Critical Aspects when using Total Stations and Laser Scanners for Geotechnical Monitoring

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Abstract

Modern geotechnical monitoring is based on a variety of surface based and integrated sensors. This article discusses the potential but also the limitations of total stations and laser scanners in monitoring of civil infrastructure and natural phenomena. We report about our experiences gained in long term monitoring projects and discuss the impact of the setup location, the signal travel path and the target. Although, modern instruments are capable of measurements with accuracies of a few millimetre or better, neglecting error sources like temperature dependence of the tilt sensor, orientation of the used prism and refraction can easily cause errors of several millimetres or even centimetres.

Keywords: Geotechnical Monitoring, Geodetic Sensors, Total Station, RTS, Laser Scanning, TLS

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Introduction

The task of geotechnical engineering is to build structures like tunnels within the ground or to provide solid foundations for structures above the ground. Geotechnical monitoring is used to assess the behaviour of these structures during construction and in the long term. Geotechnical monitoring is also important for the early warning of natural hazards such as landslides, rock falls, sinkholes and debris flows. Objects under consideration are manmade structures like tunnels, dams, piles, retaining walls or pipelines and natural objects like rock faces, landslides or caves. Deformations of the surface of a structure like a landslide can be depicted with a variety of sensors. Current methods are for instance airborne and terrestrial laser scanning (ALS and TLS), measurements to prisms with robotic total stations (RTS), GNSS measurements and ground or satellite based interferometric synthetic aperture radar (InSAR), see Figure 1.

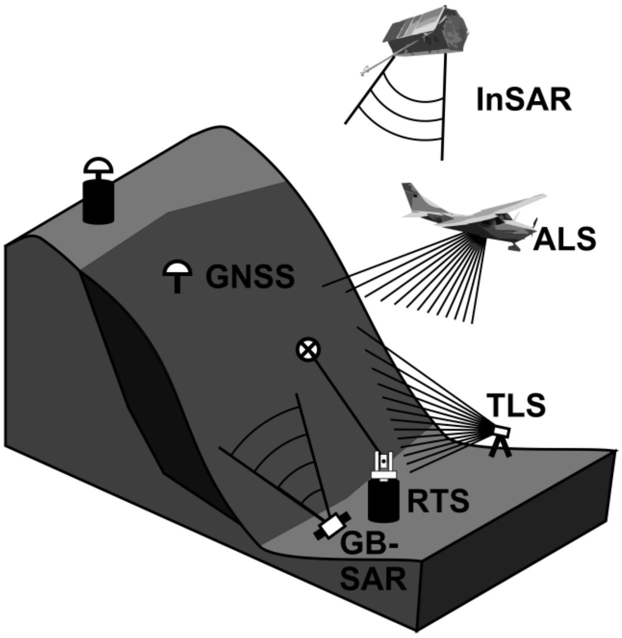

Figure 1: Different methods for the deformation monitoring of the surface of a landslide

The accuracy of contactless measurements with total stations and terrestrial laser scanners always depends on the three components: Setup point, measurement path and measurement target. The setup point includes the instrument itself, the stability of the support and the objects in the vicinity of the instrument. The measurement path is influenced by the atmospheric conditions which have an impact on the travel speed of the signal. Furthermore, temperature gradients can cause a curvature of the measurement path. The final critical component is the target. The achievable accuracy depends on the target type, e.g. prism or rock, the inclination angle of the measurement path with respect to the target and the target material. In the following we discuss the possible degradation of the measurement accuracy under different circumstances.

Robotic Total Station Measurements

Modern robotic total stations (RTS) can automatically find and track prism targets. RTS are commonly used for the monitoring during tunnel construction and to assess the stability of water dams, landslides and rock faces. To instruments are often placed in a measurement chamber and thus protected from adverse environmental conditions.

Figure 2: RTS measurement setup for the monitoring of a water dam

However, the glass window also has an impact on the measurement accuracy. The angle measurements are distorted (parallel shifted in case of a homogenous glass with parallel sides) and the measured distance is longer than the real distance due to the slower travel speed of light within glass. This impact can be calculated theoretically but also shown experimentally. In the example displayed in Figure 3 a very thin glass window (thickness 1.75 mm) was used which caused already distance deviations of several tenths of a millimetre. This impact increases in case of thicker window glasses. In deformation measurement this impact can often be neglected because deformation measurements are always measurements relative to a first measurement epoch and thus constant impacts cancel out. Nevertheless, care has to be taken in case a window glass is being replaced.

