

Field Test of Long Range Terrestrial Laser Scanner and Ground Based Synthetic Aperture Radar for Area-monitoring in Open Pit Mines

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Abstract

Slope Stability Monitoring (SSM) has improved dramatically over the past few years with the introduction of total stations, radar and other advanced technologies. This trend is continuing with the use of Terrestrial Laser Scanners (TLS) to enable three-dimensional analysis of slope movements. With useful range of the instruments typically limited by the balance of eye-safety and laser power the application of TLS systems has been limited to short range scenarios. However, applying infrared wavelengths and novel innovations, these limitations have been surmounted and now monitoring applications beyond 2000m are possible at high measurement rates without the safety hazards associated with typical Class 3R long-range laser scanners (LR-TLS). It is now possible to use LR-TLS technology effectively for long range SSM and surface deformation analysis.

In a cooperative field test conducted by RIEGL LMS, DMT GmbH & Co. KG, and RWE Power AG, an online-waveform processing LR-TLS instrument was deployed in the RWE Hambach open pit mine near Cologne, Germany. LR-TLS data was continuously acquired for a period of 48 hours concurrent with a long range ground-based Interferometric Synthetic Aperture Radar (GB-InSAR) system and a total station monitoring system. Results from this field test demonstrate the potential of this new LR-TLS sensor technology and are compared with the results from those achieved via the GB-InSAR, LR-TLS and Total Station systems to determine the level of usability in active mining situations.

1 Introduction

Mountains crumble, hills erode, and cliffs tumble into the sea. This process has been occurring since the beginning but never before has it been as important as it is today. With a growing number of developments being established in, on and around these active surfaces, the importance of monitoring these surfaces for deformation is becoming more important.

Remote sensing technologies are actively employed in detecting and quantifying such movements. The ability to optimize warning time before such events occur and to develop an understanding of the mechanisms involved, is determined in large part, by the accuracy, frequency and density of the spatio-temporal aspects of the measurements acquired during the events. For detection of larger movements is possible from satellite-borne remote sensing technologies, but more refined spatial and temporal resolutions are required for detecting and quantifying surface deformations on a smaller scale.

Terrestrially-based active Remote Sensing technologies provide the ability to acquire the necessary level of spatio-temporal resolution needed for tracking slope deformation in real-time. A number of these technologies are employed in slope deformation monitoring, with Interferometric Synthetic Aperture Radar (GB-InSAR) and Tachymeters combined with prism networks the primary sources of such datasets. GB-InSAR has proven to be a reliable technology for providing such datasets and is a de-facto standard in the mining industry for monitoring surface deformations in real-time. However, GB-InSAR and Tachymeter networks leave a gap in information; highly detailed and accurate surface modelling of deformation in 3 dimensions. GB-InSAR provides the ability to produce a high-frequency 2D image sequences of deformation, but for spatial reference, these images require projection onto another reference surface, such as a DEM, or similar model. The Tachymeter provides precise 3D positions, but is limited to specific reference points; a prism network.

Long Range Terrestrial LIDAR Scanning (LR-TLS) technology has the potential to fill this gap in technology: high density spatio-temporal datasets collected in small time intervals. While short-range terrestrial LIDAR scanning technology has been around for approximately 20 years, systems achieving reliable data beyond 2km have only been introduced in the past few years. As the technology is still quite new, testing is needed to ensure it can achieve satisfactory data for this field.

2 Installation

The field test consisting of an IDS IBIS-L GB-InSAR system, a *RIEGL* VZ-4000 LR-TLS and a Leica Tachymeter w/ prism network and was conducted on a section of the RWE Hambach open pit mine near Cologne, Germany in September of 2014. The test field was composed of clay and soft rock with bench angles of roughly 10°. The instruments were installed in an advantageous position to balance the range, perspective and region of interest requirements. The test ran for approximately 2.5 days of nearly uninterrupted observation; from Sept 22-24th 2014. In the course of the test, continued rainfall resulted in some localized slope movements which were detected by multiple systems. The quantity of change and resulting difference map for these movements were produced and a basic report on the result from each system examined.

The installation of each of the systems is as follows:

1. The GB-InSAR system (see notes appendix about IDS radar) was housed in a shipping container and mounted on concrete blocks. An aperture in the side of the shipping container provided an unobstructed view of the test site.
2. The LR-TLS instrument was mounted on a steel column which protruded from a 1 meter cube of concrete with two holes for transport by forklift. The mount was installed between the GB-InSAR and Tachymeter instruments, approximately 3m from each.
3. The Tachymeter was installed within a glass shield and on top of an apx 2.5m tall concrete monument which was submerge approximately 1m under the surface.



Figure 1 Installation of GB-InSAR (1), LR-TLS (2), and Tachymeter(3) with Test Field in background.

3 Configuration and Data Processing

All sensors were configured to optimize range and resolution performance. The manufacturer's respective software packages for each system were employed to produce the best possible results. A significant difference between the systems entails the level of development each system has undergone. The GB-InSAR is a provided a well-developed software package specifically tailored to the application, which provided real-time processing and analysis. As LR-TLS is still relatively new, the software available to support real-time operation is not readily accessible from the manufacturer. Thus all data acquired during the test was post-processed and only the final results were compared.

The project was a joint venture and one team operated the GB-InSAR system while the other operated the LR-TLS system. No results were exchanged until all processing had been completed. This ensured there would be no ability to alter the LR-TLS results by utilizing the GB-InSAR values.

