

# Direct Georeferencing with GPS in Terrestrial Laser Scanning

Yuriy Reshetyuk

## Summary

In this paper, a combined terrestrial laser scanning survey system is presented, where GPS can be used for direct georeferencing of the point clouds. The results of investigations of this system show that it is possible to achieve the coordinate accuracy of better than 1 cm in the point cloud, both in plane and height, at the object distance of up to about 70 m.

## Zusammenfassung

*In diesem Artikel wird ein kombiniertes terrestrisches Laser-scanning-Vermessungssystem vorgestellt, bei dem GPS für eine direkte Georeferenzierung der Punktwolken verwendet werden kann. Die Ergebnisse der Prüfung dieses Systems zeigen, dass es möglich ist, eine Koordinatengenauigkeit von mehr als 1 cm in der Punktwolke, sowohl in Fläche wie Höhe, bei einer Objektdistanz von bis zu 70 m zu erreichen.*

## 1 Introduction

The first step in data processing from terrestrial laser scanning (TLS) is registration of multiple scans and georeferencing. The latter procedure implies transformation of the point clouds from the scanner to an external coor-

dinate system. Most modern scanner models can be centred over a known point, levelled and oriented to a known backsight, like total stations. Hence, we can determine the scanner position and orientation (azimuth) in the field and use these data to georeference the point clouds. This routine is called direct georeferencing. It is advantageous to use GPS for this purpose, since in this case, the scanner position and orientation can be determined parallel to the scanning, without the need for existing survey control.

Several researchers report on the use of GPS for direct georeferencing of point clouds. Schuhmacher and Böhm (2005) describe an integrated survey system developed at University of Stuttgart, Institute for Photogrammetry. The system consists of a laser scanner Leica HDS 3000, low-cost GPS receiver and digital compass (both are co-located and mounted on top of the scanner). The GPS receiver operates in differential mode, with the estimated position accuracy of about 1 m in plane and 2 m in height. The total accuracy (in plane and height) of direct georeferencing achieved with this system is estimated in Schuhmacher and Böhm (2005) at about 4 m. The authors see the main usability of this method in providing initial values for georeferencing of the point clouds via surface matching to »pre-referenced« datasets, e.g. virtual 3D city models and Digital Surface Models derived from airborne laser scanning data.

Paffenholz and Kutterer (2008) present an approach for direct georeferencing of static laser scans, parallel to the scanning, using two GPS antennas mounted on top of the scanner (Leica HDS 4500), at the distance of 0.6 m from each other. The position and orientation of the scanner are estimated from post-processed kinematic GPS observations collected during the scanner rotation at a high rate [10 and 20 Hz in (ibid.)]. The results of the accuracy tests have shown that the metric uncertainty of about 1 cm at the distance of up to 30 m from the scanner can be achieved. However, at larger distances (between 30 and 53 m, the maximum range of the scanner used), the metric uncertainty is on the order of 10 cm. Therefore, this approach can only be used for direct georeferencing of point clouds taken at medium ranges to the objects, e.g. up to 30 m, which is normally the case for phase-difference scanners. Obviously, the attainable accuracy of the azimuth determination is limited by the distance between GPS antennas mounted on the scanner. The authors give no precision and accuracy estimates for the computed scanner position.

The purpose of this paper is to present a combined TLS survey system, where GPS can be used to georeference point clouds, and the results of its accuracy investigation. The system was developed during doctoral research at the Royal Institute of Technology (KTH) in Stockholm.

## 2 The combined survey system

### 2.1 Strategy for direct georeferencing of point clouds with GPS

Some scanner models, e.g. Riegl (LMS-Z series), Callidus CP-3200, Trimble GX and I-Site 4400 LR are equipped with an adapter or a centric standard 5/8" thread mount for mounting a GPS antenna (or receiver) on top of scanner, so that the former is centred on its vertical axis at a known height from the scanner centre. Then the scanner position can be determined from post-processing of static GPS observations collected under the duration of the scan. For scanners that lack such mounts a suitable adapter for fitting a GPS antenna to the instrument should be designed, e.g. like that presented in Schuhmacher and Böhm (2005). Since in this case it may be difficult to centre a GPS antenna precisely on the scanner vertical axis, we have to determine the scanner position from kinematic GPS observations collected during the rotation of the scanner, with the moving GPS antenna acting as a rover. In this case we can use either conventional Real-Time Kinematic (RTK) positioning or RTK positioning based on the Virtual Reference Station (VRS) concept (Leick 2004). In Sweden, the latter is implemented as Network-RTK service provided by SWEPOS, the Swedish

network of permanent reference stations (Jonsson et al. 2006). The RTK-data are distributed via GSM/GPRS. The estimated position accuracy is 3 cm in plane and 5 cm in height at 95 % confidence level (ibid.).

