

Popovici, B., Pelorosso, R., Herbei, M.V., Sala, F., Avădanei, M. (2026). Integrating terrestrial laser scanning and GNSS for forest infrastructure design in remote areas: A case study from Săcele, Romania. *Agriculture and Forestry*, 72 (3): 25-35. <https://doi.org/10.17707/AgricultForest.72.3.02>

DOI: 10.17707/AgricultForest.72.3.02

**Bogdan POPOVICI^{*1}, Raffaele PELOROSSO²,
Mihai Valentin HERBEI³, Florin SALA³, Mihai AVĂDANEI⁴**

INTEGRATING TERRESTRIAL LASER SCANNING AND GNSS FOR FOREST INFRASTRUCTURE DESIGN IN REMOTE AREAS: A CASE STUDY FROM SĂCELE, ROMANIA

SUMMARY

Accurate topographic information is essential for civil engineering, especially in forested environments where steep terrain, dense canopy, and limited visibility complicate field measurements. Traditional Total Station (TS) surveys provide high precision but rely on unobstructed lines of sight, making them slow and difficult to apply under heavy vegetation. To overcome these limitations, this study evaluates the integration of Terrestrial Laser Scanning (TLS) with static Global Navigation Satellite Systems (GNSS) for the design of a concrete bridge along a forest road in Săcele, Braşov County, Romania. The site, characterized by mixed spruce–beech stands and restricted access, offers a representative setting for testing survey techniques in operational forest conditions. TLS data were compared with TS measurements to assess performance in terms of accuracy and operational efficiency. Results show that TLS, supported by static GNSS positioning, delivers high-resolution topography suitable for forest infrastructure design. The strong agreement between TLS and TS observations ($R^2=0.994$), combined with minimal discrepancies and the absence of systematic bias, confirms that TLS can reliably capture elevation and geometric information even where traditional methods are constrained. These findings demonstrate that TLS is a practical and robust alternative for surveying forest roads, bridges, and culverts, particularly in areas that are difficult to reach or have limited visibility. The dense and accurate point clouds produced also make TLS well suited for As-Built verification, ensuring consistency between project design and field implementation.

Keywords: 3G/4G, point cloud, GNSS, Trimble R8s, Leica ScanStation C10, forest infrastructure

¹Bogdan Popovici, Stefan cel Mare University of Suceava, Suceava, 720229, ROMANIA;

²Raffaele Pelorosso, Tuscia University, Viterbo, 01100, ITALY;

³Mihai Valentin Herbei (corresponding author: mihaiherbei@usvt.ro), Florin Sala, University of Life Sciences “King Mihai I” from Timişoara, Timişoara, 300645, ROMANIA;

⁴Mihai Avădanei, University of Petroşani, Petrosani, 332006, ROMANIA

Notes: The authors declare that they have no conflicts of interest. Authorship Form signed online.

Received:23/05/2026

Accepted:15/07/2026

INTRODUCTION

Topography is a fundamental component of civil engineering, providing the spatial framework required to design, plan, and position infrastructure. In forested landscapes—where irregular terrain, dense vegetation, and limited visibility hinder field operations—high-quality topographic information becomes even more critical. It supports safer routing of roads and utilities, reduces construction risks, and ensures that projects align effectively with the natural environment throughout their life cycle (Pădeanu *et al.*, 2024). Traditional surveys often rely on the Total Station (TS), that combines electronic distance and angle measurements with precise optical targeting to pinpoint positions in the field. As a result, TS measurements can be slow, costly, and difficult to deploy under such conditions (Vosselman and Maas, 2010).

