Transforming big monitoring data into reliable information about movements

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SUMMARY

The demand for deformation monitoring has grown significantly in recent decades, driven by the need to enhance safety and mitigate risks in monitored areas. Coupled with requirements to optimise production, reduce costs, preserve evidence, and validate designs, the importance of information about movements is higher than ever. Modern monitoring systems must be able to adapt to the evolving environment and dynamics of monitoring projects, leading to rapid developments in monitoring technology.

During 35 years in the automated monitoring market, Leica Geosystems' solutions have evolved from simple readouts of the first total stations to highly resilient systems that incorporate multiple monitoring technologies. Since each technology has strengths and limitations, their fusion enables comprehensive and reliable information. Monitoring projects today are unimaginable without the use of hybrid techniques, like geodetic and geotechnical monitoring. As the size of monitored areas increases, so too does the range of monitoring sensors needed to achieve comprehensive data acquisition. For example, landslides and open pit mines often require the broadest spectrum of monitoring technologies to provide extensive coverage of several square kilometres with high density. This includes remote sensing technologies, like ground-based or satellite radar interferometry, together with webcams, manual inspections, imagery and a whole palette of other data sources.

As data capture sources become more advanced and comprehensive, the challenge lies in processing big monitoring data to provide reliable information about movements. In this context, the role of monitoring software is crucial. Efficiently cross-analysing vast amounts of data and displaying the deformations in a single interface enables the transformation of raw data into actionable insights. Improving and automating this transformation process drives the Leica Geosystems monitoring solutions innovations, equally in hardware and software components. Critically, these innovations aid the engineers responsible for operating monitoring systems in their intricate responsibility to answer a fundamental question for decision-makers: what is the magnitude and direction of movements?

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1. INTRODUCTION

Since the beginning of the 1990s and the first applications of automated prism monitoring (Brown, Kaloustian, & Roeckle, 2007), the demand for deformation monitoring has experienced a significant surge and technological development driven by the need to enhance safety and mitigate risks in monitored areas. Coupled with requirements to optimise production, reduce costs, preserve evidence, and validate designs, the importance of information about movements is higher than ever. Modern monitoring systems must be able to adapt to the evolving environment and dynamics of monitoring projects, leading to rapid developments in monitoring technology.

As a manufacturer and provider of the complete monitoring portfolio, including hardware and software for geodetic solutions, Leica Geosystems' innovations over the past 35 years evolved from simple readouts of the first total stations to highly resilient systems that incorporate multiple monitoring technologies. Other monitoring technologies, like remote sensing or geotechnical and environmental deformation monitoring, have experienced a similar renaissance, starting from simple manual measurements and progressing to fully automated cloud-computing solutions.

The current monitoring possibilities are extensive and allow solutions to be tailored precisely to the monitoring project requirements. The architects of monitoring projects determine the configurations that will generate the required information about movements, considering the strengths and limitations of each technology. This paper will focus on the complementarities of different sensors and techniques as well as the role of monitoring software to compute and cross-analyse the measured data. Through a selection of the most common monitoring segments and applications, the impact of the monitoring project environment on the choice and configuration of monitoring equipment will be clearly presented.

2. MONITORING TECHNOLOGIES

Monitoring solutions are uniquely tailored to the project environment, data type, measurement frequency and accuracy requirements, factoring in local hazards, geological constellations, budget constraints and risk factors. Deformation monitoring technologies have different advantages and limitations that must be evaluated when designing the optimal configuration to meet project requirements. Therefore, there are no good or bad, or right or wrong monitoring technologies, only those better suited to project requirements.

For example, in the case of geodetic monitoring, prism and GNSS measurements provide a complete 3D understanding of movements but are limited to a small number of single points. Geotechnical sensors, such as inclinometers or extensometers, also represent one point per sensor, but in a relative, non-georeferenced environment. However, due to cost-effectiveness, their installation magnitude per project is usually much higher and can cover the surface and underground areas. Laser scanning applications can collect thousands of points per second, but require extensive data processing times, while advanced remote sensing techniques like ground-based and satellite radar interferometry can only detect a single component of the slope's movement vector but provide the fastest 360° or areal measurements. Therefore, the fusion of these technologies enables comprehensive and reliable information about movements.

