University of Applied Sciences and Arts Northwestern Switzerland
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Automation Ready Laser Tracker Compensation

Oldenburger 3D-Tage

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Motivation for Compensation

- Motivation
  - Compensation cost a lot of time
  - Some calibration methods for Hexagon Laser Trackers (LTs) were designed for field

- ADM-Offset: Distance correction between ADM zero and Tracker centre
  - Also know as R0
  - Distance error

- Ve Telescope Bending Gravity Error
  - Height error

1µm = 0.001mm

1 Blatt Papier: 0.1 mm

Research Questions

RQ 1. *How can the calibration process for the ADM-Offset compensation and the Ve compensation of Hexagon Laser Trackers be optimized/automated to meet the company's requirements for automation, resource efficiency, accuracy, minimal repositioning, re-calibration, robustness, and availability?*

RQ 2. *What new approaches and tools can be developed to improve the efficiency of these calibration methods, and how do they compare to the existing calibration method in terms of performance and practicality under real-world conditions?*

ADM-Offset non-automated approach

- Three stationing setups and two tripods with targets
- About 25 minutes

inside-outside test / Step 1 (Wolf, 2023a)

inside-outside test / Step 2 (Wolf, 2023a)

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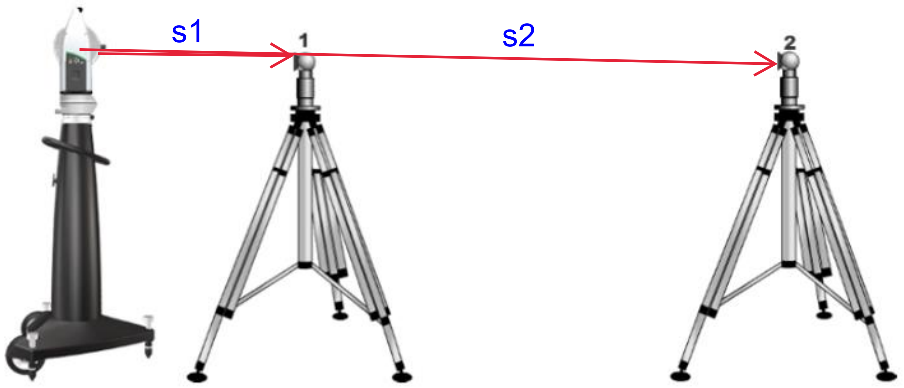
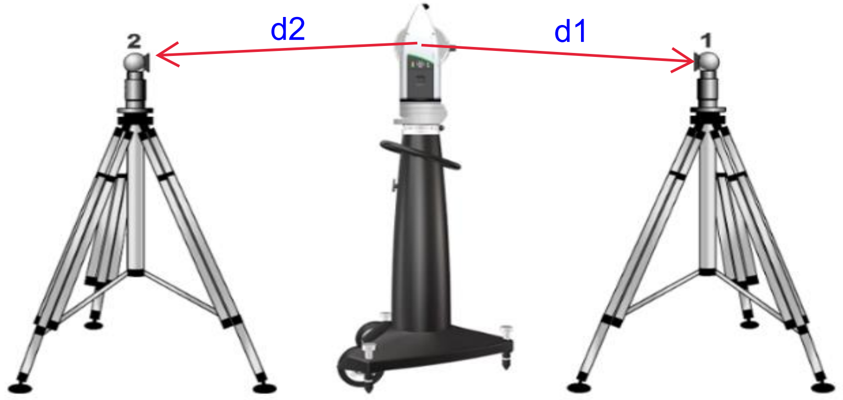


inside-outside test / Step 1 (Wolf, 2023a)

D12=(s2+x)-(s1+x)
D12=s2+x-s1-x
D12=s2-s1

D12=(d1+x)+(d2+x)
D12=d1+d2+2x



inside-outside test / Step 2 (Wolf, 2023a)

ADM-Offset non-automated approach

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inside-outside test / Step 1 (Wolf, 2023a)

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ADM-Offset automated approach with a scale bar

- Calibration of the scale bar with a Monitoring LT
  - Accuracy of 0.83 µm 2σ

- Measure the scale bar multiple times

- Calculate the ADM-Offset

- Almost the same principle as for the non-automated process
  - Problem Eccentricity e

