Influence of Control Points Configuration on the Mobile Laser Scanning Accuracy

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Abstract. Mobile mapping systems (MMS) are becoming widely used in standard geodetic tasks more commonly in the last years. The paper is focused on the influence of control points (CPs) number and configuration on mobile laser scanning accuracy. The mobile laser scanning (MLS) data was acquired by MMS RIEGL VMX-450. The resulting point cloud was compared with two different reference data sets. The first reference data set consisted of a high-accuracy test point field (TPF) measured by a Trimble R8s GNSS system and a Trimble S8 HP total station. The second reference data set was a point cloud from terrestrial laser scanning (TLS) using two Faro Focus3D X 130 laser scanners. The coordinates of both reference data sets were determined with significantly higher accuracy than the coordinates of the tested MLS point cloud. The accuracy testing is based on coordinate differences between the reference data set and the tested MLS point cloud. There is a minimum number of 6–7 CPs in our scanned area (based on MLS trajectory length) to achieve the declared relative accuracy of trajectory positioning according to the RIEGL datasheet. We tested two types of ground control point (GCP) configurations for 7 GCPs, using TPF reference data. The first type is a trajectory-based CPs configuration, and the second is a geometry-based CPs configuration. The accuracy differences of the MLS point clouds with trajectory-based CPs configuration and geometry-based CPs configuration are not statistically significant. From a practical perspective, a geometry-based CPs configuration is more advantageous in the nonlinear type of urban area such as our one. The following analyzes are performed on geometry-based CPs configuration variants. We tested the influence of changing the location of two CPs from ground to roof. The effect of the vertical configuration of the CPs on the accuracy of the tested MLS point cloud has not been demonstrated. The effect of the number of control points on the accuracy of the MLS point cloud was also tested. In the overall statistics using TPF, the accuracy increases significantly with increasing the number of GCPs up to 6. This number corresponds to a requirement of the manufacturer. Although further increasing the number of CPs does not significantly increase the global accuracy, local accuracy improves with increasing the number of CPs up to 10 (average spacing 50 m) according to the comparison with the TLS reference point cloud. The accuracy test of the MLS point cloud was divided into the horizontal accuracy test on the façade data subset and the vertical accuracy test on the road data subset using the TLS reference point cloud. The results of this paper can help improve the efficiency and accuracy of the mobile mapping process in geodetic praxis.

1. Introduction
Mobile laser scanning (MLS) methods have become widely used to capture accurate 3D point clouds for many applications, for example, urban planning, 3D city modeling, civil engineering, and road surveying [1, 2, 3]. The geometric accuracy of the final product is one of the fundamental properties,
depends on a large number of factors. These factors are the input data accuracy, density, and the algorithms used.

The accuracy of MLS data can be divided into absolute and relative components, which correspond to the positioning subsystem and mapping subsystem of the mobile mapping system (MMS). The positioning subsystem uses an Inertial Measuring Unit (IMU), Global Navigation Satellite System (GNSS), and Distance Measurement Indicators (DMIs) [4, 5]. The result of GNSS, IMU, and DMI data combination in a Kalman filter is Smoothed Best Estimated Trajectory (SBET). The accuracy of SBET can be improved by using control points (CPs) [6]. The mapping subsystem performs the spatial data acquisition and typically consists of one or more LIDAR sensors and cameras. Accurate calibration of both subsystems is a prerequisite for accurate georeferenced LIDAR data.

Many authors have investigated methods for assessing and improving the accuracy of MMS data. The geometric accuracy of the resulting point clouds is commonly improved by using signalized CPs [7] observed in multiple MMS passes [8, 9]. Increasing the number of CPs leads to more difficult processes and costs. The aim is to minimize the number of control points for maximizing the efficiency of laser scanning and photogrammetry processes [10]. Independent quantification of errors is realized using check points (validation points) [9, 11]. For this purpose, a test point field (TPF) can be created in the urban reference area, through which the MMS can be driven. To ensure the necessary reliability of the resulting statistics, the TPF must have a sufficient density and a sufficiently high number of test points. The advantage of TPF-based accuracy testing is the ability to determine the coordinates of signaled check points with high accuracy. However, TPF-based accuracy testing may suffer from the significant disparity in data density between the MLS and the independently surveyed points.

