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# Public road infrastructure inventory in degraded global navigation satellite system signal environments

**Abstract:** Recent advancement of land-based mobile mapping enables rapid and cost-effective collection of high-quality road related spatial information. Mobile Mapping Systems (MMS) can provide spatial information with subdecimeter accuracy in nominal operation environments. However, performance in challenging environments such as tunnels is not well characterized. The Norwegian Public Roads Administration (NPRA) manages the country's public road network and its infrastructure, a large segment of which is represented by road tunnels (there are about 1 000 road tunnels in Norway with a combined length of 800 km). In order to adopt mobile mapping technology for streamlining road network and infrastructure management and maintenance tasks, it is important to ensure that the technology is mature enough to meet existing requirements for object positioning accuracy in all types of environments, and provide homogeneous accuracy over the mapping perimeter.

This paper presents results of a testing campaign performed within a project funded by the NPRA as a part of SMarter road traffic with Intelligent Transport Systems (ITS) (SMITS) program. The testing campaign objective was performance evaluation of high end commercial MMSs for inventory of public areas, focusing on Global Navigation Satellite System (GNSS) signal degraded environments.

**Keywords:** Global navigation satellite system; inertial; mobile mapping; tunnels

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## 1 Introduction

Responsibilities of the Norwegian Public Roads Administration (NPRA) include managing and maintaining the National Road Data Bank (NVDB) – an information database created for optimization of management and development of the national road infrastructure and road surface quality monitoring Vegdirektoratet (2012). Data registered in the NVDB includes detailed information about the road network structure including information about a number of different objects connected to the road infrastructure such as traffic signs, manholes, street lights, drains, etc. One of the parameters that is registered for each object is its position. In addition to that, as a partner of the Norwegian joint mapping national cooperation program Geovekst, NPRA is contributing to establishing and maintaining the joint map database (FKB) Vegdirektoratet (2012). Thus, when the NPRA obtains information for an object/asset it has to register it in both databases. The goal with both NVDB and FKB is to establish and maintain common sets of high quality data. Therefore, the requirements for the positioning information to be registered are quite high, in general at the 1 - 2 dm level Vegdirektoratet (2012); Kartverket (2013).

Currently, positioning of the objects connected to the road infrastructure has been carried out by the NPRA using two different approaches:

*Indirect positioning approach*

The indirect positioning approach is based on the use of existing road reference network Kartverket (2013) and uses either just an odometer, or odometer combined with a GNSS receiver installed on the roof of the measurement vehicle, positioned over the driver's side to be close to the centre line of the road/link along which the object of interest lies. When the object is reached, its distance perpendicular to the centre line and the distance from the previous node are recorded as the position of the object of interest. The measured position is then registered bounded to the road reference network coordinates. Indirect positioning has the advantage of being applicable in the areas with poor or no GNSS satellite visibility and of not requiring the GNSS receiver to be dis-mounted and taken to the object directly. However, by representing object coordinates as relative offsets from nodes/links, the system is vulnerable to road changes.

*Direct positioning approach*

The direct positioning approach differs from the indirect approach by requiring that the GNSS receiver antenna is taken to the object to be positioned thereby creating a direct position measurement of the object, which is then converted into an offset and distance referred to the road/link and node. While the advantage of direct positioning is that the produced positions have independent geometry and are not affected by changes in the road route/length, the method still does have the disadvantages of poor or no performance in degraded GNSS signal areas, requires a 2-worker team for safety reasons, and needs a worker to physically approach every object to be positioned.

To achieve flexibility and higher quality of the data registered in the NVDB, a new requirement has been set for object positioning information to be registered in NVDB. All objects are to be measured with independent geometry, i.e. with UTM coordinates independent of the road reference system Kartverket (2013). This requirement made the indirect positioning approach obsolete, and posed a challenge to the remaining measurement techniques practiced by the NPRA. To be more specific, a large part of the national road network is located in dense urban areas that often include a large proportion of environments with limited or no sky view (areas with a large number of bridges and overpasses, tunnels, etc.). As mentioned above, the approach currently used to achieve positioning of objects with independent geometry is in most cases not capable of performing in such environments. An alternative solution could use survey teams with traditional surveying equipment. This approach is effective in terms of the achieved positioning accuracy and ability to operate in GNSS-denied environments, but is time consuming and very expensive. For example, in order to carry out a measurement campaign in a tunnel, it has to be completely closed to traffic. Another complication with this approach is that the governmental organizations such as NPRA do not often have their own survey teams, thus the service has to be bought from external vendors, creating additional costs.

