Research Journal of Agricultural Science, 58 (1), 2026; ISSN: 2668-926X;

http://doi.org/10.59463/RJAS.2026.1.28

LOCAL ATMOSPHERIC REFRACTION IMPACT ASSESSMENT ON TOTAL STATION MEASUREMENTS IN FOREST ENVIRONMENTS

Bogdan POPOVICI[1], (ORCID:0009-0002-0232-2794); Mihai Valentin HERBEI[2,3], (ORCID :0000-0002-3884-3658); Mihai AVĂDANEI[2], Florin SALA[3], (ORCID :0000-0002-8876-590X), Olivier BOURIAUD[4]
[1]Ștefan cel Mare University of Suceava, 13 Universitatea Street, Suceava, Romania
[2]University of Petroșani, 20 University Street, Petroşani, Romania
[3]University of Life Sciences 'King Mihai I' from Timisoara, 119 Calea Aradului, Timisoara, Romania
Corresponding author: mihaiherbei@usvt.ro

Abstract. *This study analyzed the influence of environmental conditions on the accuracy of total station measurements in forest environments, with a focus on the effects of local atmospheric refraction and observation conditions under dense canopy. Data was collected during two measurement campaigns (16/06/2023 and 20/06/2023), using the same instrumental setup and measurement geometry from a GNSS-determined station point. The results were validated indirectly through independent total station measurements from a separate GNSS-determined station located outside the forest perimeter, thereby ensuring stable reference conditions and eliminating GNSS signal degradation under the canopy. The analyzed point, physically established in the field, was identified as point 3000 and point 2000 in the two campaigns, representing the same physical location. The comparative analysis revealed significant planimetric deviations of 0.244 m and 0.670 m, corresponding to exceedances of 61–168 times the nominal instrument accuracy. The directional distribution of errors and their variability between campaigns indicated a systematic environmental influence, associated with local thermal gradients under the forest canopy. Through the systematic exclusion of instrumental, station, orientation and transformation errors, the results suggested that the primary source of deviations was local atmospheric refraction, amplified by the interaction of the EDM signal with the forest environment. This study highlights the limitations of standard atmospheric models used in total stations and emphasizes the need to adapt measurement strategies according to environmental conditions.*

Keywords: *atmospheric refraction, total station, beech forest, 360° prism, Trimble S5, forest surveying, Stereo70, GNSS verification*

INTRODUCTION

Modern total stations have been the main instruments used for precision topographic surveys, including in forest environments (forest cadaster, management, logging routes). According to the manufacturer's specifications (TRIMBLE INC., N.D.), the Trimble S5 total station, with a nominal accuracy of 5″ angular and 2 mm + 2 ppm for distances, has enabled the achievement of positional errors of less than 0.005 m under standard conditions. However, the specific conditions of the forest environment have introduced sources of error not accounted for by standard atmospheric models (LIENHART, 2017). Atmospheric refraction is the deviation of an electromagnetic ray caused by variations in atmospheric conditions (KAHMEN AND FAIG, 1988; BRUNNER, 1984). In geodetic practice, a standard value of the refractive index $k \approx 0.13–0.14$, representative of average atmospheric conditions, has been frequently used (KAHMEN AND FAIG, 1988; BRUNNER, 1984). HIRT ET AL. (2010) demonstrated that this coefficient can vary significantly under real-world conditions, and BASELGA (2014) highlighted that using a constant value can lead to errors under non-standard conditions. Atmospheric refraction is a complex phenomenon, influenced by variations in environmental conditions, which can affect geodetic measurements under real-world conditions (HIRT et al., 2010; BASELGA, 2014). In forest environments, the use of 360° prisms can introduce cyclic errors in the millimeter or centimeter range (LACKNER AND LIENHART, 2016; LIENHART, 2017). GNSS measurements have shown significant limitations under dense canopy (PIRTI ET AL., 2010; BAKULA ET AL., 2009), with errors of up to several meters having been reported (TOMAŠTÍK ET AL., 2021; FENG ET AL., 2021), and errors of approximately 0.7 m even for high-precision systems (KAARTINEN ET AL., 2015). In this context, total stations have remained the reference method for precise measurements in forest environments (VALBUENA ET AL., 2010). In this study, significant planimetric deviations of 0.244 m and 0.670 m were investigated at points located in a beech forest (*Fagus sylvatica* L.), approximately 53.6 m from the station, under conditions of partially obstructed line of sight due to vegetation and direct sunlight. By applying a systematic exclusion methodology, the results suggested the existence of complex environmental effects, possibly associated with localized atmospheric refraction, as well as with other signal propagation phenomena under conditions of dense forest canopy. The aim of the study was to identify and explain the causes of the planimetric errors observed in total station measurements in forest conditions.

