Comparison of Tunnel Convergence Measurement Methods

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Methods

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Abstract

When creating cavities below ground, movements occur in the surrounding soil due to disrupted equilibrium. In tunnel constructions these displacements are referred to as tunnel convergence. This report compares four different methods for monitoring tunnel convergence with regards to both measurement precision and method cost. Three of the methods are based on displacement measurements of optical targets placed at regular intervals in the tunnel. Presented is also a method using a combination of wireless tilt and distance sensors to monitor tunnel convergence. The overall conclusion is that measurement precision and cost are well correlated. However, important to consider is that tunnel convergence monitoring cost is faceted and not only the obvious cost of equipment and labour, but also the indirect cost from interfering with other activities in the tunnel. Measurement precision of the different methods was determined by applying the methods in a lab environment, configured to eliminate any possible movements, and analysing the distribution of the displacement demonstrated by each method. In addition, information regarding the labour effort required to prepare and perform the measurements was also collected. Based on the experiments and literature studies, the report discusses the criteria to consider when selecting a tunnel convergence monitoring method and presents a comparison of the four methods included in the study.

Keywords: tunnel; convergence; displacement; tilt; sensor

TRITA-ABE-MBT-20404
Sammanfattning


Nyckelord: tunnel; konvergens; förskjutning; tilt; sensor
TRITA-ABE-MBT-20404
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1 Introduction

1.1 Background

For the development of modern civilization, tunnels play an important role in many infrastructure solutions. Its importance is increasing as building methods develop, allowing tunnels to be built over longer distances and under more complex geological conditions.

Evident benefits of tunnels are the reduction in transport distance and time. A tortuous road conformed to the terrain can be replaced by a direct connection passing through the obstacle. The issue tunnels solve in urban areas is often more related to traffic optimization and environmental improvements of residential areas.

Tunnels save cost both from lowered fuel consumption and resource occupancy. Less fuel usage leads to reduced vehicle emissions which reduce the negative impact on the environment, both locally and globally. The confined space of a tunnel is an issue for the air quality inside the tunnel but also an opportunity to lower the environmental impact by utilizing advanced ventilation and air treatment systems [1].

The tunnel build methods are very much dependent on the geology of the area in which the tunnel is constructed. Soft ground requires significantly different method compared to hard rock. A tunnel crossing water is often built as a “tube” on the seabed. Common for all tunnel engineering is the challenge to design the tunnel to withstand the imposed loads with proper margins, neither over- nor under-dimensioning the construction.

Most tunnel constructions involves the process of removing material and by that affecting the equilibrium in the surrounding ground. As a consequence, there might be ground movements until new equilibrium is reached. It is of great importance that these displacements are monitored to gain knowledge of the adequacy of the tunnel construction. The safety of both construction workers and end-users of the tunnel depend on this activity being properly executed.

Depending on the type of soil in which the tunnel is embedded, the deformations will differ both in magnitude and duration. In many cases there is a need for deformation monitoring also long after the tunnel has been opened
for commercial use. Existing tunnel constructions could also be subject for deformation monitoring due to other constructions in the surrounding area, causing new ground movements and potential tunnel deformation.

Deformation monitoring is not only used for tunnels but in many areas of engineering construction [2]. The infrastructures that support our modern society heavily rely on these constructions to function. Deformation detection has been studied extensively on different types of structures such as; bridges [3], dams [4], [5], [6] and buildings [7]. Similar measuring techniques are applicable also for tunnel convergence measurements.

There exist a number of methods for detecting unexpected ground movements related to a tunnel project. Some focus on detecting displacements of critical structures (e.g. buildings) in the vicinity of the tunnel, others measure changes inside the ground surrounding the tunnel. This study focus on methods for monitoring deformation of the tunnel itself, more precisely the walls (and ceiling) of tunnel cross-sections. Articles 8 and 9 provide an overview of tunnel deformation measurements.

Most ground deformation occurs during the construction close to the tunnel face, in the range about 1.5 tunnel diameter behind and ahead of the face [10]. The earlier the deformation measurements can start the better the control of the ground movements will be. For this reason there is an urge to set-up measurement equipment as the tunnel face moves forward. Hence, an important requirement on the measurement procedure is to not interfere with the ongoing tunnel construction work. In the selection of methods to include in this study, this has been a decisive criteria, therefore the mechanical method of distometer has been omitted, even though it is proven to be very accurate and extensively used [11].

Another crucial aspect of monitoring during ongoing tunnel construction is the work environment. It is challenging for instruments (especially those relying on optics) as well as humans mounting equipment and performing measurements. The air can be heavily polluted and equipment may be hit by rubble from rock blasting activities.

Because of the rotational symmetry of tunnels, the most probable direction of deformations is radial towards or away from the centre of the cross section. However all tunnels are not exactly circular and the concept of convergence is therefore expanded to the following: For all tunnels with
convex shape, convergence is the displacement of a point in the direction perpendicular to the tangent of the cross section profile in the same point. If the motion is inwards or outwards depends on the load situation around the tunnel, see Figure 1. For tunnels located at great depths both ceiling and walls move inwards. For shallow tunnels the ceiling moves outwards (up) if the horizontal load on the tunnel walls is high and the opposite with no or low wall load [12].

Figure 1: Tunnel convergence, three different scenarios. Figures from [12].

1.2 Purpose

The purpose of this study is to evaluate different methods for detecting tunnel convergence, both in terms of precision and cost. For a tunnel through bedrock the expected magnitude of the displacement is on mm level. This is the most stringent requirement on the measurement method. On the other hand, if the surrounding ground is soft and the movements are larger and perhaps more common, a precise measurement method is anyhow necessary to make reliable predictions of the deformation. Cost is divided into labour and equipment cost and the distribution between them is determined by the degree of automation in the measurement process.

The result of this study will increase knowledge in the field of tunnel convergence measurement and quantify the relation between precision and cost. The tunnel convergence measurement methods (A-D) that are included in this study are listed below. Their names refer to the equipment that captures the raw data or the method principle used to determine any movements in the tunnel construction:

- Method A: Total station
- Method B: Laser scanner
- Method C: Photogrammetry
Method D: Wireless sensors

Displacement measurements can be performed with or without georeferencing, depending on if absolute or relative movements is required. Georeferencing demands stable reference points, connected to a geodetic reference system, and since the whole tunnel construction may move, the reference points need to be located outside the tunnel. In this study, all measurements are relative and positions are defined in a local coordinate system.

In the following subsections each of the methods are described in general which includes information from other studies relevant to the objective of this study. Details on how the measurements and post-processing was carried out in this study are presented in section 2.

1.3 Total station

The use of total station to determine the positions of optical targets has been, and still is the dominant method for tunnel convergence monitoring, [13]. Typically 5-7 targets are mounted in cross sections along the tunnel [10]. One target is positioned at the highest point of the tunnel profile (the crown) and the others evenly distributed over the profile ceiling and walls. The slant distance together with horizontal and vertical angle is measured using a total station. Measurements are performed at multiple station positions and network adjustments is used to determine precise coordinates of the targets.

A common distance between the cross sections being monitored is 15-20 meters, but depending on the specific properties of the ground surrounding the tunnel, the distance between cross sections may vary substantially. Detailed description of how the total station is used for convergence measurement is found in 2.3.

Swedish Institute for Standards (SIS) has published a technical specification presenting a classification of total stations based on measurement uncertainty requirement for different use cases, see [14]. Measuring settlement and other deformations requires a total station of class T1, which means a standard uncertainty in horizontal and vertical angle of 0.15 mgon and distance 1 mm + 1 ppm. Article [15] reports an accuracy of 1 mm for measuring convergence of tunnels with total station. An earlier study [16] concludes an accuracy of a few mm.
In manual mode, the operator of the total station has to aim the instrument at the target in question. This requires operator skills influencing the quality of the measurements. Both black and white (B/W) targets and prism targets can be used in manual mode, see photo embedded in Figure 2. Many total stations also offer automatic aiming function for prism targets. In the total station used for this study (Trimble S8), this functionality is called Autolock [17]. The first measurement of each target need to be aimed manually for the total station to recognize the targets and their position. The subsequent aiming and measurement are then automatically performed by the instrument.

1.4 Laser scanner

The use of laser scanning for deformation detection is getting more common as the scanner becomes more portable and user friendly. Development in data processing software also contribute to making the laser scanner useful for measuring small displacements. A review of applications for laser scanning of tunnels is presented in [18]. An advantage of laser scanning compared to conventional deformation monitoring methods such as tape extensometer and total station is the number of monitoring points that can be analysed in terms of deformation [19]. However, for detecting deformation the exact same points need to be identified and measured in measurements performed at different epochs.

In this study the displacement was determined for a limited number of targets in a cross section of the tunnel. Laser scanner creates a 3 dimensional image of the scanned environment. By installing targets that are detectable in the point cloud (digital model) and scanning the scene at different occasions, the potential displacements can be measured. Targets are mounted in cross-sections at regular distance intervals the same way as for the method using total station. Further details on the laser scanning method used in this study is found in section 2.4.

Regarding measurement accuracy, [10] reports an accuracy of ±5 mm for a measurement method based on laser scanning of tunnel wall surface. This accuracy is confirmed in [20] which also mentions that many attempts have been made to reduce the uncertainty by exploiting the very high point density.
1.5 Photogrammetry

In photogrammetry a digital 3D model (point cloud) is created using images captured with a normal camera and processed by software. Once the point cloud is created, the procedure used in this study is the same as for laser scanner. One distinctive advantage of photogrammetry is the relatively low cost of the required equipment.

