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Research paper

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Assessment of the consistency of geometric axis determination for lattice transmission towers using tachymetric and terrestrial laser scanning (TLS) methods: a case study

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Summary

Geometric monitoring of slender structures in power transmission infrastructure, particularly steel lattice towers of high-voltage lines, is an important engineering surveying task due to their susceptibility to environmental loads and their role in operational safety. This study compares the determination of the geometric axes of lattice transmission towers using classical tachymetric measurements and terrestrial laser scanning (TLS) performed with a compact Leica BLK360 scanner.

The objective was to assess the consistency of these two methods in determining planimetric axis deviation, and to evaluate how the quality of point cloud registration impacts the results. The analysis was carried out at fourteen height levels, with deviations referred to the lowest measurement level. The TLS data were evaluated using registration quality parameters (overlap, strength, cloud-to-cloud, and global bundle error) obtained in Cyclone REGISTER 360 PLUS. Registration was performed in cloud-to-cloud mode without the use of control points.

The results revealed significant discrepancies between the two methods, with local deviations exceeding 100 mm. The maximum planimetric axis deviation derived from TLS reached 140 mm, whereas the corresponding value obtained from tachymetry did not exceed 44 mm at the same inclination. Increasing differences were observed in the upper parts of the structure.

These findings suggest that TLS measurements taken without stable geometric control cannot be relied upon to accurately assess axis deviation. In practice, combining the geometric stability of tachymetric measurements with the spatial completeness of TLS data offers the most effective solution for precise axis evaluation and comprehensive geometric documentation.

Keywords

terrestrial laser scanning (TLS) • inventory survey • lattice tower • verticality assessment • tachymetry • comparison of measurement methods

1. Introduction and literature review

Slender structures play a key role in the technical infrastructure of modern power systems. This category includes, among others, industrial chimneys, telecommunications masts, steel towers and power line poles, which are characterised by a high height-to-transverse dimension ratio - usually exceeding values in the range of 5–10 (a classification criterion for slender objects in static and dynamic analyses of tower structures) ‑ as well as considerable susceptibility to environmental impact. Subject literature emphasises that even minor thermal or dynamic loads can lead to noticeable deviations in the vertical alignment of the structure, increasing with the height of the object [Chmielewski et al. 2009, Gikas 2012].

Classical methods of controlling the verticality of slender structures primarily rely on precise tachymetric measurements, as well as trigonometric and directional intersection methods. These methods provide high-accuracy point measurements and a well-established methodology for developing results, as confirmed by studies on industrial chimneys and steel structures [Marjetič 2018, Daliga and Kurałowicz 2019]. However, a notable limitation of these methods remains in the discrete nature of observations, which makes it difficult to fully analyse the spatial behaviour of an object over its entire height. This restricts the application of these methods to tasks requiring a comprehensive geometric inventory.

Although, the terrestrial laser scanning (TLS) technology has introduced new possibilities for capturing spatial data of slender structures, it requires verification to ensure compliance with classical geodetic methods. TLS enables the fast acquisition of a dense, three-dimensional point clouds, creating an almost continuous geometric representation of an object. Numerous studies have demonstrated the effectiveness of TLS for analysing the verticality and deformation of chimneys, cooling towers and other structures, using methods based on analysing horizontal sections and fitting geometric models [Barazzetti et al. 2019, Beshr et al. 2023, Muszyński and Milczarek 2017]. However, the authors emphasise that the accuracy of surveys based on TLS depends heavily on the quality of the point cloud recording and the geometry of the scanning stations. Vezočnik et al. [2009] showed that even minor recording errors can lead to significant discrepancies when determining the object axis during long-term monitoring. In turn, Popović et al. [2022] highlight the need to critically evaluate parametric models used to interpret tilt trends, especially for objects with complex spatial geometry.

A particularly challenging group of objects for TLS are steel lattice transmission towers. Unlike objects with continuous lateral surfaces, such as chimneys or tubular towers, these towers have openwork, discontinuous geometries that cause large variations in point cloud density and local data gaps. Research on the automatic assessment of the verticality of objects with complex geometry indicates that selecting an appropriate algorithm for point cloud analysis is crucial [Matwij et al. 2024], and that the results of the analysis should be interpreted in terms of the quality and completeness of geometric data.