In this regard, it has become desirable to look into new approaches and technologies that can meet the accuracy requirements and potentially make the asset positioning and registration process more efficient and less expensive. For this purpose, an evaluation campaign of two different MMSs has been conducted with a focus on performance in tunnel interiors.

# 2 Methods

## 2.1 New Approaches Evaluated

Vehicle-borne mobile mapping systems are already widely used for inventory of public areas due to their ability to achieve sub-decimeter accuracy Haala et al. (2008); Eugster et al. (2012). Therefore, two mobile mapping systems adopting different mapping sensor technologies were selected for testing. One system uses a 3D laser scanning technology, Optech Lynx Mobile Mapper operated by TerraTec TerraTec AS (2013); Optech Inc. (2014), the other one adopts a dual 360° camera system from Cyclomedia B.V. operated by Blom Geomatics AS Cyclomedia Technology B.V. (2010, 2011). Fig. 1 shows hardware components setup as installed on the test vehicles.

Both systems considered in this project can be conceptually divided into two elements: the mapping sensors and the navigation platform. It is the performance of the systems navigation platform that determines the mapping accuracy. To be more specific, the mapping accuracy depends mostly on the exact determination of the position and orientation of the mapping sensors during data acquisition. This in turn relies on the accuracy of the systems navigation platform that computes the position and orientation of the vehicle.

**Figure 1:** Left: Optech Lynx Mobile Mapper system installed on a vehicle. Right: Cyclomedia mobile mapping system Cyclomedia Technology B.V. (2010); Applanix (2014).

*Cyclomedia Mobile Mapping System*

The mapping sensor element of the Cyclomedia system is composed of multiple cameras allowing the vehicle to produce a complete 360° image around the vehicle along its route of travel. By tracing lines of sight to the same object from successive points of view the system can position the selected object relative to the vehicle. The navigation platform element used to position the Cyclomedia vehicle includes a dual frequency GNSS receiver, a tactical grade IMU (iMAR FSAS NovAtel Inc (2014)), and distance measurement instrument (DMI) to assist in navigating during extended outages. The system is also capable of providing highly accurate post-mission GNSS-intertial position and orientation solution by combining the measurements with GNSS reference data Cyclomedia Technology B.V. (2011). Cyclomedia offers a unique processing solution for the data recorded by the system, called GlobeSpotter Cyclomedia Technology B.V. (2011). GlobeSpotter allows one to access the 360° panoramic photos (cycloramas) and/or other visual products of CycloMedia. It is available as a web-based application and API.

*Optech Lynx Mobile Mapper operated by TerraTec*

In the case of the TerraTec vehicle the element responsible for positioning the objects of interest relative to the vehicle is the Lynx Mobile Mapper V100. It is a pair of high rate laser scanners using pulses of laser light to illuminate the surroundings of the vehicle, forming a grayscale reflectivity image of the surroundings. Since the azimuth and elevation of the laser beam are known for each point in the image, and the distance to each point is measured by timing the return flight of the laser pulse, objects of interest can be positioned relative to the vehicle from a single illumination point. The Cyclomedia system by comparison requires two independent images of the same point in space in order to determine the coordinates of that point. Conceptually this provides an advantage to the TerraTec system. Similar to the Cyclomedia system, the TerraTec vehicle is positioned using dual frequency GNSS, tactical grade inertial sensors Applanix (2014) and DMI. Additionally, the navigation platform of the system includes a secondary GNSS antenna for heading calibration, and is also capable of operating in differential and/or real time kinematic modes.

There exist several different commercial and open source software tools that can be used for processing the LiDAR data. The one most typically used by industry professionals is a commercial solution from Terrasolid (TerraScan package) Terrasolid (2014, 2013). It works as a plugin for MicroStation and is capable of processing both data from airborne mapping laser scanners as well as vehicle-borne mobile laser scanners, such as the one used by the TerraTec system.

## 2.2 System Comparability

While the mapping sensor technologies used in the Cyclomedia and TerraTec systems are different, their underlying navigation systems and methods are nearly identical. Since both systems integrate an inertial navigation system they will accumulate position error when operating in GNSS denied environments such as tunnels. The projected performance of the IMUs of the two systems is presented in Table 1, for purposes of comparison.

