

The concept of metrological validation of active measurement sensors - CENAGIS-MET

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Abstract

Advances in optical measurement technologies have increased demands for accuracy, speed, and automation in coordinate metrology. This contribution introduces CENAGIS-MET, a metrological verification standard developed at the Warsaw University of Technology for assessing active range-based systems such as terrestrial laser scanners (TLS). Unlike traditional calibration fields designed for small ranges, CENAGIS-MET enables evaluation over large measurement areas, in accordance with modified VDI/VDE guidelines. The methodology incorporates probing error, sphere-spacing error, and flatness assessment using high-precision ceramic artefacts. Tests were conducted on Leica RTC360, Leica Nova MS60, Z+F 5006h, and a handheld Livox-based scanner (Mandeye). Results show RTC360 and MS60 fully meet the 1/5 relative error criterion, confirming suitability for engineering-grade applications. Z+F 5006h achieves partial compliance, requiring careful configuration, while Mandeye exceeds permissible thresholds, limiting its use to qualitative documentation. The article provided broader analyses of the accuracy of 3D shape reconstruction used for probing error, as well as roughness and planarity assessments to evaluate the overall distribution of the reference plane.

1. Introduction

In recent years, significant advancements in measurement methods have been observed, accompanied by increasingly sophisticated control performed by modern measurement devices. These developments have placed growing demands on coordinate metrology, particularly in terms of the accuracy of manufactured components, measurement speed, and the degree of automation. As industries continue to evolve, the expectations for product quality rise accordingly, presenting new challenges for metrologists in areas such as estimating measurement uncertainty, calibration procedures, and supervising optical measurement systems (Fan, 2016; Śladek, 2016; Yang et al., 2015).

The continuous progress in optical measurement technologies has led to the emergence of innovative calibration techniques and new approaches to evaluating measurement accuracy. Within the domain of optical metrology, systems can be categorised based on structured light (Li et al., 2023), photogrammetry utilising laser triangulation (Chen et al., 2019), Time of Flight (TOF) measurements (Frangé et al., 2022), as well as advanced imaging methods such as computed tomography (CT) (Carmignato et al., 2012) and magnetic resonance imaging (MRI) (Zanini and Carmignato, 2019). Each of these technologies offers distinct capabilities and introduces specific requirements for ensuring the reliability and precision of measurement results.

The German metrology institute PTB (Physikalisch-Technische Bundesanstalt), together with the Association of German Engineers (VDI) and the Association for Electrical, Electronic and Information Technologies (VDE), established the VDI/VDE 2634 series as one of the most widely recognised guideline sets for evaluating the performance of optical 3D measurement systems (VDI/VDE 2634). These guidelines provide standardised procedures for calibration, verification, and acceptance testing of different classes of optical sensors, including point-by-point probing systems (Part 1), single-view area-scanning systems (Part 2),

and multi-view area-scanning systems (Part 3). Their purpose is to ensure traceable and comparable metrological performance, particularly in industrial contexts where non-contact measurement systems exhibit sensitivity to environmental and operational conditions (Icasio-Hernández et al., 2024). VDI/VDE 2634 should be understood as a practical metrological benchmark: it defines the types of test artefacts (e.g., calibrated spheres, ball-bars, planar surfaces), specifies how these artefacts must be scaled and calibrated, and prescribes test procedures that target the most common system-level errors. The standard explicitly requires verification of system behaviour under realistic operating conditions, including variations in temperature, lighting, mechanical stability, and sensor orientation. According to the guideline, system accuracy is assessed through three principal error types: (1) probing error, characterising the intrinsic accuracy of the optical sensing head; (2) sphere-spacing error, capturing the system's ability to measure calibrated distances; and (3) flatness measurement error, which evaluates deviations when measuring planar geometries. Recent research shows that the sensitivity of these VDI/VDE-based tests is essential for detecting systematic errors in optical and structured-light systems, highlighting the ongoing relevance of the guideline in modern dimensional metrology.

This article presents a novel methodology for range-based optical system verification, based on the modified VDI/VDE standard. Calibration fields based on this standard are typically designed for small measurement ranges, often for structured light measurements. At the Centre for Geospatial and Satellite Analysis, Faculty of Geodesy and Cartography (CENAGIS), Warsaw University of Technology, a calibration standard has been developed for evaluating large measurement areas, specifically designed for active laser systems based on Terrestrial Laser Scanners (TLS). This article presents the testing procedure for static laser scanners on the CENAGIS Metrological Verification Standard (CENAGIS-MET) test field. In this study, two terrestrial laser scanners, the Z+F5006h and Leica RTC360, a handheld

laser scanner (Mandeye) equipped with a Livox Mid-360 (tested in static mode), and the Leica Nova MS60 scanning total station were analysed. Measurement uncertainties, standard deviations, and device classification into accuracy categories were determined.