In recent years, there has been growing interest in the use of compact TLS scanners for inventory and monitoring tasks. Devices such as the Leica BLK360 offer high mobility and considerably reduce field measurement time, making them attractive from an engineering practice perspective. However, their technical parameters – especially range, single-point accuracy and recording stability in systems without control networks – require verification for tasks requiring millimetre geometric stability [Głowacki 2022, Wawrzyniak and Łańduch 2025]. When it comes to the geometric inventory of lattice structures, it becomes important to properly define the scope and purpose of using these types of devices. For lattice transmission lines, the consistency of the results of determining the structure axes obtained by the TLS method and classical tachymetry is still unclear, particularly when using compact scanners and free recording without control points.

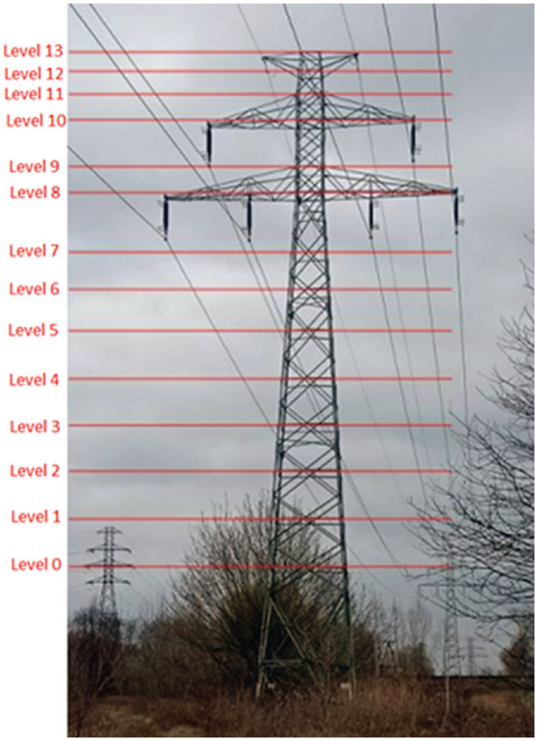
An important aspect of monitoring slender structures is also the effect that environmental conditions have on measurements. Studies have demonstrated that uneven sunlight can result in momentary thermal deformations in steel structures, with the amplitude comparable to or even greater than the measurement uncertainty [Gradka 2025]. This phenomenon can directly impact the interpretation of the results of a single measurement campaign and comparisons between different measurement techniques, especially when the analysis is based on a one-off inventory of the object.

This paper aims to compare the results of determining the geometric axis of a lattice transmission line obtained by the tachymetric method and the terrestrial laser scanning method. It also assesses the usefulness of a compact TLS scanner for inventorying lattice structures carried out in free cloud-to-cloud recording mode. Particular attention was paid to the analysis of the consistency of planimetric values of axis deviations and the identification of factors influencing discrepancies between measurement methods.

2. Characteristics of the research object

The research object was a steel lattice transmission line, placed on a reinforced concrete foundation (Fig. 1). The total height of the analysed tower was approximately 28 m. The structure is spatial, consisting of thin-walled steel elements arranged in a lattice with a variable cross-section. Due to the lack of a continuous side surface and the presence of numerous diagonal elements as well as structural nodes, the tower is a particularly challenging object from the point of view of TLS point cloud analysis.

The complex geometry of the structure causes uneven point cloud coverage, local shading, and increased sensitivity of the results to the geometry of the scanning stations. These features are key in geometric inventory because they influence both the completeness of point cloud registration and the way the obtained spatial data is interpreted.



Source: Author's own study

Fig. 1. Arrangement of measurement levels on a steel lattice transmission line

3. Research methodology and data analysis

3.1. Tachymetric measurements and determination of the reference axis

Tachymetric measurements were taken at characteristic points of the structure, at fourteen height levels. These points were used to determine the tower's reference axis and to verify the TLS results, with tachymetry serving as the reference method due to its high geometric stability.

