Monitoring Mining Areas from Space

InSAR technology as a tool for the evolution of mining industry

Fernando Bellotti

Geospatial World Forum, Rotterdam, 4th May 2023

Introduction

- Implementing a risk management and mitigation program is a necessary way to ensure safe and profitable a mining operation.
- Since it’s beginning in 1992, InSAR has grown to be an easy-to-integrate companion of in-situ monitoring instrumentation and has proven itself as an effective technology for monitoring surface deformation.
- InSAR is now recognized as a reputable monitoring solutions thanks to its capability of extending the monitoring scale to the entire mine site facilitating strategic monitoring.

Hazard Mitigation and Risk Reduction

- Increasingly important for mining operations as highlighted by recent catastrophic failures of tailings dams worldwide.
- These events have focused industry attention on the importance of developing and implementing effective monitoring strategies on all mine sites.

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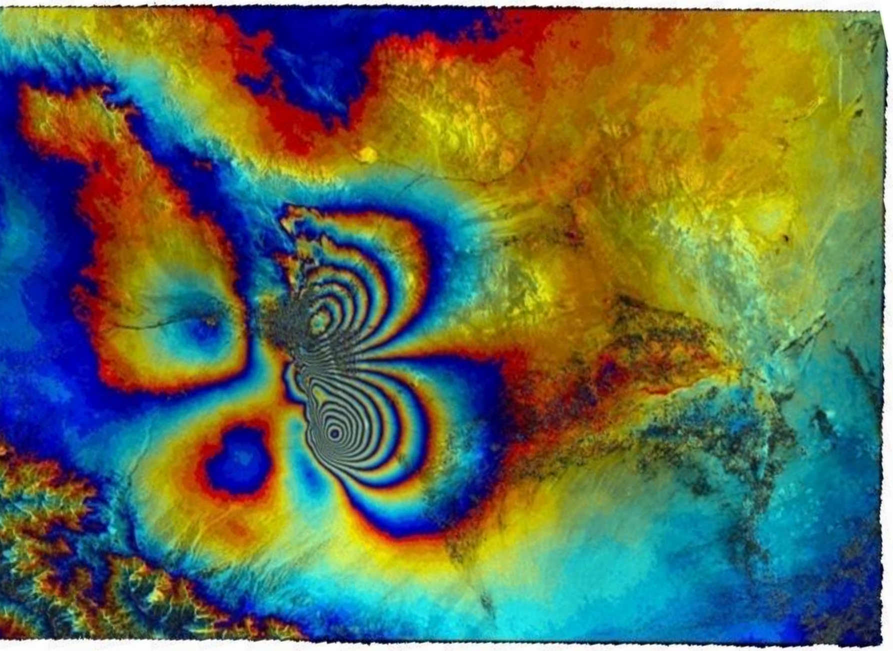
INSAR TODAY

Satellite Radar Interferometry

A remote sensing technique capable of identifying and measuring ground deformation widely adopted in slope stability assessment and monitoring globally.

What is InSAR?

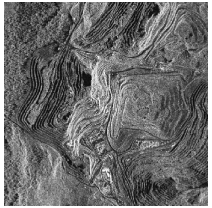


Interferometric Synthetic Aperture Radar

- Using data from radar satellites the first deformation maps were produced in 1992 to measure the effects on an earthquake.
- InSAR technology has rapidly advanced to become a remote sensing technique for measuring ground deformation.
- Uses high-resolution sensors, with automatic, robust and scalable processing algorithms.

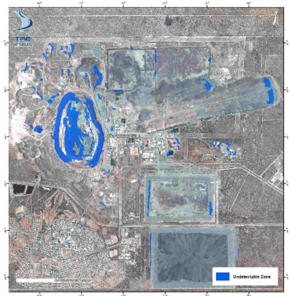
Basic Deformation Maps

T$_1$
Acquisition

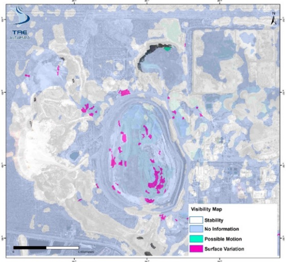


T$_2$
Acquisition

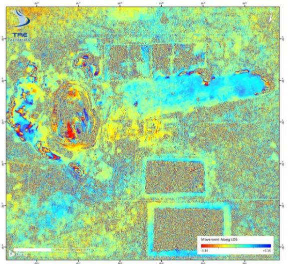
Visibility
Analysis

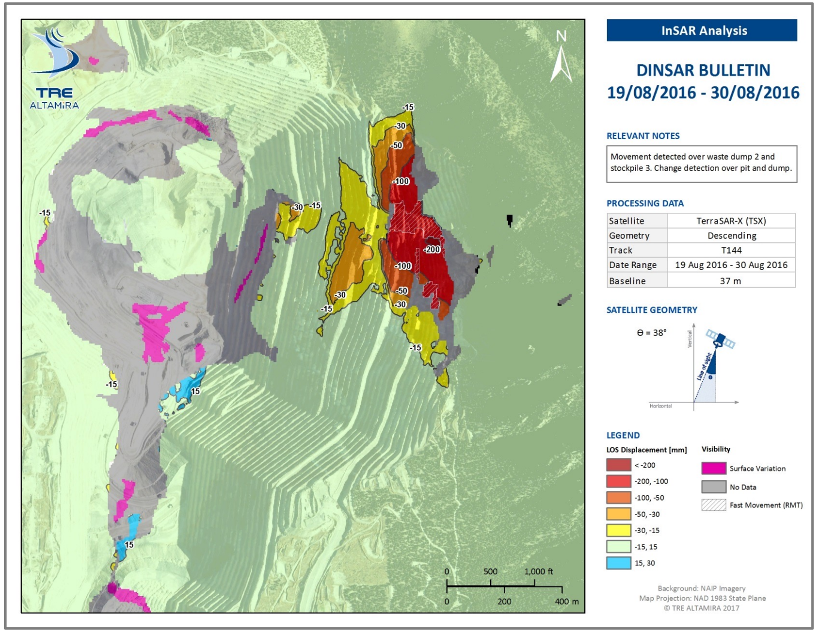


Change
Detection
Analysis



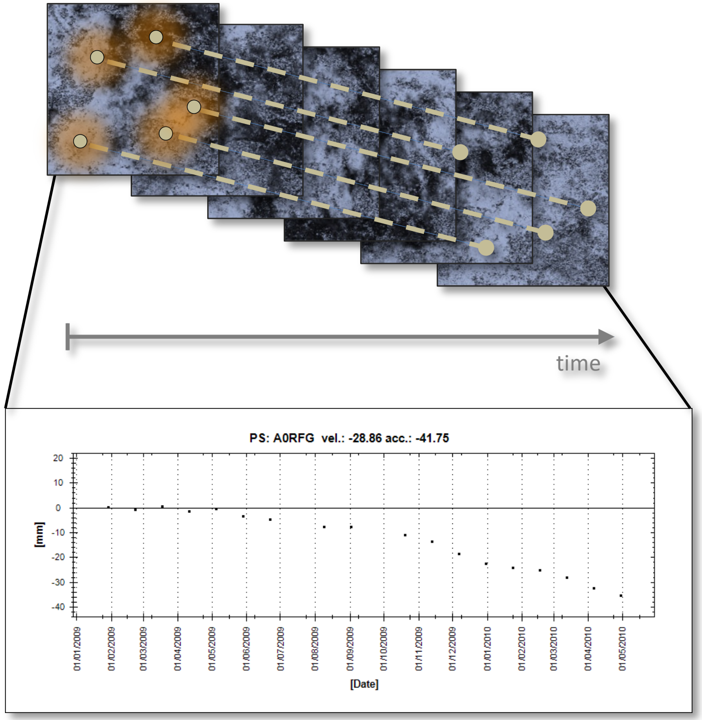
DInSAR
and RMT
Analyses





Contour map of recent deformation

SqueeSAR® Technology



- Requires 15+ images.
- Identify point targets on the ground.
- No instrumentation or site access required.
- Removal of:
  - Atmospheric Noise
  - Topographic Noise
- Produces high-density point cloud of measurements.
- Every point has a time-series of deformation.

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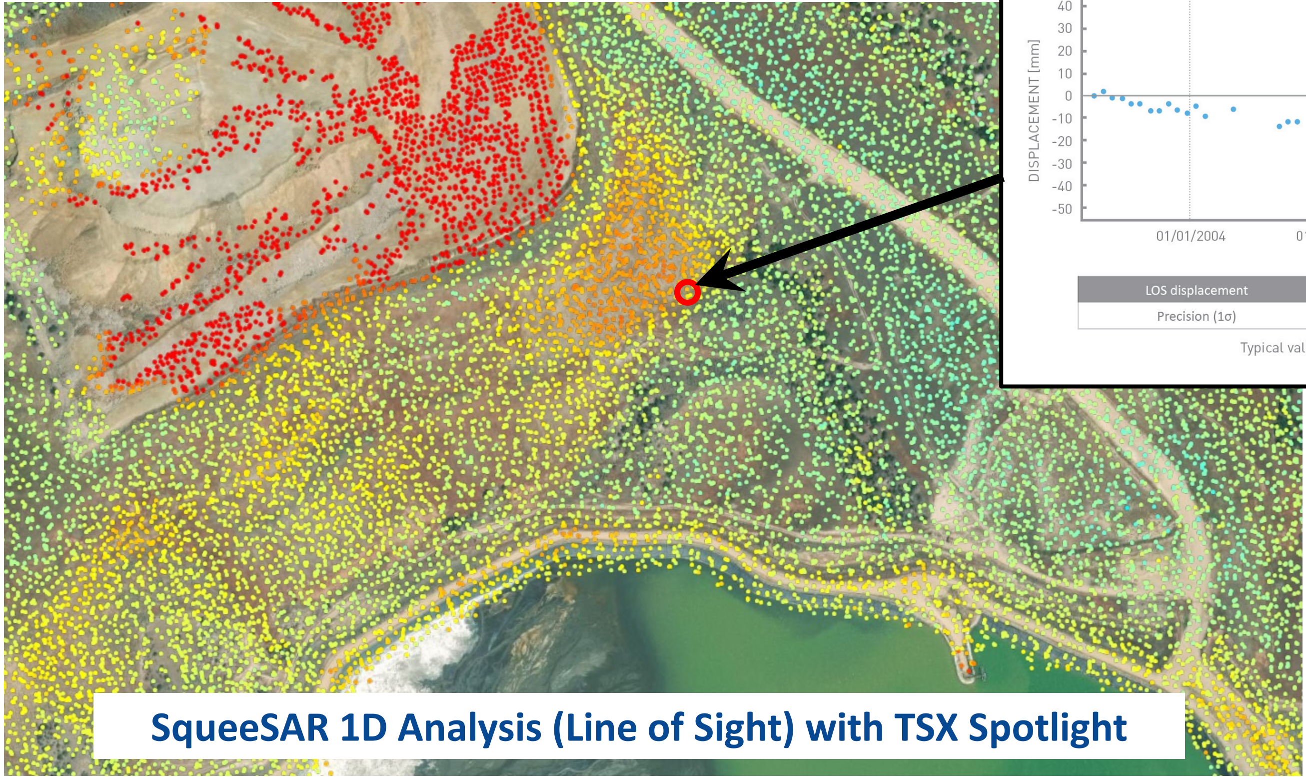
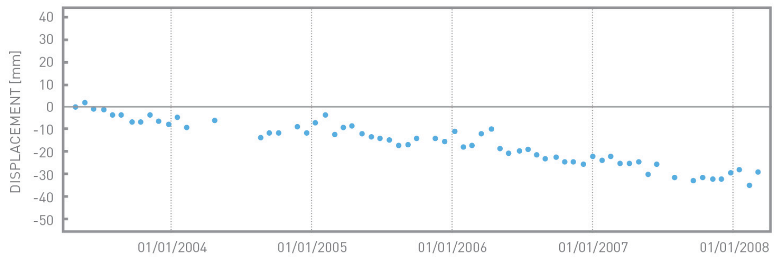
InSAR Measurements (SqueeSAR)