The contents of Table 1 show that the two systems' performance levels inside tunnels, with no external source of aid, should be similar after one minute of GNSS outage.

When purchasing GNSS/GNSS-based equipment for object positioning and registration application, a typical requirement set by the NPRA for the system accuracy is 10 cm ($1\sigma$), in real time. Both the Cyclomedia and the TerraTec systems are capable of meeting this requirement when operating in clear-sky conditions with good satellite visibility. However, as shown in Table 1, in the cases where GNSS signals are not available the positioning accuracy will quickly degrade with time. This implies that the required accuracy might only be achieved by post processing the collected data. In the case of the Cyclomedia system, the recorded vehicle position data is post processed by a forward-backward smoothing algorithm Cyclomedia Technology B.V. (2011). Forward-backward smoothing is also applied in the POSPac$^{TM}$ software suite from Applanix Applanix (2014) to create the Smoothed Best Estimate Trajectory (SBET) for the TerraTec system. In both the mobile mapping (Cyclomedia) solution and in the terrestrial mobile laser scanning (TerraTec) solution, the mismatch between overlapping vehicle passes changes over time during the measurement campaign, depending on the quality of the GNSS signal in different environments and the quality of the INS.

In this regard, the TerraTec approach offers the user the capability to mitigate the positioning error due to this mismatch by importing coordinates of pre-surveyed reference points (typically coordinates of the objects that would be easily identifiable in the point cloud). This allows one to match the laser data from overlapping vehicle passes and to measure the differences between laser surfaces at these points. The measured differences are then translated into correction values for the system's location, orientation, INS, and laser misalignment. At the time of the project Cyclomedia's software solution did not have any mechanism to utilize this form of information.

## 2.3 Data Collection Activities

To evaluate the object positioning accuracy and the effectiveness of the systems in GNSS degraded environments, several data collection campaigns were carried out. A trajectory passing through two consecutive tunnels, the Ilsvik tunnel (length: 235 meters) and Skansen tunnel (length: 510 meters) was selected. For both systems the trajectory was traversed twice, once in each direction along the road-

**Table 1:** Best expected performance of the underlying IMUs of the two positioning systems when encountering a GNSS outage, such as a tunnel, of 60 seconds.

| System | TerraTec | Cyclomedia |
|---|---|---|
| **IMU model** | POS LV420 Applanix (2014) | iMar FSAS NovAtel Inc (2014) |
| **Horizontal accuracy** | 12 cm RMS | 13 cm RMS |
| **Vertical accuracy** | 10 cm RMS | 5 cm RMS |
| **Heading** | 0.02 deg RMS | 0.016 deg RMS |

way. These tunnels were selected by the NPRA as good test candidates since they contained a representative set of diverse infrastructure elements that would be positioned by the MMSs.

In order to perform a comparative analysis of the positioning results, a set of reference measurements was obtained by subcontracting a professional survey team from Nidaros Oppmåling AS. A total of 209 different objects along the segments of the test trajectory within the tunnel interior were positioned using total station equipment, see Fig. 2. In the analysis these measurements were assumed to have negligible error to allow direct comparison of the systems considered. It should be noted that the types of objects selected for use in this test represent a challenging subset of the total asset population. Figure 3 shows examples of some of the objects used.

**Figure 2:** Trajectory and positions of the reference solution measurements (green circles) inside Ilsvik and Skansen tunnels, obtained by using total station equipment. Data collection performed by Nidaros oppmåling AS.

In the case of the Cyclomedia system, the mapped image data was already available through a demo project conducted by the Norwegian Public Roads Administration Halvorsen et al. (2012), where the data collection was performed by the Norwegian Cyclomedia system operator - Blom Geomatics AS. For this project the data from the ar-

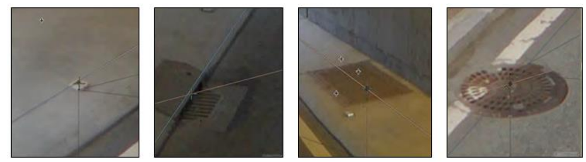

**Figure 3:** Sample examples of object types used in the measurement campaign (lamp, reflector mark, storm drain, manhole).

eas of interest (Ilsvik and Skansen tunnels) was processed using the Cyclomedia's GlobeSpotter software, and objects for which the reference solution was available were positioned. Data using the Optech Lynx Mobile Mapper was collected by TerraTec AS along the same trajectory and the same objects were then positioned using the TerraSolid software Terrasolid (2014, 2013).

