

Calibration of storage tanks in the oil and gas sector based on the concept of digital metrology and big data analytics – Part II

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Abstract – Part II of this study presents the practical implementation and evaluation of the digital paradigm for storage tank calibration in the oil and gas sector, as conceptually and methodologically established in Part I. This section demonstrates the practical application of digital methods for calibration, including 3D laser scanning, the analysis and description of the final results obtained through the processing of collected measurements, the establishment of the metrological traceability chain, and a brief overview of key measurement uncertainty components. The findings indicate the potential for a shift from reactive to predictive calibration strategies, in alignment with Industry 4.0 principles and contemporary requirements for interoperability and digital metrology.

Keywords: digital metrology, 3d laser scanning, tank calibration, digital twin, industry 4.0

I. INTRODUCTION

This paper represents a continuation of the previous study described in Calibration of storage tanks in the oil and gas sector based on the concept of digital metrology and big data analytics – Part I, in which the conceptual and methodological foundations of digital metrology applied to the calibration of industrial tanks were established. Within this second part, the focus is placed on the experimental application and technical evaluation of the digital calibration paradigm, with the aim of quantitatively verifying the accuracy, data quality, and traceability of measurements under real industrial conditions. Through the scanning of three horizontal and three vertical steel tanks, factors influencing the quality of the collected data, geometric accuracy of the models, and reliability of the volumetric calibration tables were analyzed. The scanning was conducted from multiple positions, with point cloud registration carried out in the Leica Cyclone REGISTER 360 software environment, and further processing in Cyclone 3DR, using Python scripts for

volume correction, temperature influence simulation, and digital deformation modeling. The resulting models were used for geometric analysis in accordance with API 650/653 standards and for the calculation of measurement uncertainty in line with GUM and EA-4/02 guidelines.

The aim of this part of the study is to demonstrate the technical feasibility, benefits, and challenges of digitizing the calibration process for large industrial tanks, as well as to provide foundation for the future integration of interoperable digital solutions into accredited calibration protocols.

II DATA PROCESING AND GEOMETRIC RECONSTRUCTION

During the scanning of horizontal storage tanks, it was observed that the interior did not contain structural elements capable of generating additional signal noise (e.g., heaters, mechanical obstructions). This favorable condition enabled the acquisition of homogeneous and high-fidelity point clouds (Figure 1), without the need for additional post-processing aimed at filtering spurious reflections. In contrast, vertical tanks were equipped with internal components, such as heaters, instrumentation, and piping systems, that introduced localized artifacts into the point cloud by reflecting the laser signal. To mitigate their influence on volume estimation, an analytical correction procedure was applied, in which the volumes of these internal elements were identified, geometrically modeled, and subtracted from the total reconstructed tank volume. This procedure ensured a metrologically valid result. In this context, there is scope for integrating machine learning algorithms into the software environment, enabling the automated identification of critical internal structures based on their volumetric impact on total tank volume. These elements could then be retained or excluded from the final model according to predefined thresholds. Such internal components fall under the definition of “dead volume,” as further described in ISO 7507-1. Based on Figure 2, it can be concluded that the models for the horizontal tanks (R1, R2, R3) exhibit a high degree of

symmetry, with clearly defined end caps and no visible deformations along the cylindrical body. The absence of “cold” zones (indicated by blue and green tones) suggests high registration accuracy and good positional stability during point cloud processing.

