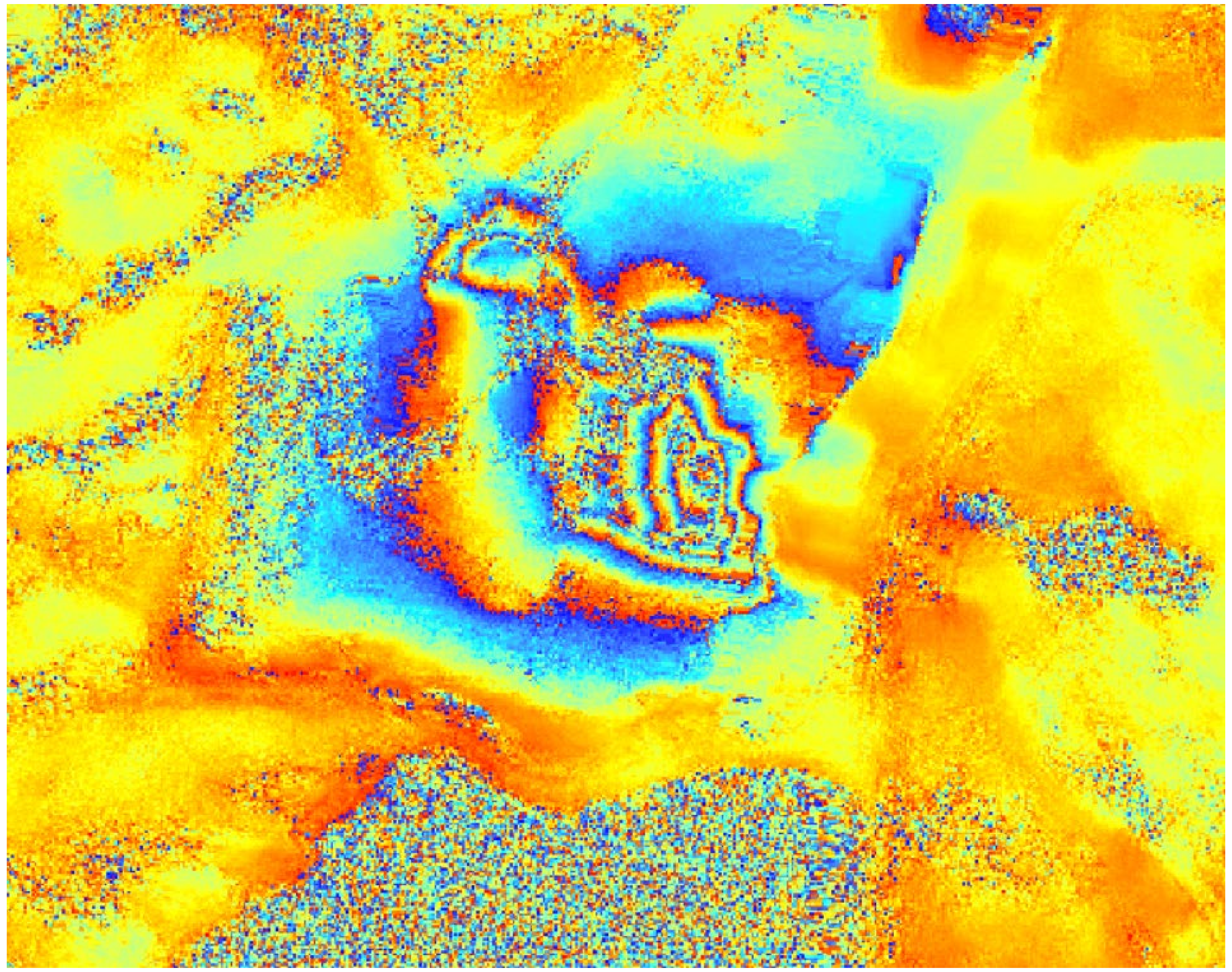
Permanent target

Permanent target with noisy interval