Monitoring projects today, especially ones utilising automated monitoring techniques, are unimaginable without the use of hybrid techniques, like geodetic and geotechnical monitoring (Špiranec, 2023) or remote sensing (Carlà, et al., 2019). As the size of monitored areas increases, so too does the range of monitoring sensors needed to achieve comprehensive data acquisition. This article focuses on big monitoring data and therefore only covers monitoring technologies whose data acquisition can be automated, i.e., geodetic monitoring, remote sensing and geotechnical and environmental monitoring, intentionally omitting conventional methods such as visual inspections, precise levelling and any other manual monitoring techniques.

2.1 Geodetic monitoring

Geodetic deformation monitoring technologies deliver measurements of geo-referenced displacements or movements in one, two, or three dimensions. This includes prism monitoring and laser scanning by total stations, GNSS technology, or precise levelling, which is rarely used in automated techniques. As a surface monitoring technology, geodetic monitoring measures the same object repeatedly and analyses the displacements.

2.1.1 Total Stations and Scanning Total Stations

The primary instruments used for automated geodetic deformation monitoring are total stations (**Figure 1**). From their design, robotic total stations and 3D laser scanning total stations, like the Leica Nova MS60 MultiStation, are the most complex. Both types of instruments require measurements to reference (control) prisms in stable areas for their orientation and positioning (defining the reference frame of the geodetic network). Measuring to control prisms also ensures that instrument movements do not influence measurements since they are often located in movement zones.

Monitored objects or structures are measured either by installing prisms (reflectors) or using laser scanning technology (Wöllner, 2017) or reflectorless measurements. However, advanced laser scanning is becoming the predominant contactless method because it delivers reliable information from hundreds or thousands of measured points compared to one reflectorless measurement. Integrated into customised monitoring configurations, these technologies can capture high-accuracy, automated measurements. For example, Leica Geosystems systems can achieve millimetre-level accuracy over 150-metre distances with both prism measurements and laser scanning with the Leica MultiStations. It is crucial to combine the equipment designed specifically for monitoring applications, including the instruments, such as the Leica Nova TM60 or MS60, the original Leica accessories, like reflectors, and Leica GeoMoS monitoring software for the results of the highest accuracy.

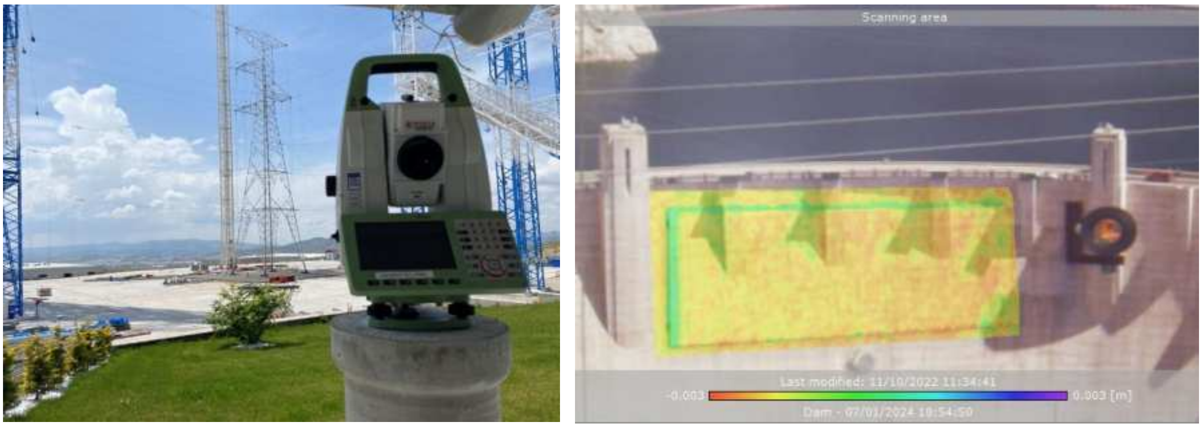

Figure 1 Monitoring total station and 3D laser scanning in monitoring

Laser scanning and prism measurements have clear advantages as they deliver 3D information about movements (displacements in northing, easting and height). Recent developments in the intelligence and autonomy of the monitoring system also overcome many environmental conditions that previously threatened data acquisition and communication with these methods. As described in (Špiranec & Niel, 2021), changing environmental parameters such as brief line of sight interruptions, variable visibility conditions due to weather, and temporary communication and power outages do not affect the data completeness of the Leica Geosystems' monitoring solutions. However, any permanent hindrance or inclement (foggy) weather still impacts data completeness due to the measurement technology physics. Additionally, compared to remote sensing technologies, prism measurements and laser scanning are significantly slower and cover only single points or specific small areas (scan patches).