Photogrammetric measurements are inherently dimensionless [21], there is a scale ambiguity associated with the created 3D image. A way to remove this ambiguity and scale the photogrammetric measurement is to include at least one known distance in the captured scene. It can be a clearly visible object or the distance between targets.

There are studies on photogrammetry methods that has manage to obtain accuracy below 1 mm [20] and [22]. The following factors are listed in [21] as important regarding measurement accuracy; camera resolution and quality, size of measured object, number of photographs, geometry of image plane and object.

1.6 Wireless sensors

The use of sensors is steadily increasing within the field of deformation monitoring. A system of sensors has the advantage of lowering or completely removing the need for measurement personnel in the tunnel at each measurement occasion. This lowers the cost of each measurement occasion, allowing for them to be more frequent. In a study from 2004, sensor technology was suggested for continuous monitoring of tunnel deformations [23]. Electric resistance strain gages (or fibre optics sensors) were the sensors suggested to be mounted on steel arches that were part of the tunnel support system.

Sensors detecting changes in inclination was the base for a study about monitoring and analysing structural movements made in 2006 [24]. It concludes that digital double axis inclination sensors with micro-radian precision can efficiently be used for monitoring movements in large engineering structures.
Recent progress in wireless telecommunication and specifically wireless networks has provided structural deformation monitoring with even more efficient tools. Instead of having to connect sensors with wires and having to visit the tunnel for collecting data, wireless technology is used to send the data to a central storage. If internet connection can be provided inside the tunnel, the data can be accessed anywhere there is internet access.

A network technology well suited for sensors is the mesh network, in which all nodes connect directly, dynamically and non-hierarchically to as many nodes as possible. Each node participate in relaying information. Hence, there is no need for direct connection between origin and destination node. As long as there is at least one path through a chain of nodes, the data can be successfully transferred. In [25], mesh networks is used in structural health monitoring of a bridge using wireless acceleration sensors.

2 Method and measurement set-up

2.1 Comparison of measurement methods

All methods covered in this study (see 1.2), are based on analysing movements of selected points along cross sections of the tunnel. Methods A-C use targets together with an optical instrument to measure/register the targets so that their relative positions may be determined. The method using wireless sensors (method D) is of a type that detect tilt movements of the surface the sensors is attached to. Some sensors are additionally capable of measuring distance from the sensor to a point to which the sensor laser is aimed. The measurement set-ups for optical targets and wireless sensors are described in separate sections below.

By analysing measurement uncertainty for the different methods, conclusions can be made regarding the magnitude at which deformation can be detected. For this purpose a measurement set-up was chosen, where no movements were anticipated. Measurements were performed at two different epochs separated by approximately 24 hours, the dates were August 15 and 16, 2019. The expected difference in target distance at the two measurement occasions is expected to be zero and the deviation reflects the measurement error.

Due to the similarities of methods using optical targets, the next section is covering common aspects for method A to C. In subsequent sections,
specifics are presented for each of the methods including the sensor based one (method D).

2.2 Target-based measurement

2.2.1 Measurement set-up

By attaching targets along a cross section of a tunnel and determining the targets positions in a local coordinate system at different occasions (epochs), information is retrieved that can be used to understand the deformation of the tunnel profile. Premises was chosen at KTH that offered a possibility of setting up targets in a way that resembles the positions one would get in a real tunnel cross section, regarding both shape and size. The targets were mounted on surfaces that are expected not to be exposed to any motion. Figure 2 shows the measurement set-up, both prism targets (mounted on magnetic feet) and Black & White targets (printed on plain paper) were used.

Figure 2: Approximate target positions in the premises used for convergence measurements.

Measurement methods A-C calculate the coordinates (n, e, h) of the mounted targets in a local coordinate system as an intermediate step when deriving displacements from measurement data. With known coordinates of a number of points along a cross-section of the tunnel, the horizontal and
vertical distance between every pair of points are determined. This is illustrated in Figure 3. How the coordinates are determined from the instrument output is presented in separate sections for method A, B and C below.

With the point coordinates as input, the horizontal and vertical distances between point i and j are calculated according to the following formulas:

\[
D_{hrz} = \sqrt{(n_j - n_i)^2 + (e_j - e_i)^2} \tag{1}
\]

\[
D_{vrt} = h_j - h_i \tag{2}
\]

The relative horizontal and vertical displacement is then the distance difference between epoch 2 and epoch 1:

\[
dD_{hrz} = D_{hrz}^{(ep2)} - D_{hrz}^{(ep1)} \tag{3}
\]

\[
dD_{vrt} = D_{vrt}^{(ep2)} - D_{vrt}^{(ep1)} \tag{4}
\]

Figure 3: Calculating horizontal and vertical distance from coordinate measurements.

The primary direction of typical tunnel convergence is in direction of the surface normal. This implies, for a certain combination of points, the major part of the motion can be associated to one of the points depending on
the geometry. For example, if one point is at the crown of the tunnel and the other is situated on a vertical wall, the contribution to the vertical motion is more prone to come from the ceiling point and the horizontal ditto from the vertical wall target. With this knowledge, together with horizontal and vertical distance measurements between all targets, it is possible to draw quite accurate conclusions about the absolute displacement of each target.

2.2.2 Uncertainty analysis

All measurements are subject to uncertainty. Many times the quantity being measured (input quantity) is not the quantity that is of primary interest for a study and a function describing the relation between input and output quantity needs to be applied. This is called indirect measurement and the uncertainty of the measured quantity propagates through the function to the output quantity also called measurand.

Let \( u(x_n) \) denote the uncertainty of a measured variable \( x_n \). Given that the function \( f(x_n) \) describes the relation between measured quantity and measurand \( (y) \), and assuming uncorrelated multiple sources of uncertainty, the combined propagated uncertainty is calculated using the following formula [26]:

\[
    u(y) = \sqrt{\left[ \frac{\partial f}{\partial x_1} \cdot u(x_1) \right]^2 + \left[ \frac{\partial f}{\partial x_2} \cdot u(x_2) \right]^2 + \cdots + \left[ \frac{\partial f}{\partial x_n} \cdot u(x_n) \right]^2} \tag{5}
\]

As described above, the measurements performed in this study are about determining the difference in distance (displacement) between points. The analysis is separated in horizontal and vertical displacement. Common for the target-based methods is the determination of target coordinates in a local coordinate system. In reality there will be certain correlation between the sources of uncertainty which will add covariance terms to Equation (5). However, in this study the correlation is assumed to be small and therefore not having significant impact on the end result. Good correspondence between the variance calculated by Equation (5) and variance determined directly from the distribution of the measurand supports this assumption.

For method A (total station), network adjustment is used when deriving the coordinates. Apart from coordinate values the network adjustment procedure also calculates the standard uncertainty related to the data used. In this case, the coordinates \((n, e, h)\) can be seen as the input quantity and
the horizontal and vertical distance the output quantity (measurands). For
the horizontal distance, the function \( f(x_n) \) in Equation (1) and the partial
derivatives in Equation (5) becomes:

\[
\begin{align*}
\frac{\partial f}{\partial n_i} &= -\frac{(n_j - n_i)}{D_{\text{hrz}}} = -\frac{\Delta n_{ij}}{D_{\text{hrz}}} \\
\frac{\partial f}{\partial n_j} &= \frac{(n_j - n_i)}{D_{\text{hrz}}} = \frac{\Delta n_{ij}}{D_{\text{hrz}}} \\
\frac{\partial f}{\partial e_i} &= -\frac{(e_j - e_i)}{D_{\text{hrz}}} = -\frac{\Delta e_{ij}}{D_{\text{hrz}}} \\
\frac{\partial f}{\partial e_j} &= \frac{(e_j - e_i)}{D_{\text{hrz}}} = \frac{\Delta e_{ij}}{D_{\text{hrz}}} 
\end{align*}
\]

Let \( u(\text{coord}_{\text{hrz}}) \) denote the uncertainty for one of the coordinates in
the horizontal plane, i.e. we assume the uncertainty is the same in both \( n \)
and \( e \) direction. Inserting the partial derivatives presented above and all
uncertainties equal to \( u(\text{coord}_{\text{hrz}}) \) in Equation (5) one gets:

\[
\begin{align*}
u(D_{\text{hrz}}) &= \sqrt{\frac{\Delta n_{ij}^2}{D_{\text{hrz}}^2} + \frac{\Delta e_{ij}^2}{D_{\text{hrz}}^2} + \frac{\Delta e_{ij}^2}{D_{\text{hrz}}^2}} = u(\text{coord}_{\text{hrz}}) \cdot \sqrt{2} \quad (6)
\end{align*}
\]

This is in fact the same as the uncertainty of a point in 2 dimensions
\( u(\text{point}_{\text{hrz}}) \) assuming the uncertainty of the underlying co-ordinates are the
same \( u(n) = u(e) \), [26]:

\[
u(\text{point}_{\text{hrz}}) = \sqrt{u(n)^2 + u(e)^2} = u(\text{coord}_{\text{hrz}}) \cdot \sqrt{2} \quad (7)
\]

In the vertical direction the distance, i.e. function \( f(x_n) \) is just a subtraction
of two height coordinates, Equation (2). Hence the partial derivatives
takes the values 1 and -1. If we let \( u(\text{coord}_{\text{vrt}}) \) represent the coordinate uncertainty in the vertical direction, the vertical distance uncertainty becomes:

\[
u(D_{\text{vrt}}) = u(\text{coord}_{\text{vrt}}) \cdot \sqrt{(1)^2 + (-1)^2} = u(\text{coord}_{\text{vrt}}) \cdot \sqrt{2} \quad (8)
\]

The uncertainty of the displacement, which is the difference between the
distance measured at 2 epochs, is calculated in the same manner for both
horizontal and vertical direction:

\[
u(dD_{\text{hrz}}) = \sqrt{2} \cdot u(D_{\text{hrz}}) = 2 \cdot u(\text{coord}_{\text{hrz}}) \quad (9)
\]
\[ u(d_{vrt}) = \sqrt{2} \cdot u(D_{vrt}) = 2 \cdot u(coord_{vrt}) \] (10)

The standard uncertainty, tells us that the measured value falls within an interval \( \pm u \) centred around the mean value of the measurements with an estimated probability of around 68%. By increasing the confidence interval the corresponding probability or confidence level increases. This is called expanded uncertainty. A commonly used confidence level is 95% which corresponds to an interval almost twice (1.96) as wide as the standard uncertainty.