Tachymetric data were developed in order to standardise the measurement data and determine the position of the geometric axis of the surveyed tower. The basis for this operation were the coordinates of the extreme points of the object's contour, determined using the method of surrounding tangents. For each height level, a set of extreme points was available, obtained from four independent measurement stations. The chord centre was defined from each pair of extreme points, and then lines perpendicular to the corresponding chords were drawn. The position of the object axis at a given level was determined based on a system of lines derived from pairs of opposite measurement stations. The lack of perfect coplanarity and the occurrence of observational errors means these lines did not intersect at one point. The final axis position was identified as a supernumerary solution determined by the least squares method, which minimises the sum of the squares of the distances of the axis point from all analysed lines.

The lowest measurement level was adopted as the reference level. For the remaining levels the increments of the axis coordinates and the planimetric deviation of the axis distance were calculated.

Table 1. Deviations of the tower axis determined by the tachymetric method in a local system (representative levels)

Point	H [m]	ΔX [mm]	ΔY [mm]	Δd tach [mm]
C0	6.419	0	0	0
C5	16.430	5	–3	2
C9	22.511	15	–6	9
C11	25.688	47	–8	39
C13	27.567	52	–8	44

The deviations of the tower axis, determined by the tachymetric method, are related to the geometric axis, which was derived from discrete point observations, carried out at selected height levels and in a limited number of observation directions. In this study, the tachymetric method serves as a reference method for comparing results and interpreting TLS data. The accuracy with which the geometric axis can be determined using the tachymetric method depends on the observation geometry and the accuracy with which the extreme points can be measured. This can be estimated to be at the level of several millimetres (2–4 mm). It is significantly more accurate than the observed differences between tachymetry and TLS results in the upper parts of the structure.

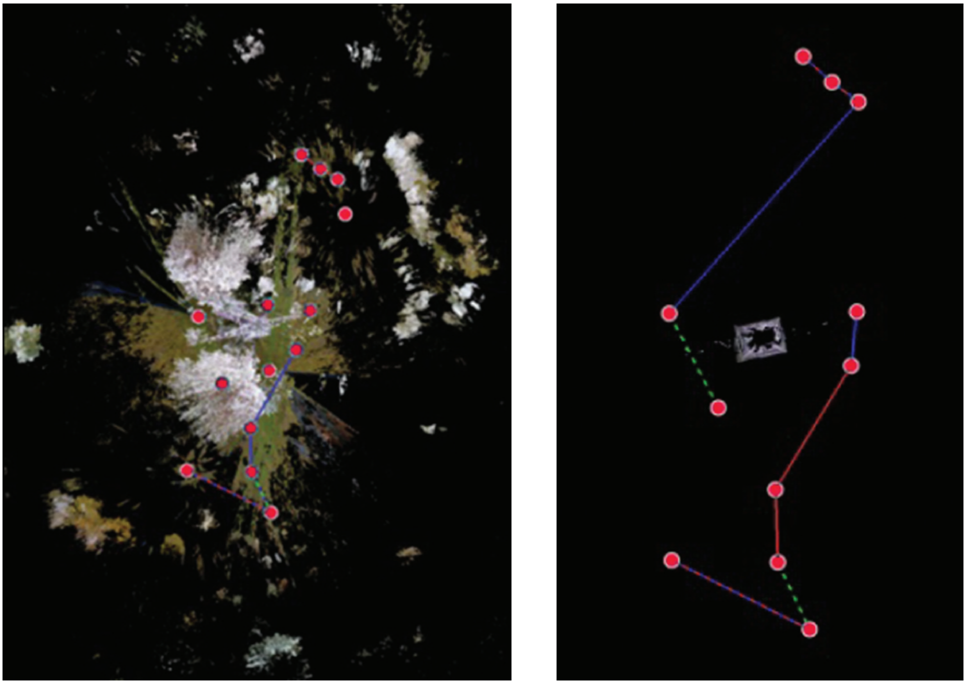
3.2. Terrestrial laser scanning (TLS)

Terrestrial laser scanning measurements were performed using a Leica BLK360 compact scanner from eleven stations located around the surveyed object. This scanner was chosen as a representative example of a compact TLS scanner, commonly used in engineering practice for fast inventory of infrastructure facilities. The locations of the stations were arranged in a way that allowed for the most complete geometric coverage of the structure, taking into account its openwork structure and local measurement shadows.