Using RTK, the scanner position can be determined in one of the following ways, provided a suitable adapter is available for a GPS antenna mounting on top of it. If a GPS antenna can be mounted very close to the scanner vertical axis, the scanner position can be computed as a weighted mean of the collected RTK-GPS-positions. On the other hand, if a GPS antenna can only be mounted at an offset from the vertical axis, the trajectory of antenna reference point (ARP) during the scanner rotation will be a circle in 3D space (cf. Paffenholz and Kutterer 2008). The scanner position has to be computed in a different way. If the offset is small, e.g. several centimetres, the scanner height can be computed as a mean of vertical RTK-GPS-positions. The horizontal position of the scanner can be obtained through a circle fitting to the horizontal RTK-GPS-positions, and estimation of its centre coordinates and radius. Since all modern laser scanners can be levelled (with a bull's-eye level), we can assume with sufficient accuracy that the circle lies in the horizontal plane. Since the distance from the scanner centre to the phase centre of the GPS antenna will typically be very short (not longer than 0.5 m), the error in the horizontal position due to non-precise levelling will be below 1 mm. Naturally, the adapter for mounting a GPS antenna onto the scanner should be roughly levelled as well, e.g. with the aid of a bull's-eye level. However, the levelling requirements in this case can be relaxed since during the scanner rotation the ARP moves around the scanner vertical axis along a circle, which, as mentioned above, is assumed to lie in the (sufficiently) horizontal plane if the scanner is levelled, no matter if the adapter is levelled or not. Levelling of the adapter will affect only the scanner height. However, due to the short distance from the scanner centre to the ARP, the error will be negligible. Since during one rotation of the scanner we can collect a large number of observations, depending on the sample rate, the precision of the computed scanner position can be higher than the precision obtained from a single RTK (or Network-RTK) measurement. If the scanner rotation at the station is less than 360°, we could make an additional manual slow rotation of the scanner, after finishing the scan, under about 1 min, in order to get the RTK-GPS-positions over the whole circle and provide better reliability of the position computation. The position computation in the field can be performed with a computer program specifically written for this purpose. In fact, this approach is based on the idea of the integrated laser scanning system described in Schuhmacher and Böhm (2005).

If the magnitude of the offset is significantly larger than the noise in the vertical RTK-GPS-positions, they should be first projected onto a best-fitting plane, and the circle fitting should be done in this plane (cf. Paffenholz and Kutterer 2008). Note that in order to achieve a suf-

ficiently large offset the user might need to construct a complicated adapter, which may not be quite practical. In addition, the scanner rotation, and thus the data quality, might be negatively affected by the unbalanced weight of the GPS antenna (cf. *ibid*).

The position of the backsight target can be determined either from static GPS measurements or using RTK. The first approach is most suitable when the place for the target can be chosen in such a way that it is visible from all the intended scanner stations. Therefore, it does not need to be moved, unlike the scanner, during the whole TLS survey, which would normally last for a few hours and at the maximum the whole working day. On the other hand, if the target should frequently be moved to a new location, e.g. due to limited line-of-sight, we can use RTK or Network-RTK measurements for determination of its coordinates.

A suitable adapter should be made for mounting a GPS antenna on top of the target. It is good to use a spherical target, since it is omnidirectional and does not need to be rotated when the scanner is moved to a new station. In addition, in direct georeferencing, we need to know, in fact, only horizontal coordinates of the backsight target. This is particularly advantageous when using GPS measurements where the height is determined less accurately than the planar coordinates. Therefore it is sufficient to mount the target so that its vertical axis coincides with the vertical axes of the adapter and the GPS antenna, and level the target. Optionally, the target can be centred over a point on the ground, so that it can be used for possible future surveys. We do not need to measure the target height. For this reason, it is also possible to use a cylindrical target. In the latter case, the horizontal coordinates of a point on the cylinder's vertical axis can be used for the scanner orientation.

If the scanner position is to be determined from RTK measurements, the station where the backsight target is located could be used as a temporary RTK reference station. In this case, after the position of the reference station has been determined from post-processing in the office, precise coordinates of the scanner can be determined as well and the scanner data can be georeferenced in the office.

## 2.2 Design of the combined survey system

We have developed a combined survey system, which allows point clouds to be directly georeferenced with the aid of GPS. The system consists of the following components (see also Fig. 1):

- A terrestrial laser scanning system: a laser scanner, laptop computer with the dedicated software, batteries and tripod;

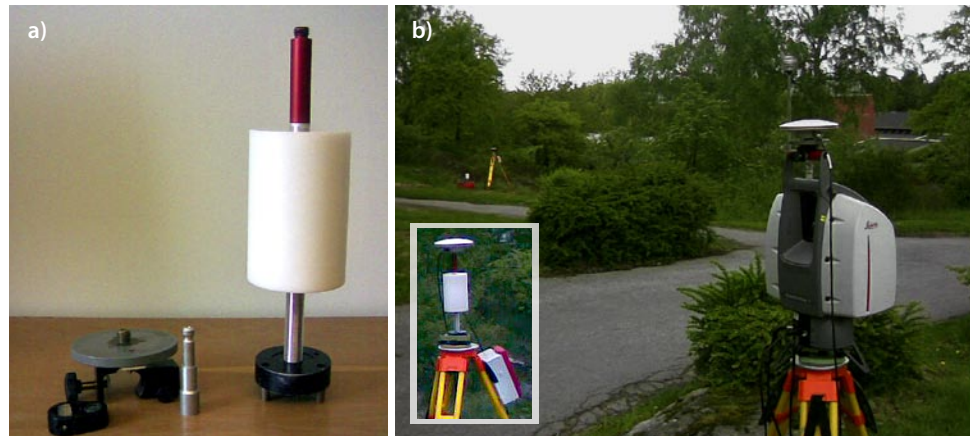


Fig. 1: a) An adapter for mounting a GPS antenna onto the scanner and a target for the scanner orientation. The image shows also a bubble level for adapter levelling. b) A GPS antenna Leica AT502 mounted on top of the scanner under the accuracy tests. An inset shows a GPS antenna Leica AT502 mounted on top of the orientation target in the field.

