ITAtech Guidelines for Remote Measurements Monitoring Systems

ITAtech Activity Group
Monitoring

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1 >> Introduction

In the last years an ever increasing use of remote measurements technologies could be seen for the construction of underground infrastructures.

These technologies are in quite many cases innovative and offer new ways and means to cover monitoring needs in the different phases of such projects. However the novelty of the technologies also may be seen as an obstacle to apply the technologies in the most performing manner and to combine them efficiently with more current technologies.

This guideline should thus describe the new technologies, describe their technical features and give recommendations and examples of tender specifications of remote measuring systems for today monitoring projects. Some case studies also show how these technologies have been applied successfully already for monitoring purposes in underground infrastructure construction.

The guideline has been written to assist tunnel designers, contractors and owners in understanding the benefits and limitations of the today used technology for monitoring with remote measurements systems. The guideline will cover three technologies: Satellite radar interferometry, laser scanning and reflectorless measurements with total stations. These three Technologies has been chosen by the Activity Group as the once which are the biggest interest of the industry.

2 >> Satellite Radar Interferometry

BACKGOUND

Satellite Radar Interferometry is a technology that remotely measures surface displacement from space. It has existed for many years and complements existing and well-known in situ technologies.

Since 1978, when the first radar images of the Earth's surface were acquired from Synthetic Aperture Radar (SAR) sensors mounted on satellites, Satellite Radar Interferometry gained increasing attention for its unique technical performance and cost-effectiveness, being able to provide high-quality, remotely acquired data about surface movements over large areas.

Satellite Radar Interferometry aims at exploiting all available data acquired over a certain area of interest by identifying radar targets on the Earth's surface exhibiting a stable temporal electromagnetic response. These radar targets generally correspond to ground elements such as manufactured structures (buildings, monuments, streets, railway lines, antennas, lattice structures, metallic elements, etc,) or natural elements (rocky outcrops, debris accumulations, etc.).

Refinement of the technology, in particular after the development of the Permanent Scatterers technique in the late nineties [Ferretti et al., 2001], has allowed millimetre precision to be achieved in the estimation of the ground displacement measurements. This particularity, along with the characteristics of remote sensing systems (such as the capacity to cover large areas of the Earth's surface from a few to thousands of square kilometres), represents a new and very efficient tool for high precision monitoring of surface deformation phenomena. It is moreover a useful support for geological, geotechnical and geophysical interpretation on different scales and for detailed studies on single specific structures.

Today Satellite Radar Interferometry has become a standard monitoring tool to provide useful information in the various stages of tunnel and underground infrastructure realization, from design to construction and management.

Since Satellite Radar Interferometry is based on space-borne radar sensors, it covers large areas and allows the detection of a high number of surveying points. For each of them, surface movement information can be calculated up to millimetric precision - depending on boundary conditions. As such, the technology can support to overcome some of the restrictions of terrestrial surveying methods in terms of extent of the monitored area, as well as surveying points density. Satellite Radar Interferometry is therefore extremely interesting for integration with terrestrial surveying technologies: drawbacks of the one technique could be balanced by advantages of the other technology [Petrat et al., 2009].

The following section gives a short introduction to the main principles of the Satellite Radar Interferometry technology as well as a summary of considerations regarding the operational use within an underground construction project.

2 >> Satellite Radar Interferometry

2.1 TECHNOLOGY

Satellite Radar Interferometry is a remote sensing tool that measures ground displacement [Ferretti et al., 2001; Hanssen R., 2001; Kampes B., 2006; Ketelaar V.B.H., 2009]. Radar sensors mounted on specific satellites transmit radar signals toward the Earth, some of which reflect off objects on the ground, bouncing back to the satellite. These 'back scattered' signals are captured by the satellite's sensors and used to compile radar images of the earth's surface. Radar signals are unaffected by darkness or clouds, in terms of visibility of the land surface. As clouds do not obstruct the passage of the satellite signal, satellite platforms mounting Synthetic Aperture Radar (SAR) are all-weather systems that can function 24 hours a day, 365 days per year.

Pairs of SAR images can be compared to detect changes in the surface profile and these changes relate to displacement (upward and downward) that occurred between the acquisition dates of the pairs of images under analysis. Satellite Radar Interferometry technique is the measurement of signal phase change, or interference, over time. The distance between the sensor and the point on the ground also changes meaning that the phase value recorded by a SAR satellite orbiting along a fixed path is affected too. As a consequence, any displacement of a radar target along the satellite Line Of Sight (LOS) creates a phase shift in the radar signal that can be detected by comparing the phase values of two SAR images acquired at different times (Figure 1).

The main limitation of this approach is the effect of the atmosphere on the propagating signal, resulting in artefacts which can hamper the precision of the measurements, if not properly removed. This limitation can be overcome by comparing many SAR images rather than just two, as in conventional Interferometry (InSAR). Then, the analysis is focused on the radar targets that exhibit a very stable radar signature in all the processed images. This approach, called «Interferometric Time Series Analysis», allows the implementation of powerful filtering procedures to estimate and remove atmospheric noise. Results can be accurately geocoded and integrated with other prior information in geographic information systems. Common to all geodetic applications, the results are computed with respect to a ground control point of known elevation and motion.

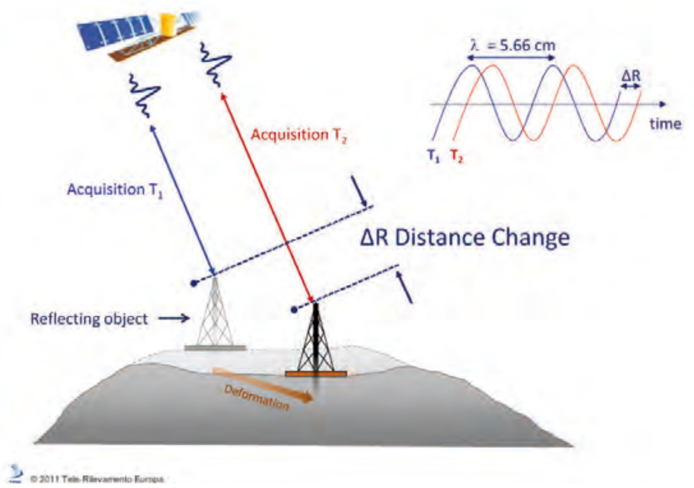
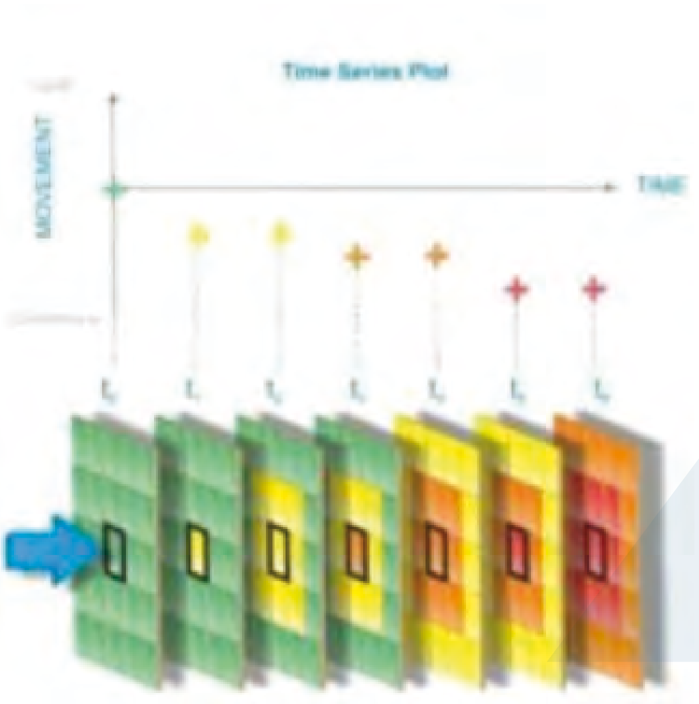


Figure 1: A schematic showing the relationship between ground displacement and signal phase shift; the numeric value of the wavelength λ (5.66 cm) is a sample for ERS satellite operated by the European Space Agency (ESA).

2 >> Satellite Radar Interferometry



The operational usage of interferometric time series analysis for monitoring purposes requires today a high number of SAR datasets typically to be acquired within the monitoring period. For each suitable pixel in the SAR dataset, a times series of displacements referred to one reference acquisition is finally achievable. Sampling of the time series is given by the acquisition dates of the SAR datasets incorporated into the Satellite Radar Interferometry Analysis (Figure 2).

In practice, the time series analysis incorporates different individual processing technologies like Persistent Scatterer Interferometry (PSI) and others. Detailed information about the technologies are given in [Ferretti et al. 2001] for PSI, [Berardino et al. 2002; Lundgren et al. 2001; Usai S. 2001] for SBAS and [Ferretti et al. 2011] for new algorithms.

Figure 2. Radar Interferometric Time Series Analysis: sample time series of surface displacements generated from a number of SAR datasets acquired at t0, t1, … t6

Signal returns can be exploited from two families of ground measurement points on Earth's surface (Figure 3).

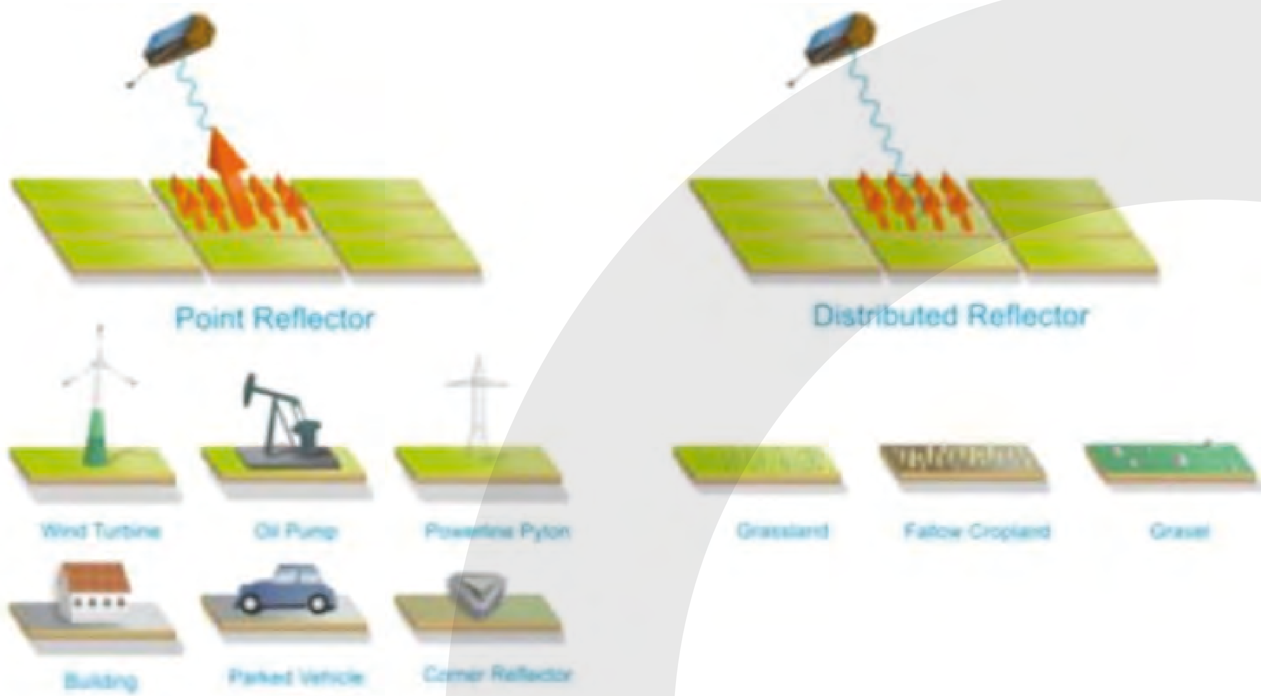


Figure 3. Types of Satellite Radar Interferometry reflectors: Point and Distributed.

2 >> Satellite Radar Interferometry

Point Reflectors (also called Permanent Scatterers, PS) are «objects» already existing on the ground which create high reflectivity values and thus very bright pixels in the SAR scene. They must be stable in their physical backscattering characteristic during the entire monitoring period, i.e. in all the set of images processed. Samples are given in Figure 3 (a). If no point reflectors are existent, the installation of artificial Corner Reflectors could be considered. Corner Reflectors are man-made metallic object specifically designed to be visible from SAR satellites, hence to create a measurement point on the ground where it is missing because of local conditions (typically dense vegetation).

Distributed Reflectors (also called Distributed Scatterers, DS) do not have a dominant source of radar backscattering signal, like point reflectors, but produce a coherent signal over a certain time mainly from a number of adjacent pixels, due to not varying surface conditions [Ferretti et al. 2011]. Samples are given in Figure 3 (b).

All areas, which are stable in terms of physical radar backscattering behaviour, can be considered for this technology - e.g. urban environment with buildings or rocky deserts: Phase information from one acquisition to the other needs to be coherent. This is not the case in areas, which are temporarily varying in terms of radar backscattering e.g. forest through vegetation growth or movement, agricultural areas through agricultural activities, larger construction sites with earth movements and construction activity, water or sand dunes. These environments could be very challenging for the application of the technology.
Point and Distributed Reflectors represent the set of Measurement Points for which surface movement information can be derived to millimetre precision.

