LA-UR-26-28317

Approved for public release; distribution is unlimited.

Title:	Scorpius Unified Spatial Metrology Network (USMN) Optimization, Predictive Network Design, and Empirical Results
Author(s):	Archuleta, Daniel Estevan; Gilbane, Brian; Lobas, Jonathan Alyn; Lane, Robert Houston; Lane, Calder E; Tuttle, Joseph M; Kilian, Thomas M; Washington, Alexandrea D
Intended for:	Meeting: International Workshop on Accelerator Alignment (IWAA), 2026-10-05 - 2026-10-09 (Tsukuba, JAPAN)
Issued:	2026-09-16

Los Alamos
NATIONAL LABORATORY

Scorpius Unified Spatial Metrology Network (USMN) Optimization, Predictive Network Design, and Empirical Results

D. E. Archuleta[†,1], B. P. Gilbane[1], J. A. Lobas[1], R. H. Lane[1], C. E. Lane[2], J. M. Tuttle[2], T. M. Kilian[2], A. D. Washington[2]
[1]Los Alamos National Laboratory, Los Alamos, United States of America
[2]Nevada National Security Site, Las Vegas, United States of America

Abstract

In 2021, a design was proposed as the foundational metrology network for the forthcoming Scorpius linear particle accelerator. By contrasting simulated network conditions with empirical findings, this paper highlights the benefits of predictive network design for novel or unfamiliar operational environments. Located at the Nevada National Security Site's (NNSS) Primary Underground Laboratory for Subcritical Experimentation (PULSE), the Scorpius metrology network spans a total area of approximately 838 m^2 and is 140 m at its maximum length. Due to unique environmental constraints, the design of the network was limited to two primary planes offset by 0.61 m. To ensure compliance with project requirements, the design of the network was completed using an iterative process in which a Unified Spatial Metrology Network (USMN) was modeled in SpatialAnalyzer®. The overall goal of the simulation, in conjunction with other design parameters, is to determine the total estimated error for placement of the Scorpius beamline. The chosen figure of merit (FOM), root mean square (RMS) of point error, was minimized across several dozen permutations and provided an associated overall point error of 25 µm. A parametric simulation study was conducted on the monument network design parameters, such as spacing, grid geometry, and tracker placement, as means to optimize the monument network. The simulated FOM was combined with several other design inputs to calculate the estimated total error for final placement of the Scorpius beamline. In April of 2026, metrologists completed network measurements and analysis of the as-built Scorpius metrology network. Based on data collected and lessons learned from other parts of the Scorpius project, additional monument nests were added to the as-built design. Original estimates, derived from the institutional knowledge of Subject Matter Experts (SMEs) consulting on the project, projected the as-built configuration would provide a FOM with a magnitude double that of the simulation. The final as-built USMN analysis provided a FOM of 17.8 µm, much smaller than expected given the as-built real-world conditions.

*Work supported by the U.S. Department of Energy National Nuclear Security Administration (NNSA) Office of Defense Programs under the Advanced Sources and Detectors (ASD) project. Los Alamos National Laboratory is operated by Triad National Security, LLC for the National Nuclear Security Administration of the U.S. Department of Energy under Contract No. 89233218CNA000001.
†dea@lanl.gov

Keywords: Unified Spatial Metrology Network (USMN), Metrology, SpatialAnalyzer®, Root Mean Squared (RMS), Nevada National Security Site (NNSS), Primary Underground Laboratory for Subcritical Experimentation (PULSE), Scorpius, Figure of Merit (FOM), Optimization, Predictive Network Design,

INTRODUCTION

The Advanced Sources and Detectors (ASD) Scorpius Project is responsible for developing a Linear Induction Accelerator (LIA) that produces a multi-pulse, single-axis radiography capability that will be deployed in the Primary Underground Laboratory for Subcritical Experimentation (PULSE) complex at the Nevada National Security Site (NNSS). Final placement of the LIA beamline with respect to the required Global Zero (GZ) experimentation location is critical to ensure the results from the diagnostics are accurate. A high-level axial field requirement of 200 µm Root-Mean-Squared (RMS) was imposed by the project to ensure beamline position. Several compounding errors including but not limited to RMS network point error, instrument error, and magnetic field characterization and fiducialization error will be used in the final RMS calculation. Commonly, the beamline design is conducted through complex calculations and component testing [1], [2]. Network design is seemingly considered an afterthought, as metrology is only used for alignment of the machine components [3]. The above-mentioned field requirements and space restrictions within PULSE demand a new methodology. Thus, metrology simulation was conducted as a means to design the metrology network for PULSE. This novel approach not only allows for the placement of the beamline, but it also considers future alignment of the accelerator solenoids.