If no displacement has occurred, the distribution of measurement values will be scattered around the value zero. Measurements within the limits \( \pm 1.96 \cdot u \), demonstrate with 95% confidence that no displacement has occurred. Consequently, if the measurement falls outside the mentioned interval, the probability that there has been no displacement is 5%. The latter is the so called type I error in hypothesis testing, i.e. the null hypothesis \( H_0 \) (no displacement) is true, but incorrectly rejected since the measurement in question is outside the chosen confidence interval. The probability for type I error is commonly denoted \( \alpha \).

Assuming there has been a displacement of 1 mm in a certain direction, what is the probability to detect such movement from a single measurement? As an example, we assume the expanded uncertainty (95%) to be 0.9 mm. As stated above, measurements larger than 0.9 mm are required in order to declare a displacement \( (H_0 \text{ is false}) \). From Figure 4 one can see how a measurement value below 0.9 mm can possibly belong to either distribution. There is a risk to incorrectly interpret a measurement value as no displacement when a displacement has actually occurred (null hypothesis is false). In hypothesis testing this is referred to as type II error and the probability for it to occur is denoted \( \beta \). Furthermore is the probability for the opposite to occur \( (H_0 \text{ is false and correctly rejected}) \) \( 1-\beta \). In this specific example \( 1-\beta \) corresponds to 62%.
The probability $1-\beta$ increases with the size of the actual displacement and reaches 95% at 1.6 mm. This means an observation can be interpreted as a displacement with a probability of at least 95%, only if the actual displacement is 1.6 mm or larger. So, the minimum displacement, that can be detected at a reasonable confidence level, is significantly larger than the measurement uncertainty of the measurement system being used. See also [27].

2.3 Method A: Total station

The total station used in this study was a Trimble S8. According to the data sheet [28] the total station has a standard uncertainty for horizontal and vertical angle measurement down to 0.15 mgon. Furthermore is the standard uncertainty for distance measurements 0.8 mm + 1 ppm. Relating to the total station requirements mentioned in section [2.6.4] it can be concluded that Trimble S8 fulfils the performance required for deformation measurements.

Measurements were performed at 4 different total station positions varying both the distance to the tunnel cross-section and the location between the tunnel walls, see Figure 5. Both B/W targets (printed on regular paper) and prism targets were used. The number of B/W targets used was 11 while the number of prism targets were only 4 due to limited availability.
For each of the total station positions, measurements were performed in 2 full sets. In each set, the targets were measured in the 2 faces of the total station to cancel out any vertical and horizontal collimation error. A local coordinate system was used, i.e., a position with certain coordinates was chosen as reference point and a direction close to north as reference direction. What position and direction that are chosen as reference does not really matter. However, it is good practice to select numbers so that all measured becomes positive. The measured quantities are listed below and illustrated in Figure 6:

- distance between the position of the total station and each target
- horizontal angle to each of the measurement targets relative a reference
direction defined by the total station

- vertical angle relative the horizontal plane, defined by precise levelling of the total station

The measured angles and distances constitute a network of triangles where more parameters are known (from measurements) than needed for calculating the local coordinates of the targets. The system of equations describing the geometry of this network is said to be over determined. Network adjustments were used to determine the target coordinates. With those as input, distance differences in horizontal and vertical direction between epoch1 and epoch2 were calculated according to Equations (3) and (4). The result is found in Table 13 and 14 of Appendix A.1.

In this study the total station method involved measurements from all four total station locations in the network adjustments. This gives a robust network able to increase accuracy and reliability of the positions determined from redundant measurements. Fewer measurement location will require less time for measuring but at the same time compromise the reliability of the final result. The impact of different geometry on the measurement performance was not investigated in this study, but definitely something that can be examined further.

2.3.1 Measurement uncertainty

Each of the measured input values is afflicted with random errors which is called observation residual. In the least squares network adjustment, the sum of the squares of the residuals are minimized. The network adjustments were made in SBG GEO [29], and the output is in the form of 3D coordinates for each target and the standard uncertainty for each of the coordinate directions.

Two different uncertainty values (average & max) were derived for the B/W targets measured manually and for prisms measured with both manual and autolock method, see header row in Tables 1 and 2. The average and max values are determined based on the uncertainty values of n and e coordinates for horizontal and h coordinate for vertical from the two epochs. The max-values reflect a worst case scenario while the average values provides a more optimistic view on the measurement precision.

Table 1 presents the standard uncertainty value for co-ordinate, 2D
Table 1: **Standard uncertainty in the horizontal plane (e, n) as a result of total station measurements and subsequent network adjustments (unit: mm).**

<table>
<thead>
<tr>
<th>Unit:</th>
<th>Prism, auto</th>
<th>Prism, manual</th>
<th>B/W, manual</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm avg max</td>
<td>mm avg max</td>
<td>mm avg max</td>
</tr>
<tr>
<td>( u(..._{hrz}) )</td>
<td>1.5 3.1</td>
<td>1.5 3.0</td>
<td>0.4 0.8</td>
</tr>
<tr>
<td>( u(..._{hrz}) )</td>
<td>2.1 4.4</td>
<td>2.1 4.2</td>
<td>0.5 1.1</td>
</tr>
<tr>
<td>( u(..._{hrz}) )</td>
<td>3.0 6.2</td>
<td>2.9 6.0</td>
<td>0.7 1.5</td>
</tr>
</tbody>
</table>

Point, distance and displacement in the horizontal plane, calculated according to what was explained in section 2.2.2. Table 2 does the same but in the vertical direction. Vertically there is just 1 dimension, hence there are no values for 2D point in Table 2. The tables show how the standard uncertainty propagates to the output quantity. Hence the last row of the table shows the standard uncertainty of the displacement (difference in distance between two epochs).

Table 2: **Standard uncertainty in the vertical direction as a result of total station measurements and subsequent network adjustments.**

<table>
<thead>
<tr>
<th>Unit:</th>
<th>Prism, auto</th>
<th>Prism, manual</th>
<th>B/W, manual</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm avg max</td>
<td>mm avg max</td>
<td>mm avg max</td>
</tr>
<tr>
<td>( u(..._{vert}) )</td>
<td>0.9 1.1</td>
<td>1.0 1.2</td>
<td>0.2 0.3</td>
</tr>
<tr>
<td>( u(..._{vert}) )</td>
<td>1.2 1.5</td>
<td>1.4 1.7</td>
<td>0.3 0.5</td>
</tr>
<tr>
<td>( u(..._{vert}) )</td>
<td>1.7 2.1</td>
<td>2.0 2.4</td>
<td>0.4 0.7</td>
</tr>
</tbody>
</table>

Applying the reasoning in section 2.2.2 on the uncertainty values derived above, it can be stated (at a confidence level of 95%) that an actual displacement has occurred if the observed distance difference is larger than \( 1.96 \cdot u(D) \). These limits, separating displacement from no displacement, are presented in Table 3.

Comparing the uncertainty values reveal some unforeseen results. The uncertainty of manual and autolock method for prism targets are very similar. It also contradicts the result of [30], claiming that manual aiming creates larger uncertainty in horizontal direction and lower in vertical compared to using autolock. The uncertainty figures above show a slight indication of the opposite, i.e. lower horizontal and higher vertical uncertainty for manual mode compared to autolock. In this context it is also necessary to regard
there were just four prism targets, leading to a weaker statistical basis.

Furthermore, the measurements made with the B/W targets outperforms the ones done with prism targets regarding measurement precision. The B/W uncertainty values are approximately $\frac{1}{4}$ of the corresponding values for prism targets. This is not expected since the more precise distance measurement obtained by using prisms is expected to improve the uncertainty in the derived coordinates. The reason for the prisms showing lower precision than expected is probably due to non-optimal alignment with the total station. As mentioned previously, have measurements been performed from four different station positions, the prisms directions were not adapted between the different measurements. Such miss-alignment leads to an increase in uncertainty both for distance and angle measurements [30]. This also means the measurement system is not precise enough to distinguish any difference between manual and autolock mode as seen in the result above.

