



— BUREAU OF —  
RECLAMATION

# Demonstration and Use of Advanced 3D Measuring Techniques Using Portable Laser and Arm Technology

Science and Technology Program  
Research and Development Office  
Final Report ST-2021-19146-01



REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188		
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. <b>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</b>					
1. REPORT DATE (DD-MM-YYYY) 12/15/2021		2. REPORT TYPE Research		3. DATES COVERED (From - To) 10/1/2019 – 12/31/2021	
4. TITLE AND SUBTITLE Demonstration and Use of Advanced 3D Measuring Techniques Using Portable Laser and Arm Technology			5a. CONTRACT NUMBER XXXR4524KS-RR.4888FARD.1900901/ F014A		
			5b. GRANT NUMBER -		
			5c. PROGRAM ELEMENT NUMBER 1541 (S&T)		
6. AUTHOR(S) Chad Paulson, <a href="mailto:cpaulson@usbr.gov">cpaulson@usbr.gov</a> , 303-445-2293			5d. PROJECT NUMBER Final Report ST-2021-19146-01		
			5e. TASK NUMBER -		
			5f. WORK UNIT NUMBER -		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Denver Federal Center Bureau of Reclamation, Bldg. 67, 11 <sup>th</sup> -Floor 6th & Kipling Street Denver, CO 80225			8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Science and Technology Program Research and Development Office Bureau of Reclamation U.S. Department of the Interior Denver Federal Center PO Box 25007, Denver, CO 80225-0007			10. SPONSOR/MONITOR'S ACRONYM(S) Reclamation		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S) Final Report ST-2021-Project ID 19146-Report Number 01		
12. DISTRIBUTION/AVAILABILITY STATEMENT Final Report may be downloaded from <a href="https://www.usbr.gov/research/projects/index.html">https://www.usbr.gov/research/projects/index.html</a>					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT Research Question: Can Reclamation harness this powerful new toolset to three-dimensionally map componentry and equipment, with high-accuracy and speed, while subsequently reducing maintenance and repair costs through time-savings and an expansion of in-house capability?  Laser metrology equipment was purchased to explore their use around Reclamation facilities during mechanical maintenance and inspections, and in a lab environment for analysis of test samples and mechanical parts. Various case studies revealed many applications in which laser metrology equipment could be used around Reclamation to aid in the measurement and analysis of hydro-generators, geological samples, and machine parts. The capability of digitally three-dimensionally mapping components adds significant advantages over traditional measurement methods including, measurement accuracy, validation, and the ability to archive measurements. The studies also revealed instances in which laser metrology is inferior to traditional measurement methods due to the measurement complexity, time requirement, and error that is required by a measurement.					
15. SUBJECT TERMS FARO, Metrology, Measurements, Modeling, Reverse Engineering					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Chad Paulson
a. REPORT U	b. ABSTRACT U	THIS PAGE U			19b. TELEPHONE NUMBER (Include area code) 303-445-2293

## **Mission Statements**

The Department of the Interior (DOI) conserves and manages the Nation's natural resources and cultural heritage for the benefit and enjoyment of the American people, provides scientific and other information about natural resources and natural hazards to address societal challenges and create opportunities for the American people, and honors the Nation's trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities to help them prosper.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

## **Disclaimer**

Information in this report may not be used for advertising or promotional purposes. The data and findings should not be construed as an endorsement of any product or firm by the Bureau of Reclamation, Department of Interior, or Federal Government. The products evaluated in the report were evaluated for purposes specific to the Bureau of Reclamation mission. Reclamation gives no warranties or guarantees, expressed or implied, for the products evaluated in this report, including merchantability or fitness for a particular purpose.

## **Acknowledgements**

The Science and Technology Program, Bureau of Reclamation, sponsored this research. I would like to acknowledge Jordan Lemer, Marcel Sorel, Derek Hurelle, and John Germann for their contributions to this project.