The point cloud was recorded in the Cyclone REGISTER 360 PLUS environment using the cloud-to-cloud method, without the use of shields or control points, which was suitable to the conditions typical for a fast inventory of infrastructure facilities in the field. This approach allows for the assessment of practical use of a compact TLS scanner for documentation tasks with minimal intervention in the object's environment.

The geometric axis at a given level was determined as the centroid of the points representing the outline of the structure in a separate height layer of the point cloud. However, this method is susceptible to displacements resulting from non-uniform sampling density and asymmetric scanning geometry.

The generated point cloud formed the basis for further analysis of the tower geometry, in particular for the determination of horizontal sections and the approximation of structure axes at subsequent heights.



Source: Żurawski [2025]

Fig. 2. Arrangement of scanning stations around the lattice tower: A – diagram of scan links (left), B – link diagram/point cloud after cleaning (right)

3.3. Quality of TLS point cloud registration

A key element of developing the TLS data was the analysis of the quality of point cloud registration, which was carried out on the basis of reports generated in the Cyclone REGISTER 360 PLUS environment. This assessment was crucial for the further interpretation of the results of the analysis, especially for the inventory of openwork structures.

The recording process involved eleven scanning stations, forming a network with ten cloud-to-cloud relationships. The average overlap value between scans was 33%, while the strength parameter reached 63%, indicating moderate but sufficient geometric consistency of the data. The global bundle error value was 19.7 mm. It is a synthetic measure of the cumulative fit error of all scans. While a global registration error below 20 mm is acceptable for visualisation purposes, it can generate systematic model drift in the upper parts of slender structures, leading to systematic twisting of the point cloud in a reference network. The importance of data harmonisation and the influence of recording parameters on the stability of geometric analyses based on TLS point clouds are also emphasised by Zaczek-Peplińska et al. [2022].

A detailed analysis of cloud-to-cloud errors revealed significant variation in the quality of the individual links. For the selected relations, the mean errors reached values of the order of 25–28 mm, while the overlap varied from a few percent to several dozen percent. The observed relationship confirms that in the case of lattice structures, high overlap does not guarantee low registration errors, and that the geometry of the scanning station arrangement and the local nature of the point cloud coverage play a key role.

The obtained error values imply that the discrepancies between the TLS and tachymetry results, observed in the remaining part of the paper cannot be analysed in isolation from the quality and consistency of the point cloud recordings. From a geometric inventory point of view, this necessitates a critical evaluation of TLS-based results and deliberate definition of their scope of application.

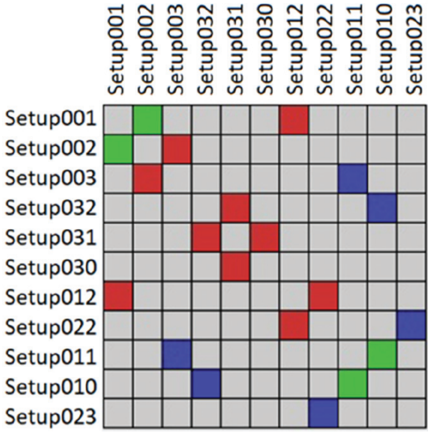
As review studies on large-scale TLS point clouds indicate, the quality and geometry of the registration have a key impact on the subsequent geometric analysis of objects, especially for structures with complex spatial structure [Dong et al. 2020].

Table 2. Basic quality parameters for TLS point cloud registration

Parameter	Value
Stations	11
Links	10
Average overlap	33%
Strength	63%
Global bundle error	19.7 mm

Analysis of the link-quality matrix (Fig. 3) reveals an uneven structure to the registration network. Colours designate intervals of the average cloud-to-cloud registration error between pairs of stations: green – error ≤ 15 mm, yellow – 15–20 mm, red ≥ 20 mm, blue – zero-error links resulting from insufficient overlap of point clouds or lack of stable geometric features. Grey boxes indicate absence of a direct link between stations.

There are numerous links with an error exceeding 20 mm (red fields) and links with a zero error value (blue fields). The latter arise from insufficient overlap of point clouds or a limited number of common geometric features. This arrangement of links suggests poor network redundancy and susceptibility to local registration errors.