Table 3: Expanded uncertainty (confidence level 95%) for network adjusted total station measurements of horizontal and vertical displacement.

<table>
<thead>
<tr>
<th>Unit: mm</th>
<th>Prism, auto $1.96 \cdot u$ (avg) (max)</th>
<th>Prism, manual $1.96 \cdot u$ (avg) (max)</th>
<th>B/W, manual $1.96 \cdot u$ (avg) (max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u(dD_{hrz})$</td>
<td>5.9</td>
<td>12.2</td>
<td>5.8</td>
</tr>
<tr>
<td>$u(dD_{vert})$</td>
<td>3.3</td>
<td>4.1</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Since the B/W target measurements show better uncertainty values that are in line with expected result, they are selected to represent method A when comparing measurement precision. To compare the propagated uncertainty calculated based on the output from the network adjustment made in SBG GEO, the actual uncertainty obtained from the distribution of displacement values was determined. Figures 7 and 8 present distribution of horizontal and vertical displacement, for all possible combinations of target pairs (difference in distances between epoch 1 and epoch 2). Included in these figures are also the approximated normal distribution curves.
Figure 7: Distribution of horizontal displacement for the B/W targets (determined from using total station) and a normal distribution approximation.

Figure 8: Distribution of vertical displacement for the B/W targets (determined from using total station) and a normal distribution approximation.

From the measurement data the expanded uncertainty (corresponding to 95% confidence level) is estimated to 2.4 mm and 1.8 mm in the horizontal and vertical direction. Results are discussed further in section 3.1.

2.4 Method B: Laser scanner

A laser scanner (Leica BLK360 [31]) was used to capture the B/W measurement targets in a 3D point cloud. A scan was made from 3 different positions; P1) right under the cross section where the targets are attached,
P2) approximately 5 meters from the targets and P3) around 10 meters from the targets. The purpose was to evaluate if different geometries had an effect on the precision of the measurements. Figure 9 shows the set-up for the laser scanning.

![Sketch of the laser scanner set-up with three different instrument positions.](image)

Figure 9: Sketch of the laser scanner set-up with three different instrument positions.

The data from the laser scanner was imported into Leica Cyclone where the captured scene was registered with the external coordinate system defined by 3 control points (20, 27 and 111) whose positions were determined by the total station method.

For each of the B/W targets an object was created in Cyclone with its centre point aligned with the center point of the B/W target, see Figure 10. The tool provides a function that detects the B/W target in the point cloud and places the created object with its vertex in the position of the target vertex and its axis aligned with the axis of the local coordinate system.

With all the objects created for each target, the relative coordinates of the objects are exported as a comma separated text format.
In the next step the distances and difference in distances between the 2 epochs were calculated as described above in section 2.2. The results for the three scanning positions are presented in Appendices A.3, A.4 and A.5.

2.4.1 Measurement uncertainty

According to [31], the Leica BLK 360 laser scanner has the following measurement standard uncertainty:

- Ranging accuracy: 4 mm @ 10 m
- 3D point accuracy: 6 mm @ 10 m

The 3D uncertainty can be calculated from the uncertainty of each coordinate components according to this formula [26]:

\[ u_{3D} = \sqrt{u(e)^2 + u(n)^2 + u(h)^2} \]  \hspace{1cm} (11)

We assume the uncertainty to be equal in all three directions, hence the coordinate uncertainty can then be computed as:

\[ u(e) = u(n) = u(h) = u_{3D}/\sqrt{3} \approx 3.5 \text{mm} \]  \hspace{1cm} (12)

Leica has separately specified a ranging accuracy of 4 mm @ 10 m, which corresponds well to 3.5 mm applying a safety margin by rounding up. Using the previously described method for calculating the corresponding uncertainty for coordinate, point, distance and distance difference, the result presented in Table 4 is obtained.

Table 4: Standard uncertainty for the Leica BLK360 laser scanner, separated in horizontal plane and vertical direction.

<table>
<thead>
<tr>
<th>Unit: mm</th>
<th>Horizontal</th>
<th>Vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td>u(coord)</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>u(point)</td>
<td>4.9</td>
<td>-</td>
</tr>
<tr>
<td>u(D)</td>
<td>4.9</td>
<td>4.9</td>
</tr>
<tr>
<td>u(dD)</td>
<td>7.0</td>
<td>7.0</td>
</tr>
<tr>
<td>1.96·u(dD)</td>
<td>13.7</td>
<td>13.7</td>
</tr>
</tbody>
</table>

The last row of the table shows the expanded uncertainty values for confidence level 95%. Standard uncertainty was determined from the distribution of displacement values. The displacement was calculated from
measurements as described in the previous section. Examples of horizontal and vertical displacement distributions, from scanning position P3, are presented in Figures 11 and 12.

Figure 11: Distribution of horizontal distance difference (determined from laser scanning) and a normal distribution approximation.

Figure 12: Distribution of vertical distance difference (determined from laser scanning) and a normal distribution approximation.

From the example graphs above the expanded uncertainty (corresponding to 95% confidence level) is estimated to 5.1 mm and 3.1 mm in the horizontal and vertical direction. The full result regarding measurement uncertainty for method B (laser scanner) is presented and discussed in section 3.1.1.
2.5 Method C: Photogrammetry

Photos were taken of the B/W target set-up so that each photo overlapped with the neighbouring photo by at least 2 targets. Approximately 70 photos were captured distributed over 14 different location. The Camera positions were equally divided in high and low positions. Around 5 photos at each position was required to capture all the targets.

![Illustration showing the principle of capturing photos for the photogrammetry method.](image)

Figure 13: *Illustration showing the principle of capturing photos for the photogrammetry method.*

Agisoft Metashape [33] was used to build a point cloud from the photos. In the same tool the point cloud was registered (and scaled) to the reference system used in the total station measurements. For this the B/W targets were used as tie points. The point cloud was then imported into Cyclone in which the same method as described in 2.4 was applied to determine the horizontal and vertical change in distance between the different targets. The result is presented in Tables 23 and 24 of Appendix A.6.

2.5.1 Measurement uncertainty

Figures 14 and 15 presents the distribution of the calculated deformation in horizontal and vertical direction respectively. Uncertainty in horizontal displacement at confidence level 95% is around 5 cm (43 mm) and the corresponding value in the vertical direction is 3 cm (24 mm).
Figure 14: *Distribution of horizontal distance difference (determined from Photogrammetry) and a normal distribution approximation.*

As seen in Figure 14, the shape of measurement values frequency distribution does not resemble much of the bell shaped normal distribution curve. A probable reason is too few measurement samples for the high uncertainty of this particular method. The corresponding measurements for the vertical distance difference, Figure 15, does match the normal distribution better.

Figure 15: *Distribution of vertical distance difference (determined from Photogrammetry) and a normal distribution approximation.*

The result of photogrammetry uncertainty is further discussed in [3.1.1](#).
2.6 Method D: Wireless sensors

2.6.1 General

For the purpose of this study, sensors were borrowed from the company Senceive and configured in a wireless network called FlatMesh. FlatMesh uses the meshed network technology in which all nodes are inter-connected and share data with each other. A gateway in the mesh network is in turn connected to the internet through a mobile network (GSM or UMTS). For this study, three optical displacement sensors and four tri-axial tilt sensors were used to collect measurement data, please refer to Senceive’s web page for product information [34]. Both sensor types measure tilt the same way, but the displacement sensors also has the ability of measuring distance.

The placement of the sensors were decided with the purpose of understanding the characteristics of the products, primarily regarding measurement accuracy but also practical aspects relevant to deployment in tunnel environment. Table 5 presents details of the sensors installation.

Table 5: The list of sensors used in this study and their respective installation characteristics.

<table>
<thead>
<tr>
<th>ID</th>
<th>Type</th>
<th>Stability</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>ODS_001</td>
<td>Distance &amp; Tilt</td>
<td>3</td>
<td>Mounted on floor-standing metal cabinet</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Laser incident angle: ( \sim 75^\circ ) (wall)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Distance to target: ( \sim 4.4 ) m</td>
</tr>
<tr>
<td>ODS_002</td>
<td>Distance &amp; Tilt</td>
<td>5</td>
<td>Mounted on metal consol bolted to wall</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Laser incident angle: ( \sim 90^\circ ) (ceiling)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Distance to target: ( \sim 1.2 ) m</td>
</tr>
<tr>
<td>ODS_003</td>
<td>Distance &amp; Tilt</td>
<td>4</td>
<td>Mounted on floor-standing shelving</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Laser incident angle: ( &lt; 45^\circ ) (ceiling)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Distance to target: ( \sim 1.9 ) m</td>
</tr>
<tr>
<td>TILT_001</td>
<td>Tilt</td>
<td>4</td>
<td>Mounted on radiator bolted to wall</td>
</tr>
<tr>
<td>TILT_002</td>
<td>Tilt</td>
<td>2</td>
<td>Mounted on ventilation tube</td>
</tr>
<tr>
<td>TILT_003</td>
<td>Tilt</td>
<td>5</td>
<td>Mounted on metal lid bolted to wall</td>
</tr>
<tr>
<td>TILT_004</td>
<td>Tilt</td>
<td>5</td>
<td>Mounted on metal lid bolted to wall</td>
</tr>
</tbody>
</table>

2.6.2 Mounting stability

The sensors were deliberately mounted with different stability to investigate the effect on the tilt and distance measurements. Column 3 indicates this as
a number from 1 to 5, the higher the number the more stable the installation. The sensor with least stability were ODS_001 and TILT_002. ODS_001 were mounted on a metal cabinet standing on the floor with a height of 2 meters. TILT_002 was mounted on a metal ventilation tube which allowed the sensor to swing perpendicular to the longitudinal direction of the tube which was aligned with the y axis of the sensor. Even though these sensors had a less stable mounting, they did not move unless they were exposed to an external stimuli.