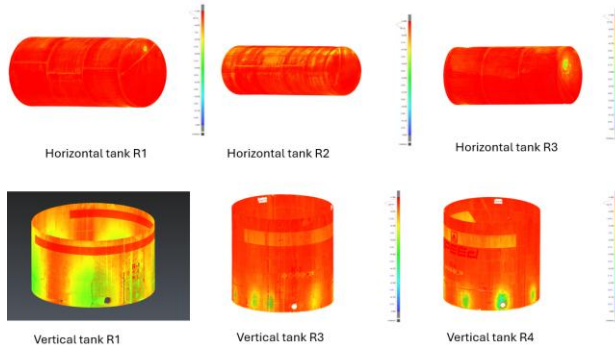


Figure 1. Registered point clouds of scanned tanks

In contrast, the models for the vertical tanks (R1, R3, R4) display greater color variation, particularly in the lower regions (blue/green areas), indicating the presence of localized deformations or internal structures such as heaters, sensors, and piping systems. Vertical tank R1 shows a distinctly multicolored distribution, suggesting more complex internal geometry and potential signal disturbances during scanning. Vertical tanks R3 and R4 exhibit pronounced horizontal bands, resulting from the joints between steel plates of varying thicknesses. The color-coded deviation patterns are more prominent (green and blue tones), indicating a broader range of deviations, potentially reaching up to ± 5 mm in certain localized areas. Data acquisition was performed from multiple scanner positions to ensure full coverage of the internal surface. Point cloud registration was carried out in the Leica Cyclone REGISTER 360 software environments using an automated workflow. Alignment of individual scan coordinate systems was performed via a seven-parameter Helmert transformation, ensuring accurate spatial integration of all points into a unified global reference frame. A prerequisite for this method was the availability of spatial coordinates of signal targets, distributed such that at least three common reference targets were visible within the overlap area of any two adjacent scans. Thanks to recent research on scan planning optimization (including the number of scan positions, distribution of reference targets, and required overlap), individual scan pairs exhibited a high degree of spatial overlap, facilitated by the geometrically constrained cylindrical shape of the tanks.

The number of reduced points, following the application of filtering and point cloud optimization, was approximately 440,000 per individual point cloud. This represents a significant reduction compared to the initial datasets, which contained several tens of millions of

points. The reduction was carried out while preserving spatial resolution in critical areas, such as the transitions between the tank walls and bottom, as well as in regions where deformations were identified. This approach enabled more efficient numerical processing without compromising the geometric accuracy or the metrological relevance of the reconstruction. After the filtering stage, a three-dimensional surface mesh was generated (Figure 2). In the context of laser scanning, a mesh constitutes a continuous geometric approximation of discrete measurement points, whereby adjacent points are connected via triangular or quadrilateral facets to form a coherent digital surface. The resulting 3D model (Figure 3) served as the analytical foundation for deformation analysis, ovality detection, numerical volume computation, and visualization of deviations from ideal geometry.

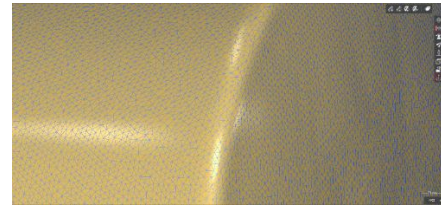


Figure 2. Meshed Surface of the Storage Tank

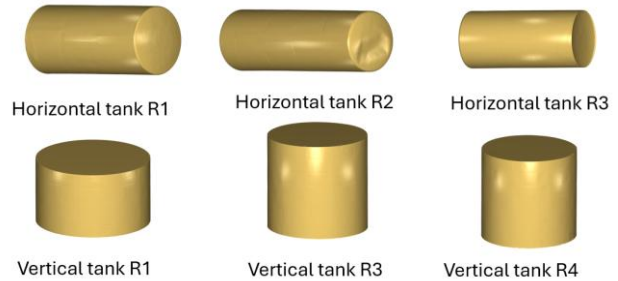


Figure 3. 3D models of tanks

Based on the 3D models of the scanned storage tanks (Figure 3), it can be concluded that all analyzed structures, three horizontal and three vertical tanks, exhibit topologically continuous and coherent surfaces, confirming successful point cloud registration and mesh generation. Horizontal tanks show a high degree of longitudinal symmetry and minimal artifacts, indicating effective scan planning with optimal overlap that mitigated shadowing and loss of data density. Vertical tanks R3 and R4 display mild geometric irregularities, such as local ovality and deviations from ideal cylindrical form, likely caused by internal components (e.g., heaters or piping), occluded scan areas, or meshing limitations. In horizontal tank R2, a slight deformation of the front-end cap and discrete horizontal surface variations suggest minor geometric imperfections potentially arising from operational stress, pressure variations, or fabrication

inaccuracies. Despite localized anomalies, all models maintain sufficient geometric fidelity to support advanced analyses, including ovality assessment, corrected volume computation, and digital twin development. For final verification, comparison with CAD reference models and extraction of sectional profiles is recommended, in line with the applicable standards for dimensional tolerances.

