RAPPORT
Utveckling mobil datafångst:
Evaluation of testing methods for positioning modules
Projektnummer: FOI-projekt 5148
1. Introduction

This report was written as a part of the project “Utveckling mobil datafångst” FOI-projekt 5148 carried on at Royal Institute of Technology (KTH) in Stockholm. In the project, one report has been published (Jansson and Horemuž, 2013). This is the second and final report.

In this report we use terminology according to the Guide to Uncertainty in Measurements (GUM) (International Organization for Standardization, 2008).

1.1. Background and Goal

The mobile data collection has received much attention from researchers all over the world during the past 15 – 20 years. The result of this extensive work is a number of commercially available products, usually called mobile mapping systems (MMS), which are used for collection of geospatial data from cars or aircrafts. The heart of each MMS is the positioning module based on a combination of a GNSS receiver and an inertial navigation system (INS). The module determines the position and orientation of the platform. The platform is equipped with a mapping sensor, usually a laser scanner and/or one or more digital cameras. The accuracy of the collected data greatly depends on the accuracy of the positioning module.

The data delivered by the MMS is a point cloud of the area of interest. Each point in the point cloud has 3D coordinates expressed in a required reference system and eventually other attributes like intensity of returned signal or colour. The quality of the data depends on many factors. The term “quality” usually refers to completeness and accuracy of data. In this report we focus only on the accuracy aspect of the quality. The term “accuracy” depicts the degree of conformance between the “true” and measured quantity (coordinates, velocity and orientation).

There are three groups of uncertainty sources, which affect the accuracy of each individual point in the point cloud (Jansson and Horemuž, 2013):

- Uncertainty from positioning module, i.e. errors stemming from gyroscopes, accelerometers, GNSS and processing errors
- Uncertainty from mapping sensor, i.e. errors from laser scanner or cameras
- Environmental and calibration uncertainties, i.e. atmospheric influence and uncertainty in knowledge of the offset and relative orientation between IMU and mapping sensors and IMU and GNSS antenna.

The goal of this project is to describe and evaluate two field test methods to be used to verify the performance of a positioning module as part of a MMS.

1.2. Uncertainty for Positioning Modules

It is possible to assess the accuracy of the positioning module analytically, i.e. to compute the expected accuracy taking into account the contribution from all possible error sources. In this case we do not know the “true” values; therefore, we refer to this analysis as uncertainty, or precision analysis. The result of the
analysis is expected standard uncertainty (expressed in term of standard deviation) of the determined quantities, in our case the coordinates, velocity and orientation of mapping sensor and coordinates of mapped points.

In Jansson and Horemuž (2013) an uncertainty analysis is performed analytically. They present achievable standard uncertainties in the orientation for GNSS aided tactical and navigational grade INS. The analytically computed uncertainties are slightly more optimistic than for example those published by Skaloud (2002), which is expected, since the analytical computations take into account only the sensor noise and ideal GNSS observations. In practice, we will never get these ideal conditions and the results will be affected by other error sources, namely unmodelled GNSS systematic effects (mainly multipath and atmosphere) and errors coming from processing algorithm limitations. These limitations are caused by approximations that are necessary to apply when integrating the output from gyroscopes and accelerometers. Another cause of these limitations is the fact that the inertial sensors do not measure the acceleration and rotation rate continuously, but discretely, usually with frequency 100 – 300 Hz. These limitations can cause errors in both position and orientation and they are especially pronounced in high dynamics environment, e.g. sudden manoeuvres or vibrations caused by vehicle’s engine (Jansson and Horemuž, 2013).

In order to verify the performance of a GNSS/INS positioning module in a production environment and to get more realistic uncertainty values we need field test methods.

1.3. Test Methods for Positioning Modules

As we could see from the previous discussion, a MMS is a complex system with many possible error sources. The analytical study can predict the precision (or uncertainty) but cannot guarantee the accuracy of the results. This can be compared with other surveying methods, e.g. measurements with RTK or total station, where the accuracy is verified experimentally either by measuring on known points (calibration baselines) or by comparing the measurements to those performed by other instrument/methods. Similar principles can be applied also to accuracy verification of positioning modules.