MATERIAL AND METHODS

Study area

The study was conducted in Brașov County, Romania, in a forest area dominated by beech (*Fagus sylvatica* L.), characterized by a dense canopy. The coordinates were determined using the national Stereo70 system, based on the Krasowski ellipsoid and the Pulkovo 1942(58) projection. Station point 1002 has the following coordinates: N= 458,289.9345 m, E= 546,489.3855 m, Z= 681.2250 m. The area features hilly terrain and continuous forest cover, with dense foliage during the measurement period (June).

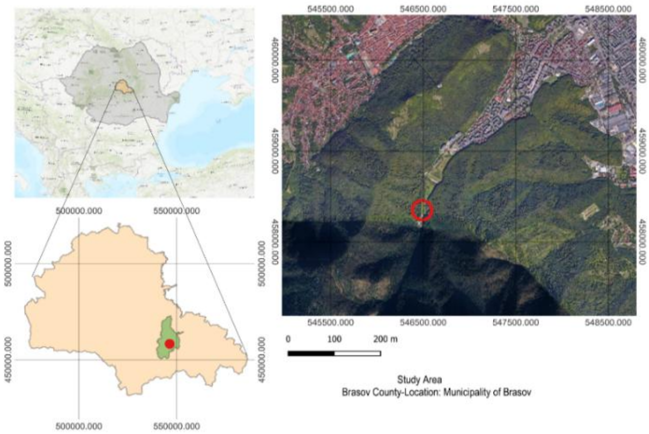


Figure 1. Study area – Brașov County, Romania. Beech forest perimeter including the measurement area

Equipment used

The measurements were taken using a Trimble S5 total station with a 360° prism. The atmospheric parameters were entered according to the values measured in the field, with the refractive index kept constant. A 360° prism, known for its orientation-dependent cyclic errors (Lackner and Lienhart, 2016), was used , mounted on a survey stake at a height of 1.80 m during session C1 (16/06) and 1.50 m during session C2 (20/06). The atmospheric parameters entered were: for session C1 (16.06) – 931.80 mbar, 19.5°C and 21.6 ppm; for session C2 (20.06) – 938.30 mbar, 25.6°C and 25.0 ppm, with the refractive index being maintained at the instrument's default value (Trimble Inc., n.d.), although the literature recommends correcting it under real field conditions (INGENSAND, 2008). Orientation was achieved by targeting point 5000, with an accuracy of ±0.0015 gon for angles and ±0.002 m for distance. Point 82 was determined to be approximately 56.7 m away, with an accuracy of ±0.004 m. This approach is supported by the literature, which shows that RTK positioning under forest canopy does not provide the necessary accuracy for topographic surveys (PIRTI ET AL., 2010; KAARTINEN ET AL., 2015).

Figure 2. Equipment used: Trimble S5 5″ total station (left); prism pole with 360° prism (centre); prism pole with 360° prism and Trimble R8s GNSS receiver (right).

Measurement periods

Both campaigns (C1 and C2) were conducted from the same station point (1002), using the same orientation line of sight and the same equipment. The coordinates were transformed by translation and rotation, using reference points with known coordinates (KAHMEN AND FAIG, 1988). Campaign V1 (verification campaign – 24/06/2023) was carried out for the independent verification of the positions, using GNSS measurements taken from outside the forest perimeter.