- 2 GPS receivers and 2 GPS antennas;
- An adapter for mounting a GPS antenna on top of the scanner and a bubble level for its rough levelling;
- An adapter onto which the target for the scanner orientation and a GPS antenna can be mounted;
- A computer program (written in MATLAB®) used to compute the scanner position.

The position of the scanner can be determined from kinematic GPS observations using either RTK or Network-RTK techniques, with the approach described above. In the field tests, the description of which will follow, we used the pulsed laser scanner Leica Scan Station 2, GPS receivers Leica 530 and GPS antennas Leica AT502. The scanner was provided by the company Leica Geosystems AB.

A GPS antenna can either be screwed to the adapter or mounted using a standard aluminium stub (shown in Fig. 1a). The adapter can be levelled with a bubble level for a GPS antenna pole from Trimble, and attached to the scanner's handle, at an offset from its vertical axis. Therefore the scanner height and planimetric position can be computed separately: the height as the weighted mean of vertical RTK-GPS-positions and the planimetric position through a circle fitting to horizontal RTK-GPS-positions (Sect. 2.1). An important consideration is the weight of the adapter. According to the information received from the manufacturer, the maximum weight that can be placed on the scanner without damaging its hard-



ware is 1 kg. In our case, if a GPS antenna Leica AT502 is screwed to the adapter, the total weight is about 0.8 kg, which is within the limit.

The backsight target is a white plastic cylinder with the diameter of 100 mm and height of 150 mm. It can be screwed on a metal pole with the centric standard 5/8" thread mount on top, to which a GPS antenna can be attached (see Fig. 1b). The pole can be placed on a standard survey tripod, levelled and centred over a point on the ground. The high manufacturing quality guarantees that the vertical axes of the target, the pole and the GPS antenna (when mounted) coincide. Therefore, there is no need for additional calibration of the target. As mentioned above, there is neither a need to determine the height of the target during the survey.

We have written a computer program in MATLAB® for determination of the scanner position from RTK measurements. The position can be computed using two different methods described in Sect. 2.1. In the first method, the position is computed as a weighted mean of Easting (E), Northing (N) and Height (H) coordinates in a single adjustment, which is done with a robust parameter estimation method »reweighed least squares for correlated observations« (RLSCO) (Wieser and Brunner 2002), since the coordinates are correlated. In the second method, the scanner height is computed as a weighted mean of H coordinates using the Danish method. The scanner planar coordinates are computed via circle fitting to Easting and Northing RTK-positions. The adjustment is based on the following equation of a circle:

$$\sqrt{(E_i - E_0)^2 + (N_i - N_0)^2} - r = 0, \quad (1)$$

where  $(E_i, N_i)$  are the observed coordinates of the  $i$ -th RTK-position,  $(E_0, N_0)$  are the coordinates of the centre of the circle and  $r$  is the radius of the circle. The adjustment is carried out with the mixed model that can be found in Reshetyuk et al. (2005). The solution is obtained with conventional least-squares. The outliers are detected and eliminated with Data Snooping, and as a criterion we use the distance of a point (i.e. RTK-position) from the computed circle:

$$\Delta r_i = \left| \hat{r} - \sqrt{(E_i - \hat{E}_0)^2 + (N_i - \hat{N}_0)^2} \right|, \quad (2)$$

where  $\Delta r_i$  is the distance of the  $i$ -th point from the circle, and the caret symbol indicates the estimated parameters. In Data Snooping, we use the test statistics  $\Delta r_i / \sigma_{\Delta r_i}$ , where  $\sigma_{\Delta r_i}$  is the estimated standard deviation of  $\Delta r_i$ , which is computed through error propagation in Eq. (2). The point is considered an outlier and deleted from the dataset if

$$\frac{\Delta r_i}{\sigma_{\Delta r_i}} > t_\alpha, \quad (3)$$

where  $t_\alpha$  is the critical value of  $t$ -distribution corresponding to the significance level  $\alpha$ . In our case, we use

$\alpha = 1\%$ . A similar procedure was used by Schulz (2007) in the adjustment of a sphere.

