Comparative Analysis of Classical Geodetic Methods and Terrestrial Laser Scanning for Tilt Determination of a High Metal Lattice Structure

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Abstract

This study aims to evaluate the applicability and accuracy of terrestrial laser scanning (TLS) compared to classical geodetic methods for determining the tilt of a high metal lattice structure. The structure under investigation is a 65.5-meter-high lighting mast characterized by complex spatial geometry and an open lattice design, which presents significant challenges for deformation monitoring using conventional surveying techniques. Deviations from the vertical axis were assessed through a series of horizontal cross-sections, analyzed using both total station measurements and TLS point cloud data. Classical geodetic measurements involved angular intersections and trigonometric leveling, performed within a local geodetic control network. TLS data were acquired using a Trimble TX6 scanner and processed through a registration process and georeferenced using target spheres. To evaluate the consistency and accuracy of both methods, graphical comparisons and analyses of the measured values were performed. The results demonstrate a high degree of agreement between the two approaches, with deviations remaining within a few centimeters. These results confirm the potential of TLS as a reliable and efficient method for monitoring structural deformations in high-rise engineering structures with complex geometries.

Keywords: *terrestrial laser scanning, total station, deformation monitoring, vertical axis deviations, accuracy*

1. Introduction

The investigated object is a 65.5-meter-high lighting mast designed for stadium illumination. The structure is a spatial metal lattice tower, narrowing towards the top and mounted on a 10-meter-high reinforced concrete base. The base dimensions are approximately 5.40 × 5.30 m, narrowing to 2.60 × 2.70 m at the top (Fig. 1). The framework comprises vertical load-bearing profiles connected through diagonal and horizontal elements forming a three-dimensional lattice system. A massive floodlight array is mounted at the top, making the structure sensitive to dynamic and quasi-static movements such as tilt, torsion, and warping.

Monitoring such deformations in real-world conditions is an engineering challenge. The complex spatial geometry and open lattice form obstruct the installation of stable reference points, limiting the effectiveness of classical geodetic and optical techniques. Therefore, modern monitoring relies on integrated high-precision non-contact methods such as TLS. While offering detailed spatial data, TLS requires complex data processing and precise temporal synchronization. This article compares the accuracy and performance of classical and TLS-based methods, assessing their advantages and practical applicability.

Fig. 1. Overview of the studied metal lattice lighting tower.

1.1 Tilt Determination Methodology

The selected method for determining the tilt primarily depends on the specific characteristics and geometric complexity of the structure. The design vertical axis of the structure is defined as a perpendicular to the base plane. The actual position of the vertical axis, or the degree of tilt, is determined by identifying the centre of the structure at various rectangular cross-sections located along the height of the metal construction. Each cross-section is defined by four target points (N_{si}) (Fig. 2). Seven sections were selected at visually accessible and clearly distinguishable locations along the structure:

- Section 1 - Ground level – H= 497.75 m
- Section 2 - Base – H= 507.75 m
- Section 3 - Level 1 – H= 520.25 m
- Section 4 - Level 2 – H= 526.25 m
- Section 5 - Level 3 – H= 532.25 m
- Section 6 - Level 4 – H= 544.65 m
- Section 7 – Top of the structure – H= 563.25 m

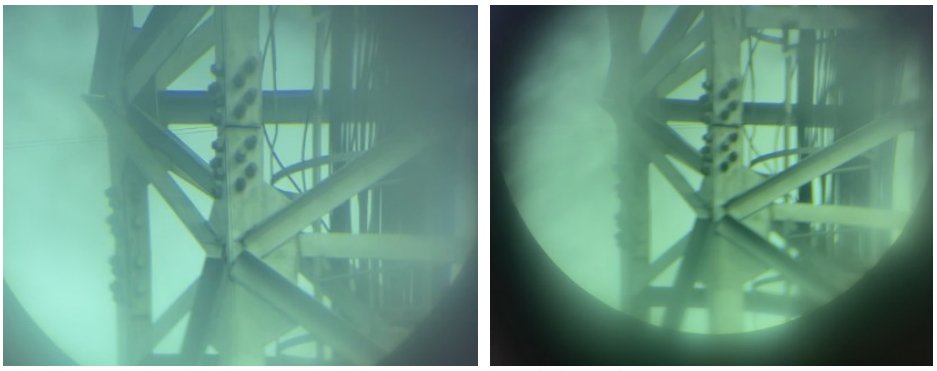


Fig. 2. Observation of a target point through the total station eyepiece.