There are several alternatives how to verify the performance of a GNSS/INS positioning module (Jansson and Horemuž, 2013):

- Laboratory testing
- Field testing using an independent positioning system – direct method
- Field testing using the mapping sensors – the indirect method

Laboratory testing is not considered because this project is aiming at field test methods. In the direct method (field testing using an independent positioning system), position and orientation of the positioning module is determined directly by an independent method. By “direct” determination we mean that the position and orientation of the platform itself is measured. The independent method should be accurate and reliable, so that any gross or systematic error can be detected. “Indirect” determination refers to methods where the position
of surveyed objects (by MMS) is used to determine the accuracy of the positioning module. In this case, however, the position of surveyed objects is also influenced by errors in the mapping sensor which have to be taken into consideration.

The direct method is in principle identical to laboratory testing described in Jansson and Horemuž (2013). The main difference is that the testing is done in field in a production environment and that the reference (“true”) values are not determined with as high accuracy as in the laboratory testing.

In the indirect method (field testing using the mapping sensors), the mapping sensors are attached to the positioning module and they measure the surrounding objects. Then it is possible to compare measured coordinates of the objects with the coordinates measured by some other, preferably more accurate method/instrument (Jansson and Horemuž, 2013).

In the following sections, we will describe and evaluate the direct and the indirect field test methods.

2. Measurements

The goal of the measurements was to evaluate direct and indirect test methods for positioning modules. The purpose of these test methods is to determine the precision of the platform’s position and orientation. The direct method uses total station (TS) observations towards prisms mounted onto platform to determine its position and orientation. The indirect method makes use of surveyed objects, which were scanned by the laser scanner mounted on the platform.

2.1. Location of Test Measurements

The test measurements were performed on November 6, 2013 in Gärdet, Stockholm. The road is marked by the red line in Figure 1, the length is approximately 500 m. The chosen area is ideal for GNSS observations as there are no obstacles blocking the satellite signals.

Figure 1. Test area in Gärdet, Stockholm.
2.2. Instruments
We used the mobile mapping system GeoTracker (Figure 2) provided by company WSP. Its positioning module consists of a geodetic dual frequency Novatel ProPak-V3 GNSS receiver, inertial navigation system Inertial+ and an odometer. According to the specifications published by the manufacturer\(^1\), Inertial+ can determine roll and pitch with standard uncertainty 0.03° and heading 0.1°. These values are valid if the INS is supported by GNSS positions (0.5 s update) with positional standard uncertainty of 2 cm. To be able to apply the direct testing method, we installed 5 prisms onto the platform: 4 prisms at the corners and 1 prism under the GNSS antenna – see Figure 2. The prisms were surveyed by three total stations Trimble S3, which were established with help of Trimble R4 GNSS receivers using RUFRIS method (Andersson 2012). GeoTracker is equipped with four SICK LMS511 PRO laser scanners, which serve as mapping sensors. According to the manufacturer’s specification ”statistical error (1σ) using high resolution in 1 – 10 m range is ±7 mm”.

![Figure 2. Mobile mapping system GeoTracker.](image)

2.3. Measuring Procedure
The car drove the road six times and in each run we collected data necessary for both test methods. Before we started the driving, we set up:

- 8 targets to be scanned (MT1 – MT8)
- 3 total stations (TS1 – TS3)
- 2 reference GNSS receivers (REFT, REFL)

The locations of the set-ups are shown Figure 3. They were marked by wooden stakes in the ground.

\(^1\) [http://www.oxts.com/products/inertial/](http://www.oxts.com/products/inertial/)
The total stations were established by the RUFRIS method, i.e. we used RTK method to determine the coordinates of prisms, which were measured by the total station. At least 19 such measurements were used for the establishment of the total stations and they were distributed around the respective total station and placed up to 400 m distance from the TS. RTK reference receiver REFT (Trimble) was used for RUFRIS measurements and the computation was done in real time, but raw GNSS observation from the reference and roving receivers were stored and hence post processing was possible. After the establishment of TS we surveyed all targets (MT) by all 3 TS and we also measured horizontal directions towards the TS, i.e. we aimed at the string of plumb attached underneath of TS tripod. We used two types of targets. The size of the first type is 24 x 16 cm (Figure 4 left) and the size of the second is 10 x 10 cm (Figure 4 right) – this type was used only on one point – MT3.