Table 1

Overview of measurement campaigns and field observations

Campaign	Data	Weather conditions	Points measured	Remarks
C1	16/06/2023	Morning, clear sky	465 points measured	Deviation at point 3000: 0.244 m
C2	20/06/2023	Morning, clear sky	280 points radiated	Deviation at point 2000: 0.670 m
V1	24/06/2023	Overcast, after rainfall		Determination of point 82 (reference)

Table 2

Control point coordinates in the Stereo70 coordinate system

Point	Campaign	N (m)	E (m)	Z (m)	Dist. from 1002 (m)	Type
1002	C1/C2	458289.9345	546489.3855	681.225	—	Fixed station
3000	C1- 6.06	458342.6852	546479.8791	680.885	53.63	Total station det.
2000	C2-20.06	458342.7460	546480.3020	680.882	53.89	Total station det.
82	V1-24.06	458342.6720	546479.6360	680.850	53.61	Total station det.

Point 82 was determined during campaign V1 from station 5002, using a line of sight oriented towards point 5000, thereby providing an indirect verification through re-determination from a different station compared to the measurements taken during campaigns C1 and C2.

Analysis methodology

The term "localized" refers to the variation in atmospheric conditions along the line of sight (~50 m) within the forest environment. Errors were assessed by comparing the coordinates of points 3000 (campaign C1 – 16/06/2023) and 2000 (campaign C2 – 20/06/2023) with the coordinates of point 82 (campaign V1 – 24/06/2023). Points 3000 and 2000 represent the same physical bolt, determined independently in the two campaigns; point 82 was re-determined from outside the forest area and constitutes the independent reference value. A graphical representation of the measurements is shown in Figure 3, where campaign C1 is depicted in blue, campaign C2 in magenta, and the independent verification V1 in black.

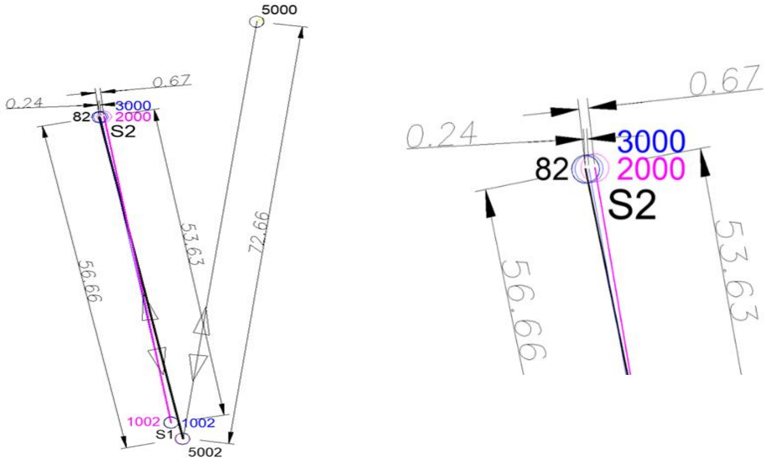


Figure 3. Equipment used**:** Trimble S5 5″ total station (left); 360° prism mounted on a pole (centre); 360° prism on a pole with Trimble R8s GNSS receiver (right).

The analysis followed the principles of precision geodesy (KAHMEN AND FAIG, 1988), by verifying the influence of the instrument, atmospheric parameters and geometric configuration. To interpret the deviations, the classical curvature–refraction relationship was used (BRUNNER, 1984; KAHMEN AND FAIG, 1988):

$$\varepsilon = \frac{(1-k)*S_1}{2R} \tag{1}$$

where S = horizontal distance, R = mean Earth radius, k = refractive index.

This relationship describes the vertical deviation under homogeneous conditions; under non-homogeneous conditions (forest environment), lateral variations in the refractive index can induce horizontal deviations – explaining the planimetric nature of the observed errors. In forest environments, EDM signal propagation can be influenced not only by atmospheric parameters but also by interaction with vegetation, which can introduce additional effects such as signal scattering, multipath reflections and partial obstruction of the line of sight.