	Setup001	Setup002	Setup003	Setup032	Setup031	Setup030	Setup012	Setup022	Setup011	Setup010	Setup023
Setup001		🟩					🟥				
Setup002	🟩		🟥								
Setup003		🟥							🟦		
Setup032					🟥					🟦	
Setup031				🟥		🟥					
Setup030					🟥						
Setup012	🟥							🟥			
Setup022							🟥				🟦
Setup011			🟦							🟩	
Setup010				🟦					🟩		
Setup023								🟦			

Source: Author's own study based on Żurawski [2025]

Fig. 3. Link-quality matrix for TLS point cloud registration

It is particularly important to note that the network structure is open, rather than being closed at stable points of the control network. Consequently, even individual links with increased error can propagate geometric errors through the upper parts of the model, resulting in systematic twisting of the point cloud. This phenomenon is directly reflected in the increasing deviations of the structure axes observed above a certain height.

3.4. Determination of axis and verticality using the TLS method

The geometric axis of the tower was determined based on TLS data by analysing the horizontal sections of the point cloud at subsequent heights. At each height level, a set of points representing the outline of the structure was extracted, and then the axis position was identified as a point approximating the centroid of the cross-section.

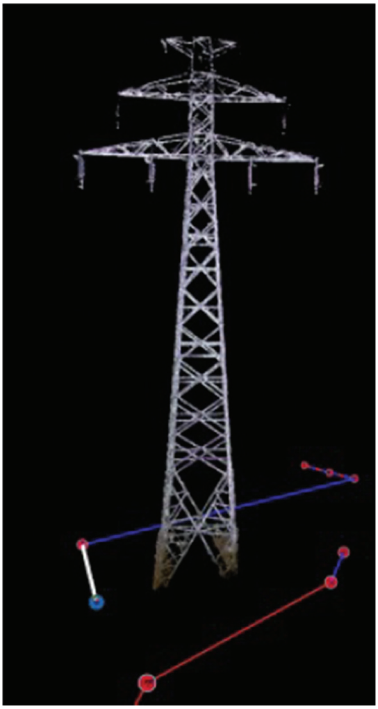
Unlike the tachymetric method, which determines the axis from discrete extreme points, the TLS method uses a quasi-continuous representation of the object geometry, including the complete outline of the structure at a given level. Consequently, the established TLS axis can account for the influence of local irregularities, asymmetries in the lattice elements, and inhomogeneities in the point cloud distribution, stemming from both the geometry of the object and the quality of registration.

The lowest level of the analysed cross-section was adopted as the reference level, while for the remaining levels the increments of the axis coordinates and the planimetric axis deviation were calculated. These values should be interpreted as a description of the structure's overall geometric behaviour, rather than solely as a measure of the point deviation of the axis.

Table 3 shows the tower axis deviations determined by the TLS method for levels corresponding to the tachymetric measurement levels, which allows a direct comparison of the results of the two methods, while maintaining the geometric consistency in the analysis.

Table 3. Tower axis deviations determined by TLS (levels consistent with tachymetry)

Point	H [m]	ΔX [mm]	ΔY [mm]	Δd TLS [mm]
C0	6.419	0	0	0
C5	16.430	10	11	15
C9	22.511	48	37	61
C11	25.688	104	93	140
C13	27.567	91	82	122



Source: Żurawski [2025]

Fig. 4. The course of the geometric axis of the lattice tower determined by the TLS method

4. Results

Analysing the measurement data allowed us to compare the geometric axis of the lattice tower, as determined by the tachymetric method and terrestrial laser scanning.

The results were presented in tabular and graphical form, enabling an assessment of changes in the position of the axis as a function of the object height.

Figure 5 shows the dependence of the planimetric deviation of the tower axis on the height of the structure for both measurement methods. In both methods, the direction of the structure's deflection (NE) was consistent, although the values of the planimetric axis deviation differed significantly. In the case of the tachymetric method, the deviation values gradually increase with height, reaching a maximum of 44 mm. In contrast, the TLS method shows a considerably greater rate of increase in deviation, with a maximum value of 140 mm.