Figure 3. Location of the targets (MT), total stations (TS), reference GNSS receivers (REFL, REFT) and stops (S) of the car.

Figure 4. Two types of targets. Left figure: MT1, MT2, MT4 – MT8, right figure MT3.
After these measurements we could start to drive the car. Each run started with ca 50 m driving and then the car stopped either at S1 or at S6, depending on the direction of the run. When the car stopped, the TS operators surveyed all visible prisms mounted on the platform and the operator in the car marked the stop in the trajectory data. Numbering of the prisms on the platform is shown in Figure 5. Since we measured every prism in every run 5 times, we denoted the prisms as KísjpK, where Ki (i = 1 … 6) denotes run (Körning), Sj (j = 1 … 5) denotes stop and Pk (k= 1 … 5) denotes prism. For example, when we measured prism P5 in the first run and the first stop, it was named as K1S1P5. When all operators completed the measurements, the car moved to the next stop (S2 or S4) and the prisms were again surveyed by all 3 TS. This procedure was repeated in the remaining stops. It took 13 – 16 minutes to complete one run.

![Figure 5. Numbering of prisms on the mobile platform. Arrow indicates driving direction.](image)

After we completed 6 runs, we tested tracking the platform by TS. The goal with this test was to verify whether it is possible to determine the position and orientation of the platform without necessity of stopping the car. Since the TS was unable to “snap” on a prism if there were more visible prisms, we had to remove all but one prism, i.e. only prism 5 was tracked. The tracking experiment was performed only in one run.

As the last steps in the measuring procedure, we verified the stability of all set-ups by checking the centring and we performed TS observation between station points and towards point REFT. We also performed levelling between TS points and REFT.

### 3. Computations

#### 3.1. Reference system

All computations were done in reference system SWEREF 99 18 00, geoid model SWENo8 RH2000. Our measurements were connected to this system by baseline between SWEPOS point MOSE and our GNSS station REFL. We used ca 3 hours of static GNSS observations to compute this ca 3 km baseline, which gave 1 mm horizontal and 5 mm vertical standard uncertainty (68%).

The reference station REFL was used for the GNSS/INS processing in GeoTracker system, i.e. the platform’s trajectory and the point cloud is georeferenced relative to this point. The TS observations are georeferenced relative to REFT point located ca 10 m from REFL. REFT was determined by processing baseline REFL-REFT using ca 1.2 hour static GNSS observations, which gave 0.5 mm horizontal and 1 mm vertical standard uncertainty (68%).
Please note, that the choice of reference system does not affect the tested methods. In principle we can choose any system; it is only important that all kind of observations are processed in the chosen system.

**3.2. Processing of TS measurements**

The TS observations and all GNSS observations performed relative to REFT were processed in software Trimble Business Centre (TBC). All RTK observations were re-computed in post-processing mode using REFT as reference (fixed) point. Then all RUFRIS and TS observations towards P, MT and TS points were adjusted together. The precision of all P and MT points was approximately equal, since all points were measured from 3 TS with approximately equal geometry.

**Precision of coordinates of P1 – P5, MT1 – MT8**

Standard uncertainty of horizontal and vertical coordinates determined by least-squares adjustment is \( u(E_{TS}) = u(N_{TS}) = 2 \text{ mm} \) and \( u(H_{TS}) = 1 \text{ mm} \).

**3.3. Processing of platform’s observations**

The processing of observations coming from the platform’s sensors was performed by WSP in software GeoTracker Office (bilskanning.se). The result of this processing was the trajectory of the platform and georeferenced point cloud. The trajectory is given in form of coordinates (N, E, H in meters), orientation angles (roll, pitch, heading in degrees) and their standard uncertainties. The coordinates of prism P5 and the orientation angles for all stops are given in Appendix 6. These values are extracted from the trajectory file for the time instance immediately after the stop.