A. Geometric Analysis and Deformation Assessment

As part of a modern digital metrological approach, once a three-dimensional model of the tank is generated, a comprehensive geometric analysis is conducted to identify deviations and deformations relative to the design geometry. This analysis is performed in accordance with the requirements of API 650 [1] and API 653 [2]. One of the key steps is the analysis of shell ovality, which is carried out by evaluating horizontal cross-sections along the height of the tank. In each cross-section, deviations in radius from an ideal circular form are measured, enabling the identification of potential distortions resulting from non-uniform loading, thermal gradients, or mechanical damage to the structure. Ovality testing for vertical tanks was conducted using cross-sectional samples at 1-meter height intervals, while for horizontal tanks, the analysis was performed at 0.5-meter intervals along the horizontal cylindrical axis. Figure 4 presents representative examples of ovality profiles for Vertical Tank R4 at heights of 1 m, 5 m, and 10 m, and for Horizontal Tank R1 at longitudinal positions of 0.5 m, 3.5 m, and 5.5 m.

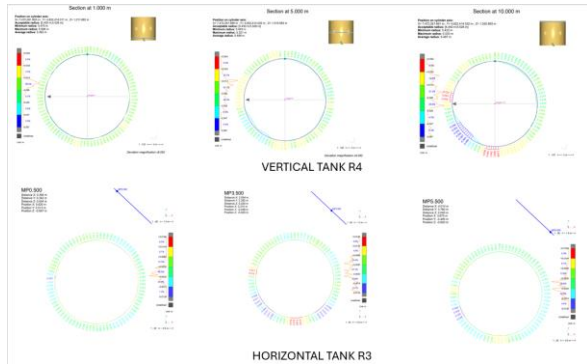


Figure 4. Representative Samples of Ovality Testing: Vertical Tank R4 and Horizontal Tank R1

In addition to ovality analysis, deviation maps (Figure 5) are generated, which provide a visual representation of local discrepancies between the reconstructed model and the reference geometric shape (in our case, the best cylinder shape). These maps allow for the efficient detection of localized anomalies, including dents, bulges, and other irregularities that may indicate structural weaknesses, material erosion, or damage sustained in prior operational cycles.

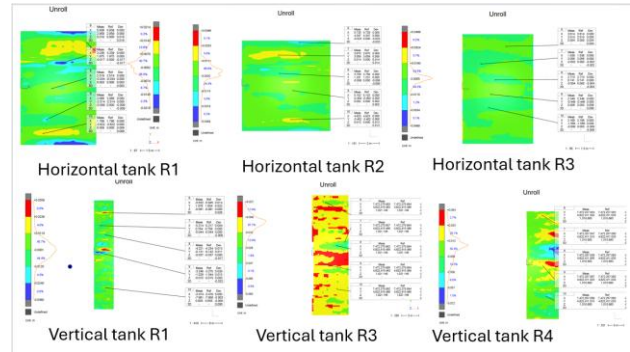


Figure 5. Deviation maps of the tank shell

From Figure 5, shows that for the horizontal tanks (R1, R2, R3), the colors are predominantly green, yellow, and partially blue and orange. Green means small deviations; the surface is very close to an ideal cylinder. Yellow/Red means bulges (positive deviation). Blue means indentations (negative deviation). The horizontal tanks are generally in good geometric condition. Maximum deviations are below ± 5 mm. Vertical tanks (R1, R3, R4), the colors include a wider range of shades, including red and dark blue. Vertical tank R3 shows deviations (red and yellow zones) – deviations reach ± 7 mm or more. Tank R1 displays a localized deviation zone (dark red), which may indicate a deformation or dent, but of a very localized and isolated nature. Tank R4 shows a localized bulge deviation (blue and dark blue zones).

The analysis of the spatial orientation of the vertical axis of the tank enables detection of tilt, curvature, or eccentricity in the structure, which is especially critical for the safe operation of tanks equipped with floating roofs or subject to dynamic loading conditions. This is achieved by determining the orientation of the tank's central axis based on multiple horizontal cross-sections taken along the tank's height. Across 10 cross-sections, each spaced 18 degrees apart, the ovality assessment was performed circumferentially around the tank shell in a clockwise direction. An example of a single ovality evaluation is shown in Figure 6 corresponding to Vertical Tank R4, specifically for the sector between 0° and 180° .