2. CENAGIS-Metrological Verification Standard

This chapter presents the assumptions underlying the proposed CENAGIS-MET methodology for range-based testing of measurement systems. The characteristics of reference shapes for the metrological evaluation of measurement systems will be described (Section 2.1), along with the data acquisition and processing workflow (Section 2.2).

2.1 Hardware description

To calibrate active measurement systems, a measurement station was constructed according to the standards set forth by Ostrowska et al. (2012) and by Smarttech (Gębarski and Jasiński, 2014). The "measurement station" (Figure 1) consists of: (1) a rigid measurement frame in the shape of a cube with dimensions: 1.5 m length, 1.5 m height, 1 m depth, mounted on additional legs; (2) a stable column stand allowing height adjustment within a range of at least 1 m and rotation around its own axis; (3) a (photographic) head enabling the mounting of calibration patterns for analysis and their rotation along three axes; (4) three calibration artefacts.

For the analysis of probing error, a sphere with a diameter of 47.63831 mm (measurement uncertainty of 1.5 μm) was manufactured from ceramic material with a texture designed to diffuse light effectively. The sphere-spacing error is examined using a calibration artefact consisting of two ceramic spheres with diameters of 47.6333 mm and 47.6307 mm, positioned at a centre-to-centre distance of 710.1688 mm with a measurement uncertainty of 6.0 μm . The spheres are mounted on a carbon fibre structure with a thermal expansion coefficient $\alpha=0.23 \cdot 10^{-6} \cdot \text{K}^{-1}$. To determine the flatness measurement error, a spatial flatness calibration artefact measuring 720 mm $\times$ 200 mm with a chemically matte surface was produced. The flatness error is 0.0528 mm, with a measurement uncertainty of 4.4 μm .



Figure 1. CENAGIS-MET measurement station.

2.2 Methodology of data acquisition and processing

To assess the metrological quality of the range-based sensors, a modified approach based on the VDI/VDE-3 standard was adopted. Accordingly, an extended analysis was conducted, including Probing Error, Sphere Spacing Error, and Flatness Assessment. In Figure 2, the potential position of the calibration artefacts used for probing error, sphere-spacing error, and flatness assessment is presented. All possible measurement modes are analysed to identify trends and determine the minimal settings at which the assumptions of metrological verification based on the CENAGIS-MET standard are fulfilled.

2.2.1 Probing error

The error of the optical head system (probing error) represents a characteristic deviation in optical 3D measurement systems based on surface scanning within a limited measurement range. To evaluate this, the distance between the centre of the sphere, determined using the Gauss criterion (least squares method), is calculated and expressed as $2R$ (where R is the radius of the fitted sphere). The shape error of the reference sphere must remain below one-fifth of the dimensional characteristic of the sphere artefact used. Measurements are performed with the sphere positioned in at least ten different positions throughout the entire measurement volume to ensure comprehensive coverage.

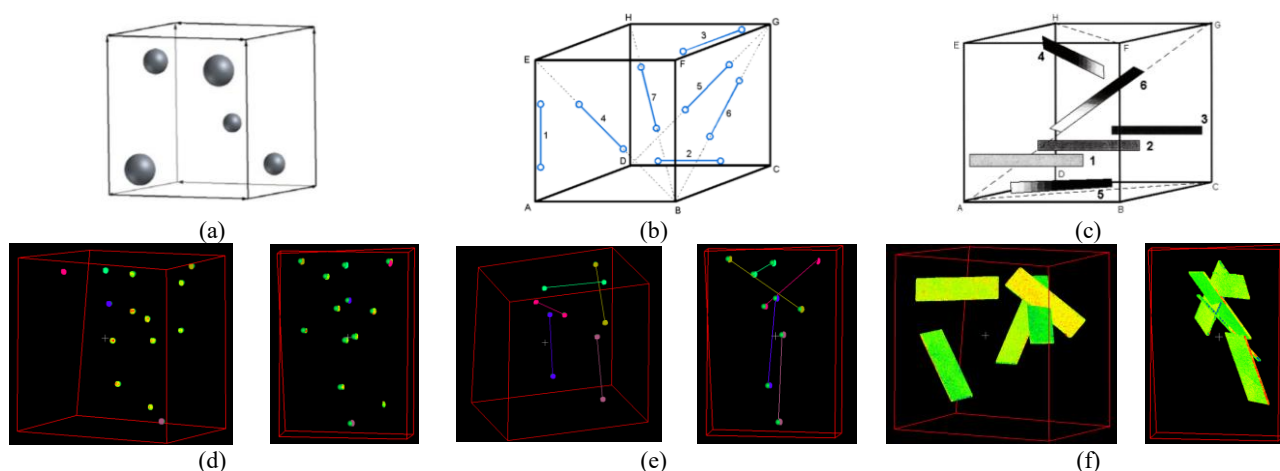


Figure 2. Position of standards on the VDI/VDE-3 (a-c) (Ostrowska et al., 2012) and CENAGIS-MET (d-f) measurement station: (a, d) probing error, (b, e) sphere-spacing error, (c, f) flatness measurement error.