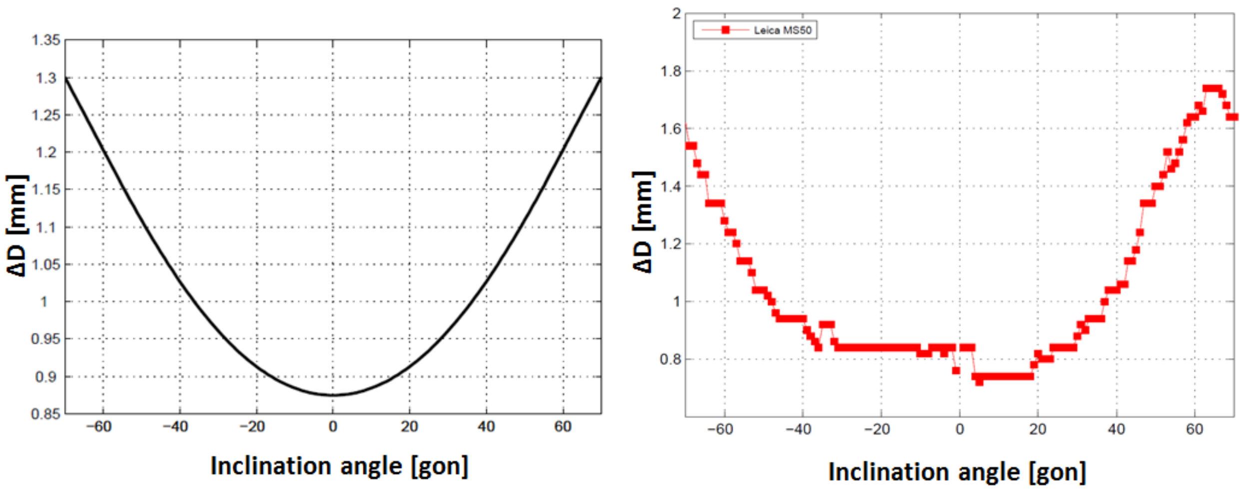

Figure 3: Example of theoretical impact of glass window on distance measurement (left), empirically verified impact (right).

What is more critical in deformation measurements are direct reflections from the glass back into the telescope of the instrument. A RTS sends out a laser beam for the distance measurement and illuminates the measurement scenery with infrared light for the automated detection of targets. The electronic distance measurement (EDM) sensor as well as the targeting sensor are influenced if the signals are not only reflected by the prism but also by the glass window. Therefore, measurements orthogonal to the glass window have to be circumvented. The critical angle in which useful measurements cannot be performed depends on the beam divergence of the transmitted beams, the acceptance angle of the sensors, the distance of the glass window to the instrument and of course on the angle between glass window and sighting axis. Figure 4 shows examples of measurement situation which should be avoided.