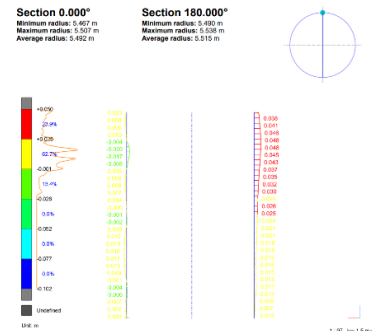


Figure 7. The spatial orientation of the vertical axis of the tank R4 Vertical, position 00° - 180°

Furthermore, evaluation of the flatness and roundness of the tank bottom and roof structure could also be performed, particularly in designs featuring flat or conical foundations. Deviations in these zones can lead to uneven stress distribution, sediment accumulation, leakage, or structural vulnerabilities, and in accordance with API 653 guidelines, they require continuous monitoring and, if necessary, implementation of corrective measures. For the purposes of this study, this segment was not taken into consideration.

All the analytical procedures can be performed within the Leica Cyclone 3DR software environment, utilizing its built-in tools for sectional analysis, deviation map generation, axis transformation, and geometric evaluation of roundness and flatness. Alternatively, the same analyses can be automated and further adapted to specific industrial needs using the Python programming environment, supported by point cloud processing libraries (e.g. *Open3D*, *PCL*, *NumPy*, *Matplotlib*) and customized numerical algorithms. This enables a flexible and scalable application of the described procedures, both in commercial software platforms and in open-source systems that support full automation, integration with industrial databases, and real-time connectivity with monitoring systems.

In this phase of the inspection analysis of tank geometry, which precedes the computation of the geometric and subsequently corrected volume tables adjusted to reference conditions, a broadening of the analytical concept is proposed through the integration of additional sensor data. In this context, the use of advanced UAV systems designed for ultrasonic, thermal and visual inspection is considered highly relevant. By integrating these multi-source datasets with the point cloud obtained through laser scanning, it becomes possible to construct a unified informational model that supports a comprehensive analysis of both the geometric integrity and operational status of the tank. This approach not only extends the scope of metrology within inspection procedures but also facilitates intelligent decision-making in the context of preventive maintenance, as well as the development of digital twins based on multi-validated input data.

B. Volume Calculation

As part of an advanced digital metrology approach, following the generation of a high-density 3D point cloud model of the storage tank, a numerical computation of geometric volume as a function of filling height was conducted. This calculation is based on an accurate reconstruction of the tank's internal surface, with a volumetric table generated at a vertical resolution of 1 cm (layer-by-layer integration). The resulting table serves as the fundamental numerical structure for subsequent analyses and simulations within the digital twin environment.

To correct the nominal geometric volume and more accurately approximate the actual behavior of the tank under operational conditions, a custom Python script was developed to automatically apply multifactor corrections to each volumetric entry, in accordance with the specifications of ISO 7507-1:2003. The correction model includes the following physical influences:

- Hydrostatic pressure correction, implemented according to Annex A of the standard.
- Correction to the reference shell temperature, as defined in Section 16.1 of the standard,
- Deadwood volume correction, as described in Section 17.1 of the standard;
- Inclination correction, following the guidelines in Section 16.2 of the standard.

Additionally, particular emphasis was placed on modeling hydrostatic wall deformation, calculated as a function of the liquid column height, fluid density (ρ), Young's modulus (E), and local wall thickness (t). For vertical tanks, these parameters were defined across elevation segments, enabling a layer-wise structural compliance analysis (*segment-wise compliance model*). Results are presented at Table 1 and Table 2.

The Python script ingests input data from a CSV table of geometric volumes per elevation layer and applies the defined correction expressions to each vertical unit. The corrected values are then aggregated into a final volume table, representing the numerical output of the digital twin, ready for integration into asset management systems, structural health monitoring platforms, and decision-making processes related to preventive or corrective interventions.

Beyond correction, the system also enables simulation of tank volume behavior under varying operational scenarios, including filling with different fluids possessing distinct physical properties (e.g., crude oil, water, chemicals), exposure to temporal and seasonal temperature variations, and estimation of volume differences before and after service cycles, to quantify deformation effects under real-world conditions.

This approach supports dynamic modeling and digital tracking of tank behavior throughout its entire life cycle. It is fully grounded in traceable measurement data and algorithmically consistent processing procedures, adheres to the methodological principles of contemporary digital metrology, and aligns with the operational philosophy of the digital twin concept in industrial applications.