Furthermore, the distribution of measurement points must uniformly cover the entire measurement space to ensure a reliable assessment of system accuracy and repeatability (Figure 2a). Additionally, a shape analysis was carried out based on eigenvector evaluation and variance of normal vector changes.

2.2.2 Sphere-spacing error

Sphere-spacing error is a key metric used to verify the system's ability to reproduce length accurately. It is defined as the difference between the measured value and the calibrated reference distance between two spheres (Figure 2b). The test is performed using a certified artefact on which two spheres, typically made of steel, ceramics, or other suitable materials, are mounted. Measurement uncertainties must be known and should not exceed one-fifth of the evaluated quality parameter, ensuring compliance with metrological standards. This procedure guarantees that the system can reliably reproduce dimensional characteristics within the specified tolerance range.

2.2.3 Flatness error

Flatness error is defined as the range of distances between the measured points and the plane constructed using the least squares method for best fitting. Standards in the form of parallelepipeds made of steel, ceramics, aluminium, or other low-reflectivity materials are applied. These standards should have widths of not less than 50 mm and lengths of at least 0.5 times L_0 (where L_0 is the dimension of the measured frame). The deviation of the measurement points from the best-fit plane constitutes the flatness error. Compliance is confirmed when the maximum permissible error is not exceeded, and the flatness error of the reference standard should not be greater than one-fifth of the measured characteristic. Additionally, to assess the quality and correctness of the reference plane reproduction, an analysis of eigenvectors is performed along with evaluations of roughness, planarity, density, and normal vector variance.

2.3 The description of verified range-based sensors

To verify range-based sensors with the CENAGIS-MET standard, two Terrestrial Laser Scanners (Leica RTC360 and Z+F 5006h), the Leica MS60 scanning total station and the low-cost SLAM system Mandeye were selected for use (Figure 3).



Figure 3. Utilised sensors.

The Leica RTC360 is a high-speed TLS that uses advanced Waveform Digitising (WFD) technology to enhance time-of-flight measurements. It operates with a Class 1 laser at 1550 nm, ensuring eye safety while delivering precise results. The scanner offers a full 360° horizontal field of view and a 300° vertical field of view, with a measurement range of 0.5 m to

130 m. It achieves a scanning speed of up to 2,000,000 points per second. It provides three selectable resolution settings (3, 6, or 12 mm at 10 m), with angular precision of 18", range accuracy of ± 1.0 mm plus 10 ppm, and 3D point accuracy ranging from 1.9 mm at 10 m to 5.3 mm at 40 m. Range noise remains minimal at 0.4 mm at 10 m and 0.5 mm at 20 m.

The Z+F IMAGER 5006h is a high-precision TLS designed for industrial and architectural applications. It features a laser measurement system with an ambiguity interval of 79 m, a minimum range of 0.4 m, and a resolution of 0.1 mm. The scanner achieves a maximum data acquisition rate of 1,016,727 points per second, with linearity error kept below 1 mm up to 50 m. Range noise varies with surface reflectivity and distance: at 10 m, it ranges from 0.4 mm RMSE for white surfaces to 1.2 mm RMSE for black surfaces; at 50 m, noise increases to 1.8 mm RMSE for white and 6.8 mm RMSE for black surfaces. The deflection unit employs a rotating mirror system, offering a 360° horizontal field of view and a 310° vertical field of view, with an angular resolution of 0.0018° and an accuracy of 0.007°. Scanning speeds reach up to 50 rotations per second (rps), with typical operation at 25 rps. Resolution settings include preview (1,250 pixels per 360°), middle (5,000 pixels), and high (10,000 pixels), with scanning times ranging from 13 seconds in low-quality mode to 6 minutes 44 seconds in high-quality mode.

The Leica MS60 MultiStation combines total station functionality with high-speed 3D scanning and imaging capabilities. It offers absolute, continuous angle measurement with an angular accuracy of 1" (0.3 mgon) for both horizontal and vertical axes. Distance measurement is highly versatile: using a prism, it covers ranges from 1.5 m to over 10,000 m with an accuracy of $\pm(1 \text{ mm} + 1.5 \text{ ppm})$ and a typical measurement time of 1.5 seconds; for single measurements on any surface, the range extends up to 2,000 m with an accuracy of $\pm(2 \text{ mm} + 2 \text{ ppm})$. The system utilises Waveform Digitising technology with a coaxial visible red laser, featuring a dot size of 8 mm $\times$ 20 mm at a distance of 50 m. Scanning performance includes a maximum scan rate of 30,000 Hz and up to 30,000 points per second. Depending on the mode, the maximum range varies: 60 m in 30 kHz mode (with 3 mm noise at 50 m), 150 m in 8 kHz mode (1.5 mm noise), 300 m in 1 kHz mode (1.0 mm noise), and up to 1,000 m in 1 Hz mode (0.6 mm noise at 50 m).

