Integrating Certified Lengths to Strengthen Metrology Network Uncertainty

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New River Kinematics

Engineered for Extreme Measures.

Introduction

- **Process**
  - Scaling 3D Metrology to reference temperature
- **Problem**
  - Coefficient of Thermal Expansion Compensation Uncertainty
- **Understanding**
  - Scale Bar/Length Traceability & Uncertainty
- **Solution**
  - Integrating Traceable Scale Lengths into USMN
- **Results**
  - Improved CTE Compensation with Uncertainty Analysis
- **Summary**

Process: Scaling 3D Metrology to Ref Temperature

- **Why Scale 3D Measurements?**
  - Object dimension is dependent on temperature
  - Reference Temperature is 20°C (68°F)
  - Nominals are given at reference temperature
  - Objects are measured at temperatures other than at reference
- **Scale object measurements from actual to reference temperature**
  - Scale is dependent on:
    - Material Properties (CTE)
    - Temperature difference from reference
    - Object constraints

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Thermal Length Compensation

Must scale measurements to reference temperature for comparison against nominals or between surveys

$$L_i = L_0(1-\alpha\Delta T)$$

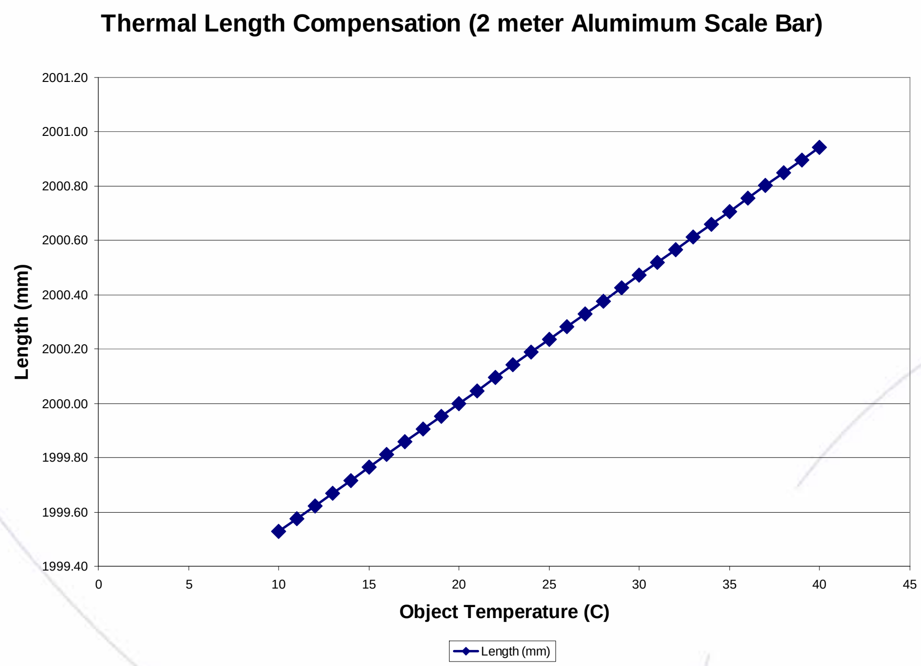
where:

L_i = actual length at temperature

L_0 = calibrated length at reference temperature

α = CTE for scale bar material (ppm/^{o}C)

ΔT = temperature delta between actual and reference temperature (^{o}C)



Objects change length as temperatures changes

Process: 3D Measurement Traceability

- **Survey scale is set with calibrated Temperature and CTE**
  - Thermocouples to measure object temperature … e.g., ± 0.5°C (k = 2)
  - Published Material Type CTE e.g., ± 3-5% (k = 2)
- **Survey scale is checked (confirmed) against traceable lengths (NIST, PTB, NPL)**
  - Bars calibrated with interferometer at reference temperature
  - Fixed Targets on Bars
  - Bar Material = Object Material
  - Length uncertainty set by lab

Propagation of Uncertainty

- **Effect of variable uncertainties (or errors) on the function uncertainty**
- **Probable true value lies in interval**
  - $x - \Delta x$
  - $x + \Delta x$
- **Define uncertainty by relative error $\Delta x / x$ (percentage)**
- **Assume difference between a measured value and true value is normally distributed using standard deviation as uncertainty of measurement**

