euspen's 25th International Conference & Exhibition, Zaragoza, ES, June 2025

www.euspen.eu

Unlocking the Power of Simulation in Large and Complex Measurement Scenarios

U.Mutilba [1, *], D.Serveille[2], Z.Rogers[2], B.A.Chekh[1], J.Eguskiza[1]

[1] *Department of Industrial Metrology, Tekniker, 20600 Eibar, Spain*

[2] *Manufacturing Intelligence division, Hexagon, 35578 Wetzlar, Germany*

**Corresponding author: unai.mutilba@tekniker.es*

Abstract

Large-scale measurement scenarios present significant challenges due to environmental influences, instrument limitations, alignment and calibration complexities, restricted access to the measurand, and line-of-sight constraints. These factors collectively hinder traceability and complicate the evaluation of measurement uncertainty, particularly in scenarios where limited measurand access further restricts the deployment of optimal metrology solutions. To address these challenges, the JCGM 101:2008 framework offers a robust alternative to the GUM uncertainty framework, enabling effective modelling of intricate measurands and the development of measurement strategies through a priori and posteriori Monte Carlo simulations.

This work highlights custom modelling exercises conducted in the SpatialAnalyzer© simulation platform, leveraging advanced techniques to overcome the challenges of large-scale metrology. Key examples include simulations for precise pointing models in large telescopes, integration of multiple measurement principles to address complex scientific installations, and a priori uncertainty assessment strategies for cylinder-type measurands. These case studies demonstrate the potential of simulation-based approaches to enhance accuracy, traceability, and efficiency in large-scale measurement applications.

Metrology, accuracy, simulation, large-scale

1. Introduction

The production of high-value components—such as those used in aerospace, automotive, wind energy, or large-scale scientific facilities—demands increasing customisation and adherence to critical tolerances. Many of these components exceed the size capacity of conventional Coordinate Measurement Machines (CMMs) and cannot be feasibly transported to controlled measurement environments. Consequently, measurements are often performed close to the manufacturing site, where large-scale measurement scenarios introduce significant challenges. These include environmental variability, alignment and calibration complexities, restricted access and mobility around the measurand, line-of-sight limitations, limited instrument range and resolution, and reduced accuracy over long distances.

To address these challenges, researchers have developed a range of advanced measurement technologies tailored for large-scale metrology. Innovations such as laser-based systems (e.g., laser tracers and laser trackers with absolute distance meters and scanning capacity) have improved precision, traceability, and portability. Distributed and multi-sensor systems, incorporating technologies like photogrammetry, indoor GPS, and integrated laser systems, offer enhanced coverage and adaptability for specific applications [1–4]. Meanwhile, optical techniques, such as structured-light scanners, six-degree-of-freedom measurement accessories, vision-based systems, and long-range scanning systems, facilitate non-contact measurements of complex and freeform geometries, significantly reducing data acquisition time.

This research addresses these challenges by presenting custom modelling exercises performed within the SpatialAnalyzer© simulation platform. The objectives are:

a) to develop a priori measurement strategy designs that consider limited access to the measurand during preparation;

b) to estimate the order of magnitude of measurement uncertainty expected during the actual survey; and

c) to demonstrate the effectiveness of the proposed measurement strategy in overcoming the challenges inherent to real-world measurement scenarios.

2. Traceability and Measurement Uncertainty

Despite these advancements, significant challenges remain, particularly in ensuring traceability and assessing measurement uncertainty. While the current state of traceability in the field of large-scale metrology is primarily focused on ensuring the traceability of individual measurement principles and the associated measurement procedures, the determination of the measurement uncertainty shall include contributions from the measurement system, the component under measurement and the environment where the measurement is performed [3].

The Guide to the Expression of Uncertainty in Measurement (GUM) [5] provides a standardized framework for uncertainty evaluation. However, its general approach has limitations in complex and dynamic scenarios, such as large-scale metrology.

A key limitation of the GUM framework is its reliance on the assumption that all input quantities and their uncertainties are well-characterized. This assumption is often untenable in environments with variable factors like temperature gradients or gravitational deformations that influence measurements. Additionally, the GUM's deterministic approach to uncertainty propagation may fail to capture interactions between measurement components and environmental conditions, making it less effective for the holistic modelling of large-scale measurement scenarios.