The Mandeye system, equipped with the MID-360 LiDAR sensor, is a low-cost mobile scanning solution designed for SLAM-based mapping. It operates at a wavelength of 905 nm and complies with Class 1 laser safety standards (IEC60825-1:2014). The detection range varies with surface reflectivity, ranging from 40 m for 10% reflectivity to 70 m for 80% reflectivity, with a proximity blind zone of 0.1 m. The field of view spans 360° horizontally and ranges from -7° to 52° vertically, providing comprehensive spatial coverage. Range precision is ≤ 2 cm at 10 m and ≤ 3 cm at 0.2 m, while angular precision remains below 0.15°. The sensor delivers a point rate of approximately 200,000 points per second (first return) at a typical frame rate of 10 Hz. These characteristics make Mandeye suitable for dynamic and static scanning scenarios where cost efficiency and mobility are prioritised over ultra-high accuracy, offering practical performance for indoor mapping, construction monitoring, and rapid documentation tasks.

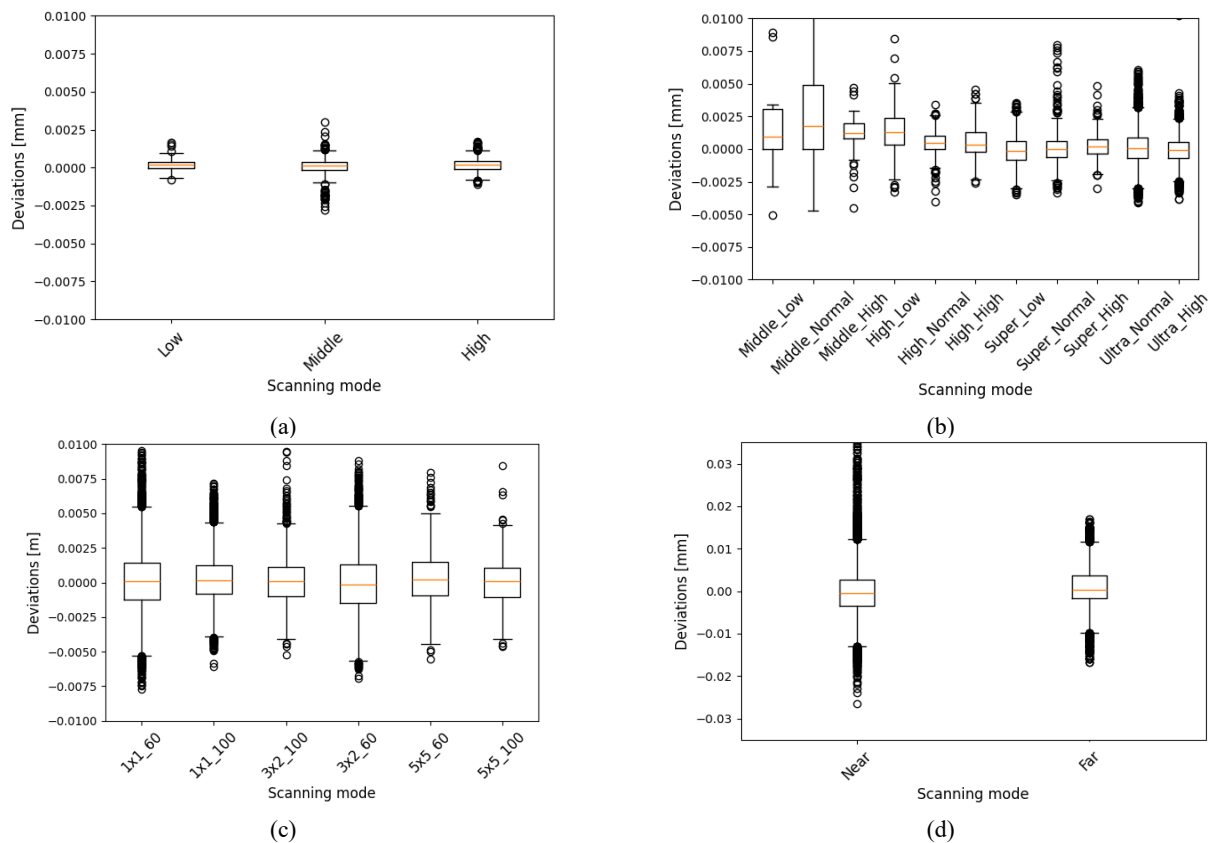


Figure 4. Analysis of probing error results presented as a boxplot: (a) Leica RTC360, (b) Z+F 5006h, (c) Leica MS60, and (d) Mandeye.