The most stable sensors, indicated as 5, were attached to metal objects that were firmly bolted to the concrete walls of the premises. This resulted in a stability comparable to the sensor being mounted directly on the concrete wall. Senseive’s magnetic mounting kit was used for all the different configurations. The premises is in the basement of a building at KTH and the temperature was stable at 23°C.

### 2.6.3 Measurement uncertainty

In the sensor product information, Senceive presents values for resolution and repeatability, see Table 6. Precision is in fact the resolution with which the data is reported from the sensors, i.e. only certain values are indicated by the measurement system. Hence, there is a range of input signals to the sensor spanning a known interval that gives the same indication. This contributes to the uncertainty with $\frac{1}{12}$ of the resolution [35].

According to the same document, repeatability is defined as "closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement". To be able to compare the uncertainty of the other measurement methods, sensor measurements were performed to determine the statistical distribution and from that calculate the measurement uncertainty.

**Table 6: Sensor measurement performance values as presented by the vendor.**

<table>
<thead>
<tr>
<th>Tilt (µm/m)</th>
<th>Distance (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precision</td>
<td>1.75</td>
</tr>
<tr>
<td>Repeatability</td>
<td>± 8.7</td>
</tr>
</tbody>
</table>

Measurements were collected every 5th minute over a time period of 18 days, which resulted in over 5000 samples. The distribution of the measured
quantities (angle of rotation around the 3 axis and distance) were plotted, and the expected normal distribution could be confirmed. Figure 16 is an example of such distribution plot. The narrow bars reflect the resolution of the distance measurement sensor being 0.1 mm. Included in the plot is also a normal distribution approximation having the same standard uncertainty and mean value as calculated from the measurement data. The expanded uncertainty at confidence level 95% as seen in the distribution plot is approximately 0.3 mm.

![Figure 16: An example of sensor distance measurement distribution and normal distribution approximation.](image)

The sensors used in this study, measure tilt in degrees, for the three directions; x, y and z. A y-tilt for example means the sensor has rotated around the x-axis (rotation axis), with a rotation direction parallel to the yz-plane (rotation plane). This is illustrated in Figure 17. The positive tilt direction is determined by the cross product of the rotation axis and the 'tilt-axis', i.e. \( \mathbf{x} \times \mathbf{y} \). This direction is parallel to the z-axis.

![Figure 17: Definition of tilt direction.](image)
With a tilt sensor attached to a beam, the measured tilt can be converted to relative displacement between two points. Attaching the tilt beam to a measurement object at these points allow for precise measurement of relative displacement. The distance between the anchor points needs to be known with a precision on par with the required displacement uncertainty. The relative displacement is calculated using this equation (see also Figure 18):

$$dD = Tilt \cdot \frac{\pi}{180} \cdot L$$  \hspace{1cm} (13)

With the tilt beam installed in a tunnel for convergence measurements, displacements may occur at both ends of the beam. In that case the total relative displacement ($dD$) is the sum of the displacement at both ends with the positive direction aligned with the direction of the measured angle.

$$dD = dD_a + dD_b$$  \hspace{1cm} (14)

The distribution of the total displacement over the 2 beam-ends depends on the location of the tilt beam’s rotation point. This location is not known, hence only the total relative displacement can be determined with a single tilt beam.

This way of calculating the desired quantity from measured values is, as previously stated in section 2.2.2, called indirect measurements. In this case the input quantity is the tilt angle and the function describing the relation between the measurand and the input quantity is Equation (13). From Equation (5) this uncertainty propagation function can be derived:

$$u(dD) = \frac{\pi}{180} \cdot L_{beam} \cdot u(tilt)$$  \hspace{1cm} (15)

Figure 18 shows the distribution of the relative displacement, calculated from the same tilt measurements presented above using Equation (13) and assuming a tilt beam length of 1 meter. The resolution of the tilt measuring sensor is 0.0001 °, corresponding to 1.75 µm/m. This is illustrated in the graph by narrow bars at each resolution value.
Figure 19: An example of sensor tilt measurement distribution and normal distribution approximation (sensor ODS.002).

Presenting the tilt measurements in this way, makes it possible to compare with the measurement precision of the target-based measurements. Based on the calculated displacement values, the expanded uncertainty at a confidence level of 95% was calculated to approximately 12 µm for a 1 meter tilt beam. As expected, the same result was obtained when applying Equation (15) with the corresponding uncertainty for the measured tilt as input.

This basic method, for measuring relative displacement using tilt sensor on a tilt beam, can be expanded to multiple tilt beams mechanically connected in a chain with the ability to monitor displacements in a tunnel profile. This expanded method is presented in the following section (2.6.4).

2.6.4 Measuring tunnel convergence by sensors

If we assume the soil surrounding the tunnel being homogeneous then the displacement of the tunnel surface (ceiling and walls) are expected to be symmetrical on both sides of the tunnel’s vertical symmetry line. A point on the tunnel surface will move in the direction parallel to the surface normal at that same point.

According to [12], rotation will only appear if the deformation is asymmetric and as Gothäll expresses it; for all plausible small displacements this component will be very small. Hence, measuring tilt in one specific point
will not provide valuable information regarding tunnel convergence, the dis-
placement along the surface normal is the primary focus. A tilt sensor in
such point would not be exposed to any rotation, it will only make a trans-
lational motion.

As discussed in the previous section (2.6.3), the relative displacement
between two points along the surface normal can be captured by mounting
the tilt sensor on a beam and attaching its two ends to the tunnel surface.
The displacement will give rise to a rotation only if the two points move
different distance or in opposite directions. Limiting to movements perpen-
dicular to the tilt beam (i.e. along the tunnels surface normal), any tilt
beam displacement can be divided into translation and rotation around the
beam center, as demonstrated in Figure 20.

Figure 20: Tilt beam movement separated into rotation and translation

By configuring the tilt beams in a chain, two adjacent tilt beams share
one anchor point and the displacement experienced by the joint tilt beam
terminations will be the same. Figure 21 illustrates that the expected dis-
placement direction (parallel to the tunnel surface normal) is not really
perpendicular to the tilt beam.
However, as long as the movement is small, the formulas presented here are valid. Also, the smaller the change of direction between adjacent tilt beams, the more accurate the calculations are. Based on this chain configuration, where tilt beams share anchor points, and assuming the direction of motion will be along the surface normal, the following equation is derived. Adjacent tilt beams are denoted by index (n-1) and n respectively and the unit of Tilt is radians (or mm/m).

\[
dD_{nb} = dD_{(n-1)a} \Rightarrow -Tilt_n \cdot \frac{L_n}{2} + dD_{Tn} = Tilt_{(n-1)} \cdot \frac{L_{(n-1)}}{2} + dD_{T(n-1)} \Rightarrow
\]

\[
dD_{Tn} = Tilt_{(n-1)} \cdot \frac{L_{(n-1)}}{2} + Tilt_n \cdot \frac{L_n}{2} + dD_{T(n-1)} \quad (16)
\]

If we apply Equation (16) on a tilt beam chain of N tilt beams we get the following series of equations:
By measuring the tilt beam rotation and knowing the beams lengths, the relation between translation for adjacent tilt beams is known. The first and the last tilt beam in the chain do not share one of their anchor points. The displacement of those points can be expressed as (see also Figure 20):

\[ dD_{T1} = Tilt_1 \cdot \frac{L_1}{2} + Tilt_2 \cdot \frac{L_2}{2} + dD_1 \]

\[ dD_{T2} = Tilt_2 \cdot \frac{L_2}{2} + Tilt_3 \cdot \frac{L_3}{2} + dD_2 \]

\[ \vdots \]

\[ dD_{TN} = Tilt_{(N-1)} \cdot \frac{L_{(N-1)}}{2} + Tilt_N \cdot \frac{L_N}{2} + dD_{T(N-1)} \]

Note that positive direction is towards the symmetry line of the tunnel cross section. Inserting Equations (17) and (18) instead of \(dD_{T1}\) and \(dD_{TN}\) into the series of equations above results in:

\[ dD_{Na} = dD_{1b} + \sum_{n=1}^{N} Tilt_n \cdot L_n \]

To calculate the translation for each tilt beam the translation of the first or the last beam need to be determined. With the tilt sensor mounted on the beam we only know the displacement due to rotation. It could be sufficient to just set one of the tilt beam chain end points as the reference. A drawback from that approach is however the uncertainty regarding movements in the selected reference point. Another is the significant error imposed on the anchor point in the opposite end of the beam chain, due to error propagation through the series of equations above.