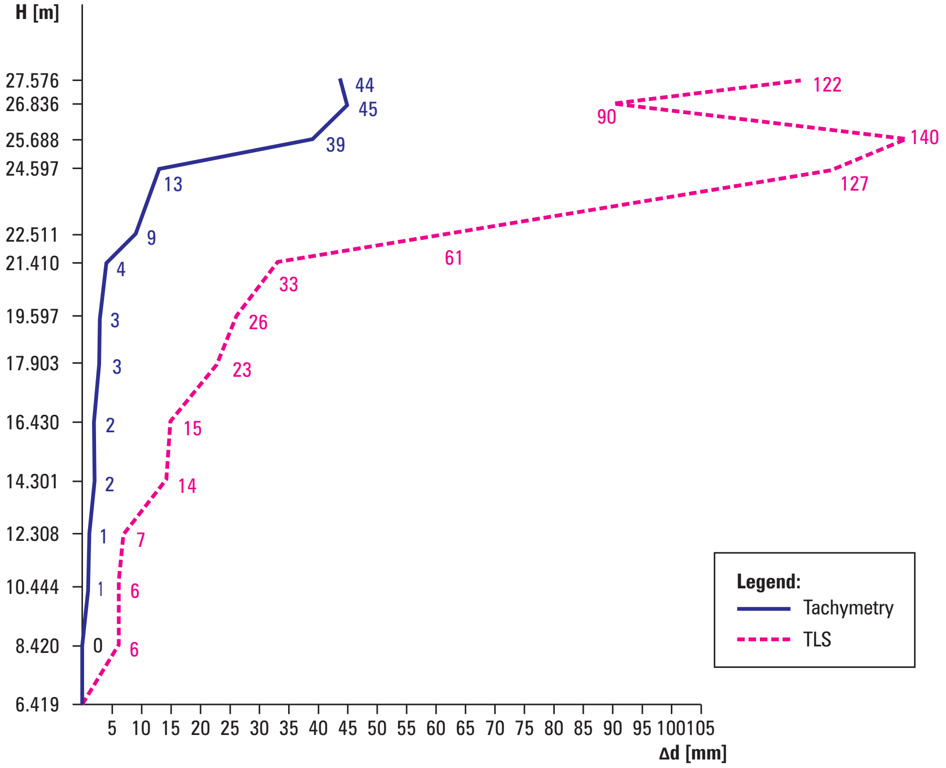
It should be emphasised that the observed difference in axis deviation values cannot be unambiguously interpreted as a TLS measurement error in the instrumental sense. The consistency in the direction of the deviation indicates that the global geometric inclination of the structure has been correctly captured. The discrepancy in amplitude stems from the different representations of the geometry (discrete vs quasi-continuous models), the sensitivity of the axis estimator to the distribution of the point cloud, and the propagation of registration errors in the cloud-to-cloud system in the absence of a control network.

A summary of the detailed axis deviation values for selected height levels is presented in Tables 4 and 5. This comparison shows that the axis deviation values determined by the TLS method are several times greater than the tachymetric results. The maximum planimetric axis deviation obtained from the point cloud exceeds 100 mm, whereas the corresponding value established by the tachymetric method does not exceed several dozen millimetres.

Analysis of the graph (Fig. 5) reveals a sharp, nonlinear increase in deviation in the TLS method above 20 metres in height. The observed difference of over 100 mm between the two methods indicates a significant discrepancy in the planimetric values of the axis deviation, which increases in the upper sections of the structure. This is a characteristic symptom of the propagation of registration errors in open networks (without closure at control points), exacerbated by the decrease in point cloud density in the upper parts of the structure. The scale of the observed increase in deviation is proportional to the height of the structure, signalling an accumulation of errors along the model axis. These results confirm the distinct nature of the geometric description obtained by the TLS method.

Studies based on the analysis of TLS point clouds of power infrastructure have shown that taking into account a complete, dense representation of object geometry leads to a significantly different description of their shape and position compared to methods based on a limited number of characteristic points. Previous studies indicate that, especially in the case of lattice structures and transmission line components, local irregularities and complex spatial geometry have a significant impact on the results of analyses based on TLS data [Yu et al. 2023].