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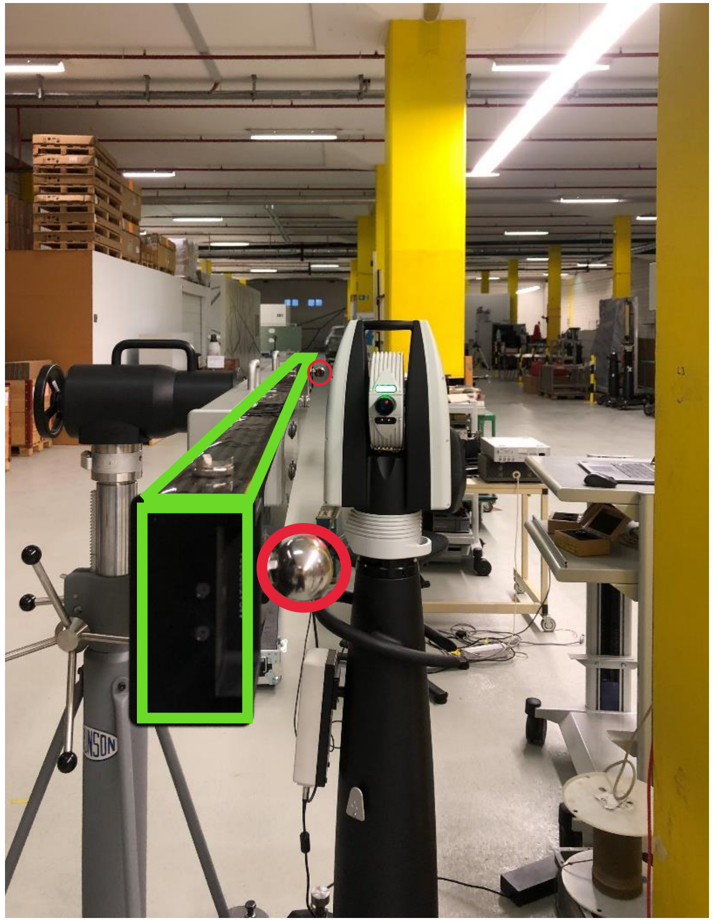
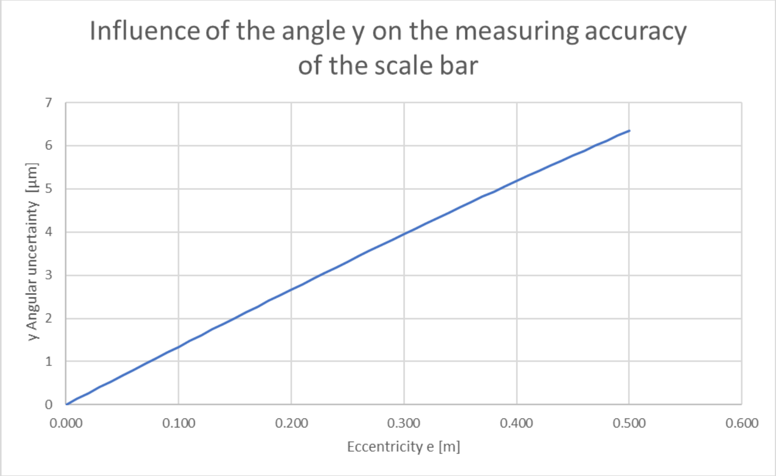
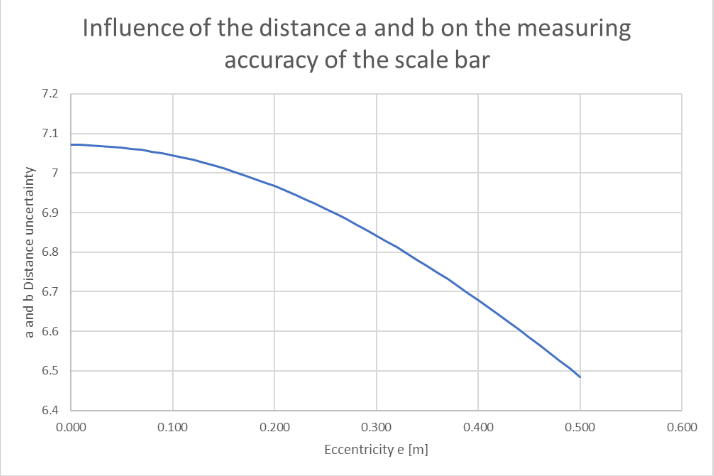