### 3 Experiments on the accuracy investigation of the combined survey system

#### 3.1 Simulated case

In order to study the accuracy of scanner position that can be obtained with the combined system, we performed

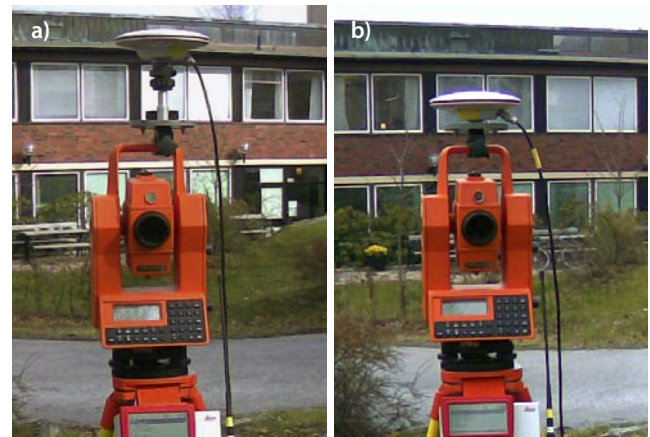


Fig. 2: Some of the configurations used in the investigation of the scanner positioning accuracy.

measurements where the scanner was »simulated« with the total station Geodimeter 640M. The tests were carried out at KTH campus in April 2008. The adapter with GPS antenna was attached to the total station's handle. Four different configurations were studied: with the GPS antenna mounted (screwed and on the stub) at an offset from the vertical axis (Fig. 2a) and close to it (Fig. 2b) (also screwed and on the stub).

The total station was set up over a known point (rover station), and an RTK reference station was established at about 15 m away. The coordinates of both points were determined earlier from static GPS measurements with the precision of about 1 mm in plane and 2 mm in height. Before starting the RTK measurements, we measured the total station height over the point and the height of the ARP over the instrument centre. The sum of the two heights gave the height of the ARP over the point. In each configuration, the total station was rotated manually clockwise under about 10 to 11 min, as uniformly as possible, in order to simulate the scanner rotation. During the rotation RTK-positions were recorded in the Swedish reference system RT90 with the sample rate of 1 s. In each configuration, the measurements were done twice.

The RTK measurements were exported from the receiver to the software SKI-Pro from Leica Geosystems, where the results were first visualized. Afterwards, the measurements and their covariance information were exported to a text file, which was then used as an input for

our MATLAB®-program, where the position of the rover station for each configuration was estimated. It is also possible to export the data to a text file directly on the receiver.

### 3.2 Real case – field measurements

In May 2008 we performed investigation of the coordinate accuracy that can be achieved with the combined system in outdoor measurements of built-up areas. For this purpose, we established a test field at KTH campus,



Figure 3: A fragment of the test field and close-ups of some natural points.

consisting of 22 natural points on the buildings, most of which were window corners, distributed around the intended scanner station (see Fig. 3). The variation of the point heights was not large, since the area was surrounded by relatively low-storey buildings. In fact, this would be a common situation in an outdoor TLS survey where the scanner position was to be determined with GPS. The coordinates of the natural points were determined in Topocad® in the reference system RT90 from a total station survey. The smallest and largest standard deviations of the planar coordinates were 0.6 and 3.2 mm, respectively. Most planimetric standard deviations were below 2 mm. The standard deviations of the height coordinate components were below 0.8 mm. Such precision was achieved due to quite strong geometry and high redundancy of the network. It is not possible to achieve this precision in directly georeferenced point clouds from the scanner Leica Scan Station 2, since coordinates of single points are determined via non-redundant polar measurements, and coordinate precision is influenced mainly by precision of the range measurements.

Before the tests we performed a simple calibration in order to determine the vertical offset between the ARP (when the GPS antenna was mounted on the scanner with the adapter) and the origin of the scanner coordinate system. In the field, the scanner was set up over a known point, centred and levelled, and its height above the point was measured with a tape. The backsight target (cylinder) was set up over another known point determined with the precision of about 1 mm with total station. The backsight station was at the same time the reference station for the rover receiver at the scanner station. During the measurements we had many problems with connection to the scanner. Because of this and due to the fact that the scanner was available for about 1.5 days, we took only two scans. First, we scanned the whole test field with the nominal resolution of  $0.1 \times 0.1$  m at 50 m. The temperature and pressure were measured and entered into the scanning software Cyclone before the scanning in order to apply the atmospheric correction to the range measurements. Afterwards, we scanned only the locations of the natural points with the nominal resolution of  $1 \times 1$  or  $2 \times 2$  mm at the distance to the natural point. We used a Leica HDS 6" circular tilt and turn target as the backsight target. After the target was scanned with high resolution and automatically identified by Cyclone, we replaced it with our cylindrical target, which was scanned with the nominal resolution of  $2 \times 2$  mm at the distance to the target. Afterwards, it was replaced by Leica GPS antenna AT502 mounted on the Leica GRT 144 carrier. The scan was georeferenced in the field. The second scan was made with the GPS antenna mounted onto the scanner with our adapter. The resolution was set to  $0.2 \times 0.2$  m at 70 m, and the scan took about 15 min. RTK measurements were collected during the scan with the sample rate of 1 s. No high-resolution scan of the points was made. In fact, the purpose of making this scan was rather to collect RTK measurements necessary for the determination of the scanner position. The coordinates determined from RTK would be used for georeferencing of the first captured point cloud.