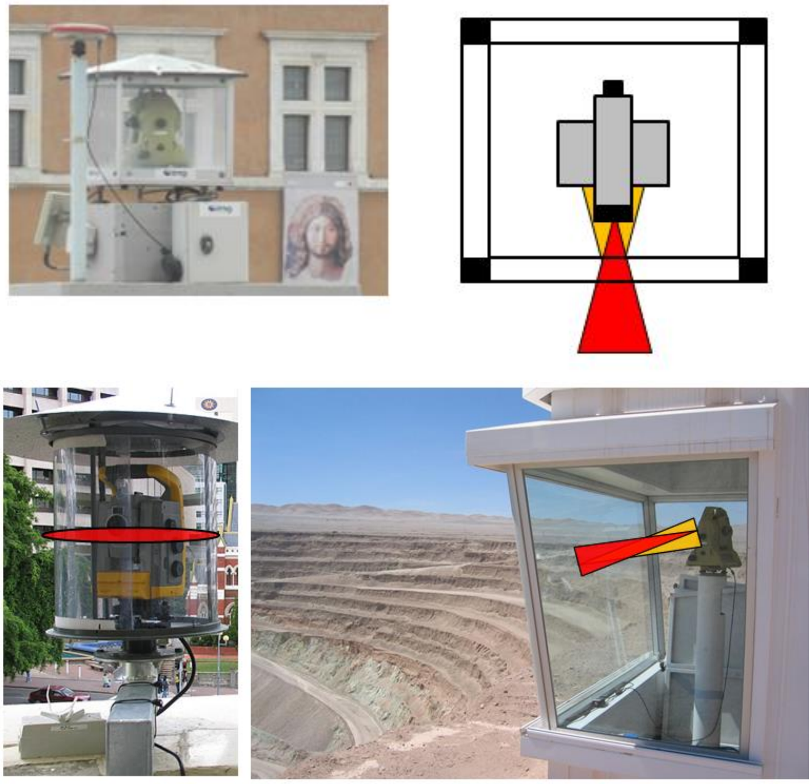

Figure 4: Problematic measurement situations where the beam transmitted by the instrument (red) is back reflected (orange) into the instrument

Considering this aspect it is preferable to avoid glass windows altogether. This is a common approach in inner city monitoring installations, see Figure 5-left. In such a setup the measurements are not influenced by a glass window but experience all changes of the environmental conditions. For instance a temperature change causes a change of the zero point of the internal tilt sensor of the instrument. This tilt sensor is used to automatically correct angle measurement of an unlevelled instrument. Figure 5-right shows the temperature dependence for different instruments. It has to be noted that an error of the tilt reading results in an error of the vertical angle of the same size. As can be seen in Figure 5 large temperature differences can cause tilt errors of more than 80 cc. This corresponds to a height error of 8 mm of a target which is in 60 m distance. In order to avoid this error the zero point of the tilt sensor should be determined in regular intervals.

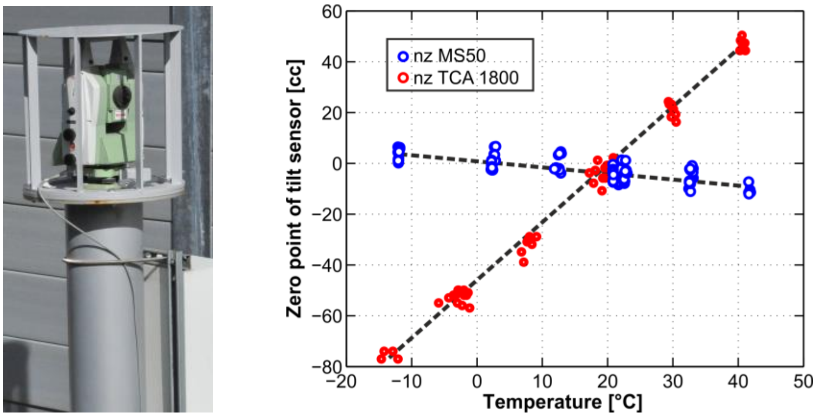

Figure 5: RTS monitoring setup without windows (left) and impact of temperature changes on the tilt sensor of different RTS (right)

As mentioned before the setup point is only one essential component. The second component is the measurement path. Potential problems are discussed using the monitoring of a rock face as example.