A dense reference point cloud can be used for accuracy testing of MLS as a variant to TPF. The accuracy of the reference point cloud should be higher than the accuracy of the tested MLS point cloud. The reference point cloud is usually acquired by static terrestrial laser scanning (TLS). The accuracy tests of MLS data can be based on a comparison of TLS point cloud with MLS point cloud, and the methods used for comparison can vary. The TLS-based approach does not suffer from poor density and allows a better local errors evaluation of the tested point cloud. The disadvantage of the TLS-based approach may be a large amount of reference data and lower accuracy compared to the TPF-based approach.

Kaartinen et al. [12] tested five MMSs at 1700 m of the road environment. They quantify horizontal and vertical accuracy using independently surveyed point features (reference objects) like poles, curb corners, and building corners extracted from the point cloud. The vertical accuracy was better than ±35 mm up to a range of 35 m (with all professional systems correctly calibrated). The best system had a horizontal accuracy of ±25 mm, even with a range of 45 m, and vertical accuracy of ±1–2 cm with a range of 35 m.

Xu et al. [13] use to assess accuracy 45 control points and approximately 90 obvious feature points (such as building and window corners, poles, and traffic signs) in the TPF (approx. area size 1700 m × 550 m). Their TPF accuracy is in the order of centimeters, and the resulting accuracy of tested data is approx. ±2 decimeters.

Johnson et al. [9] in their manual for MLS report two test points with checkpoints, an urban test site, and a rural highway test site to test the MMS performance of four commercial vendors. The accuracy of four MMS is tested with signalized control points and TLS reference data. Accuracies obtained by design-grade mobile mapping systems did not exceed ±80 mm in horizontal component and 50 mm in vertical component (at the 95% probability level).
Fryskowska and Wróblewski [14] also use TLS reference data for accuracy testing of an MMS. Their assessment is performed using the lengths of building features (e.g., roof edges) and 395 check points. They analyzed point clouds in terms of object identification and geometric potential (in many object classes). The overall horizontal accuracy of the MLS point cloud was ±60 mm, and the overall vertical accuracy was ±42 mm. The percentage distribution of the errors is also tested.

This paper aims to determine the influence of CPs number and configuration on mobile laser scanning local and global accuracy. In contrast to other works, for testing, we use high-accuracy TPF, which has several times higher accuracy (±1.6 mm in horizontal and ±1.4 mm in vertical component) than the tested MLS point cloud with the reference TLS point cloud.

2. MMS description
The MMS RIEGL VMX-450 (table 1) integrates two RIEGL VQ-450 laser scanners, a modular VMX-450-CS6 camera system with four industrial cameras, POINT GREY Ladybug5 spherical camera imaging system, GNSS/IMU navigation hardware, distance measurement unit VMX-450-DMI, and a portable control unit VMX-450-CU.

| Sensor  | Property name              | Property value                                      |
|---------|-----------------------------|-----------------------------------------------------|
| VQ-450  | Measuring principle         | Time of Flight                                      |
|         | Max. measurement rate       | 1.1 MHz (2×0.55 MHz), \( \varphi \geq 10 \% \) up to 140 m |
|         | Scan rate (selectable)      | up to 400 lines/sec                                 |
|         | Accuracy                    | 8 mm, 1\( \sigma \) @ 50 m range                   |
|         | Precision                   | 5 mm, 1\( \sigma \) @ 50 m range                   |
| IMU/GNSS| Absolute position accuracy  | 0.02–0.05 m, 1\( \sigma \)                         |
|         | Relative position accuracy  | 0.01 m, 1\( \sigma \) (with a CPs spacing <100 m)   |
|         | Roll and pitch accuracy     | 0.005°, 1\( \sigma \)                              |
|         | Yaw (heading) accuracy      | 0.015°, 1\( \sigma \)                              |

RIEGL defines the accuracy in the datasheet [15] as a degree of conformity of measured quantity to its true value in the VQ-450 section of table 1. The precision RIEGL defines in datasheet [15] as repeatability (the degree to which further measurements show the same result). Values in the IMU/GNSS section of table 1 are valid if the following conditions are fulfilled: no GNSS outages, DMI option, and post-processed using base station data. The relative position accuracy value in the IMU/GNSS section of Table 1 is valid with a CPs spacing of less than 100 m.