The centre point of each cross-section (O_i) has been subsequently determined by the intersection of the diagonals (Fig. 3).

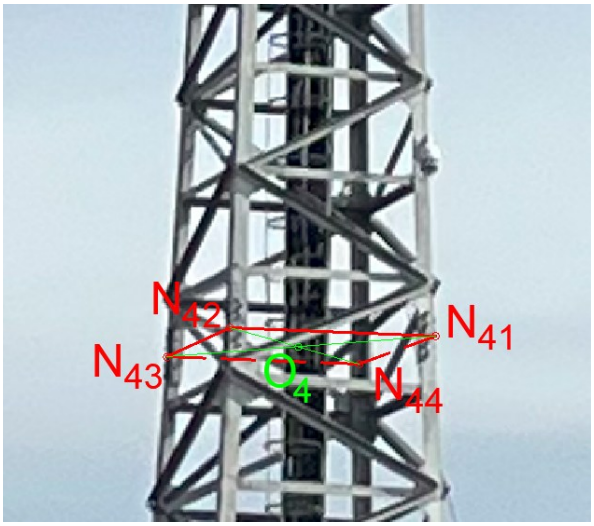


Fig. 3. Location of the target points and the center determined by diagonal intersection at Level 4.

In this way, the tilt of each cross-section relative to the top of the concrete base can be determined. The centre of the mounted plate at the top of the structure was clearly visible and was therefore directly measured as a single point. The maximum tilt was determined by comparing the position of the top section to that of the Base section.

The main challenges in selecting and measuring target points on such types of structures include:

- The placement of permanent markers or other physical indicators on the observed points is either impossible or extremely time- and effort-consuming;
- The presence of bolts and other metal elements complicates the selection of a point that belongs to the structural frame rather than to a protruding component;
- Visibility from all total station positions is limited — depending on the station's location, some points remain obscured and cannot be measured.

1.2 Survey equipment

Initial measurements were carried out using a classical geodetic method with a Leica TCR403 total station, featuring an angular accuracy of 10^{cc} and a distance accuracy of $\pm(2 + 2 \cdot S)$ mm, where S is the measured distance in kilometres (Fig. 4-a). Subsequently, terrestrial laser scanning was performed using a Trimble TX6 system (Fig. 4-b) with the following technical specifications:

- Scan accuracy: <2 mm on most surfaces
- Maximum range: 80 m (extendable to 120 m)
- Scan density: 6–10–34 mm at 10–30–100 m

- Scan rate: 500,000 points per second
- Scan method: Vertical rotating mirror on a horizontally rotating base

Both types of measurements were conducted approximately at the same time and under identical environmental conditions.

(a) (b)

Fig. 4. Leica TCR403 Total Station and Trimble TX6 Terrestrial Laser Scanner used in the study.

2. Classical Geodetic Measurements

To determine the horizontal position of the observed points, multiple angular intersection measurements were performed. The elevations (heights above sea level) were determined using trigonometric leveling [1].

For the purpose of conducting the measurements, a local geodetic control network (LGCN) was established, consisting of four permanently stabilized control points (101, 102, 103, 104) located around the structure at distances ranging from 30 to 70 meters.

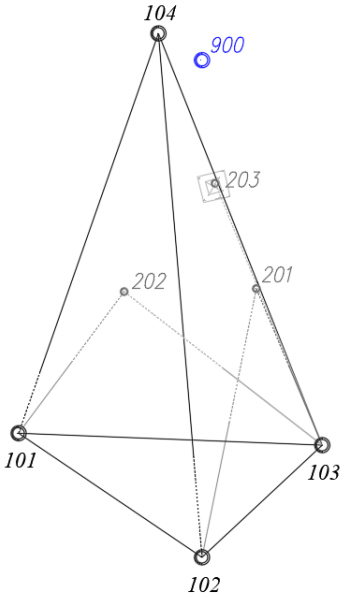


Fig. 5. Overview of the studied metal lattice lighting tower.