Figure 4 illustrates the principle: the building and the artificial Corner Reflector yield a Measurement Point whereas other parts (e.g. cropland) cannot be fully analysed with the Satellite Radar Interferometry technology along the whole monitoring period, because of its changing radar backscatter characteristic.

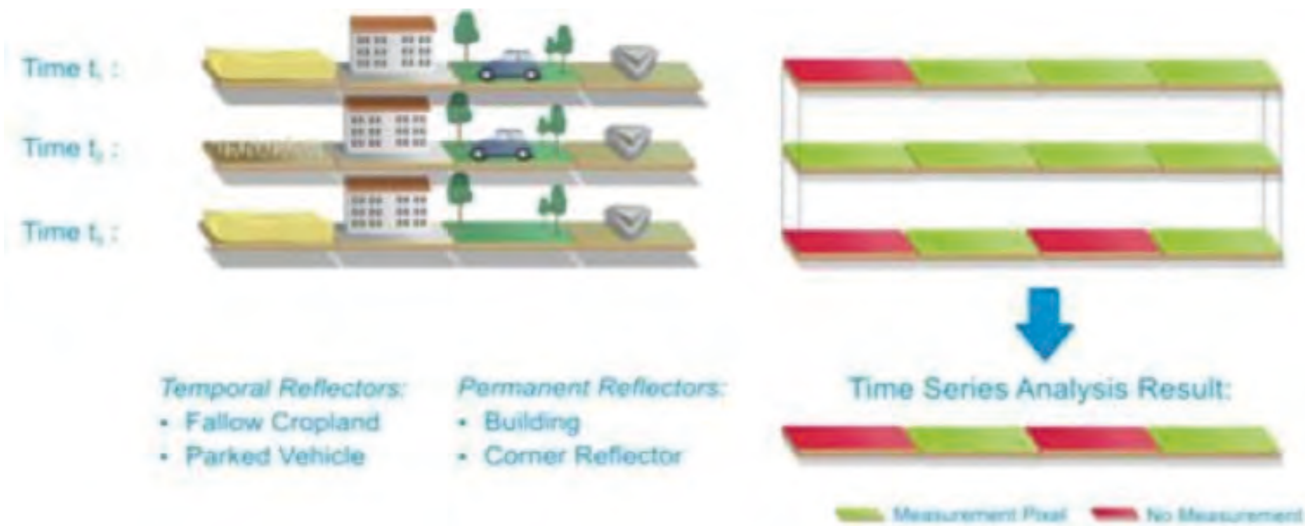


Figure 4. Types of Satellite Radar Interferometry reflector with surface movement information.

Provided that enough SAR images (min. 20-25) are available over the Area Of Interest (AOI), whatever the type of Measurement Point identified by the algorithm (PS or DS), the following information can be retrieved for each of them:

- geographic coordinates of the measurement point (latitude, longitude and elevation);
- average annual displacement rate of the measurement point [mm/yr];
- Time-Series of displacement of the measurement point [mm vs. time].

2 >> Satellite Radar Interferometry

All displacement measurements associated with a Measurement Point are calculated along the Line Of Sight (LOS) of the satellite. Therefore, they are the projection along the LOS of the real displacement vector affecting the Measurement Point identified on the ground. These are differential measurements with respect to a reference point, time referenced to the acquisition date of the first image. Movement data exhibited by a measurement pixel are then relative, not absolute, data.

The distribution of measurement points (MP) can be seen as a 'natural' ground network of radar benchmarks, similar to a GPS (Global Positioning System) network. The network can be used to monitor both the displacement of individual structures (a building for instance), and the evolution of a large displacement field affecting hundreds of square kilometres (due, for example, to subsidence, slope instability, fault creeping, volcanic activity, etc.). It should be noted that measurement point density is usually much higher than the density of benchmarks used in any conventional geodetic network (sometimes thousands of MP/km^2 with new high resolution satellites).

Moreover these measurements do not require any installation and fast algorithms allow the update of the information concerning thousands of points quickly and reliably.

A further advantage of Satellite Radar Interferometry with respect to conventional techniques is the possibility to exploit radar data already acquired, taking advantage of the historical archives of SAR data. The following Table 1 summarizes the SAR satellites available today and in the past for Satellite Radar Interferometry analysis. It is to be noted that, whenever a set of min. 20-25 images is acquired over a certain Area Of Interest by a specific satellite, Satellite Radar Interferometry can be carried out and surface deformation provided. Many regions in Europe, North America, and Japan have been covered since 1992. Wherever SAR images are not available, new acquisitions by the current operating satellites can be tasked in order to create a first baseline for surface deformation analysis.

SATELLITE	PROPERTY	BAND	SIGNAL WAVELENGHT	REVISITING TIME	GROUND RESOLUTION	PERIOD OF ACTIVITY
ERS1-2	European Space Agency	C	5,6 cm	35 days	20x5 m	1992-2001
ENVISAT	European Space Agency	C	5,6 cm	35 days	20x5 m	2003-2010
RADARSAT-1	Canadian Space Agency	C	5,6 cm	24 days	Up to 10x5 m	1995-2013
RADARSAT-2	Canadian Space Agency	C	5,6 cm	24 days	Up to 3x3 m	2008 – today
SENTINEL-1A	Italian Space Agency	C	5,5 cm	12 days	20x5 m	2014 – today
TerraSAR X	German Space Agency	X	3,1 cm	11 days	Up to 1x1 m	2008 – today
COSMO-SkyMed	Italian Space Agency	X	3,1 cm	8 days	Up to 1x1 m	2008 – today

Table 1: Typical values of precision for a point less than 1 km from the reference point for a dataset of at least 30 scenes spanning a 2 year period.

The recent introduction of new X-band SAR (TerraSAR-X and COSMO-SkyMed), characterized by higher sensitivity to surface deformation (compared to previous available sensors), higher spatial resolution (down to 1 m), as well as better temporal frequency of acquisition (down to a few days, rather than a monthly update), has further increased the quality of measurements, playing a key role in monitoring individual buildings and structures [Giannico et al., 2012, Ranvier et al., 2010].

A typical Satellite Radar Interferometry result for an urban area is illustrated in Figure 5: up to 20,000 measurement pixels have been achieved in this case for the City of Amsterdam. For each building, a number of measurement points can be identified.

For each measurement point a time series of movement can be given, as shown in Figure 5 (top, left). Time sampling rate is determined by the acquisition dates/times of radar acquisitions incorporated in the interferometric time series processing. The higher the radar acquisition frequency, the higher is also the temporal sampling of the time series.

The example in Figure 5 shows, that stronger subsidence is occurring along the new railroad accessing central railway station in Amsterdam. Focus of subsidence are railroad dams, whereas bridges in between are not subject to surface movements.

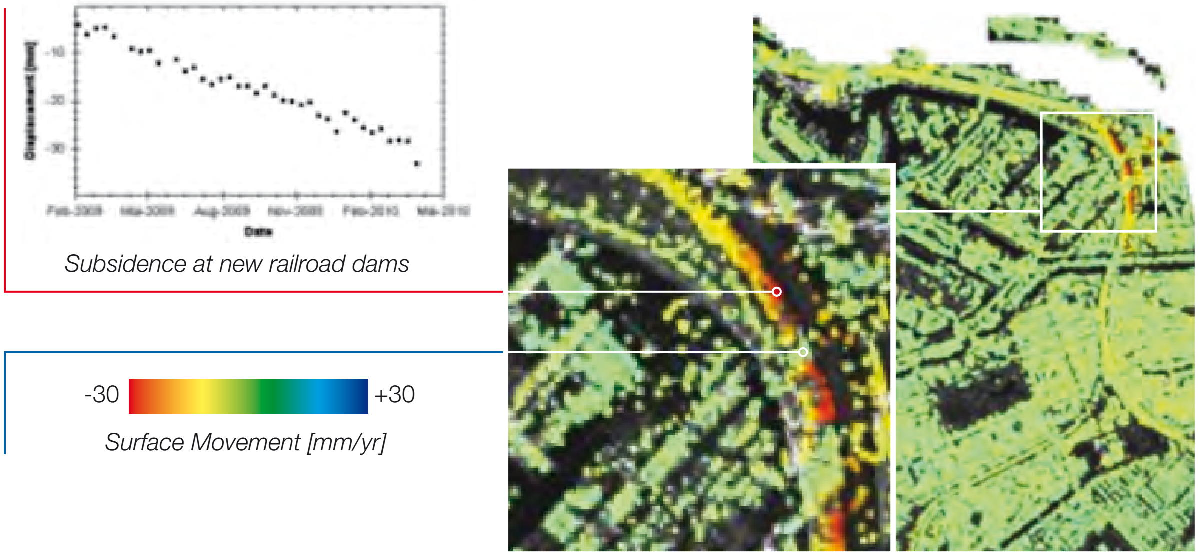


Figure 5. Sample result of a time series interferometric analysis of Amsterdam (right: Overview; centre: Zoom along a new railroad dam; left: time series of the movement of one selected reflector along the railroad); © Astrium Services.

Measurement points are generally missing over vegetated areas, or water covered areas or where heavy construction activities are ongoing. This because it is not possible to identify statistically stable (permanent) radar targets (scatterers) in all the images processed. In fact, changes induced by plant growth, or moving water surface, or terrain movements, result in variable physical backscattering in subsequent radar imagery.

2.2 ACCURACY/PRECISION

Error bars of Satellite Radar Interferometry measurement are extremely complex to be estimated theoretically, before actually processing the data available. In fact, the precision of the displacement measurements depends on many different factors, such as: the number of images used for analysis; the spatial density of the measurement points (the lower the density, the higher the error bar); the quality of the radar targets (signal-to-noise ratio levels); the climatic conditions at the time of the acquisitions; the distance between the measurement point and the reference point; the repeat cycle of the satellite (the lower, the better). An overall picture of the typical precision obtained by Satellite Radar Interferometry analysis is provided in Table 2, which shows the values of standard deviation for average annual velocity, single measurement and positioning in terms of geographical coordinates (North, East, Height).The main limitation of this approach is the effect of the atmosphere on the propagating signal, resulting in artefacts which can hamper the precision of the measurements, if not properly removed. This limitation can be overcome by comparing many SAR images rather than just two, as in conventional Interferometry (InSAR). Then, the analysis is focused on the radar targets that exhibit a very stable radar signature in all the processed images. This approach, called «Interferometric Time Series Analysis», allows the implementation of powerful filtering procedures to estimate and remove atmospheric noise. Results can be accurately geocoded and integrated with other prior information in geographic information systems. Common to all geodetic applications, the results are computed with respect to a ground control point of known elevation and motion.

PRECISION (1)	C BAND SATELLITE	X BAND SATELLITE
Positioning (E-W)	7 m	4 m
Positioning (N-S)	2 m	1 m
Elevation (referred to ellipsoid WGS 84)	1,5 m	C
Average annual velocity	<1 mm/year	C
Single Measurement	< 5 mm	C

Table 2: Typical values of precision for a point less than 1 km from the reference point for a dataset of at least 30 scenes spanning a 2 year period.

2.3 MAIN FIELDS OF APPLICATIONS

Over the last decade Satellite Radar Interferometry has been successfully used in many diverse applications, spanning from the oil&gas sector for monitoring surface effect of hydrocarbon exploitation, to natural hazard sector for monitoring landslides and subsidence.
With particular reference to the Civil Engineering sector, Satellite Radar Interferometry measurements are used in the following phases:

Project Planning:
- Site and route planning
- Identification of unstable areas
- Reconstruction of historical displacement

Construction:
- Map local ground deformation
- Deformation directly due to excavation activities

Operation and Maintenance:
- Highlight areas of ground movement
- Monitor and asses areas at elevated risk of landslides, subsidence or structural integrity issues

Given the availability of historical images, for many areas it is possible to conduct:
- **Historical analysis:** performed in order to understand the evolution of historic ground deformation phenomena, which can due to either: subsidence, landslides, seismic faults, etc. This process fundamentally recovers ground deformation information otherwise unobtainable from traditional monitoring techniques.
- **Monitoring:** tasking satellites to acquire images over a particular area of interest it is possible to guarantee the availability of data, in particular over areas of known activity and risk. This method allows a monitoring program to identify, with regular updates, displacements occurring over an area of interest.

Satellite based Satellite Radar Interferometry offers, especially in urban environment, the advantage of a wider extended result about surface movements. This advantage can be exploited during and after the construction in order to complement very often spatially restricted terrestrial surveying results. This approach can be interesting, if during or after construction damages on buildings occur which are related to the underground construction activities by building owners. In these cases very often also compensation requests are made towards the construction owner. A clarification of the justification of these requests could be difficult if the relevant buildings are located outside the terrestrial surveying corridor: No surveying data are existent. In this case a satellite based «Back-up Monitoring» concept can support, if it is applied preventative: a continuous data acquisition during and after construction yields the data background without knowledge of the public. These data could be used for a regular (e.g. quarterly) processing and delivery of results to the building owner also for areas outside the terrestrial monitoring corridor. The data could also be used for any kind of stand-by processing - just in case a compensation request occurs during or after the construction with the need for justification.

2.4 GENERAL CHARACTERISTICS

The following Table 3 is intended to be a general reference document for requesting monitoring services with Satellite Radar Interferometry. Service levels can be different depending on the selected data and service provider.