In these experiments, the RTK reference station was set up over a known point. However, under real field conditions its coordinates would have to be determined parallel to the scanning. For this reason, 1.5 hours of static GPS observations (not continuous) with a sample rate of 1 s were recorded at the reference station in order to determine its coordinates.

### 3.3 Real case – data processing

First, we processed the GPS measurements in order to have the data for the georeferencing of the point cloud. The RTK measurements collected during the scanner rotation were exported to a text file on the receiver and used in the MATLAB®-program in the circle fitting, where the scanner coordinates and the circle radius were estimated.

The 1.5 hours of static GPS observations at the RTK reference station were processed in the software Trimble Total Control™ relative to the SWEPOS reference station STHO located at about 5 km from KTH. The coordinates of the scanner and backsight stations computed from the GPS observations were then compared to their known coordinates.

Processing of the scanner measurements included identification of all the natural points in the captured point cloud and manual insertion of vertices into their locations in the software Cyclone. The coordinates of the 22 vertices were exported to a text file. In order to be able to use the cylindrical target as the backsight, we performed a constrained fitting of the cylinder to it, i.e. with the known diameter (0.100 m). In order to have a reference point for georeferencing, we placed a vertex, in Cyclone, at the lower end point of the cylinder centreline, in order to minimize the errors due to non-perfect levelling of the target. Afterwards, we performed direct georeferencing of the point cloud in Cyclone using two different strategies that employed different methods for the determination of the coordinates of the scanner and backsight target:

- Strategy 1: the scanner and backsight target are set up over known points;
- Strategy 2: the scanner position is determined from RTK GPS measurements (with the adapter) and the backsight station coordinates are determined from static GPS measurements.

Practically, this was achieved through importing new coordinates into the Scan Control module of Cyclone and performing georeferencing like we would do in the field. After the results of a new georeferencing were applied to the point cloud, the coordinates of the vertices inserted at the natural points were exported to a text file. The distances from the scanner to the natural points varied between about 15 and 72 m.

## 4 Results

### 4.1 Accuracy of scanner positioning – simulated case

Tab. 1 shows differences (in E, N and H directions) between the estimated and known position of the total station, which was used to simulate the scanner, from the eight series of measurements described in Sect. 3.1. The last line shows the root-mean-square (RMS) of the differences. The number of satellites tracked during the measurements varied from 5 to 10, and the GDOP values varied from 1.9 to 3.9. As we can see, subcentimetre accuracy can be achieved if the scanner position is determined during rotation from RTK measurements.

Tab. 1: Differences (denoted by  $\delta$ ) between the computed (from the RTK measurements during rotation) and known coordinates of the rover station

Series	$\delta E$ , mm	$\delta N$ , mm	$\delta H$ , mm
1	5.4	1.6	-8.9
2	6.9	5.1	-4.0
3	1.8	1.5	9.0
4	-0.6	6.9	8.2
5	2.1	2.6	-2.8
6	1.3	4.6	6.2
7	0.7	9.0	-5.5
8	7.9	1.1	0.9
RMS	4.3	4.9	6.3

Examples of the collected datasets are shown in Fig. 4 and 5 along with the results of the position computation. Note that in these figures the origin of the coordinate system is shifted to the centroid of the data points. The standard deviations of the station coordinates computed from the adjustment of RTK measurements collected during GPS antenna rotation were at the submillimetre level. However, this is the result of a very high redundancy of the adjustment since the number of the observations from each test (from 10 to 11 min of the observations) varied between 600 and 700, and it does not give any meaningful indication of the position quality.

### 4.2 Coordinate accuracy achieved with the combined system

In order to estimate the expected coordinate accuracy for the combined system, we performed error propagation for simulated measurements to a point with the following polar coordinates: range – variable from 10 to 80 m, horizontal angle 50°, vertical angle 16° (the biggest vertical angle to the natural point at the test field). The simulations were carried out in MATLAB® using the mathematical models given in Lichti and Gordon (2004) where the reader is referred for more details. The following data were used:

- Standard deviations of the scanner position – 5 mm in E and N directions, 6 mm in H direction (based on the RMS values in Tab. 1);
- Standard deviation of the E and N coordinates of the backsight target – 5 mm (based on the specifications for baseline precision given in Leica Geosystems 2002). Given the above-mentioned data, the »horizontal coordinate precision« (Lichti and Gordon 2004) for the scanner and backsight stations was computed to  $5\sqrt{2}$  mm;
- Distance to the backsight target – 15 m;