3.1 GB-InSAR Configuration

The GB-InSAR system was configured to acquire data on a recurring 5 minute interval with the Field of View (FOV) determined by the physical characteristics of the radar frequency (xxx Mhz) which resulted in FOV as delineated in Table 1. All data was automatically processed in near-real-time by the manufacturer's supplied software and displacement values exported for later comparison.

Table 1 GB-InSAR Parameters

Parameter	Applied Value
Horizontal Field of View	60deg
Vertical Field of View	60deg
Range Resolution	~0.75m
Azimuth Resolution	~ 4.4m @ 1000m
Maximum Range	4000m

3.1 LR-TLS Configuration

The LR-TLS system was configured to automatically acquire data on a fixed 10 minute interval with the parameters in Table 2.

In addition to the scheduled 10 minute scanning interval, the scanner was set up to automatically acquire a network of 10 reflectors every two hours. The process of acquiring all 10 reflectors required approximately 10 minutes each interval, which resulted in the forfeit of one scan sequence every two hours. Aside from initial configuration, all data was acquired by the LR-TLS system autonomously.

Table 2 LR-TLS Parameters

Parameter	Applied Value
Horizontal Field of View	90deg
Horizontal Step-width (resolution)	0.014deg
Vertical Field of View	20deg
Vertical Step-width (resolution)	0.018deg
Maximum Range	4000m
Pulse Repetition Rate	50kHz

3.1 LR-TLS Data Processing

The LR-TLS data was post-processed after the field test was fully completed. The data was processed using a combination of software tools developed for the test, software provided by the manufacturer for geometric adjustments to each dataset (adjusting roll, pitch and yaw to each complete scan), and in a final step, software provided by the manufacturer for *simulated* real-time data processing (all datasets were processed automatically with one set of parameters to simulate real-time processing).

3.1.1 LR-TLS Atmospheric Scaling Correction

The first step in the post-processing stage was the application of range corrections induced by atmospheric scaling factors. These values were calculated from atmospheric readings acquired by an onsite weather station. The range variances to 10 planar reflectors prior to correction are shown in Figure 3 as grey lines. The standard deviation of all values was 5.1mm over all ranges (min = 120m, max = 2.4km) The calculated range correction in ppm is overlaid and the polarity of the charts displays the required adjustment.

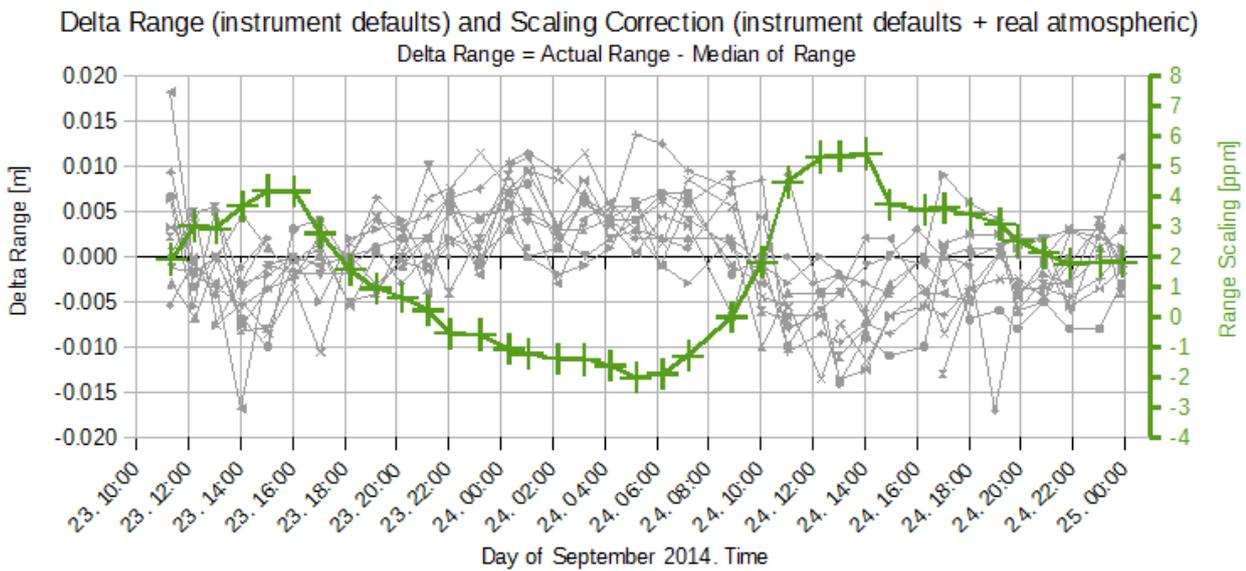


Figure 2 Range variances to reflector network overlaid with computed atmospheric scaling corrections

With the atmospheric range corrections applied, the relative differences in range were again charted, resulting in a final standard deviation of 3.7mm. The final result can be seen in Figure 4, below.