Prism measurements, as the first automated deformation monitoring technique, have the biggest application in all segments, including buildings and structures, transportation infrastructure, environmental monitoring, energy infrastructure, and mining. 3D laser scanning in automated monitoring is primarily used to monitor objects where prism installation isn't allowed, such as roads and highways, light rail systems, and heritage buildings. Scanning is quickly configured and requires no additional accessory installations and is therefore often used in combination with prism measurements to capture more comprehensive data.

2.1.2 GNSS

Global Navigation Satellite System (GNSS) technology in monitoring is mainly used to provide a stable reference frame and monitor movements within the affected area. When larger areas are impacted by movements, all georeferenced monitoring sensors are under the same influence, causing the positioning error to constantly affect all measurements. GNSS is the only technology that can annul this effect by calculating longer baselines from the base GNSS station in the stable area. When combined with total station measurements, the application of GNSS collocated with prisms or total stations with continuously updated positioning will eliminate all reference frame movements and ensure that the deformation within the monitored area is calculated with maximum accuracy and reliability (**Figure 2**).

GNSS-based monitoring systems can measure at high rates up to 50 Hz with low latency, operate in all weather conditions, have synchronised measurements, do not require line of sight to ground marks/targets, can measure over long baselines, and have low maintenance needs and a long service life (Brown, Kaloustian, & Roeckle, 2007). However, they require an open sky with a 10°–15° cut-off elevation angle. This means that in urban areas GNSS must be mounted on top of the buildings to avoid the multipath effect from skyscrapers and other structures, which deteriorates the measurement accuracy. Additionally, GNSS monitoring is vulnerable to signal interference, spoofing, and jamming as well as to high ionospheric and tropospheric activities (partially mitigated with modelling), which cause delays that can introduce errors in GNSS measurements. The majority of GNSS manufacturers have developed algorithms and tools for the mitigation of signal interference and ionospheric effects.

Figure 2 Collocated 360-degree prism with GNSS antenna

GNSS technology in monitoring is, like total stations, used in all segments, especially as the provider of a stable reference frame for the entire monitored area. Considering the monitoring environment and the limitations of the technology, these are the most common applications for GNSS monitoring of movements per segment:

- Buildings and structures: construction of high-rise buildings (verticality monitoring)
- Transportation infrastructure: high-speed bridge monitoring, airport construction
- Environmental monitoring: landslides, subsidence, faults, volcanos, earthquakes
- Energy infrastructure: dams, offshore platforms
- Mining: tailings dams and waste dams

2.2 Remote sensing

Remote sensing deformation monitoring includes diverse technologies and sensors which provide displacement information based on contactless measurements of the object. Remote sensing sensors operate from ground, air, or space-based platforms and use electromagnetic waves emitted, reflected, or diffracted by the sensed objects. Hence these technologies also provide only surface monitoring.

The remote sensing technologies most commonly used for deformation monitoring include ground-based (GB-InSAR) and satellite interferometry (Satellite InSAR), close-range photogrammetry (Jun, Ensheng, & Jiayu, 2021), and LiDAR (Rui, Zhixiang, Xi, Wei, & Junhao, 2022). As the first two have the broadest application, the subchapters below explain them in more detail.

2.2.1 Ground-based radar interferometry

Ground-based radar interferometry has been rapidly developing in the past decades primarily to monitor ground deformation over large areas. The two main types of ground-based interferometric radars used in slope monitoring (Pieraccini, 2013) are Real Aperture Radars (RAR) and Synthetic Aperture Radars (SAR). Both technologies measure small displacements of targets by transmitting microwave signals and measuring the phase difference ($\Delta\varphi$) of the target's backscattered signal in between two consecutive acquisitions. The main difference is in the way they resolve the monitored scenario (**Figure 3**): RAR moves a high directive antenna, typically a parabolic dish, to scan the monitored scenario and resolve the surface in a resolution cell (radar measurement point) given by the antenna's narrow beam footprint, whereas a small low-gain SAR antenna moves along a linear or circular trajectory to "simulate" a larger real aperture antenna and obtain the radar image.