RESULTS AND DISCUSSION

Analysis of errors at the control points

The complete comparative results are presented in Table 3. The values show that the recorded errors significantly exceed the nominal accuracy of the Trimble S5 total station (Trimble Inc., n.d.), a value adapted to σ = 0.004 m under real field conditions for a distance of approximately 53.60 m. For both points analyzed, the deviations are more pronounced in the east direction, indicating a systematic bias in the line-of-sight direction. This trend suggests the influence of local atmospheric effects, generated by the lighting conditions at the time of the measurements (09:31 EEST), when solar radiation can cause variations in air temperature under the forest canopy (Hirt et al., 2010). The exceedance factor was determined as the ratio between the observed error (Δ) and the nominal accuracy of the instrument (σ), according to the formula:

$$F = \Delta / \sigma \qquad (2)$$

where Δ represents the observed error, and σ represents the nominal accuracy of the instrument.

For the Trimble S5 total station, the manufacturer specifies the distance accuracy as ±(2 mm + 2 ppm). For the distance analyzed (~53.60 m), this corresponds to a theoretical value of approximately 0.002 m. In the specialist literature, the accuracy specified by the manufacturer represents an accuracy determined under controlled laboratory conditions and standard atmospheric conditions. Under real-world field conditions, the accuracy of measurements is influenced by additional factors such as line of sight through vegetation and the type of reflector (Lienhart, 2017), as well as by atmospheric variability (Ingensand, 2008). In this context, for a realistic assessment of errors, an adjusted precision value of σ = 0.004 m was adopted. This value reflects the combined influence of line of sight through vegetation, the use of a 360° prism, and the variability of atmospheric conditions on the precision of the measurements.

For the points investigated, the following values were obtained:

$$F_1 = 0.244 / 0.004 = 61 \qquad (3)$$

$$F_2 = 0.670 / 0.004 = 167.50 \approx 168 \qquad (4)$$

These values indicate significant exceedances of the instrument's specified performance.

Table 3

Error assessment of control points based on indirect verification via re-determination
from an independent station (point 82)

Point	Date	ΔN (m)	ΔE (m)	ΔZ (m)	ΔXY (m)	ppm	Factor vs. S5 accuracy
3000	16/06/2023	+0.0132	+0.2431	+0.0350	0.2435	4543	×61
2000	20/06/2023	+0.0740	+0.6660	+0.0320	0.6701	12438	×168

The planimetric deviation ΔXY was calculated based on the components ΔN and ΔE, using the formula:

$$\Delta XY = \sqrt{(\Delta N^2 + \Delta E^2)} \qquad (5)$$

where: ΔXY represents the planimetric deviation, and ΔN and ΔE represent the coordinate differences in the North and East directions.

Systematic exclusion of alternative sources of error

Instrumental error – The accuracy of the Trimble S5 total station (±(2 mm + 2 ppm)) corresponds, for a distance of ~50 m, to an error of approximately 0.002 m. The observed values (0.244–0.670 m) are 61–168 times greater, which clearly indicates that the error does not originate from the instrument (TRIMBLE INC., N.D.).

Station and orientation error - Verification performed on 06/24/2023 confirms that the station position and orientation were correct. If there had been an orientation error, it would have affected all points in a similar way. In contrast, the large differences between C1 (0.244 m) and C2 (0.670 m), under the same geometric conditions, indicate that the primary influence is due to the surrounding environment.

Standard atmospheric refraction – Although the classical atmospheric refraction model described by BRUNNER(1984) explains the deviation of the beam as a function of atmospheric conditions and distance, for sight lengths of ~50 m, the theoretical effect is submillimetric and insufficient to explain the observed errors. This suggests that classical models do not fully describe signal propagation in the environment under analysis. Analysis of the 9 common points (ΔXY: 0.010–0.083 m, mean 0.039 m, RMSE ≈ 0.05 m), compared to the significantly larger deviations recorded at points 3000 and 2000, indicates that the errors are not systematic in nature, but are distributed unevenly and have a localized character. Under these conditions, the propagation of the EDM signal through vegetation can generate local refraction, scattering and multiple reflection effects, which cannot be corrected by standard atmospheric models. (LIENHART, 2017; ARTESE AND PERRELLI, 2018)."