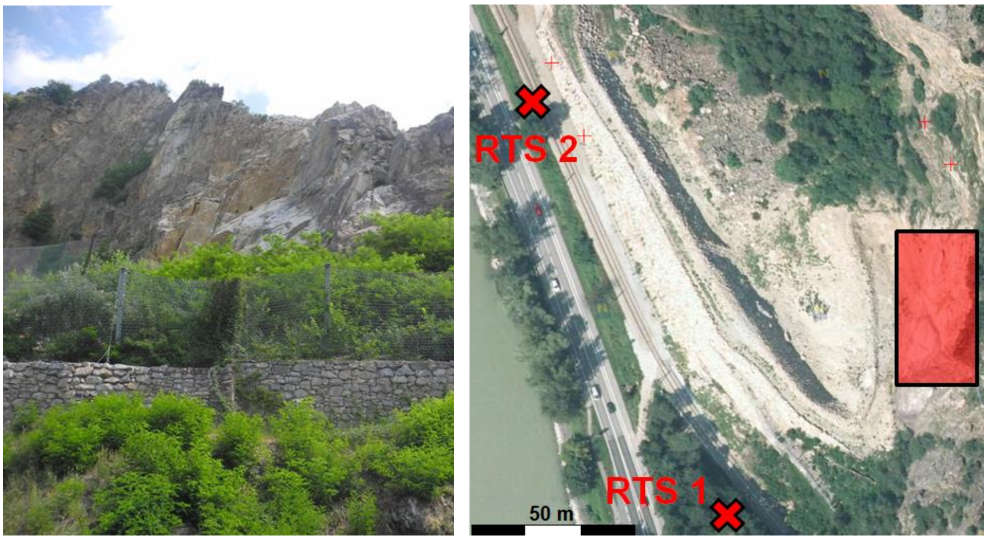

Figure 6: Monitoring of the unstable Biratalwand (left and red area right) with two RTS

The rock face “Biratalwand” was monitored using two RTS, see Figure 6. The instruments performed automated measurements in regular intervals to prims installed in the unstable area of the rock face. It can be seen in Figure 7 that the vertical angle measurements show daily cycles. It is obvious that the rock face does not move down and up again. Therefore, uncorrected systematic effect must be inherent in the measurement data.

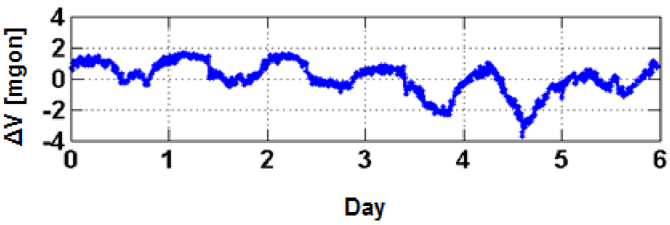

Figure 7: Vertical angular readings to a prism in the unstable area of the Biratalwand

A detailed investigation of the measurement data and additional experiments on site revealed that a potential cause of the impact is geodetic refraction which causes beam bending. The impact of refraction on automated angle measurements is shown in Figure 8. At the start of every measurement epoch the instrument turns to the stored position of the target point (1). In case of no refraction and no movement of the target the instrument points directly to the target. However, in case of refraction the measurement path is curved and thus the instrument incorrectly assumes a movement of the target and turns until the aiming sensor detects the target again (2). When the target is found the angle reading is stored (3) which is in fact the tangent to the curved measurement path at the instrument position.

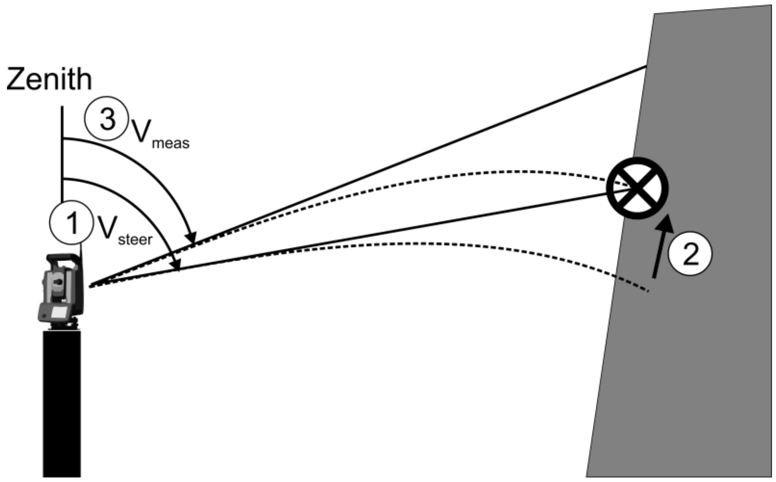

Figure 8: Impact of refraction on automated angle measurements

In order to eliminate this impact it is possible to use a stable target in the vicinity of the moveable area. This stable target can be used as calibration target to calculate the current impact of the refraction and apply numerical corrections to the measurements of the moveable targets. Figure 9 shows the time series of the vertical angle to the target in the unstable area after the correction. It can be seen that the daily cycles are not present anymore and that the rock was in fact stable within the displayed six days.