By measuring the horizontal distance change between the first and the last tilt beam anchor points, the loop can be closed and the errors kept to a
minimum. Let $D_l$ denote the distance between the first and the last anchor point of the tilt beam chain, then the horizontal distance difference between epoch 1 and epoch 2 follow this expression:

$$D_l^{epoch1} - D_l^{epoch2} = dD_{Na} + dD_{1b}$$ (20)

We now have two unknown parameters, $dD_{1b}$ and $dD_{Na}$ and two Equations (19) and (20), hence the displacements of the utmost anchor points of the beam chain can be determined. From those, the displacement of each anchor point can be calculated using the theory presented above.

Measuring the horizontal distance between anchor points 1b and Na requires special arrangements. Both the sensor, generating the laser, and the reflecting surface at the opposite side must be attached to and follow any motion of points 1b and Na. There is a need to initially level the laser as well as the surface the laser is aimed at, to create an incident angle close to $90^\circ$. The displacement are expected to be small and predominantly in the horizontal direction (the direction of the surface normal). The potential rotation on the laser and laser target, due to rotation of first and last tilt beam in the chain, is assumed to have insignificant impact on the measured distance.

Figure 22 illustrates a suggested way to measure the horizontal distance with a laser following the principles just described.

Figure 22: Measurement of horizontal distance to determine the relative displacement between the two end points of a tilt beam chain configuration. Double directional arrow indicates the possibility to level the laser beam and target.
2.7 Comparison of cost

When deciding on what measurement method to use for a project, measurement precision needs to be balanced against cost. Costs for measuring can be divided into cost of work labour (the time and competence required) and equipment costs. An additional aspect that needs to be considered when it comes to measurements in tunnels, is to what extent the measuring process interfere with other activities. Such activities are those related to the construction of the tunnel or, in case the tunnel is in operation, the intended traffic.

To be able to compare the cost, a reference project is defined by listing the material needed and working tasks required to perform measurement. Since the target-based methods have many similarities and there are substantial differences compared to the sensor based method, two separate reference projects are defined. The following was assumed in order to present a perceptible figure for cost. These assumptions are the same for both reference projects:

- Tunnel length: 100 m.
- Number of cross-sections: 6. (15 m. apart)
- Number of measurements (epochs): 26 (every second week during one year)

During the measurements performed within the scope of this study, the time required for each task was recorded. Based on those observations, an estimate have been derived taking into consideration the difference in working conditions between that of a laboratory, with controlled indoor climate in terms of temperature, humidity, visibility and air pollution and that of a tunnel being constructed.

2.7.1 Reference project for target-based methods

For the target-based methods the following products are required. The prices are in Swedish kronor (SEK):

- Measuring equipment:
  - Total station (method A): 1 000 SEK per day (price from Trimble sales personnel)
– Laser scanner (method B): 2 500 SEK per day (price from Trimble sales personnel)
– Camera (method C): 11 000 SEK (Canon D6 Mark II, price from www.prisjakt.nu)

• 9 targets per cross-section (Note: More advanced targets than the ones used in this study. Prices from www.berntsen.com):
  – Magnetic survey prisms w. protection cover (method A): 5 000 - 13 000 SEK
  – B/W targets (method B): 2 000 SEK
  – B/W targets (method C): 2 000 SEK

• mobile hydraulic lift platform: 500 SEK per day (average price from rental companies)

• Data processing software:
  – SBG Geo (method A): 17 000 SEK (www.sbg.se)
  – Leica Cyclone (method B & C): 22 000 SEK (www.transitandlevel.com)
  – Agisoft Metashape (method C): 34 000 SEK (www.agisoft.com)

Activities associated with target-based methods, that require human intervention are listed below. An estimate of the time duration for each activity are presented. Common for the target-based methods is the need to mount targets before the measurement activity can start. The time required for setting up the targets was not measured during lab set-up, since the procedure and targets used are very different compared to what would be the case in a real tunnel. The number are instead based on the company WSP’s experience in this kind of activities. An hourly tariff of 800 SEK has been used to convert labour hours into cost in the Swedish currency.

It is of high importance, the targets are steadily mounted on the tunnel surface. A large number of targets exists on the market designed for certain measurement equipment and with different means of installation, tailored to be mounted in a variety of foundation material.

1. Install the targets and perform initial measurement:
   • 2 500 SEK (method A)
   • 1 300 SEK (method B)
2. Measure one cross section (instrument establishment included if applicable):

- Automatic: 20 min or Manual: 30 min per measurement position and cross-section (method A)
- 10 min (method B)
- 15 min assuming 60-70 photos (method C)

The average time it takes to mount one target in a tunnel cross section is estimated to around 10 minutes. Hence, installing all 9 targets in one cross section would take 1½ hour. During this time vehicle traffic need to be partly or completely stopped. It is assumed that a mobile hydraulic lift platform is used to reach the higher target positions.

The total station measurements (method A) performed in this study, involved measuring one tunnel cross section from 4 different TS positions. At each position the total station where established and the targets were measured at 2 full sets. Presented above are the measurement time required for one total station position. Thus, to reach the level of uncertainty reported in this study, the time required for measuring autolock and manual mode is 1½ and 2 hours respectively.

When it comes to photogrammetry, images of the tunnel cross section are captured in multiple camera positions. In this study, 14 positions where used of which half were at a level of approximately ½ meter above the floor while the other half where captured using a ladder reaching a camera height around 2.5 meters above the floor.

The number of photos needed (from each camera position) depends on the size of the tunnel cross section and the focal length of the camera. An overlap of at least 2 targets are required for the tool converting the photos to 3 dimensional point clouds to achieve an acceptable result. In this study, the time required to take a complete set of photos was ¼ hour. Hence, the average time required for one pair of low and high camera position was calculated to around 2 minutes.
2.7.2 Reference project for sensor based methods

For the measurement method using tilt sensors the following products are required. The prices are in Swedish kronor (SEK):

- Measuring equipment per cross section (prices from Senceive sales personnel):
  - 11 sensors: 70 000 SEK per
  - 10 tilt beams: 20 000 SEK
- 3G gateway: 23 000:- (price from Senceive sales personnel)
- mobile hydraulic lift platform: 500 SEK per day (average price from rental companies)

For the sensors based method the installation procedure is similar to installing targets, except that each end of the tilt beams in a daisy chain is to be mounted along the profile of a tunnel cross-section. Hence, due to handling of bulkier items the required installation time (per tilt beam) is estimated 15 minutes. During this time the possibility for vehicles to pass this section of the tunnel will be limited.

3 Results and discussion

3.1 Measurement precision

3.1.1 Target-based measurements

This section presents for the methods that uses optical targets, the obtained accuracy from measurements performed in the lab environment described in 2. An uncertainty value was derived from an approximated normal distribution having the same mean and standard uncertainty as the distance differences calculated from measured values.

Table 7 presents the uncertainty values determined from measurement for the target based methods. Method A (total station) has the lowest uncertainty. This is in line with what was concluded from the uncertainty calculations performed in subsection 2.3 of the Method section, although the vertical uncertainty determined from the distribution plot is higher. Prism targets are expected to provide better measurement precision due to more
Table 7: *Comparison of displacement measurement uncertainty for target based methods A-C. Expanded uncertainty at confidence level 95%.*

<table>
<thead>
<tr>
<th>Measurement method</th>
<th>Uncertainty 1.96-u(dD), 95% conf.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (total station):</td>
<td>horizontal: 3 mm</td>
</tr>
<tr>
<td></td>
<td>vertical: 2 mm</td>
</tr>
<tr>
<td>B (laser scanner):</td>
<td>horizontal: 5 mm</td>
</tr>
<tr>
<td></td>
<td>vertical: 3 mm</td>
</tr>
<tr>
<td>C (photogrammetry):</td>
<td>horizontal: 43 mm</td>
</tr>
<tr>
<td></td>
<td>vertical: 24 mm</td>
</tr>
</tbody>
</table>

Precise distance measurements compare to B/W targets. As mentioned earlier the result was actually the opposite and the reason most probably due to misalignment between prisms and total station. This result shows that prisms should be carefully selected to comply with the measurement set-up.

For laser scanner (method B), the uncertainty values presented in Table 7 are estimates based on the measurement result from three different scanner positions. Table 8 presents the result from each position. The middle position, approximately 5 meters from the measured cross-section, demonstrated the lowest uncertainty.

Table 8: *Expanded uncertainty (confidence level 95%) for displacement measurements based on laser scanning.*

<table>
<thead>
<tr>
<th>Unit: mm</th>
<th>Position P1</th>
<th>Position P2</th>
<th>Position P3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.96-u(dD_hrz)</td>
<td>4.9</td>
<td>4.4</td>
<td>5.1</td>
</tr>
<tr>
<td>1.96-u(dD_vrt)</td>
<td>3.0</td>
<td>1.8</td>
<td>3.1</td>
</tr>
</tbody>
</table>

Corresponding uncertainty values based on product specification were determined in the method section for laser scanner (2.4.1). The result is 2-3 times higher than the ones obtained from measurements. Other studies, as mentioned in literature review section for 1.4, report an uncertainty in the order of 5 mm, which supports the result presented in the tables above.

As seen in Table 7, the measurement uncertainty for method C (photogrammetry) is, without doubt, the highest of the targets based methods. Articles about deformation detection using photogrammetry reveal a much better measurement precision, as high as sub mm level, see the literature...
review related to 1.5. Please note that a different approach is used to reach such high precision. More sophisticated equipment and software is used which are not comparable with the price reported in this study for method C (photogrammetry). It demonstrates however that progress is made in the photogrammetry area which is of high interest for deformation monitoring.