**Precision of trajectory determined by GeoTracker**

Standard uncertainty of horizontal and vertical coordinates is 2 - 3 mm and 5 mm respectively. Standard uncertainty of roll and pitch is 0.01˚ and of heading 0.1˚. These values were reported by software.

Another deliverable from the mobile platform was georeferenced point cloud, where the targets MT are visible. The centre coordinates of the targets were extracted manually: the operator identified all points belonging to the target and fitted a rectangular patch to them. The centre point of the patch was considered as MT point. Moreover, we extracted even coordinates of the prisms mounted on top of the targets wherever it was possible – see Figure 6. The extracted coordinates are reported in Appendix 4.
Since the distance between individual laser points on the target was ca 2 cm in longitudinal direction and ca 4 cm vertically, we estimate that the standard uncertainty of the extracting procedure is about 1 cm longitudinally, 2 cm vertically and 0.5 cm transversally.

### 3.4. Determination of platform’s orientation by TS observations

The orientation of the platform is described by a rotation matrix between the platform’s and a horizontal coordinate system. Generally a rotation matrix between two frames (coordinate systems) $a$ and $b$ is given as:

$$
R_b^a = \begin{bmatrix}
\cos(h)\cos(p) & \sin(h)\cos(p) & -\sin(p) \\
\sin(h)\cos(r) + \cos(h)\sin(p)\sin(r) & \cos(h)\cos(r) + \sin(h)\sin(p)\sin(r) & \cos(p)\sin(r) \\
\sin(h)\sin(r) + \cos(h)\sin(p)\cos(r) & -\cos(h)\sin(r) + \sin(h)\sin(p)\cos(r) & \cos(p)\cos(r)
\end{bmatrix}
$$

(1)

where $r$, $p$, $h$ are orientation angles, i.e. the amount of rotation of a frame around its around $x$, $y$, $z$ axes. In our case we use the horizontal system SWEREF99 18 00, denoted as n-frame and the order of axes is Northing, Easting, Down, where Down is minus height (-H). We have two coordinate frames attached to the platform: one is defined by the sensitive axes of the INS (b-frame) and the other one is defined by the prisms (P1 – P5) mounted onto the platform; we will call it t-frame and its definition is explained in Figure 7.
The orientation angles between frames n and b are called roll, pitch and heading (rotation matrix $R_b^a$) and we will refer to the orientation angles between n- and t-frames (rotation matrix $R_t^n$) as roll_t, pitch_t and heading_t.

The coordinates of P1 – P5 prisms in t-frame were computed in two steps. In the first step we defined t-frame coordinates of P3, P4 and P1 computed for each stop as:

$$
\begin{array}{ccc}
\text{x} & \text{y} & \text{z} \\
\text{P1} & d_{31} \cos \varphi_{31} & d_{31} \sin \varphi_{31} & 0,000 \\
\text{P3} & 0,000 & 0,000 & 0,000 \\
\text{P4} & 0,000 & d_{34} & 0,000 \\
\end{array}
$$

where

$d_{31}, d_{34}$ – slope distance between P3 and P1 (resp. P4) computed from n-frame coordinates determined by TS observations

$\varphi_{31}$ – bearing from P3 to P1 computed in t-frame using distances $d_{31}, d_{34}$ and $d_{41}$ computed as slope distances in n-frame. (Solving triangle P1-P3-P4 using cosine rule.)

The coordinates of P2 and P5 were computed by Helmert transformation

$$X^t = T^t + R_t^n X^n \quad (2)$$

where $X^t$ is vector containing t-frame coordinates, $X^n$ is vector containing n-frame coordinates and $T^t$ and $R_t^n$ are translation vector and rotation matrix estimated by the least-square method using three common points (P3, P4, P1).

The final t-frame coordinates of all prisms (P1 – P5) were computed as average from all stops, see Table 1.