In such cases, alternative methodologies like Monte Carlo simulations based on the JCGM 101:2008 framework are increasingly used to complement the GUM framework. These methods provide robust uncertainty estimations tailored to the complexities of specific measurement scenarios, particularly for in situ or shop-floor measurements [6].

3. Simulation scenarios - examples

3.1. Example 1 – Uncertainty of scientific equipment relative to each other

In industries such as aerospace, military, and research centres, the position of a transmitter relative to a receiver is often critical. Users frequently must determine this relative position to adjust the component's placement and optimise efficiency.

In this specific case, two scientific equipment need to point at the same direction as accurately as possible. Unfortunately, the environment in which they operate offers limited space for adjustment. Once positioned, the scientific equipment forms a barrier, separating the front and back of two rooms connected by multiple corridors.

There is some space in the front where the reference points on the front of each piece of equipment can be observed, though they are located meters away due to a trough running along the area. A narrow corridor at the back allows for metrology instruments to measure reference points on the rear of the equipment. A minimum of two laser tracker positions are required to measure all the reference points at the back. With only one station, fewer than half of the reference points could be measured. To strengthen the measurement network, two monuments could be placed in the corridor between the instrument positions.

To estimate which scenario results in the smallest uncertainty for the position of one scientific equipment relative to the other, three possible scenarios were simulated for the measurement, as shown in Figure 1.

- From the front, using a single instrument position.
- From the back, using two instrument positions.
- From both the back and the front, using three instrument positions.

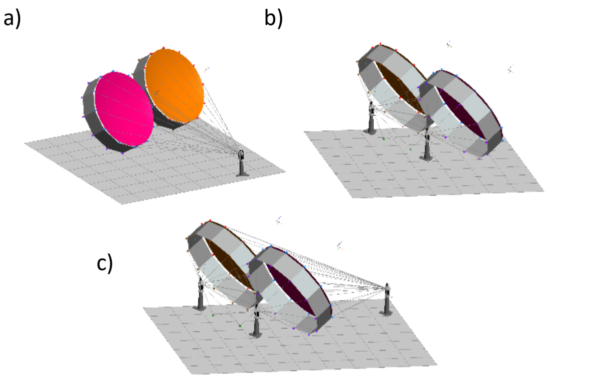

Figure 1. Several scenario simulations: a) One instrument at the front, b) Two instruments at the back, and c) One instrument at the front and two at the back.

First, each piece of equipment was characterized in a separate room with sufficient space around it, allowing for the placement of four laser tracker instrument stations to perform measurements. Reference points were placed both at the front and the back of the equipment. Eleven monuments were added to the floor to strengthen the network, as shown in Figure 2. The nominal coordinates of each reference point, relative to the scientific equipment frame, were used in the Unified Spatial Metrologic Network (USMN) [7]. As a result, the coordinates of each reference point on the scientific equipment were obtained, along with their measurement uncertainty, relative to the equipment frame.

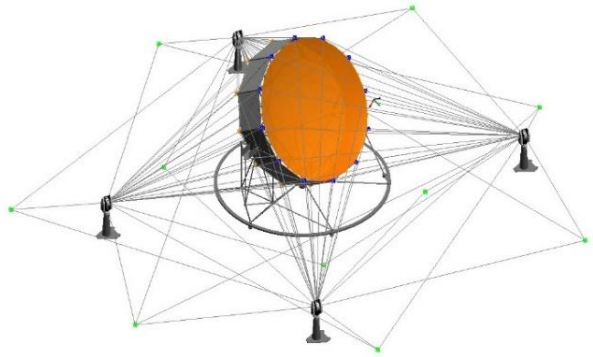

Figure 2. Characterisation using four laser tracker positions.

Each scientific equipment was then simulated within SpatialAnalyzer© as an instrument, with the equipment frame serving as the instrument frame and the reference points considered as measurements with known measurement uncertainty relative to the instrument frame. Consequently, the network could now include the characterized equipment.

For each possible scenario, the instrument representing the main equipment was considered fixed to propagate uncertainty to the instrument representing the other equipment. As a result, one USMN operation was computed for each case, allowing to obtain the measurement uncertainties of any instrument position, specifically the one representing the second equipment.

As shown in Table 1, the scenario using measurements from both the back and front results in the lowest uncertainty, despite the absence of common measurement between the instruments at the back and those at the front.