At this stage of the process, a clear opportunity is identified for integration with permanently installed temperature sensors on the tank, which would enable real-time modeling of volumetric capacity as a function of ambient temperature. Furthermore, the development of a simulation model is proposed to analyze the behavior of the scanned tank geometry in relation to the spatial distribution of atmospheric temperature, derived from the generation of heat islands using satellite imagery of the

area where the tanks are located. This approach would allow for the identification and quantification of the impact of climate-induced temperature variations on storage capacity.

This analysis opens a promising field for further research, particularly in the direction of linking the digital twin of the tank with the spatial distribution of urban heat islands derived from satellite observations. Specifically, by integrating surface temperature data obtained from remote sensing platforms (e.g., Landsat, Sentinel-3, MODIS), it becomes possible to incorporate external climatic parameters into the simulation model of the digital twin. This integration would enable predictive modeling of temperature effects on tank volume under real operational and environmental conditions.

Such integration represents a significant step toward the spatiotemporal coupling of large-volume metrology with geo-environmental parameters and opens new avenues for optimizing storage systems in the context of climate change and energy analyses.

Table 1 Correction-adjusted volumetric tables for vertical storage tanks

Tank ID	Design Volume [m ³]	Volume at Max Height [m ³]	Max Filling Height [cm]	Reference Height [cm]
R1	1000	1045.295	735	777.5
R3	1000	930.386	975	1081.6
R4	1000	929.193	975	1081.7

From Table 1, following the applied volume corrections, it was observed that Tank R1 exceeds its nominal design capacity, while Tanks R3 and R4 exhibit slightly lower effective volumes compared to their respective design specifications. This discrepancy may be attributed, in the case of R1, to the removal of an internal membrane that is present in the original design drawings but absent in the as-built configuration. Conversely, the reduced effective volumes of R3 and R4 may result from the subsequent installation of internal components, such as heaters, which are physically present in the tanks but not reflected in the original design documentation. It is important to emphasize that the available design drawings appear to be outdated. Therefore, it is strongly recommended that the tank owner/operator undertake a formal review and validation of the technical documentation considering these structural modifications introduced during the operational lifespan of the tanks.

Table 2 Correction-adjusted volumetric tables for vertical storage tanks

Tank	Nominal Volume	Measured Volume	Max Filling Height	Deviation from the Design Volume [%]
R-1	40 m ³	40.105 m ³	275 cm	0.263
R-2	60 m ³	58.999 m ³	276 cm	-1.668
R-3	40 m ³	39.949 m ³	278 cm	-0.128

As shown in Table 2, the measured volumes are very close to the nominal design specifications, which indicates a high degree of manufacturing precision and confirms the reliability of the volumetric tables generated through the calibration process.

C. Traceability of measurement

As part of the calibration campaign, all storage tanks were measured using key metrological equipment a 3D laser scanner that had been previously calibrated in an accredited laboratory, in accordance with the requirements of ISO/IEC 17025. The accredited laboratory includes within its scope of accreditation a specific method for the calibration of 3D laser scanners, thereby formally confirming its competence to verify the spatial accuracy of optical measurement systems.

This calibration method is based on the use of highly precise and traceable reference instruments, including a laser interferometer for the verification of length measurements and a precision theodolite for the validation of angular measurements. Both instruments had previously been calibrated in a Swiss accredited laboratory, thereby ensuring the traceability of measurement results to the national standards for the SI units of length and angle, maintained by METAS. Length and angle represent fundamental physical quantities in 3D metrology and, for the purposes of this study, form the basis for the reconstruction of the three-dimensional position of points on the object surface, the generation of the geometric 3D model of the tank, and the volumetric computation through digital surface integration. Through this measurement chain, the entire sequence of results, from raw data to the final volume computation, remains fully metrologically traceable, providing a robust foundation for technical validity, regulatory compliance, and international acceptance of the calibration results.

A useful point to note is that ISO 17123-9 is also available, defining a method for field calibration of terrestrial laser scanners, thereby further enhancing measurement reliability and metrological traceability in accordance with internationally recognized procedures.