The measurement data have been processed in two subsequent stages:

Stage 1: Aimed at determining the coordinates and elevations of the control points within an independent local coordinate and height system. The coordinate system was approximately oriented in a north–south direction (+X ≈ N; +Y ≈ E). The network adjustment was performed using the Least Squares Method, beginning with a preliminary adjustment based on a single reference point (Point 102) and a direction toward a theoretical point (Point 900). As a result, the coordinates of neighbouring points in the LCGN (Points 101 and 103) were obtained with Root Mean Square Error in both plan and elevation of less than 2 mm.

Stage 2: Final adjustment, incorporating measurements to an additional network point (Point 104). After completing the final network adjustment, the coordinates and elevations of all control points (101–104) were determined. The Root Mean Square Errors for the least accurately defined point (Point 104) are as follows:

- $m_S = \pm 4.0$ mm (horizontal position)
- $m_H = \pm 2.5$ mm (elevation)

In the second stage, the coordinates of the target points on the lighting mast were also calculated. Directions and zenith angles were measured from at least two or three different stations located at the LCGN points. Measurements were performed in both face positions of the instrument (face left and face right) in a single repetition (set). The elevations of the cross-sections at the observed

points were determined by trigonometric leveling, and the horizontal distances were computed from the previously derived horizontal coordinates, with an accuracy of less than 1.5 cm [1].

The Root Mean Square Errors for the target points (N_{si}) on the structure are as follows:

- $m_S = \pm 5.5$ mm (horizontal position)
- $m_H = \pm 4.5$ mm (elevation)

Subsequently, the coordinates and elevations of the central points of each cross-section (O_i), defined as the intersection points of the diagonals, were calculated based on the previously determined target points [2]. The resulting Root Mean Square Error for the central points in plan and elevation are as follows:

- $m_S = \pm 7$ mm (horizontal position)
- $m_H = \pm 6$ mm (elevation)

The displacements of the central points of all sections relative to the central point at the base (O_B) have been computed (Tab. 1). The resulting deviations (Q_i) and orientation angles (α) have been referenced to the defined local coordinate system, centred at the base central point (O_B). The directions of the orientation angles (α) are represented in Fig. 6.

Tab. 1. Results of tilt determination using Classical Geodetic Measurements.

CLASSICAL GEODETIC MEASUREMENTS					
Section	Elevation */m/*	Deviations (Q) */cm/*	Orientation angle (α) */g/*	Height of the metal part */m/*	Height of the whole structure */m/*
Level 1	520.25	1.4	321.0694	12.5	22.5
Level 2	526.25	3.0	379.5563	18.5	28.5
Level 3	532.25	6.8	10.6314	24.5	34.5
Level 4	544.65	16.7	6.2588	36.9	46.9
Top	563.25	26.5	13.5663	55.5	65.5

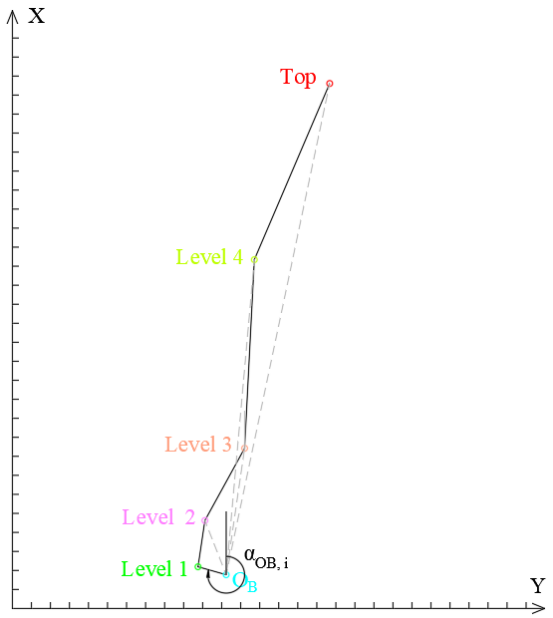


Fig. 6. Directions of the orientation angles (α).