Table 1 Measurement uncertainty (k=2) of the equipment relative to the other in various scenarios.

Instrument Position	U_x µm	U_y µm	U_z µm	U_{Rx} µ°	U_{Ry} µ°	U_{Rz} µ°
Front	9	13	13	279	252	224
Back	8	18	12	215	203	279
both	5	10	9	162	158	151

3.2. Example 2 – Uncertainty assessment on geometry criteria

In the mechanical engineering industry, every measured dimension is assigned a specific tolerance, with some tolerances being particularly tight relative to the geometry's size, such as the shaft diameters of turbines or propellers. The uncertainty of a diameter measurement is influenced by several factors, including the uncertainty of individual measured points, the spatial distribution of these points, and the extent of surface coverage achieved during measurement. Thus, time can also be a critical factor in production processes.

When using a laser tracker for measurements, the measurand must remain static relative to the instrument, and the line of sight must remain unobstructed, making coactivity infeasible in our case. Therefore, an efficient method is required to achieve the highest possible measurement accuracy within the shortest time frame.

To estimate measurement uncertainty, the SpatialAnalyzer© software was employed. The process began with the creation of an instrument network to assess the instrument's inherent uncertainty, which was necessary for simulation. A USMN [7] was implemented in a similar environment, employing six monuments and five instrument positions, along with a specific measurement profile, as shown in Figure 3.

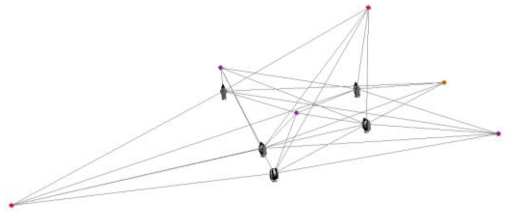

Figure 3. Simulation measurement scenario within SpatialAnalyzer©.

The cylinder to be measured has a diameter of 1.5 meters, with its axis centre located 3 meters radially from the laser tracker. Using the instrument uncertainty results derived from the previous network as input for the cylinder measurement simulation, multiple scenarios were considered as depicted in Figure 4:

1. Initial Case: Measuring 48 evenly distributed points around the entire cylinder surface. This serves as a reference solution, even though it is impractical due to line-of-sight limitations.
2. Reduced Case: Measuring 26 points distributed across the visible half of the cylinder.
3. Time-Constrained Cases: Given the limited measurement time, a maximum of 12 points could be measured. Three additional configurations were tested:
    - A uniform distribution of 12 points across the visible half-cylinder.
    - Two cases with denser point distributions near the visible extremities.

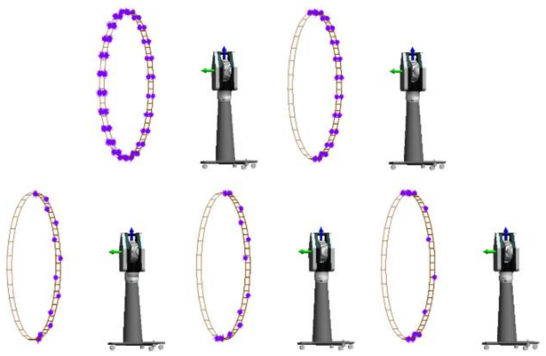

Figure 4. Simulation measurement scenario within SpatialAnalyzer©.

The results in Table 2 demonstrate that the number and distribution of measured points significantly influence the uncertainty of the measured diameter. By employing an optimized distribution of measurement points, it is possible to achieve the same level of uncertainty with fewer points.

Table 2 Cylinder measurement simulation results.

Point distribution	Number of measured points	Diameter Uncertainty (k=2) in µm
All around the cylinder	48	4
Half the cylinder	26	9
Evenly distribute	12	15
2 points by extremity	12	11
4 points by extremity	12	9

To validate the process, a measurement campaign was conducted, consisting of 25 real measurements of the same part. The chosen configuration involved using four points at each extremity, as this setup yielded the smallest uncertainty while requiring only 12 measured points. In this way, to ensure maximum accuracy of the measured points on the part, a specialized magnetic device was employed. This device maintained stable contact between the reflector and the part without requiring operator intervention.