SqueeSAR 1D Analysis (Line of Sight) with TSX Spotlight

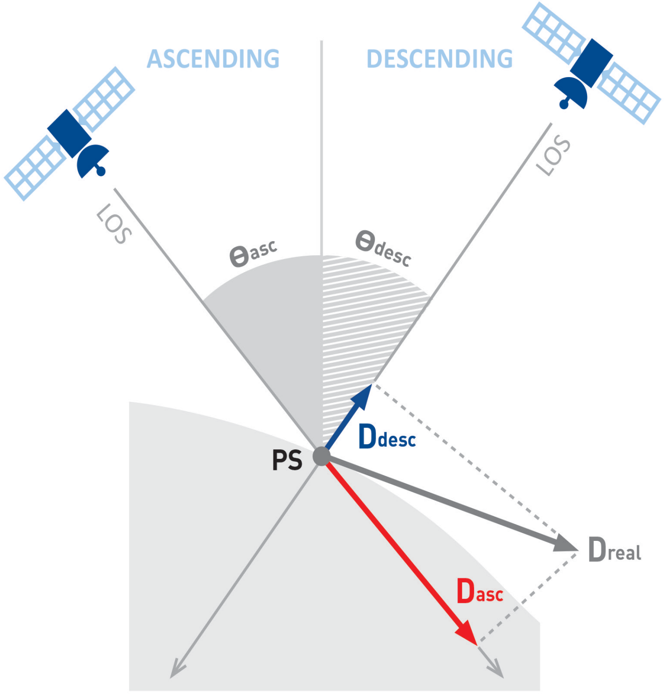


LOS displacement	Average displacement rate	Single measurement
Precision (1σ)	< 1 mm/yr	± 5 mm

Typical values < 1 km from the reference point, 5 year dataset

- Each measurement point has an associated time-series.
- Maps typically have thousands of points.

Vertical and Horizontal East-West Decomposition



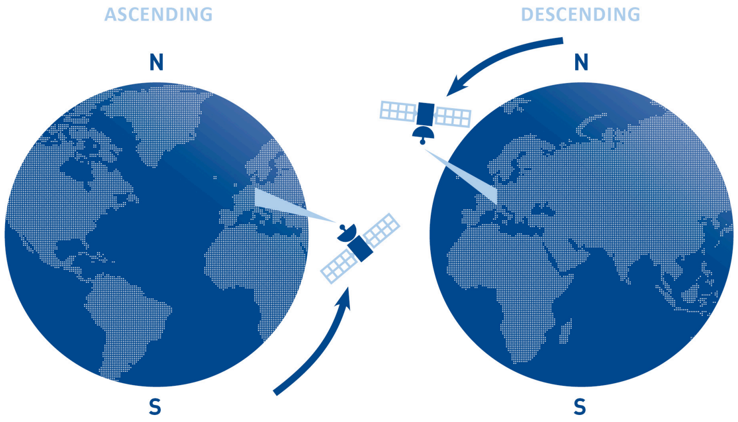
» SAR satellites navigates along near-polar orbits - sensitive to surface change occurring along a line-of-sight (LOS).
  - Basic InSAR measurements are a one-dimensional (1D).
  - Single geometry may miss steep slopes on one side of a pit.

» Combining the Earth's rotation with satellite orbital paths captures the Earth's surface in two satellite geometries (2D).
  - Ascending (or east-looking)
  - Descending (or west-looking)

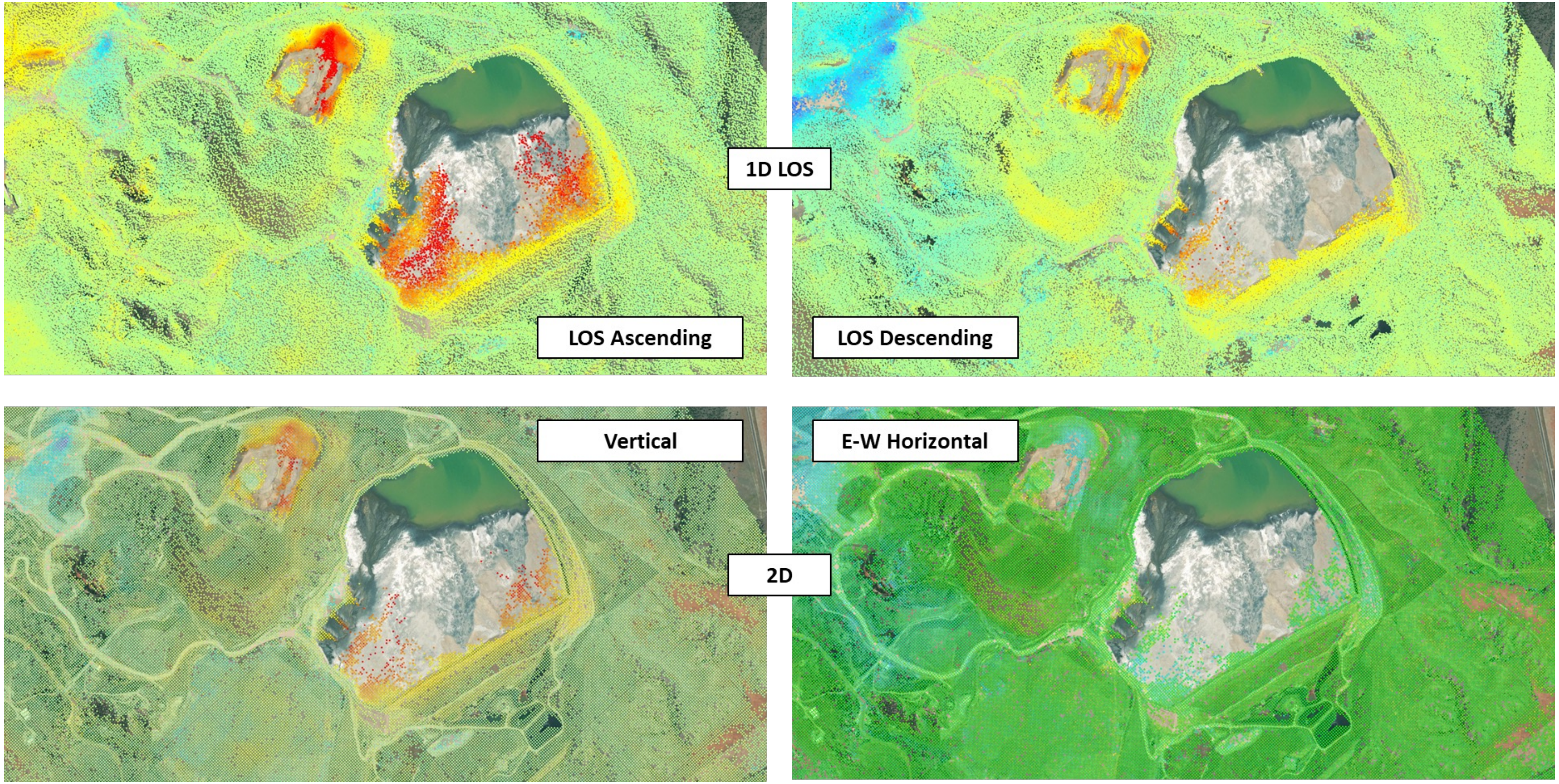
The Strength of Double Geometry

Combining Ascending and Descending data sets:

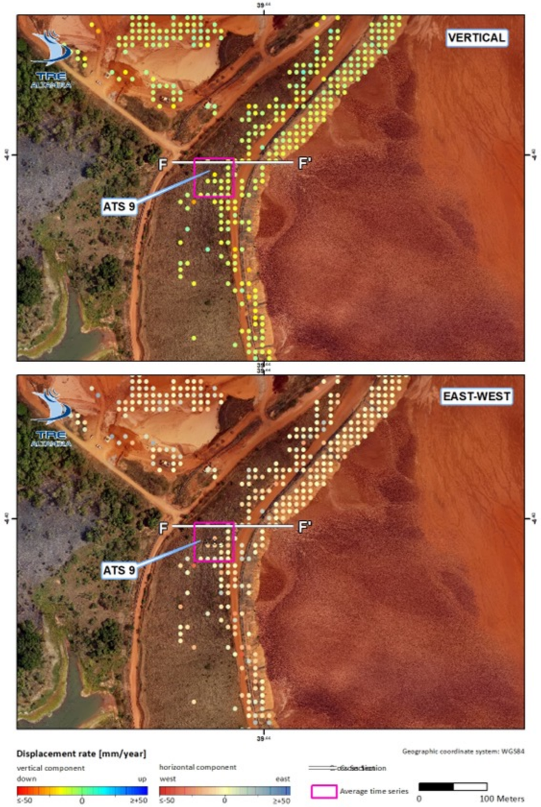
- Maximises the coverage of ground features, especially in areas with strong topography.
- Simplifies the interpretation of InSAR results by providing true vertical and horizontal east-west data instead of simple LOS measurements.
- Enhances the integrability of InSAR data with geotechnical sensors, Automatic Total Stations (ATS), levelling, GNSS and slope stability radars.