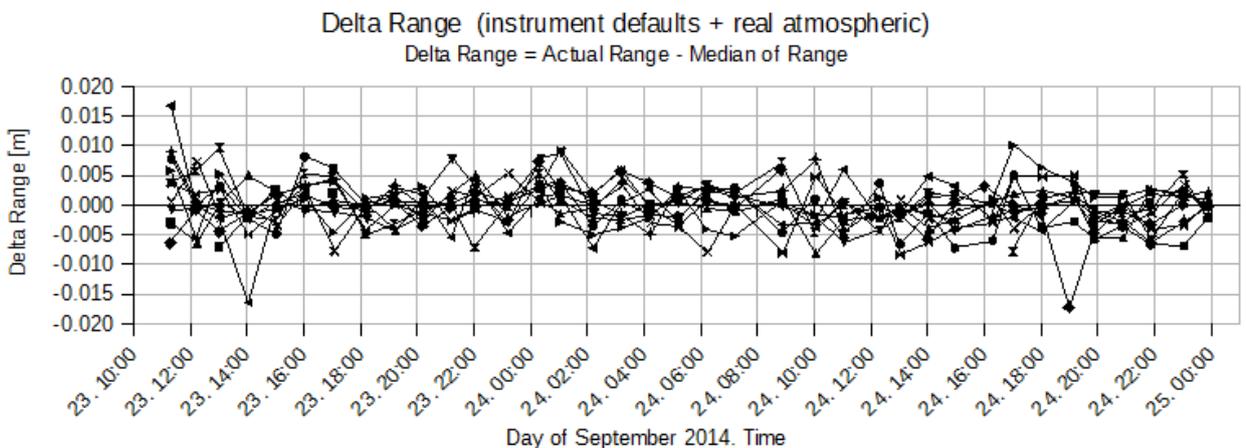


Figure 3 Range variances to reflector network *after* application of atmospheric scaling corrections

3.1.2 LR-TLS Data Adjustment

Persistent operation of LR-TLS systems in active mining environments presents a few challenges. The instrument may be disturbed by machinery in the immediate vicinity (as was the case during this test), blasting or any other number of disturbances. Likewise, moderate rainfall, geological rebounding of the mine, and other natural influences can cause minor changes to the material under the concrete mount. Thermal expansion and contraction of the steel beam of the LR-TLS mount according to which side the sun heats also incurs variation to the position and (more significantly) orientation of the instrument. Therefore a method of registering the datasets together to adjust this error is required.

Two approaches were tested to determine an optimal method for adjustment. The first method invoked was a least-squared adjustment of the observed values on the reflector network (acquired every 2 hours). For validation, a second adjustment was performed utilizing an iterative closest point (ICP) algorithm on planes extracted from each scan from each epoch with the first scan held as a reference for all others. The ICP algorithm is also known as MSA in the software used for adjustment. The results of each independent method are presented in Figure 4. Note the dramatic influence of the machinery between 23. 07:00 and 23. 17:00!

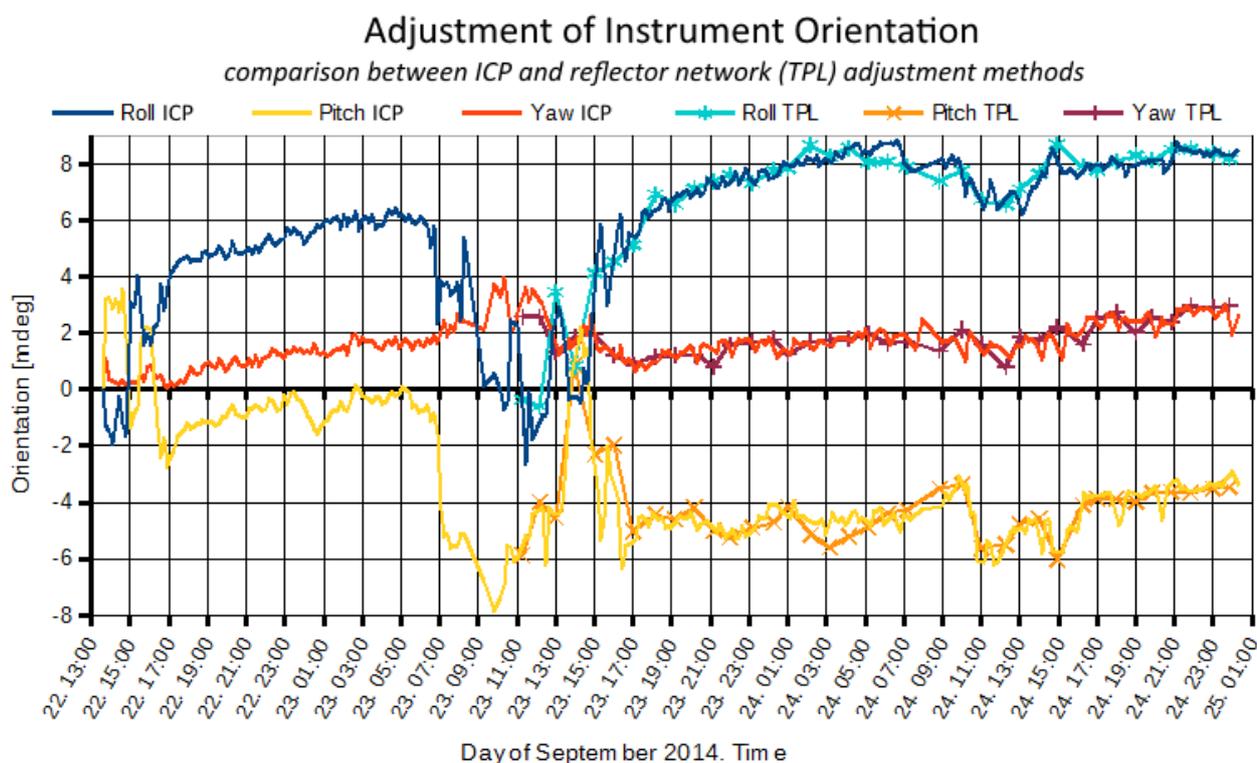


Figure 4 Comparison of Reflector Network (TPL) and ICP adjustment results

2.1.1 LR-TLS Deformation Analysis

The final analysis used to derive deformation values was completely automated. Parameters were established to optimize results and the automated process was started.