When compared to the nominal value provided by a Leitz© CMM, the 25 diameter measurements exhibited a deviation (average) of 3 µm, with a minimum deviation of -10 µm and a maximum deviation of +13 µm. These results align closely with the simulated uncertainties. Notably, the real measurement campaign required four hours to complete, whereas simulating all five scenarios took only 10 minutes once the instrument uncertainty was known. This highlights the significant value of performing simulations to evaluate multiple scenarios and select the most efficient approach before conducting real measurements.

3.2. Example 3 – Measurement Procedure Development for the Large Synoptic Survey Telescope

The Large Synoptic Survey Telescope (LSST), located atop Cerro Pachon in Chile, exemplifies many challenges inherent in large-scale metrology. The LSST has a substantial scale, with dimensions of 40 m in diameter and 10 m in height, and is subject to environmental variations [8]. Additional challenges include restricted access to the measurand during the preparation phase of the measurement strategy, line-of-sight limitations to the surrogate mass of the main mirror and the floor where fiducials are fixed, and reduced measurement accuracy over long distances.

To address the challenges of measuring the pointing accuracy of the Telescope Mount Assembly (TMA), a novel procedure was developed. This procedure involves positioning a laser tracker near the TMA's origin and establishing a metrology network comprising a fiducial point cloud fixed to the floor, surrounding the telescope. The network is essential, as the TMA's pointing accuracy is determined by measuring these fiducial points using the laser tracker [9].

However, implementing this procedure presents several significant challenges:

- Visibility Constraints: Ensuring a clear line of sight between the laser tracker positioned inside the TMA and the surrounding fiducial points.
- Thermal Drift Effects: Mitigating the impact of thermal expansion and contraction on fiducial points mounted on the floor.
- Measurement Uncertainty: Addressing uncertainties associated with referencing the M1M3 mirror plane for TMA pointing accuracy.
- Automation and Virtual Commissioning: Simulating the measurement procedure and automating data acquisition to minimize thermal drift effects during real-world measurements.

These complexities complicate the direct application of the GUM. Correlations and non-linear relationships among input quantities render standard uncertainty propagation methods unsuitable. To overcome these issues, a Monte Carlo simulation approach was implemented using advanced metrology software such as Spatial Analyzer©. This approach allows realistic simulations of the measurand under operational constraints, addressing technical challenges posed by the LSST's scale and environment.

Visibility Simulation

The first challenge involves validating the visibility between the laser tracker and fiducial points at each calibration position. This step is critical for assessing the feasibility of the measurement procedure. The software provides functionality to simulate and verify the line of sight, ensuring alignment accuracy. Figure 5 illustrates visibility tests virtually conducted at different calibration positions.

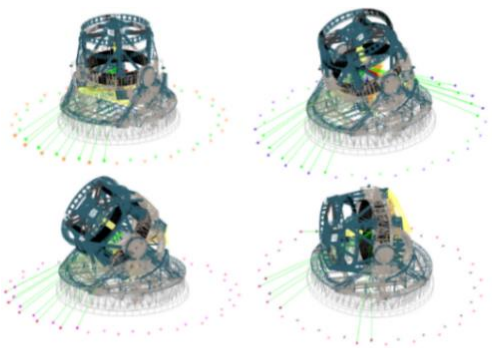

Figure 5. Visibility simulation during the measurement strategy preparation stage.

Uncertainty Characterization

The second challenge is characterizing the measurement uncertainties and their contributors. A Monte Carlo simulation model was developed to assess the pointing accuracy of the TMA based on the measurement procedure. This model incorporates:

- 5.000 sensitivity samples generated using a Gaussian random number generator (Box-Muller algorithm).
- Laser tracker error parameters (Leica AT402 specifications) at a confidence level of 68.3% (k=1):
  - U_F: Fixed length uncertainty (0.00762 mm).
  - U_M: Distance-dependent uncertainty (2.5 µm/m).
  - U_A: Angular measurement uncertainty (1 arcsecond).

The simulation is executed in two stages:

1. Fiducial Point Characterization: Fiducial points are characterized using the USMN tool to establish a reliable reference framework. Figure 7 shows the simulated measurement uncertainty results, considering the effects of thermal drift on the fiducial points.
2. Mirror Plane Measurement: Retroreflectors on the M1M3 mirror plane are used to measure the TMA's pointing accuracy. The M2 plane is also characterized to evaluate parallelism between the M1M3 and M2 mirrors.