3. Reference datasets
Two different reference data sets were used for accuracy testing (TPF, TLS). The first reference data set consisted of a high-accuracy test point field (TPF) measured by a Trimble R8s GNSS system and a Trimble S8 HP total station. The second reference data set was a point cloud from terrestrial laser scanning (TLS) using two Faro Focus3D X 130 laser scanners. Identifiability of the points is an essential property for resulting accuracy. We can distinguish two types of point identification errors for our purposes. The first type is an error of identification in real-world and the second type is an error of identification in point clouds. The resulting point coordinates error consists of the identification error and used coordinate determination method error. For example, the error of a point determined by a total station is affected by a point identification error in the real world. The error of a point measured from a point cloud is affected by a point identification error in a point cloud.
In this paper, we focus on the errors of the method used. In the case of a TLS dataset, the cloud-to-cloud comparison method eliminates the error from identifying points. In the case of TPF, we used signaling targets to minimize the impact of identification errors.

The TPF was created within the faculty research project FAST-S-19-5704 “Geometric accuracy of mobile mapping systems” of internal grant system of Brno University of Technology (BUT) in the area of Advanced Materials, Structures and Technologies (AdMaS) research centre. The TPF consists of 214 points signalized and stabilized using checkerboard targets. Horizontal targets (119) were marked by white color on asphalt roadways (figure 1). The vertical targets (95) were made of aluminum sheets (figure 1). Vertical targets were placed on buildings, vertical traffic signs, concrete pillars, and other suitable vertical structures. The targets on the buildings were placed in two height levels above the ground: 2 m, 10 m.

![Figure 1. Test point field (left), checkerboard targets (middle and right)](image)

The geodetic network and the test point field were measured with high accuracy. Trimble S8 HP total station and Trimble R8s GNSS system were used. Firstly, a purpose-built geodetic network was created. Secondly, test field points were determined. The coordinates of the test field points were calculated by the geodetic network least-squares adjustment with a combination of GNSS and terrestrial measurements. The European Terrestrial Reference System 89 (ETRS89) and European Terrestrial Reference Frame 2000 (ETRF2000) were used [16]. The minimum-constrained network adjustment was used for computing of geodetic network. Input data in adjustment was polar coordinates measured by the total station and coordinates of four points determined by the static GNSS method. The constrained network adjustment was used for computing of test field attached to fixed points (the geodetic network). The overall accuracy of the test field determined by adjustment can be expressed as the estimate of the 3D standard deviation \( s_{3D} = \pm 2.0 \text{ mm} \). The estimates of horizontal, vertical, and 3D standard deviations \( (s_H, s_V, \text{ and } s_{3D}) \) of both reference datasets are in table 2.

![Table 2. Accuracy of reference datasets](image)

|            | horizontal \( s_H \) | vertical \( s_V \) | 3D \( s_{3D} \) |
|------------|----------------------|-------------------|-----------------|
| TPF        | \( \pm 1.6 \text{ mm} \) | \( \pm 1.4 \text{ mm} \) | \( \pm 2.0 \text{ mm} \) |
| TLS point cloud | \( \pm 7.4 \text{ mm} \) | \( \pm 4.1 \text{ mm} \) | \( \pm 8.5 \text{ mm} \) |

The TPF values were obtained from the least-squares adjustment, while the TLS point cloud values were obtained from the differences between the reference coordinates of the TPF points and their coordinates determined from the TLS point cloud. Therefore the TLS point cloud values include errors of TPF points identification in the TLS point cloud, so the real accuracy of this dataset is slightly better.

4. MMS data acquisition and processing

MMS data were acquired by two vehicle passes (in both directions) 600 m long at a speed of 20 km/h. The scanned area dimensions are approximate length 190 m, width 90 m, and height range 20 m,
including buildings. Laser data were acquired at a frequency of 1.1 MHz. The MMS trajectory was calculated using Applanix POSPac. The GNSS Post Processing Kinematic method results were refined and smoothed by a forward-backward Kalman filter using IMU and DMI data.

The processing of MLS data was performed in RIEGL RiPROCESS. RiPROCESS processing consists of data conversion, MLS point clouds generation, and trajectory adjustment. In the first stage, the MLS point cloud was created based on the POSPac trajectory. Furthermore, CPs and check points in the MLS point cloud were manually identified. More accurate trajectories for different configurations and CPs numbers were processed using the RiPRECISION module based on correspondences between point clouds and CPs. In this step, the trajectories can be refined using CPs, which is essential, especially in environments with poor GNSS conditions (e.g., urban areas). The resulting point clouds consist of two partial point clouds corresponding to two vehicle passes and contain more than 247,000,000 points with a density of about 4 mm. Finally, MLS point cloud filtering is performed in the CloudCompare v2.11 software.