# Advanced 3D Measuring Techniques

*prepared by: Chad Paulson, Mechanical Engineer Mechanical Equipment Group 86-68410*

**Technical Service Center**

**Chad Paulson, Mechanical Engineer Mechanical Equipment Group  
86-68410**

# Peer Review

Bureau of Reclamation  
Research and Development Office  
Science and Technology Program

Final Report ST-2021-19146-01

Report Title

---

Prepared by: Chad Paulson  
Mechanical Engineer, Mechanical Equipment Group, 86-68410

---

Peer Review by: Jordan Lemer  
Mechanical Engineer, Mechanical Equipment Group, 86-68410

*“This information is distributed solely for the purpose of pre-dissemination peer review under applicable information quality guidelines. It has not been formally disseminated by the Bureau of Reclamation. It does not represent and should not be construed to represent Reclamation’s determination or policy.”*

# Acronyms and Abbreviations

Reclamation	Bureau of Reclamation
SMR	Spherically Mounted Retroreflector
LLP	Laser Line Probe
CAD	Computer Aided Design
USBR	U.S Bureau of Reclamation
GD&T	Geometric Dimensioning and Tolerancing
TSC	Technical Service Center
TGB	Turbine Guide Bearing
LGB	Lower Guide Bearing
UGB	Upper Guide Bearing
DED	Direct Energy Disposition
PBF	Powder Bed Fusion
ABS	Acrylonitrile Butadiene Styrene

## Measurements

°F	degree Fahrenheit
cm	centimeter
µg/L	microgram per liter

# Contents

	Page
<b>Mission Statements</b> .....	<b>iii</b>
<b>Disclaimer</b> .....	<b>iii</b>
<b>Acknowledgements</b> .....	<b>iii</b>
<b>Peer Review</b> .....	<b>v</b>
<b>Acronyms and Abbreviations</b> .....	<b>vi</b>
<b>Measurements</b> .....	<b>vi</b>
<b>Executive Summary</b> .....	<b>ix</b>
<b>Introduction</b> .....	<b>1</b>
<b>Theory of Measurements</b> .....	<b>2</b>
<b>User Interface &amp; Training</b> .....	<b>4</b>
<b>Case Studies</b> .....	<b>5</b>
FARO Tracker Case Studies .....	<b>6</b>
Pre-Teardown Alignment Readings.....	<b>6</b>
Turbine Pit Measurements for Concentricity.....	<b>7</b>
Unit Runner Interference .....	<b>9</b>
Unit Distributor Measurements.....	<b>12</b>
FARO Arm and Laser Line Probe Case Studies .....	<b>14</b>
3D Printed Parts Quality Control .....	<b>14</b>
Concrete Joint Analysis.....	<b>17</b>
Cavitation Volume Estimation .....	<b>19</b>
Reverse Engineering a Miniature Turbine Runner.....	<b>22</b>
Reverse Engineering a Jet Valve.....	<b>25</b>
Unit Rotor Crack Analysis.....	<b>27</b>
Diversion Dam Model Embankment Variation .....	<b>30</b>
<b>Conclusions</b> .....	<b>32</b>
<b>References</b> .....	<b>34</b>
<b>Appendix A – Equipment Purchased</b> .....	<b>35</b>
Tracker Equipment .....	<b>35</b>
Arm Equipment.....	<b>37</b>
Shared Equipment.....	<b>38</b>
<b>Appendix B – Quick-Start Guides</b> .....	<b>39</b>
FARO Tracker Quick-Start Guide .....	<b>39</b>
FARO Arm and LLP Quick Start Guide.....	<b>47</b>