The process operates in the following manner:

1. The objective surface was modeled via a 2.5D Raster methodology. Each scan was divided into 7 segments, with an optimum reference plane defined for each segment. Each of these planes served as the base of a rasterized grid. Each raster cell of each plane was projected through the point cloud data and all points contained within each raster were averaged to obtain a single height above the plane. The result is a 2.5D value for each cell.

2. That raster information for each epoch was then compared to the reference epoch by differencing the raster distance values for each cell along the normal direction of the reference plane. Any cell containing less than was filtered to eliminate poor results caused by insufficient data.

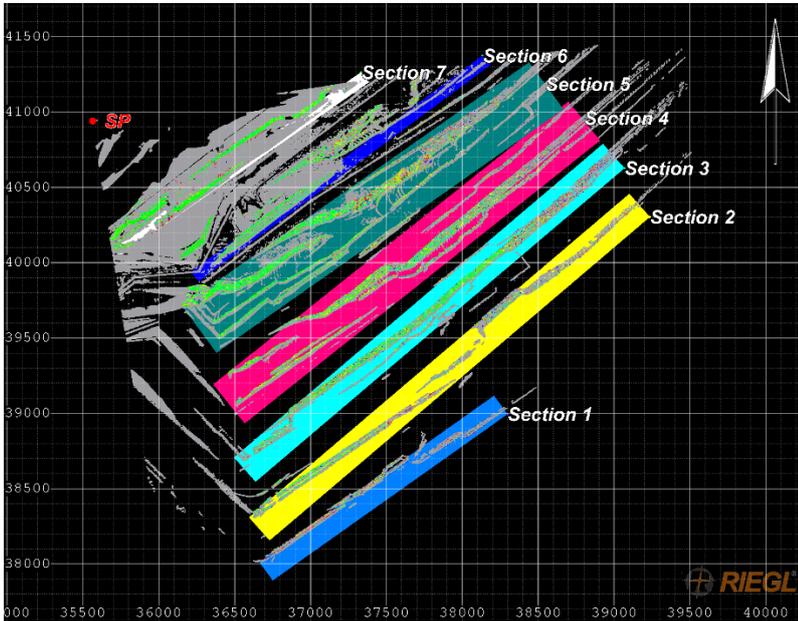


Figure 5 LR-TLS Raster Planes

4 Results



During the course of the monitoring period, moderate rain showers occurred which resulted in some minor slope deformation in a number of locations within the test field. The extents of these deformations was further investigated. However, as there were a number of smaller events, only the most pronounced were investigated. Typical deformations were selected to provide a representative sample of the overall performance for each system.

Figure 6 RIEGL VZ-4000 scanning in a moderate rainstorm

The final step in the project, correlating the two datasets, proved to be more challenging than planned. Although the GB-InSAR system was georeferenced using RTK-GNSS to measure the origin and georeferenced corner cube reflectors used to determine the orientation, assimilating the GB-InSAR and LR-TLS datasets proved to be a challenge due to the large beam size and relative orientation errors encountered with the GB-InSAR system.

In contrast, the LR-TLS system was relatively easy to precisely georeference provided its integrated sensors: Inclination, GNSS, and precise reflector scanning capabilities (see Figure 3 for range measurement errors to multiple reference targets). The resulting positioning accuracy of the LR-TLS data was at the centimeter level.

However, with a bit of trial and error, the shift between the GB-InSAR and LR-TLS datasets was found to be around 20-30m, depending on the range. The challenge this presented was simply one of logistics; the size

of the slope deformations often were not larger than 20-30m and therefore positively identifying displacements between systems via geodetic coordinates was achieved only after a great deal of coordination between datasets.

4.1 System Coverage

Both instruments are specified to achieve measurement performance up to 4000 meters. As the site was limited to roughly 3000 meters, the ability to test this aspect of performance was not available. The immediate difference between the two technologies is evident in the Laser Scanner's ability to scan a configurable 360° window, while the GBInSAR system is limited to 60° x 60°. This creates a striking difference when comparing coverage of each system (see Figure 6) as the LR-TLS was configured to acquire a 90° horizontal window. The LR-TLS system easily covered the same region as the GB-InSAR system and extended well beyond in the horizontal aspect. While the LR-TLS system covered a much wider Field of View, it required twice as much time (10 minutes) as the GB-InSAR system to do so. There is a direct tradeoff between the configured Field of View and required scan time for the Laser Scanner and this should be considered for optimizing for different applications in the future.