D. Uncertainty Contributions

In accordance with the principles of the Guide to the Expression of Uncertainty in Measurement (GUM) [3], [4], and relevant ISO standards (e.g., ISO 7507 -1 Annex D), the overall measurement uncertainty in the calibration of storage tanks, particularly when using 3D laser scanning technologies, arises from multiple sources. These sources can be grouped into distinct categories:

Instrumentation-Related Uncertainty (Type B): The intrinsic accuracy of the laser scanner, in terms of both angular and distance measurements; Traceability and calibration of the reference standards used in scanner calibration, such as laser interferometers and precision theodolites, which ensure alignment with SI units of length

and angle; Systematic errors in the scanner itself, including scale factor deviations, angular misalignments, and instrumental drift.

Environmental Influences (Type A & B): Temperature fluctuations during data acquisition affect both the thermal expansion of the tank walls and the physical behavior of the stored fluid; Vibrations, wind, and platform instability may compromise scanner stability; Atmospheric pressure and humidity impact the refractive index of air, potentially altering laser path lengths.

Object-Specific Uncertainty (Type B): Deviations from ideal geometry, such as ovality, out-of-roundness, and eccentricity; Non-uniform wall thickness, which affects the elastic deformation under hydrostatic loading; Unknown or unaccounted deadwood volume, including internal fixtures such as heaters or pipelines, particularly when these are absent from design drawings.

Data Processing and Software Uncertainty (Type B): Surface fitting, segmentation, and interpolation routines can introduce errors if the point cloud quality is compromised; Numerical integration techniques for volumetric calculation and temperature correction algorithms must be validated; Software limitations, including floating-point rounding and processing precision, may affect results.

Procedural and Human Factors (Type A & B): Scanner positioning and number of scan stations influence data completeness and registration accuracy; Manual interpretation of structural features and validation steps may introduce operator-dependent variability.

Modeling and Correction Uncertainty (Type B): Thermal expansion correction, based on assumed coefficients of expansion for the tank material and the fluid; Inclination correction, as per ISO 7507-1:2003, clause 16.2.; Hydrostatic deformation modeling, requiring accurate inputs for modulus of elasticity, local wall thickness, and fluid density.

A comprehensive uncertainty evaluation in tank calibration encompassed all identified sources, using both statistical analysis (Type A) and expert-based estimation (Type B). The combined standard uncertainty is aggregated through root-sum-square methods and expanded using a coverage factor (typically $k=2$ for a 95% confidence level). Taking into account the significance, distribution, and spatial propagation of the identified uncertainty sources, the combined measurement uncertainty was evaluated also in accordance with the methodology prescribed in the EA-4/02 guideline [3]. For the vertical storage tanks included in this study, the resulting expanded uncertainty was estimated at 0.2% of the calibrated volume, while for horizontal tanks, the corresponding value was 0.3% of the total volume. These values reflect the cumulative effect of instrumental, environmental, object-specific, and processing-related influences, and are considered compliant with

internationally recognized practices for large-volume calibration.

IV CONCLUSIONS

This study demonstrates the application and further full potential of digital metrology for the calibration of both vertical and horizontal storage tanks using high-density terrestrial laser scanning. All analyzed tanks were accurately reconstructed as 3D digital models with topologically coherent meshes and geometric deviations well within the permissible limits defined by API 653 (≤ 0.105 m), confirming structural compliance and axial symmetry. Each tank was modeled from over 440,000 filtered spatial points, ensuring high geometric fidelity. The measurement process adhered to full metrological traceability, based on ISO/IEC 17025-accredited calibration procedures for laser scanners and reference instruments (interferometer and theodolite). Volume calibration tables were generated and corrected using custom-developed Python scripts, incorporating hydrostatic pressure, thermal expansion, inclination, and deadwood volume effects, in line with ISO 7507-1. The estimated expanded uncertainties were $\leq 0.2\%$ for vertical and $\leq 0.3\%$ for horizontal tanks, in accordance with OIML R 71. The study emphasizes the value of digital twins for real-time volume simulation and structural monitoring. It also recommends the integration of machine learning algorithms for automated detection of internal components, data fusion with visual and ultrasonic inspection systems, and coupling with real-time temperature monitoring platforms to model capacity variations due to environmental conditions. These findings underscore the transformative potential of digital calibration in improving traceability, operational efficiency, and predictive maintenance, contributing to the evolution of Industry 4.0-compliant metrological infrastructures.

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