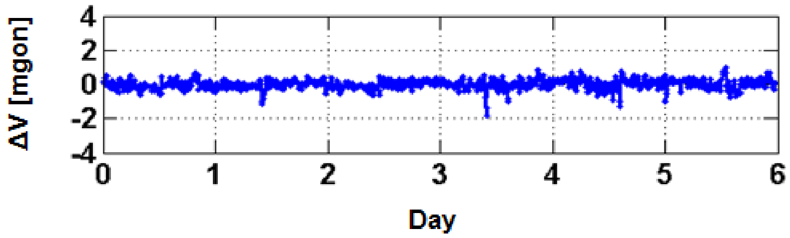

Figure 9: Vertical angular readings to a prism in the unstable area of the Biratalwand after correction for atmospheric impacts

The final component which can have an impact on the accuracy of RTS measurements is the target. Commonly prisms of various sizes and shapes are used as target for automated measurements. Very convenient are the so called 360° prisms because measurements to these prisms are possible from every horizontal angle. Therefore, measurements to these targets can be made from several RTS from different location. However, it has to be noted that 360° prisms show systematic error patterns which significantly degrade the measurement accuracy.

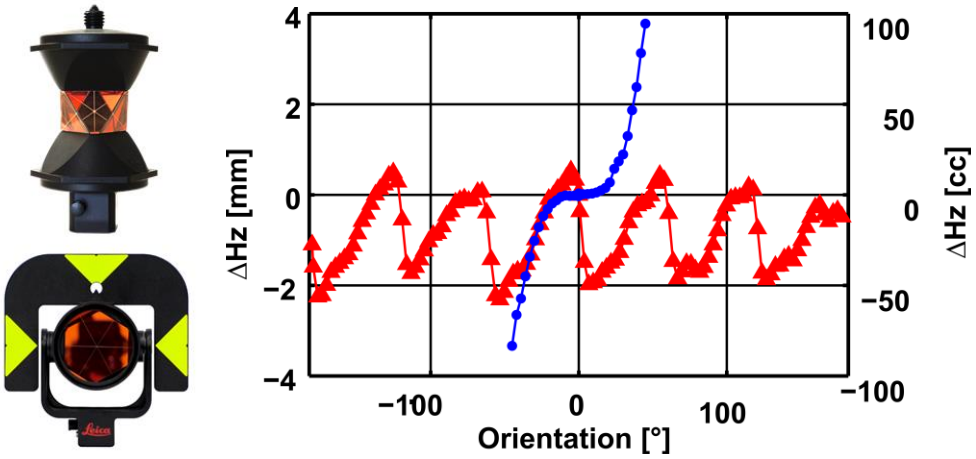

Figure 10: 360° prism (left: top, right: red) and round prism (left bottom, right: blue)

360° prisms have several facets which cause cyclic errors. Figure 10 shows the results for horizontal angle measurements to a Leica GRZ122 360° and a Leica GPR121 round prism. The prisms were located at a distance of 26 m and automatically turned. The GRZ122 has six facets which can be clearly identified in the error plot. The deviations cover a range of more than 2 mm. Measurements to the round prim are much more accurate if the prism is well aligned to the instrument. If this is not the case the deviations increase rapidly. As a conclusion 360° prisms cannot be used for measurements with highest accuracy demands and round prisms should be well aligned to the instrument.

Laser Scanning

Laser scanning, also called light detection and ranging (LiDAR) is based on a rotating laser beam which is mounted on a stable platform like a tripod or a pillar or on a moveable platform like a car, airplane or UAV. Modern laser scanners are capable of measuring more than 1 million points per second. Such a fast measurement rate results in huge data amounts within a short time. Today laser scanning is a valuable tool for geotechnical monitoring because, contrary to total station measurements, it is not necessary to mount targets on the object. Figure 11 shows an example of one of our projects where we performed scanning during a slope stability experiment. A point cloud of one measurement epoch is displayed in Figure 11-left and Figure 11-right indicates the result of a deformation analysis.