Table 4

Comparison of coordinate deviations (ΔN, ΔE, ΔZ, ΔXY) for common points (C1–C2)

Points C1/C2	ΔN (m)	ΔE (m)	ΔZ (m)	ΔXY (m)	Assessment
139/120	+0.010	-0.002	-0.002	0.010	Within tolerance
20/2014	-0.069	-0.046	-0.018	0.083	Attention
19/500	+0.044	+0.045	+0.004	0.063	Attention
251/175	-0.017	-0.003	-0.017	0.017	Within tolerance
440/188	-0.015	+0.017	-0.003	0.023	Within tolerance
412/270	-0.030	+0.048	+0.016	0.057	Attention
413/268	-0.014	+0.016	-0.009	0.021	Within tolerance
414/266	-0.023	-0.029	-0.008	0.037	Within tolerance
323/219	+0.008	+0.036	-0.017	0.037	Within tolerance

For a detailed interpretation of the error behavior, the values in Table 4 were analyzed statistically, and the results are presented in Table 5. The deviations determined for the 9 common points, with ΔXY values ranging from 0.010 m to 0.083 m (mean 0.039 m), are significantly smaller than the deviations observed at points 3000 (0.244 m) and 2000 (0.670 m). Statistical analysis of these deviations reveals low error values (RMSE ≈ 0.05 m), confirming the consistency of the results between the two surveys. The results suggest that the major errors are not uniformly distributed across the dataset but are determined by local factors specific to the measurement conditions. In contrast, the comparison with the external reference point (point 82) indicates significant deviations, suggesting the localized nature of the errors and ruling out their systematic behavior.

Table 5

Statistical analysis of deviations (ΔX, ΔY, ΔZ, ΔXY) for common points (C1–C2)

Points_C1	Points_C2	ΔX	ΔY	ΔZ	ΔXY
139	120	-0.010	0.000	0.002	0.010
20	2014	0.069	0.000	0.018	0.069
19	500	-0.044	0.000	-0.004	0.044
251	175	0.017	0.000	0.017	0.017

440	188	0.015	0.000	0.003	0.015
412	270	0.030	-0.100	-0.016	0.104
413	268	0.014	0.000	0.009	0.014
414	266	0.023	-0.100	0.008	0.103
323	219	-0.008	0.000	0.017	0.008
METRICA		**ΔX**	**ΔY**	**ΔZ**	**ΔXY**
BIAS		0.012	-0.022	0.006	0.043
MAE		0.026	0.022	0.010	0.043
RMSE		0.032	0.047	0.012	0.057