Eccentricity e

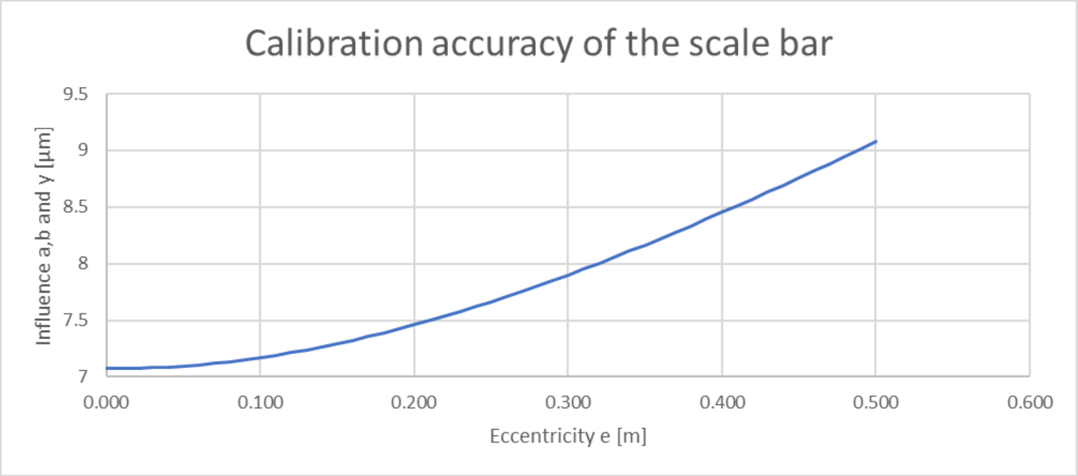




- A priori analysis with half MPE values

- The effect at 17 cm
  - Angular: 2.3 µm 2σ
  - Distance: 7 µm 2σ

- In total 7.4 µm 2σ + 3 µm (Red-Ring Reflector) = 10.4 µm



Calculation of the ADM-Offset

- Problem of Eccentricity e

$$L\text{: Known distance of the scale bar}$$

$$l = |\overrightarrow{P_1} - \overrightarrow{P_3}|\text{: Apparent length of the scalebar}$$

$$\overrightarrow{P_1}, \overrightarrow{P_3}\text{: Apparent position of the two points on the scalebar}$$

$$\cos\gamma = \frac{\overrightarrow{P_1} \cdot \overrightarrow{P_3}}{a * b}\text{: Included angle}$$

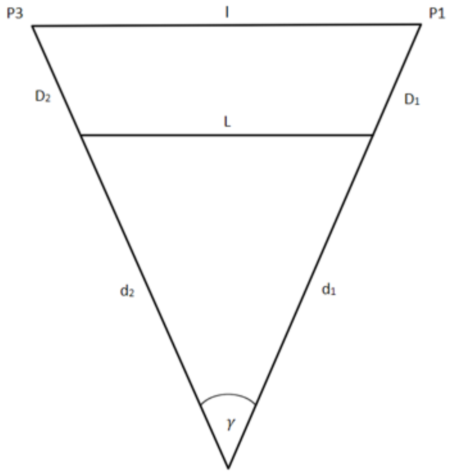


Figure 25: Sketch for the calculation of the ADM-Offset / top view

Searched quantity, the true distances A and B, respectively the ADM-Offset d_0:

$$D_1 = d_1 - d_0$$

$$D_2 = d_2 - d_0$$

Cosine theorem for the large triangle:

(Wolf, 2023f)

$$l^2 = d_1^2 + d_2^2 - 2d_1 d_2 \cos\gamma$$

Cosine theorem for the small triangle:

$$L^2 = D_1^2 + D_2^2 - 2D_1 D_2 \cos\gamma$$

ADM-Offset calculation

$$L^2 = (d_1 - d_0)^2 + (d_2 - d_0)^2 - 2(d_1 - d_0)(d_2 - d_0)\cos\gamma$$

$$L^2 = (d_1^2 + d_2^2 - 2d_1 d_2 \cos\gamma) - 2d_0\big((1 - \cos\gamma)(d_1 + d_2)\big) + 2d_0^2(1 - \cos\gamma)$$

$$L^2 = l^2 - 2d_0\big((1 - \cos\gamma)(d_1 + d_2)\big) + 2d_0^2(1 - \cos\gamma)$$