Input Component Uncertainties…

- **Measurement uncertainty is higher**
  - CTE uncertainty characterization is significant (> 5% of CTE)
  - Material temperature measurement uncertainty
  - Object temperature measurements one or a few observations
- **Survey scale is set with uncertain temperature and CTE**
- **Process time is lost**
  - Get measurements of scale bars to check to tight tolerances … re-measure bars n times → find right temperature
- **Setting scale with less precise process then having to check with higher precision**

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CTE Thermal Length Uncertainty

$L_i = L_0(1 - \alpha \Delta T)$

$f(L_0, \alpha, \Delta T) = L_i$

Uncertainty of L_i is a function of $L_0, \sigma_L, \alpha, \sigma_\alpha, \Delta T, \sigma_T$

Example : 2 meter Alum Scale Bar from 10^o to $40^o C$

$L_0 = 2000 \text{ mm} \; \sigma_L = 0.02 \text{ mm}$

$\Delta T = -10 \ldots 20 \; {}^oC \; \sigma_T = 0.5^oC$

$\alpha_{alum} = 23.8 \; ppm/{}^oC \; \sigma_\alpha = 5\%\alpha$

Propagation of Uncertainty

$$\text{Model}: L_i = L_0(1-\alpha\Delta T) = f(L_i)$$

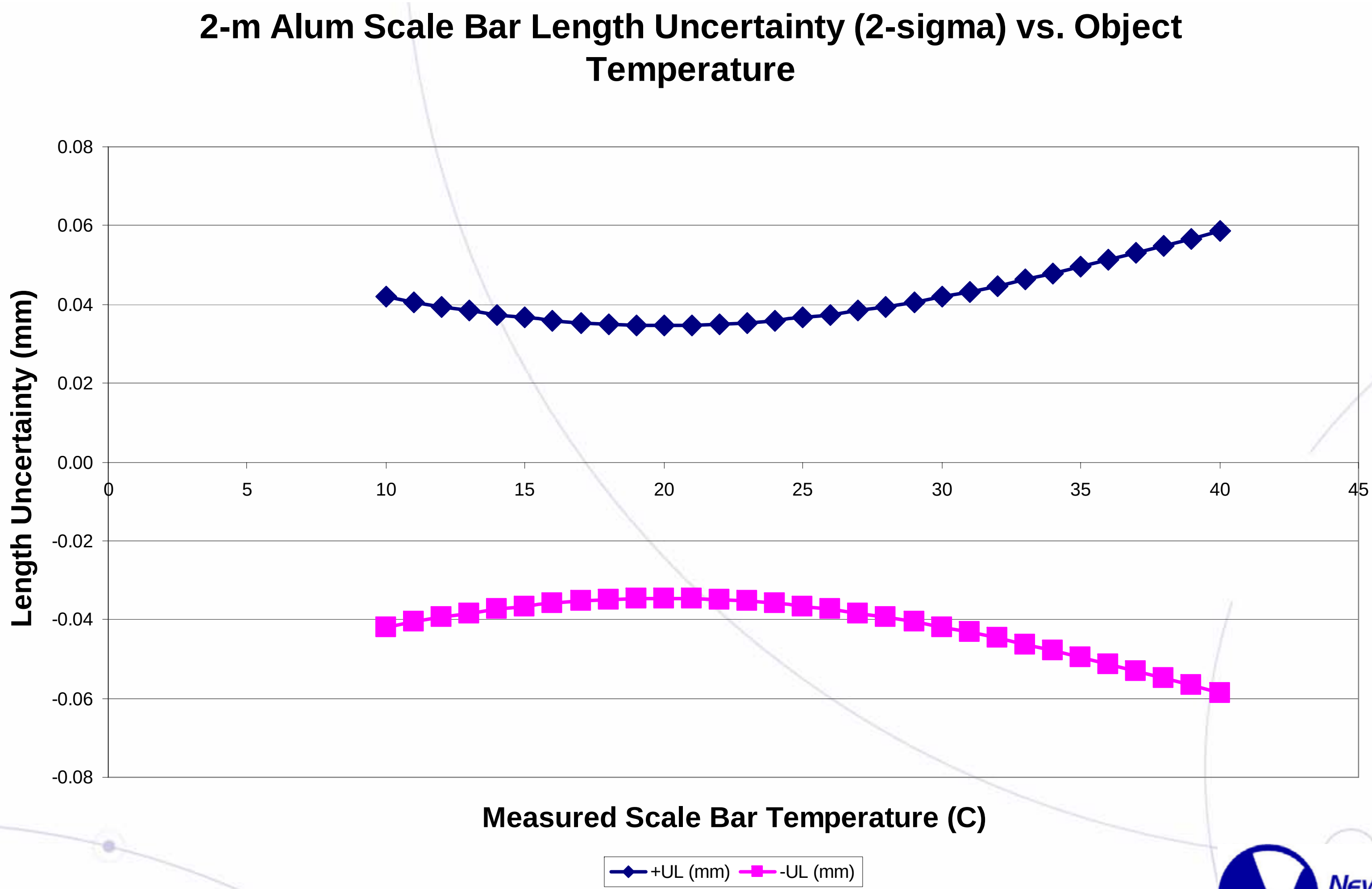
$$U[f] = s_f = \sqrt{\left(\frac{\delta f}{\delta L_0}\right)^2 \sigma_L^2 + \left(\frac{\delta f}{\delta \alpha}\right)^2 \sigma_\alpha^2 + \left(\frac{\delta f}{\delta \Delta T}\right)^2 \sigma_T^2}$$