5. Accuracy evaluation methodology
The accuracy evaluation is based on a comparison of the tested MLS point clouds variants with reference datasets. TPF-based testing uses the differences between the reference coordinates of the TPF points and their coordinates determined from the MLS point cloud. TLS-based testing uses a comparison of the TLS reference point cloud with the MLS point clouds in CloudCompare v2.11 software. The differences between the clouds were estimated using the Cloud-to-Cloud Distance function with local modeling using the Least Squares Plane [17]. The point clouds were divided into the façade data subset and the road data subset in the TLS-based accuracy testing. Horizontal accuracy was tested on a façade data subset and vertical accuracy on a road data subset. The length of the selected façade is 80 m and the height 9 m.

We use estimates of horizontal, vertical, and 3D standard deviations (68% confidence interval) for accuracy characteristics. We test the relative number of stragglers ($\alpha = 5 \%$ critical value) and outliers ($\alpha = 1 \%$ critical value) according to [18]. The control points were not used as check points to ensure independent accuracy evaluation.

There is a minimum number of 6–7 CPs in our scanned area (based on MLS trajectory length) to achieve the declared relative accuracy of trajectory positioning according to the RIEGL datasheet. The GNSS/IMU relative positioning uncertainty ($\pm 10$ mm, 68% confidence interval) is under the condition of a CPs spacing <100 m.

We tested two types of GCPs configurations for 7 GCPs, using TPF reference data. The first type is a trajectory-based CPs configuration, and the second is a geometry-based CPs configuration. We tested the statistical significance of accuracy differences of the MLS point clouds with trajectory-based CPs configuration and geometry-based CPs configuration using the F-test [19]. Also, the influence of changing the location of two CPs from ground to roof and the effect of the number of CPs on the global accuracy of the MLS point cloud was tested using F-test.

6. Results
The results are divided into two subsections according to the used reference dataset.

6.1. TPF-based accuracy test
The accuracy estimates of trajectory-based and geometry-based GCPs configurations for 7 GCPs, using TPF reference data, are in table 3. The relative numbers of stragglers and outliers are in table 4. The configurations of GCPs (marked with red dots) are shown in figure 2.
Table 3. TPF-based accuracy of trajectory-based and geometry-based GCPs configurations

|                       | horizontal $s_{h}$ | vertical $s_{v}$ | 3D $s_{3D}$ |
|-----------------------|--------------------|-----------------|-------------|
| Trajectory-based (7 GCPs) | ±18 mm             | ±8.1 mm         | ±20 mm      |
| Geometry-based (7 GCPs)   | ±16 mm             | ±8.6 mm         | ±19 mm      |

Table 4. Stragglers and outliers of trajectory-based and geometry-based GCPs configurations

|                       | horizontal | vertical | 3D |
|-----------------------|------------|----------|----|
|                       | stragglers | outliers | stragglers | outliers | stragglers | outliers |
| Trajectory-based (7 GCPs) | 0 %       | 0 %      | 1 % | 4 % | 0 % | 0 % |
| Geometry-based (7 GCPs)   | 1 %       | 0 %      | 3 % | 3 % | 0 % | 0 % |

Figure 2. Overview of trajectory-based (left) and geometry-based (right) GCPs configurations

The accuracy differences of the MLS point clouds with trajectory-based CPs configuration and geometry-based CPs configuration are not statistically significant. From a practical perspective, a geometry-based CPs configuration is more advantageous in the nonlinear type of urban area such as our one. The following analyzes are performed on geometry-based CPs configuration variants.

The effect of changing the location of two CPs from the ground to the roof is shown in table 5. Variants with only GCPs are marked as ground, and variants with two GCPs replaced by roof CPs are called the roof. The configurations of CPs are shown in figure 3.

Table 5. TPF-based accuracy – influence of two GCPs replacing by roof CPs

|       | horizontal | vertical | 3D |
|-------|------------|----------|----|
|       | ground     | roof     | ground | roof | ground | roof |
| 6 CPs | ±16 mm     | ±17 mm   | ±8.2 mm | ±9.0 mm | ±18 mm | ±19 mm |
| 10 CPs| ±15 mm     | ±15 mm   | ±8.2 mm | ±9.1 mm | ±17 mm | ±17 mm |

Figure 3. The configurations of GCPs (red and blue) with green roof CPs (replacing blue GCPs)
The maximum difference of stragglers and outliers of ground and roof variants is 2%. The accuracy differences of the MLS point clouds (ground and roof CPs variants) are not statistically significant. The effect of changing the location of two CPs from the ground to the roof on the accuracy of the tested MLS point cloud has not been demonstrated.