## 3 Results

### 3.1 System Performance Analysis

When considering either of the mobile mapping systems from Cyclomedia or TerraTec it is important to remember that both of these systems are fundamentally a GNSS plus IMU combined navigation system that supports relative positioning of objects via a stereo vision camera system or 3D laser scanner, respectively. Since both systems rely on an IMU and odometry when GNSS signals are blocked, the expected performance of these systems will degrade progressively the longer their GNSS antenna is blocked, such as when traversing a tunnel. An additional note on performance analysis is that neither the TerraTec nor the Cyclomedia systems offer the user the ability to see internal position accuracy estimates of the vehicle itself. As such it is not directly possible to separate the noise and error due to the imaging or laser scanning, but only to see the combined inaccuracy.

*TerraTec System Performance*

Please note that in the analysis of the TerraTec asset positioning results, reference will be made to the terms 'matched' and 'unmatched'. These terms refer to the matching of points positioned by the TerraTec laser scanner to points pre-surveyed by an independent and accurate positioning system. When matched data points are available they are used by the processing software to limit error growth in the data set as the vehicle passes through the tunnel or other region without GPS assistance. For this particular test, seven reference points were surveyed using Leica Viva GNSS GS15 receiver operating in network Real Time Kinematic (RTK) mode prior to the data collection. Fig. 4 illustrates their location along the test trajectory.

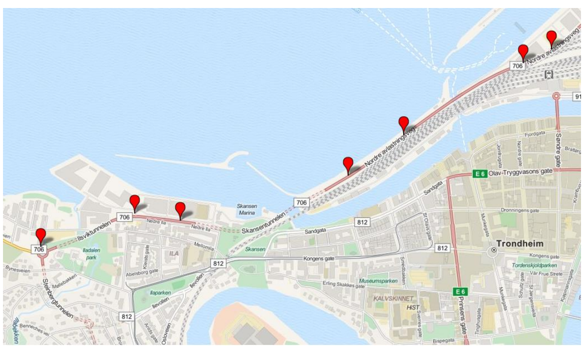


**Figure 4:** Location map of the positions surveyed in the areas outside the tunnels to be used for the point cloud data matching process. Location of the points was selected to cover the test trajectory Røsjorde Lund (2013).

Also, when comparing the determined positions of assets between the TerraTec system results and the Nidaros survey results, it is important to consider that these results exclude the small roadside reflector units shown – first image on the left of Fig. 3. These assets are excluded since their outer surface was not distinguishable in the TerraTec point cloud data due to the poor reflectivity contrast of these lights and the surrounding pavement at the wavelength of the TerraTec scanning laser. Because of this exclusion, results are based on only 81 of the 209 objects included in the reference survey data set. This result indicates that the TerraTec system is unable to position certain assets due to their low contrast relative to their surroundings at the infra-red wavelength of the laser.

When considering the remaining 56 objects in the Skansen tunnel, a clear advantage is available when the TerraTec system is provided with reference or matching points, as seen in Figs. 5 and 6. Of the successfully positioned (located/identified in the images or point clouds by a human operator) assets, the matching process does not substantially change the already small systemic bias results, though it does reduce the positioning noise by a large margin, from 17.9 cm in three dimensions to 5.4 cm at the 1 $\sigma$ level. Of the 56 objects in the Skansen tunnel 23 were successfully positioned, resulting in a success rate of 41%.

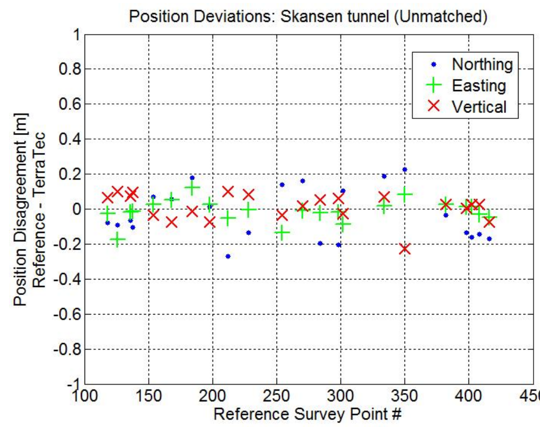


**Figure 5:** TerraTec system solution deviations relative to the reference measurements, when matching is not utilized, Skansen tunnel.