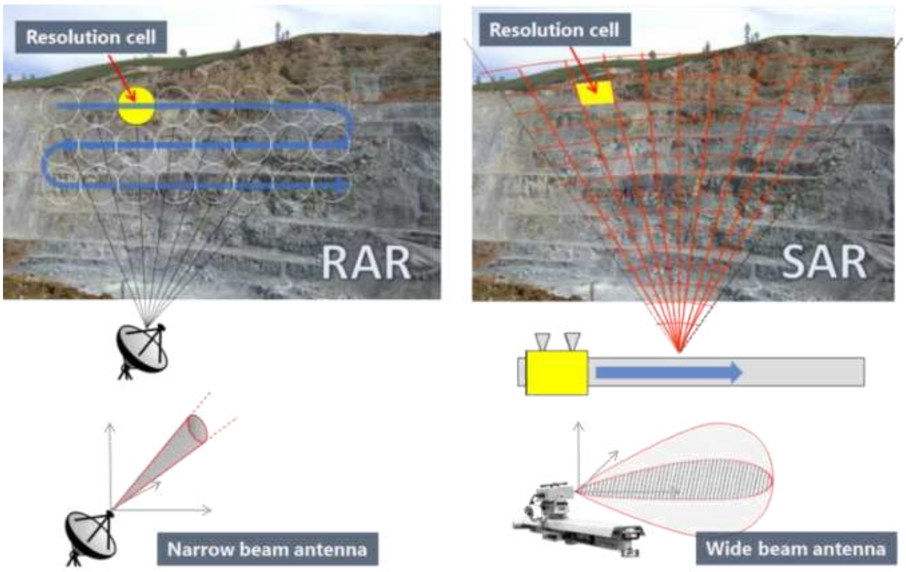

Figure 3 Working principles of RAR and SAR **(Špiranec, Coppi, & Coli, 2021)**

Both radar technologies measure the line of sight displacement d_{LoS} of each radar pixel (resolution cell), corresponding to the projection of the real displacement direction d along the radar's line of sight (**Figure 4**). Every scan of an interferometric radar provides a new deformation measurement for all the radar pixels with sub-millimetric accuracy by exploiting the interferometric technique precision with a distance range from a few metres to several kilometres.

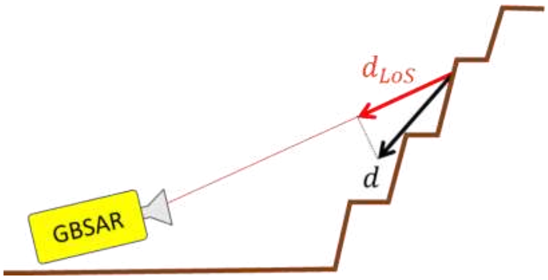

Figure 4 Line of sight displacement and GB-InSAR in a mine

While real aperture radar has its own advantages, such as broader coverage and larger-scale mapping capabilities, GB-InSAR's cost-effectiveness, flexibility, high temporal resolution, and localized monitoring capabilities make it a popular choice for many applications. By comparing the phase differences between multiple radar images acquired over time, GB-InSAR can detect and measure subtle ground movements, such as slope stability, subsidence, landslides, and glacier dynamics. It is commonly used in geotechnical engineering, environmental monitoring, and natural hazard assessment, but also in civil structure monitoring, like monitoring of bridges (Miccinesi, Beni, & Pieraccini, 2021), dams, towers, or buildings due to its fast deployment.

The key advantage of radar systems is their capability to cover large areas continuously, achieving sub-millimetre accuracy in a short scan time. Additionally, radars have the unique ability to penetrate dust and fog, which is not possible with optical devices. However, they provide only 1D movement information in the radar's line of sight and are significantly more expensive than most other monitoring sensors, which limits their utilisation.

2.2.1 Satellite interferometry

Satellite interferometry, also known as InSAR (Interferometric Synthetic Aperture Radar), involves the use of satellite-borne radar instruments to measure ground movements with high precision. A series of radar images of the target area are captured over time from multiple satellite passes and contain information about the phase of the radar waves reflected from the ground. By comparing the phase differences between the radar images, the phase shift of back-scattered electromagnetic waves between coherent acquisitions is established (**Figure 5**). The recorded scene is arranged into pixels in a two-dimensional image (Colesanti & Wasowski, 2006) with various factors contributing to the phase values, such as decorrelation, stereoscopic effects, and atmospheric artefacts. The technique isolates the phase term associated with variations of the sensor-to-ground path length, indicating pixel movement.