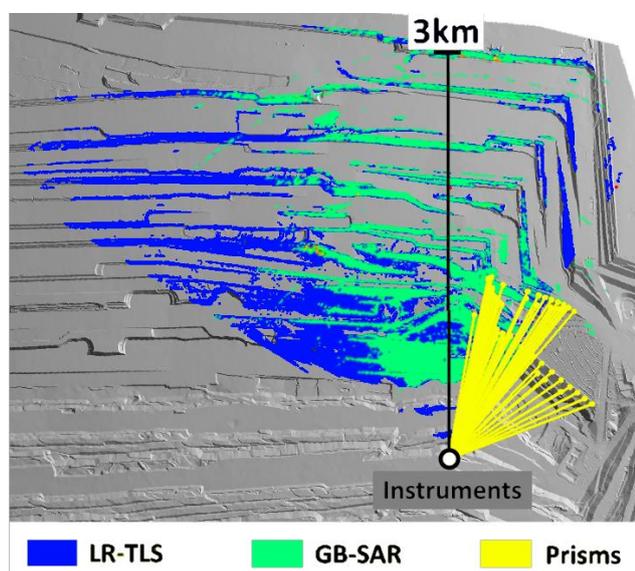


Figure 7 Sensor coverage map. Note: GB-InSAR (Green) overlaps LR-TLS (Blue).

4.2 Detection Capabilities

There is a large difference in the detection capabilities afforded by the two systems. Basic physics dictate the characteristics of each. Radar has a large footprint due to its wavelength, but the benefit of the same wavelength is the ability to resolve relative changes to millimeter precision, given that the surface encountered by the radar beam is relatively planar.

The LR-TLS used in this test provided a large number of discrete points with a much smaller beam diameter (See Table 3) compared with the radar system, but each point has a precision of 10mm, which means that the variability of each point will create a noisier result, but a more accurate result due to the nature of the system.

In principle the differences (see Table 3) can be summarized as this: GB-InSAR provides precise change detection and LR-TLS provides accurate change detection. The difference is not simply a change in terms, it is the difference between tracking fast and slow moving surfaces. Typically the precision required to repeatably detect change is determined as the capability to measure and order of magnitude more precise

than the change itself. In this case, the InSAR system potentially has the ability to detect changes on the order of 0.1mm, which means it can reliably detect changes of 1mm. However, due to the limitation of the technology, rapid deformations result in a complete loss of data integrity. A change has occurred, but it cannot be quantified.

LR-TLS does not suffer this issue as it measures in true 3D. However, the results from this test show that the systems can resolve to approximately 4mm (Section 3.1.1), which translates to a detectable change of 40mm or greater.

Table 3 System Characteristics

	IDS IBIS-L / IDS Guardian	RIEGL VZ-4000 / RiMONITOR
Measurement Type	2D	Discrete Points
Measurement Attributes	Amplitude and Phase	X, Y, Z, θ , ϕ , r Amp., Reflectance, Deviation
Beam Footprint	Resolved to ~5m	0.15m @ 1000m (to perpendicular surface)
Displacement Calculation Method	1D Line of Sight	1D Plane Raster (this test) (Future: 3D)
Change Detection Limitation	Wavelength and Temporal Frequency dependent	4000m

4.3 Detected Events

Four represented deformation events were selected to represent the diverse conditions which were encountered (although there were several more noted). The range and location of which are depicted in Figure 8 and a side-by-side comparison of events is provided in Table 4. All images in Table 4 are scaled from -10mm to +10mm of displacement.