With the project beamline requirements and future alignment efforts in mind, this paper highlights the RMS network point to point error, as it is the most diagnosable source of error. Thus, by implementing a predictive study, the error can be minimized via optimization of the design parameters. Furthermore, this paper examines the validity of the simulation results against the empirical data collected on the monument network. More specifically, this study focuses exclusively on the RMS of point error as the chosen Figure of Merit (FOM) to compare the original 2021 model to the as-built configuration of the metrology network. During the original modeling process consulting SMEs, using years of institutional knowledge, estimated the as-built metrology network would produce a FOM double that of the idealized model simulation. By comparing the estimated FOM from the original 2021 model to the FOM of the as-built network, it is possible to determine the value of future metrology work through predictive design.

METHODOLOGY

Due to the nature of the NNSS PULSE facility and the fine alluvial sediment which makes up the ribs (walls) and back (ceiling) of the drifts (tunnels), finding stable and reliable network nest locations was a concern. A determination was made early on to confine network nest locations to the concrete slab which acts as the foundation of the Scorpius machine. This decision was made to reduce the potential of differential settlement as a significant contributor of unpredictable error. The Scorpius machine foundation was designed in such a way that no significant movement of the slab, with respect to itself, is expected. Recent settling and movement surveys of the machine slab have confirmed this to be the case. The monument network was designed to fit within the physical envelope of the Scorpius machine.

It should be noted that the foundational concrete slab on which the Scorpius machine sits, is split into two distinct sections of differing height a "Lower Region" and a "Step-Up" region. The difference between the Lower Region and the Step-Up region is 0.61 m, creating two distinct network planes on which nets will reside. The USMN utilizes all points from both planes in the final characterization. The area of the Scorpius envelope spans approximately 838 m^2, is approximately 140 m at its maximum length and 25 m at its maximum width configured in a "T" shape.

Model Design

The spatially limited operating environment of the Scorpius machine places significant limitations on the monument network. Beamline components, Solid State Pulses Power (SSPP) racks, cabling, cooling water, service air, and other required systems obstruct visibility and available concrete area for monument placement. These limitations also affect instrument placement. Steel plates placed over the top of planned utility trenches serve as inadequate basis for instrument placement due to lack of rigidity and restrict placement to tripods that can span gaps or single leg variable-height Brunson stands. The limited operating environment constrains placement of nests normal to the beamline axis; however, it allows for significant movement along the length of the beamline axis.

An initial single unified monument network of magnetically mounted reflectors was modeled at equidistant intervals, uniformly across the available surface area of the accelerator drift. Initially, this design incorporated the full measurement range of the chosen corresponding instruments used. The uncertainty associated with this first design was unsuitably large due to the linear distance uncertainty scaling associated with each instrument, which masked the uncertainty associated with network geometry and instrument placement. To better understand network geometry uncertainty a decision was made to run a series of simulations with varying monument locations and restricting instrument measurement range to between 1.5 m and 15 m. This new instrument measurement range was picked to include the instruments minimum range of 1.5 m and to ensure that at least three measurements of every monument location in that range would occur.

Simulation Setup

To run a series of monument designs, simulated networks were designed in SpatialAnalyzer® and accompanying point generation, iteration, and result visualization scripts were written in MATLAB®. Monument networks were created and modified in scripts which would generate points along length of the accelerator drift. Instrument locations were also generated in this fashion. Both points and instruments were imported into SpatialAnalyzer® using Measurement Plans (MPs). Automation through MATLAB® and corresponding MPs were utilized to limit manual workload associated with file generation and analysis. Dozens of simulations were conducted with slight variations to these design parameters to optimize the monument network. The Figure of Merit (FOM) chosen to optimize the monument network was the Root Mean Square (RMS) of the system point error calculated using the SpatialAnalyzer® Unified Spatial Metrology Network (USMN) tool. The final chosen network design was that which output the lowest FOM. It should be noted that the computationally simulated nature of this work is contrary to typical large-scale network surveying methodologies. This methodology was adopted due to constraints in the team's technical expertise, limited personnel to pull from, and restricted resources at the time.

As-Built Design

In the intervening years since the original 2021 model was chosen, additional nest locations were added to the network design based on lessons learned, data collected from other parts of the Scorpius project, and with recommendations from outside SMEs. Based on this input an additional 22 nests were added at various locations. Besides the added nest locations, no other changes were made to the as-built configuration. The empirical data was collected utilizing a combination of pedestal stands secured to the invert concrete and mobile stations using heavy duty rolling stands. The calibrated instruments used for data collection were the Leica® AT960-LR and AT930-LR along with high precision 1.5-inch diameter Spherically Mounted Retroreflectors (SMRs) placed on Hubbs® Foundation Sphere Mounts (FSM). Data was collected in SpatialAnalyzer® using precision point measurements.

RESULTS

Simulation Results

An understanding of laser tracker measurements alongside the utilization of automation tools allowed for the development, analysis, and refinement of the nest network over forty-eight separate simulated permutations. Results were accomplished by constraining instrument measurements to within a fixed radial area around each tracker, by maximizing orthonormal measurements of each point relative to each point's own arbitrary coordinate system, and by optimizing the number of nests contained within the network. The chosen FOM was optimized down to a final RMS point error of 25 µm (Figure 1).