The standard deviation of the calculated deviations has been derived as a function of the computed coordinates of the central points [3]. The Root Mean Square Error m_Q for the measured deviations of the cross-sections (Q_i) is:

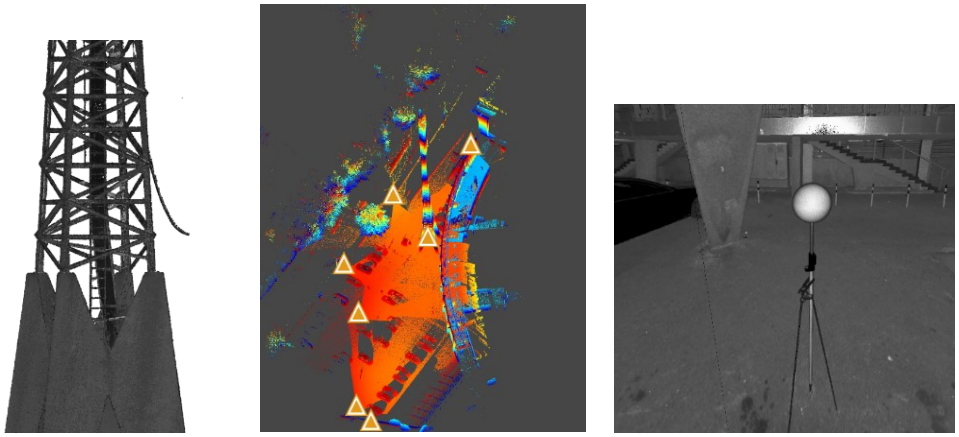
- $m_Q = \pm 9$ mm

To support the transformation of subsequent terrestrial laser scanning (TLS) data acquired by a stationary scanner, the spatial coordinates (X, Y, H) of three reference points were determined. These points were stabilized with metallic bolts near the investigated structure. During scanning, the control points were marked with clearly visible spherical targets mounted on geodetic poles. Following the network adjustment, the coordinates and elevations of the centers of these spheres (Points 201, 202, and 203) have been calculated. The Root Mean Square Errors for the most inaccurately determined point is:

- $m_S = \pm 4$ mm (Point 201 – horizontal position)
- $m_H = \pm 3$ mm (Point 202 – elevation)

3. Terrestrial Laser Scanning (TLS)

To create a three-dimensional model of the investigated object (Fig. 7-a), terrestrial laser scanning (TLS) technology was employed. In this method, scans from different stations are aligned within a common coordinate system through a process known as registration. Measurements were conducted from a total of seven stations (Fig. 7-b). The resulting point cloud was processed using Trimble RealWorks software [4]. The registration process uses target spheres for the registration of scans (Fig. 7-c), as they are uniform in shape and easily recognizable by processing software [5]. The spheres placed at control points 201, 202, and 203 were predefined during the earlier classical geodetic measurements to serve as reference points for georeferencing the point cloud, ensuring that the resulting coordinates (X, Y, H) are in the same coordinate system as the one used in the classical geodetic survey.



(a) (b) (c)

Fig. 7. Overview of the studied metal lattice lighting tower.

According to the generated *Registration Report* for the project (Tab. 2), a total of six scan stations were used, with successful correspondences registered between them. The overall registration error among all stations is 2.46 mm, indicating a high level of geometric consistency between the individual point clouds.

Tab. 2. Registration Report.