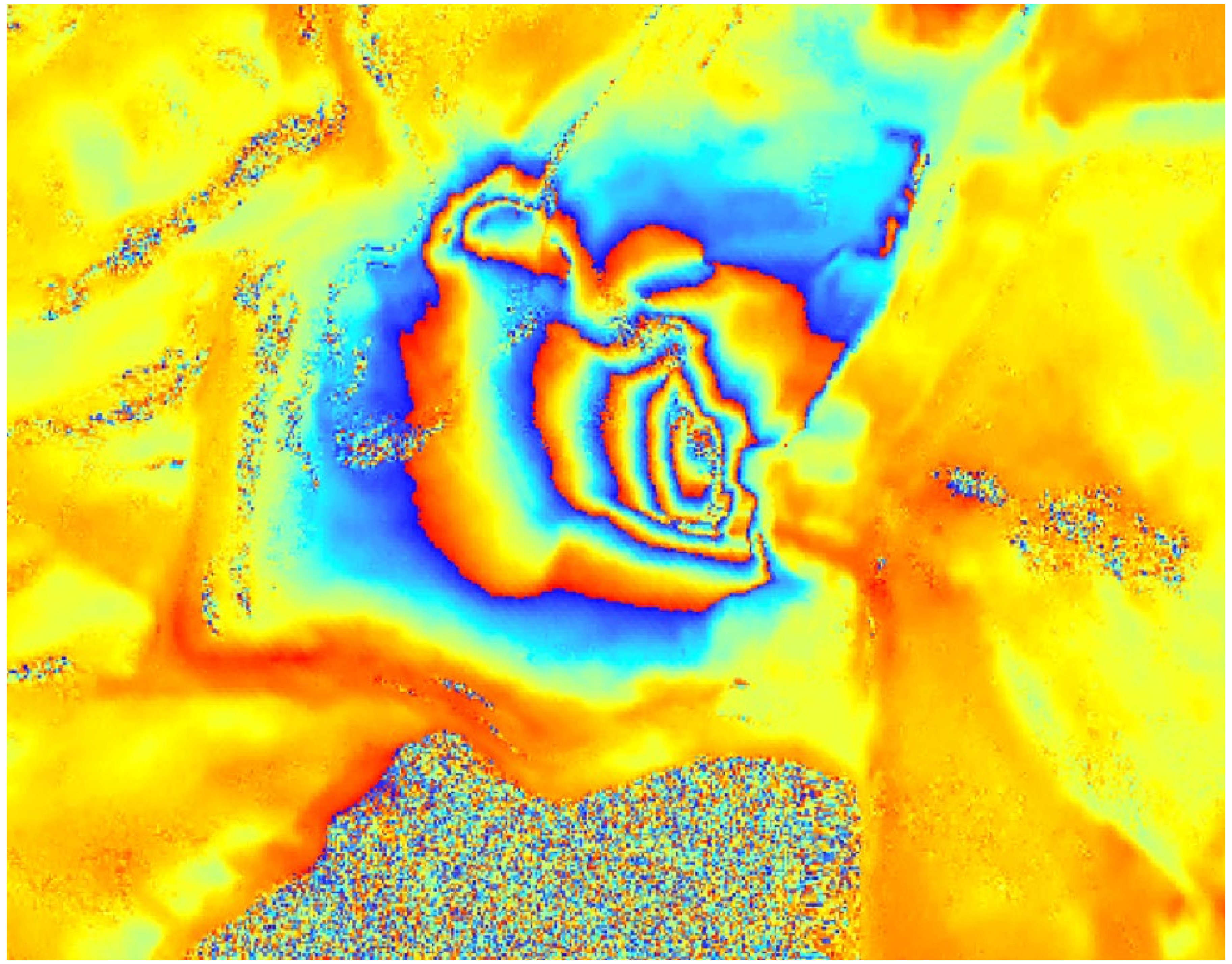
Temporary target (i.e. becomes different target after surface changes)