The results of the TPF-based global accuracy test of various numbers of GCPs (red dots) are shown in table 6. The configurations of CPs are shown in figure 4.

Table 6. TPF-based accuracy – various numbers of GCPs

| Check points number | horizontal $s_h$ | vertical $s_v$ | 3D $s_{3D}$ |
|---------------------|-----------------|----------------|-------------|
| 0 GCPs              | ±36 mm          | ±127 mm        | ±130 mm     |
| 1 GCPs              | ±26 mm          | ±42 mm         | ±59 mm      |
| 2 GCPs              | ±32 mm          | ±43 mm         | ±64 mm      |
| 3 GCPs              | ±18 mm          | ±33 mm         | ±49 mm      |
| 4 GCPs              | ±17 mm          | ±59 mm         | ±59 mm      |
| 5 GCPs              | ±20 mm          | ±37 mm         | ±51 mm      |
| 6 GCPs              | ±16 mm          | ±30 mm         | ±48 mm      |
| 7 GCPs              | ±16 mm          | ±30 mm         | ±46 mm      |
| 10 GCPs             | ±15 mm          | ±32 mm         | ±46 mm      |
| 13 GCPs             | ±14 mm          | ±34 mm         | ±43 mm      |

Figure 4 The configurations of various numbers of GCPs

In the overall statistics using TPF, the accuracy increases significantly with increasing the number of GCPs up to 6. This number corresponds to a requirement of the manufacturer (CPs spacing <100 m). The maximum difference of stragglers and outliers of 6 GCPs and more GCPs variants is 1%. Increasing the number of CPs over six does not significantly increase global accuracy.

6.2. TLS-based accuracy test

The results of the TLS-based test of the road data subset (vertical accuracy) and the façade data subset (horizontal accuracy) are in table 7.
Table 7. TLS-based accuracy – various numbers of GCPs

|          | horizontal $\delta H$ | vertical $\delta V$ |
|----------|------------------------|---------------------|
| 6 GCPs   | ±14 mm                 | ±7.7 mm             |
| 7 GCPs   | ±14 mm                 | ±7.4 mm             |
| 10 GCPs  | ±6.1 mm                | ±7.7 mm             |
| 13 GCPs  | ±5.9 mm                | ±7.9 mm             |

The maximum relative number of stragglers is 3 %, of outliers is 2 %. The difference of stragglers and outliers of 6 GCPs and more GCP variants is 0.5 %. Although increasing the number of GCPs over six does not significantly increase the global accuracy, local accuracy improves with increasing the number of CPs up to 10 (average spacing 50 m). This fact is evident from the façade statistics in table 7 and the visualizations of the differences in figure 5 and figure 6 (points with differences > 20 mm are marked in red).

Figure 5. TLS-based testing – road data subset (vertical accuracy)

Figure 6. TLS-based testing – façade data subset (horizontal accuracy), 6, 7, 10, and 13 GCPs subsequently
7. Conclusions
The use of CPs significantly helps to increase the MLS accuracy, especially in environments with poor GNSS conditions (e.g., urban areas). Therefore, we tested the influence of CPs configuration and number on the MLS point cloud accuracy. The accuracy evaluation is based on comparison of the tested MLS point clouds variants with reference datasets (TPF and TLS). The point clouds were divided into the façade and the road data subsets for TLS-based accuracy testing. Horizontal accuracy was tested on a façade data subset and vertical accuracy on a road data subset.

The accuracy differences of the MLS point clouds with trajectory-based CPs configuration and geometry-based CPs configuration are not statistically significant. From a practical perspective, a geometry-based CPs configuration is more advantageous in the nonlinear type of urban area such as our one. Also, the effect of changing the location of two CPs from the ground to the roof on the accuracy of the tested MLS point cloud has not been demonstrated.

In the overall statistics using TPF, the accuracy increases significantly with increasing the number of GCPs up to 6. This number corresponds to a requirement of the manufacturer (GCPs spacing <100 m). Although increasing the number of GCPs over six does not significantly increase the global accuracy, the results of the TLS-based accuracy test shows that local accuracy improves with increasing the number of CPs up to 10 (average spacing 50 m).