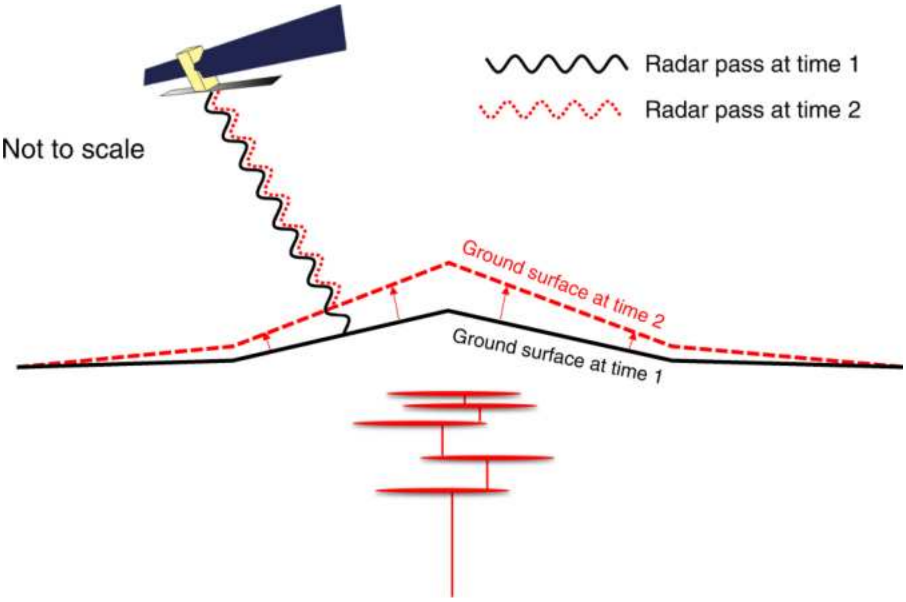

Figure 5 The working principle of InSAR technology (Biggs & Wright, 2020)

The resulting deformation measurements can be used for a variety of purposes, such as monitoring land subsidence, detecting tectonic movements along fault lines, assessing slope stability in landslide-prone regions or open-pit mines, and monitoring glacier dynamics.

Satellite interferometry offers several advantages for deformation monitoring. It provides wide-area coverage, allowing for the monitoring of large regions, as well as measurements over inaccessible or hazardous terrain, where ground-based techniques may be impractical. Generally, satellite InSAR can provide deformation measurements with accuracies ranging from a few centimetres to several millimetres, depending on the specific application, satellite system, and data processing techniques used. Other factors influencing accuracy include baseline length, vegetation cover, and the presence of temporal and geometric decorrelation.

2.3 Geotechnical and environmental monitoring

Geotechnical and environmental monitoring encompasses a wide array of sensors used to measure displacements, environmental conditions, ground and soil parameters, and other relevant factors. These include extensometers, piezometers, tilt meters, accelerometers, strain gauges, load cells, borehole inclinometers, weather stations, seismic and vibration monitoring sensors, and various other devices (**Figure 6**). The purpose of such monitoring is to gather data on movements, environmental effects and ground conditions for applications in geotechnical and environmental engineering, ensuring the safety and stability of structures and the surrounding environment.

Over the past few years, advancements in technology have revolutionised geotechnical and environmental monitoring sensors, transforming them from manual devices into autonomous IoT monitoring systems with edge computing and cloud technology.

Figure 6 Examples of geotechnical sensors: 3D crack meter, In-place inclinometer and Hydrostatic levelling equipment

Sensors used in geotechnical and environmental monitoring are more cost-effective compared to geodetic and remote sensing devices, leading to their widespread use across all monitoring applications and segments. However, as these sensors primarily measure relative, non-georeferenced movements, it is often necessary to combine them with geodetic monitoring for a complete understanding of the nature of these movements.

2.4 Sensor and technology fusion

To ensure a thorough understanding of deformations and movements, the selection of monitoring technology and sensors is vital in any monitoring project. As each technology has its own strengths and limitations, their fusion enables comprehensive and reliable information. This fusion can take place either within a single sensor where multiple measurement technologies are integrated or through the use of multiple different and independent monitoring systems that complement each other. Examples of multi-technology sensors are:

- Leica MultiStations which combine optical measurements with laser scanning

- GNSS sensors with inertial or tilt sensors which measure the roll and pitch of the position tracking GNSS antennas (pillar stability)
- Omni tilt and distance sensors which measure tilt in 3 dimensions and the distance to a specific object

Monitoring projects today are unimaginable without the use of hybrid techniques, like geodetic and geotechnical monitoring or remote sensing (**Figure 7**), where each of the monitoring systems runs independently from the other, as in examples described in (Carlà, et al., 2019), (Scaioni, Marsella, Crosetto, Tornatore, & Wang, 2018) or (Selvakumaran, Rossi, & Marinoni, 2020). This allows for data redundancy and diversity, which means that monitoring information will be available in cases when one of the technologies fails or produces erroneous data, when it cannot fully represent the deformation, or when an independent check of monitoring alerts is required.