Content

Satellite Radar Interferometry measures ground displacement by processing sets of radar images acquired by SAR satellite.
Measurement Points already existing on the ground (houses, buildings, metallic objects, pylons, antennae, exposed rock surfaces) or properly created (corner reflectors) are identified from the processing of SAR images. MP displacement is measured to millimetre precision. A suitable SAR interferometric time series analysis is applied on an increasing temporal stack of input data. The deliverables comprise a movement map of the average displacement rate (velocity) and the detailed movement history for each measurement point, as well as technical reports about the analysis. Series of Surface Movement Analysis with updated results can be carried out on a regular basis.
Note: The movement rates are inherently detected by the SAR sensor in Line-Of-Sight (LOS) direction. This is also the default component delivered. Vertical and East-West components can be delivered by properly combining and processing images acquired from ascending and descending orbits.

Requirements

The general scope is the detection and monitoring of surface displacement over the construction area and its surroundings.
It is requested:

- to define the satellite coverage of Area Of Interest (AOI) for the analysis;
- to identify Measurement Points (MP) in the AOI;
- to provide MP displacement (avg. displacement rate and time series) along the Line Of Sight of the Satellite;
- to provide MP displacement (avg. displacement rate and time series) along the Vertical and Horizontal (East-West) component, if ascending and descending images are available or planned;
- to provide an Historical Analysis, if an existing dataset of radar images is available;
- to update the SAR interferometric time-series analysis on a regular basis (annual, quarterly, monthly, etc.)
- to deliver reports and database of the results

Methodology

The choice of the technique to be adopted depends on local conditions. SAR interferometric time-series analysis available:

- Persistent Scatterers Interferometry (PSI);
- Corner Reflector Interferometry with SAR (CRInSAR);

Commercial algorithms/services and software are available.

Geographic Coverage

Worldwide.

Geometric Accuracy (horizontal)

It depends on input data source and available Digital Elevation Model (DEM).
For TerraSAR-X or COSMO-SkyMed, in flat areas typical figures: <1m.

Movement Precision

Precision figures are up to:

PRECISION (1)	C BAND SATELLITE	X BAND SATELLITE
Positioning (E-W)	7 m	4 m
Positioning (N-S)	2 m	1 m
Elevation (referred to ellipsoid WGS 84)	1,5 m	
Average annual velocity	<1 mm/year	
Single Measurement	< 5 mm	

Table 3: Satellite Radar Interferometry – General Characteristics

Update Frequency
Update Frequency of the analysis depends on the revisting time of the satellite and can be adapted/requested according to user requirements. Satellite revisting time: High resolution • TerraSAR-X: 11 days (4/7 days with the upcoming constellation of TerraSAR-X and PAZ) • COSMO-SkyMed: 8 days using the first two satellites of the constellation (up to 3-4 with the combination of the third anf fourth satellite of the constellation) Medium resolution • RADARSAT-2: 24 days • Sentinel-1A: 12 days Typical values of the SAR interferometric time-series analysis updates are: • Annual, bi-annual, quarterly, monthly
Geometric Resolution
Not applicable, if result is a vector file. If result is a raster map, depends on the resolution of the input data of the satellite. Maximum density of PS-points is defined by pixel size of input data, e.g. TerraSAR-X StripMap and COSMO-SkyMed Strip Map: each 3x3 m.
Input
In order to start a monitoring project with SAR interferometric time-series analysis inputs are: • Area Of Interest • Methodology • SAR images • Frequency of Updates • Geographic reference coordinates for the results
Input Data Sources
Preferred SAR data source for underground construction are high resolution SAR data like: • TerraSAR-X • COSMO-SkyMed. Alternatively, other SAR sensors at medium resolution are used (e.g. for a historical analysis): • ERS-1 / 2, • Envisat ASAR, • JERS and ALOS Palsar • Radarsat-1 / 2 • Sentinel-1A Initial baseline analysis is based on a dataset of approximately 15-20 SAR images. Updates are based on datasets of 4 – 6 SAR images, which complement an existing data stack.

Output
Minimum outputs of the analysis are: Reports • description of SAR data used for processing • description of applied Time-Series Analysis steps • movement map of the defined time period • accuracy estimation and a discussion of results with regard to given conditions Database of Measurement Points movement: • average displacement rate [mm/yr] • time series of displacement [mm]
Data Type
Report, database, raster map.
Delivery Format
Reports in: • Adobe PDF (.pdf) • MS Office • other formats on request Point vector data including average linear surface movement rates [in mm / year] and time series of displacement for each Measurement Point: • ASCII, CSV, MS Excel files or any other digital database • Digital ArcGIS files (or other GIS format)
Output Database Attributes
• Scatterer location : x, y, z coordinates [m] • Average displacement rate of the scatterer: v [mm/year] • Standard deviation of v [mm/year] • Local SAR incidence angle [degree] • Time series of movements [mm] All MP values relative
Coordinate Reference System
Reference system can be defined with the service provider on the basis of final user needs. Typically, results are produced in: • Datum: WGS84 • Projection: UTM
Output Delivery
• On digital support (CD, DVD, Hard Disk, ftp, etc.) • Through secure web platform
Metadata
ISO 19115 compliant XML file

2.3 STRENGTHS AND WEAKNESSES

STRENGTHS	WEAKNESSES
"Remote" derivation of surface movements without stepping into the field - no public attention; applicable also in sensitive or difficult terrain,	Distribution of Measurement Points dependent on land cover: Corner reflectors necessary in case of unsuitable land cover (e.g. stronger vegetation),
no "on-site preparation" efforts and costs as no benchmarking necessary if sufficient measurement pixels are naturally existent,	Satellite Radar Interferometry faces challenges in close vicinity of high buildings,
assessment of historical surface movement situation possible through the use of historic archives (e.g. ESA archive back to 1992),	Satellite Radar Interferometry cannot measure displacements along the North-South direction with millimeter or even centimeter accuracy as these movements are almost parallel to the satellite orbit direction.
Technology can be used complementary to conventional surveying techniques,	exact location of backscattering source is often not precisely known,
Wide area coverage: Anomalies also outside the expected impact areas can be detected, no detailed information about the foreseen impact area necessary.	intensive surface construction work with stronger earth movements or the appearance of snow / ice can challenge the analysis,
Improved spatial resolution of movement signal through high point density in infrastructure areas (up to 20.000 measurement pixels per sqkm) provided,	Estimation of abrupt and very localized movements is limited by the radar wavelength and spatial resolution of satellite data used (see figure 7). Movements larger than 1/4 of the SAR sensor's wavelength (e.g. for TerraSAR-X: approx. 1 cm) between two SAR acquisitions affecting a single point cannot be correctly estimated. However when the displacement affects many radar targets it is possible to overcome this limitation.
Good applicability for wide extended areas to be monitored as the size of area is not significantly influencing service price.	measurements are done in line-of-sight. Typically discrimination between vertical and horizontal movements can only be estimated if several geometries are used. No full 3D results are achievable
Satellite Radar Interferometry allows one to carry out multi-scale analyses. It can be used for regional studies, as well as for monitoring individual buildings and structures	Temporal updates are limited by satellite repeat-cycle, technology thus not suitable for realtime monitoring
Surface deformation can be measured over areas of thousands of km² at a fraction of the cost of conventional surveys - while achieving much higher spatial densities of measurement data	

Table 4: Strengths and Weaknesses of Satellite Radar Interferometry based monitoring

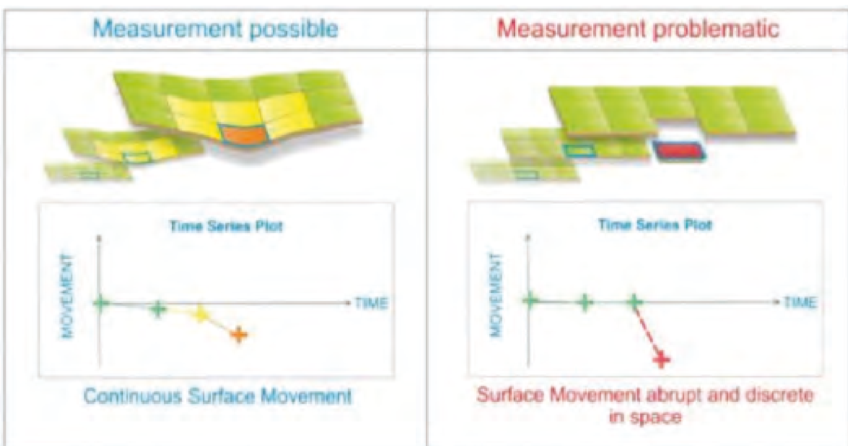


Figure 6. Measurement of abrupt and discrete movements

2.6 REFERENCE PROJECTS

Selected case studies will be presented in this section, demonstrating how satellite radar data can provide useful information during the various phases of underground infrastructure realization, from design to construction and management.

2.6.1 Bologna High-Speed Train Station (IT)

Background

In the framework of the construction of the high-speed railway from Milan to Naples, a tunneling work under the city of Bologna (Italy) has been recently completed [Pigorini et al. 2010]. It is a double-track tunnel with an excavation area of approximately 130 m^2, crossing urban surroundings at shallow depths (approximately 10 m) with a high density of commercial activities and residential housing.

Objectives

Considering the delicate urban and geotechnical context and the expected effects induced by the tunnel, during the construction phase it was decided to combine the comprehensive in situ monitoring system with satellite remote sensing data.

Approach

Satellite Radar Interferometry was carried out using both RADARSAT-1 (2003-2011) and ERS-1/ERS-2 (1992-2000) images (>280 images in total). Further comparison with tradtitional in situ survey data was carried out as well in order to verify and integrate different surveys technique for a more comprehensive understanding of the phenomena.

Results

The alluvial deposits, on which the Bologna city is build, are affected by land subsidence mainly induced by natural sediment compaction and groundwater exploitation for industrial, domestic and agricultural uses (Bitelli et al., 2000, Carminati et al. 2002). The overall subsidence was properly measured from satellite (Figure 7). The effects induced by tunnel construction arose in addition to these preexisting deformation phenomena. In order to highlight the displacements induced by tunneling activities alone, it was considered appropriate to select a reference point in such a way to minimize the displacement gradients due to generalised subsidence and to detect the sole displacements induced by the excavation works (Figure 8).

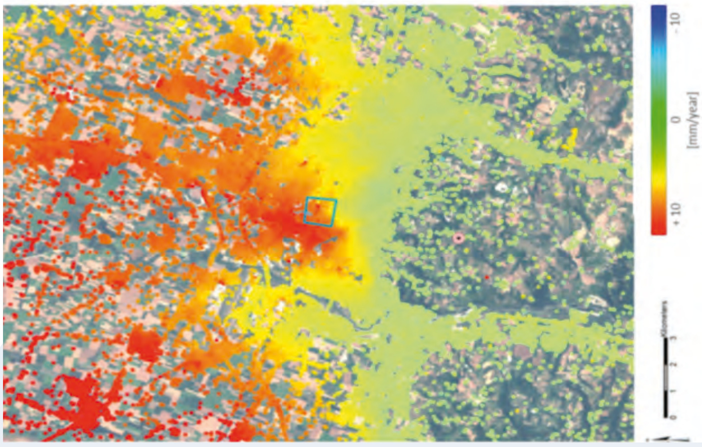


Figure 7: The subsidence of Bologna, map of PS/DS average displacement rate [mm/yr] along satellite LOS in the period 2003-2011; © Tele-Rilevamento Europa – T.R.E. Srl (TRE).

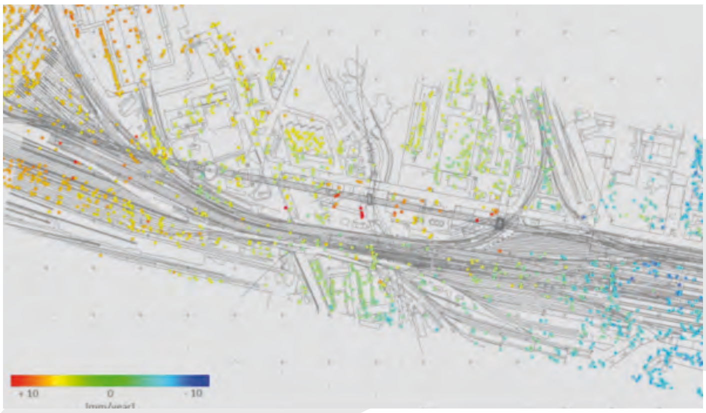


Figure 8: Bologna, map of PS/DS average displacement rate [mm/yr] along satellite LOS in the period 2003-2011; © Tele-Rilevamento Europa – T.R.E. Srl (TRE).

A Critical analysis of each single MP displacement time series, along with the chronology of the site and tunnel excavation activities (even before initiation of site works) have provided a detailed evaluation of any interference and other interesting deformation effects that have occurred at ground level.

Figure 9 shows an example of an historical displacement time series of a Measurement Point located near the tunnel center line. After the first section of the time series (2003-2007), which exhibits a general stability, the image shows an increase in the displacement values during 2007 and 2009-2010, both followed by stable periods. This behavior is in perfect agreement with the site work activities: the first increase in displacement values is related to the construction of 10 micro-tunnels between March and October 2007; the second is related to the tunnel advance in the first months of 2010. In the subsequent period the excavation front was far from the considered point (MP), and displacement stopped, confirming the final stable section of the displacement time series.