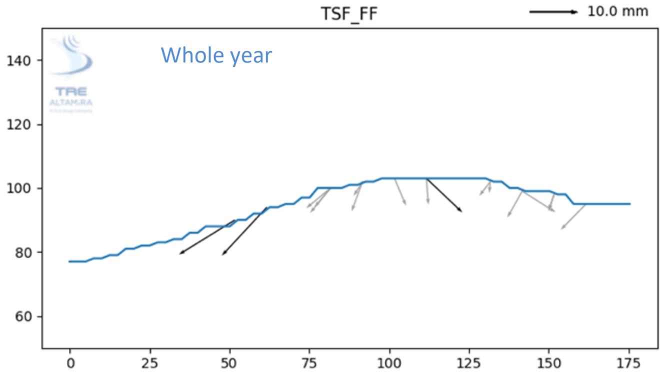


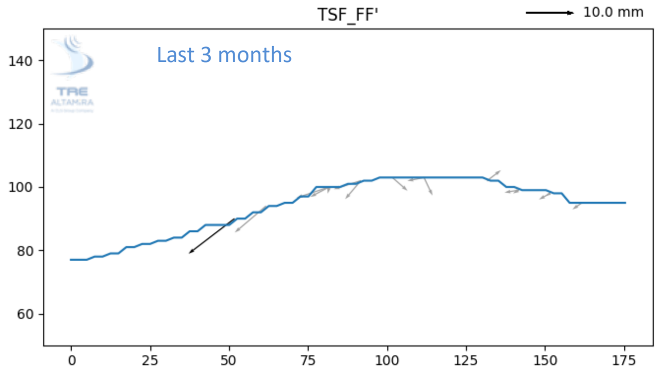
2D Analysis Maps



East-West Cross Section





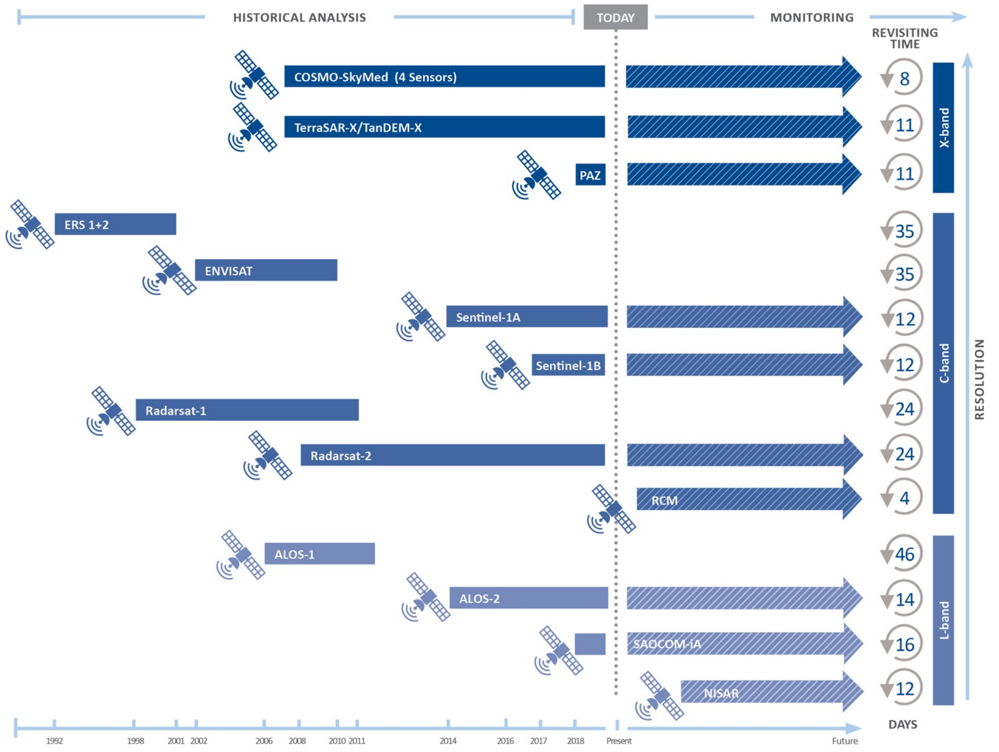


SATELLITE RADAR SENSORS

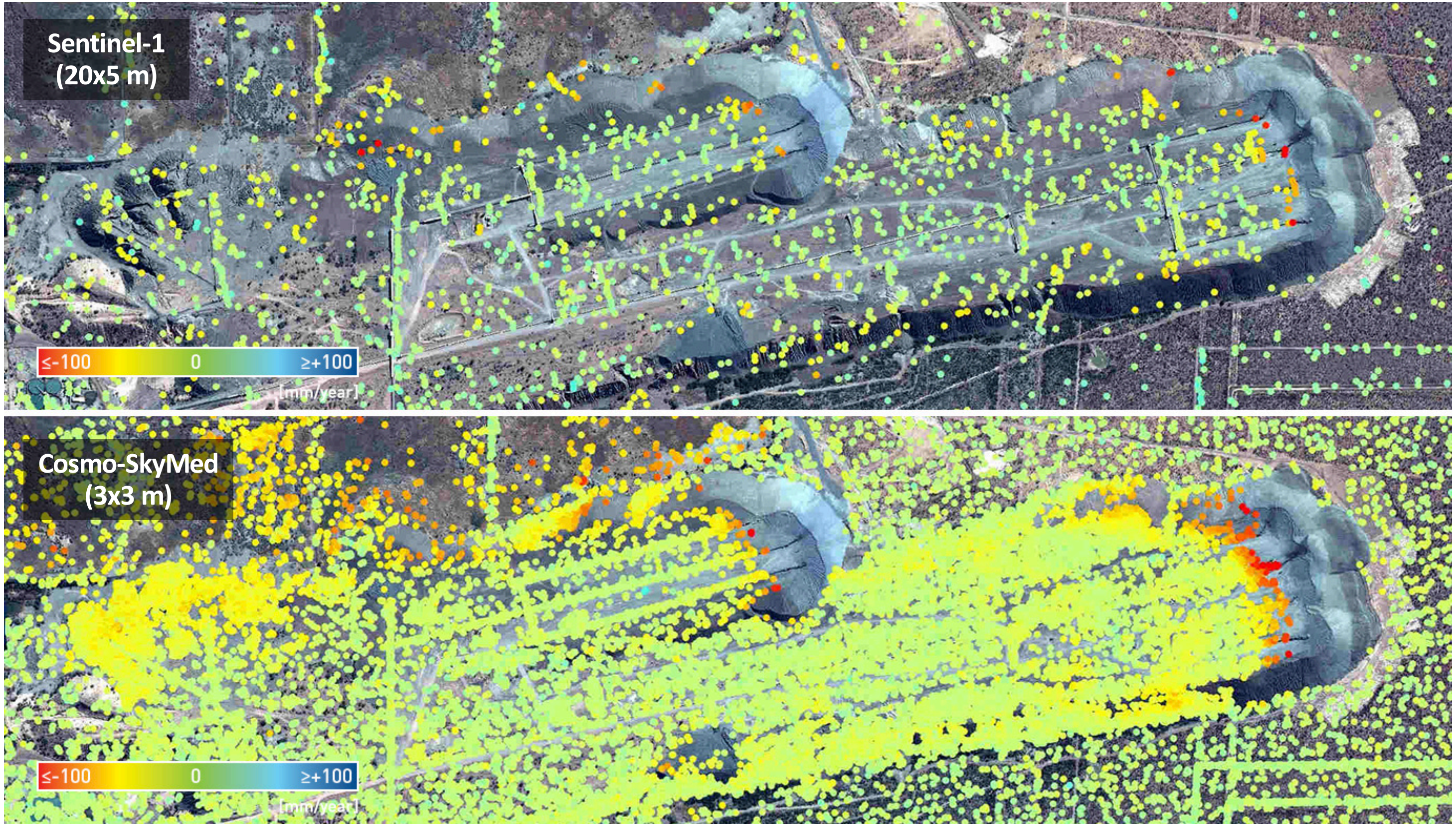
High resolution and Medium Resolution

Current State

- More than 15 satellite options with different frequencies, spatial resolutions, orbits and revisit times.
- New satellites are being set in orbit to replace older generations.
- Additional satellites are being added to existing constellations.
- New constellations are scheduled to take orbit in the near future.



Sentinel vs COSMO-SkyMed – Waste Piles



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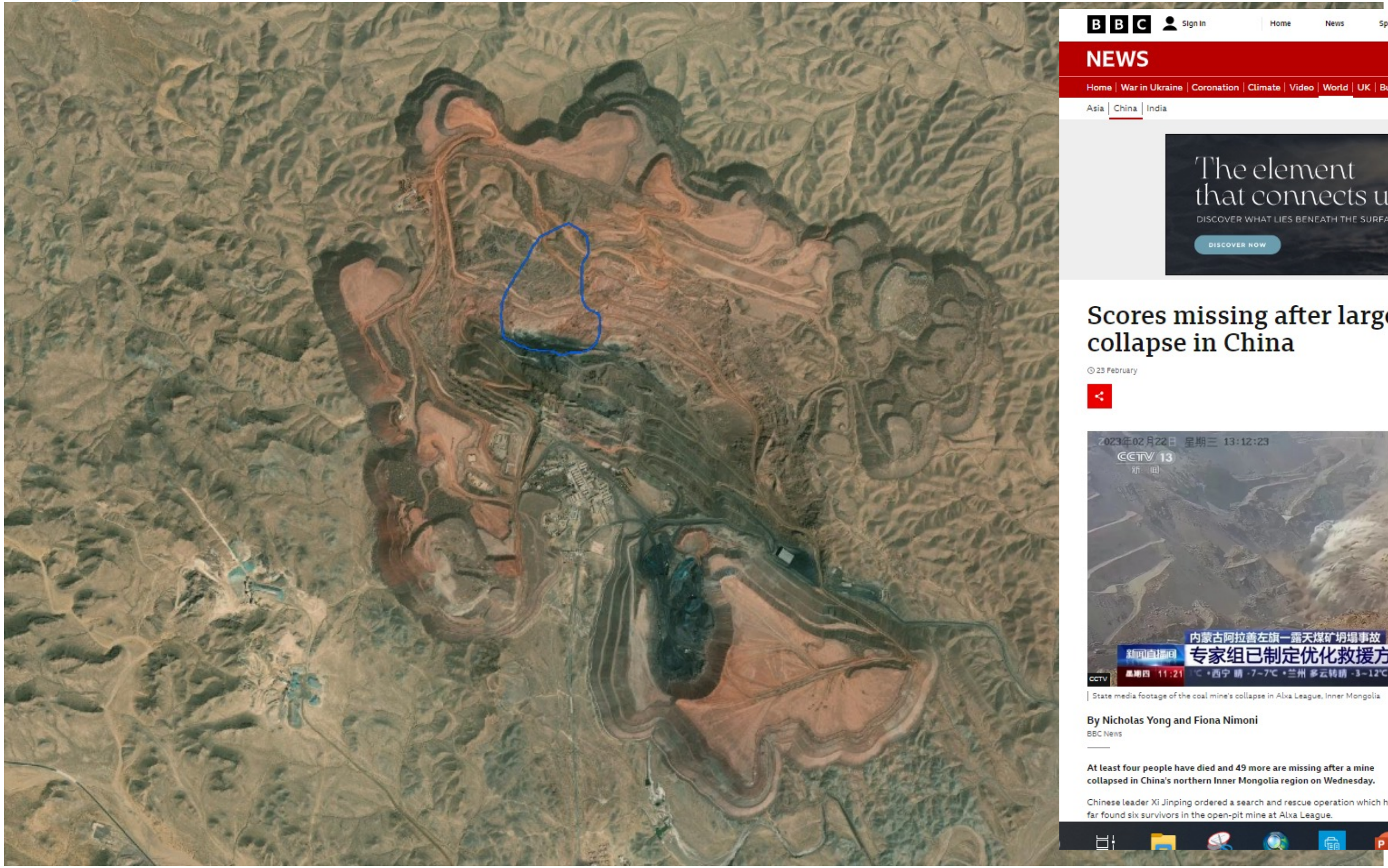
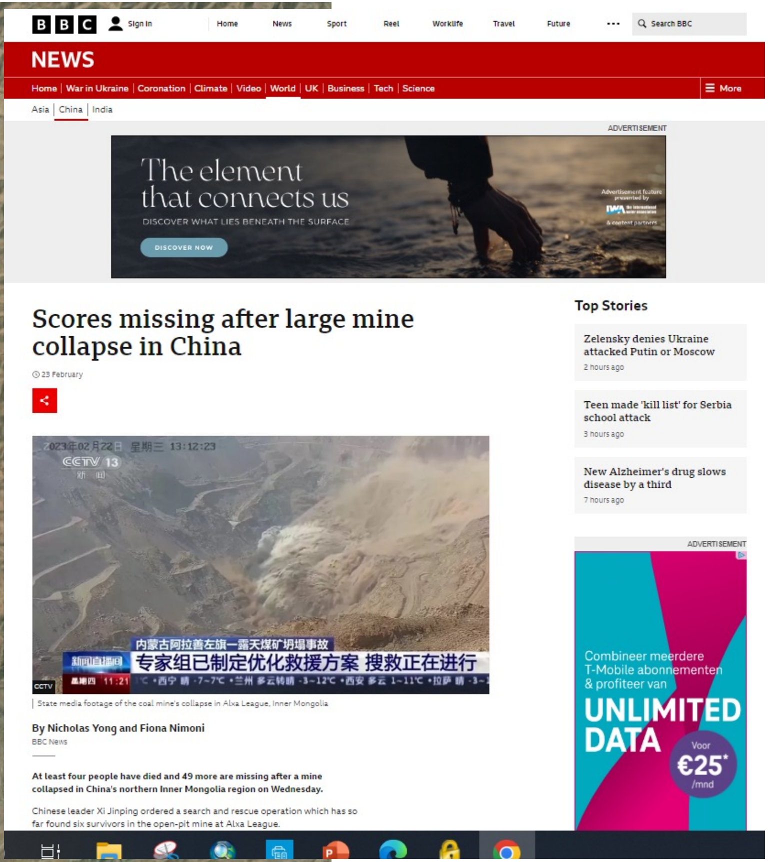
A RECENT CASE STUDY

Xinjing Mine Slope Failure

Collapsed area

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Scores missing after large mine collapse in China

23 February

State media footage of the coal mine's collapse in Alxa League, Inner Mongolia

By Nicholas Yong and Fiona Nimoni
BBC News

At least four people have died and 49 more are missing after a mine collapsed in China's northern Inner Mongolia region on Wednesday.