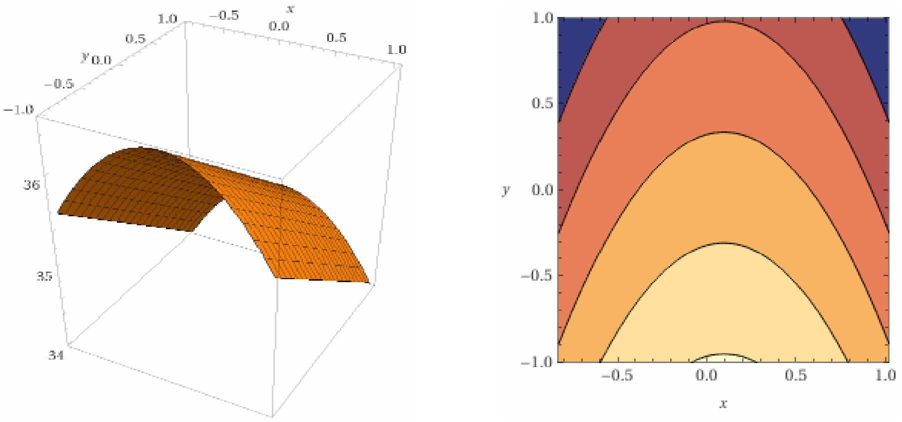
In complex forest environments, ESM signal propagation is influenced not only by atmospheric refraction but also by interaction with vegetation. The presence of leaves and branches can cause signal scattering, multipath reflections and partial obstruction of the line of sight. These phenomena can affect both the direction and the length of the measured path, and are frequently reported in studies on GNSS and LiDAR measurements conducted under forest canopies. In this context, the deviations observed in the study can be interpreted as the result of combined effects of signal propagation in non-homogeneous environmental conditions. This difference indicated that the major errors were not uniformly distributed within the dataset, but rather exhibited a localized nature. Such behavior was considered incompatible with instrumental or transformation errors, which would generate similar systematic deviations for all the points analyzed (INGENSAND, 2008). Instead, the results suggested the presence of local electromagnetic signal propagation effects associated with environmental conditions, such as spatial variations in air temperature and interaction with vegetation. This type of behavior has been reported in the literature for situations where the line of sight is partially blocked by vegetation, where combined effects of localized atmospheric refraction, scattering and multiple reflections may occur (LIENHART, 2017). Therefore, the non-uniform distribution of errors supported the hypothesis that the deviation observed at points 3,000 and 2,000 was caused by specific local conditions and not by an overall error in the measurement system.

Regression analysis described the variation of the parameter **Δ**Z in relation to **Δ**X and **Δ**Y according to Equation (6), under conditions of statistical reliability, $R^2 = 0.774$, with the graphical distribution shown in Figure 4.

$$dZ = ax^2 + by^2 + cx + dy + exy + f \qquad (6)$$

where: **Δ**Z – vertical deviation; *x* – **Δ**X – horizontal deviation along the X coordinate, and *y* – **Δ**Y – horizontal deviation along the Y coordinate, variables from Equation (4); a, b, c, d, e, f – coefficients from Equation (6);

a = -1.117752; b = 0; c = 0.205184; d = -0.775733; e = 35.745153; f = 0.008512.



(a) (b)

Figure 4. Graphical representation of the distribution of ΔZ as a function of ΔX (x-axis) and ΔY (y-axis): (a) 3D surface model; (b) contour map.

Atmospheric parameters and limitations of the standard model

The refraction coefficient k = 0.142, fixed in the Trimble S5 instrument (Trimble Inc., n.d.), is representative of an open field with an approximately constant vertical temperature gradient (Kahmen and Faig, 1988; Brunner, 1984). It does not reflect the actual variability of the lower atmosphere (the first 20–30 m above the ground), where the thermal gradient can vary significantly depending on solar radiation, surface type and local conditions (Hirt et al., 2010; Eschelbach, 2009). In forest environments, these variations are amplified by the structure of the canopy and the uneven distribution of solar radiation. Using the standard value without adapting it to the actual conditions can contribute to significant errors, in combination with other environmental factors (Baselga, 2014), an aspect also highlighted in this study. However, advanced models based on heat and momentum transfer processes (Eschelbach, 2009; Flach, 2000) require detailed atmospheric measurements, which were not available for this study.

Table 6

Atmospheric parameters recorded by the instrument in both campaigns

Parameter	16/06/2023	20/06/2023	24/06/2023	Remark
Atmospheric pressure (mbar)	931.80	938.30	—	Different values
Temperature (°C)	19.5	25.6	—	Different values
PPM correction	21.6	25.0	—	Different values
Refraction coefficient k	0.142	0.142	0.142	Fixed default in instrument
Field weather conditions	Morning; clear sky	Morning; clear sky	Overcast; rainfall	Variable
Observed planimetric error (m)	0.244 (pt. 3000)	0.670 (pt. 2000)	< 0.020	Highly variable

Although k remained constant (0.142), the significant variability of the observed errors (0.244 m in C1 vs 0.670 m in C2, under similar geometry and weather conditions) demonstrates that the standard value does not reflect the actual signal propagation conditions in the forest environment analyzed.