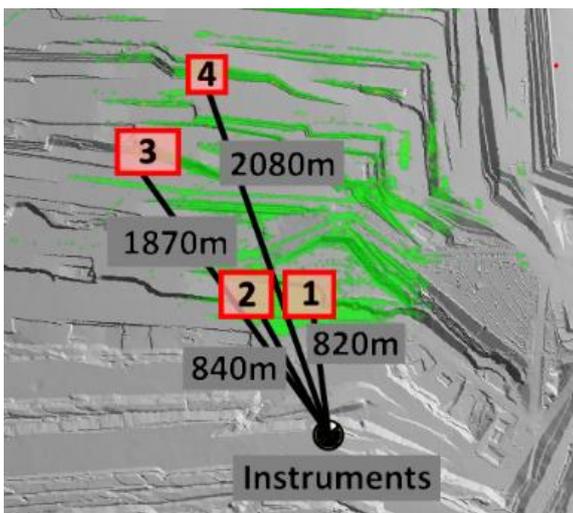
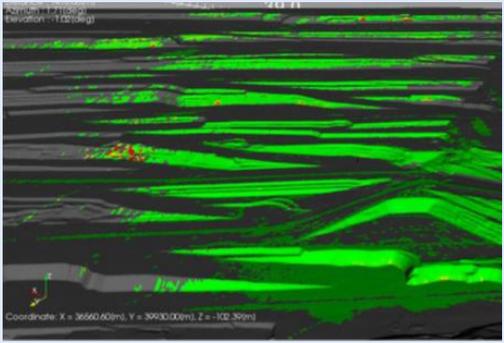
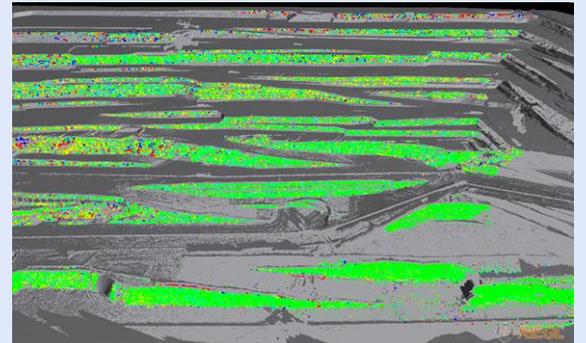
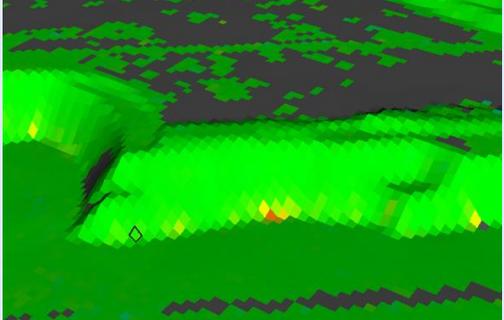
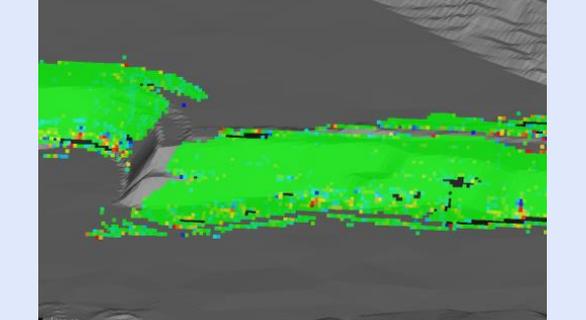
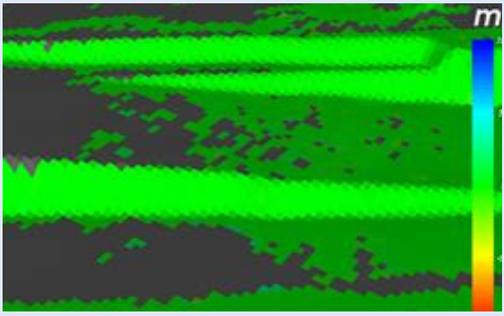
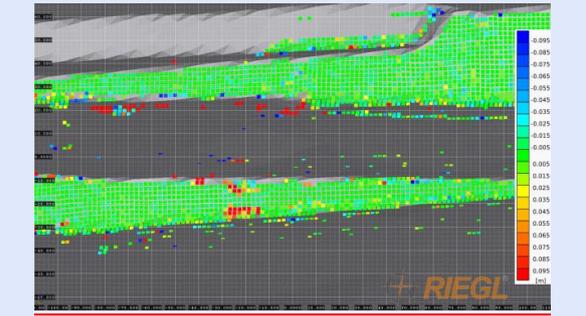
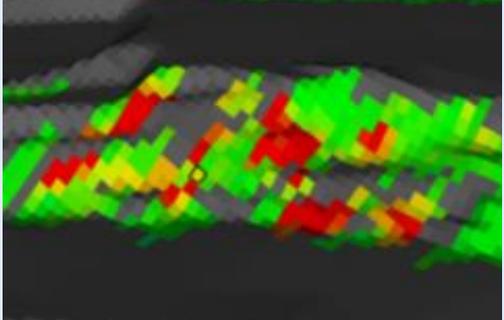
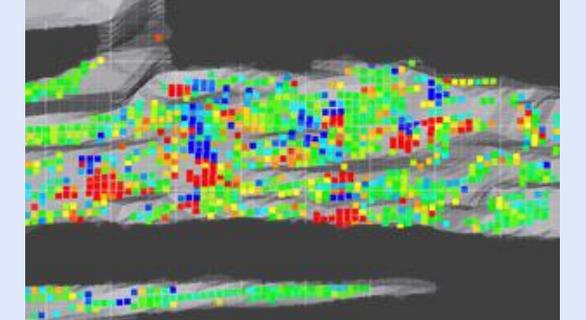
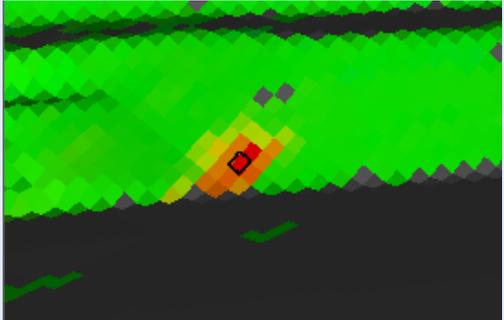
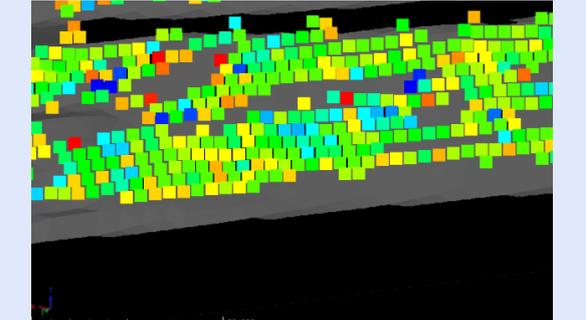