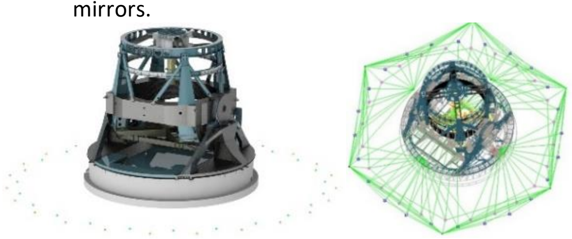

Figure 6. TMA measurement scenario (left) and metrology network characterisation within Spatial Analyzer© (right).

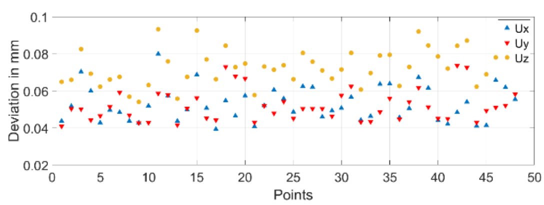

Figure 7. Measurement uncertainty simulation results for the fiducial points (k=2).

Automation for Real-World Implementation

The final challenge involves converting the simulation into executable survey code to automate the data acquisition process. Minimizing acquisition time is crucial to mitigate thermal drift effects in the real-world measurement scenario. By utilizing the simulation model, the setup time for the actual survey is substantially reduced. The laser tracker within the TMA is integrated with the TMA controller via a TCP/IP connection, enabling full automation of the measurement procedure. The complete calibration of 16 TMA pointing positions during the real survey is accomplished in 70 minutes.

Figure 8. TMA real survey scenario (left) and laser tracker placed within the TMA and a detailed view of the laser tracker positioned within the TMA alongside reflectors mounted on the M1M3 dummy (right).

5. Conclusions

This work showcases several custom modelling exercises conducted within the Spatial Analyzer© simulation platform for modelling intricate measurands and developing appropriate measurement strategies through both a priori and posteriori Monte Carlo simulations. Through real case studies in applications such as communication antennas and large telescopes, the effectiveness of these approaches in accurately estimating uncertainty and optimizing measurement strategies has been demonstrated. The study also tackles additional challenges inherent in large and complex measurement scenarios, such as line-of-sight limitations, environmental effects, and the complexities associated with instrument alignment and calibration within the measurement scenario, all of which are thoroughly evaluated in advance.

References

[1] Maropoulos PG, Guo Y, Jamshidi J, Cai B. Large volume metrology process models: A framework for integrating measurement with assembly planning. CIRP Ann - Manuf Technol 2008;57:477–80.

[2] Peggs GN, Maropoulos PG, Hughes EB, Forbes AB, Robson S, Ziebart M, et al. Recent developments in large-scale dimensional metrology. Proc Inst Mech Eng Part B J Eng Manuf 2009;223:571–95.

[3] Schmitt R, Peterek M, Morse E, Knapp W, Galetto M, Härtig F, et al. Advances in Large-Scale Metrology – Review and future trends. CIRP Ann - Manuf Technol 2016.

[4] Muralikrishnan B, Phillips S, Sawyer D. Laser trackers for large-scale dimensional metrology: A review. Precis Eng 2016;44:13–28. https://doi.org/10.1016/j.precisioneng.2015.12.001.

[5] Joint Committee for Guides in Metrology. JCGM 100:2008 – Evaluation of measurement data – Guide to the expression of uncertainty in measurement. 2008.

[6] (JCGM) JC for G in M. JCGM 101:2008 – Evaluation of measurement data - Supplement 1 to the "Guide to the expression of uncertainty in measurement" – Propagation of distributions using a Monte Carlo method. 2008.

[7] Calkins JM. Quantifying coordinate uncertainty fields in coupled spatial measurement systems. 2002.

[8] Sebag J, Gressler W, Neill D, Barr J, Claver C, Andrew J. LSST telescope integration and tests. Proc SPIE 2014;9145:91454A.

[9] Mutilba U, Kortaberria G, Egaña F, Yagüe-Fabra J, Mutilba U, Kortaberria G, et al. 3D Measurement Simulation and Relative Pointing Error Verification of the Telescope Mount Assembly Subsystem for the Large Synoptic Survey Telescope. Sensors 2018, Vol 18, Page 3023 2018;18:3023. https://doi.org/10.3390/S18093023.