Analysis of environmental factors

The beech (*Fagus sylvatica* L.), the dominant species in the study area, exhibits a fully developed canopy in June (dense cover, large leaf area), which promotes the formation of a non-uniform microclimate beneath the canopy. At the time of the measurements (09:31 EEST, 16 June), the transition from the nocturnal to the diurnal thermal regime, combined with the solar position, generated local thermal gradients in the direction of the line of sight – conditions under which k can vary significantly over time and space (HIRT ET AL., 2010). The intraday difference in errors (C1: 0.244 m; C2: 0.670 m), obtained under apparently similar conditions (morning, clear sky), reflects the unstable variability of the lower atmospheric layer beneath the canopy, influenced by solar radiation and air circulation (HIRT ET AL., 2010; ESCHELBACH, 2009).

In contrast, campaign V1 (24/06/2023, overcast, rain) produced errors of less than 0.020 m – the uniform temperature distribution and high humidity reduced the local thermal gradients, effectively eliminating the localized refraction effect.

Influence of the 360° prism and sighting conditions

The 360° prism used in the measurements (Trimble type, with six facets) may have introduced additional systematic errors associated with the geometry of the reflector. Experimental studies have shown that omnidirectional prisms exhibit cyclic errors dependent on their orientation relative to the instrument, with magnitudes in the millimetre range (LACKNER AND LIENHART, 2016), which in certain configurations can exceed 2–3 mm. Under conditions of partially obstructed line of sight, autolock systems can lock the prism at unfavorable angles, leading to the amplification of these errors (LIENHART, 2017). Furthermore, prism-related effects can interact with atmospheric refraction and line-of-sight obstructions, generating additional deviations (LIENHART, 2017). However, the magnitude of these errors remained limited to the millimetre scale and could not explain the significant deviations observed (0.244–0.670 m). Therefore, prism-related errors were considered a secondary factor, contributing only to local variations in the measurements. It should be noted that no direct comparison with a standard prism was carried out, which represents a methodological limitation of the study.

CONCLUSIONS

The errors of 0.244 m (16/06/2023) and 0.670 m (20/06/2023), recorded at a distance of approximately 53.6 m from the station, exceeded the nominal accuracy of the Trimble S5 total station (TRIMBLE INC., N.D.), adjusted to σ = 0.004 m, by approximately 61–168 times and could not be attributed to instrumental, station, orientation or transformation errors. The most plausible explanation for the observed deviations is a combination of environmental effects influencing the propagation of the EDM signal, including localized atmospheric refraction, signal scattering, multiple reflections, and partial obstruction of the line of sight in the forest environment. The standard value of the refractive index (k = 0.142) proved inadequate under conditions of thermal instability. The observed deviations suggested apparent refraction effects corresponding to values of the refractive index different from the standard value, without directly determining the refractive index. The inter-diurnal variability of the errors highlighted the unstable and difficult-to-model nature of local refraction, which could not be corrected using standard atmospheric models. Based on the results, the following recommendations were made:

- Avoiding measurements in conditions of direct morning sunlight;
- using standard prisms instead of 360° prisms;
- carrying out measurements under overcast conditions or when the temperature gradient is low;
- conducting GNSS checks outside the forest perimeter.

The results showed that the standard atmospheric models of total stations are insufficient for high-precision measurements in complex forest environments.

The study has limitations specific to measurement conditions in forest environments. It was not possible to fully separate the effects of atmospheric refraction from those caused by scattering and multiple reflections of the EDM signal under conditions of line of sight partially obstructed by vegetation; therefore, the observed deviations were interpreted as combined effects of signal propagation under variable environmental conditions. Furthermore, no direct measurements of atmospheric parameters along the line of sight (e.g., temperature gradient) were taken, which limited the rigorous quantification of the refractive index under real-world conditions. The study was based on experimental field observations rather than a controlled experiment, which meant that the measurement conditions were naturally variable. However, the consistency of the results obtained and the application of a methodology to systematically exclude sources of error supported the validity of the proposed interpretation. An additional relevant element was point 5006, determined by GNSS, which exhibited a deviation of approximately 0.06 m, significantly smaller than the observed deviations (0.244 m and 0.670 m), suggesting that the major errors were not associated with general GNSS limitations, but rather with specific local measurement conditions.