Chinese leader Xi Jinping ordered a search and rescue operation which has so far found six survivors in the open-pit mine at Alxa League.

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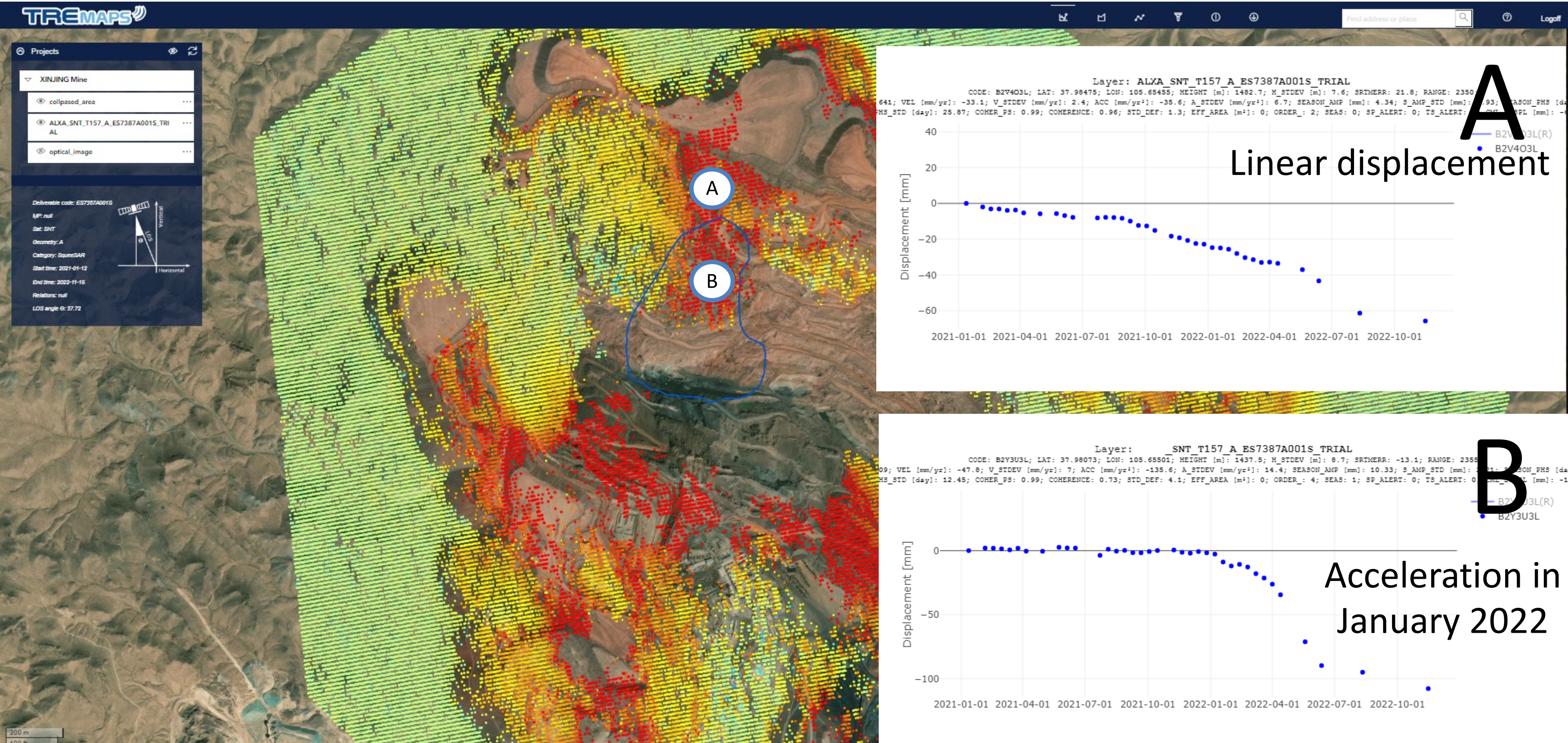
Sentinel-1 Results



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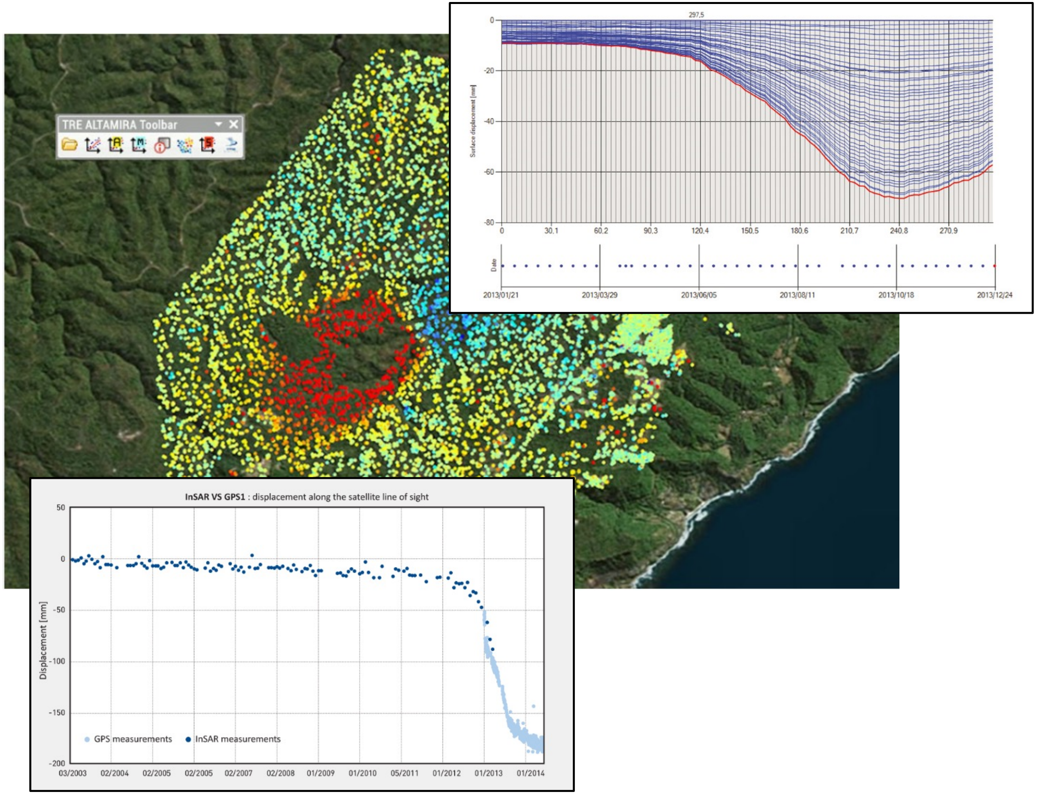
MONITORING WITH INSAR: A REAL PERSPECTIVE

How We Get There



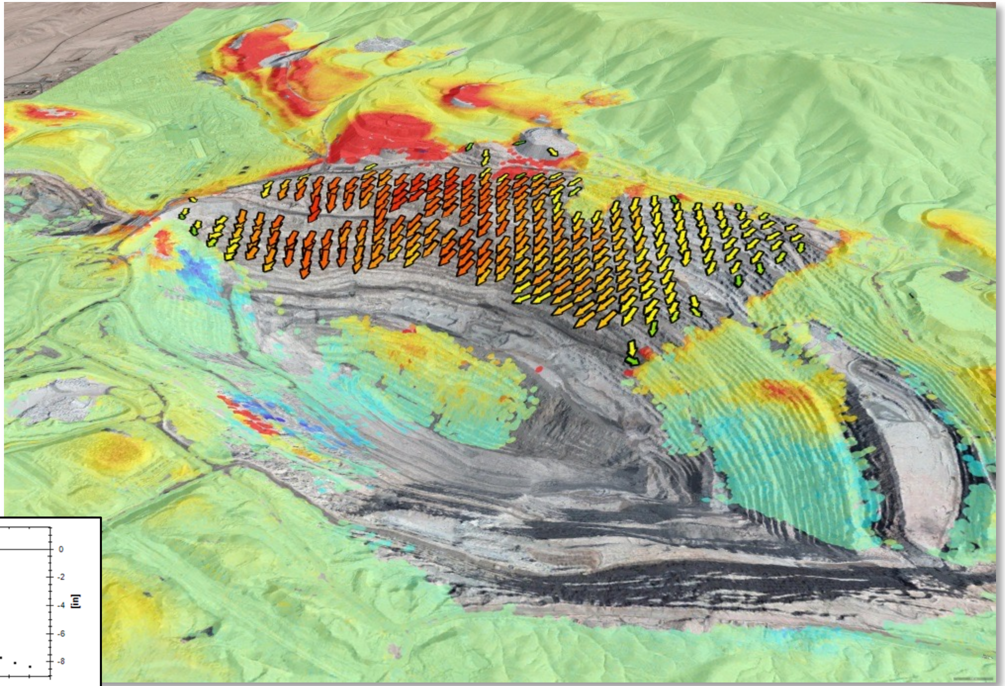
- Higher frequency of observations will make InSAR monitoring programs even more effective for rapid decision making.
- Continuous improvement of machine-learning algorithms such that users have the ability to take advantage of present and past data to predict future trends based on probabilistic geotechnical models.

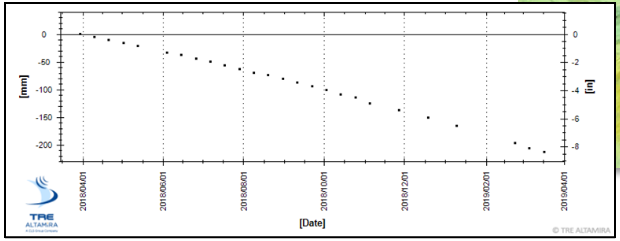
InSAR Monitoring Services

- Today's InSAR services and tools used in mining:
  - Identifying slope instabilities and associated risks
  - Mapping & measuring subsidence
  - Identification of active faults
  - Monitoring block caving induced subsidence
  - Monitoring TSF integrity
- Fully remote monitoring service using improved satellite constellations.
- Provides a site-wide bird's eye view of surface deformation over multiple assets.
- Complements other monitoring methods and easy to integrate in data integration platforms.