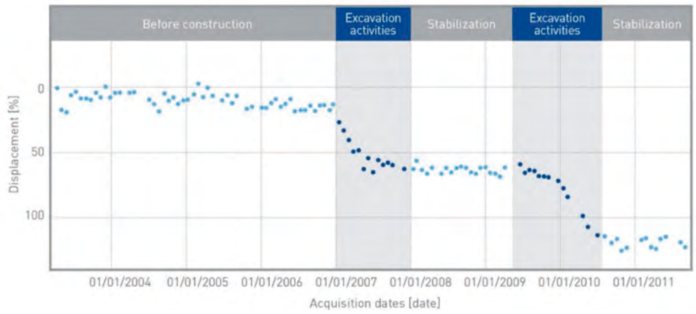


Figure 9: MP displacement time series, showing the effects induced by tunnel excavation; © Tele-Rilevamento Europa – T.R.E. Srl (TRE)

The use of satellite data provided a very useful dataset to be compared with the displacement values measured by in situ instruments. In this case, it was also possible to compare the Measurement Point displacement time series provided by the Satellite Radar Interferometry analysis with the settlement rates estimated by optical leveling surveys. In order to make such a comparison possible, it was necessary to define a common reference point and reproject ground measurements along the satellite line of sight.

Figure 10 shows a comparison between a MP displacement time series and the settlement time series of the corresponding topographic leveling benchmark.

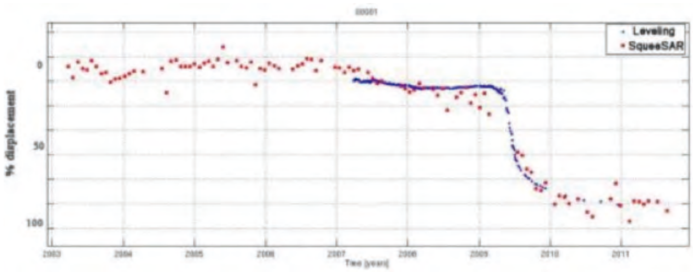


Figure 10: Comparison between satellite data (red dots) and traditional topographic data from levelling surveys (blue dots); © Tele-Rilevamento Europa – T.R.E. Srl (TRE)

The optimal correlation between the two data-sets confirmed the precision of the Satellite Radar Interferometry technique for the detection and estimation of surface displacement phenomena. It should also be noted that the positive result of the comparison gave evidence to the accuracy and reliability of the satellite data, not only for monitoring slow and constant-velocity movements, but even in cases characterized by small absolute displacements with abrupt changes and significant variations in average velocity values.

2.6.2 Scianina-Tracoccia Tunnel (IT)

Background

In September 2001, during the excavation of the Scianina-Tracoccia tunnel for the Palermo-Messina railway line, a landslide occurred on the North slope of the hill near the village of Tracoccia [Pigorini et al. 2010]. The tunnel excavation section on the Messina side (about 156 m) was completely destroyed, as well as part of the tunnel entrance. The landslide created an escarpment exceeding 20 m in height and caused a percolation leak from the nearby dump.
Tunnel restoration required the slope to be restabilised with reprofiling intervention consisting of the construction of an embankment of about 60 m height. The tunnel was then reconstructed according to the original layout, by carrying out significant consolidation treatments.

Objectives

After the landslide, an accurate monitoring system aimed at monitoring the status of the slope and the safety of preexisting structures was proposed. Given the complexity of the context in which the tunnel was constructed, it was suggested to continue the monitoring activities of the structural stability of the slopes for a further three years after the completion date, in accordance with the recent Italian regulations.

Approach

The monitoring plan included not only the conventional control of the deep displacements by means of geotechnical instruments (e.g. inclinometers), but also surface displacement monitoring by means of satellite data. Since there were no natural reflectors on the slopes because of the severe changes in the surface profile due to the landslide, a network of artificial Corner Reflectors was installed (Figure 11). The artificial reflectors do not require any supply or maintenance activities and can be used, if considered necessary, even for long periods. The processing, spanning July 2009 till July 2012, has been performed with the aim of retrieving the vertical and easting component of the ongoing deformation. This is possible since artificial reflectors are designed so that they are visible to the satellite in both satellite acquisition geometries (ascending and descending), representing the very same point on the ground.

Results

Satellite results are in good agreement with deep slope displacements measured by inclinometers and guarantee the restabilisations works effectiveness. Average deformation rates along with displacement time series have been exploited: the result of the analysis demonstrate that all reflectors are affected by slow movements. The main motion component is vertical, but in some cases also a significant East-West component is present (no info regarding the N-S component has been given, since the satellite in almost blind in this direction). Figure 12 shows the Time Series of the Vertical and East-West component (positive values toward East direction) of one of the Corner Reflector installed.
A Critical analysis of each single MP displacement time series, along with the chronology of the site and tunnel excavation activities (even before initiation of site works) have provided a detailed evaluation of any interference and other interesting deformation effects that have occurred at ground level.

Figure 11. View of an artificial reflector installed on the slope of Tracoccia, Sicily; © Tele-Rilevamento Europa – T.R.E. Srl (TRE).

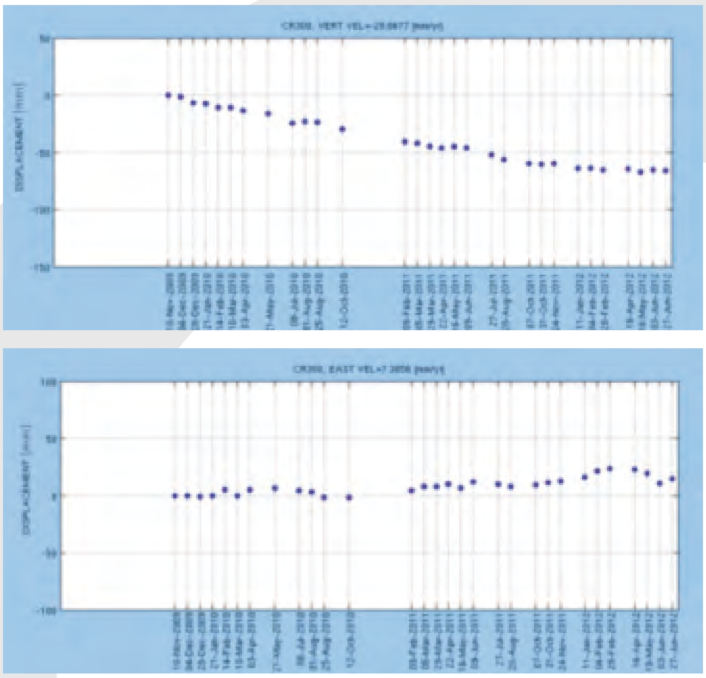


Figure 12: (up) Vertical and (down) East-West (positive values toward East) Time Series of displacement of one of the Corner Reflectors installed in Tracoccia, Italy; ©Tele-Rilevamento Europa – T.R.E. Srl (TRE).

2.6.3 Budapest Metro 4 (HU)

Background

In Budapest the new Metro4 subway line has been constructed from 2006 until 2009 using tunnel driving machines for the tunnel itself and a Top-Down method for the metro stations. During construction, an intensive terrestrial surveying program has been established in order to monitor surface movements related to the construction. Subsidence occurred due to underground construction in the order of up to 6,5 cm resulting in slight effects on buildings, too.

Objectives

The objective of this project was to use TerraSAR-X and a Persistent scatterer interferometric (PSI) processing approach to resolve surface movements related to the subway construction. Furthermore, a comparison between the results derived from TerraSAR-X and terrestrial surveying was foreseen.

Approach

A PSI processing has been done on base of in total 43 TerraSAR-X StripMap datasets, which have been acquired between 24/10/2008 and 16/04/2010. As such, the time period of available TerraSAR-X data was not fully covering the time of underground construction. From the data stack, persistent scatterer point candidates have been estimated. Initial topographic information derived from an initial SRTM digital elevation model has been corrected using phase information from the available data stack. This updated information has been used in order to correct for the topographic phase. An atmospheric phase model has been generated from the available data stack and used for reducing the influence of existing atmospheric phase.

Linear phase distributions have been derived resulting in displacement velocities for each PSI point in the area of the City. Specific emphasis has been given to the existent of also non-linear surface movements resulting due to the temporarily restricted operation of the tunnelling driving machines. For this purpose also a Small Baseline Subset (SBAS) approach has been used.

Results

The illustration of linear surface displacement rates in Figure 13 clearly shows the line shape of surface movements is clearly visible aligned from North East to South West to the river. It is related to a subway construction of Metro4 in Budapest. The highly non-linear surface movements related to the construction of metro station Szent Gellerért tér nearby the river have also been resolved.

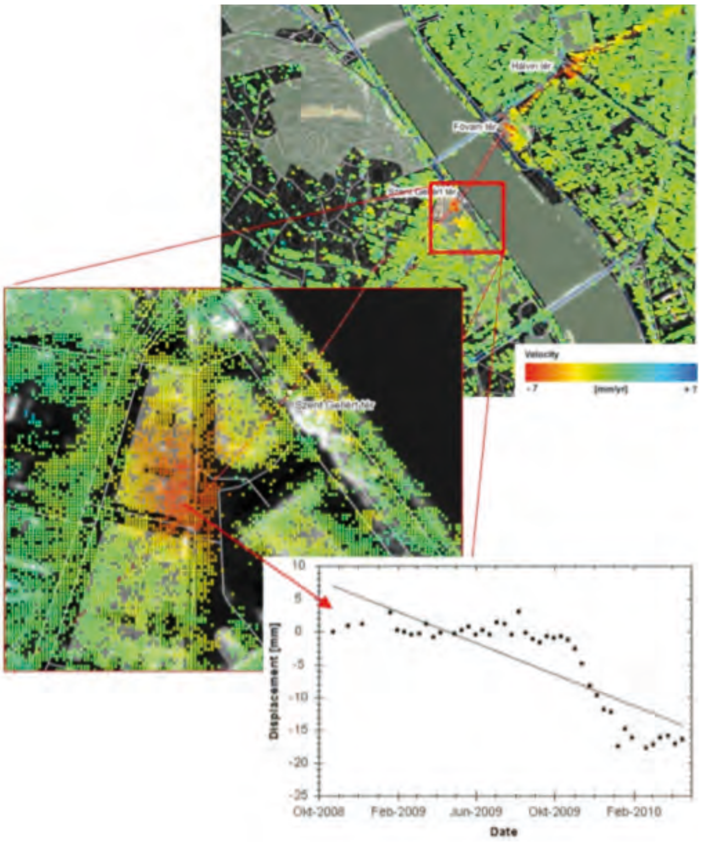


Figure 13: (a) PSI Analysis in the wider area of Station Scent Gellerért tér on base of 43 TSX satellite data sets between 24/10/2008 and 16/04/2010; (b) focused SBAS Analysis in the area of Station Scent Gellerért tér on base of 8 TSX satellite data sets between 28/08/2009 and 05/04/2010; (c) sample time series of surface displacements showing the highly non-linear displacements induced by temporarily restricted time of construction; © Astrium Services

2.6.4 Further Reference Projects

- **Venice-Trieste New Railway Line (IT).**

Satellite Radar Interferometry has been applied in the preliminary design of the new Venice-Trieste railway line for the assessment of the planned alignment [Pigorini et al. 2010]. The analysis highlighted an active landslide along the proposed alignment. The integration of the results with geological studies and other geotechnical surveys allowed the identification of an alternative alignment in a more suitable area for the construction of the definitive route (Figure 14).

- **Brisbane, Airport Link (AUS).**

The Airport Link is a tunnelled motorway grade road which is under construction in the northern suburbs of Brisbane, Queensland, Australia. It will connect the Brisbane central business district and the Clem Jones Tunnel to the East-West Arterial Road which leads to the Brisbane Airport. The Airport Link and busway project involves 15 km of tunnelling. Satellite Radar Interferometry highlighted surface movements aligned according to the tunnelling project in the northern part of the processing area which relates to the progress of the underground tunnelling machine, plus an area of strong subsidence in the South due to groundwater extraction (Figure 15).

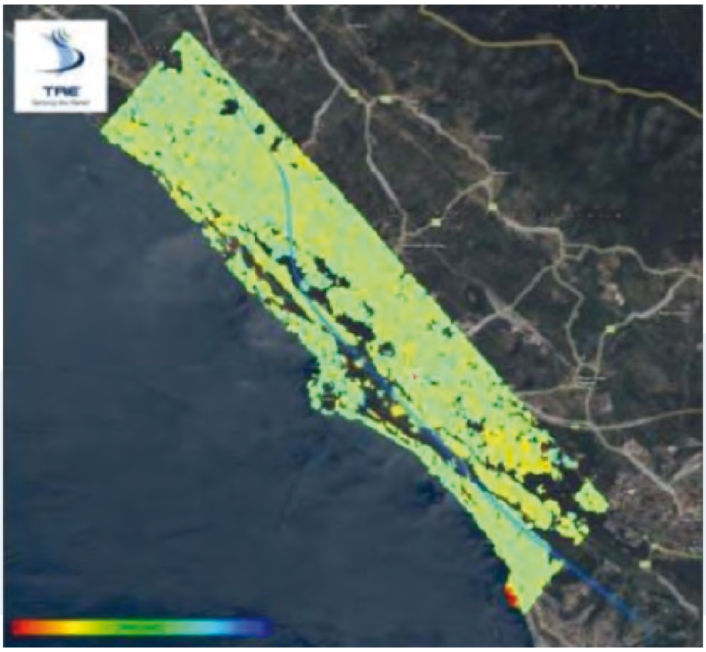


Figure 14. View of an artificial reflector installed on the slope of Tracoccia, Sicily; © Tele-Rilevamento Europa – T.R.E. Srl (TRE).