ML for Filtering Noise

Classic Approach

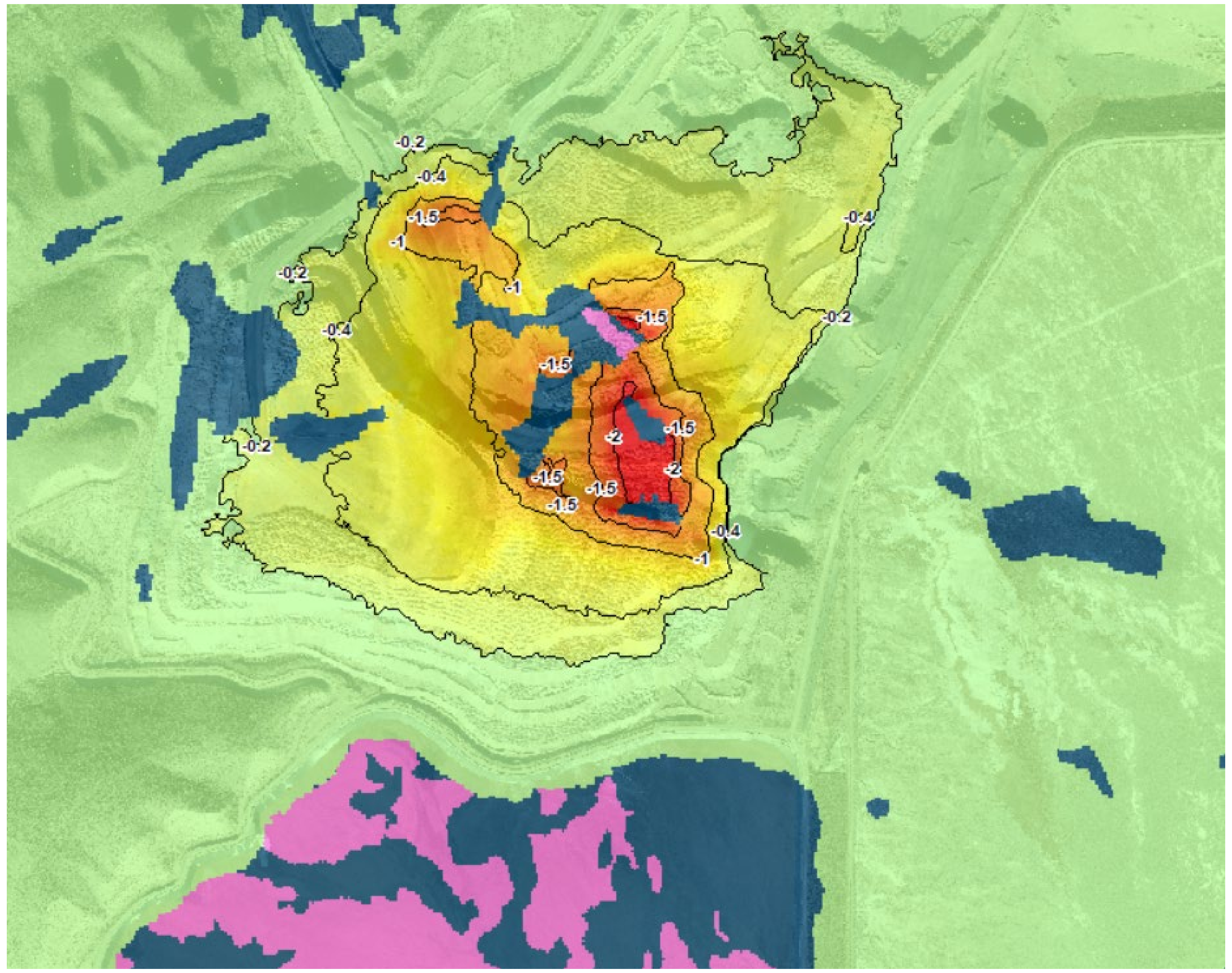


ML Approach

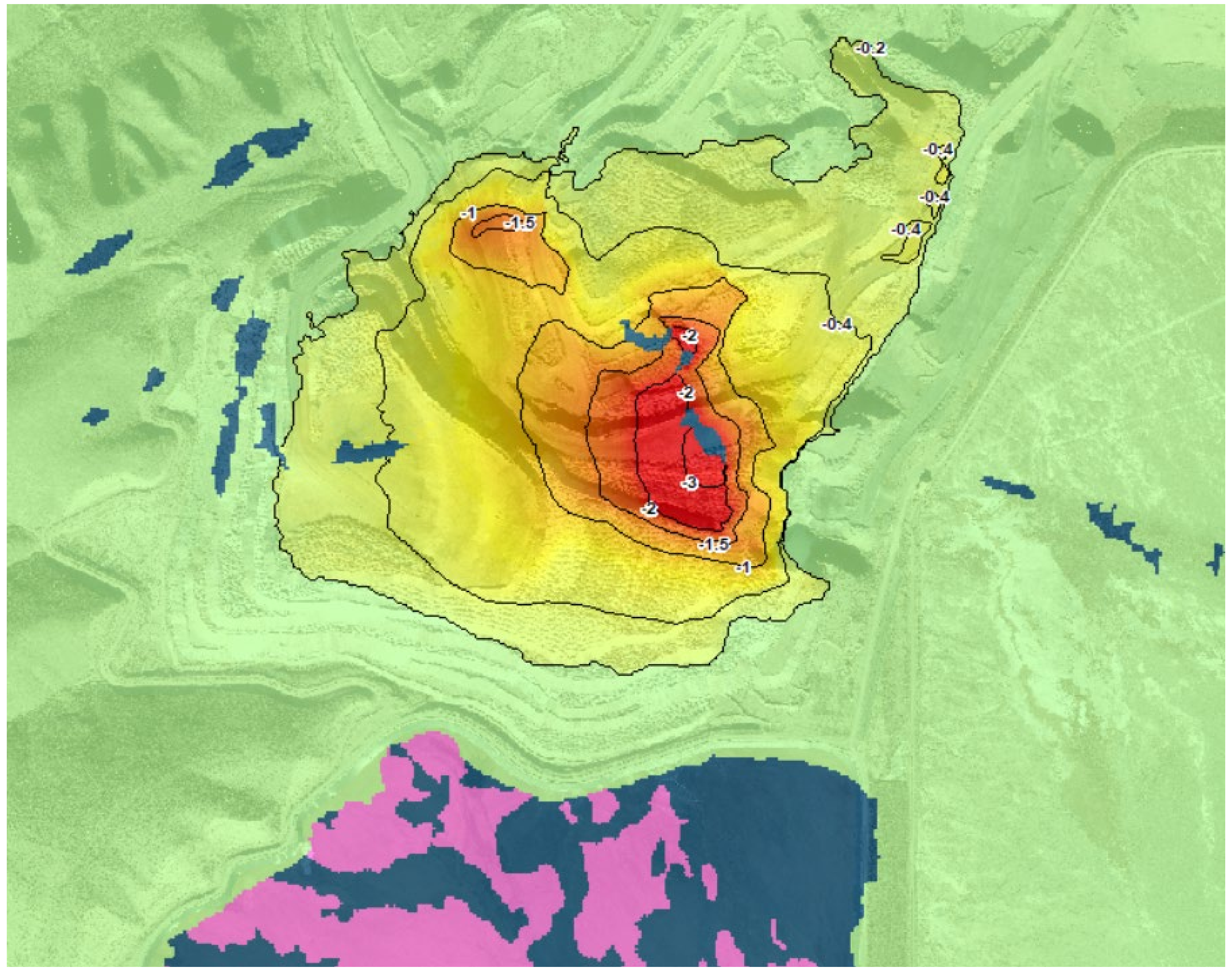


ML for Filtering Noise

Classic Approach



ML Approach



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