$$U[L_i] = s_L = \sqrt{(1-\alpha\Delta T)^2 \sigma_L^2 + (L_0\Delta T)^2 \sigma_\alpha^2 + (L_0\alpha)^2 \sigma_T^2}$$

- **Formula for the variance between products**
- **Propagation of error approach combines estimates from individual auxiliary measurements`**

Leo Goodman (1960). ***"On the Exact Variance of Products"*** in *Journal of the American Statistical Association*, December, 1960, pp. 708-713.

Scale Bar Length Uncertainty vs. Temperature



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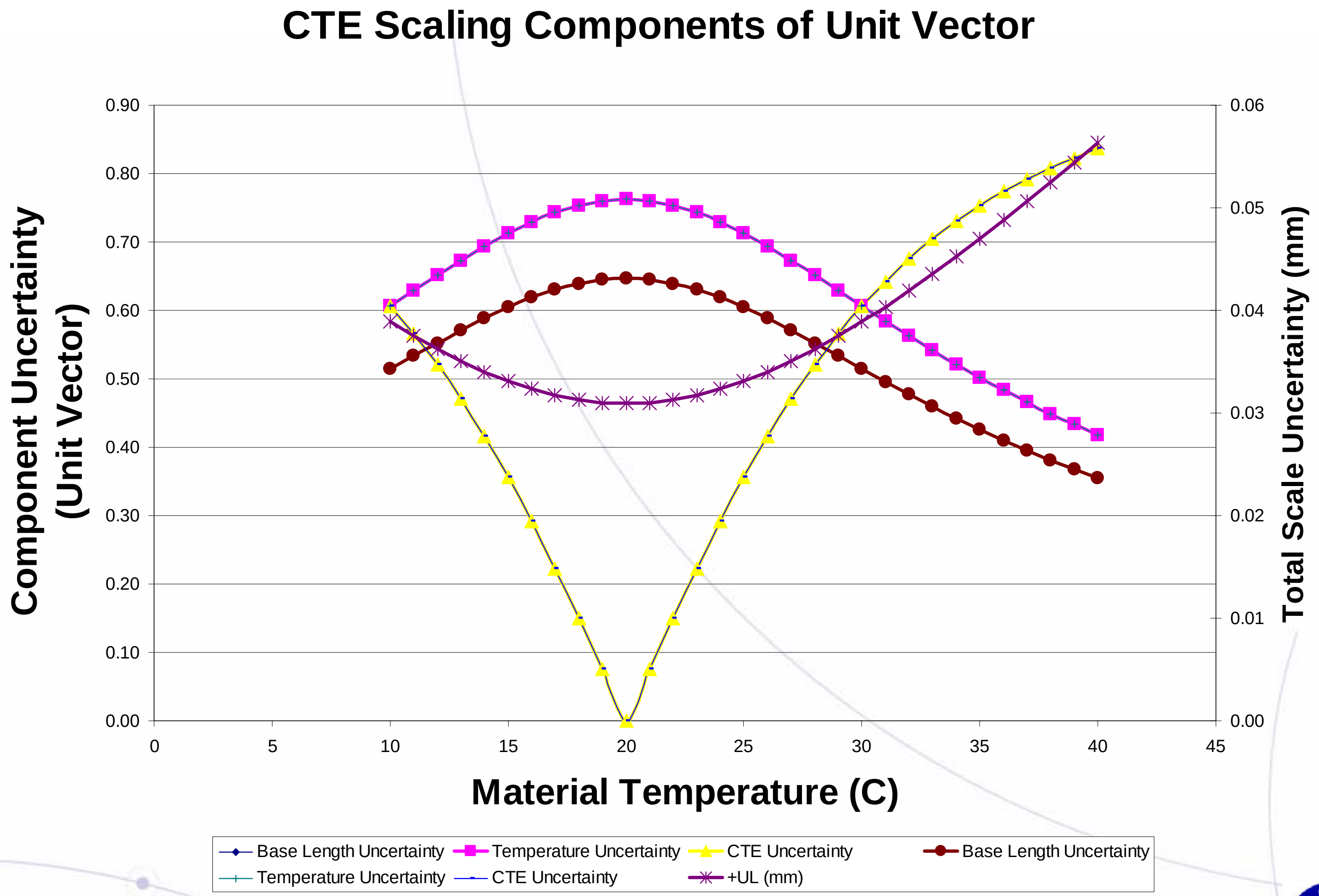
Scale Length Uncertainty Components