Common for the target-based methods is that they separate the displacement in a horizontal and vertical component. This is achieved by a reference coordinate system defined from measurement performed with a precisely levelled total station. A possibility for precise levelling of a laser scanner would remove the need for registering the generated point cloud with total station measurements. For the photogrammetry method, an object with known length and a precise vertical orientation could replace the total station measurements when it comes to scaling and levelling.

3.1.2 Sensor based measurements

As opposed to the previous section which presented and discussed the uncertainty values of the target based methods, this section presents not only the uncertainty figures, but also how they are derived for the suggested method of using tilt sensors mounted on tilt beams joined together in a chain. This is because the method itself is as much a result as the uncertainty values.

The uncertainty of the measured tilt values and the corresponding displacement values were presented in section 2.6.3. When using a tilt beam chain for tunnel convergence monitoring the uncertainty will propagate along the beam chain based on the formulas presented in 2.6.4 according to the theory outlined in section 2.2.2.

With Equation (20) the sum of the translation of the first and last tilt beam can be calculated based on beam length, distance and tilt measurements.

\[
dD_{T1} + dD_{TN} = (D_{epoch1}^{epoch1} - D_{epoch2}^{epoch2}) + Tilt_1 \cdot \frac{L_1}{2} - Tilt_N \cdot \frac{L_N}{2} \tag{21}
\]

Applying Equation (5) and assuming the uncertainties to be equal for
the same type of measurement, the uncertainty becomes:

\[
\begin{align*}
    u(d_{T1} + d_{TN}) &= \\
    &= \sqrt{2 \cdot u(D_t)^2 + \frac{(L_1)^2 + (L_N)^2}{4} \cdot u(Tilt)^2 + \frac{(Tilt_1)^2 + (Tilt_N)^2}{4} \cdot u(L)^2}
    \tag{22}
\end{align*}
\]

The last term, including square of Tilt will be so small it can be disregarded. For example, assume the uncertainty of the distance between the 2 anchor points of the tilt beam, \((u(L))\) is 1 cm (a rather loose requirement), then even a tilt as large as 5° will make the last term in Equation (22) much smaller than the other terms inside the square root. For the measurement performed in this study, where no motion is anticipated, the uncertainty of \(L\) becomes insignificant for sure.

If we assume the uncertainty for \(d_{T1}\) and \(d_{TN}\) are equal, then the uncertainty of the sum of these variables is given by:

\[
\begin{align*}
    u(d_{T1} + d_{TN}) &= \sqrt{2} \cdot u(d_{T1}) \\
    \Rightarrow u(d_{T1}) &= u(d_{TN}) = \frac{u(d_{T1} + d_{TN})}{\sqrt{2}}
    \tag{23}
\end{align*}
\]

The uncertainty of the translation will propagate step wise based on the relation given in Equation (16). Equation (5) was used to derive an expression illustrating the uncertainty relation between two consecutive tilt beams, \(T_n\) and \(T(n-1)\). If we neglect the term containing the square of Tilt, as discussed above, one get:

\[
\begin{align*}
    u(d_{Tn}) &= \sqrt{\frac{(L_{(n-1)})^2 + (L_n)^2}{4} \cdot u(Tilt_n)^2 + u(d_{T(n-1)})^2}
    \tag{24}
\end{align*}
\]

Equation (22) together with Equation (23) is used to determine the uncertainty of the translation of the first and last beam \((u(d_{T1})\) and \(u(d_{TN})\). In section 2.6.3, uncertainty values at confidence level 95% were determined from tilt and distance measurements. These are inserted in Equation (22) as values for variable \(u(D_t)\) and \(u(Tilt)\) respectively. Translation uncertainty for the subsequent beams is calculated using Equation (24).

Figure 20 introduces the equation(s) for calculating the displacement of anchor point “a” (and “b”) for tilt beam 1. Generalizing to the \(n^{th}\) tilt
beam, the corresponding equation for uncertainty propagation becomes:

\[ u(dD_{na}) = \sqrt{\frac{(L_n)^2}{4} \cdot u(Tilt_n)^2 + \frac{(Tilt_n)^2}{4} \cdot u(L_n)^2 + u(dD_{Tn})^2} \]  

Equations (24) and (25) were used to produce the plot in Figure 23 (a beam length of 2 meters was used). It illustrates how the uncertainty of displacement measurements increases as a function of number of tilt beams. Performing the calculations in reverse, starting from the last beam, will give the same result for the same distance from the start point. Hence, the maximum uncertainty will be in the crown of the tunnel cross-section. Note that even for as many tilt beams as 16, the uncertainty does not exceed 1 mm.

![Graph showing uncertainty of convergence measurements as a function of number of tilt beams.](image)

**Figure 23:** Uncertainty of convergence measurements as a function of number of tilt beams. Expanded uncertainty at confidence level 95%

The graph reveals the main contributor to the uncertainty is from the translational motion. Uncertainty contribution from the tilt measurements is hardly visible in the plot of Figure 23.

### 3.2 Method costs

Table 9 presents a summary of the cost associated with the different measurement methods based on the reference projects defined in section 2.7. To avoid making assumptions on parameters that differ significantly between
projects, the cost is divided into cost per suitable units. The choice of unit depends on the characteristics of the cost. In this study equipment rent is presented as cost per day, target related cost is compared per cross-section and software license is treated as a fixed cost.

The initial measurement is grouped with the cost for installing the targets/sensors and the cost for each additional measurement is presented separately. As seen from Table 9, methods B (Laser scanner) and C (Photogrammetry) has similar cost apart from the cost for renting the laser scanner. Laser scanner lease time can however be kept to a minimum since the measurement procedure is relatively quick.

Table 9: Comparison of relative cost for the different measurement methods.

<table>
<thead>
<tr>
<th>(Cost in kSEK)</th>
<th>A: Total Stn</th>
<th>B: Laser Scan</th>
<th>C: Photogr.</th>
<th>D Sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipm. rent (/day)</td>
<td>1.5</td>
<td>3</td>
<td>0.5</td>
<td>0.5*)</td>
</tr>
<tr>
<td>Targets**)</td>
<td>5-13</td>
<td>2</td>
<td>2</td>
<td>95</td>
</tr>
<tr>
<td>Fix cost</td>
<td>17</td>
<td>22</td>
<td>67</td>
<td>23</td>
</tr>
<tr>
<td>Install. &amp; meas.**)</td>
<td>2.5</td>
<td>1.3</td>
<td>1.4</td>
<td>2</td>
</tr>
<tr>
<td>Each epoch meas.**)</td>
<td>1.5</td>
<td>0.2</td>
<td>0.3</td>
<td>0</td>
</tr>
</tbody>
</table>

*) only at initial installation and epoch0 measurement  
**) for 9 targets or 10 tilt sensors on tilt beams + 1 distance sensor

What makes method A (total station) significantly more expensive than method B (laser scanner) is the cost per cross-section. This includes purchase and installation cost of the targets as well as the cost for each additional measurement per epoch. Method D (wireless sensors) has a very different cost structure compared to the other methods. The sensors are much more expensive to purchase but the variable cost is very close to zero, disregarding the installation cost. One reason the cost difference is so large is due to the assumption the expensive measurement instruments of method B and C are hired instead of purchased. However, the cost of method D is still very much higher since it is directly proportional to the number of cross section. Note that the total cost of the sensors and tilt beams is considered in Table 9, in reality the same equipment will be re-used in subsequent projects during the battery lifetime of of the sensors which is 12-15 years for the tilt sensors [34].

Another crucial factor when selecting a suitable tunnel convergence mea-
measurement method is how much it hinders other activities in the tunnel. This can result in extensive cost if it slows the progress of the tunnel project. Table 10 presents the duration of activities that eliminate or significantly reduce the possibility of passing through the tunnel section in question. Other tunnel work close to the measurement area will be limited as well. To what extent depends on how it impacts the work environment for the measurement engineers. The table shows how the much higher purchase cost of method D pays off as the obstruction caused by measurements is zero.

Table 10: *Comparison of obstruction cost for the different measurement methods.*

<table>
<thead>
<tr>
<th>(Per cross-sect.)</th>
<th>A: Total Stn</th>
<th>B: Laser Scan</th>
<th>C: Photogr.</th>
<th>D Sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial inst &amp; meas.</td>
<td>3 h</td>
<td>1½ h</td>
<td>1½ h</td>
<td>2½ h</td>
</tr>
<tr>
<td>Each epoch meas.</td>
<td>1 - 2 h</td>
<td>10 min</td>
<td>15 min</td>
<td>0</td>
</tr>
</tbody>
</table>

With the assumptions made in section 2.7 and the relative cost figures presented in Table 9 and 10 a total cost for a 100 meter tunnel, measured every second week during one year was calculated. The result is presented in Table 11. Here obstruction time is displayed as the sum of two terms where the first is the number of days required for installation of targets including initial measurement (*epoch*$_0$) and the second, shows the number of days needed per measurement for each of the subsequent epochs. The latter is multiplied by the number of remaining two-week periods in a year.