Station	Minimum Cloud-to-Cloud Error	Maximum Cloud-to-Cloud Error	Remarks
Station 1	0.60 mm to S2	4.29 mm to S007	Good relation with other stations
Station 2	0.60 mm to S1	6.48 mm to S005	Relatively high error toward S005
Station 3	1.17 mm to S4	2.79 mm to S005	Excellent registration
Station 4	1.17 mm to S3	3.40 mm to S002	Balanced accuracy
Station 5	1.17 mm to S7	6.48 mm to S002	Inconsistent match quality
Station 6	Removed from registration process		
Station 7	1.17 mm to S5	4.29 mm to S001	Good registration, high confidence

The minimum reported cloud-to-cloud error between stations is 0.60 mm, while the maximum is 6.48 mm, with the majority of values falling below 3 mm. The overlap of points between the individual scans ranged from 26% to 50%, and the confidence level of the automatic registration exceeded 92% in all cases, reaching above 98% in most.

These results confirm that the TLS data acquisition and registration process ensured high spatial accuracy, making the dataset reliable for subsequent deformation analysis and geometric modeling of the structure. To transform the point cloud into the local coordinate system established by the classical geodetic measurements, the georeferencing has been performed. The achieved accuracy during this process is given in Tab. 3:

Tab. 3. Accuracy of georeferencing process.

Control point	Error
Point 201	2.91 mm
Point 202	9.99 mm
Point 203	7.94 mm

3.1 Extraction of Analogous Cross-Sections in AutoCAD Environment

For the purpose of comparing the two methods, analogous rectangular cross-sections were generated from the point cloud corresponding to the previously surveyed sections.

When transferring the point cloud into the AutoCAD environment, a major challenge lies in defining the contour of each section to clearly represent the part of the metal structure that defines its external boundary. Careful selection is required to determine the most appropriate section by fine-tuning both the thickness and the elevation of the slice. Challenges related to extracting accurate sections from point clouds in CAD environments have also been discussed by Antova and Tanev [6].

Ultimately, after optimizing the sectioning parameters, the differences between the visible points were found to be in the range of 1–2 cm (Fig. 8).

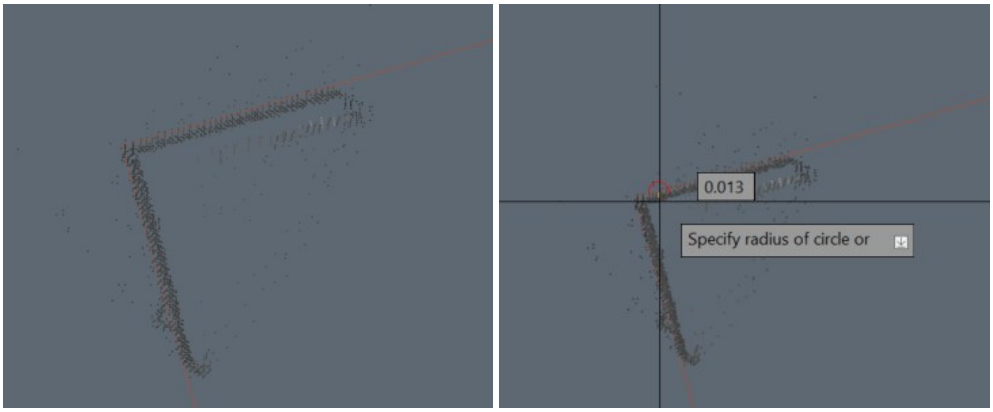


Fig. 8. Cross-section extraction from point cloud in AutoCAD.

Sometimes, adjacent structural elements are captured within the point cloud section, however, by carefully adjusting the slicing range, a clearer cross-section can be obtained, allowing for accurate delineation of the rectangular outline (Fig. 9). This issue is similar to the challenges described in the previous method, where structural complexity and limited visibility also obstructed the accurate selection and measurement of target points.