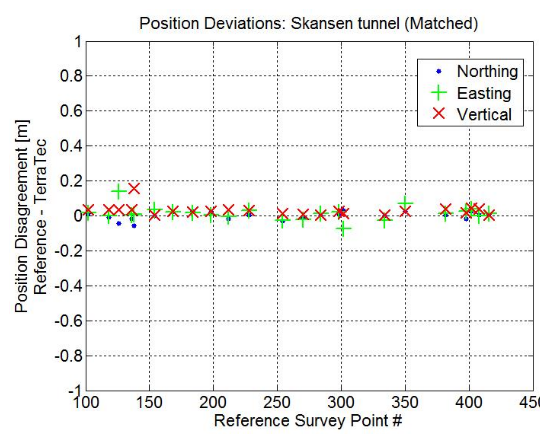


**Figure 6:** TerraTec system solution deviations relative to the reference measurements when matching is utilized, Skansen tunnel.

The Nidaros survey data captured 51 asset positions of which 26 were reflective roadside marks which are excluded from this analysis. Of the remaining 25 objects in the Ilsvik tunnel 18 were successfully positioned for a success rate of 72%. While matching points with known references did not improve performance as substantially in the Ilsvik tunnel as was the case in the Skansen tunnel, the system was still able to provide a 3D deviation of 11 cm at the 1 $\sigma$ confidence level after matching. The TerraTec system results in the shorter Ilsvik tunnel are shown in Fig. 7 and 8.

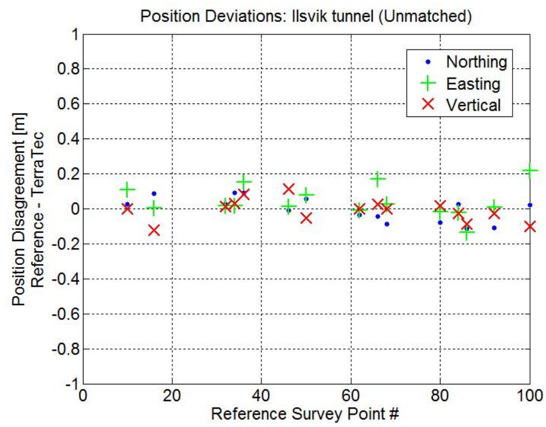


**Figure 7:** TerraTec system solution deviations relative to the reference measurements when matching is not utilized, Ilsvik tunnel.

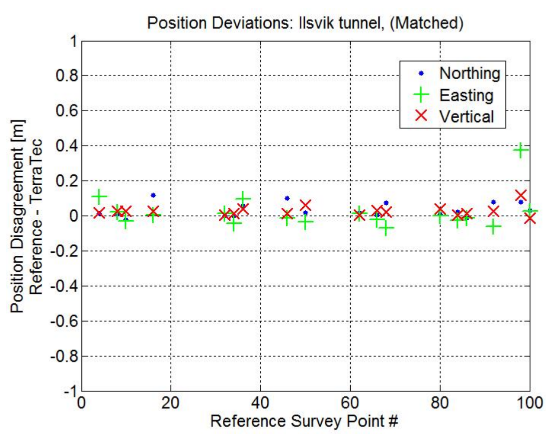


**Figure 8:** TerraTec system solution deviations relative to the reference measurements when matching is utilized, Ilsvik tunnel.

In summary the TerraTec system exhibited very low position biases through both tunnels, and a random noise component between 5 cm and 11 cm at the 1 $\sigma$ uncertainty level when utilizing matched data points to aid positioning. When not utilizing matched data positioning uncertainty was higher – between 13 and 18 cm at the 1 $\sigma$ uncertainty level. Excluding the reflective roadside marks which the TerraTec laser scanner could not detect, the rate of successful asset location was between 41% and 72%.