# Table of Figures

Figure 1: Interferometer visualized.....	2
Figure 2: Encoder Disks. Left: two channel incremental encoder with index. Right: binary absolute encoder 45° resolution.....	3
Figure 3: Structure light 3D scanning.....	3
Figure 4: Turbine pit measurement locations .....	8
Figure 5: Wear plate minimum fit deviations .....	10
Figure 6: Runner band maximum fit deviations .....	10
Figure 7: Wear plate deviations from max runner band .....	10
Figure 8: Distributor best-fit features .....	13
Figure 9: Final measurement results .....	13
Figure 10: Printed ABS speece cone(left) and square-to-round transition (right) quality control .....	15
Figure 11: Metal 3D printed boxes quality control.....	16
Figure 12: Rock specimen 1 – shear test comparison.....	17
Figure 13: Rock specimen 2 – shear test comparison.....	17
Figure 14: Cavitation sample scan deviation colormap.....	19
Figure 15: PolyWorks volume calculation visualized .....	20
Figure 16: Actual runner vs. final CAD part .....	22
Figure 17: Scanned runner mesh.....	22
Figure 18: Runner blade surface.....	23
Figure 19: Runner crown and nose cone cross-section outline.....	24
Figure 20: Actual 6-inch jet valve vs. final CAD part.....	25
Figure 21: Tracing valve cross-section .....	26
Figure 22: Full spider arm scans. arms 2 (left) and 6 (right) .....	27
Figure 23: Flange deflection spider plots.....	28
Figure 24: PolyWorks caliper determining deviation.....	29
Figure 25: Diversion Dam 3000 CFS Colormap .....	31

## Executive Summary

In 2019, laser metrology equipment was purchased to assess their capabilities within the TSC's realm of expertise. The equipment consisted of a FARO Vantage E Tracker, FARO Quantum S 2.5m 7 axis Arm, FAROBlu HD Laser Line Probe (LLP), and the supporting equipment required to use these devices. Research and demonstrations into their practical applications were then explored around many of the Bureau of Reclamation's (Reclamation) facilities during maintenance activities. The research sought to explore the limitations of the devices, introduce Reclamation to the technology, and integrate laser metrology into the maintenance activities of Reclamation facilities.

The research found many uses for laser metrology equipment and aided in analysis of power generating components, manufactured objects, and geotechnical specimens. The FARO Tracker was used to attempt pre-teardown alignment measurements, measure turbine pit components to verify shaft concentricity, determine distributor - turbine interferences after a failed reassembly, and verify generator measurements taken by another type of measurement tool. The FARO Arm and LLP was used to determine variances of parts from their Computer Aided Design (CAD) models, scan concrete joint specimens to identify shear surface changes after joint testing, estimate volumes of cavitation damage in samples, reverse engineer complex surfaces, analyze surface deviations created from a rotor crack, and compare soil embankments on a hydraulic model.

The results of this research proved laser metrology equipment does provide a significant advantage over traditional metrology methods including speed and accuracy in most tasks. The FARO Tracker excels at large feature measurements important when conducting unit overhauls. The FARO Arm and LLP is great at comparing parts to their CAD model or previous state, reverse engineering complex surfaces, and analyzing volumes of defects. However, this equipment is not beneficial to all Reclamation metrology activities. LLP scans of large areas are cumbersome and time consuming as compared to photogrammetry. Traditional methods have also proven to be more effective at tasks that require repetitive measurements at numerous device locations. Additionally, the data analysis must be conducted by someone who is familiar with the measurement software.

It is recommended that the purchased laser metrology equipment should continue to be used around Reclamation facilities as seen fit. Further exploration into the limits and capabilities of the equipment should be conducted alongside typical maintenance practices.

# Introduction

Across Reclamation there has been a need for a more powerful toolset to perform precision infrastructure measurements and dimensional mapping of critical components. Much of Reclamation's existing measurement technologies are obsolete, some dating back to the early 1900's. A laser tracker and track arm toolset would fill this void. These advanced technologies utilize high precision laser instrumentation and techniques to digitally 'map' components, both large and small, by quickly taking thousands of precise measurements where before only a single measurement would be taken and manually recorded. This increases speed, measurement precision, and reliability.

Laser metrology, such as this, is a service offered by contractors across the globe for various industries such as automotive, aerospace, and manufacturing. The Bureau of Reclamation's Technical Service Center (TSC) saw the advantages these systems have and wanted to explore their practicality in the hydropower space.