Solution … Better Metrology Practice

- **Use traceable scale lengths to set object scale**
  - Certified scale lengths of like kind material (soaked with object)
  - Multiple scale bar positions
  - Local Scale Differences
  - Observations from multiple stations
- **Solve with Weighted Mean Scaling (Least Squares) per station/instrument**
- **Check scale with temperature and CTE**
  - Confirm the scale factor maps to object temperature and material CTE

Scale Length in USMN

- **Integrate scale length into Uncertainty Field Analysis**
  - Scale length uncertainty from traceable certification
  - Multiple bar positions and orientations
  - Multiple stations
  - Local scale deformations due to object temperature gradient

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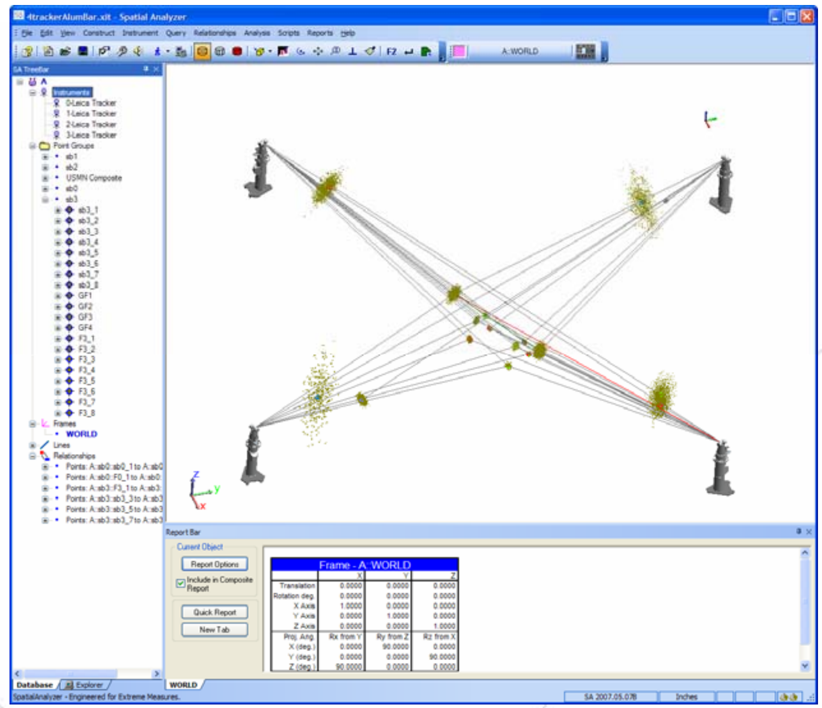
Scale with Certified Lengths…