InSAR Monitoring Services on TREMAPS

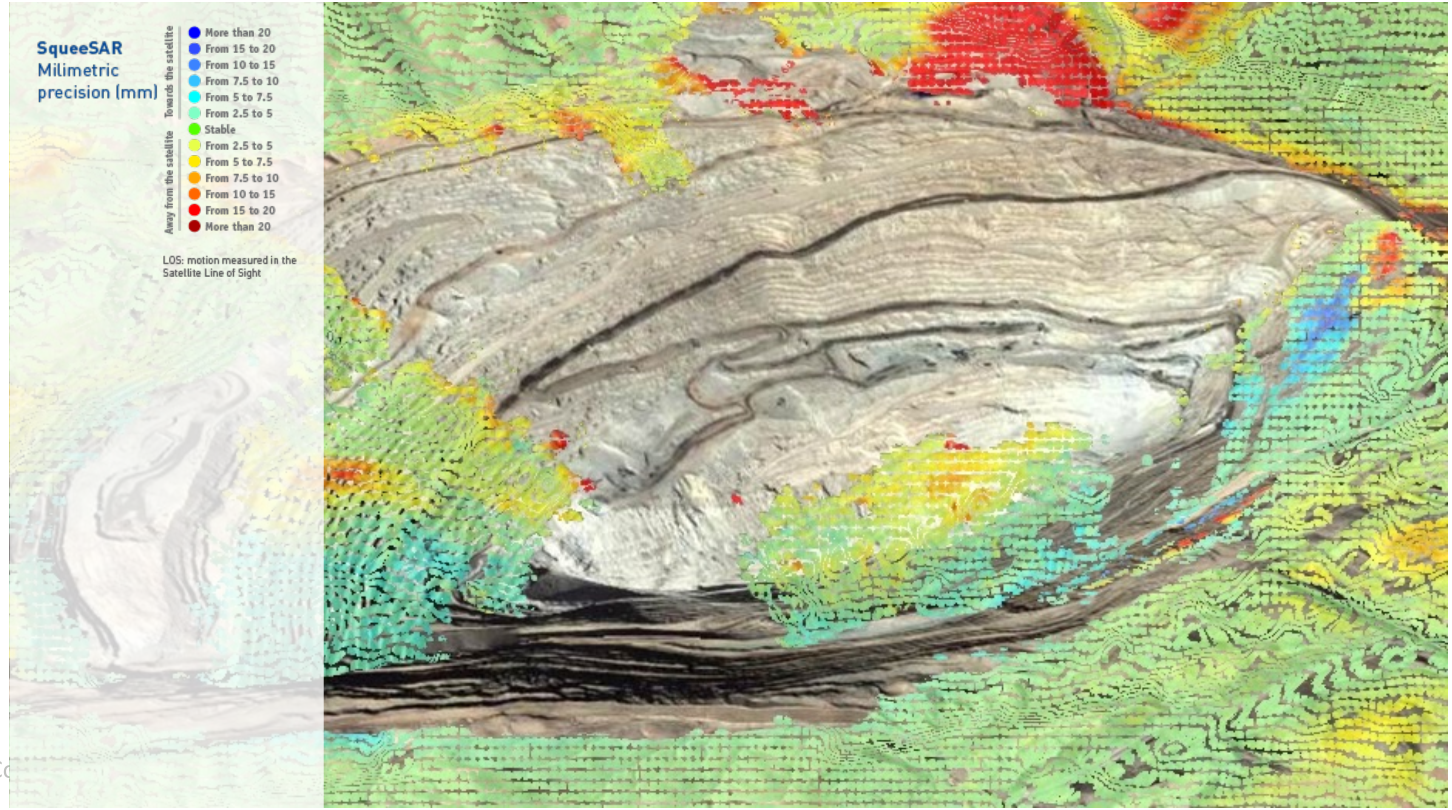
- Displacement updates with every new acquisition.
- Time-series of deformation describing the evolution of surface displacement in terms of velocity, acceleration or seasonality.
- Potential updates up to every 2 days (in the future) using a variety of constellations acquiring simultaneously.





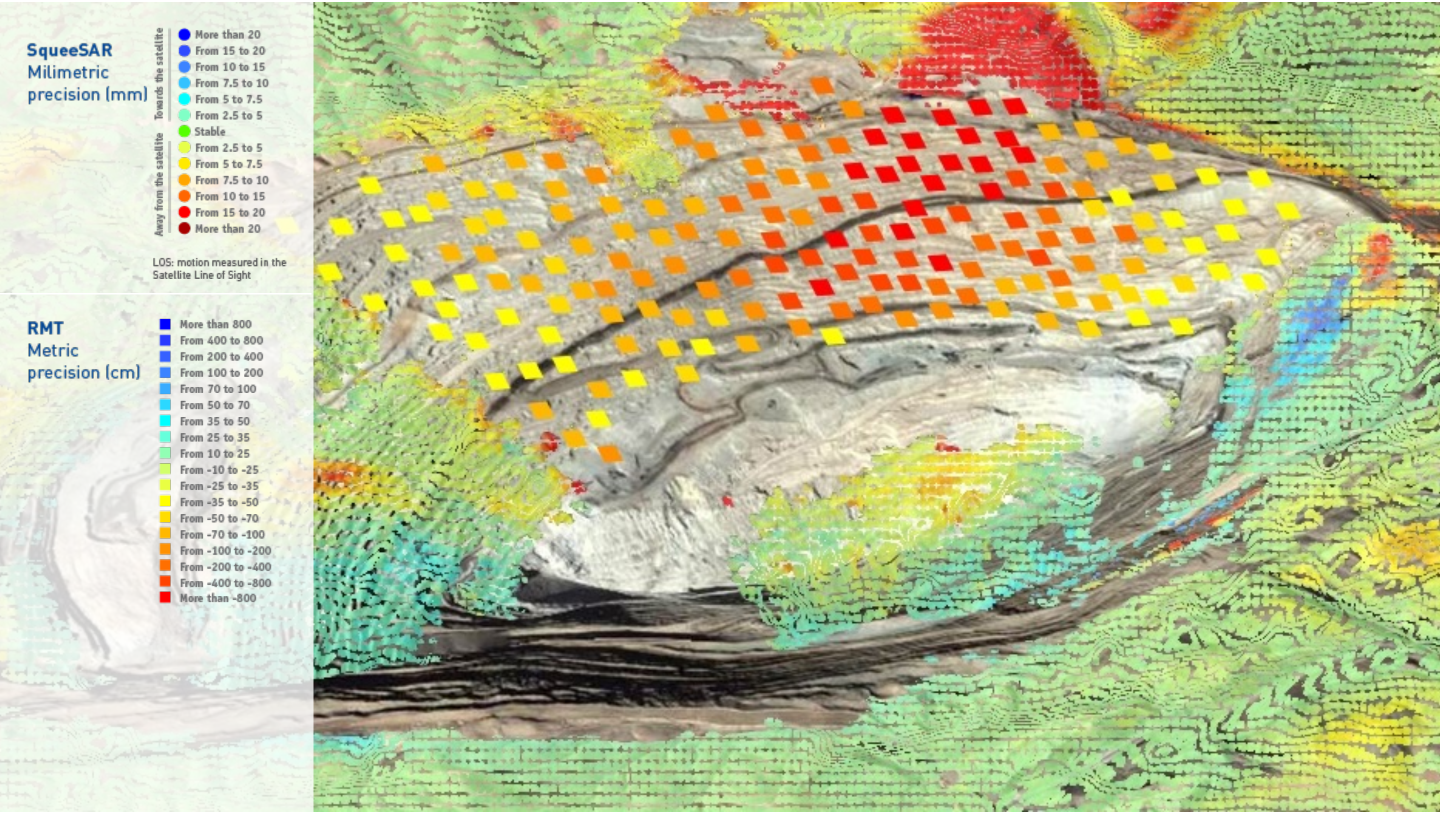
InSAR technology for mining activities

SqueeSAR [mm]



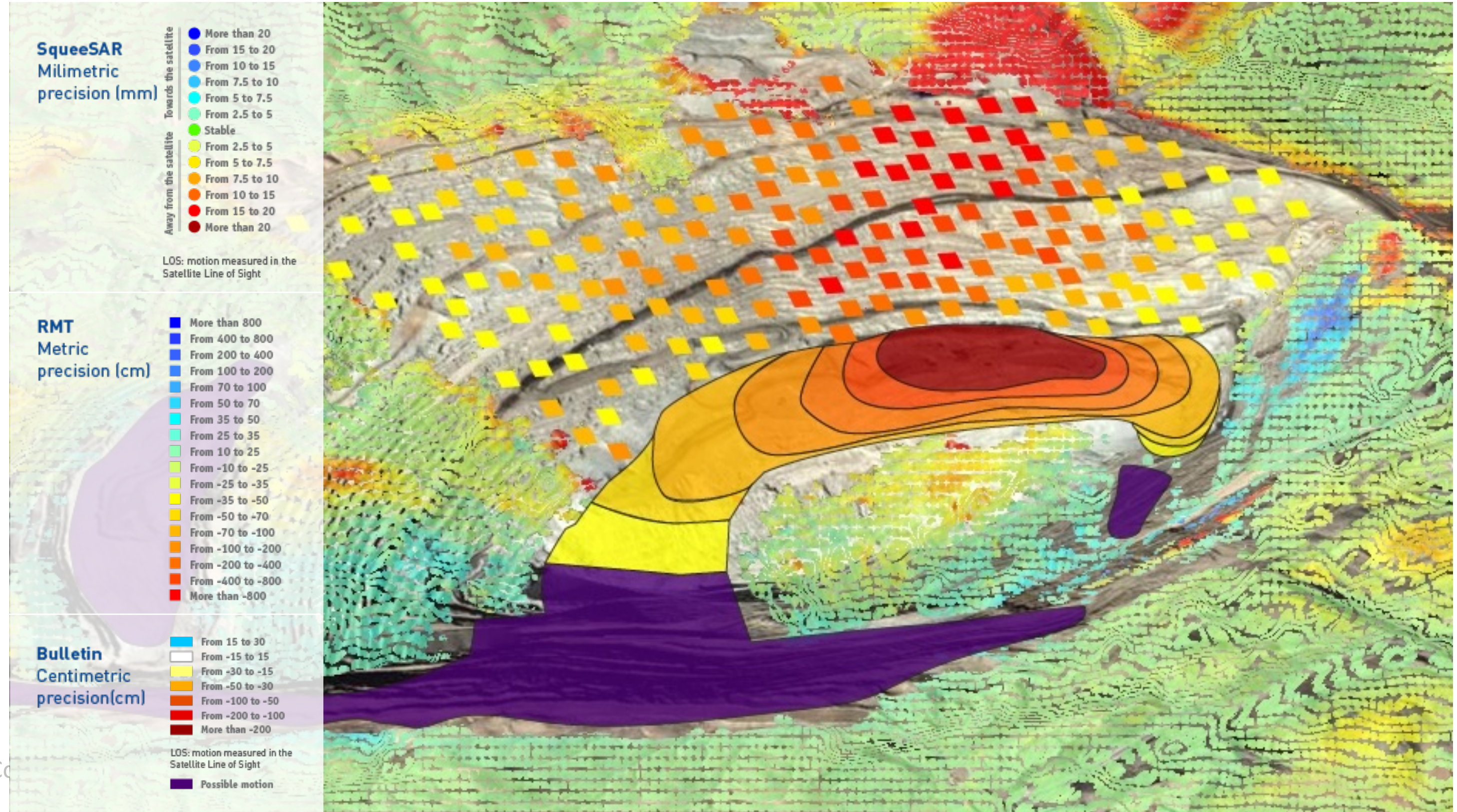
InSAR technology for mining activities

Rapid Motion Tracking [dm - m]



InSAR technology for mining activities

InSAR Bulletin [cm - dm]