Figure 8 Detected Events and distance from instruments

Table 4 Event Displacement Map Comparison

Event	GB-InSAR Displacement Map	LR-TLS Displacement Map
ALL	 A 3D visualization of a displacement map for the 'ALL' event using GB-InSAR. The terrain is shown in grayscale, with displacement values overlaid in a color gradient from green to red. A coordinate system is visible in the bottom left corner with values: X = 36560.60(m), Y = 39930.00(m), Z = -102.30(m).	 A 3D visualization of a displacement map for the 'ALL' event using LR-TLS. The terrain is shown in grayscale, with displacement values overlaid in a color gradient from green to red. The map shows a different spatial distribution of displacement compared to the GB-InSAR map.
1	 A 3D visualization of a displacement map for Event 1 using GB-InSAR. The terrain is shown in grayscale, with displacement values overlaid in a color gradient from green to red. A small white diamond marker is visible on the terrain.	 A 3D visualization of a displacement map for Event 1 using LR-TLS. The terrain is shown in grayscale, with displacement values overlaid in a color gradient from green to red.
2	 A 3D visualization of a displacement map for Event 2 using GB-InSAR. The terrain is shown in grayscale, with displacement values overlaid in a color gradient from green to red. A vertical color scale bar labeled 'm' is on the right side.	 A 3D visualization of a displacement map for Event 2 using LR-TLS. The terrain is shown in grayscale, with displacement values overlaid in a color gradient from green to red. A vertical color scale bar is on the right side, with values ranging from -0.0995 to 0.0995. The RIEGL logo is visible in the bottom right corner.
3	 A 3D visualization of a displacement map for Event 3 using GB-InSAR. The terrain is shown in grayscale, with displacement values overlaid in a color gradient from green to red.	 A 3D visualization of a displacement map for Event 3 using LR-TLS. The terrain is shown in grayscale, with displacement values overlaid in a color gradient from green to red.
4	 A 3D visualization of a displacement map for Event 4 using GB-InSAR. The terrain is shown in grayscale, with displacement values overlaid in a color gradient from green to red. A small white diamond marker is visible on the terrain.	 A 3D visualization of a displacement map for Event 4 using LR-TLS. The terrain is shown in grayscale, with displacement values overlaid in a color gradient from green to red.

4.3.1 Event 1

Both systems detected this event (center of each image in Table 3, Row 1). The immediately notable difference between each result is the ability of the LR-TLS system to accurately depict erosion and deposition, while the GB-InSAR provides the information that an event has occurred, but does not provide any ability to quantify the erosion and deposition activity.

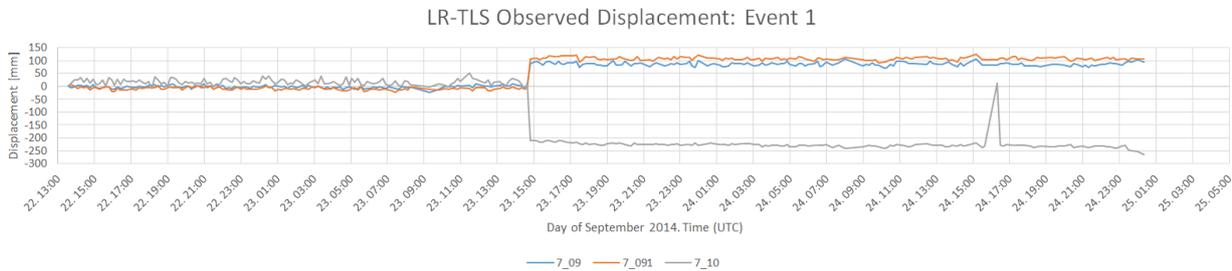


Figure 9 LR-TLS displacement chart from 3 Cells demonstrating erosion and deposition quantification

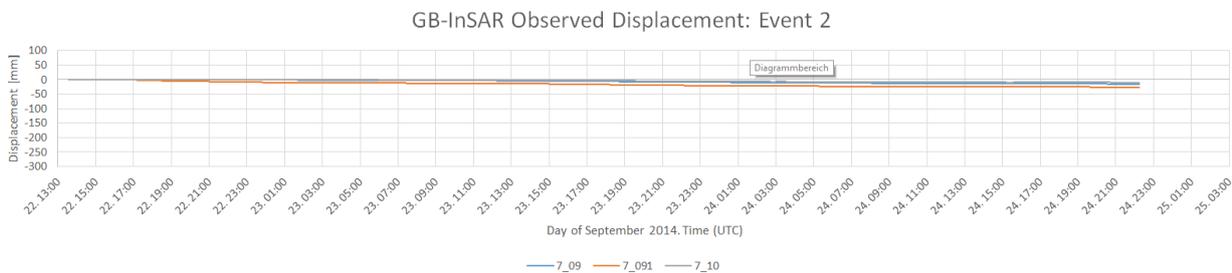


Figure 10 GB-InSAR displacement chart from 3 Cells detecting deposition but no erosion

4.3.2 Event 2

Caused by earth moving equipment, this is not a failure of any sort. Rather, it is material which has been deposited due to machine activity. It could not be determined whether this activity was filtered by the GB-InSAR processing software, or simply not detected. Displacement graphs for each system are provided in the following graphs.