Substitution

$$a = 2(1 - \cos\gamma)$$

$$b = -2(1 - \cos\gamma)(d_1 + d_2)$$

$$c = l^2 - L^2$$

ADM-Offset

$$d_0 = \frac{-b - \sqrt{b^2 - 4ac}}{2a}$$

(Wolf, 2023f)

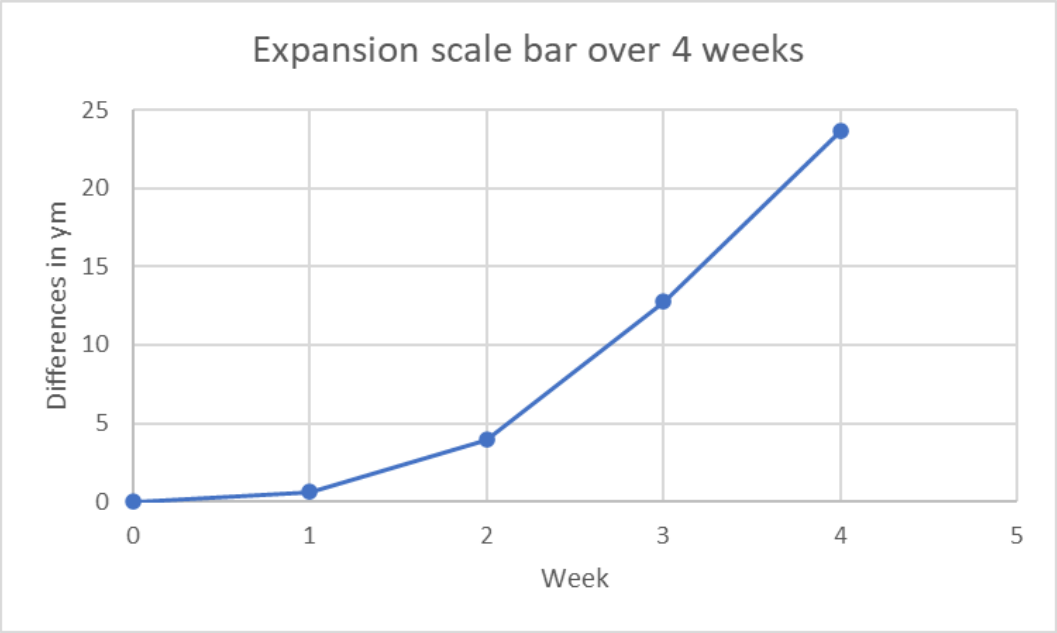
Accuracy comparison of the non-automated procedure with the automated procedure

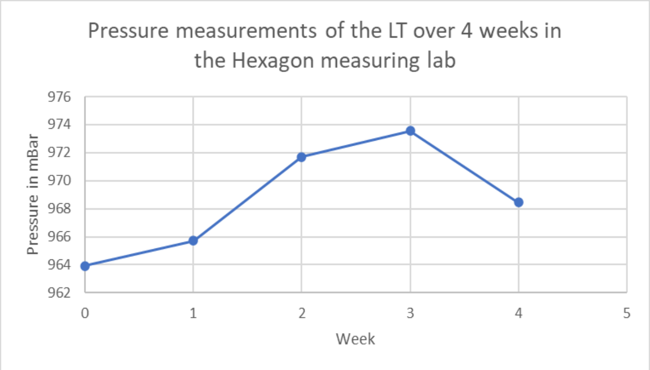
Automated ADM-Offset in µm		
Correction	Standard Deviation 2σ	Time
-0.6	0.1	10:55
-0.6	0.4	11:05
-0.8	0.4	11:15
Not automated ADM-Offset in µm		
Correction	Standard Deviation 2σ	Time
-1.8	1.2	11:20
0.7	2.5	11:30
0.3	1.6	11:35