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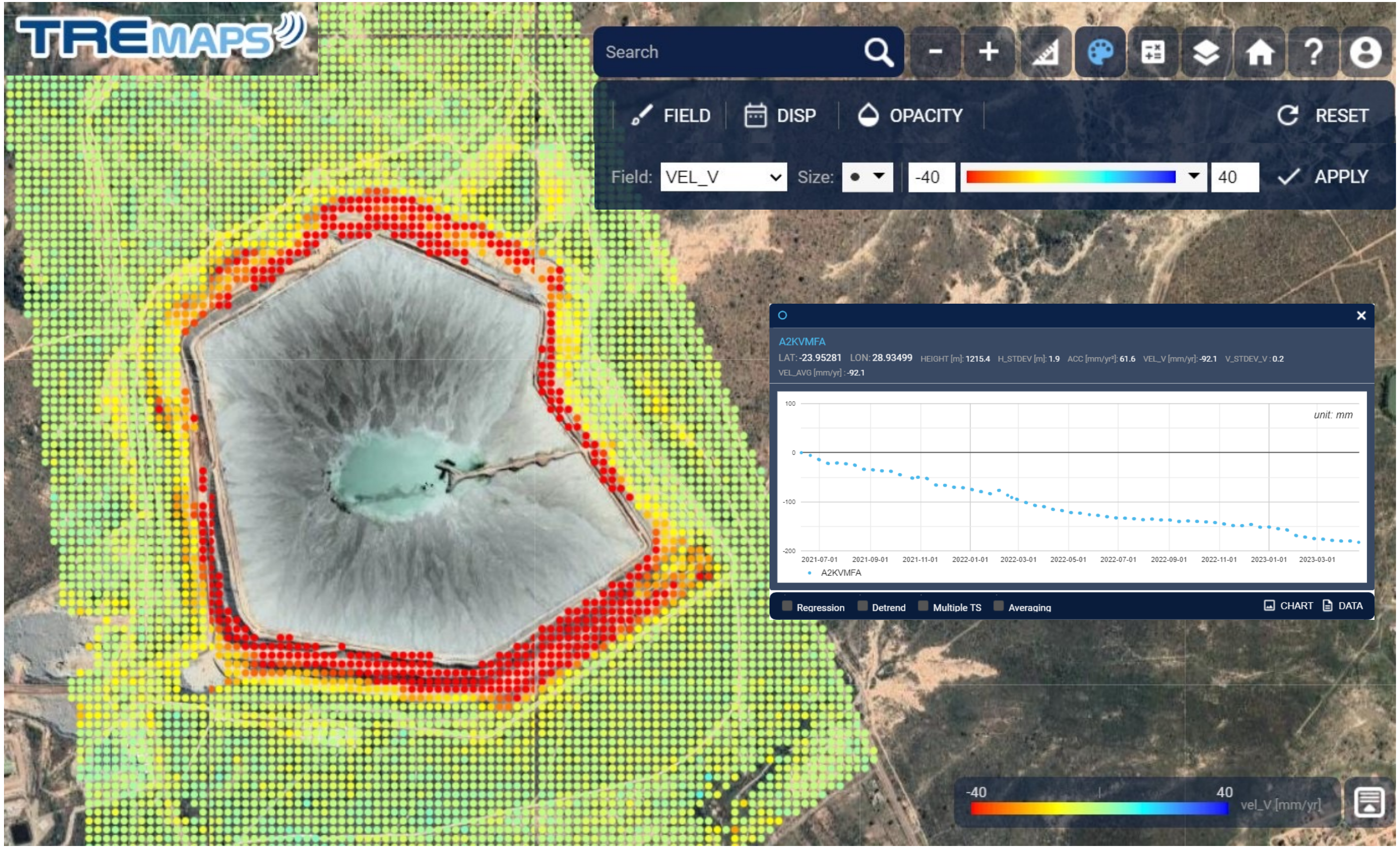
EXAMPLE OF CURRENT SERVICE

Continuous Monitoring over TREMAPS Portal

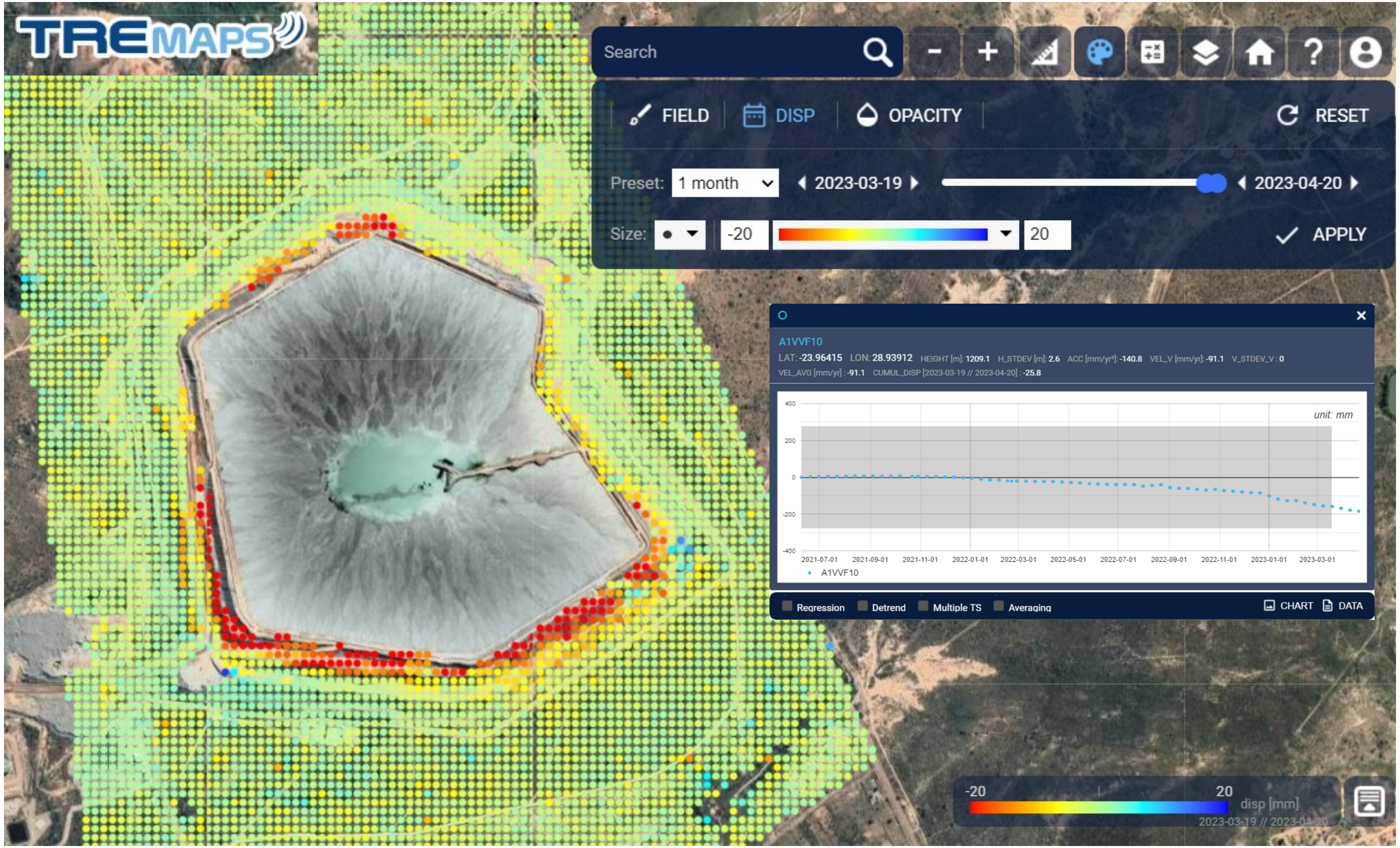
TREMAPS WEB PORTAL

- Web portal to distribute our data an provide some analysis tools to the clients
- Easy to access to several operators or working groups related to a single mine areas i.e. (mine managers, Geotech, surveyors)
- The data can be downloaded to use in GIS systems

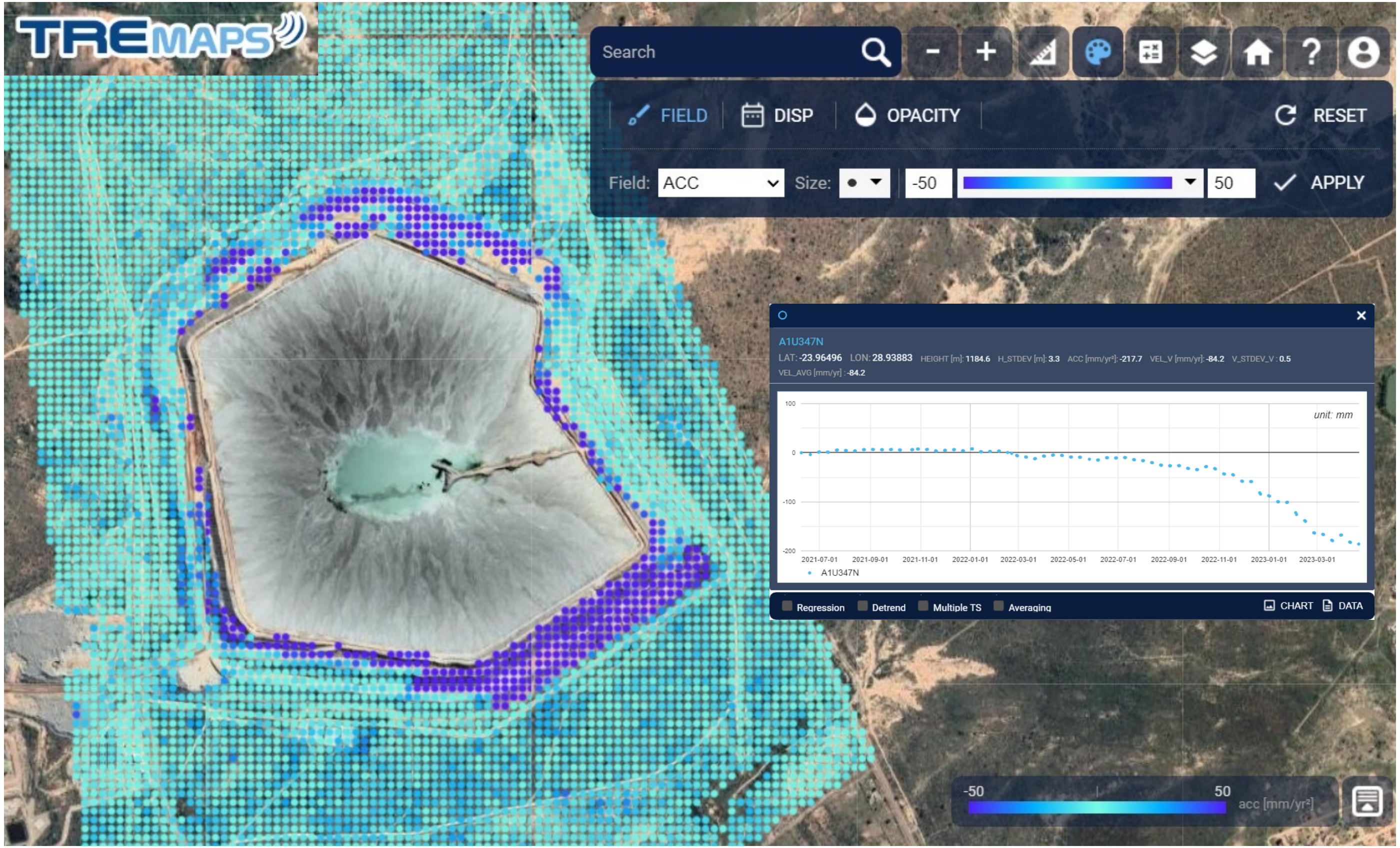
TREMAPS: toward a dynamic use of our data