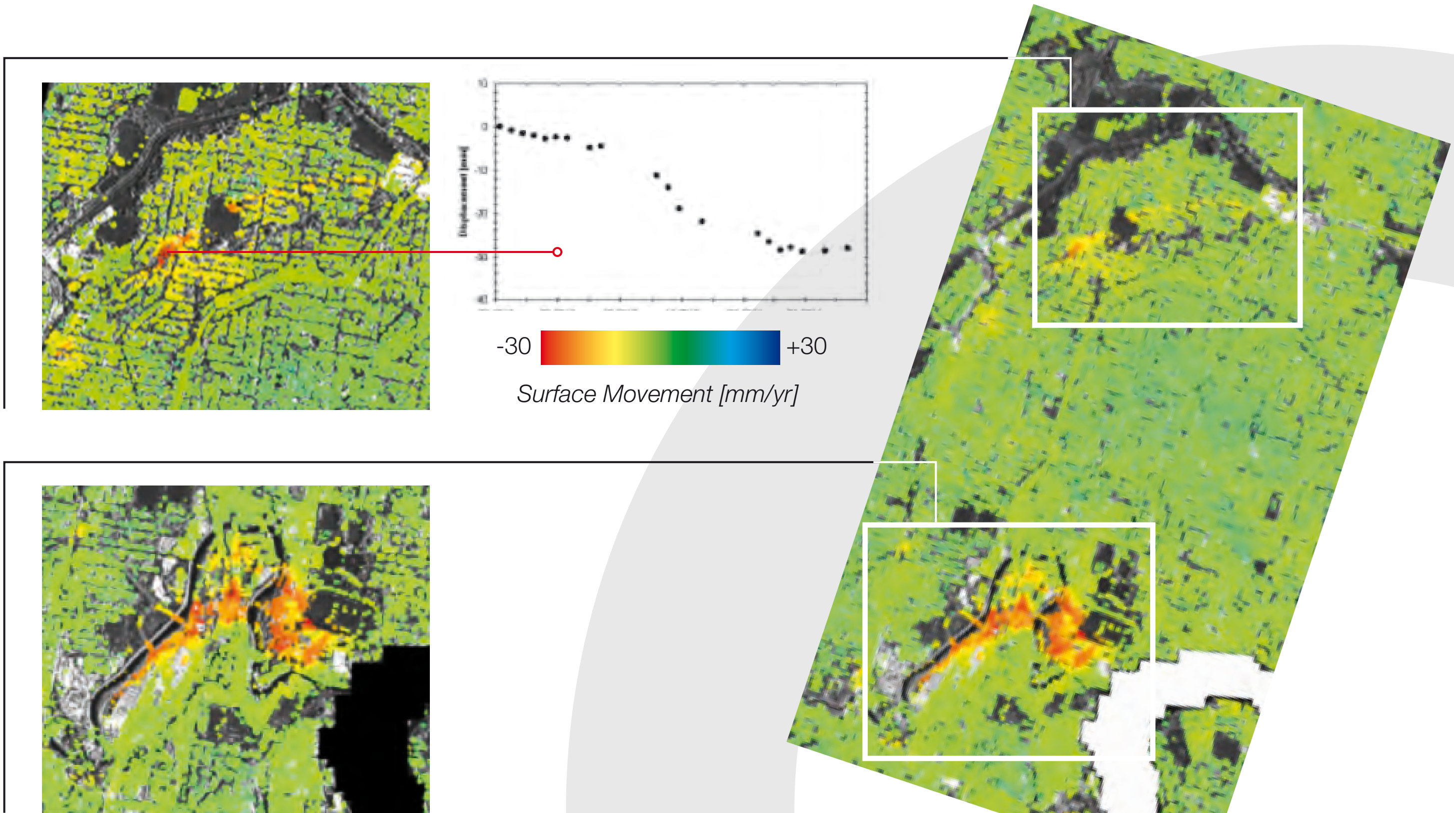


Figure 15: SBAS Analysis for the wider area of Brisbane Airport Link Tunneling project on base of 20 TSX satellite data sets between 05/06/2010 and 16/04/2011 including some Zoom-Ins and a sample time series of displacements; © Astrium Services

2.7 APPLICATION RECOMMENDATIONS

Satellite Radar Interferometry has been already applied in many projects related to underground tunnelling and has proven to be a useful tool in all stages of an underground project, from design to construction and management. Compared to conventional surveying methods, Satellite Radar Interferometry provides higher spatial resolution at lower cost, being particularly convenient for wide areas monitoring. Satellite Radar Interferometry usually does not require any in-situ ground instrumentation. Occasionally, where no Measurement Points already exist, Corner Reflectors can be properly installed and monitored.

Satellite Radar Interferometry it is recommended when you want:

- To have a synoptic view of the local dynamics, before the beginning of excavation. Archive data are available since 1992.
- To integrate conventional monitoring during construction phase and to enlarge monitoring areas outside terrestrial surveying corridor.
- To verify compensation requests during legal disputes for damage claims when buildings are not monitored by other techniques.
- To monitoring longterm displacements during operational phase.

Costs of a Satellite Radar Interferometry monitoring service for an underground construction sites are very project specific. In fact they may vary due to different boundary conditions as well as different specific user requirements. Typically, the following parameters influence the costs of the service:

- Number of SAR images to be processed

A dense temporal sampling of the monitoring program requires a dense temporal acquisition of suitable SAR datasets, which increases the costs of the service.

- Update Delivery Frequency

The higher the frequency for delivering Satellite Radar Interferometry results, the higher are also processing efforts: a monitoring project with monthly updates is more expensive than one with quarterly deliveries.

- Size of the area of interest

The larger the area to be monitored, the higher the processing efforts and the relative costs. However, since each satellite image covers a wide area (100x100 Km or 30x50 Km, depending on the satellite used) the increase in cost is not significantly related with the extent of the area to be monitored. Economies of scale apply. It is also to be noted that, in contrast to terrestrial approaches Satellite Radar Interferometry service costs are not dependent on the number of surveying points, i.e. Measurement Points.

User requirements and boundary conditions must be clearly communicated in order to have precise and reliable quotation.

Laser scanning is becoming increasingly popular in tunnelling, as the technology becomes mature, devices more robust and affordable. However laser scanning is not a new technology in tunnelling applications. It was first used in underground environment around 2003 and is used there since then for different applications. The most common ones are described below:

3.1 TECHNOLOGY

With laser scanning it is possible to get a 3D picture of the real world with millions of points in a very short time. The technology was first used for rapidly capturing the shapes of objects such as buildings and landscapes. In the meantime, laser scanning is used in many different environments and domains. There are several manufacturers that provide diverse scanner models that differ in limitations, specific advantages and costs. Some of them match the requirements in measurement precision and range of monitoring applications in tunnelling.

Principle of a laser scanner technology

A) Time-of-flight

Time-of-flight scanners emit a pulse of light which is reflected from the surface of an object. The device measures the time until the reflected pulse is received and is able to calculate the distance, based on the speed of light. The precision of the distance measurement is therefore largely limited by the precision of the clock. The strength of this technique lies in its ability to measure data at very long ranges compared to the phase-shift approach described below. Measuring speed is up to about 100’000 points per second for current high-end devices, which is significantly less compared to what can be achieved by comparable phase-shift scanners.

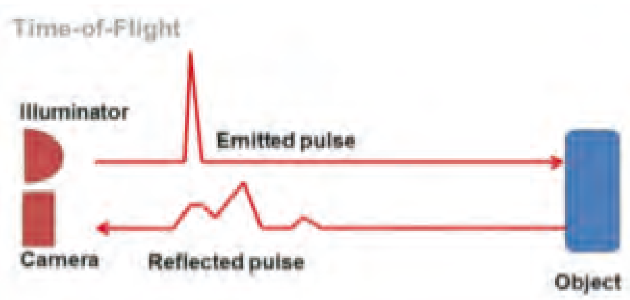


Figure 16. Time-of-flight principle.

B) Phase-shift

Scanners using phase-shift technology emit a constant laser beam. The laser beam is typically split and each part modulated with different wavelength. The distance is then determined by measuring the phase shift of the reflected beam. The limiting factor for the unambiguously measurable distance is the longest wave length of the emitted signal. With current high-end devices, up to 1 million measurements can be recorded per second. In the last few years, phase-shift technology has become dominant in the industry.

C) Full waveform digitization

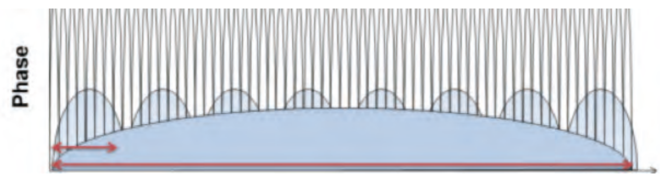


Figure 17. Phase-shift principle.

Full waveform digitization (FWD) is an emerging technology in laser scanning, based on a similar principle as time-of-flight method. With FWD, the returning signal is sampled over its whole length, so that several echoes can be extracted in case of half-penetrable surfaces. Also information about the surface can be derived from the sampled signal. This technology offers comparable range and measurement speed as its time-of-flight counterpart.

Stationary vs. kinematic laser scanning

Time-of-flight scanners emit a pulse of light which is reflected from

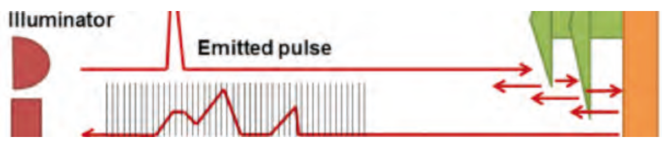


Figure 18. Full waveform digitization principle.

The measuring method can be roughly separated into two groups: stationary and kinematic. In stationary scanning, spherical scans are recorded from discrete positions in the tunnel. As opposed to this, in kinematic scanning, the scanning device is mounted on a vehicle that moves through the tunnel while continuously recording a helical point cloud. Depending on the measuring method, different positioning/georeferencing methods can be used.

Figure 19. Stationary system on a trolley (left) and kinematic scanning system (right).

3.2 ACCURACY/PRECISION

Stationary scanning typically uses reference targets (spheres, cylinders, black/white targets) for connecting to a given project coordinate system, and bundle adjustment/free stationing technique provides high absolute and relative precision in the low mm range if the frame conditions are good, e.g. a high control point network quality is guaranteed a sufficient and well distributed number of reference targets is available. In a tunnel environment, this approach has some weaknesses. Progress of measuring works can be slow because targets need to be mounted, surveyed and moved between setups. Extra equipment may be necessary, e.g. to set bolts for the targets. New targets must be mounted and measured with the total station frequently. For each laser scanner position at least 3 targets must be visible. In an active tunnel heading a quite high number of targets is usually needed so that the general construction process doesn't hide too many targets.

Kinematic laser scanning offers high relative precision and very dense and regular point clouds. Absolute accuracy is limited by the longitudinal component, which depends largely on the precision of the synchronization between the tracking total station, the sensors on the trolley and the scanner itself. For deformation analysis, relative accuracy is the important factor. In order to reach the best results, a stable track along the entire scanning area is required, which is not always available. Compared to rail-based systems, road-based systems require regularly paved surfaces without obstacles. The necessary equipment for kinematic scanning is more bulky compared to stationary scanning, resulting in higher logistic efforts. A major application for kinematic scanning is real time clearance, where the requirements are usually met.

The following table summarizes some of the characteristics of the discussed methods.

METHOD	STATIONARY	KINEMATIC
Achievable relative accuracy	~ 5 mm	~ 3 mm
Achievable absolute accuracy	~ 5 mm	5 - 10 mm
Achievable meters per hour	Up to 150 m/h	Up to 500 m/h
Personnel	1-2	2

Table 5: Comparison of laser scanning methods in tunnelling and achievable accuracy from reference projects carried out in the past years.

3.3 MAIN FIELDS OF APPLICATIONS

In the last years the detection of tunnel surface deformation using laser scanning was used in several underground projects around the world. However, there have been also discussions about several topics: data processing, data accuracy, real time availability and point density.

When using the laser scanning option the main applications are
- the deformation detection of inner lining segments
- the deformation detection of SCL Linings
- the deformation detection of any underground surface

Figure 20 Deformation detection of SCL Linings (left) and deformation detection of inner lining segments (right).

3.4 GENERAL CHARACTERISTICS

General characteristics which may be different depending on the specific task and selected service provider are shown in Table 6.