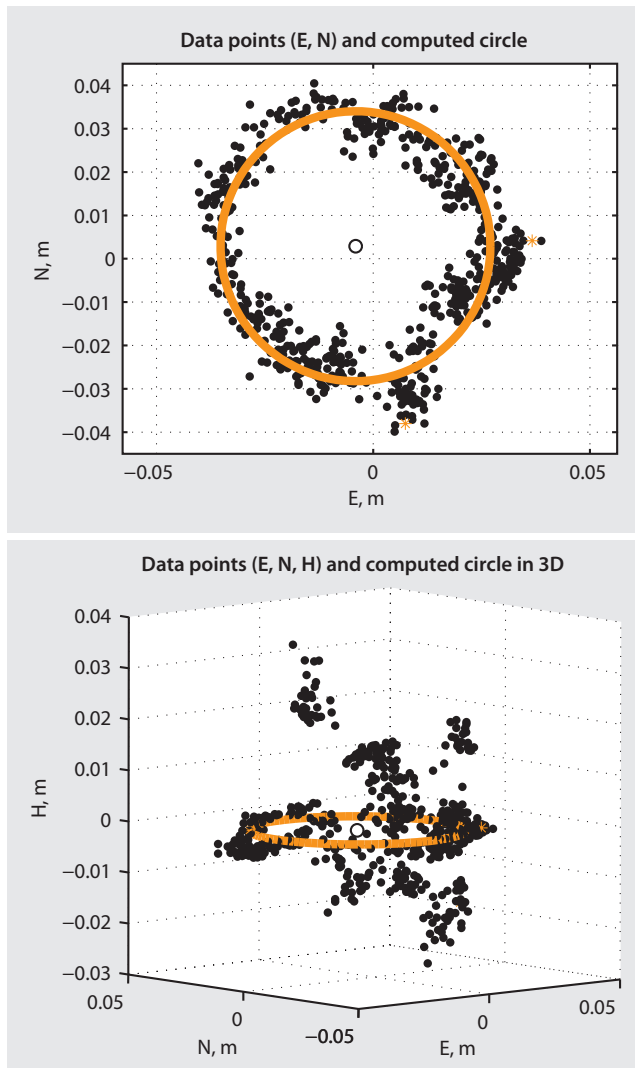


Fig. 4: Dataset from the »simulated« tests, the GPS adapter is mounted off-centre. Top: E and N RTK-positions and the computed circle. Bottom: E, N and H RTK-positions and the computed circle in 3D. The outliers are shown as orange asterisks.

- Standard deviations of the scanner observables – 4 mm for range and 60  $\mu\text{m}$  for horizontal direction and vertical angle (from the manufacturer's specifications);
- Setting accuracy of the dual-axis compensator – 1.5" (from the scanner manual). Standard deviation of the error in the vertical angle was assumed to be 0.2 times 1.5" (cf. *ibid.*);
- Centring precision of the optical plummet – 0.5 mm/m;
- Beam divergence – 0.15 mrad (from the manufacturer's specifications);
- Sampling interval on the surface of the backsight target was assumed to be 1 mm (fine scan) at the distance of 15 m. It was further assumed that a flat target was used, since the error model given in (*ibid.*) is valid for this kind of target.

The results of the simulations are shown in Fig. 6. The largest contribution to the error budget came from the

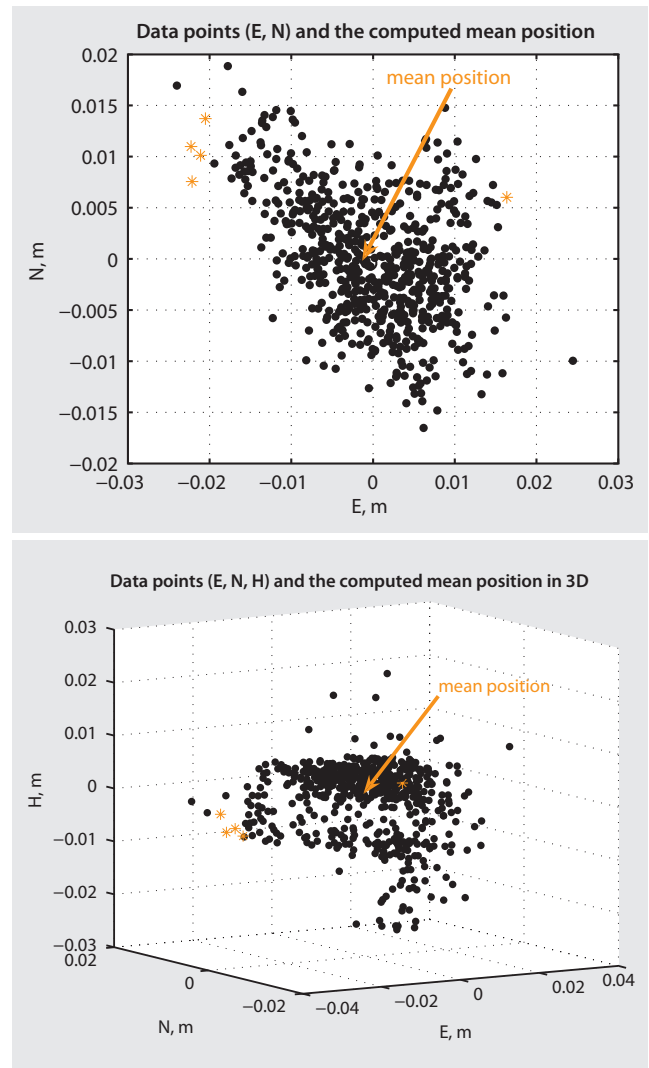


Fig. 5: Dataset from the »simulated« tests, the GPS adapter is mounted close to the vertical axis. Top: E and N RTK-positions and the computed mean position (2D). Bottom: E, N and H RTK-positions and the computed mean position in 3D. The outliers are shown as orange asterisks.