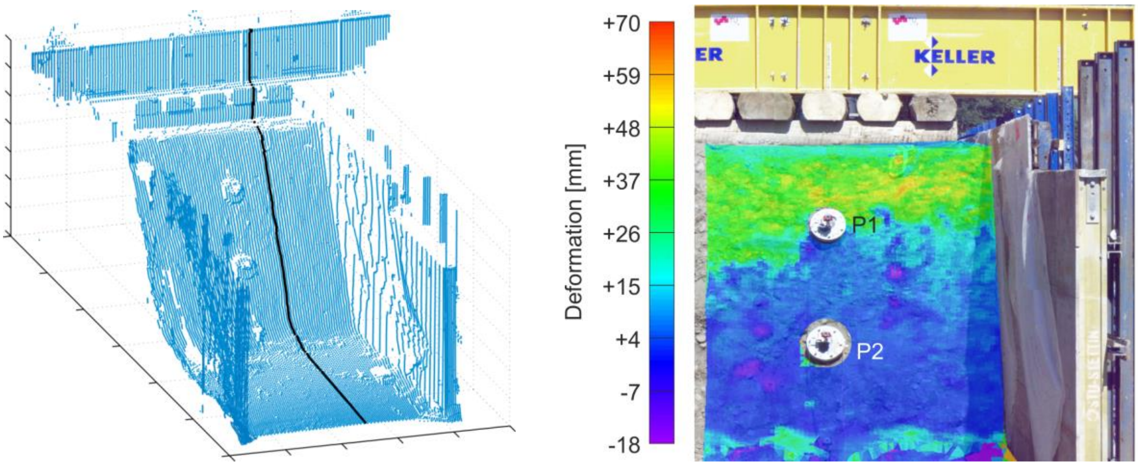

Figure 11: Scanned point cloud of an earth dam (left), result of deformation analysis (right)

Nevertheless, it is has to be noted that laser scanning is also affected by refraction. On the one hand the travel speed of the laser beam is dependent on the atmospheric conditions and on the other hand beam bending does also have an impact, see Figure 12. Contrary, to total stations, laser scanners cannot track targets. The horizontal and vertical angles are always only the steering angles. In case of refraction the beam at the same steering angle curves and therefore a different part of the object is measured. Depending on the shape of the object this can have a significant impact on the measured distance.

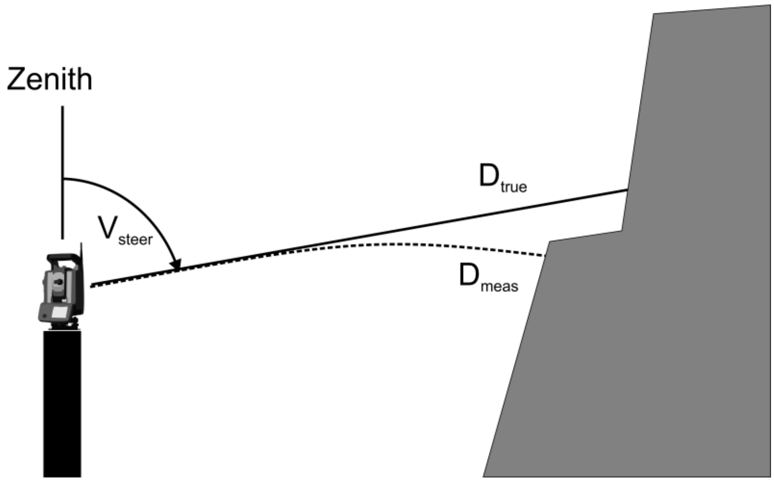

Figure 12: Impact of refraction on laser scanner measurement

We took a closer look at this impact at the monitoring site Biratalwand were reflectorless distance measurements showed daily cycles which could not be explained by variations of the signal travel speed. Therefore, dedicated experiments were carried out. Figure 13, shows an overview and close up image of an inclined rock face of the Biratalwand. As it was discussed before the RTS measurements were influenced by daily cycles of the vertical angle within a range of 6 mgon. As can be seen in Figure 14, such vertical angle variations can result in distance variations of several millimetres due to the inclination of the rock face with respect to the sighting axis.