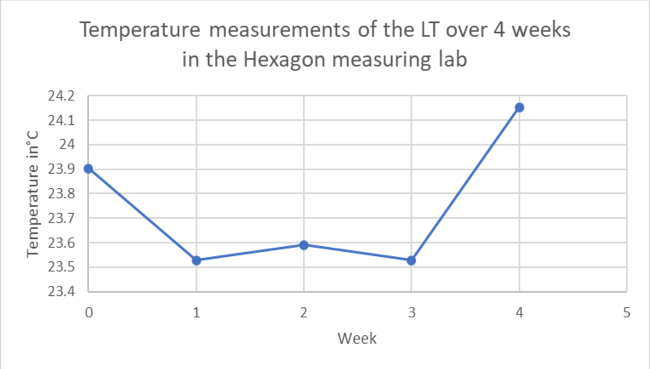
Mean Value Automated ADM-Offset in µm	-0.64
Mean Value Not automated ADM-Offset in µm	-0.27
Difference Automated ADM-Offset vs. Not automated ADM-Offset in µm	**0.4**

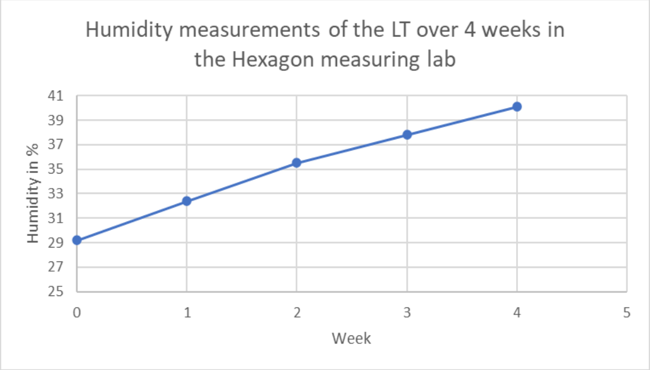
Length consistency of the scale bar

- Measure over 4 weeks
- Expansion of 23.6 µm after 4 weeks
- Its not clear how often it needs to be calibrated