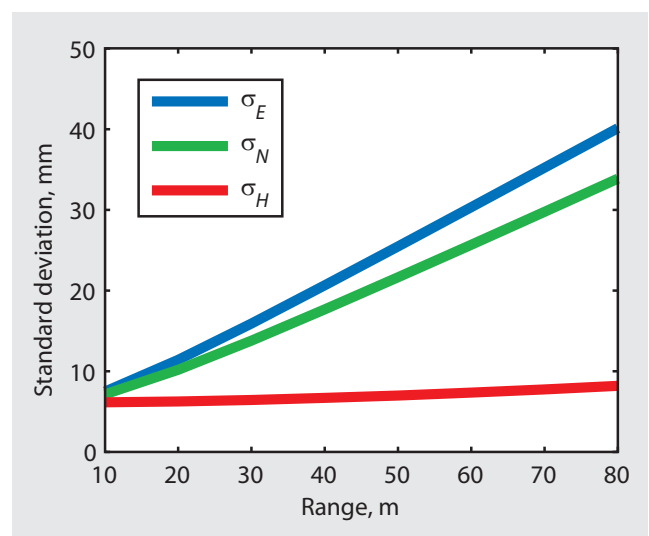


Fig. 6: Standard deviations of E, N and H coordinates of a directly georeferenced scanned point from the simulations.

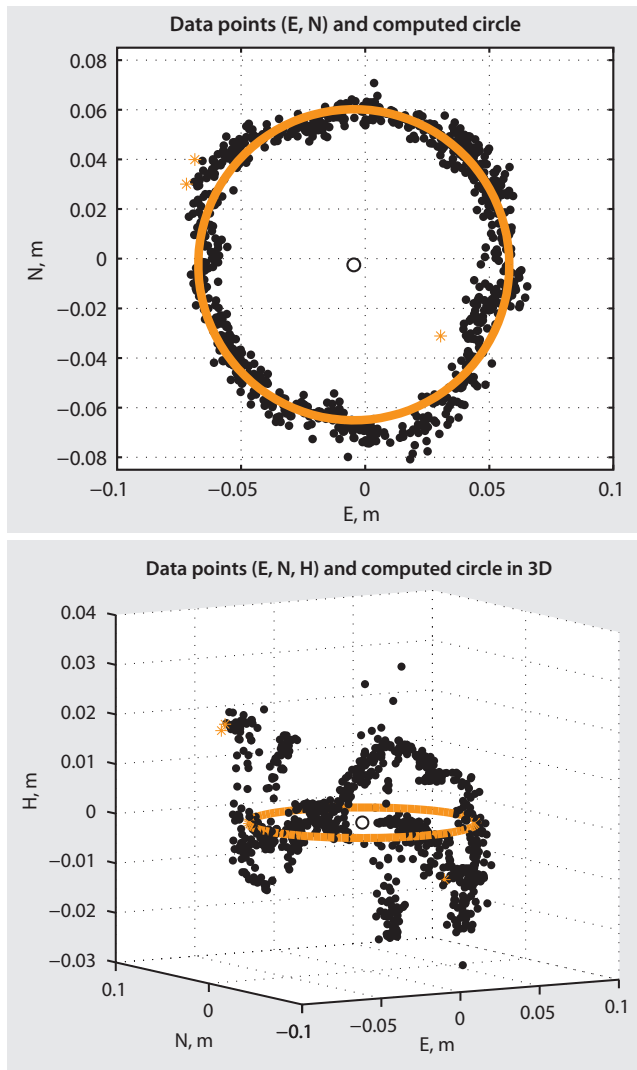


Fig. 7: Dataset from the accuracy investigation of the combined survey system. Top: E and N RTK-positions and the computed circle. Bottom: E, N and H RTK-positions and the computed circle in 3D. The outliers are shown as orange asterisks.

scanner position and orientation, while the smallest – from the scanner levelling (error in height of about 0.1 mm at the distance of 80 m). The latter was due to the high accuracy of the dual-axis compensator in the scanner.

The results of scanner position estimation and the dataset from real RTK-GPS measurements are shown in Fig. 7. The differences between the known and computed coordinates of the scanner station were 0.2, -0.5 and 3.0 in E, N and H directions, respectively. The corresponding differences for the backsight station were -2.8, 6.0 and 6.4 mm. The precision of the backsight station position computed from 1.5 hours of static GPS measurements was about 2 mm in plane and 3 mm in height. We computed differences between the coordinates of the natural points extracted from the point cloud and their known coordinates in MATLAB® for the two georeferencing