*Cyclomedia System Performance*

When comparing the Cyclomedia data to survey based reference data in the Skansen tunnel, there are multiple sources of likely disagreement between the two systems. Firstly both the Cyclomedia and survey data can be expected to possess a certain level of measurement noise that will be uncorrelated over time. When calculating the difference between the two data sets it is expected to appear as random fluctuation. An example of this type of expected error can be seen in Fig. 9, particularly on the red and blue traces over short time periods. A secondary source of error is expected to be slowly increasing systemic errors in the inertial navigation system of the Cyclomedia vehicle that will accumulate during tunnel navigation. This is expected to appear as a slowly varying bias in the difference between the two information sources, and is most evident on the blue and red traces in Fig. 9. Over short periods of time the random fluctuations are larger than the slowly varying bias, however over longer periods of time where GNSS updates are not available to the Cyclomedia system, this error will grow to exceed the short term fluctuations. In the red vertical trace in Fig. 9 the trend is clear and consistent over the trajectory. The third source of error is due to the use of slightly different map projection/height model data used when visualizing the data in the GlobeSpotter software compared to that used by the reference survey data. The datum used by the Nidaros survey data was EUREF89 - zone 32 NN2000, while the closest available option in the GlobeSpotter software was WGS 1984 - zone 32 NN1954, which is implicitly assumed by the software to be equivalent within the uncertainty of the conversion parameters between EUREF89 and WGS84. Given that the two tunnels are entirely contained within a 1km stretch of road, the bias should be considered constant over the test area. The fourth source of error is the dependency of the result on the trajectory used (from which measurements are made to position an object) due to uncorrelated inertial drift between the two traversals of the same road.

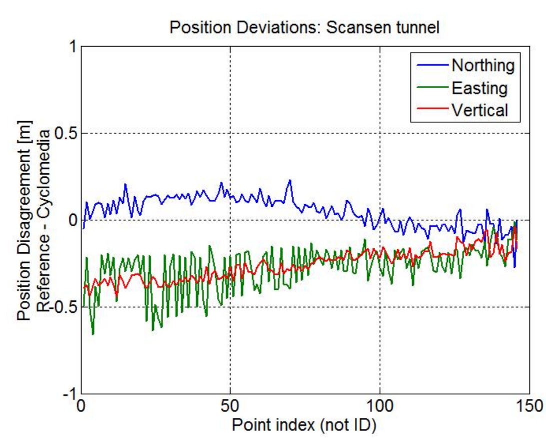


**Figure 9:** Differences in position between Cyclomedia based and survey based in-tunnel positioning inside the Skansen tunnel.

As illustrated in Fig. 10, the easting position disagreements between the Cyclomedia and survey data appear to show points clustering around two separate trend lines, which is not consistent with expected measurement noise or IMU drift within a single traversal. This behaviour is likely present in the TerraTec solution as well due to both systems utilizing IMU as their primary positioning reference, however the IMU in the TerraTec system may take slightly longer to reach this noticeable level of divergence. The Terratec system is also likely helped by the use of coordinate matching which is not available to aid the Cyclomedia solution. It is noted that in Fig. 9, 10 and 11 point index starts at one end of the tunnel and proceeds along the direction of the tunnel towards the exit of the same, simplifying plotting of trends along the length of the tunnel.

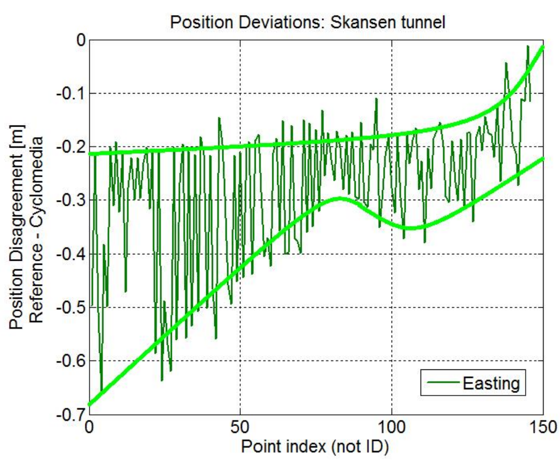


**Figure 10:** Object positioning results' dependence on the trajectory used as observed along the East axis, Skansen tunnel result.

The differences between the object positions as measured by the Cyclomedia system and as surveyed in the Ilsvik tunnel by Nidaros Oppmåling are shown in Fig. 11. Similar to the results produced in the Skansen tunnel, the position differences drift over time indicating systemic errors from the Cyclomedia system IMU. While the large offset errors might be due to map datum differences between the survey data and the Cyclomedia post processing software, the variability is not attributable to this potential error source.