Recent advances in Terrestrial Laser Scanning (TLS) offer a compelling solution. TLS sensors record millions of georeferenced points in minutes, delivering high-resolution, non-contact data with minimal field staff (Mrics *et al.*, 2005). The technology has already proved valuable for road-corridor design and surface-wear monitoring (Akgul *et al.*, 2017). To anchor these dense point clouds to national mapping frameworks, Global Navigation Satellite Systems (GNSS) supply the control points needed for robust georeferencing. Multi-constellation receivers (GPS, GLONASS, BeiDou, Galileo) enhance positional accuracy and signal availability, even in inaccessible terrain (Valbuena *et al.*, 2010; Lee *et al.*, 2020) and large areas (Shan and Toth, 2018). The use of GPS in kinematic mode for the control of forest roads has been demonstrated as a practical and efficient approach for field survey operations (Rodriguez-Solano and Peces, 2002). In forest inventory applications, mobile TLS has also enabled the automatic estimation of tree positions and stem diameters without requiring precise positioning of the scanner itself (Oveland *et al.*, 2017). Under closed canopy, however, GNSS performance deteriorates: multipath reflections, signal interruptions and limited sky visibility inflate positional error (Deckert *et al.*, 1996; Bakula *et al.*, 2006). Accuracy also varies seasonally, improving when foliage is absent (Sigrist *et al.*, 1999; Abdi *et al.*, 2014; Tomaščík *et al.*, 2017). Along forest road corridors, canopy openings suitable for reliable GNSS fixes are scarce (Lepoglavec *et al.*, 2023). In many forest-infrastructure surveys, continuous real-time GNSS is therefore replaced by static observations or post-processing, especially where mobile-network coverage is lacking. Earlier studies have shown that GNSS point accuracy under closed forest canopy is strongly influenced by multipath effects, signal attenuation, and reduced satellite geometry, with errors typically ranging from a few centimetres to several decimetres depending on canopy density and receiver type (Næsset, 1999). Static GNSS is a high-precision positioning method based on fixed receivers and post-processed satellite observations, commonly used to obtain centimetre-level coordinates (CHCNAV, 2025; Correa-Muñoz, 2018). In mountain forests, well-designed roads improve extraction efficiency, wildfire response and ecological performance when their density and layout are optimised (Petković and Potočnik,

2018; Krč and Beguš, 2013; Laschi *et al.*, 2019). Accordingly, the aim of this research is to evaluate whether a TLS workflow, georeferenced with static GNSS control points, can provide topographic data of sufficient accuracy for forest-road and bridge design under dense canopy, limited line-of-sight and lack of 3G/4G coverage. The significance of the study lies in demonstrating a practical field workflow for remote forest infrastructure projects, where conventional TS surveys are often constrained by vegetation, terrain and the need for repeated instrument set-ups.

MATERIAL AND METHODS

The study site is located in Săcele, Braşov County, Romania, at 452103.716 N and 554806.316 E (Fig. 1). The area is managed by the Săcele Local Forest Authority, lies at about 816 m above sea level, and includes mixed deciduous and coniferous stands at the harvesting stage. The analysed location corresponds to a planned concrete bridge over the Gârcini Stream, where dense canopy, steep terrain and the lack of 3G/4G coverage required post-processed GNSS positioning instead of real-time ROMPOS corrections.

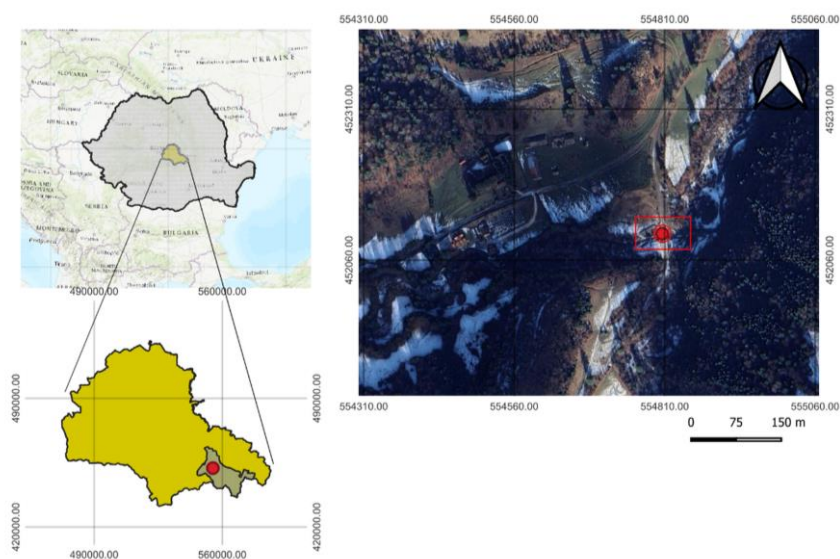


Figure 1. Study area – Romania, Braşov County. Location: Municipality of Săcele

The workflow combined TLS and TS scanning, GNSS control point acquisition, point-cloud processing, georeferencing and accuracy assessment (Fig. 2), producing an integrated 3D model for bridge design and validation. TLS data were acquired with a Leica ScanStation C10 from 13 stations, positioned to cover the forest road and bridge area with sufficient overlap. Medium-resolution scans and 360° HDR images were collected to support point-cloud interpretation and alignment.