The Bureau of Reclamation has a large array of mechanical equipment in use across its many facilities. Reclamation's Technical Service Center provides in-house engineering services for much of its-own equipment, such as hydro-unit shaft alignments, large gate and valve repairs and generator turbine overhauls and replacement. Most of Reclamation's large equipment has aged significantly and requires increased maintenance and repair now more than ever before.

Due to the age of the generating equipment, manufactures that had supplied these components no longer stock the parts required to maintain these machines or are no longer in business. This requires the need to reverse-engineer components for fabrication or for a machinist to duplicate parts without accurate dimensions of the old component. Another challenge found around Reclamation facilities is the lack of drawings for their equipment. Repair of this equipment requires precision measurements to ensure the proper fit and function of new parts installed. As such, Reclamation is forced to contract out work to private companies to measure these components, or resort to trusting that components will fit, without verification, exposing workers to unnecessary hazards if reassembly fails. These processes can significantly increase outage times resulting in the loss of revenue to the plant. The ability to three-dimensionally map componentry and equipment with better speed and higher precision can greatly improve the capability of maintenance for Reclamation.

Can Reclamation harness this powerful new toolset to three-dimensionally map componentry and equipment, with high-accuracy and speed, while subsequently reducing maintenance and repair costs through time-savings and an expansion of in-house capability? This is the question this research sought to answer.

TSC Mechanical Engineers Chad Paulson, Marcel Sorel, Jordan Lemer, John Germann, and Derek Hurelle worked in the TSC hydraulic labs and various Reclamation facilities to conduct case studies on the feasibility of the FARO equipment in TSC's services. The case studies took place in TSC labs, California-Great Basin Region, and the Upper Colorado Basin Region.

## Theory of Measurements

Laser metrology is a relatively new technology invented in the 1980's. Advancements in sensor technology in the past 40 years have made these systems invaluable to manufacturing and inspection processes around the world. FARO is a leader in this field, specializing in 3D measurement technology. The pieces of equipment acquired for this research use a series of precise sensors to accurately track the position and surface of a feature in pursuit of a common goal; create a point cloud of an object for digital analysis.

The FARO Vantage E tracker uses both an optical interferometer and two angular encoders to accurately track the location of a Spherically Mounted Retroreflector (SMR) relative to the device's position. This location can be obtained with incredible accuracy in relatively quick succession allowing for the measurements of complex shapes to be mapped in short amounts of time.

The FARO Quantum S 7-axis Arm utilizes numerous angular encoders with known component lengths to track the position of the tip of the arm. As each joint is pivoted, the 3-dimensional position of the tip is recalculated. When used in combination with the Laser Line Probe, a device that uses structured light 3D scanning, this arm can produce a high-quality 3D image of a part in a surface mesh.

Interferometry utilizes the interference of waves to obtain meaningful data from superimposed waveforms. This method exploits the phenomenon of a wave's ability to create constructive or destructive interference when combined with another wave. An optical interferometer, as used in the FARO Tracker, can analyze these "fringes" to determine how far the combined waves are out of phase. This, along with the information of how many cycles of fringes,  $N$ , the detector has gone through, can be used to calculate a precise distance a light beam has traveled (Interferometry explained, n.d.). Figure 1 illustrates this concept.