The results confirm that the tachymetric and TLS methods produce different planimetric values for axis deviations while maintaining a consistent direction of structure deflection.



Source: Żurawski [2025]

Fig. 5. Dependence of the planimetric axis deviation Δd on the tower height for the tachymetric and TLS methods

Table 4. Comparison of tower axis deviations determined by tachymetry and TLS

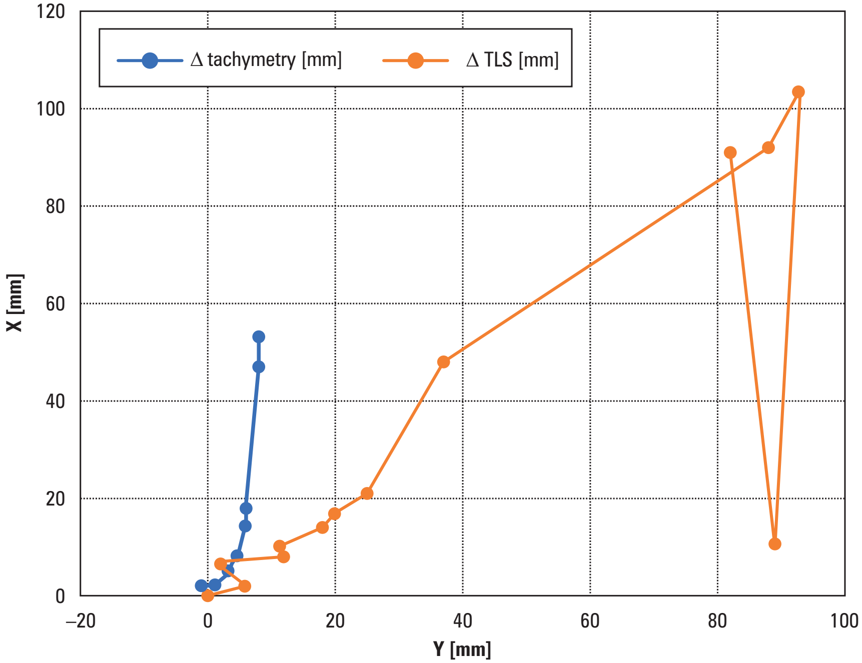
Point	H [m]	Δd tach [mm]	Δd TLS [mm]	Difference [mm]
C0	6.419	0	0	0
C5	16.430	2	15	13
C9	22.511	9	61	52
C11	25.688	39	140	101
C13	27.567	44	122	78

The differences between the methods increase with the height of the structure: at the level H = 16,430 m they are 13 mm, at the level H = 22,511 m – 52 mm, while at the level H = 25,688 m they reach 101 mm.

Table 5. Comparison of maximum tower axis deviations determined by the tachymetric and TLS method

Measurement method	Maximum axis deviation Δd [mm]	Level H [m]	Direction of deviation
Tachymetry	44	27.567	NE
TLS (BLK360)	140	25.688	NE

Figure 6 illustrates the significant differences in the character of the axis of the structure determined by the two methods, indicating a stable, quasi-linear trend of axis deviations in the case of tachymetry, and a clear, nonlinear axis drift derived from TLS data, increasing with the height of the structure.



Source: Author's own study

Fig. 6. Top projection (XY) of the geometric axis of the steel lattice tower determined on the basis of tachymetric measurements and TLS data

5. Discussion

A review of studies on the application of terrestrial laser scanning for monitoring deformations of engineering objects indicates that the interpretation of point cloud-based results requires the registration quality and the adopted geometric model of the object to be considered simultaneously [Shen et al. 2023]. The results obtained in this study confirm significant discrepancies between the tower axis deviation values determined by the tachymetric method and TLS data, while maintaining the consistency in the direction of the structure's deflection.

These divergences are not related to a faulty measurement process or random observation errors, but are a consequence of the different nature of the input data and the method of estimating the geometric axis. In tachymetric measurements, the axis of the structure is determined based on discrete extreme points, which ensures high geometric stability and control of point accuracy, but leads to a simplified description of the object geometry. In effect, the obtained axis deviation values refer to an idealised geometric model of the structure, rather than to its actual, complete outline.