Two static GNSS control points, point2000 and point3000, were measured with a Trimble R8s receiver and used to georeference the TLS point cloud in Stereo 70. Although the baseline length was about 34 km, one-hour sessions were accepted because PDOP remained below 4, at least four satellites were continuously tracked, and both baselines converged to FIXED ambiguity solutions (Bos *et al.*, 2015; Correa-Muñoz, 2018). The main characteristics of the GNSS positioning methods considered in this study are summarized in Table 1.



Figure 2. Integrated workflow for TLS, GNSS and TS data acquisition, processing and validation (Source: developed by the authors)

Table 1. GNSS positioning methods and main characteristics (Source: Bos *et al.*, 2015, p. 169)

Method	Application Conditions	Accuracy	Observation Duration	Advantages	Disadvantages	Applications
STATIC	Large baselines over 10 km, dual-frequency receiver (L1,L2)	+/- (5 cm + 1 ppm)	30 min–1 h	High and homogeneous accuracy over large areas	Long observation time	Fundamental geodetic networks
RTK	Special logistics baselines under 35–40 km	+/- (1 cm + 2 ppm)	10–15 sec	Real-time positioning with good accuracy	Receivers with special software	Support and survey networks

The recommended observation durations according to baseline length are presented in Table 2.

Table 2. GNSS session duration depending on vector length and observation time (adapted from Păunescu, 2012, as cited in Bos *et al.*, 2015, p. 188)

Method	No. of Satellites (GDOP < 8)	Vector Length Between	Session Duration (Day)	Session Duration (Night)
STATIC	Minimum 4	15–30 km	1–2 hours	1 hour
STATIC	Minimum 4	over 30 km	2–3 hours	2 hours

The GNSS antenna was centred with a bipod, antenna height and settings were recorded, and a 10° minimum satellite elevation angle was used. The two control points were placed to ensure stability and visibility for georeferencing (Fig. 3), while antenna mounting height was controlled because it affects GNSS accuracy under forest canopy (Brach and Zasada, 2014). TS measurements were acquired with a Trimble S5 and used as ground-truth elevations for validating the TLS-derived surface. Observations were referenced to the same coordinate system defined by GNSS control points 2000 and 3000. A comparative overview of the three surveying techniques used in this research is presented in Table 3.

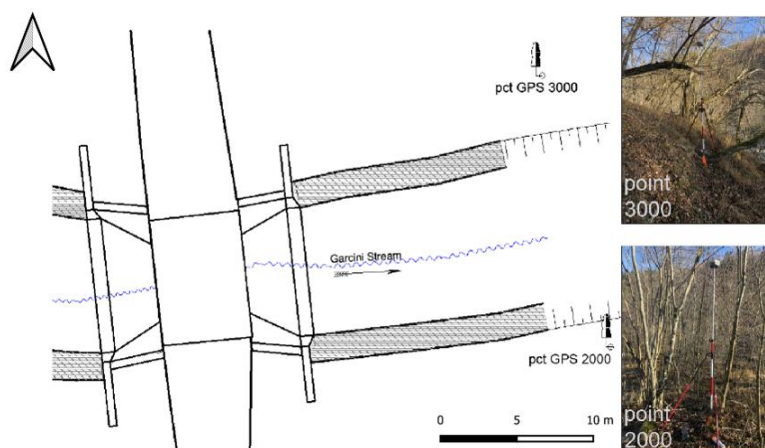


Figure 3. Static GNSS control points used for TLS data georeferencing

Accuracy was assessed by comparing TLS-derived elevations with nine nearby TS points located in the road-ramp and bridge transition area (Fig. 4). Because the two datasets did not perfectly coincide planimetrically, RMSE indicators were used to quantify the resulting discrepancies (Wolf and Ghilani, 2012; Van Sickle, 2015). Altimetric accuracy was evaluated using the Mean Absolute Error (MAE), the Root Mean Square Error (RMSE), and the coefficient of determination (R^2). MAE expresses the average absolute error, RMSE is more sensitive to larger deviations and possible outliers, while R^2 indicates the degree of agreement between TLS-derived and TS reference elevations (Chai and Draxler, 2014; Willmott and Matsuura, 2005).