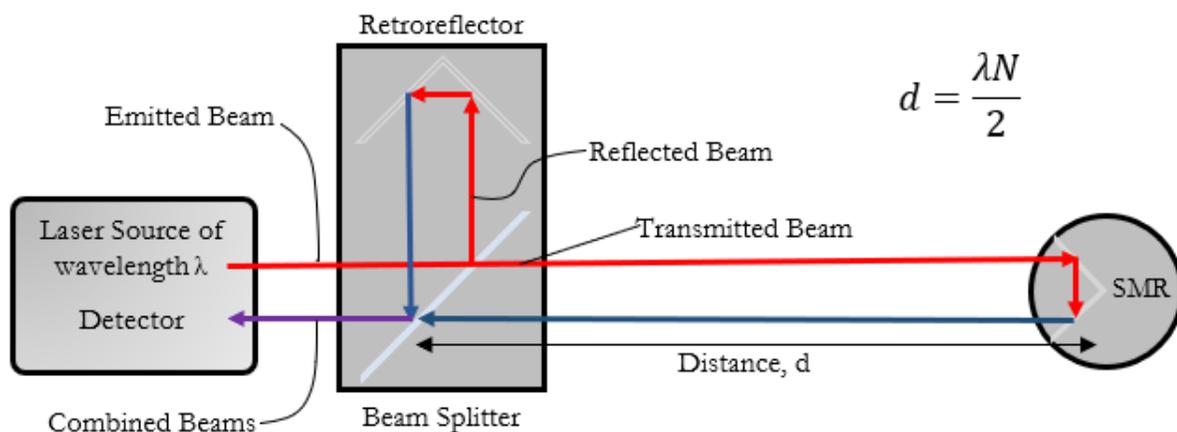


Figure 1: Interferometer visualized

Angular encoders are common amongst many measurement tools. There are a few different types of angular encoders. Incremental angular encoders, for example, use sensors to count pulses as a disk turns. Multiple channels can be used to determine the direction the disk is turning, thus adding or subtracting from the number of pulses passed. The number of pulses passed can then be related to

the angle of the device. Absolute encoders utilize a unique serial number for each position of a disk. This code can be derived from a series of channels whose binary code relates to a unique angle. The more channels, the higher the resolution of the encoder (Interferometry explained, n.d.). Figure 2 shows the general concepts of these types of encoders.

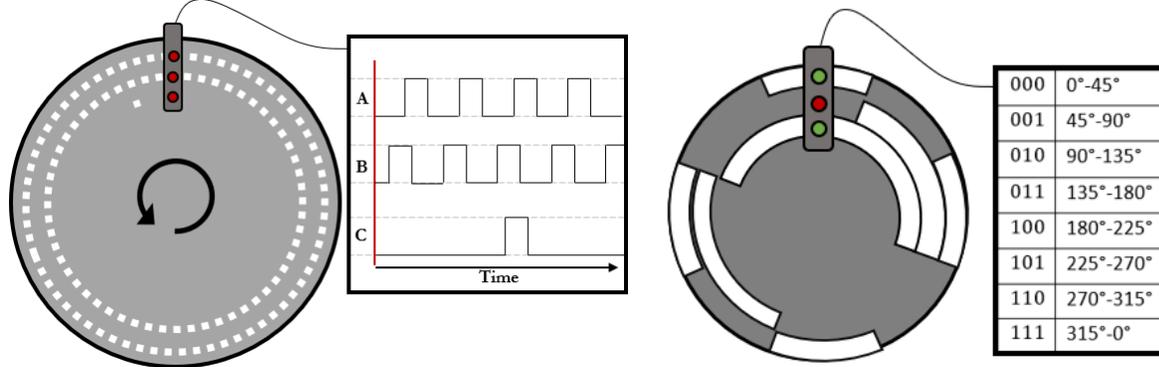


Figure 2: Encoder Disks. Left: two channel incremental encoder with index. Right: binary absolute encoder 45° resolution.

Structured light 3D scanning as used by the FARO LLP is a method that exploits light's ability to distort as the distance and surface of a part changes. A camera, set at a fixed angle from the laser source, rapidly takes pictures as lines from the laser are projected onto a surface. As the surface of the part changes, the laser lines distort allowing for the camera to determine curvatures of the part's surface to create a 3D point cloud (Wheeler, 2017). Figure 3 illustrates this concept.