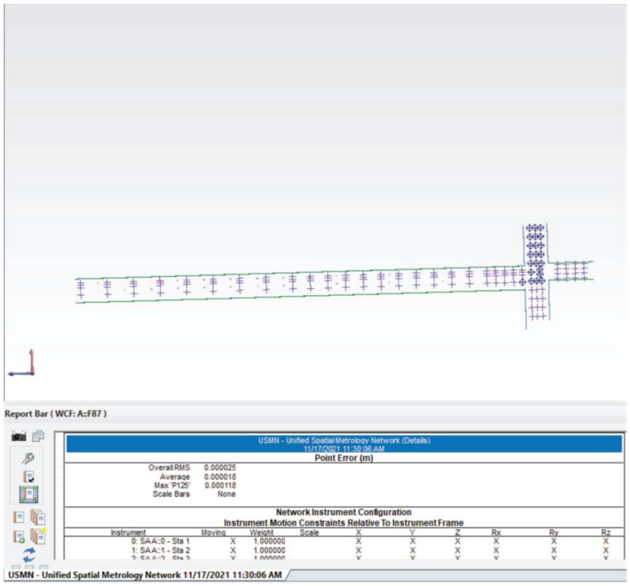

Figure 1: Resulting Simulation USMN Figure of Merit.

As-Built Results

As-built nest network characterization took place at the NNSS PULSE facility over the course of seven weeks. Every effort was made to maintain the same tracker locations used in the model, as well as the same instrument measurement envelope radius. Due to schedule and resource constraints, the as-built USMN network could not be assessed both with and without the additional 22 nests. Consequently, it remains unclear what effect the added nests had on the following results. In total the final network was comprised of 45 instrument locations, and 171 nest locations with a grand total of 1,287 individual measurements taken. Analysis of the 1,287 measurements within the SpatialAnalyzer® USMN analysis resulted in the detection and exclusion of 71 statistical outliers, or 5.52% of the total data. Final USMN analysis of the as-built network provided an RMS point error of 17.8 µm with an average error of 12.8 µm and a maximum error of 96.6 µm (Figure 2).

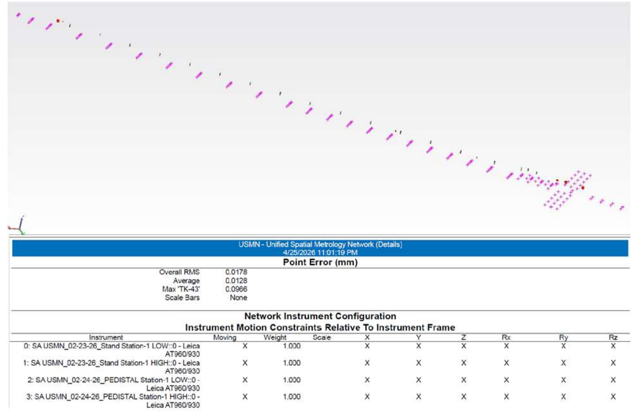

Figure 2: As Built USMN Figure of Merit.

CONCLUSION

Contrary to expectations, the as-built USMN analysis showed superior performance in the FOM relative to the idealized 2021 model simulation. Original estimates placed the expected as-built FOM closer to double the error found in the model. While this project's environmental constraints are likely to limit its direct use in similar metrology projects, this predictive design model itself remains highly valuable. If adapted properly it could help determine the viability of other networks in similarly challenging environments.

Future Work

The as-built USMN will serve as the basis envelope for all metrological alignment operations related to the Scorpius machine at the PULSE facility. Future alignment related operations at PULSE include component installation, component Straight Wire Alignment Technique (SWAT), component alignment, final beamline smoothing, and invert settlement monitoring. Additionally, the calculated as-built FOM will be used as one of the inputs to demonstrate that the high-level LIA beamline axial field requirement has been met. Initial calculations based on other unrelated assumed values indicate that the network point error will be the smallest contributing factor to overall error associated with high-level beamline alignment.

REFERENCES

[1] D. Angal-Kalinin *et al.*, "Design, specifications, and first beam measurements of the compact linear accelerator for research and applications front end," *Physical Review Accelerators and Beams*, vol. 23, no. 4, Apr. 2020, doi: 10.1103/physrevaccelbeams.23.044801.

[2] P. Emma et al., "FEL2014," in *Electron Bunch Generation and Manipulation*, pp. 743–747

[3] M. Saadatseresht, C. S. Fraser, F. Samadzadegan, and A. Azizi, "Visibility Analysis In Vision Metrology Network Design," *The Photogrammetric Record*, vol. 19, no. 107, pp. 219–236, Aug. 2004, doi: 10.1111/j.0031-868x.2004.00280.x.