Table 3. Comparative characteristics of TLS, TS, and static GNSS methods in forest infrastructure surveys

Parameter	TLS	TS	GNSS static
Measurement principle	Laser-based point cloud acquisition	Optical angle and distance measurements	Satellite-based positioning
Typical accuracy	2–4 cm	1–2 cm	2–10 cm
Data density	Very high	Low	Very low
Acquisition speed	High	Moderate	Low
Performance under forest canopy	Good	Limited by line-of-sight	Affected by signal obstruction
Requirement for direct line-of-sight	No	Yes	Partial sky visibility required
Primary output	Dense 3D point cloud	Discrete topographic points	Georeferenced control points
Adaptability to complex terrain	Excellent	Moderate	Good
Primary role in this study	Surface modelling	Accuracy validation	Georeferencing

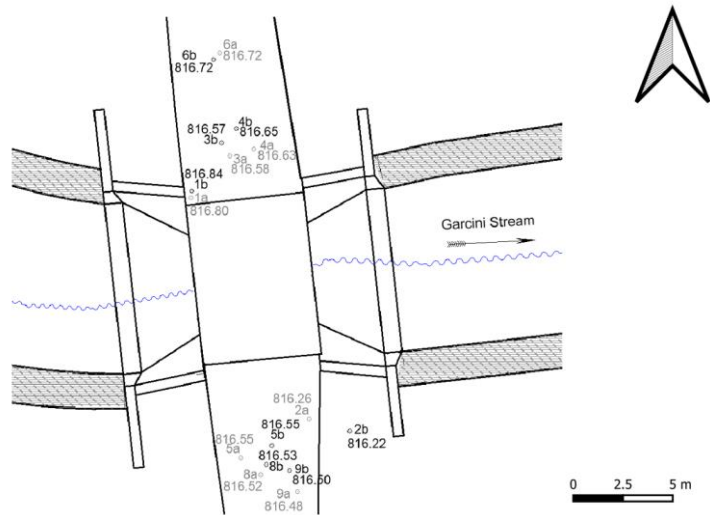


Figure 4. Spatial distribution of the nine TLS–TS point pairs (1a–9a and 1b–9b) used in the elevation accuracy analysis

RESULTS AND DISCUSSION

The registration of the TLS network produced 13 setups, 20 valid links, a network strength of 26%, and an average overlap of 15%, values consistent with dense forest conditions where vegetation reduces inter-station visibility.

According to Leica Geosystems (2020), the Bundle Error falls within the high-accuracy threshold of 0.015 m, supporting the reliability of the final registration.

Static GNSS processing produced FIXED solutions for both baselines (Table 4). Horizontal precisions of 0.0295 m and 0.0222 m and vertical precisions close to 0.096 m were adequate for georeferencing the TLS point cloud in this bridge-design context. Figure 5 compares the elevation profiles obtained from TLS and Total Station measurements, and a strong linear relationship between both measurement techniques is further illustrated in Figure 6. The comparison between the elevations measured by Total Station and those derived from TLS is presented in Table 5.

Table 4. Static GNSS baseline results for control points 2000 and 3000

Observation (From–To)	Solution Type	Horizontal Precision (m)	Vertical Precision (m)	Ellipsoidal Distance (m)	Height Difference (m)
Permanent station →2000	Fixed	0.0295	0.0952	34,202.217	271.038
Permanent station →3000	Fixed	0.0222	0.0966	34,004.117	271.786

Table 5. Comparison of altitude measurements between selected TS and TLS points

No.	Point ID (TS)	Z (TS)	Point ID (TLS)	Z (TLS)	Residual	Std. Residual
1	1a	816.84	1b	816.80	0.04	1.75
2	2a	816.22	2b	816.26	-0.04	-1.75
3	3a	816.57	3b	816.58	-0.01	-0.44
4	4a	816.65	4b	816.63	0.02	0.87
5	5a	816.55	5b	816.55	0.00	0.00
6	6a	816.72	6b	816.72	0.00	0.00
7	7a	815.85	7b	815.83	0.02	0.87
8	8a	816.53	8b	816.52	0.01	0.44
9	9a	816.50	9b	816.48	0.02	0.87

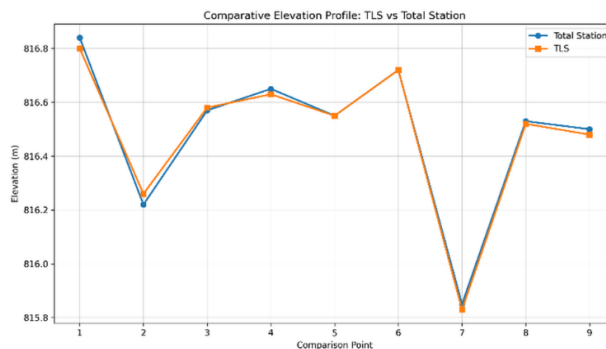


Figure 5. Comparative elevation profile derived from TLS and TS measurements

Residual plots and histograms (Figs. 7-9) show a compact, nearly symmetric distribution centred close to zero, indicating no relevant systematic bias.