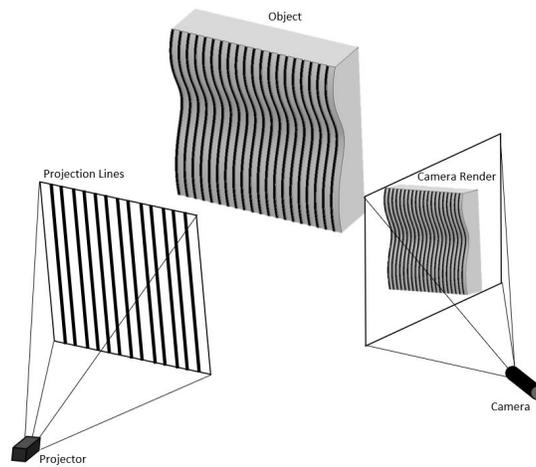


Figure 3: Structure light 3D scanning

Combined with a powerful user interface and data analysis tool, the three unique measurement methods allow for a wide variety of metrological use cases.

## User Interface & Training

An important aspect of any digital equipment is the user interface. The acquired FARO equipment requires complex programs in order to access the many different settings of the measurement devices. Two programs are available, FARO's inhouse program, CAM2, or a third-party program, PolyWorks. It was recommended by FARO representatives that, while CAM2 is more intuitive, PolyWorks is a far superior tool when analyzing scanned data. Therefore, PolyWorks was purchased along with a three-day instruction course to train five mechanical engineers on its features. This course focused on the set-up of the FARO equipment, scanning methods, and analysis of the FARO data within PolyWorks. The software purchase came with one license of PolyWorks | Inspector™ Premium. In addition, this purchase came with a version on PolyWorks | Modeler™ Lite.

PolyWorks | Inspector™ is a 3D analysis tool that enables the user to record, view, and analyze scanned point cloud data in a CAD environment. Features such as cylinders, planes, lines, and circles can be extracted from data to measure distances, radii, and thicknesses.

PolyWorks | Modeler™ Lite is a base level 3D modeling software that can manipulate point clouds to fill holes, smooth vertices, and extract other data from a scanned point cloud. Used in combination, PolyWorks enables a user to reverse engineer components, use existing CAD to compare to geometrical dimensioning and tolerancing (GD&T) criteria, or perform a myriad of other analyses on scanned or probed data sets. The program also has provisions to write macro scripts that can automate post-processes for common analyses.

To become proficient and efficient in the use of PolyWorks, many hours must be spent learning its complex functionality. In addition to taking the three-day class, it is also helpful to perform many practice scans and measurements to help cement knowledge. A background in CAD is helpful in manipulating the view ports but not critical. PolyWorks technical support was found to be extremely helpful, however, access to their services does require yearly fees.

Quick start guides for connecting and using the FARO tracker, arm, and LLP with PolyWorks were created to aid in the setup of these devices.

## Case Studies

The method for determining the usefulness of these devices was to test out scenarios in the field. The laser measurement equipment was used in both the lab and field environments for applications in industrial refurbishments, geotechnical analysis, part quality control, cavitation analysis, and reverse engineering. Not all applications once believed to be made easier with the FARO equipment proved useful when compared to traditional methods.

FARO Tracker case studies included:

- Taking pre-teardown shaft alignment readings
- Analyzing runner and distributor interference
- Verifying field measurements taken with a Brunson scope
- Determining turbine pit and shaft concentricity

FARO Arm and Laser Line Probe demonstrations included:

- Scanning 3D printed parts for depiction of variances
- Cataloging and comparing changes of rock specimens after testing
- Scanning cavitation damage
- Reverse engineering a turbine runner
- Reverse engineering a jet valve
- Scanning a spider arm joint to visualize deflections
- Comparing embankment changes in a large hydraulic model

## FARO Tracker Case Studies

### Pre-Teardown Alignment Readings

**Background:** When considering applications for this equipment and in the stages of research proposal, it was believed that the accuracy of the FARO tracker could aid in the alignment of a vertical-shaft hydro unit. To test this theory, the FARO tracker was brought to a powerplant to take pre-teardown alignment measurements alongside the traditional alignment readings.