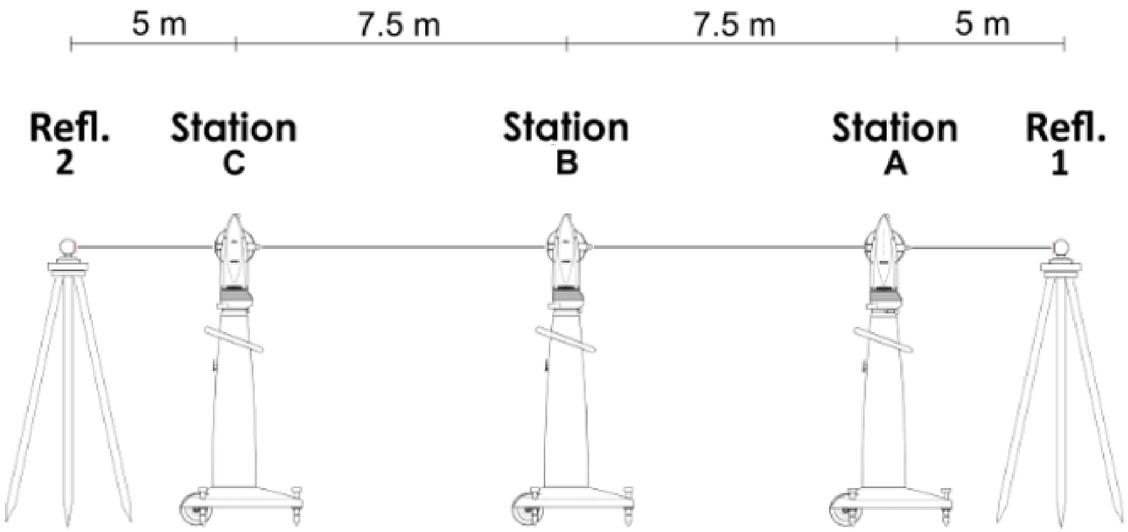






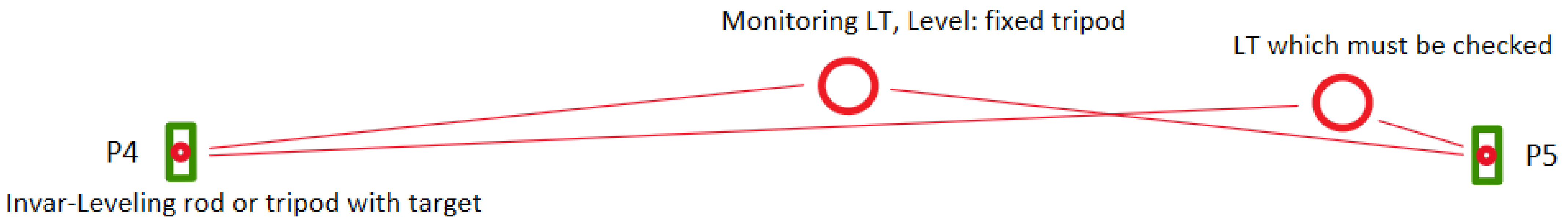
Ve-error non-automated approach

- Three stationing setups and two tripods with targets
- About 30 – 40 minutes



Ve Compensation (Wolf, 2023a)

Ve-error automated approach with a monitorng LT or Level



The fine red line represents the measuring beam / top view

Comparison of Accuracy and Usability of the LT with the Leica DNA03 Digital Level

- Height difference accuracy over 25 m
  - LT 2σ = 0.1167 mm
  - DNA03 2σ = 0.1541 mm
- Rod zero-point difference of the Level
- Digital level does not have a motor

- The LT does not have these problems
- The LT is the better choice

Accuracy comparison of the non-automated procedure with the automated procedure

Not Automated Ve

First determination of the Ve in gon	0.00091
Second determination of the Ve in gon	0.00084
Third determination of the Ve in gon	0.00092
Mean Value Ve in gon	**0.00089**
Ve Standard Deviation 2σ in gon	0.00009
Automated Ve in gon	
0.00078	
0.00079	
0.00089	
0.00091	
Mean Value Ve in gon	**0.00084**
Ve Standard Deviation 2σ in gon	0.00013
Difference Ve automated vs. Ve not automated in gon	**0.00005**

New ADM-Offset and Ve-Error Compensation Workflow

- Combination of both Compensation
- Fix setup
- The new automated process only requires 1 stationing
- the non-automated process requires 5 stationings and 4 tripods
- Time saving of approximately 50 minutes
- Robust and always available

References

Brunson. (2023, 04 21). *Brunson Helping The World Measure*. Retrieved from Brunson Helping The World Measure: https://www.brunson.us/brunson-kinairy-laser-tracker-evaluation-system.html

Construction Products Group. (2023, 03 16). *illbruck*. Retrieved from illbruck: https://www.illbruck.com/de_CH/service/wissenscenter/waermeausdehnung-von-materialien-und-bewegungsbereich-von-fugen/

Conte, Santolaria, Majarena, & Acero. (2016). *Modelling kinematic parameter identification and sensitivity analysis of a Laser Tracker having the beam source in the rotating head.* Zaragoza, Spain: Elsevier.

Conte, Santolaria, Majarena, & Aguilar. (2013). *Identification and kinematic calculation of Laser Tracker errors.* María de Luna 3, 50018, Zaragoza, Spain: Elsevier.

D. Lee, V., Blackburn, C., Muralikrishnan, B., Sawyer, D., Meuret, M., & Hudlemeyer, A. (2014). *A Proposed Interim Check for Field Testing a Laser Tracker's 3-D Length Measurement Capability Using a Calibrated Scale Bar as a Reference Artifact.* Kansas City, MO: NIST.

D. Lee, V., Blackburn, C., Muralikrishnan, B., Sawyer, D., Meuret, M., & Hudlemeyer, A. (2014). A Proposed Interim Check for Field Testing a Laser Tracker's 3-D Length Measurement Capability Using a Calibrated Scale Bar as a Reference Artifact. Kansas City, MO: NIST.

Dante, S. (2019). Varianzfortpflanzung. Muttenz CH: FHNW.

Faro. (2023, 05 25). Understanding Laser Trackers. Retrieved from Understanding Laser Trackers: https://www.faro.com/de-DE/Resource-Library/Article/understanding-laser-trackers#:~:text=The%20second%2C%20which%20FARO%C2%AE,phase%20of%20the%20signal%20received.

Gassner, R., & Ruland, R. (2008). Laser Tracker Calibration Testing the Angle Measurement System. Obergurgl, Austria.

Hughes, B., Forbes, A., Lewis, A., Sun, W., Veal, D., & Nasr, K. (2011). Laser tracker error determination using a network measurement. Middlesex TW11 0LW, UK: MEASUREMENT SCIENCE AND TECHNOLOGY.