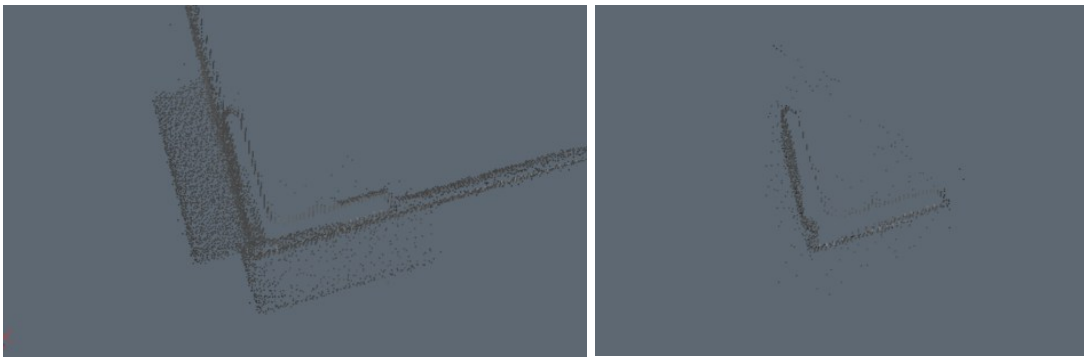


Fig. 9. Challenges in cross-section extraction due to structural complexity and obstructing elements.

3.2 Top Point Determination

Due to limited visibility in the point cloud, the top of the structure could not be directly identified and was instead approximated by intersecting the diagonals of the top rectangular metal plate (Fig. 10).

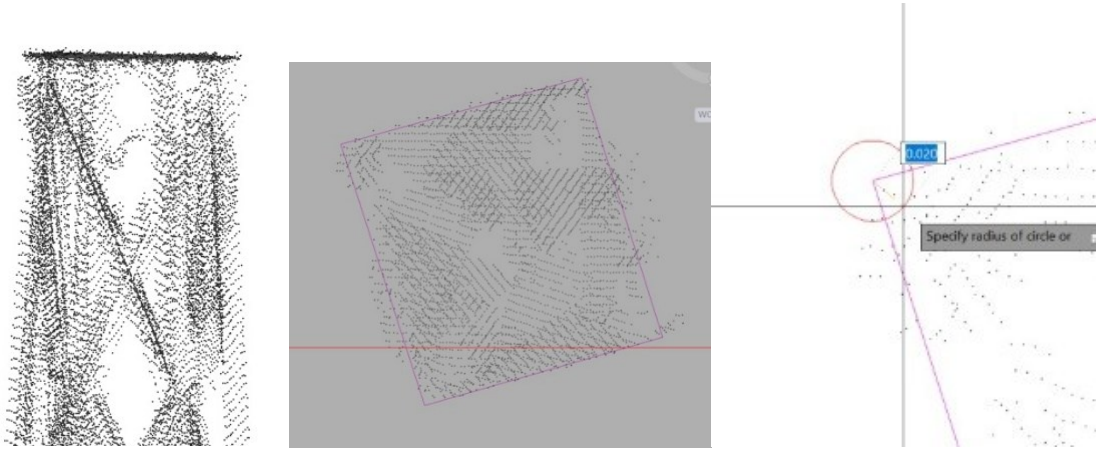


Fig. 10. Top Point Determination from the point cloud.

Tab. 4. Results of tilt determination using Terrestrial Laser Scanning.

TERRESTRIAL LASER SCANNING					
Section	Elevation */m/*	Deviations (Q) */cm/*	Orientation angle (α) */g/*	Height of the metal part */m/*	Height of the whole structure */m/*
Level 1	520.25	0.9	369.0853	12.5	22.5
Level 2	526.25	2.9	387.5753	18.5	28.5
Level 3	532.25	5.3	385.0017	24.5	34.5
Level 4	544.65	12.9	388.3005	36.9	46.9
Top	563.25	21.6	2.2323	55.5	65.5

The deviations from the vertical axis obtained from the point cloud are presented in Tab. 4, in a format analogous to the results obtained from the classical geodetic method.

4. Results

For the purpose of the comparative analysis between classical geodetic measurements and terrestrial laser scanning (TLS), graphical comparisons have been generated for each of the sections (Fig. 11). In the figure, the results from the classical geodetic measurements are shown in black, while the TLS results are shown in red. The graphical evaluation of the cross-sections from both methods demonstrates a good agreement, with the observed discrepancies generally within a few centimetres. The differences between all central points (O_i), determined from both methods are within 4-5 cm.