3. Results of data processing

The abstract presents the results of the analysis of probing, sphere-spacing, and flatness error, excluding the outcomes of the normal vector analysis, which will be discussed in the full version of the article. The results presented in Figures 4-6 illustrate the accuracy (correctness of shape reproduction) achieved across all available measurement modes.

Boxplots were used for the statistical analysis of measurement data. It shows the median, the lower and upper quartiles (forming the "box"), and the minimum and maximum values within a defined range (represented by "whiskers"), while highlighting potential outliers as individual points. Boxplots are particularly useful for comparing multiple datasets, identifying skewness, and detecting anomalies, making them a common tool in exploratory data analysis and statistical reporting.

3.1 Probing error

The first investigation was based on the probing error analysis. Results presented in Figure 4 show that the Leica RTC360 delivers the most accurate and precise results, with medians remaining essentially at zero for all scanning modes and dispersion being minimal, indicating negligible mode-dependent bias and very high repeatability. Z+F 5006h exhibits mode-specific behaviour, with visibly larger spreads and systematic offsets that reverse in sign between modes, together with more outliers. Due to this fact, it is worth mentioning that choosing the specific scanning mode influences the final quality of shape determination. The Leica MS60 exhibits a small, persistent bias (slightly negative) that remains unchanged with denser settings; higher-quality modes reduce variance somewhat

but do not eliminate the offset, indicating the need for post-processing correction. Mandeye displays the widest dispersion (note the broader y-axis scale) and a clear dependence on measurement conditions (e.g., near vs far), with both substantial bias shifts and many outliers-appropriate for rapid documentation rather than millimetric engineering tasks.

3.2 Sphere-spacing error

To verify the sphere-spacing error, the relative error was assessed. Based on the evaluation of the relative sphere-spacing error (%) (Figure 5) for average and maximum values across scanning modes, Leica RTC360 exhibits uniformly low errors with minimal separation between average and maximum, indicating high stability of scale and negligible mode dependence; Leica MS60 shows a comparable trend, with consistently small bars and a narrow Avg-Max gap across all settings. In contrast, the Z+F 5006h displays a pronounced mode effect: the Middle mode yields the largest errors, while errors decrease systematically through High, Super, and Ultrahigh mode, and the Avg-Max difference contracts accordingly, indicating improved dispersion control with increasing acquisition quality. Mandeye presents the highest relative errors among the instruments and the most significant Avg-Max disparity, accompanied by a clear distance dependence, as the Far condition markedly exceeds the Near condition; this combination suggests greater variability and more frequent extreme deviations in inter-sphere spacing. Collectively, the results differentiate the instruments by scale fidelity and repeatability, with RTC360 and MS60 remaining consistently stable across modes, Z+F 5006h improving monotonically with quality settings, and Mandeye showing substantial sensitivity to measurement conditions.