The achieved accuracy with a spacing of CPs 100 m is sufficient for most mapping purposes. However, the local accuracy increases with an increasing number of CPs up to an average spacing of 50 m. Future work will focus on testing the influence of trajectory accuracy on the local accuracy of 3D data.

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References
[1] Y. WANG, Q. CHEN, Q. ZHU, L. LIU, C. LI and D. ZHENG “A Survey of Mobile Laser Scanning Applications and Key Techniques over Urban Areas,” Remote Sensing, vol.11, no. 13, ISSN 2072-4292, 2019. doi:10.3390/rs11131540.
[2] O. Al-Bayari, “Mobile mapping systems in civil engineering projects (case studies),” Applied Geomatics 11, pp. 1–13, 2019. doi:10.1007/s12518-018-0222-6.
[3] G. R. Kimpton, M. Horne, D. Heslop, “Terrestrial Laser Scanning and 3D Imaging: Heritage case study – The Black Gate, Newcastle upon Tyne,” International archives of photogrammetry, Remote sensing and spatial information sciences, vol. XXXVIII, Part 5, commission V symposium, pp. 325–330, 2010.
[4] I. Puente, H. González-Jorge, J. Martínez-Sánchez, P. Arias, “Review of mobile mapping and surveying technologies,” Measurement, vol. 46, Issue 7, pp. 2127–2145, 2013. doi:10.1016/j.measurement.2013.03.006.
[5] L. Mattheuwsen, M. Bassier, and M. Vergauwen, “Theoretical accuracy prediction and validation of low-end and high-end mobile mapping system in urban, residential and rural areas, Int. Arch. Photogramm,” ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-2/W18, pp. 121–128, 2019. doi:10.5194/isprs-archives-XLII-2-W18-121-2019.
[6] A. P. Kerstinga, P. Friess, “Post-mission quality assurance procedure for survey-grade mobile mapping systems,” The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. XLI-B1, pp. 647–652, 2016. doi:10.5194/isprsarchives-XLI-B1-647-2016.
[7] P. Schäer and J. Vallet, “Trajectory Adjustment of Mobile Laser Scan Data in GPS Denied Environments,” ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. XL-3/W4, pp. 61-64, 2016. doi:10.5194/isprsarchives-XL-3-W4-61-2016.

[8] J. Nolan, R. Eckels, M. Evers, R. Singh, and M. J. Olsen, “Multi-Pass Approach for Mobile Terrestrial Laser Scanning,” ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. II-3/W5, pp. 105-112, 2015. doi:10.5194/isprsaannals-II-3-W5-105-2015.

[9] S. D. Johnson, J. S. Bethel, C. Supunyachotsakul, and S. Peterson, “Laser mobile mapping standards and applications in transportation,” (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2016/01), in Purdue University, 2016. doi:10.5703/1288284316164.

[10] M. Štroner, R. Urban, J. Seidl, T. Reindl, and J. Brouček, “Photogrammetry Using UAV-Mounted GNSS RTK: Georeferencing Strategies without GCPs,” Remote Sensing, vol. 13, no. 7, 2021. doi:10.3390/rs13071336.

[11] K. Al-Durgham, D. D. Lichti, E. Kwak, and R. Dixon, “Automated Accuracy Assessment of a Mobile Mapping System with Lightweight Laser Scanning and MEMS Sensors,” Applied Sciences, vol. 11, no. 3, 2021. doi:10.3390/app11031007.

[12] Z. Altamimi, “EUREF Technical Note 1: Relationship and Transformation between the International and the European Terrestrial Reference Systems,” 2018.

[13] Z. Altamimi, “Comparing The Performance Of Point Cloud Registration Methods For Landslide Monitoring Using Mobile Laser Scanning Data,” ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. XLII-4/W9, pp. 11-21, 2018. doi:10.5194/isprs-archives-XLII-4-W9-11-2018.

[14] P. Kalvoda, J. Nosek, M. Kuruc, T. Volarik, and P. Kalvodova, “Accuracy Evaluation and Comparison of Mobile Laser Scanning and Mobile Photogrammetry Data”, IOP Conference Series: Earth and Environmental Science, vol. 609, Dec. 2020. doi:10.1088/1755-1315/609/1/012091.