Dynamic use of our data: TREMAPS

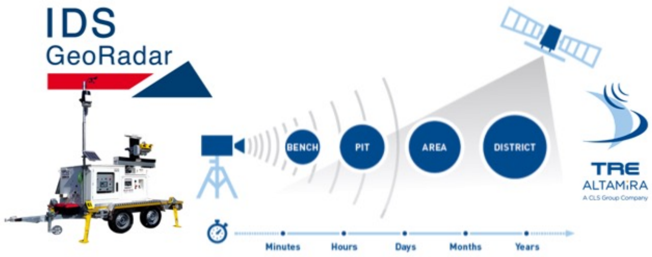


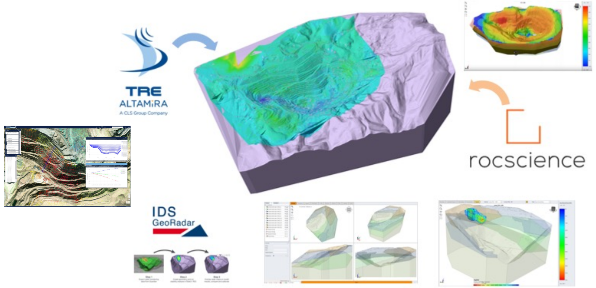
Dynamic use of our data: TREMAPS

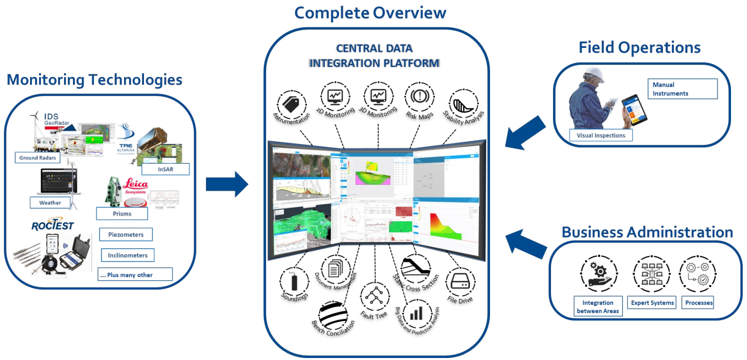


Sinergy with other techniques

- Collaborating with other monitoring service providers to ensure data products can be merged and integrated in other platforms.
- Working with clients to better understand their needs and requirement.
- Continuous development of new processes and tools to help users get the most out of our products.







Our goals

Effective monitoring programs:

- **Visualization**: Data screening tools.
- **Trend Detection**: Identification of relevant surface movement trends
- **Rapid Updates**: weekly (current) or even every day or few hours (in the future).

Client's goals

- Receive timely information
- Enable geotechnical and mine management to:
  - **Improve** strategic decision-making
  - **Optimize** operations
  - **Reduce** potential hazards

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Who We Are

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20 YEAR'S ★★★★★ EXPERIENCE

120,000 Satellite Radar **IMAGES PROCESSED**

~5,000,000 km^2 analysed everywhere in the world

1mm PRECISION on single displacement measurements

SAR satellites
PAST AND PRESENT
Ready for future platforms

600+ InSAR PROJECTS
in different market sectors

International **PATENTS**
on radar data processing
SqueeSAR® DespecKS®
Double-Geometry Corner Reflectors

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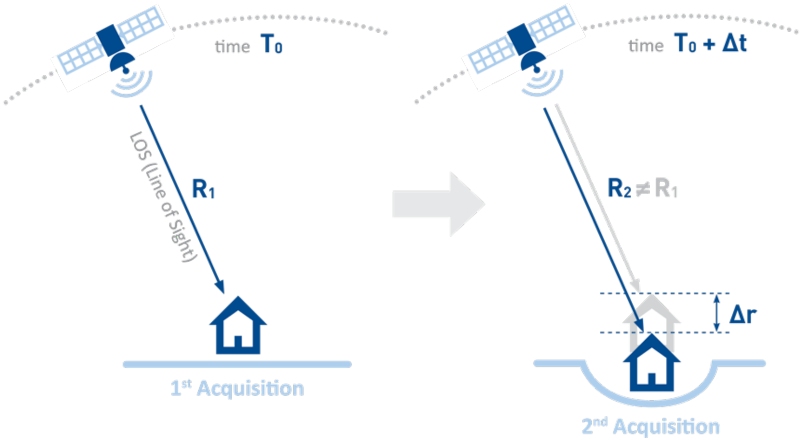
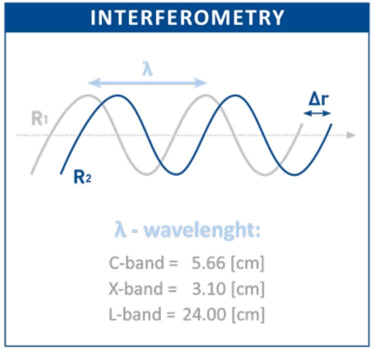
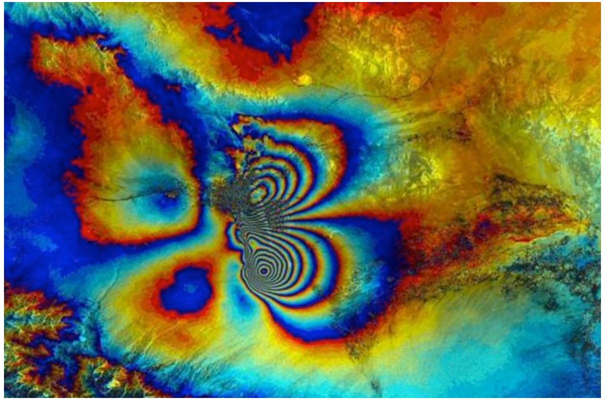
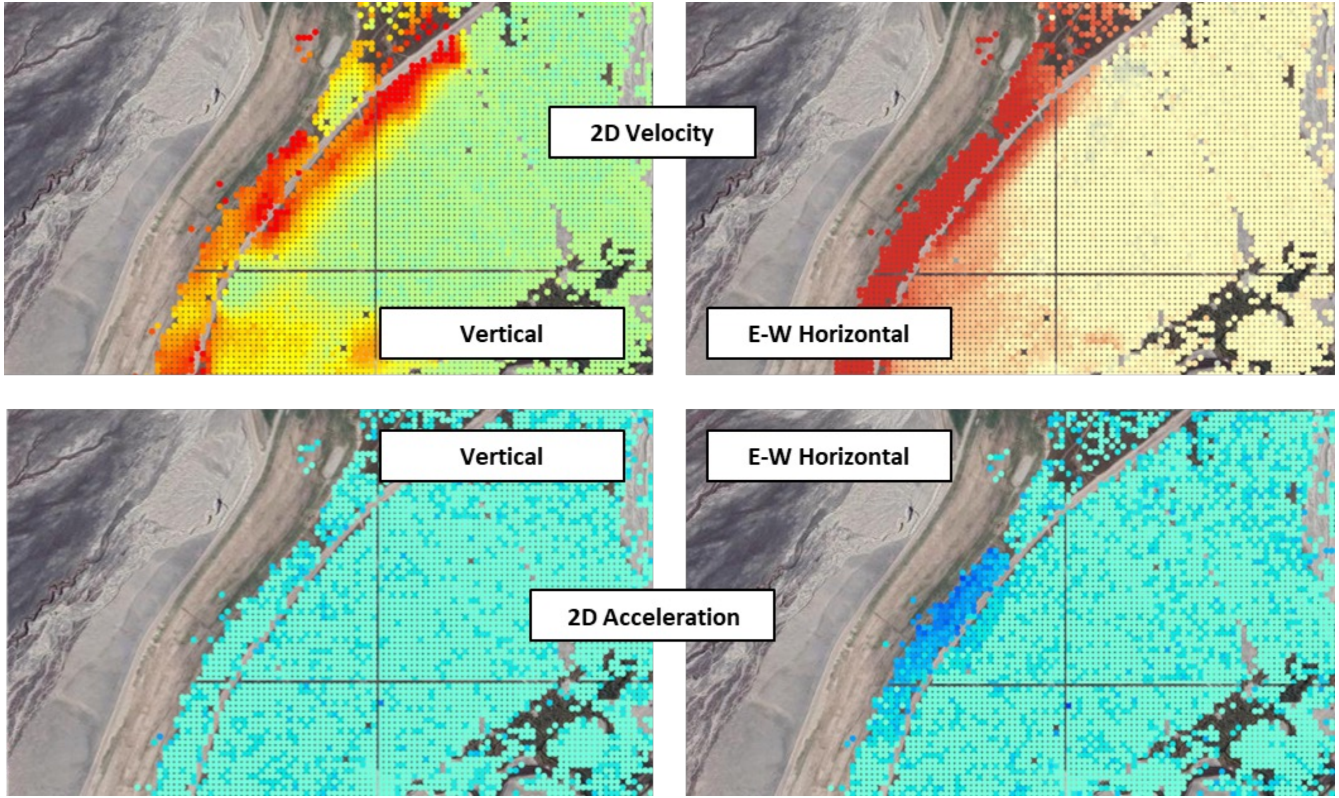
InSAR Technology Basics