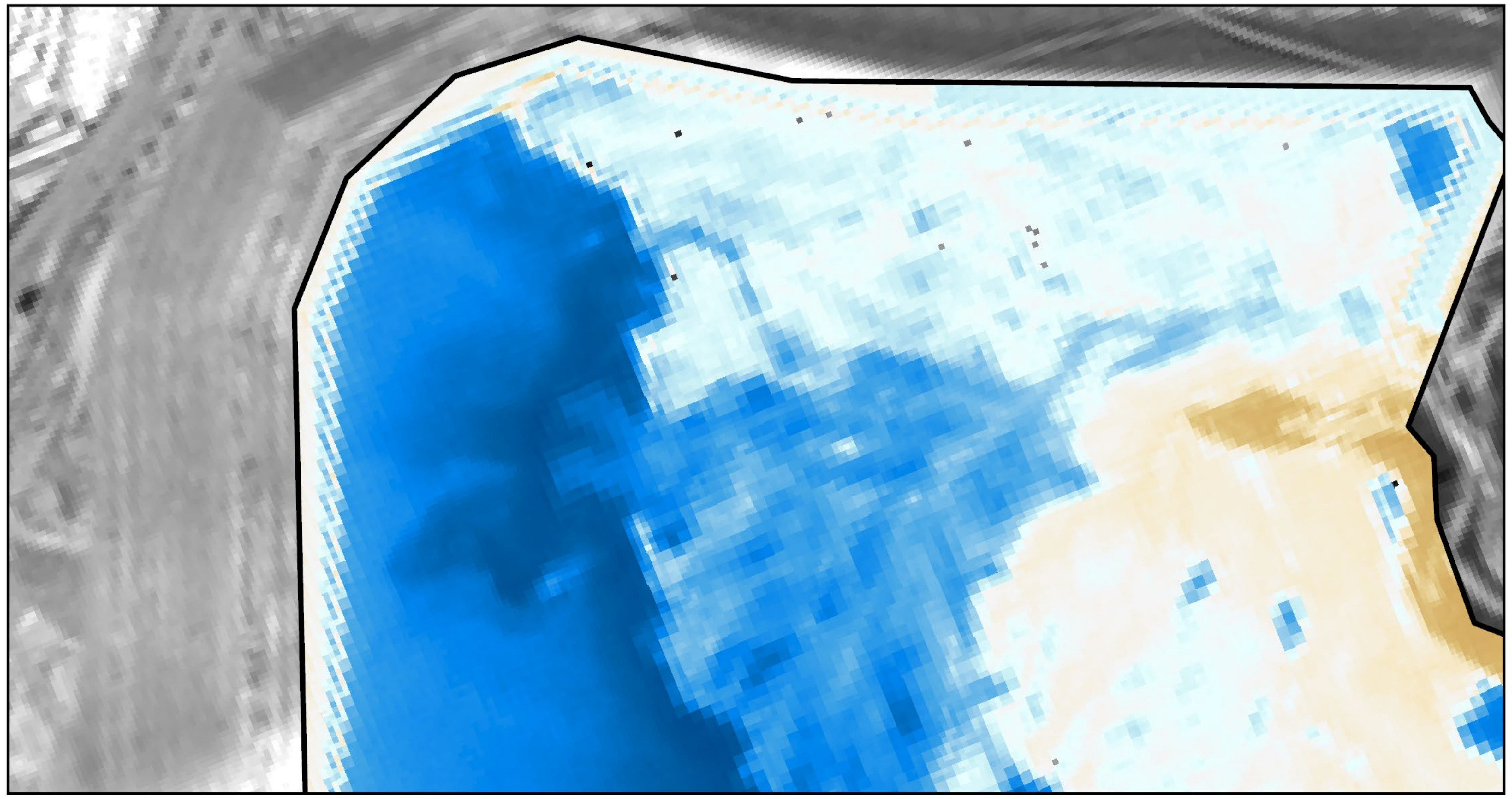
Water Saturation Mapping

- ❑ Accurate, repeatable approach to tracking supernatant ponding and saturation levels in TSFs
- ❑ Semi-automatic combination of EO layers
- ❑ Maps tailored to site needs and operational requirements
- ❑ Limited cloud cover requirement
  - ○ Incorporation of SAR data for all-weather monitoring



Water Index

Water | Transition Zone | Dry

0 | 750 | 1,500 feet

Thank you!

Thank you

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