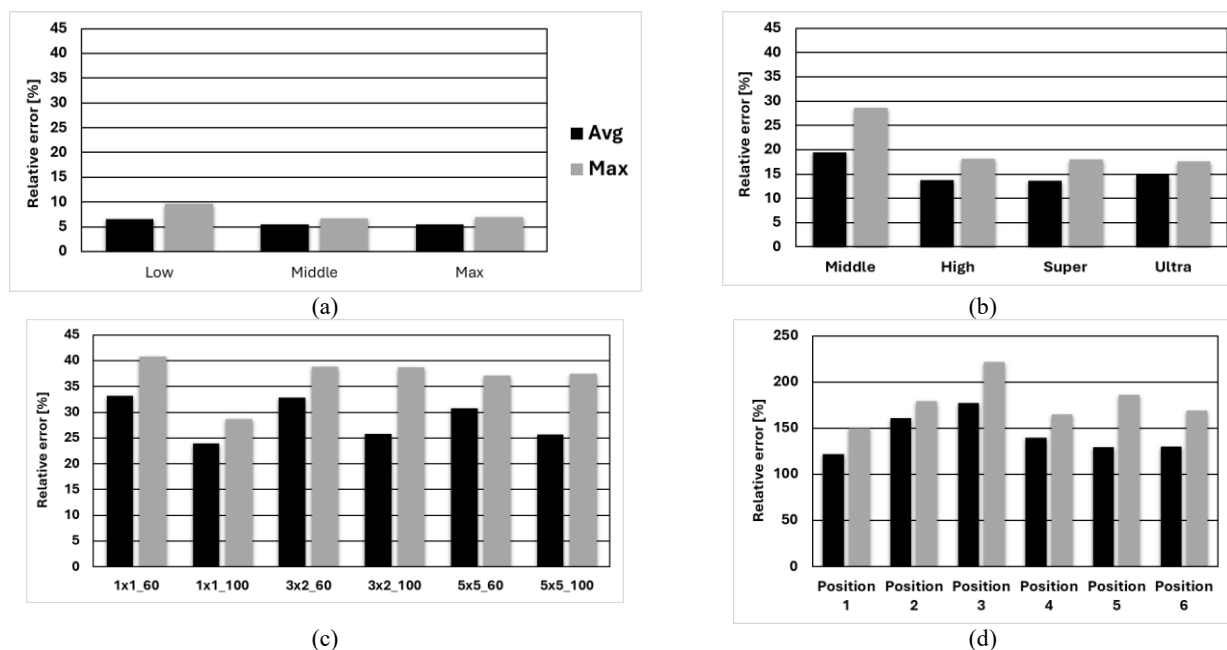


Figure 5. Sphere-spacing error results: (a) Leica RTC360, (b) Z+F 5006h, (c) Leica MS60, and (d) Mandeye.

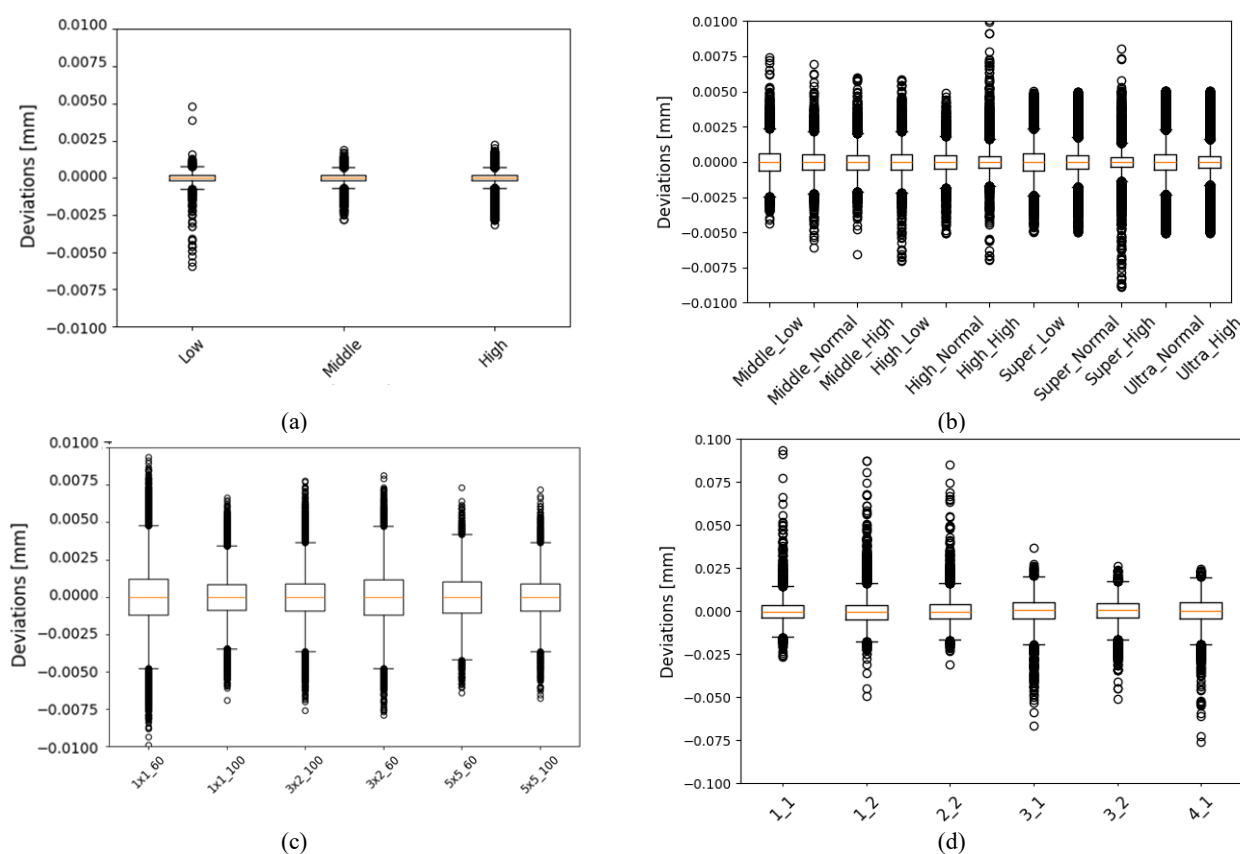


Figure 6. Flatness results: (a) Leica RTC360, (b) Z+F 5006h, (c) Leica MS60, and (d) Mandeye.