$\begin{array}{ccc}
\text{x} & \text{y} & \text{z} \\
\end{array}$
Table 1. t-frame coordinates of prisms. Their standard uncertainties are smaller than 0.5 mm.

<table>
<thead>
<tr>
<th></th>
<th>x [m]</th>
<th>y [m]</th>
<th>z [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>1.618</td>
<td>-0.397</td>
<td>0.000</td>
</tr>
<tr>
<td>P2</td>
<td>1.624</td>
<td>1.180</td>
<td>0.001</td>
</tr>
<tr>
<td>P3</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>P4</td>
<td>0.000</td>
<td>0.791</td>
<td>0.000</td>
</tr>
<tr>
<td>P5</td>
<td>0.440</td>
<td>0.290</td>
<td>-0.286</td>
</tr>
</tbody>
</table>

In the second step we used these averaged coordinates to compute the transformation parameters between n- and t-frame (T<sub>t</sub> and orientation angles roll<sub>t</sub>, pitch<sub>t</sub>, yaw<sub>t</sub>, i.e. rotation matrix R<sub>tn</sub> from Equation (2)). We computed the transformation parameters and their standard uncertainty by LSQ method for each stop; they are shown in Appendix 1.

**Precision of orientation angles determined by TS**

Mean standard uncertainty of the orientation angles is 0.062, 0.049, 0.039 degrees for roll<sub>t</sub>, pitch<sub>t</sub>, yaw<sub>t</sub> respectively.

3.5. Orientation of t-frame with respect to b-frame

The orientation of t-frame relative to b-frame must be constant, since both frames are firmly mounted to the platform. It can be computed as:

\[ R^b_i = R^n_i R^o_i \]  (3)

where \( R^o_i = \left( R^n_i \right)^T \). The orientation angles between t- and b-frame are computed as

\[ r_x = \arctan \frac{R_{23}}{R_{33}} \]
\[ r_y = \arcsin \left( -R_{13} \right) \]
\[ r_z = \arctan \frac{R_{12}}{R_{11}} \]  (4)

where \( R_{ij} \) denotes an element from \( R^b_i \) matrix, i denotes row and j column. We computed matrix \( R^b_i \) 30 times, i.e. for each stop in every run. The computed orientation angles are given in Appendix 2. Standard uncertainty of orientation angles (computed as standard deviation): \( u(r_x) = 0.061^\circ \), \( u(r_y) = 0.064^\circ \), \( u(r_z) = 0.095^\circ \).
4. Analysis

4.1. Direct method

Position and orientation of the platform determined by TS observations is used to verify the results obtained by the platform’s positioning module. As the t-frame realised by the prisms does not coincide with the module’s b-frame, we cannot compare the orientation angles directly, but we can analyse the variation of the orientation angles between t- and b-frames, \( r_x \), \( r_y \), and \( r_z \). The variation is caused by the uncertainty in TS observations as well as by uncertainty in positioning module, so we can write

\[
\begin{align*}
 u(r_x) &= \sqrt{u^2(\text{roll}) + u^2(\text{roll}_{-t})} \\
u(r_y) &= \sqrt{u^2(\text{pitch}) + u^2(\text{pitch}_{-t})} \\
u(r_z) &= \sqrt{u^2(\text{heading}) + u^2(\text{heading}_{-t})}
\end{align*}
\] (5)

or

\[
\begin{align*}
 u(\text{roll}) &= \sqrt{u^2(r_x) - u^2(\text{roll}_{-t})} \\
u(\text{pitch}) &= \sqrt{u^2(r_y) - u^2(\text{pitch}_{-t})} \\
u(\text{heading}) &= \sqrt{u^2(r_z) - u^2(\text{heading}_{-t})}
\end{align*}
\] (6)

These equations are valid only for small rotation angles between t- and b-frame and for theoretical standard uncertainties determined from infinite number of observations, which follow normal distribution. If we enter results from our test measurements (see Appendix 1 and 2) into Equation (6), we get the following standard uncertainties:

\[
\begin{align*}
 u(\text{roll}) &= \sqrt{0.061^2 - 0.063^2} \approx 0^\circ \\
u(\text{pitch}) &= \sqrt{0.064^2 - 0.048^2} = 0.042^\circ \\
u(\text{heading}) &= \sqrt{0.095^2 - 0.039^2} = 0.087^\circ
\end{align*}
\] (7)

which can be compared with the uncertainties specified by the manufacturer of the positioning module: 0.03˚ for roll and pitch and 0.1˚ for heading.