References

ISO. (2016, 04). ISO 10360-10:2016. Retrieved from https://www.iso.org/standard/56662.html

Leica Geosystems. (2006). *Leica DNA03/DNA10 Gebrauchsanweisung.* Heerbrugg, Schweiz: Leica. Retrieved from http://www.grad-gon.info/download/manuals/DNA/DNA03_DNA10_UserManual_de.pdf

Leica Geosystems. (2021, 05 20). *Leica LS Digitalnivelliere Datenblatt.* Heerbrugg, Schweiz: Leica Geosystems. Retrieved from Leica Geosystems: file:///C:/Users/manue/Downloads/Leica_LS15_LS10_Digital_Levels_DS%20(3).pdf

Leica Geosystems AG. (2020). *Leica AT930/AT960 User Manual Version 2.2.* CH-9435 Heerbrugg: Leica Geosystems AG.

Lippitsch, A., & Flucher, M. (2021). *Phasor Measurement Correction 3D.* Unterfelden CH: Hexagon.

Loser, R., & Kyle, S. (1998). *Alignment and field check procedures for the Leica Laser Tracker LTD 500.* 5035 Unterentfelden, Switzerland : Leica Geosystems AG.

Meier, E. (2023, 05 26). *edi meier + partner*, https://www.emp-winterthur.ch/produkte/hls/. Retrieved from HYDROSTATIC LEVELLING SYSTEM (HLS).

metrology store. (2023, 03 16). *metrology store*, https://www.metrologystore.com/Carbon-Fiber-Scale-Bar-1,5"-SMR-Target-Holder-Laser-Tracker-Leica-Faro-Articulated-Arm-validate-accuracy-low-weight-dimensionally-stable-2,0-m. Retrieved from metrology store.

Möllring, L. (2023, 03 10). *Messpanda*. Retrieved from Messpanda: https://messpanda.de/strecken/abweichungen-strecken/nullpunktkorrektion-additionskonstante/

Muralikrishnan, B., Phillips, S., & Sawyer, D. (2015). *Laser trackers for large-scale dimensional metrology: A review.* Engineering Physics Division, National Institute of Standards and Technology, Gaithersburg, MD 20899, United States: Elsevier.

References

Saure, M. (2023, 05 16). RE: VP2 Interim Meeting 2 / 20230510. 5035 Unterentfelden, Schweiz.

Sawyer, D., & Fronczek, C. (2003). *Laser Tracker Compensation Using Displacement Interferometry.* National Institute of Standards and Technology.

Schwarz, W., & Hennes, M. (2016). *Qualitätsbewertungen in der Ingenieurgeodäsie.* Geodätisches Institut (GIK), KIT, Karlsruhe, Deutschland: Springer-Verlag GmbH Deutschland 2016.

Wikipedia. (2023a, 02 25). *Wikipedia*. Retrieved from Wikipedia: https://de.wikipedia.org/wiki/Koordinatenmessger%C3%A4t

Wikipedia. (2023b, 03 16). *Wikipedia*. Retrieved from Wikipedia: https://de.wikipedia.org/wiki/Ausdehnungskoeffizient

Wikipedia. (2023c, 05 25). *Wikipedia*. Retrieved from Interferometrie: https://de.wikipedia.org/wiki/Interferometrie#:~:text=8%20Einzelnachweise-,Interferometer,Eigenschaften%20der%20%C3%BCberlagerten%20Welle%20%C3%A4ndern.

Wolf, M. (2023a). *Automation Readiness.* 5035 Unterentfelden, CH: Hexagon.

Wolf, M. (2023b, 03 04). Introduction Hexagon Laser Tracker. (M. Delavy, Interviewer)

Wolf, M. (2023c, 03 14). Short review VP2. (M. Delavy, Interviewer)

Wolf, M. (2023d, 04 06). Meeting VP2 MPE. (M. Delavy, Interviewer)

Wolf, M. (2023f, 04 15). ADM Offset Rechnung. Mönchmattweg 5, 5035 Unterentfelden, Switzerland.

Wolf, M. (2023g, 05 26). Besprechung LT Monitoring Kompensation. (M. Delavy, Interviewer)

Wolf, M., & Lippitsch, A. (2023, 03 03). Besprechung Studentische Arbeit. (M. Delavy, Interviewer)