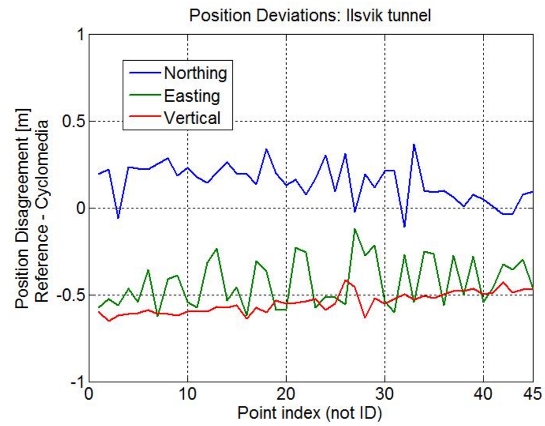


**Figure 11:** Differences in position between Cyclomedia based and survey based in-tunnel positioning, Ilsvik tunnel.

# 4 Discussion

## 4.1 Summary of the Results

The two most important characteristics which can be extracted from the comparison of the Cyclomedia and TerraTec systems to the independent GNSS survey data are considered here to be the average error (bias), and the measurement noise/uncertainty (standard deviation). Both characteristics are calculated by comparing to the coordinates for each positioned object determined by the traditional survey method, which are defined as the correct coordinates. From this starting point, the biases in each dimension are simply the average displacement between the coordinates determined by either the Cyclomedia or TerraTec system compared to the surveyed object positions. Similarly, the standard deviation reported is the standard deviation of the displacement between the coordinates determined by either the Cyclomedia, or TerraTec systems and those produced via traditional survey methods. The biases of the Cyclomedia system relative to the TerraTec system are substantially larger, and consistent with the results collected from the in-tunnel tests. However, the standard deviations of the Cyclomedia system are lower than the TerraTec system in this test, which is the opposite result to the in-tunnel tests. Despite the large bias values in the Cyclomedia system, the lower standard deviation results are of substantial interest as the biases can be overcome by utilizing 'matched' survey points similar to those used by the TerraTec system. Unlike the slowly varying bias error, the standard deviation or noise component is usually not correlated between adjacent measurement points and therefore can be thought of as the limiting performance parameter. This result indicates that if the bias component can be removed through post processing, the Cyclomedia system is capable of out-performing the TerraTec system under good operating conditions. Additionally, both systems may provide higher performance through averaging over multiple measurements of the same object, by further reducing the uncorrelated noise component.

To summarize the analysis of the high grade system performance inside the Ilsvik and Skansen tunnels, the results have been grouped to achieve better comparison visualization.

The percentage of objects that the system is capable of finding (and therefore successfully positioning) is an important indicator of the system's applicability for the object positioning task. Ideally, the solution used should be capable of positioning all the objects of interest in order to avoid additional expenses for surveying the most challenging objects 'by hand'. Fig. 12 compares the object localization success rate for the Cyclomedia system and both matched and unmatched solutions from the TerraTec system. Here the percentage is based on the number of objects found after excluding all the reflective roadside markers from the data sets.

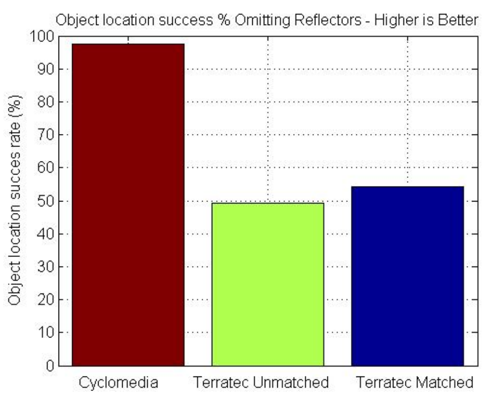


**Figure 12:** Cyclomedia and TerraTec solutions compared in terms of the percentage of the detected objects. In this plot, the reflective roadside markers were removed from the data sets since they were universally undetectable by the TerraTec system.

In Fig. 13 the same success rate comparison is repeated with all objects accounted for, including the road side reflectors invisible to the TerraTec system, resulting as expected in a much lower success rate for the TerraTec hardware.