As we can see from the equation for \( u(\text{roll}) \), we can get a negative number under the square root, due to the finite number of observations used to compute the standard uncertainties.

The position obtained by TS is compared to the position from the positioning module in Appendix 3. Average value of differences in N and E coordinates is 1 mm and standard uncertainty of the average \( u(\text{average}) = 1 \text{ mm} \). For height, the average difference is 10 mm and \( u(\text{average}) = 1 \text{ mm} \), which indicates a possible systematic effect of 10 mm in height determination. A possible explanation is the effect of GNSS configuration (RUFRIS was performed ca 2 hours earlier then car driving) or an error in antenna height measurement.
Standard uncertainty of coordinate differences is $u(\text{diffE}) = 5 \text{ mm}$, $u(\text{diffN}) = 6 \text{ mm}$ and $u(\text{diffH}) = 5 \text{ mm}$.

The standard uncertainties in coordinate differences are computed according to the following equation:

$$u(x) = \sqrt{\frac{\sum_{i=1}^{n} (\bar{x} - x_i)^2}{n - 1}}$$

and standard uncertainty in the average

$$u(\bar{x}) = \frac{u(x)}{\sqrt{n}}$$

where $x_i$ is a coordinate difference, $\bar{x}$ is average of the differences and $n$ is number of differences.

Standard uncertainties of the coordinate differences are related to the TS and positioning module (PM) standard uncertainties as:

$$u(\text{diffE}) = \sqrt{u^2(\text{E}_{TS}) + u^2(\text{E}_{PM})}$$
$$u(\text{diffN}) = \sqrt{u^2(\text{N}_{TS}) + u^2(\text{N}_{PM})}$$
$$u(\text{diffH}) = \sqrt{u^2(\text{H}_{TS}) + u^2(\text{H}_{PM})}$$

or

$$u(\text{E}_{PM}) = \sqrt{u^2(\text{diffE}) - u^2(\text{E}_{TS})}$$
$$u(\text{N}_{PM}) = \sqrt{u^2(\text{diffN}) - u^2(\text{N}_{TS})}$$
$$u(\text{H}_{PM}) = \sqrt{u^2(\text{diffH}) - u^2(\text{H}_{TS})}$$

Using our results (see section 3.2) we obtain:

$$u(\text{E}_{PM}) = \sqrt{5^2 - 2^2} = 4.6 \text{ mm}$$
$$u(\text{N}_{PM}) = \sqrt{6^2 - 2^2} = 5.7 \text{ mm}$$
$$u(\text{H}_{PM}) = \sqrt{5^2 - 1^2} = 4.9 \text{ mm}$$

which can be compared with positioning standard uncertainty of 20 mm specified by the manufacturer.

Based on our results, we can conclude that the positioning module was performing in accordance with the specifications.

### 4.2. Indirect method

In this method we use the differences between coordinates of the targets determined by TS and MMS. To be able to use the coordinate differences for the evaluation of the platform’s performance, we need to transform them into a coordinate system aligned with the driving direction (Figure 8), i.e. we compute longitudinal and transverse difference as
\[
\begin{align*}
\text{diff}T &= \text{diff} \sin \alpha \\
\text{diff}L &= \text{diff} \cos \alpha 
\end{align*}
\]

where

\[
\begin{align*}
\text{diff} &= \sqrt{\text{diff}E^2 + \text{diff}N^2} \\
\alpha &= \varphi_r - \varphi_{\text{diff}} \\
\varphi_{\text{diff}} &= \arctan \frac{\text{diff}E}{\text{diff}N}
\end{align*}
\]

\(\varphi_r = 110^\circ\) is the bearing of the road.