Figure 7 Examples of hybrid monitoring techniques

As the size of monitored areas increases, so too does the range of monitoring sensors needed to achieve comprehensive data acquisition. For example:

- Landslides and open pit mines often require the broadest spectrum of monitoring technologies to provide extensive coverage of several square kilometres with high density.
- Line objects like rails or tunnels combine 3D information provided by geodetic monitoring with relative movement information coming from geotechnical sensors.
- Construction sites require information about water level and ground movements, as well as movements of surrounding buildings and structures.

Monitoring data diversity brings obvious benefits. However, it is also time intensive to cross-analyse the data from multiple monitoring systems and time is a crucial factor for decision-making in case of movements.

3. DATA INTEGRATION

As data capture sources become more advanced and comprehensive, the challenge lies in processing big monitoring data to provide reliable information about movements. The average amount of monitoring data per project rapidly grows every year, and so do the expectations of monitoring software. Monitoring software should aggregate the data from one or multiple monitoring systems, process it, check against defined thresholds and trigger alerts or notifications in case of values exceeding them, provide map-based, tabular and chart data analysis, and enable scheduled report generation for monitoring project stakeholders.

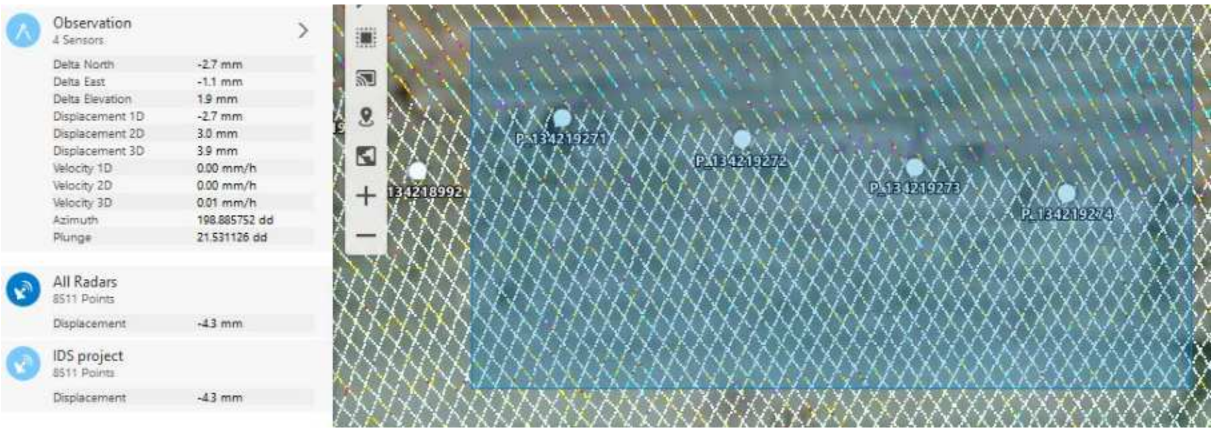

Figure 8 Cross-analysis of prism and radar monitoring data

Depending on the data type and the speed of its acquisition, some of the measurement technologies rely on edge computing to prefilter the data or guarantee the data completeness and quality. In geodetic monitoring, an example of such software is GeoMoS Edge, which is embedded in communication devices, or deployed directly on vibration sensors in the case of vibration monitoring. The data is then sent to a centralised server, where the monitoring software pulls it from, or directly to the monitoring software.

The majority of modern monitoring software products can handle data coming from geodetic, geotechnical and environmental monitoring. However, the specificity of remote sensing data means far fewer software can visualise and analyse it. Software used in mining or environmental monitoring, such as HxGN GeoMonitoring Hub can also import data coming from ground-based radars and InSAR (**Figure 8**). Whenever multiple technologies are combined in one software interface, it is crucial that they are georeferenced in the same reference frame, which is usually done by geodetic monitoring or topographic survey. The modern ground-based interferometric radars are equipped with prisms which are measured by total stations or GNSS antennas, enabling continuous tracking of their position, so that areas measured by geodetic and radar monitoring systems overlap with maximum accuracy.