- **4 Station Survey**
- **Alum 2.44 m Scale Bar in 10 positions**
- **Temp: 23±0.5°C**
- **Max Dist: 9.78 m**
- **Potential Error with CTE Scaling ±0.13 mm**
  - @22.5 → -0.13 mm
  - @23.5 → +0.13 mm
- **Potential Error with Certified Length Scaling ±0.02**
- **Net Difference: 0.11 mm (≈ ±0.004” in 386”)**



Scaled in USMN 4 stations
10 scale bar positions

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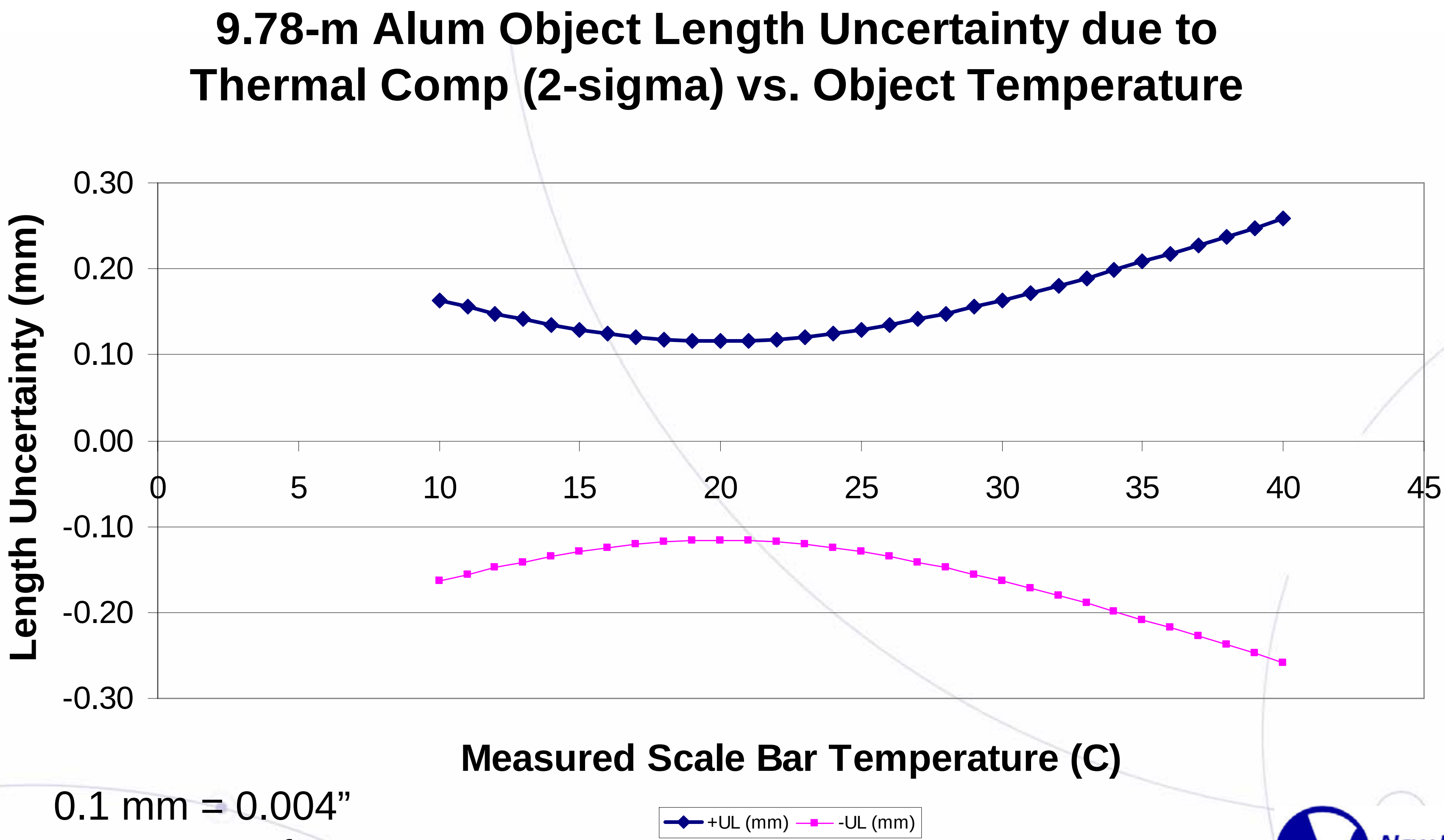
Application: Thermal Comp Uncertainty on 9.78-m Aluminum Object