Similar conclusions were presented in studies on deformation monitoring of large steel structures using TLS, where the strong dependence of the results of geometric analyses on the adopted method of object modelling and the range of spatial data taken into account was emphasised [Hao et al. 2025]. The authors point out that the discrepancies between TLS results and point methods are primarily due to the different representations of the structure geometry and the sensitivity of TLS analyses to local irregularities and deformations.

Terrestrial laser scanning provides a quasi-continuous representation of the object's geometry, including the complete outline of the structure at a given height level. The differences observed in this study between the results of both methods stem from two overlapping factors: the different definition of the structure axis and the limitations of the free cloud-to-cloud registration technology for openwork objects. In the TLS analysis, the structure axis was defined as a line connecting the centroids of successive horizontal sections of the point cloud, determined in the XY plane for the separated point layers.

The 140 mm deviation obtained by the TLS method exceeds the range explainable by the actual behaviour of the structure and indicates the presence of systematic model drift. However, it should be noted that all scanning stations were located at a similar ground level. With increasing height, this causes a deterioration in the observation geometry and a decrease in the stability of the centroid estimation. Consequently, the increase in deviation with height may be caused by both the propagation of registration errors and the limitations of the station geometry.

This means that using compact TLS scanners independently to assess the verticality of lattice structures, without a control network, increases the risk of systematic overestimation of the deflection amplitude.

A significant factor limiting the interpretation of TLS results remains the quality of point cloud registration. Cloud-to-cloud error values and global bundle error define the limits of reliable analysis of structural axes, especially for objects with discontinuous, openwork geometry. In the context of the geometric inventory of steel lattice towers, TLS should not be treated as a direct replacement for classical tachymetric measurements, but rather as a tool that enables an overall description of the actual geometry of the structure, which is important for technical documentation and diagnostics of the object's condition.

In engineering practice, the most effective solution remains the hybrid approach, where tachymetry provides stable geometric references, while TLS produces extensive spatial information about the actual geometry of the object. Furthermore, TLS data can also be employed for more complex analyses, such as the evaluation of cross-section ovalisation and axis curvatures [Pleterski et al. 2024], integration with UAV data [Ilieva et al. 2025], or the construction of numerical models and deformation simulations [Helming et al. 2021], which significantly expands their application potential.

6. Conclusion

The tests revealed substantial discrepancies between the results of determining the geometric axis of the steel lattice tower obtained by the tachymetric and the terrestrial laser scanning (TLS) methods. The maximum planimetric axis deviation read out from the TLS data was 140 mm, while the corresponding value obtained by the tachymetric method did not exceed 44 mm. The difference between the two methods locally reached 101 mm, while maintaining the consistency of the structure's deflection direction.

The obtained results confirm that both measurement techniques provide information of a different geometric nature. The tachymetric method ensures high stability of the geometric reference and enables the precise assessment of the structure's axis course based on discrete characteristic points. In contrast, the TLS method uses a quasi-continuous representation of the object geometry and reflects the complete outline of the structure. However, in configurations involving a compact Leica BLK360 scanner and free cloud-to-cloud registration without a control network, it is susceptible to the propagation of registration errors.

The analysis of the quality of the point cloud registration (average overlap 33%, strength 63%, global bundle error 19.7 mm) suggests that in the absence of network closure at stable reference points, systematic twisting of the geometric model may occur in the upper parts of the structure. Consequently, in this configuration, TLS cannot be considered as an independent tool for the precise assessment of the verticality of objects with openwork, discontinuous geometry, such as power line lattice towers.

At the same time, TLS data constitute a valuable source of information about the actual spatial geometry of the structure, including local irregularities and asymmetries of lattice elements. This information is important for technical documentation and diagnostic analyses. In engineering practice, the most effective solution is to combine both measurement techniques, in which tachymetry provides a stable geometric reference, while TLS provides a complete spatial representation of the object.

The presented results refer to a single measurement campaign and do not constitute an analysis of the temporal changes in the structure geometry. Further research should verify the impact of using a control network or registration targets on the stability of TLS models, and analyse the repeatability of results under multi-epoch measurement conditions.

Part of the field reference data was collected during earlier research activities conducted under academic supervision and subsequently reanalysed for the purposes of this study.

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