Content
Laser scanning is becoming increasingly popular in tunnelling, as the technology becomes mature, devices more robust and affordable. However laser scanning is not a new technology in tunnelling applications. It was first used in underground environment around 2003 and is used there since then for different applications. Applications such as Excavation records has been the major ones however in the past years also laser scanning technology was used for monitoring purposes. A Laser Scanner can collect within minutes millions of 3D points and images which can be compared to each other. Deliverables of laser scanning data are: • Inhomogeneas 3D point cloud with millions of points • 2D maps with the couloured raster data inforamtion of the displacement • 3D Views with coloured information of the displacement
Geographic Coverage, measurable objects, measuring range
Worldwide applicable, however in these days laser scanning technology are often in use in developed country and not in emerging markets. Optimal are objects which can be measured between an angle of incidence (from the laser beam) from 45° to 90° to the surface. Measuring distance depends on the supplier but a general range is from 2 – 100m, for high accuracy measurements up to 1.5*diameter of the tunnel (e.g. tunnel diameter 10m = 15m good measuring distance).
Input data Sources
Relative measurements of angle, distance and reflectivity in relation to the laser scanner positioning. Absolute coordinates Easting/Northing/Height and Reflectivity of the point cloud. Reflectivity describes the dense of reflection from the laser beam on the surface.
Methodology
Inhomogeneas point cloud described by angle and distance for every point.
Geometric Resolution
Measurement is done in a local coordinate system, transformation to/tying to absolute project coordinate system is possible by additional measurement of a sufficient number of reference points (targets).
Geometric Accuracy
Depends on the laser scanner supplier and the type of technology which is chosen (time-of-flight, phase-shift or full waveform digitization) a different accuracy can be reached. However the bigger impact of the accuracy is giving by the chosen positioning method (stationary or kinematic). Achievable accuracy (standard deviation) is up to 3 mm.

METHOD	STATIONARY	KINEMATIC
Achievable relative accuracy	~ 5mm	~ 3mm
Achievable absolute accuracy	~ 5mm	5 – 10mm

Movement precision
Movements in the range of 5 – 10mm can be determined
Update Frequency/Measuring interval
Depends on the application laser scanning is used. However for Laser Scanning measurements often the maximum frequencies is once a day. Often the measurements are also carried out less e.g. once a week for instance.
Delivery Format
3D Viewer of a local supplier with easy tools to navigate in a 3D view or in a deroled 2D map. Reports in (*.pdf) Diagrams, maps and contour plots showing displacements (*.pdf, *.png, *.jpg,…)
Data type
2D maps, 3D views, reports of cross sections

Table 6 Remote Measurement with Laser Scanning – General characteristics

3.5 STRENGTHS AND WEAKNESSES

STRENGTHS	WEAKNESSES
Complete coverage of the tunnel surface area and not just single points like in traditional 3D convergence monitoring (high spatial resolution of a few mm on the tunnel/object surface)	The reached absolute accuracy of 5 – 10mm is not sufficient for all kind of monitoring applications No real time capability
Achievable relative accuracy of up to 3mm Achievable absolute accuracy of 5 – 10mm	Technique can only measure surfaces but not look behind. The surface structure may not change between measurements (e.g. deformation cannot be processed if a 2nd shotcrete layer is placed between two measurements)
Capable underground and above ground	Data processing requires expertise and sophisticated software and knowledge, low degree of automation in data processing
Results are ready within a short time after measurement	Quality of results highly depends on various factors such as incidence angle, surface reflectivity, … Higher measurement effort and time compared to monitoring with total station

Table 7: Strengths and weaknesses of laser scanning technology.

3.6 REFERENCE PROJECTS

3.6.1 Rock Laboratory Mont Terri (CH)

Background

The Rock Laboratory Mont Terri is situated north of the city St-Ursanne in the canton Jura, Switzerland. The Rock Laboratory is an international research platform serving 14 project partners worldwide. The international research platform analyses the suitability of argillaceous rock – in this case the Opalinus Clay – for the disposal of radioactive waste.

Objectives

The objective of this project was to compare 3D convergence measurements against laser scanning data.

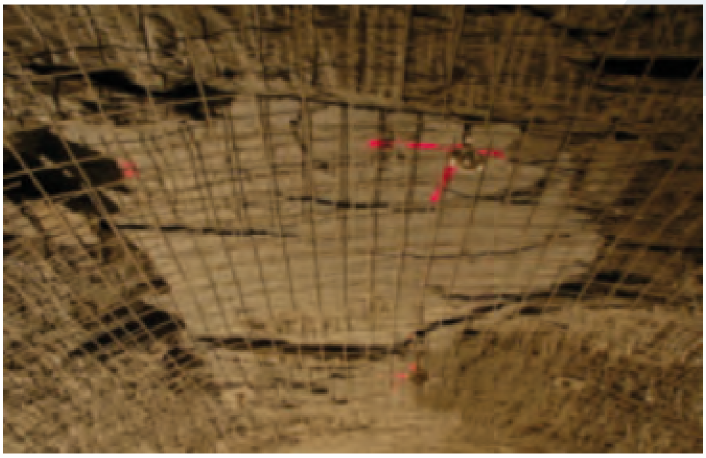


Figure 21. Fault zone in the Mt. Terri project (Lehning 2009).

Approach

In the year 2008, a surveying company carried out daily stationary laser scanning measurements during excavation of a new tunnel. For a month conventional 3D convergence measurements were taken daily in addition to the laser scanning. The source data was analysed for comparison of the laser scanning and the 3D convergence measurements. The laser scans have been recorded with a Z+F Laser scanner Imager 5006 (using phase-shift technology) and TMS Tunnelscan software. The registration of the point clouds was performed with help of four to five sphere targets per station. The resulting point clouds achieve an absolute accuracy of the scan data of 5 millimetres.

Results

To find stable control points was a big challenge in this job since the regular control points also were subject to deformation due to the on-going construction process. To reach this, high accuracy of 5 millimetres in absolute coordinates was needed. The positioning of the scan clouds was performed with the bundle adjustment method. For this specific application, the resulting absolute accuracy derived with the APMTM method was not sufficient.

In Figure 22, laser scanning data from 27th May 2008 and from 6th June 2008 are compared. Between the two scans, a steel mesh was installed due to the instability of the Opalinus Clay. On the TMS Tunnelscan report (see Figure 22), the iron mesh is highlighted in red colour. Deformation of more than one centimetre is visualised in yellow colour. The orange area indicates deformation of more than two centimetres whilst red colour indicates deformation of more than three centimetres.

The white arrows in Fehler! Verweisquelle konnte nicht gefunden werden. show the 3D convergence points. The analysis of the traditional convergence measurements shows no deformation at these points. However, just next to the 3D convergence points, the laser scanning analysis shows deformation of one centimetre in ten days, which cannot be detected by the 3D convergence measurements. This example points out the biggest benefit from surface deformation control with laser scanners.

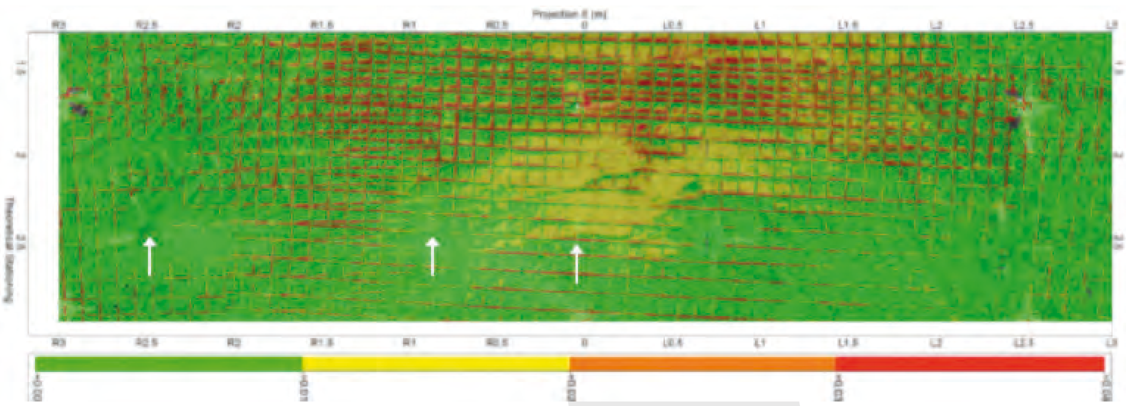


Figure 22 Deformation analysis of two laser scans with TMS Tunnelscan.

3.6.2 Bypass Biel - Tunnel Büttenberg and Längholz (CH)

Background

The construction work of the eastern part of the project “Biel bypass” (A5-Ostast) started in 2007 and is scheduled to finish in 2017. Purpose of this bypass is to connect the motorways A16 and A5 in direction of Solothurn as well as the T6 to Lyss/Bern. Thereby, the traffic load on urban roads in the city of Biel should be reduced massively. The project includes two twin-tube tunnels. Both tunnels, the Büttenberg tunnel (1460 m) and the Längholz tunnel (2480 m), were built using a tunnel boring machine with segmental lining.

Objectives

The objective of that project was to detect the deformation of the segment rings with kinematic laser scanning method.

Approach

After having finished the tunnel excavation, the customer was interested in a full as-built-documentation of the tunnel. On one hand, the as-is-state had to be compared to the design. On the other hand, the deformation of the segment rings had to be verified and documented.

In 2010 and 2012, the surveying company measured both tunnels completely (total length: 7880 m) with a kinematic laser scanning system. The major part of the job was carried out using the Amberg GRP 5000 system, a rail based kinematic laser scanning system. After pavement construction, the concrete invert was measured with the road-based equivalent system MISS (Mobile Infrastructure Scanning System).

Since the blocking period of the tunnel was very short and the requirement on accuracy very high, kinematic laser scanning emerged as the optimal method for these tasks.

Characteristics of the measurements:

- Point density of laser scanning data: 10 mm
- Precision of the point cloud (absolute coordinates): < 10 mm
- Precision of measured profiles (relative coordinates): < 2 mm

Results

As the tunnel surface was measured nearly perpendicular in kinematic scanning mode, the relative accuracy of the profile is high enough to allow the detection of deformations of the assembled segments in the range of a few millimetres.

To obtain the deformations within the required accuracy, the measured profiles of both measuring periods were matched with the design profiles by a least square calculation. A comparison of these two profiles shows the deformations.

All calculations were done using the software packages Amberg Rail and TMS Office. The results were presented in the form of profile reports as well as in the form of colour maps (Figure 23).

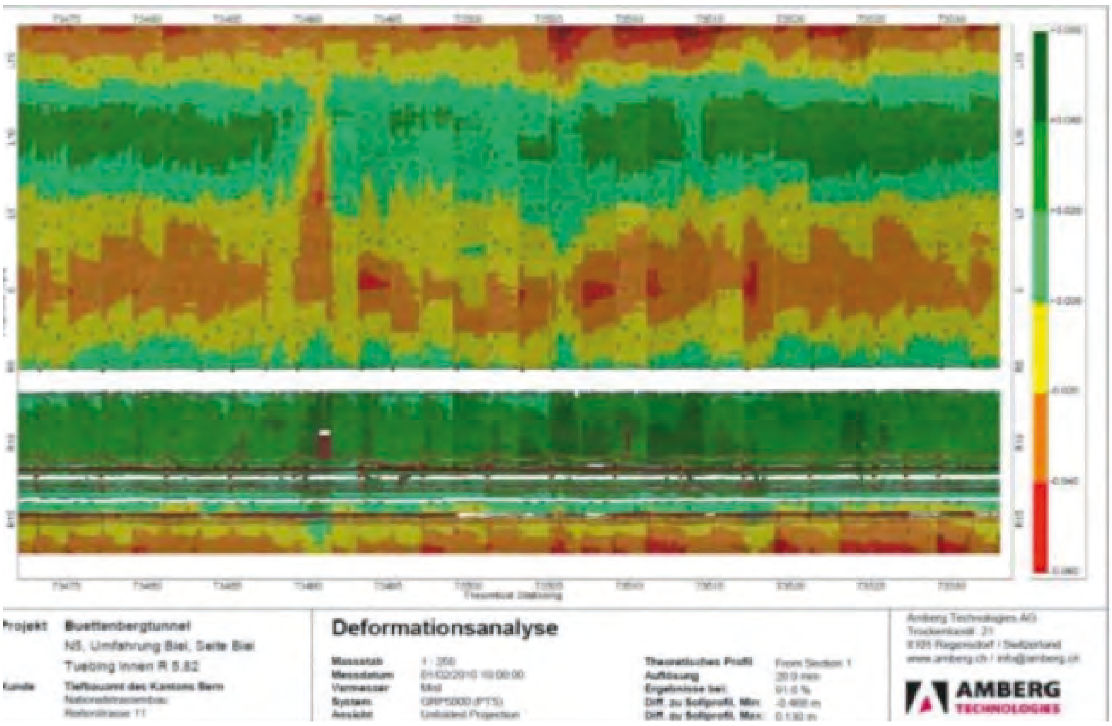


Figure 23. Colour map report of segment deformation from TMS Tunnelscan.

3.6.3 Bosrucktunnel 2nd tube (AT)

Background

Construction of the 2nd tube of the Austrian Bosrucktunnel, a 5.5 km road tunnel of the highway A9 connecting Spital am Pyhrn (province Upper Austria) and Liezen (province Styria) started 2009. The tunnel that was constructed by the New Austrian Tunneling Method (NATM) opened in 2013.