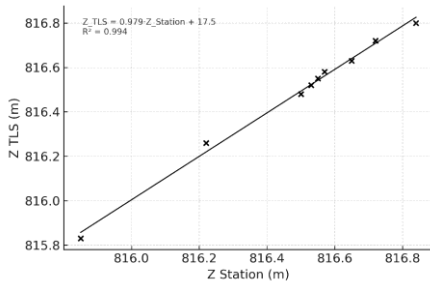


Figure 6. Linear Relationship Between TLS-Derived and TS Elevations.

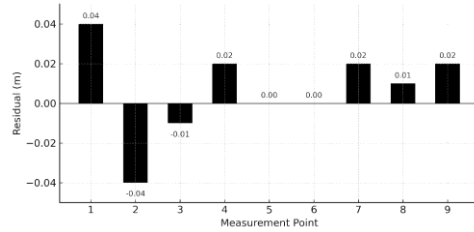


Figure 7. Distribution of residuals between the TLS-derived elevations and the values predicted by the regression model.

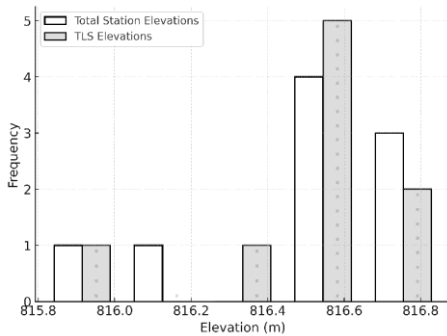


Figure 8. Histogram of Elevations

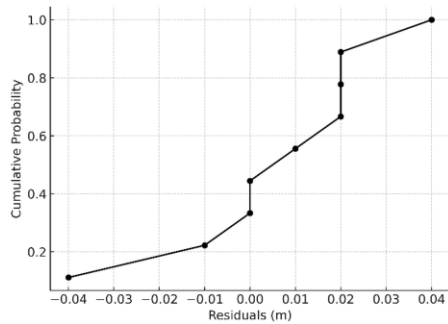


Figure 9. Cumulative Distribution of Residuals

Table 6 summarises the statistical indicators: MAE=0.0178 m, RMSE=0.0226 m, maximum residual=0.04 m, and $R^2=0.994$.

Table 6. Statistical indicators describing the agreement between TLS and TS measurements.

Statistical Indicator	Value
Mean Absolute Error (MAE)	0.0178 m
Root Mean Square Error (RMSE)	0.0226 m
Maximum Residual	0.0400 m
Minimum Residual	-0.0400 m
Coefficient of Determination (R^2)	0.994
Mean Residual Bias	≈ 0.0067 m
Residual Distribution	Approximately normal

These results confirm a high level of agreement between TLS and TS measurements. The centimetric errors are acceptable for forest road and bridge design, especially considering the difficult terrain, dense vegetation and lack of real-time GNSS corrections. The agreement obtained is operationally important because it shows that TLS can provide the spatial detail required in road-bridge transition zones, while TS remains an independent validation method. Comparable studies confirm the usefulness of TLS and GNSS for forest roads and infrastructure monitoring under difficult conditions (Akgul *et al.*, 2017; Lichti and Jamtsho, 2006; Yurtseven *et al.*, 2019; Correa-Muñoz, 2018; Valbuena *et al.*, 2010; Lovrinčević *et al.*, 2025). From an operational standpoint, TLS reduces the dependence on continuous lines of sight and enables rapid data acquisition in complex terrain. The resulting dense point cloud can support design, As-Built verification, drainage assessment and future monitoring of forest infrastructure.