3.3 Flatness error

The flatness error boxplots (Figure 6) indicate clear performance stratification across instruments: Leica RTC360 exhibits the most planar fidelity, with medians essentially at zero for all modes, very tight interquartile ranges, symmetric whiskers, and few outliers, implying negligible mode-dependent bias and high repeatability; Z+F 5006h shows medians still clustered around zero but with noticeably larger spreads; Leica MS60 presents a consistent, slightly negative median across modes together with broader dispersion and numerous outliers, so increased density reduces variance only modestly and does not remove the bias; finally, Mandeye displays the widest y-axis range, the most significant interquartile widths, many outliers, and mode-dependent shifts of the median (often with skewed distributions), indicating strong sensitivity to measurement geometry and reconstruction, and rendering it less suitable for high-precision flatness assessment without extensive control targets and post-processing.

4. Discussion

Compared with international acceptance and reverification standards for optical and coordinate-based 3D systems (VDI/VDE 2634; ISO 10360-8; ISO 10360-13) and field/medium-range protocols for TLS (ISO 17123-9; ASTM E3125), the CENAGIS-MET workflow preserves the canonical artefact-based metrics (probing, sphere-spacing, flatness) while extending them with directional-shape diagnostics (normal-vector variance) and a mode-resolved experimental design. This yields higher sensitivity to reconstruction-related distortions and exposes mode-dependent trade-offs that are invisible to standard pass/fail MPE criteria. Practically, a single, thermally stable test rig enables cross-technology benchmarking (TLS, scanning total station, handheld SLAM) under identical geometry, improving instrument selection and parameter tuning. The approach complements, rather than replaces, long-range field tests, offering repeatable, lab-scale insight into shape fidelity before ASTM/ISO field qualification.

Tab. 1 Flatness analysis

Sensor	Roughness		
	Average	Minimum	Maximum
Leica RTC360	0.000252	0.000140	0.000331
Z+F 5006h	0.000627	0.000256	0.000872
Leica MS60	0.001545	0.000615	0.002114
Mandeye	0.000724	0.000114	0.002165
Normal vector change			
Leica RTC360	0.001433	0.000362	0.002231
Z+F 5006h	0.008937	0.001388	0.015806
Leica MS60	0.014126	0.003326	0.023499
Mandeye	0.033005	0.004552	0.119190

Among all evaluated systems (Table 1), Leica RTC360 demonstrated the lowest roughness and normal vector change, confirming the highest geometric stability in planar surface reconstruction. At the same time, Z+F 5006h achieved moderate performance with slightly higher but still consistent noise levels. In contrast, Leica MS60 showed noticeably increased roughness and variability depending on scanning configuration, and Mandeye exhibited the highest surface variation and noise, indicating significant local deviations from planarity. These results clearly differentiate the systems: phase-based scanners such as Leica RTC360 and Z+F 5006h provide superior planar

fidelity, whereas Leica MS60 and especially Mandeye require more extensive filtering or denoising to achieve comparable reliability in flatness assessment.

Tab. 2 Sphere shape analysis (probing error)

Sensor	Curvature		
	Average	Average	Average
Leica RTC360	0.000001	0.000001	0.000001
Z+F 5006h	0.001299	0.001299	0.001299
Leica MS60	0.025512	0.025512	0.025512
Mandeye	0.021323	0.021323	0.021323
Normal vector change			
Leica RTC360	0.010669	0.010669	0.010669
Z+F 5006h	0.020762	0.020762	0.020762
Leica MS60	0.059560	0.059560	0.059560
Mandeye	0.135959	0.135959	0.135959

Table 2 presents the results of the analysis of curvature-based shape parameters and normal vector characteristics for the probing error assessment. The Leica RTC360 remained the most stable system, consistently producing curvature values near zero and the lowest surface variation, confirming its high reliability in spherical surface reconstruction. The Z+F 5006h scanner demonstrated stable performance, with curvature values remaining low, though still showing occasional moderate deviations compared to the other sensors. The Leica MS60 continued to exhibit higher curvature and surface variation values, indicating greater measurement noise and less uniform sampling even after removing the largest errors. The Mandeye system consistently produced the highest surface variation and elevated curvature values, revealing persistent deviations from the ideal spherical geometry. These results confirm that phase-based systems such as Leica RTC360 and Z+F 5006h deliver superior geometric fidelity on spherical artefacts, whereas MS60 and especially Mandeye require more rigorous correction or filtering to approach comparable performance.