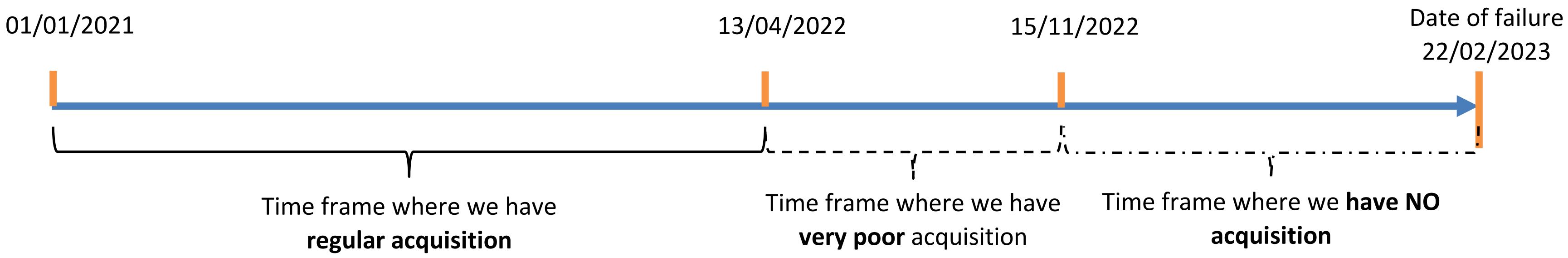


Derivative Maps

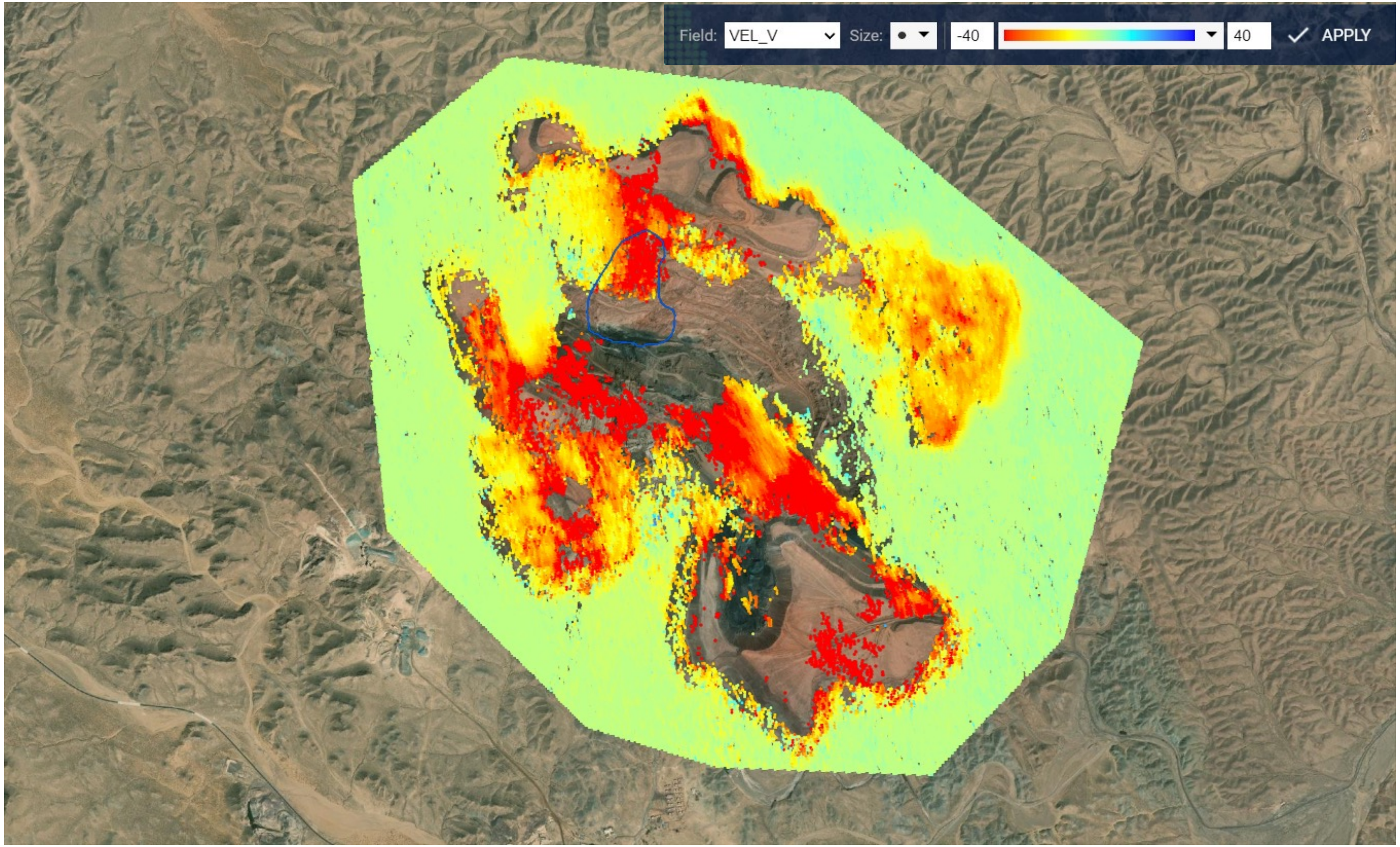


Satellite availability vs Date of Failure

- Date of failure: 22/02/2023
- Sentinel-1 – Track 157 Ascending was the **best option** among other Tracks covering the area
  - Unfortunately, Track 157 stop the acquisition 15/11/2022
  - Furthermore, between the 13/04/2022 and the 15/11/2022, Sentinel-1 acquired only 4 images (less than 1 image/month

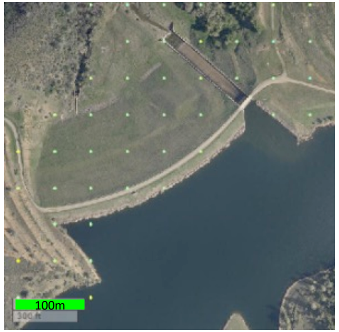
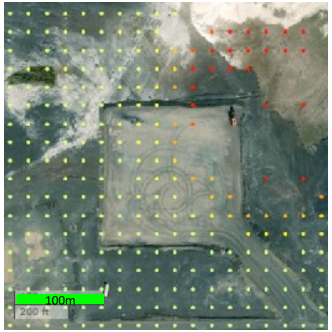
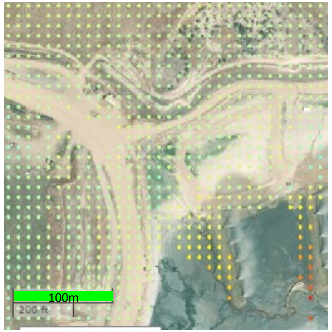
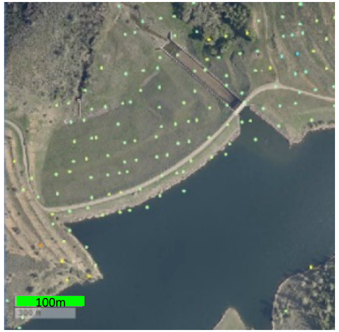
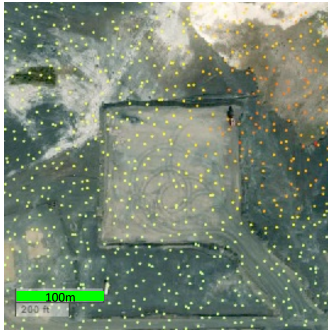
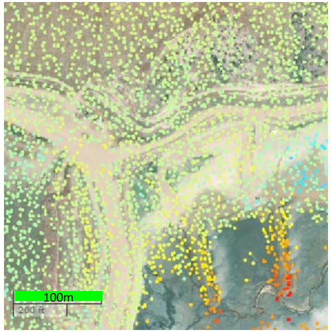


Sentinel-1 Results



Comparing Spatial Resolution

- A comparison of SNT and TSX at over mine assets at the same scale.
- Green scale bars are all 100m.
- SNT: Shows a general picture of the surface deformation.
- TSX offers more detailed characterization, and better contouring of the deformation affecting the structures.

	SNT	TSX Stripmap	TSX Spotlight
2D Results – Vertical			
1D Results – Line of sight			
	5 x 20 m	3 x 3 m	1 x 2 m

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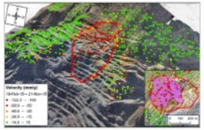
Perspectives on the prediction of catastrophic slope failures from satellite InSAR

Tommaso Carlà, Emanuele Intrieri ··· Nicola Casagli



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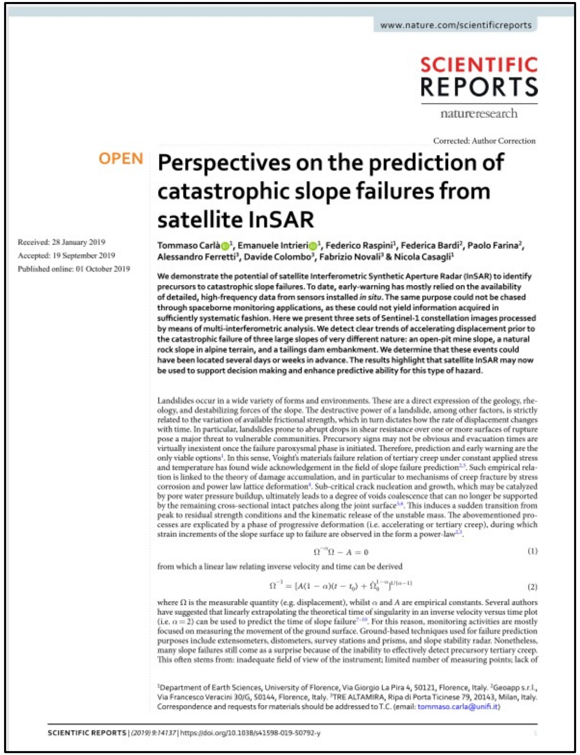

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Corrected: Author Correction

OPEN

Perspectives on the prediction of catastrophic slope failures from satellite InSAR

Received: 28 January 2019
Accepted: 19 September 2019
Published online: 01 October 2019

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We demonstrate the potential of satellite Interferometric Synthetic Aperture Radar (InSAR) to identify precursors to catastrophic slope failures. To date, early-warning has mostly relied on the availability of detailed, high-frequency data from sensors installed *in situ*. The same purpose could not be chased through spaceborne monitoring applications, as these could not yield information acquired in sufficiently systematic fashion. Here we present three sets of Sentinel-1 constellation images processed by means of multi-interferometric analysis. We detect clear trends of accelerating displacement prior to the catastrophic failure of three large slopes of very different nature: an open-pit mine slope, a natural rock slope in alpine terrain, and a tailings dam embankment. We determine that these events could have been located several days or weeks in advance. The results highlight that satellite InSAR may now be used to support decision making and enhance predictive ability for this type of hazard.

Landslides occur in a wide variety of forms and environments. These are a direct expression of the geology, rheology, and destabilizing forces of the slope. The destructive power of a landslide, among other factors, is strictly related to the variation of available frictional strength, which in turn dictates how the rate of displacement changes with time. In particular, landslides prone to abrupt drops in shear resistance over one or more surfaces of rupture pose a major threat to vulnerable communities. Precursory signs may not be obvious and evacuation times are virtually inexistent once the failure paroxysmal phase is initiated. Therefore, prediction and early warning are the only viable options[1]. In this sense, Voight's materials failure relation of tertiary creep under constant applied stress and temperature has found wide acknowledgement in the field of slope failure prediction[2,3]. Such empirical relation is linked to the theory of damage accumulation, and in particular to mechanisms of creep fracture by stress corrosion and power law lattice deformation[4]. Sub-critical crack nucleation and growth, which may be catalyzed by pore water pressure buildup, ultimately leads to a degree of voids coalescence that can no longer be supported by the remaining cross-sectional intact patches along the joint surface[5,6]. This induces a sudden transition from peak to residual strength conditions and the kinematic release of the unstable mass. The abovementioned processes are explicated by a phase of progressive deformation (i.e. accelerating or tertiary creep), during which strain increments of the slope surface up to failure are observed in the form a power-law[2,3].

$$\Omega^{-\alpha}\Omega - A = 0 \qquad (1)$$

from which a linear law relating inverse velocity and time can be derived

$$\Omega^{-1} = [A(1-\alpha)(t-t_0) + \Omega_0^{1-\alpha}]^{1/(\alpha-1)} \qquad (2)$$

where Ω is the measurable quantity (e.g. displacement), whilst α and A are empirical constants. Several authors have suggested that linearly extrapolating the theoretical time of singularity in an inverse velocity versus time plot (i.e. $\alpha = 2$) can be used to predict the time of slope failure[7–10]. For this reason, monitoring activities are mostly focused on measuring the movement of the ground surface. Ground-based techniques used for failure prediction purposes include extensometers, distometers, survey stations and prisms, and slope stability radar. Nonetheless, many slope failures still come as a surprise because of the inability to effectively detect precursory tertiary creep. This often stems from: inadequate field of view of the instrument; limited number of measuring points; lack of

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A Growing Demand

The number of SAR data sources is increasing steadily:

- Growing demand for earth observation (EO) data.
- Reduced cost in manufacturing, launches & operation.
- Increasing demand from the private sector.
- Applications evolution from Intelligence & Security to Institutional Projects to Commercial Applications.
- Complementary to optical image without susceptibility to cloud cover.
- Increasing interest from investors despite a high-risk factor still associated with the aerospace sector.

NASA illustration courtesy of Jenny Mottar

The Trend is Clear

The near future will see several new constellations of EO satellites operated by private companies.

Company		Country	Constellation (# Satellites)	Website
ICEYE		Finland	18 (4 already in orbit)	www.iceye.com
CAPELLA Space		USA	36	www.capellaspace.com
Umbra Lab		USA	12	www.umbralab.com
SYNSPECTIVE		Japan	25	www.synspective.com
Urthecast: OptiSAR		Canada	8	www.urthecast.com
XpressSAR		USA	8	www.xpresssar.com

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Small SAR Sensors

Data redundancy:

- Numerous smaller & less expensive sensors.
- Reduced risk in service interruption or failure.
- Satellite sensors easily added, replaced or upgraded.

High-resolution and short revisit cycles:

- High spatial resolution (<1 m).
- Very short revisiting time.
- Daily acquisitions as the new standard.
- Possibility to increase up to 3–4 images/day.

Image courtesy ICEYE