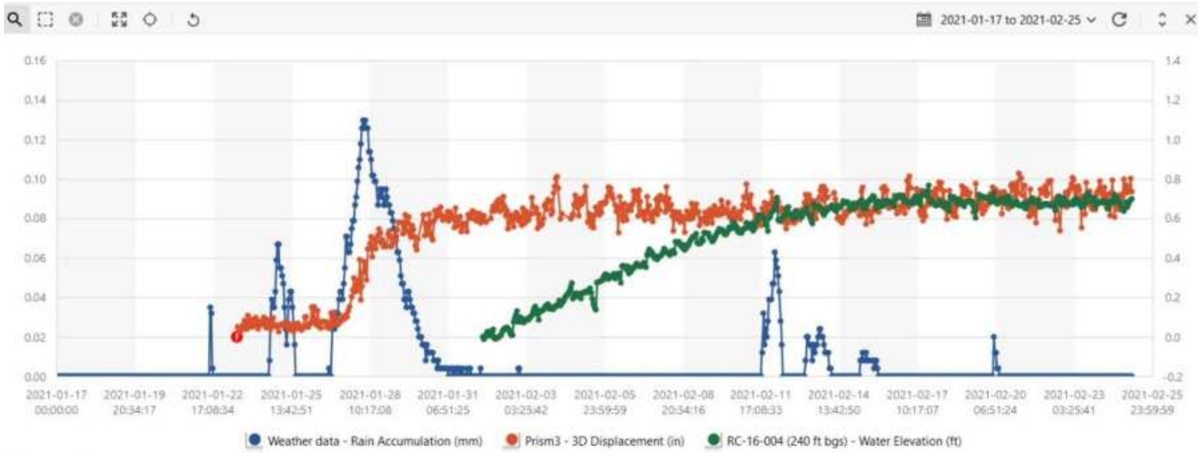

Figure 9 Prism displacements correlated with rainfall and piezometer groundwater elevation

Having all monitoring information in one view and being able to cross-reference the measurement results derived from different sensors and technologies (**Figure 9**) is the most efficient way of decision making based on monitoring data. These decisions carry significant moral and financial responsibilities due to the potential consequences involved.

An excellent real-life example of big monitoring data integration is the case of a landslide in Brienz, Switzerland (Leica Geosystems AG, 2024). Starting in 2009 with campaign prism measurements, when the velocity and the amount of movements increased, the monitoring project was scaled up with more frequent measurements and additional installed technologies. In the end, the combination of geodetic, remote sensing and geotechnical technologies gave crucial information to geologists and the community to make safety-critical decisions, such as the moment of evacuation or allowing the villagers to return to their homes in the aftermath of the event.

4. CONCLUSION

The primary objective of any deformation monitoring system is to provide accurate information about movements occurring within the monitored area. When there are gaps or poor quality in data, or unclear interpretations, real-time notifications may fail to trigger, potentially endangering both people and objects in the vicinity.

Safety and other market requirements are pushing deformation monitoring technology to constantly evolve and enable new, innovative solutions. Advancements in sensor development and the incorporation of intelligent features in both hardware and software have significantly enhanced monitoring solutions. However, in each measurement technology, there are physics and design constraints that pose disadvantages compared to other technologies. For example, for total station measurements, the clear line of sight to the prism is crucial, but with each successful measurement, there is three-dimensional information about that point.

Interferometric radar technology is much faster in data acquisition but provides only one-dimensional information in the radar's line of sight. Geotechnical and environmental sensors provide relative movement information, which can be incomplete for understanding movements, as sensor values may be influenced by drift. The solution for these limitations is sensor fusion and a combination of different monitoring technologies within a monitoring project.

Efficiently cross-analysing vast amounts of data and displaying the deformations in a single interface enables the transformation of raw data into actionable insights. Improving and automating this transformation process drives the Leica Geosystems monitoring solutions innovations, equally in hardware and software components. Critically, these innovations aid the engineers responsible for operating monitoring systems in their intricate responsibility to answer a fundamental question for decision-makers: what is the magnitude and direction of movements?

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BIOGRAPHICAL NOTES

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