Figure 13: Rock face at the Biratalwand

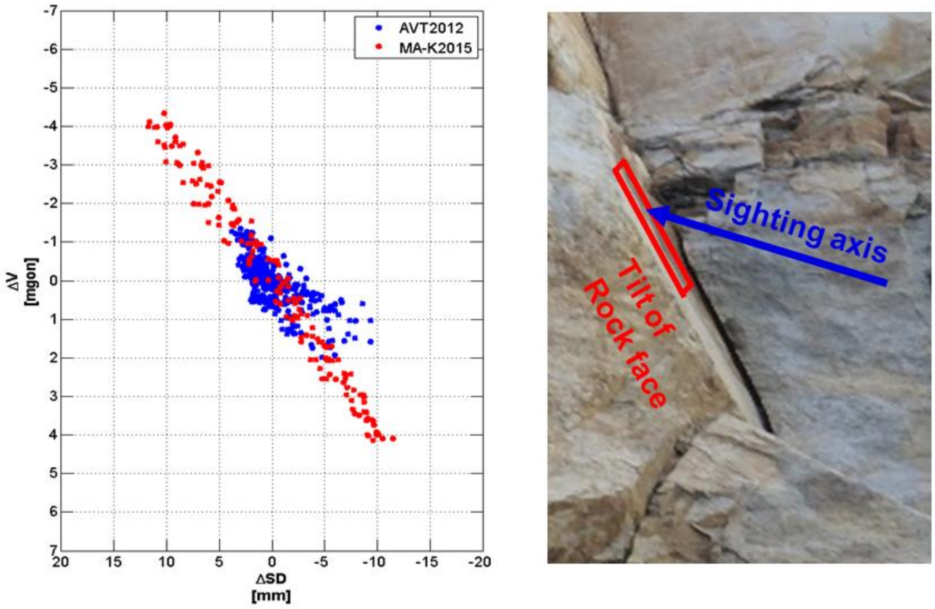

Figure 14: Impact of variations of the vertical angle on the distance measurement

Again influences on the vertical angle can be taken into account when using stable reference points in the measurement area. However, it has to be noted that in case of reflectorless distance measurements the corrections have to be applied already during the steering process of the instrument and not in post processing as is the case for RTS measurements. Currently, we also perform laser scanning measurements at a stalactite cave. In this project we combine airborne and terrestrial laser scanning. Airborne laser scanning is used to generate the digital surface model above the ground whereas the cave itself is captured using terrestrial laser scanning, Figure 15.

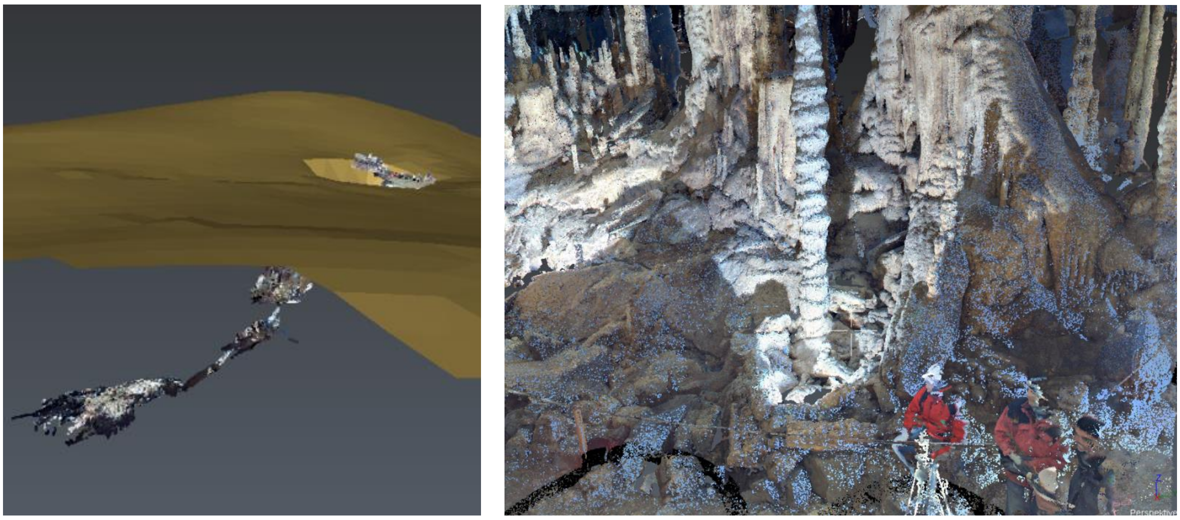

Figure 15: ALS and TLS measurements above and within a stalactite cave

Conclusion

High accurate measurements with total stations and laser scanners require a sound understanding of all potential error sources. Measurements through glass windows should only be performed when the sighting axis is not orthogonal to the window pane, the current refraction status should be evaluated by measurements to reference targets and round prisms have to be used to achieve highest accuracy.