Table 11: *Comparison of cost of a reference project for the different measurement methods.*

<table>
<thead>
<tr>
<th></th>
<th>A: Total Stn</th>
<th>B: Laser Scan</th>
<th>C: Photogr.</th>
<th>D Sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct cost (kSEK)</td>
<td>200</td>
<td>130</td>
<td>100</td>
<td>610</td>
</tr>
<tr>
<td>Obstr. time (days/year)</td>
<td>3+2x25</td>
<td>2+1x25</td>
<td>2+1x25</td>
<td>2+0x25</td>
</tr>
</tbody>
</table>

In short one can conclude that the better measurement precision the higher the cost. Method D (wireless sensors) is, due to its very high purchase cost and practically non-existent measurement cost suitable for large project with complex geological conditions that requires more careful monitoring during a long time, perhaps even during the tunnel’s complete life cycle. However, taking into the consideration the sensors and tilt beams will be reused in other project the price per project can decrease significantly. For example, using the equipment in 3 projects will take the cost down to
the same level as method A (total station).

It is difficult to put a monetary cost of the delay the measurement cause due to obstruction. The figures for obstruction time presented in Table 11 are the number of days measurements are being performed. These are not full days since it is assumed the measurement engineer is working 8 hours per day. This means the tunnel is not totally blocked all the time during a measurement day. How much the measurements activities will interfere with other tunnel activities can be controlled by careful planning. Regardless, there is no doubt that eliminating the need for personnel and obstructive equipment set-ups in the tunnel are associated with significant gains for the project as a whole.

4 Conclusion

This study has compared measurement precision and cost of four displacement monitoring methods. The method using wireless sensors is, as opposed to the others, fairly new in the field of tunnel convergence measurement. A large part of the study has therefore been dedicated to looking into how to use sensors for displacement monitoring by utilizing their ability of measure tilt with high precision.

Table 12 summarizes both measurement precision and cost for the methods evaluated in this study. To make it easier comparing the four methods included in this study, cost is grouped in equipment and labour/obstruction cost and expressed in relative terms. The relative scale is valid only when comparing these specific methods. Thus, a comparison to another method requires cost to be calculated for that method, using a specified reference project. In this way comparable numbers on an absolute scale are obtained.

Regarding measurement precision, method C (photogrammetry) stand out as having a measurement uncertainty in the order 10 times larger than the other methods. Other studies indicate that sub mm precision should be possible to obtain using photogrammetry, [20] and [22]. Due to the low cost of photogrammetry, it is of high interest for further investigation. The latter of the referenced articles uses a digital image correlation technique and reports a precision better than 0.1 mm.

Method D (wireless sensor) is reported in Table 12 as having a precision
Table 12: *Comparison of measurement uncertainty (95%) and cost for methods A-D.*

<table>
<thead>
<tr>
<th>Measurement method</th>
<th>uncertainty (95% conf.)</th>
<th>Equipment cost</th>
<th>Labour/Obstr. cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (total station):</td>
<td>Horizontal: 3 mm</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Vertical: 2 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B (laser scanner):</td>
<td>Horizontal: 5 mm</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Vertical: 3 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C (photogrammetry):</td>
<td>Horizontal: 43 mm</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Vertical: 24 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D (wireless sensors):</td>
<td>Convergence: 1 mm</td>
<td>High</td>
<td>Very low</td>
</tr>
</tbody>
</table>

of 1 mm. In reality it is possible to reach sub mm level. The highest measurement uncertainty obtained depends on the number and length of the tilt beams in the tilt beam chain. Important to notice it that method D measures the displacement only in the direction of the tunnel surface normal, the direction in which the convergence is expected to occur.

To really understand the measurement performance of wireless sensors for tunnel convergence monitoring, it is suggested to make a full scale trial of tilt beams and sensors in a lab environment similar to what was used for the target based measurements.

The overall conclusion is that the higher the monitoring precision the larger the budget. The study also shows that tilt sensors on tilt beams in a chain configuration, can achieve tunnel convergence measurements on sub mm level. Apart from low measurement uncertainty, the method is able to measure almost in real time with no need for tunnel visits (disregarding initial installation). However the equipment is costly, which makes it more feasible to projects where the geological conditions requires frequent measuring during a long period of time. The cost for method D will be comparable to the cost of the other methods if the equipment can be reused in 3-6 projects. This is highly plausible since the batteries of the tilt sensors last at least 12 years and could reach 15 years depending on the configured reporting interval.
Acknowledgements

I would like to express my very great appreciation to Milan Horemuz, my supervisor at KTH for indispensable support during this project. Further acknowledgements to Amin Alizadeh Khameneh at WSP for discussing ideas, reviewing the report and ensuring availability of crucial equipment. Thanks also to Johan Vium Andersson at WSP for participating in scope definition and establishing necessary contacts. Finally I would like to express my appreciation to the company Senceive for providing equipment for sensor measurements.
References


Appendices

A Result data

The tables in appendices A.1 - A.6 show displacement result calculated for target based methods in a situation where there was no deformation (an expected mean of zero). The numbers highlighted in light grey signify one of the targets, between which the displacement is measured, being attached to the fence of the balcony and the other to the concrete wall (see 2). Numbers highlighted in dark grey or white indicate that both targets are attached to the balcony fence or concrete wall respectively.

Appendices A.7 and A.8 present the raw data from sensor measurements. The plots show the measurements for the total measurement period of 18 days. Basically all tilt measurements show a drift during this long measurement duration. In the uncertainty analysis this drift was compensated for. The high sensitivity of tilt sensor measurement is clearly demonstrated in some of the graphs. An interesting observation is the square wave form of the tilt plots for sensor TILT_002. This is the sensor mounted on a ventilation tube and the regular movement visible in the plots is most probably from the regulation of the ventilation. Sensor ODS_001 was also exposed to a movement around lunch time October 7, this incident is visible as a displacement of 0.3 mm in the distance plot (Figure 27) and around 3 millesimal of a degree (0.05 mm/m) in the x and y-tilt plots (27 and 28).
A.1 Method A: Total station with B/W targets

Table 13: Horizontal displacement result, using total station and B/W targets.

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<th>21</th>
<th>22</th>
<th>23</th>
<th>24</th>
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Table 14: Vertical displacement result, using total station and B/W targets.

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A.2 Method A: Total station with PRISM targets

Table 15: *Horizontal displacement result, using total station and prism targets. Automatic target locking to the left and manual to the right*

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Table 16: *Vertical displacement result, using total station and prism targets. Automatic target locking to the left and manual to the right*

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A.3 Method B: Laser scanner pos P1 (under targets)

Table 17: Horizontal displacement result, laser scanner in position P1.

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Table 18: Vertical displacement result, laser scanner in position P1.

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A.4 Method B: Laser scanner pos P2 (~ 5 m from targets)

Table 19: *Horizontal displacement result, laser scanner in position P2.*

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Table 20: *Vertical displacement result, laser scanner in position P2.*

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A.5 Method B: Laser scanner pos P3 (∼ 10 m from targets)

Table 21: Horizontal displacement result, laser scanner in position P3.

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Table 22: Vertical displacement result, laser scanner in position P3.

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### A.6 Method C: Photogrammetry

Table 23: *Horizontal displacement result, photogrammetry.*

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Table 24: *Vertical displacement result, photogrammetry.*

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A.7 Method D: Sensors: Distance measurements

Figure 24: Distance measurement as a function of time for sensor ODS_001.

Figure 25: Distance measurement as a function of time for sensor ODS_002.

Figure 26: Distance measurement as a function of time for sensor ODS_003.
A.8 Method D: Sensors: Tilt measurements

A.8.1 OSD_001 (Tilt versus time)

Figure 27: *x*-tilt measurement as a function of time for sensor OSD_001.

Figure 28: *y*-tilt measurement as a function of time for sensor OSD_001.

Figure 29: *z*-tilt measurement as a function of time for sensor OSD_001.
A.8.2 ODS_002 (Tilt versus time)

Figure 30: x-tilt measurement as a function of time for sensor ODS_002.

Figure 31: y-tilt measurement as a function of time for sensor ODS_002.

Figure 32: z-tilt measurement as a function of time for sensor ODS_002.
A.8.3  OSD_003 (Tilt versus time)

Figure 33: x-tilt measurement as a function of time for sensor OSD_003.

Figure 34: y-tilt measurement as a function of time for sensor OSD_003.

Figure 35: z-tilt measurement as a function of time for sensor OSD_003.
A.8.4 TILT_001 (Tilt versus time)

Figure 36: x-tilt measurement as a function of time for sensor TILT_001.

Figure 37: y-tilt measurement as a function of time for sensor TILT_001.

Figure 38: z-tilt measurement as a function of time for sensor TILT_001.
A.8.5 TILT_002 (Tilt versus time)

Figure 39: x-tilt measurement as a function of time for sensor TILT_002.

Figure 40: y-tilt measurement as a function of time for sensor TILT_002.

Figure 41: z-tilt measurement as a function of time for sensor TILT_002.
A.8.6 TILT_003 (Tilt versus time)

Figure 42: x-tilt measurement as a function of time for sensor TILT_003.

Figure 43: y-tilt measurement as a function of time for sensor TILT_003.

Figure 44: z-tilt measurement as a function of time for sensor TILT_003.
A.8.7 TILT_004 (Tilt versus time)

Figure 45: x-tilt measurement as a function of time for sensor TILT_004.

Figure 46: y-tilt measurement as a function of time for sensor TILT_004.

Figure 47: z-tilt measurement as a function of time for sensor TILT_004.