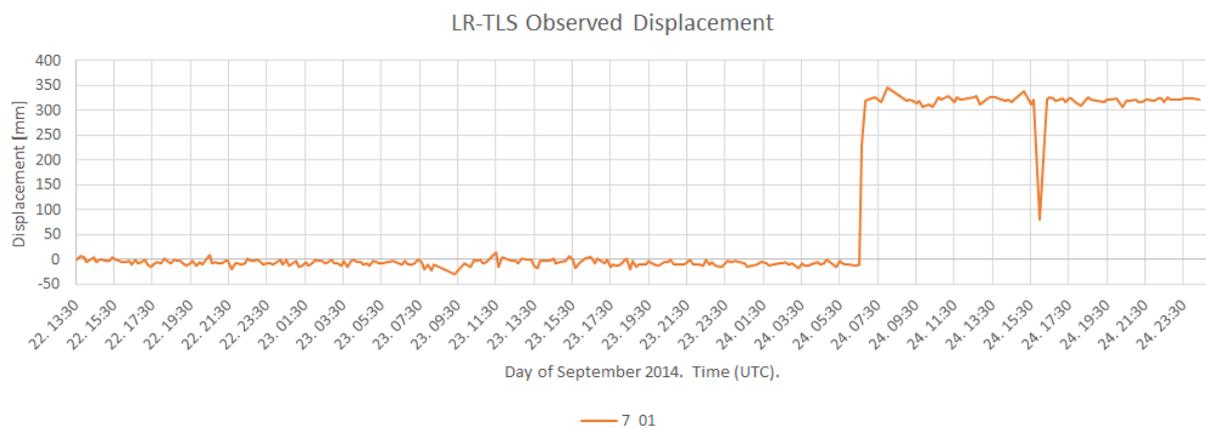


Figure 11 LR-TLS measured displacement of Event 2

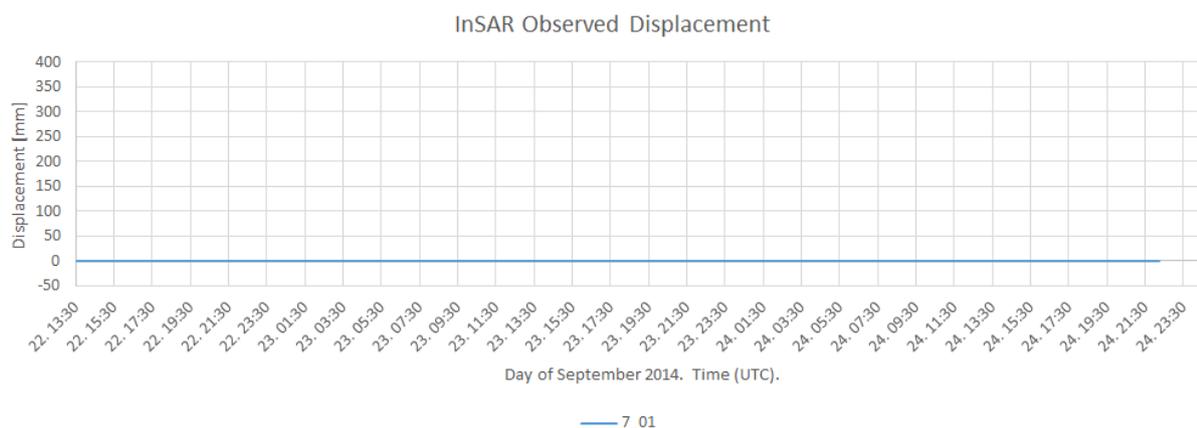


Figure 12 GB-InSAR measured displacement of Event 2

4.3.3 Event 3

This was the largest event recording during testing. A substantial difference is obvious: GB-InSAR detects the event, but only reports it as a deposition event, while the LR-TLS accurately detects both the erosion *and* deposition events. Extents of the displacement were greater than 3 meters in both deposition and erosion.

4.3.4 Event 4

What appears to be a traditional earthen creep failure. The toe of the highwall is slowly advancing as the crest is slowly subsiding. During the testing period the GB-InSAR detected changes of 50-60mm, while the LR-TLS results are less conclusive. From the results, it appears that the LR-TLS system was not able to detect the subtle displacement of this system with sufficient precision to render it visible in the displacement map.

5 Conclusions

The value of the current level of automation in today's GB-InSAR systems is not to be understated. Once configured, the system operates almost fully automatically (requiring only infrequent inspections). The merits of the technology do not need to be reiterated as they have already been proven in active minesites around the world. There are, however, limitations to the technology which leave gaps in the ability of geoscientists to accurately model and quantify surface deformations in 3 Dimensions. This aspect of analysis will prove increasingly vital to the contribution of understanding the mechanics and attributes of soil, rock and material dynamics.

To this extent, the rapid acceleration in LR-TLS developments in recent years has provided a viable means of acquiring highly accurate 4D data in dynamic conditions. The further development and improvement of the automation of these systems will prove critical to their adoption. However, it should be noted that the physical dimensions, performance and rapid improvement of the technology already enables in-depth analysis of slope dynamics with all the benefits of a Remote Sensing technology (safety, ease of deployment, resistance to atmospheric conditions, etc).

It is expected that LR-TLS systems will soon become standard equipment in monitoring applications. Further testing of post-processing and analytics automation will be required to realize a real-time LR-TLS monitoring system. Specifically, adjustments to counter for physical disturbance of the instrument, better classification and quantification of surface displacement and deformation along with seamless integration

with existing infrastructure will be required. The level of automation provided by the *RIEGL VZ-4000* enabled the acquisition process to be fully hands-free, which is a must for such automated installations. With integrated inclination sensors, GNSS and the ability to automatically acquire reflectors, the system provides a straightforward means of georeferencing datasets and therefore simplifies the process of aggregation with other sensor data.

The fusion of the resulting datasets also provides an additional challenge as the georeferencing capabilities for Radar data are rather limited due to the physical beam size and lack of internal orientation capabilities. While the radar data was georeferenced to within 5-30m (depending on where the data was sampled), attempts to combine the two was made difficult by the ambiguities inherent in the 2D radar datasets. Therefore it is highly recommended to *precisely* georeferenced installations in the future to avoid such hassles.

Acknowledgement

Thanks to RWE for providing a great test field and accommodating all the necessary requirements to fulfil the testing.

Thanks to DMT for coordinating the exchange between companies and smoothing the process.

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