A detailed interpretation of the observed deviations indicates that the primary sources of the instrument-specific errors are linked to a combination of hardware constraints and algorithmic processing strategies. For the Leica RTC360, the extremely low probing and curvature errors can be attributed to the high-frequency waveform digitising engine and efficient noise-filtering algorithms, which collectively minimise range jitter and angular quantisation effects. In contrast, the Z+F 5006h demonstrates moderate instability in shape reconstruction, particularly in mid-quality modes, which is likely caused by the mechanical mirror deflection unit introducing small repeatability variations as well as a stronger dependence of the range noise on surface reflectivity. For the MS60, the systematic bias visible in both flatness and curvature results appears to originate from its hybrid architecture: the red-laser EDM module and 3D scanning subsystem operate at differing optimal ranges, which may cause geometric inconsistencies around short distances where the spherical artefact was analysed. Mandeye, equipped with a low-cost Livox sensor, exhibits the highest sensitivity to incidence angle and sampling non-uniformity; in static mode, its non-repetitive scanning pattern generates spatially heterogeneous point densities that amplify curvature and surface variation metrics.

5. Conclusion

The presented results of the performed investigation indicate the potential for applying the proposed CENAGIS-MET standard to the metrological assessment of active (range-based) measurement systems (Figure 7).

	Leica RTC 360	Z+F 5006h	Leica MS60	Mandeye
Probing error				
Sphere space error				
Flatnes error				
	Exceeds 1/5 of the relative error value	Partly compliance with the 1/5 relative error criterion	Full compliance with the 1/5 relative error criterion	

Figure 7. Summary of the metrological performance of the four scanning systems with respect to CENAGIS-MET.

The Leica RTC360 and Leica MS60 demonstrate full compliance with the 1/5 relative error criterion across probing, sphere spacing, and flatness tests, confirming their reliability for high-precision applications. The Z+F 5006h achieves partial compliance, particularly in sphere spacing and flatness, indicating that while it is generally suitable, it requires careful configuration for tasks demanding strict dimensional accuracy. Mandeye exceeds the permissible threshold in all evaluated parameters, indicating significant limitations in 3D shape reconstruction. It is suitable only for qualitative or lower-quality documentation. These findings highlight RTC360 and MS60 as the most dependable solutions for engineering-grade measurements, with the Z+F 5006h as a conditional option, and Mandeye as restricted to low-accuracy contexts.

The results clearly show that the Leica RTC 360 exhibits the most robust and consistent performance across all examined parameters, achieving full compliance with the 1/5 relative error criterion defined in the standard. This confirms its suitability for high-precision engineering applications, especially where stringent geometric fidelity is required. The Z+F 5006h demonstrates partial compliance in several categories, indicating stable yet moderately constrained measurement quality within the context of advanced surveying tasks.

In contrast, the Leica MS60 and Mandeye systems exhibit exceedances of the allowable error thresholds for certain parameters (particularly in probing error and flatness error) highlighting limitations that may restrict their deployment in precision-critical geospatial or industrial measurement workflows. These deviations underscore the importance of standardised metrological validation as a prerequisite for selecting appropriate hardware for deformation monitoring, structural diagnostics, or detailed geometric documentation.

Overall, the results confirm the effectiveness of VDI/VDE 2634 as a rigorous framework for assessing and comparing the geometric performance of terrestrial laser scanners. The presented findings contribute to a more informed understanding of instrument capabilities and emphasise the necessity of objective, standardised testing methods in ensuring the reliability of 3D measurement technologies used in contemporary geodetic and engineering practice.

In addition to confirming the usefulness of the CENAGIS-MET validation workflow, the multi-sensor comparison highlights the fundamental performance limits of each technology class. TLS instruments (RTC360, Z+F 5006h) consistently outperform

triangulation- and SLAM-based systems due to more stable range measurement principles and reduced susceptibility to specular artefacts on ceramic standards. The MS60, despite excelling in long-range precision surveying, demonstrates that hybrid total-station architectures cannot fully match the geometric fidelity of dedicated TLS devices at close-range working distances. Mandeye's results emphasise that low-cost LiDAR systems, although practical for rapid mapping and documentation, should not be used for tasks requiring metrological traceability or shape-based verification. These distinctions underline the necessity of systematic instrument qualification on certified artefacts before applying any sensor to engineering or diagnostic workflows. The presented findings show that implementing a unified, artefact-based protocol such as CENAGIS-MET allows users to identify critical performance boundaries, optimise acquisition settings, and detect systematic distortions that are not visible in manufacturer specifications.

The observed deviations across the tested scanning systems can be attributed to a combination of hardware-related factors, such as sensor noise characteristics, optical beam divergence, mechanical stability of deflection units, and surface-dependent reflectivity responses, as well as algorithmic effects including filtering procedures, normal-vector estimation, fitting strategies (based on least squares method), and point-distribution irregularities introduced by system-specific acquisition patterns. These jointly influence the probing error, sphere-spacing accuracy, and flatness. Since the proposed CENAGIS-MET workflow aspires to function as a transferable metrological standard, this guarantees that the methodology can be reliably adopted across different system types and measuring environments, fulfilling the requirements of a robust verification standard.

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