In qualitative operational terms, the TLS survey reduced the expected field effort compared with a conventional TS-only survey. The 13 TLS setups could be completed within one morning, whereas a comparable TS survey in the same forested bridge area would require repeated line-of-sight checks, more instrument relocations and point-by-point observations, potentially extending field work over several days. From an operational perspective, the higher initial investment associated with TLS equipment may be compensated by shorter field campaigns, reduced labour requirements and the availability of dense three-dimensional datasets that can subsequently support design verification, As-Built documentation and future infrastructure monitoring without additional field surveys. The main limitations are the small validation sample, the single study site and the absence of a complete cost-benefit comparison with Unmanned Aerial Vehicle (UAV) photogrammetry, mobile Light Detection and Ranging (LiDAR) or other multi-sensor workflows (Lovrinčević *et al.*, 2025).

CONCLUSIONS

The study demonstrates that integrating TLS with static GNSS is a practical and reliable solution for forest infrastructure design in remote, densely forested areas. The method delivered dense topographic information, accurate georeferencing and strong agreement with TS reference elevations (MAE=1.78 cm, RMSE=2.26 cm, $R^2=0.994$), without systematic bias. It can support bridge, culvert and forest-road design, as well as As-Built verification, provided that registration, GNSS post-processing and datum transformation are carefully controlled. The practical value of the workflow is particularly relevant where access, canopy closure and lack of real-time corrections make conventional field surveying slower and less flexible.

ACKNOWLEDGEMENTS

The authors declare no specific funding for this research. The authors wish to thank Professor Olivier Bouriaud for his supervision and guidance throughout this study.

REFERENCES

- Abdi, E., Mariv, H. S., Deljouei, A., & Sohrabi, H. (2014). Accuracy and precision of consumer-grade GPS positioning in an urban green space environment. *Forest science and technology*, 10(3), 141–147. <https://doi.org/10.1080/21580103.2014.887041>
- Akgul, M., Yurtseven, H., Akburak, S., Demir, M., Cigizoglu, H. K., Ozturk, T., ... & Akay, A. O. (2017). Short term monitoring of forest road pavement degradation using terrestrial laser scanning. *Measurement*, 103, 283–293. doi.org/10.1016/j.measurement.2017.02.045
- Bakuła, M., & Oszczak, S. (2006). Experiences of RTK positioning in hard observational conditions during Nysa Kłodzka River project. *Reports on Geodesy*, 71–79.
- Bos, N., Iacobescu, O., Bos, N.C., (2015). *Digital Topography*. C.H. Beck Publishing, Bucharest, Romania.
- Brach, M., & Zasada, M. (2014). The effect of mounting height on GNSS receiver positioning accuracy in forest conditions. *Croatian Journal of Forest Engineering: Journal for Theory and Application of Forestry Engineering*, 35(2), 245–253.
- Chai, T., & Draxler, R. R. (2014). Root mean square error (RMSE) or mean absolute error (MAE)?—Arguments against avoiding RMSE in the literature. *Geoscientific model development*, 7(3), 1247–1250. doi.org/10.5194/gmd-7-1247-2014
- CHCNAV, (2025). Why GNSS static measurements are crucial. CHC Navigation. Available online: <https://geospatial.chcnv.com>
- Correa-Muñoz, N. A., & Cerón-Calderón, L. A. (2018). Precision and accuracy of the static GNSS method for surveying networks used in Civil Engineering. *Ingeniería e Investigación*, 38(1), 52–59. doi.org/10.15446/ing.investig.v38n1.64543
- Deckert, C., Bolstad, P.V., (1996). Forest canopy, terrain, and distance effects on global positioning system point accuracy. *Photogrammetric Engineering and Remote Sensing* 62: 317–321.
- Krč, J., & Beguš, J. (2013). Planning forest opening with forest roads. *Croatian Journal of Forest Engineering: Journal for Theory and Application of Forestry Engineering*, 34(2), 217–228.
- Laschi, A., Foderi, C., Fabiano, F., Neri, F., Cambi, M., Mariotti, B., & Marchi, E. (2019). Forest road planning, construction and maintenance to improve forest fire fighting: a review. *Croatian Journal of Forest Engineering: Journal for Theory and Application of Forestry Engineering*, 40(1), 207–219.
- Lee, W. J., Yu, W. S., Choi, Y. S., & Yoon, H. S. (2020). Improvement of Network RTK Positioning in Urban and Forest Land Using BeiDou. *J. Digit. Content Soc*, 21, 2057–2064. doi.org/10.9728/dcs.2020.21.11.2057
- Leica Geosystems, (2020). *Leica Cyclone REGISTER 360 - Quick Start Guide (v1.5)*. Leica Geosystems AG, Heerbrugg, Switzerland. Available online: <https://leica-geosystems.com>
- Lepoglavec, K., Šušnjar, M., Pandur, Z., Bačić, M., Kopssek, H., & Nevečerel, H. (2023). Correct Calculation of the Existing Longitudinal Profile of a Forest/Skid Road Using GNSS and a UAV Device. *Forests*, 14(4), 751. [doi: 10.3390/f14040751](https://doi.org/10.3390/f14040751)