Since the targets are located at approximately the same height as the mobile platform, the standard uncertainties of the coordinate differences in longitudinal coordinate system can be expressed by the following simplified equations:

\[
\begin{align*}
\text{u(diffL)} &= \sqrt{\text{u}^2(\text{GNSS} \_\text{NE}) + \text{u}^2(\text{ident} \_\text{L}) + \text{u}^2(\text{sync}) + (\text{du(heading)})^2} \\
\text{u(diffT)} &= \sqrt{\text{u}^2(\text{GNSS} \_\text{NE}) + \text{u}^2(\text{ident} \_T) + (\text{u}^2(\text{dist}))^2} \\
\text{u(diffH)} &= \sqrt{\text{u}^2(\text{GNSS} \_\text{H}) + \text{u}^2(\text{ident} \_H) + (\text{du(roll + laser)})^2}
\end{align*}
\]

where \(d\) is distance between the platform and the target, we consider a mean distance \(d = 7\) m. \(\text{u(GNSS)}\) is standard uncertainty in N, E and H coordinates determined by GNSS/INS, we consider mean values taken from Appendix 6: \(\text{u(GNSS} \_\text{NE}) = 3\) mm and \(\text{u(GNSS} \_\text{H}) = 5\) mm. \(\text{u(sync)}\) is uncertainty in longitudinal position of the laser scanner due to uncertainty in synchronisation between positioning module and the laser scanner. We do not have any information about the synchronisation uncertainty so we consider an empirical value \(\text{u(sync)} = 1\) cm. \(\text{u(ident} \_\text{L})\) and \(\text{u(ident} \_\text{H})\) is standard uncertainty of target identification in longitudinal and vertical direction, which depends on the density of the point cloud. We consider \(\text{u(ident} \_\text{L}) = 1\) cm and \(\text{u(ident} \_\text{H}) = 2\) cm (see section 3.2). \(\text{u(ident} \_\text{T})\) is standard uncertainty of target identification in transversal direction, which depends on the number of scanned points on the target that were used to fit a planar patch. Based on the “fitting quality”
descriptor obtained in Cyclone software when fitting the patches, we consider $u(\text{ident}_T) = 3$ mm. Uncertainty in height determination is influenced both by laser scanner’s angular precision as well as by the precision in roll determination. The scanner’s angular precision is not stated explicitly in the specifications, but usually the laser scanner’s angular precision is ca 10 times higher than the precision of roll, therefore we can state that $u(\text{roll}+\text{laser}) \approx u(\text{roll})$. By rearranging Equation (15) and using values $u(\text{diffL})= 0.023$ m, $u(\text{diffT}) = 0.005$ m and $u(\text{diffH}) = 0.008$ m from Appendix 5 we get:

$$
\begin{align*}
  u(\text{heading}) &= \sqrt{0.023^2 - 0.003^2 - 0.01^2 - 0.01^2} / 7 = 0.15^\circ \\
  u(\text{dist}) &= \sqrt{0.005^2 - 0.003^2 - 0.003^2} = 0.002 \text{ m} \\
  u(\text{roll}) &= \sqrt{0.008^2 - 0.005^2} / 7 = 0.05^\circ
\end{align*}
$$

(16)

Please note that we set $u(\text{ident}_H) = 0$, when computing $u(\text{roll})$ to avoid negative number under square root, so $u(\text{roll}) < 0.05^\circ$. $u(\text{pitch})$ is not possible to determine with given experimental set up. To be able to evaluate even $u(\text{pitch})$, we would need to scan some targets at different heights.

Based on the results in Equation (16), we can conclude that the positioning module was performing in accordance with specifications.