BIBLIOGRAPHY

ARTESE, S., & PERRELLI, M. (2018). Monitoring a landslide with high accuracy by total station: A DTM-based model to correct for the atmospheric effects. Geosciences, 8(2), 46.

BAKUŁA, M., OSZCZAK, S., & PELC-MIECZKOWSKA, R. (2009). Performance of RTK positioning in forest conditions: Case study. Journal of Surveying Engineering, 135(3), 125–130.

BASELGA, S., GARCÍA-ASENJO, L., & GARRIGUES, P. (2014). Practical formulas for the refraction coefficient. Journal of Surveying Engineering, 140(2), 06014001.

BRUNNER, F. K. (1984). Modelling of atmospheric effects on terrestrial geodetic measurements. In Geodetic refraction: effects of electromagnetic wave propagation through the atmosphere (pp. 143–162). Berlin, Heidelberg: Springer Berlin Heidelberg.

ESCHELBACH, C. (2009). Refraktionskorrekturbestimmung durch Modellierung des Impuls- und Wärmeflusses in der Rauhigkeitsschicht. KIT Scientific Publishing.

FENG, T., CHEN, S., FENG, Z., SHEN, C., & TIAN, Y. (2021). Effects of canopy and multi-epoch observations on single-point positioning errors of a GNSS in coniferous and broadleaved forests. Remote Sensing, 13(12), 2325.

FLACH, P. (2000). Analysis of refraction influences in geodesy using image processing and turbulence models (Doctoral dissertation, ETH Zurich).

HIRT, C., GUILLAUME, S., WISBAR, A., BÜRKI, B., & STERNBERG, H. (2010). Monitoring of the refraction coefficient in the lower atmosphere using a controlled setup of simultaneous reciprocal vertical angle measurements. Journal of Geophysical Research: Atmospheres, 115(D21).

INGENSAND, H. (2008). Concepts and solutions to overcome the refraction problem in terrestrial precision measurement. Geodezija ir Kartografija, 34(2), 61–65.

KAARTINEN, H., HYYPPÄ, J., VASTARANTA, M., KUKKO, A., JAAKKOLA, A., YU, X., ... & HYYPPÄ, H. (2015). Accuracy of kinematic positioning using global satellite navigation systems under forest canopies. Forests, 6(9), 3218–3236.

KAHMEN, H., & FAIG, W. (1988). Surveying Walter de Gruyter. Berlin, New York, 1–578.

LACKNER, S., & LIENHART, W. (2016, March). Impact of prism type and prism orientation on the accuracy of automated total station measurements. In Proc. 3rd joint international symposium on deformation monitoring.

LIENHART, W. (2017). Geotechnical monitoring using total stations and laser scanners: critical aspects and solutions. Journal of Civil Structural Health Monitoring, 7(3), 315–324.

PIRTI, A., GÜMÜŞ, K., ERKAYA, H., & HOŞBAŞ, R. G. (2010). Evaluating repeatability of RTK GPS/GLONASS near/under forest environment. Croatian journal of forest engineering: journal for theory and application of forestry engineering, 31(1), 23–33.

TRIMBLE INC. (N.D.). Trimble S5 total station datasheet. Retrieved from https://geospatial.trimble.com/products-and-solutions/trimble-s5

TOMAŠTÍK, J., CHUDÁ, J., TUNÁK, D., CHUDÝ, F., & KARDOŠ, M. (2021). Advances in smartphone positioning in forests: Dual-frequency receivers and raw GNSS data. Forestry: An International Journal of Forest Research, 94(2), 292–310.

VALBUENA, R., MAURO, F., RODRIGUEZ-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.