- Lichti, D. D., & Jamtsho, S. (2006). Angular resolution of terrestrial laser scanners. *The photogrammetric record*, 21(114), 141–160. doi.org/10.1111/j.1477-9730.2006.00367.x
- Lovrinčević, M., Papa, I., Janeš, D., Hodak, L., Pentek, T., & Đuka, A. (2025). New Possibilities of Field Data Survey in Forest Road Design. *Sensors*, 25(13), 4192. doi.org/10.3390/s25134192
- Mrics, S. W., Clegg, P., & Jones, R. (2005). Combining terrestrial laser scanning, RTK GPS and 3D Visualisation: Application of optical 3D measurement in geological exploration. In *7th Conference on Optical 3D Measurement Techniques*, Vienna (pp. 3-5).
- Næsset, E. (1999). Point accuracy of combined pseudorange and carrier phase differential GPS under forest canopy. *Canadian Journal of Forest Research*, 29(5), 547-553. doi.org/10.1139/x99-021
- Oveland, I., Hauglin, M., Gobakken, T., Næsset, E., & Maalen-Johansen, I. (2017). Automatic estimation of tree position and stem diameter using a moving terrestrial laser scanner. *Remote Sensing*, 9(4), 350. doi: 10.3390/rs9040350
- Pădeanu, M.A., Șmuleac, I.L., Șmuleac, A., (2024). The importance of topography in the execution of civil construction works. *Research Journal of Agricultural Science* 56(3).
- Petković, V., & Potočnik, I. (2018). Planning forest road network in natural forest areas: a case study in northern Bosnia and Herzegovina. *Croatian Journal of Forest Engineering: Journal for Theory and Application of Forestry Engineering*, 39(1), 45-56.
- Rodríguez-Solano Suárez, R., & Peces Peña, J. L. (2002). Aplicación del sistema GPS en modo RTK para el control de caminos forestales. *Foresta (España)*, (18).
- Shan, J., & Toth, C. K. (Eds.). (2018). *Topographic laser ranging and scanning: principles and processing*. CRC press. doi: 10.1201/9781315154381
- Sigrist, P., Coppin, P., & Hermy, M. (1999). Impact of forest canopy on quality and accuracy of GPS measurements. *International journal of remote sensing*, 20(18), 3595-3610. doi: 10.1080/014311699211228
- Tomašćik Jr, J., Tomašćik Sr, J., Saloň, Š., & Piroh, R. (2017). Horizontal accuracy and applicability of smartphone GNSS positioning in forests. *Forestry: An International Journal of Forest Research*, 90(2), 187-198. doi: 10.1093/forestry/cpw031
- Valbuena, R., Mauro, F., Rodríguez-Solano, R., & Manzanera, J. A. (2010). Accuracy and precision of GPS receivers under forest canopies in a mountainous environment. *Spanish journal of agricultural research*, 8(4), 1047-1057. doi.org/10.5424/sjar/2010084-1242
- Van Sickle, J. (2015). *GPS for land surveyors* (4th ed.). CRC Press. doi: 10.1201/b18480
- Vosselman, G., & Maas, H. G. (2010). *Airborne and terrestrial laser scanning*. Whittles publishing.
- Willmott, C. J., & Matsuura, K. (2005). Advantages of the mean absolute error (MAE) over the root mean square error (RMSE) in assessing average model performance. *Climate research*, 30(1), 79-82. doi.org/10.3354/cr030079
- Wolf, P.R., Ghilani, C.D., (2012). *Elementary Surveying: An Introduction to Geomatics*, 13th ed. Pearson, Boston, USA.
- Yurtseven, H., Akgul, M., Akay, A. O., Akburak, S., Cigizoglu, H. K., Demir, M., ... & Eksi, M. (2019). High accuracy monitoring system to estimate forest road surface degradation on horizontal curves. *Environmental Monitoring and Assessment*, 191(1), 32. doi: 10.1007/s10661-018-7155-8