0.1 mm = 0.004”
9.78 m = 32 ft

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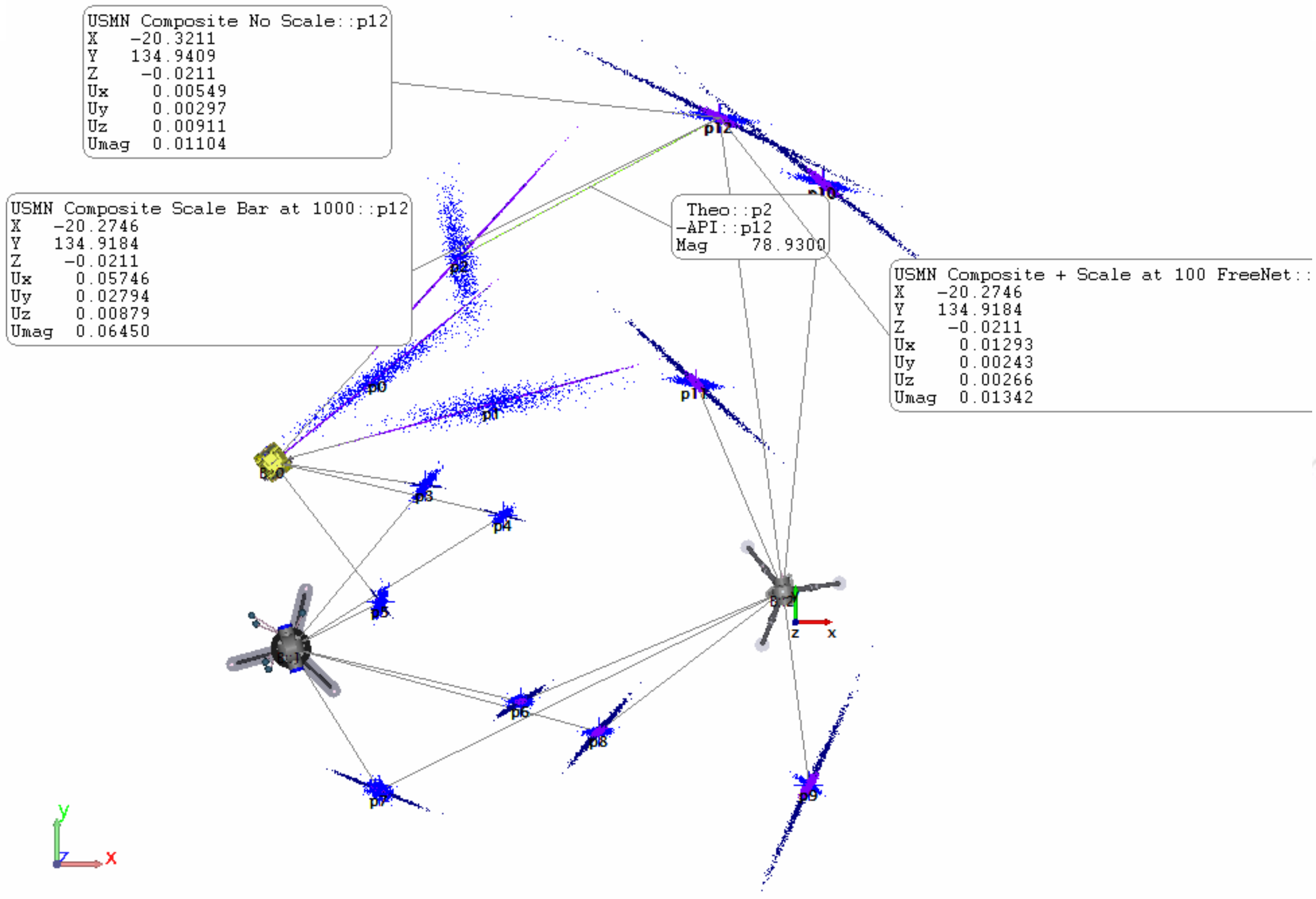
Monte-Carlo Uncertainty Analysis