### 5. Conclusions

The result of a test of positioning module should confirm or refute that the positioning module is performing in accordance with the specifications. The goal of this report was to evaluate two testing methods: direct and indirect. Both methods are capable to evaluate the performance of the positioning module, but both have advantages and disadvantages – see summary in Table 2. The main advantage of the direct method is that it tests precision of all parameters (three coordinates and three orientation angles) directly, i.e. TS measurements are compared with the output of the positioning module. On the other hand, in the indirect method we are using the output from a mapping sensor – laser scanner, which introduces a number of factors influencing the results and often it is difficult to quantify this influence. In the indirect approach, the centre of the scanned targets must be identified; it is difficult to assign a standard uncertainty of this procedure since it can vary significantly depending on the size and material of the target and on its distance from the MMS. Another uncertain factor is the synchronisation between the positioning module and the laser scanner. Moreover, determined uncertainty in the orientation angles depends on the uncertainty in GNSS coordinates, which can vary significantly from place to place. The main disadvantage of the direct method is the time consumption and necessity of two or three operators. In our test measurements we used 3 TS, hence 3 operators, which provided a homogeneous geometry for whole trajectory. In principle, one TS would suffice, but then it would not be possible to identify eventual gross errors, therefore we recommend at least 2 total stations.
Table 2. Summary of main properties of the direct and indirect methods.

<table>
<thead>
<tr>
<th>Direct</th>
<th>Indirect</th>
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<tbody>
<tr>
<td>More complicated and time consuming procedure: necessary to mount prisms onto the platform, 2 - 3 operators for TS are required,</td>
<td>Simpler procedure: a fixed test field can be re-used, no operators required</td>
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<tr>
<td>Tests all parameters: 3 coordinates and 3 orientation angles</td>
<td>Pitch is difficult to test: high/low located targets are necessary</td>
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<tr>
<td>Tests all parameters directly</td>
<td>Mapping sensor is involved, which introduces a number of effects that influence the test results. Difficult to assign an uncertainty for these effects (synchronisation, target identification)</td>
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<td>Car must stop when taking TS measurements</td>
<td>Car drives continuously</td>
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<tr>
<td>Suitable for testing the positioning module</td>
<td>Suitable for testing whole MMS</td>
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The indirect method is much less time consuming, especially in the case when a test field is already established. Then the car just drives through the test field. This method is suitable for testing the overall performance of the MMS, but less suitable for testing the performance of the positioning module only.

An improvement of the direct method would be using the tracking function of TS, i.e. TS would measure the trajectory of the prism continuously, without necessity of stopping the car. According to our experience, this is not a viable method, since the TS could not track a chosen prism, if there were more visible prisms on the platform; the TS “jumped” between prisms more or less randomly. We also tried to cover all but one prism. In this case the TS could track the prism successfully, but one prism is not sufficient to determine the orientation angles. Moreover, it was not possible to establish synchronisation between TS and platform’s observation.

We should point out that the conclusions drawn from the tests are valid for the particular conditions during the test measurements, which can be significantly different in the actual production environment.
6. References


Appendix 1

t-frame coordinates obtained by transformation from n-frame to mean coordinates computed in step 1.

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Orientation angles between n-and t-frame computed by TS measurements

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Appendix 2

Orientation angles between t-frame and n-frame ($r_x$, $r_y$, $r_z$). Standard uncertainties in orientation angles are based on measurements from positioning module and total stations.

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Appendix 3

Comparison of coordinates for prism no. 5 from positioning module and from total stations.

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Average: 0.001, 0.001, 0.010

u(diff): 0.005, 0.006, 0.005

u(average): 0.001, 0.001, 0.001
Appendix 4

Coordinates for the laser targets (MT1-8) estimated from the laser cloud (MMS)

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where:
- **average** - the average of the sample
- **u(sample)** - standard uncertainty of unit weight of the sample
- **u(average)** - standard uncertainty of the average
**Appendix 5**

Comparison of coordinates for laser targets from positioning module and from total stations.

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**diff:** difference; **fi_d:** finite difference; **diffT:** total difference; **diffL:** lateral difference; **diffH:** height difference.
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Average: 0.000, -0.001, 0.000

u(diff): 0.005, 0.023, 0.008
### Appendix 6
Coordinates of the mobile platform and orientation angles

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where:

- **DOP**: Dilution Of Precision,
- **NoSatellites**: Number of Satellites,
- **u(*)**: standard uncertainty of the given parameter
7. Abbreviations

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