While the Cyclomedia system has decisive superiority in terms of the proportion of objects successfully positioned relative to the TerraTec system, the opposite is true when considering the mean 3D positioning error and 3D

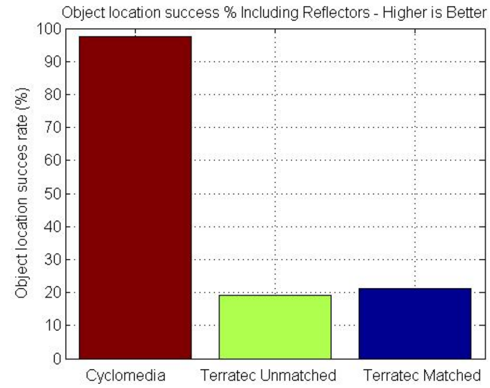


**Figure 13:** Cyclomedia and TerraTec solutions compared in terms of the percentage of the detected objects. In this plot, the reflective roadside markers are included into the data sets.

positioning standard deviation of the reported positions as shown in Fig. 14 and 15 respectively. Also, as discussed earlier, the Cyclomedia value is inflated by the use of different map/height models between the reference survey and the GlobeSpotter representation, however this contribution is not the dominant error source identified.

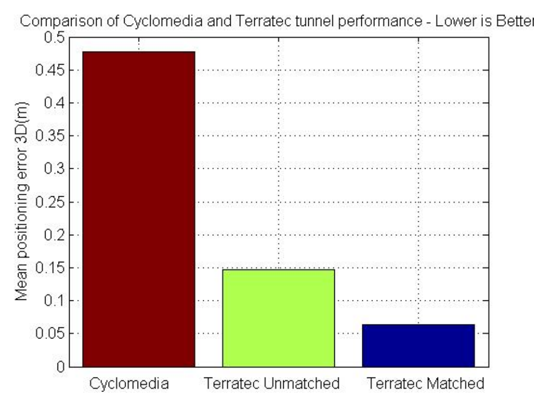


**Figure 14:** Cyclomedia and TerraTec solutions compared in the terms of the mean 3D positioning error.

## 5 Conclusions

While the Cyclomedia system provided a better than 95% success rate, neither system provided the necessary combination of success rate and accuracy required for object registration in NVDB (1-2 dm level). The laser scanner based TerraTec asset positioning approach has the relative advantage, when compared to the Cyclomedia approach, of requiring only a single line of sight to the target as-

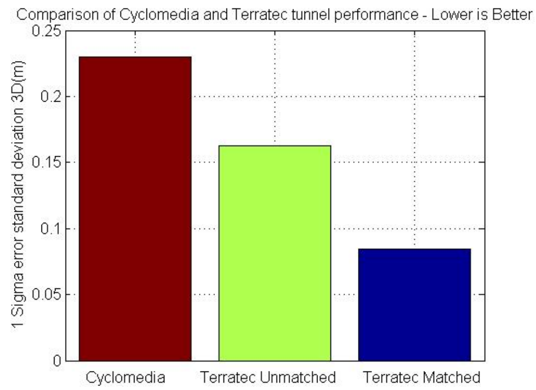


**Figure 15:** Cyclomedia and TerraTec solutions compared in terms of the 3D positioning error standard deviation.

set to position it. However the TerraTec solution can suffer from low IR reflectivity differences of many of the targets to be positioned relative to their surroundings, combined with low absolute IR reflectivity resulting in a weak return signal causing short measurement range as well as noisy/indistinct point cloud images. While some objects such as metal road signs are highly visible to the TerraTec scanning laser, these objects are typically not a challenge to isolate from their surroundings.

While both the TerraTec 3D laser scanning and Cyclomedia panoramic camera systems are promising, the Cyclomedia solution generally performed better in the tests conducted, from the standpoint of usability and detection success rate for objects to be positioned, while the TerraTec system had lower error bias and noise level, possibly due to leveraging coordinate matching. The most frequent cause of failure to position an asset in a tunnel environment was insufficient illumination. This caused the cyclorama images produced to be extremely dim, grainy and generally difficult to interpret, even for an experienced system operator. While operating outside of tunnel environments a similar problem occurred due to snow cover and occasionally due to the relative positions of other vehicles blocking all lines of sight to the desired object during the entire time it was within range.

Based on the number of limitations of each system for asset/object positioning application, the best approach to reach the desired accuracy level and higher detection rate is to upgrade the performance of the Cyclomedia system by:

- Using a better IMU to allow a slightly longer time to pass before the 10 cm accuracy level is breached.
- Adding coordinate matching support in the software to allow scanning of pre-surveyed reference positions to stabilize the IMU in challenging environments (e.g. tunnel, under bridge spans, deep in urban environments, or in a deep mountain valley). The number of such points required for various operation environments has to be investigated.

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