These results confirm the high accuracy and efficiency of TLS in modeling high structures with complex geometry, while also highlighting the value of classical geodetic measurements as a method as a reliable method for control and validation.

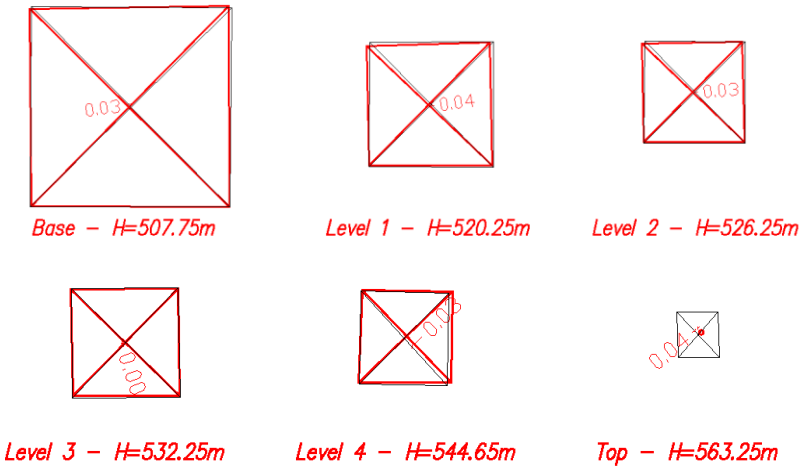


Fig. 11. Graphical comparisons of all central points (O_i).

An analysis was also conducted on the obtained results for the deviation differences (ΔQ) and orientation angles differences (Δα) from both methods, as presented in Tab 5. The differences increase with the height of the structure, likely due to limited visibility and steep sightlines.

Tab. 5. Comparison of final results from the two methods.

COMPARISON OF TERRESTRIAL LASER SCANNING WITH THE CLASSICAL GEODETIC MEASUREMENTS					
Section	Elevation */m/*	Deviations (ΔQ) */cm/*	Orientation angle differences (Δα) */g/*	Height of the metal part */m/*	Height of the whole structure */m/*
Level 1	520.25	-0.5	48.0159	12.5	22.5
Level 2	526.25	-0.1	8.019	18.5	28.5
Level 3	532.25	-1.5	-25.6297	24.5	34.5
Level 4	544.65	-3.8	-17.9583	36.9	46.9
Top	563.25	-4.9	-11.3340	55.5	65.5

The maximum deviation from the vertical axis is 4.9 cm observed from the base to the top (Fig. 12). These results are consistent with those reported by A. Abd-Elmaaboud [7], Simeonova [8], and the findings summarized by Nan Shen [9].

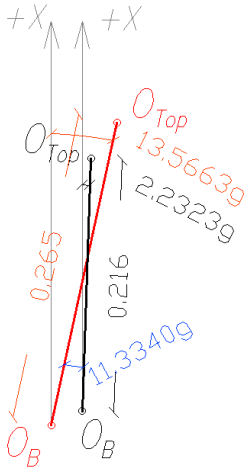


Fig. 12. Graphical comparison of both vertical deviations.

5. Conclusion

This study presents a comparative evaluation of classical geodetic methods and terrestrial laser scanning (TLS) for determining the tilt of a high metal lattice structure. The results demonstrate a high level of agreement between the two approaches, with deviations generally remaining within a few centimetres. The observed differences increase with height but remain within acceptable limits for some engineering applications.

TLS offers significant advantages in terms of spatial coverage and detail, allowing for comprehensive analysis of the structure's geometry. It is particularly suitable for initial assessments and broad deformation monitoring. However, TLS requires significantly more time for both fieldwork and processing, as well as access to specialized equipment. In contrast, classical geodetic measurements provide higher precision at specific, predefined points and remain indispensable for control and validation purposes.

In many cases, an integrated approach — employing TLS for general structural assessment and classical methods for critical point verification — offers the most effective and reliable solution for monitoring complex engineering structures.

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