Objectives

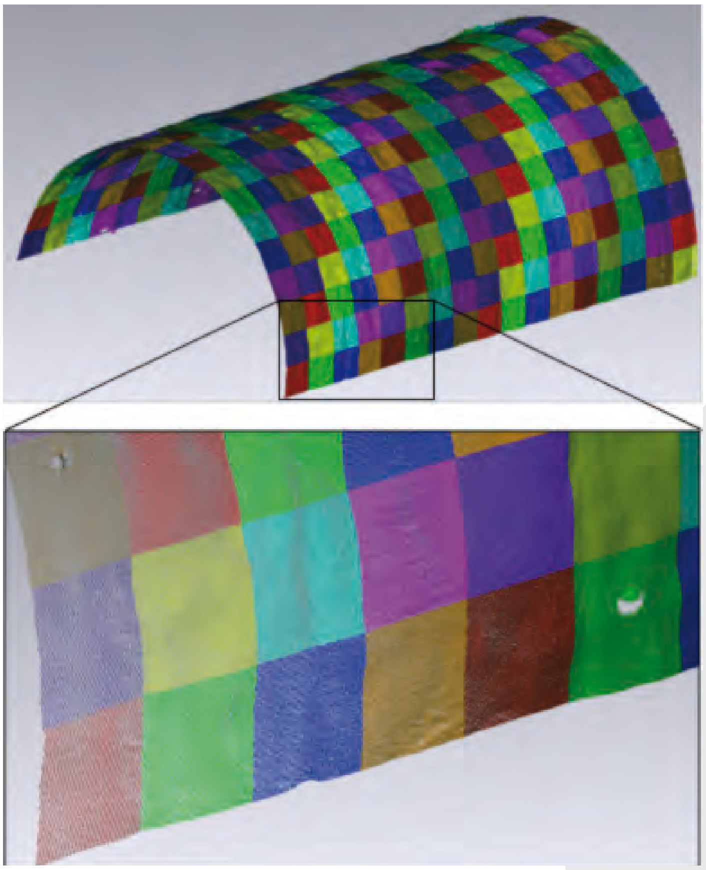
During tunnel excavation, the absolute 3D displacements of the entire shotcrete surface of the tunnel wall of a short section had to be determined with an accuracy of < 5 mm.

Approach

In order to provide the required information, static 3D laserscanning was applied using a 3D phase scanner (Faro Photon). Consecutive scans were performed, the first immediately after shotcreting, the last after several days. Each scan was connected to the absolute project coordinate system by scanning wallmounted reference targets (sphere targets) that got observed by total station measurements prior to scanning. The shotcrete surface was scanned in static mode from a tripod with a resolution of approx. 1 scan point per 5 mm2.

Results

To obtain the 3D surface displacements within the required accuracy, the scan data were processed applying a new-developed 3D surface matching technique. The technique uses the ICP-algorithm (Iterative Closest Point) to match spatial grid points located in automatically extracted tunnel surface patches of 1 x 1 m size (Figure 24 left). For each individual patch a 3D displacement vector was derived by transforming the measured point cloud onto the point cloud of its zero reading by least squares adjustment (ICP-algorithm). In this way, the 3D displacement vectors of all patches covering the whole tunnel section were derived (Figure 24 right).



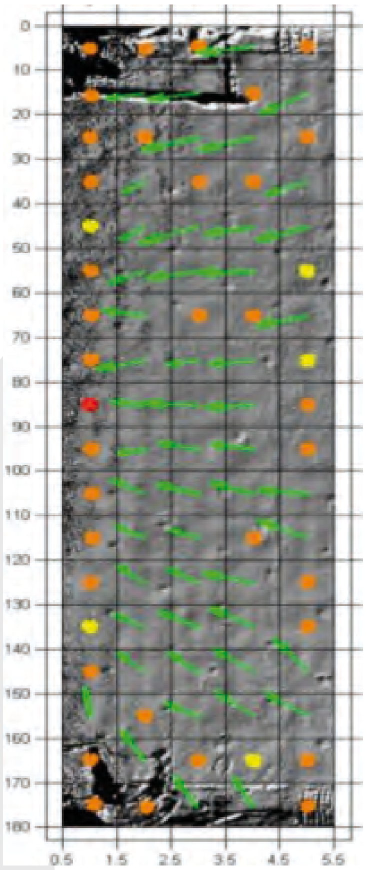


Figure 24. Automatic separation of shotcrete surface patches from the overall point cloud (left) and 3D displacement vectors of patches of a tunnel section of 5m length (right).

3.6.4 Further Reference Projects

- In Beijing (China) some section of the existing metro network are periodically monitored with stationary and kinematic laser scanning measurements. The goals of the measurements are to monitor ring convergence, cracks and leakages.


Figure 25 Stationary laser scanning in Beijing Metro Line (left) and the results in a 3D Viewer (right).

- In Kaunertal (Austria) a hydropower shaft is periodically measured to detect the pipe ovality. Therefore a traverse was measured through the whole shaft. Profiles were measured every 3 to 5 m. Deformations were displayed on the fly in the field.

Figure 26 Access to the pipe.

- In Seattle (USA) the Alaskan Way Tunnel is constructed under the city, using the world's largest TBM, at nearly 18 m diameter. Laser scanning was proposed as an alternative to traditional survey, because of its ability to provide interesting results even is very constrained environment. See photo of the scanner inside the TBM.

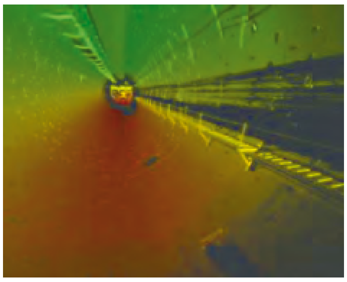



Figure 27 Laser scanning inside a TBM (left) and results in a 3D Viewer.

3.7 APPLICATION RECOMMENDATIONS

High speed laser scanning is a very fast acquisition method and allows data collection for a complete deformation analysis above and underground. Depending on where the laser scanner is placed, different positioning methods are suitable.

The results of high speed laser scanning technology can achieve a relative accuracy of 3 mm for the kinematic approach. To achieve a similar absolute accuracy, the conditions for the positioning must be ideal. However, an absolute point cloud accuracy of 5 – 10 mm is well possible with the technology available today.

Our case studies show that deformation monitoring based on high-speed laser scanning technology is feasible. This technology helps to detect smallest movements on the tunnel surface where 3D convergence measurements or other geotechnical sensors just show the movements of one specific point. For absolute movement detection, the deformation rate must be at least in the range of 5 mm.

4 >> Reflectorless Measurements with Total Stations

4.1 TECHNOLOGY

A total station is an electronic/optical instrument used in modern surveying. It is the primary survey instrument in tunnelling for about 30 years already and used for a variety of survey tasks. A total station consists of an electronic theodolite to read horizontal and vertical angles and an integrated electronic distance meter to read slope distances from the instrument to a particular point. Measurement of distance is accomplished with a modulated microwave or infrared carrier signal, generated by a small solidstate emitter within the instrument's optical path, and reflected by a prism reflector or, in case of reflectorless measurement, directly by the object's surface under survey.

Reflectorless total stations (RTS) can measure distances to any object providing an appropriate physical surface condition (i.e. sufficient reflectivity). Measuring distances may range from a few meters to a few kilometers. The reflectorless option is already utilized for a variety of short-range applications in tunnelling such as profile check and setting out. In recent years the option has also been used for deformation monitoring in automatic monitoring systems. Such systems are able to determine object (surface) deformation from periodically repeated measurements, so called monitoring epochs or cycles.

Most basically such automatic monitoring systems consist of

- a robotic total station capable to perform reflectorless distance measurements,
- a nearby control computer running a software application capable to control the instrument and to acquire, process and store the measurement data,
- a telemetry or wire-based link capable to transfer the data between the instrument, the control computer and eventually also further to a remote information system using arbitrary communication protocols (e.g. serial, WLAN, 3G, TCP-IP) and
- auxiliary equipment for power supply (e.g. batteries, solar panels) and instrument protection (casings, lightning protection).

In standard case, a monitoring epoch or cycle comprises

- an instrument self-check assuring that the instrument is correctly levelled and ready to measure,
- the measurement of reference prisms at known and stable positions outside the deformation area and
- the measurement of monitoring points (reflectorless and/or by use of prisms as required) on the deformation object.

Depending on local conditions and project requirements the instrument can be set up at a stable position outside the deformation area (e.g. on a pillar) or located within the deformation area and then derive its position periodically by measurements to stable reference prisms (free stationing technique). In complex setups and large deformation areas, various instruments can be combined and operate in parallel forming an integrated monitoring network.

The post-processing typically includes

- the reduction and correction of measurement raw data (e.g. atmospheric corrections),
- the processing of 3D coordinates,
- the processing of the deformation from repeated measurement epochs/cycles (from reflectorless measurements mostly 1D deformation such as settlement is derived) and
- visualising and reporting of results (e.g. generation of deformation reports and diagrams).

Most automatic monitoring systems already provide alarming options and services able to send alarm messages via SMS and/or e-mail to selected alarm recipients. Advanced systems also provide further features such as web-based user interfaces or tools for deformation analysis and prediction.

The main advantages of an automatic monitoring with reflectorless total stations are:

- High measuring frequencies (temporal resolution):
- Measuring a single point only takes a few seconds. Under good conditions, a measuring frequency of one minute per point (e.g. for 20 points measured subsequently from one instrument) can be achieved. However, in applications where a higher number of points must be measured or point identity must be guaranteed (meaning that exactly the same point must be measured in all epochs which requires an iterative measuring process) the measuring frequency may reduce drastically.
- High point density (spatial resolution):
- Theoretically, an unlimited number of points can be measured from one instrument station. However, reasonable numbers range from 10-100 depending on the object and measuring frequency required. A typical point spacing for monitoring road settlements, for example, ranges from 2-10 m.
- No traffic interruption is required, neither for installation nor for taking readings
- High safety:
- No surveyors on the road, no direct access to the object are required
- No installation effort and costs for monitoring points
- Low effort and costs for system operation and maintenance in comparison with classical, manual measurements

The **main limitations/restrictions** of the reflectorless method are:

- **Range:**
  The measuring distance may not exceed certain limits if accuracies in the mm-range must be achieved. In typical setups, the distances range from 20 to 80m.
- **Incidence angle:**
  The incidence angle as the angle between the line of sight and the object surface should not be worse than 1:10 (e.g. for paved roads). Too small angles are a major source of error.
- **Atmospheric conditions:**
  The physics of the atmosphere (especially the daily and seasonal changes) between the instrument and the measured point have an important influence on the electronic signal propagating through the medium air. This affects both, the measured distance and the measuring angles (refraction). For assuring high quality results a proper measurement of atmospheric parameters (temperature, air pressure) is required. The parameters can be used in atmospheric correction models to correct raw data but at least should be measured to avoid misinterpretation of data. Temperature changes also may affect the monitored objects themselves.
- **Surface conditions:**
  The mirroring effect of water covering roads in case of heavy rains and the presence of snow, leaves, waste or other kinds of objects on surfaces to be monitored are natural limitations making the measurements either impossible or erroneous. A bad reflectivity of the surface may significantly reduce the measuring range.
- **Free line of sight:**
  Very heavy traffic can make measurements impossible over longer periods of time. During rush hours readings may be blocked by vehicles most of the time. As a consequence, the control software has to be able to detect the affected data and automatically repeat the measurements. Depending on the needed repetitions the effective measuring frequency may decrease drastically.
- **Laser beam divergence, laser footprint:**
  The laser used for distance measuring has a beam divergence producing a laser spot on the object that increases in size with the distance. Due to this, the measurement of particular and small points of interest is not possible and accurate (e.g. edges of buildings). A measured point is a spot on the object and the recorded distance is the integration over the spot (laser footprint).
- **Point identity:**
  An important inherent characteristic of the method is that it does not measure signalised points but measures what it finds at preconfigured directions. When object deformations occur, slightly different points are measured on the object at each epoch, i.e. point identity is lost (Figure 28). The difference in position depends on the amount of deformation and the incidence angle. Significant interpretation errors can occur if this effect is not considered. Advanced monitoring systems can avoid this during measurement by iterating the preconfigured directions until the measured point can be considered 'identic' to the previous point (planimetric correction). If a geometric model of the surface is available, the effect can also tried to be avoided by interpolation techniques during post-processing. In any case, the effect restricts the reflectorless method to only deliver 1D deformation (e.g. settlements) although being a 3D measuring technique.

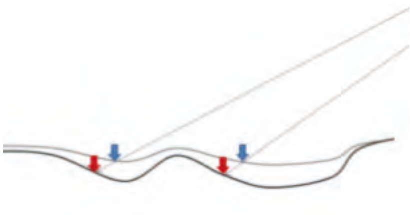


Figure 28 Different points measured in subsequent epochs due to settlement.

Current developments of instrument manufacturers aim at integrating laser scanner functionality into available RTS. Such new instruments (e.g. the Leica Multistation MS50) will make possible a further and significant increase of the temporal and spatial resolution. Other developments by system suppliers focus on issues like data filtering and correction, distribution, reporting and visualisation in order to provide integrated and complete automatic monitoring solutions. Further experience will be gained from new projects and monitoring applications, e.g. including the monitoring of railway track settlements, glass facades and other (small size) monitoring objects.