- **Uncertainty Field Analysis includes scale bar constraints**
  - Report Only
  - As Constraints
    - Weighted based on length and published uncertainty from lab
- **Monte-Carlo Uncertainty Analysis and Validation for network with modeled scale bar constraints…**
  - Confirm an instruments or stations performance within a network against certified length
  - Network Target field uncertainty analysis with graphical and component output
- **Automated outlier characterization (Ranking %) and possible elimination**
- **Shop floor users to consistently and effectively use this advanced optimization technique**

Target Uncertainty Analysis w/ Certified Lengths

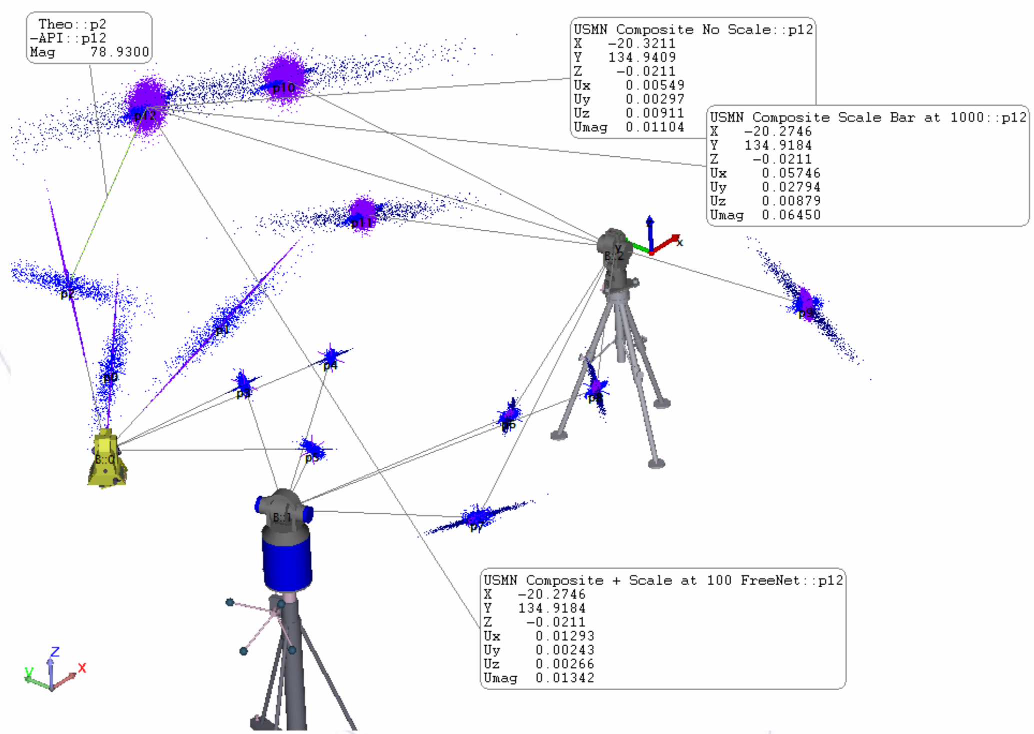


Conclusions … Summary

- **Scaling 3D metrology surveys with CTE and object material temperature delta increases uncertainty**
- **Scaling with certified lengths reduces measurement uncertainty**
  - Reduced Uncertainty
  - Enhance Traceable Reporting
- **Certified Length Standard are weighted in network optimization**
- **Instruments Uncertainty Analysis and Reports are against traceable length standards**
- **Target Uncertainty Field Analysis includes traceable length standards**

Integrating Scale Bars/Lengths to Strengthen Metrology Network Uncertainty

- **Questions**



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