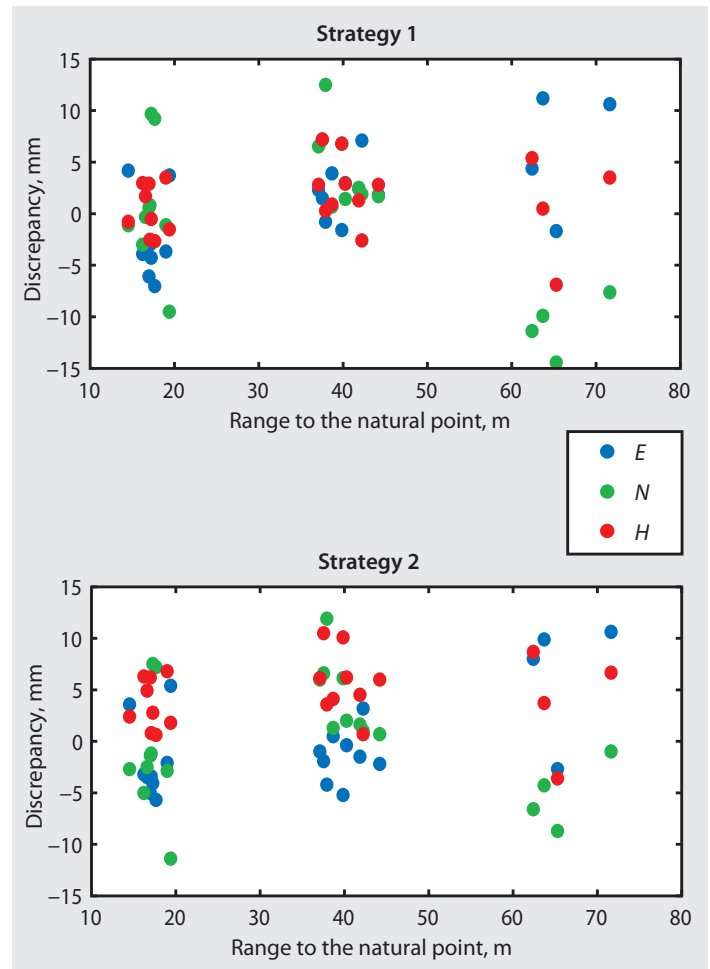


Fig. 8: Distribution of the coordinate discrepancies at the natural points.

strategies mentioned in Sect. 3.3. The RMS values of the discrepancies were 5.0, 7.0 and 3.5 mm for Strategy 1 and 4.1, 5.6 and 5.6 mm for Strategy 2, in E, N and H coordinates, respectively. Distribution of the discrepancies for both strategies is given in Fig. 8.

The magnitude of the errors in height agrees with the results of the error propagation, while the planimetric accuracy is better at the ranges of larger than about 35 m. The reason is that the accuracy of the planimetric position of the scanner was better than it was assumed in the simulations, which also contributed to the better accuracy of the scanner azimuth.

## 5 Conclusions and discussion

The results of the »simulated« experiments have shown that it is possible to determine the scanner position parallel to the scanning with subcentimetre accuracy from processing of RTK-GPS measurements. In fact, we determined the scanner position in the office but it is possible to do this in the field provided the MATLAB® program is installed on the laptop computer used for scanner control.



In our tests we determined the position of the backsight target from static GPS measurements but it is possible to do this with RTK or Network-RTK techniques. In this case, the results will be available in the field and the scans can also be georeferenced in the field. The coordinate accuracy will be somewhat worse (especially in height) in this case than with static measurements but it can be compensated for through placing the backsight at longer distance from the scanner. In addition, the height coordinate is of no interest for determination of the scanner azimuth.

The results of the coordinate accuracy tests have shown that it is possible to achieve the accuracy of better than 1 cm both in plane and height in the point cloud, at the distance of up to about 70 m to the object, with the scanner Leica Scan Station 2 when using the developed combined survey system. Similar accuracy can be achieved with the same scanner using conventional direct georeferencing. Besides the georeferencing errors, the results are influenced by uncertainty in the location of the natural points, scanner instrumental errors, object surface reflectance and identification of the natural points in the point cloud. These results show that the combined system can be successfully used for accurate surveys of built environments.

In our tests we used conventional RTK but we also see the possibility to use Network-RTK technique for this purpose. It is expected that similar accuracy level can be achieved for the scanner position and coordinates of the natural points but more investigations are required to prove this. Unlike in the georeferencing alternative described in Paffenholz and Kutterer (2008), the applicability of which is limited by the accuracy of the azimuth determination, the azimuth accuracy in our case can be increased by placing the backsight target further away from the scanner. In addition, mounting two GPS antennas onto the scanner may need a complicated (and heavy) adapter, which is not as practical as mounting only one GPS antenna. As was shown above, users may also need to consider which maximum weight can be placed on top of the scanner without damaging its hardware. Therefore, mounting of two GPS antennas may not be possible for all scanner models. We expect that our adapter and the procedure for the scanner position determination could be used with the phase-difference scanner Z+F Imager 5006 and »pulsed-wave« scanner Callidus CPW 8000, since they have handles similar to that in the scanner Leica Scan Station 2. Naturally, the user has to consult with the manufacturer about the maximum weight that can be placed on the scanner.

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## Author's address

Yuriy Reshetyuk, PhD, Lecturer in Geomatics  
University of Gävle  
Faculty of Engineering and Sustainable Development  
Kungsbäcksvägen 47, S-801 76 Gävle, Sweden  
Tel.: +46 26 648403 | Fax: +46 26 648828  
[yuyrek@hig.se](mailto:yuyrek@hig.se)