4.2 ACCURACY/PRECISION

The achievable accuracy of reflectorless measurements primarily depends on the

- instrument precision/class,
- measuring distance,
- surface physical condition (reflectivity, roughness, humidity),
- incidence angle (the angle between the line of sight and the surface) and the
- environmental conditions (temperature changes, vibrations caused by traffic etc.).

Under optimal conditions (application of a high precision instrument, short measuring distances, bright, flat and dry object surface, incidence angle close to 90°), a distance measurement accuracy of about ± 2 mm (standard deviation) can be achieved. With a proper data processing, 3D point coordinates can be determined in the accuracy range of ± 3-5 mm. From subsequent monitoring cycles 1D deformation can then be derived in the range of a few mm. Filtering techniques (e.g. moving average) may increase accuracy statistically.

4.3 MAIN FIELDS OF APPLICATION

In tunnelling, reflectorless total stations are successfully used for survey tasks such as setting out, check of tunnel profile and other single point determination tasks for many years already.

When using them for deformation monitoring, two main applications exist:

- the settlement monitoring of roads, rails, pavements and platforms during underground works and
- the monitoring of horizontal displacements of building facades and tunnel faces during construction of tunnels and shafts.

4.4 GENERAL CHARACTERISTICS

Table 8 summarizes the general characteristics of the technology which may alternate depending on project conditions and requirements.

Content

Time series of angle and distance measurements to points on the surface of deformation objects such as roads, pavements, building facades, tunnel walls and faces, tracks etc. are acquired by reflectorless total stations. The measurement raw data are processed to relative or absolute 3D coordinates of arbitrary (not necessarily identic) points for each measurement cycle. Further evaluation and analysis is done to obtain surface deformation (typically only 1D displacements such as settlements are derived). Deliverables are:
• Time series of 3D point coordinates (= usually only an intermediate result)
• Diagrams, maps and contour plots showing displacements (e.g. road settlements)
• Data processing protocols and reports discussing:
  • the raw data used for processing
  • the data processing steps and method
  • the achieved accuracy

Geographic Coverage, measurable objects, measuring range
Worldwide applicable, Optimal applicable to bright, flat, dry and planar objects (roads, facades) Measuring distances may range from a few m to several hundred m, for assuring accuracies in the mm range distances should not exceed 50-80 m.

Input data Sources	
Horizontal angles, vertical angles and slope distances	
Methodology	
Tacheometry, geodetic single point determination by angle and distance measurement Optionally: interpolation techniques for assuring point identity in consecutive measuring epochs	
Geometric Resolution	
Typically ranging from a few dm to several m on the object (= distance between neighbouring monitoring points)	
Coordinate Reference System	
Measurement is done in a local coordinate system Transformation/tying to an absolute project coordinate system is possible through additional measurements (e.g. measurements to reference points)	
Geometric Accuracy	
Depends on instrument class (precision), measuring distance and influence factors such as atmosphere (esp. temperature), exposure to sun and vibration, geometric conditions (incidence angle) and surface physics (roughness, reflectivity, humidity) Achievable accuracy (standard deviation) of a single distance measurement: up to +/- 2 mm Achievable accuracy of 3D point coordinates: +/- 3-5 mm	
Movement precision	
Movements/deformation in the range of a few mm can be determined from a time series of correctly measured, processed and filtered data	
Update Frequency/Measuring interval	
Depends on the number of monitoring points to be measured from the instrument, external factors such as disturbing cars in the line of sight and the application of iterative measuring techniques to assure point identity Minimum measurement time typically is 3-6s per point, longer times may occur In practice, frequencies typically range from 20 points per minute to 20 points per 4-5min.	
Delivery Format	
3D point coordinates stored in database, export to arbitrary ASCII or binary data formats (.txt, .xls, .xml) Data processing protocols and reports in (.pdf, .xml) Diagrams, maps and contour plots showing displacements (.pdf, .png, .jpg,…)	
Data type	
Listing, report, map	

Table 8 Reflectorless measurements with total stations.

4.5 STRENGTHS AND WEAKNESSES

STRENGHTS	WEAKNESSES
high level of automation (full automatic measurement and processing possible)	method delivers only 1D deformation (e.g. settlement)
high spatial resolution (e.g. 1 point every few meters on the object)	various geometric and physical restrictions and constraints (reflectivity of surface, dryness of surface, free line of sight, presence/absence of snow, adequate incidence angle)
high measuring frequency (up to 20 points per minute depending on measurement mode and external factors)	suitable instrument position required (erection of high pillars)
high accuracy (millimetre range at short distances) when applying filter techniques and appropriate corrections	suitable means for instrument protection and power supply required
no traffic interruption	limited range (if highest accuracy is to be achieved)
high safety (no surveyors on roads, no disturbance of road users)	qualified experts required for system design and installation
flexibility with respect to changes of the monitoring programme (adding new monitoring points, changing measuring interval etc.)	possible disturbance of car drivers and passers-by by laser beam
flexible combination of prism measurement and reflectorless measurement	little applicability on natural ground (meadow, soil)
remote-controllable, even via the Internet	
no installation effort and costs for monitoring points	
little effort and costs for regular operation and maintenance of monitoring system (typical instrument service interval: one time per year)	
low overall costs compared to classical instrumentation and monitoring methods (e.g. precise levelling) in case of long term monitoring.	

Table 9 Strenghts and weaknesses of reflectorless measurements with total stations.

4.6 REFERENCE PROJECTS

The following reference projects show recent examples of practical applications of the technology.

4.6.1 South Toulon Tunnel (FR)

Background
A motorway tunnel needed to be constructed under the city center of Toulon, in extremely variable and difficult ground conditions. The tunnel was excavated using conventional excavation method, the construction lasted from 2007 to 2011.

Objectives
Because of the conditions (highly deformable ground, old city center above the tunnel), high priority was given to the control of the settlements. The excavation support had to be adapted in 'real time' depending on the measured movements at surface. Therefore, reflectorless robotic total stations were used to measure both the movements of the ground surface and the buildings.

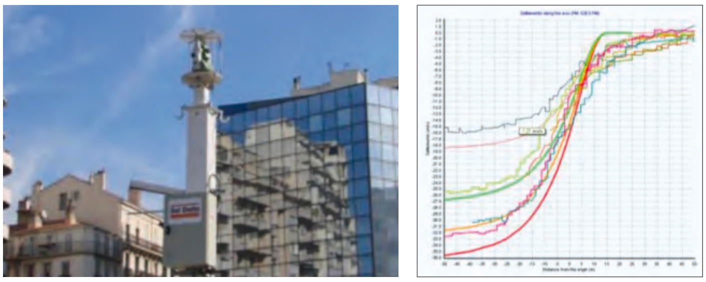


Figure 29 Reflectorless total station monitoring the road surface and the buildings (left), graph showing measured and predicted settlements in relation to the distance to the tunnel face (right).

Approach
A total of 20 automatic total stations (Figure 29) were used in the project. They were displaced as work progressed, over a total of 60 different positions. On the road surface there was a section of 5 to 10 points every 5 meters along the tunnel route giving a total of 1.830 surface points measured between 2007 and 2011. Their measuring frequency was 2 to 8 readings per day, depending on the alarm level. On the buildings, monitoring prisms were installed on each corner and measured every 2 hours. The total stations were connected to a control center using a wifi network established over the city.

Results
The monitoring results were used daily to adapt the excavation support in the tunnel. A very high precision was achieved due to careful design, short sighting distances and an important effort on maintenance and quality control.

4.6.2 Amsterdam Metro (NL)

Background
A new metro line was constructed in Amsterdam by tunnel boring machines. The soil conditions were very difficult, with existing disorders to the buildings before the start of the tunnel works. The monitoring program, largely based on robotic total stations, was launched two years before the start of the works, in order to gain a good knowledge of existing movements. The monitoring project lasted from 2000 to 2013.

Objectives
The first objective of the automatic monitoring was to measure the existing buildings. Initially the road surface was to be measured manually using precise levelling. However, in 2007 the precise levelling was replaced/completed by automatic remote monitoring using the same total stations as for the buildings (Figure 30).

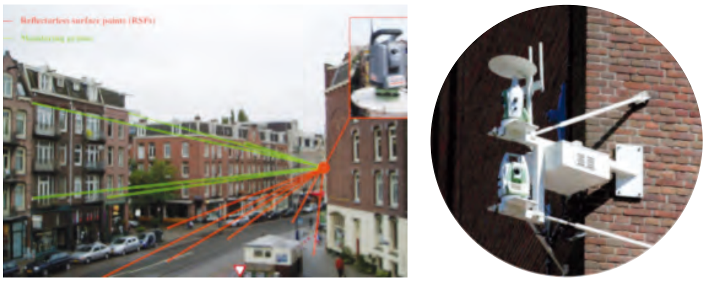


Figure 30. Reflectorless robotic total station measuring surface points on the road (red lines) and prisms on building facades (green lines) (left), doubled-up total stations to cope with more than 150 points to be measured every 1 hour (right).

Approach
Initially, 80 automatic total stations were installed along the line. However, in order to be able to keep a high frequency of one measurement per hour, sometimes with more than 150 points to measure, some total stations were doubled-up (Figure 30 right). In total, more than 5.000 prisms on the buildings and nearly as many points on the road were measured.

Results
The system functioned perfectly well during the 13 years of the project. The reflectorless addition midway through the project helped increase the measurement frequency, reduced the risks to the surveyors and avoided disturbances to road users. As the contractual frequency of 1 hour has not been sufficient to cover all risks in the project, additional instruments (piezometers, liquid levels, electrolevels) were used in combination with the total stations.

4.6.3 Edinger Storm Channel (US)

Background

In Huntington Beach near Los Angeles a new storm water channel has been designed to cross the Interstate 405, a highly frequented motorway. The length of the tunnel is 80 meters and the coverage about only 1.5 meters. It has been constructed by an innovative method involving a temporary shored bridge system.

Objectives

For monitoring road settlement during tunnel construction an automatic monitoring method has been required able to measure without causing any traffic interruption. As only 1 cm of settlement has been allowed in the project, the method has been required to provide an accuracy of only a few mm.

Approach

Approach

Two high-precision reflectorless total stations have been established on two 14 m high pillars (Figure 31 left), one on each side of the highway, measuring a total of 177 points (Figure 31 right) reflectorless on the road surface and partly stabilised with prisms, one point every approx. 2 m. The two total stations additionally measured each other and a set of reference prisms to continuously determine their own 3D positions and to check pillar inclination/stability.

Figure 31 View of freeway and high rise monitoring pillars (left), view of monitoring point distribution and resulting settlement contour plot along tunnel alignment (right).

Results

Despite heavy traffic and applying a special iterative point identification technique, it has been possible to measure every point up to four times per hour from August to December 2014 with an accuracy of a few mm. Time series of settlements and further types of settlement diagrams have been automatically produced for interpretation, an alarming service has been installed.

4.6.4 Further Reference Projects

- In Barcelona (Spain) long-term monitoring of high-speed railway tunnels and of the Metro Line 9 has been set up to monitor the settlement of roads, sometimes with heavy traffic.

- For a section of the Lyon Highway (France) road settlements have been monitored during a microtunnelling project in 2011.

Figure 32 Reflectorless total station monitoring a motorway during construction of a service tunnel underneath.

- In Washington D.C. (USA) a reflectorless total station has been used to monitor the settlements of a road under traffic above shallow twin tunnels constructed by conventional tunnelling for the route of the Crossrail expansion of the Washington Metro.

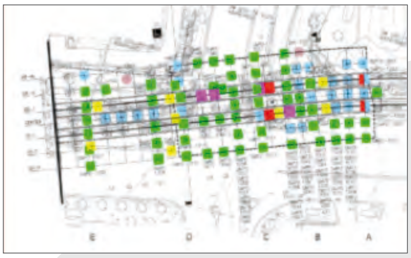


Figure 33 Total station on pillar with the monitored road (left), overview of monitoring points and their settlement values on road surface (right).

- In Vienna (Austria) a reflectorless total station has been used in the tunnel projects Lainzer Tunnel and Wienerwaldtunnel to monitor the tunnel face during conventional tunnel excavation. The system continuously measured the longitudinal deformation of small patches on the tunnel face during the short time between subsequent excavation steps in order to check tunnel face stability.

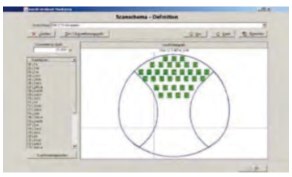


Figure 34 Tunnel face with monitoring patches (left), monitoring patches in the processing software (right).

4.7 APPLICATION RECOMMENDATION

The technology of carrying out reflectorless measurements with total stations for deformation monitoring is reportedly applied in tunnel projects since 2005. Today, it has established itself as a technically mature and highly efficient technology that is already offered by various recognized and professional suppliers of monitoring solutions.

From the gained practical experience and case studies reported so far, it can be recommended particularly for the automatic and continuous monitoring of settlements of roads, motorways and/ or pavements in the influence zone of tunnel projects. To assure a successful execution of a deformation monitoring programme the collaboration of the client and the system supplier is required/ recommended to start already at an early stage of the project.

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