**Procedure:** The tracker was set up on the turbine pit level with limited line-of-site of the unit shaft. This was determined to be the best location as it was out of a foot traffic pathway and was on solid ground. A closer location within the turbine pit was not feasible as temporary plywood planking had been installed within the turbine pit for maintenance personnel. Tracker readings were taken to the best extent practical near the turbine guide bearing (TGB) and shaft coupling. The unit was then turned 90° and readings were taken again for four iterations.

**Analysis:** The time and effort required to conduct these measurements was far too much when compared to the traditional method. The limitations in taking data of the entire shaft and the time required to process the data after its acquisition would significantly hinder the FARO's ability to perform a unit alignment. Additionally, line of site of all three bearings (TGB, lower guide (LGB), and upper guide (UGB)) from a single location is unlikely because of the geometry of the unit. Therefore, two or even three tracker locations would be required to gather the necessary data. This not only significantly increases the time required to take accurate readings for the overall task, but also introduces many opportunities for alignment errors. Furthermore, once data has been gathered from the FARO Tracker, the post-processing of this data would take a significant amount of time to interpret.

The traditional alignment method, which typically uses six dial indicators and a precision level, can quickly measure deviations as a shaft is rotated around the bearings. By using this method in conjunction with an excel spreadsheet, an experienced engineer can track the dynamic runout of a unit with minimal post-processing work required.

### Key Findings:

- 1) The FARO tracker has distinct disadvantages against traditional methods when dealing with repetitive measurements in multiple locations.
- 2) The tracker is severely limited by the base locations. The tripod requires a large space on a steady surface for the tracker to be effective. The acquisition of a magnetic mount will enable more locations within the turbine pit to be utilized as a mounting surface.

## Turbine Pit Measurements for Concentricity



*Photograph 1: Powerplant turbine pit measurements*

**Background:** A Powerplant was in the process of planning the installation of a monorail crane inside of its turbine pit. The rails of the crane were to be hung from the circular concrete ledge that creates the interior wall of the turbine pit. Two main measurements were desired for this installation: 1) The diameter of the turbine pit wall and 2) the concentricity of the pit to the shaft. These measurements would verify the radius the crane would need to be and how long the boom can be without running into the shaft. The FARO tracker was an ideal tool to measure these surfaces.

**Procedure:** This study was conducted prior to purchasing the FARO magnetic mount, thus locations for placing the tracker head was limited to concrete surfaces. The turbine pit has two concrete galleries that the tracker was able to take readings from. The 1.5" SMR was placed on the pole adapter and ran along the rim of the turbine pit ledge as seen in Photograph 1. Readings were automatically taken every 2 inches as the SMR was moved along the wall. Between the two locations, data was able to be taken approximately 200° of the 360° turbine pit. The shaft diameter and shaft coupling diameter were also measured. Figure 4 shows the areas data were able to be taken between the two locations. Certain areas within this 200° span were unable to be measured due to shaft interference.

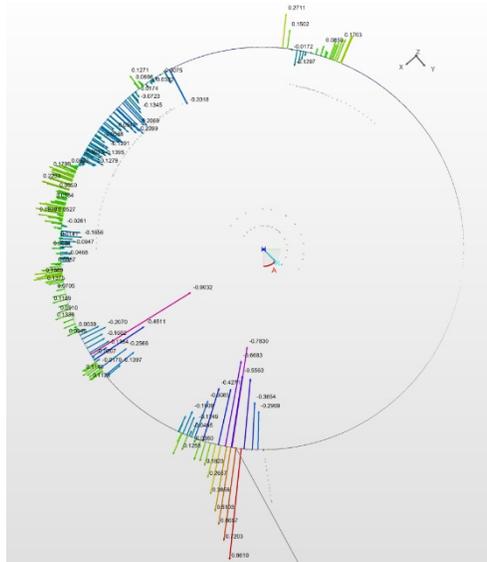


Figure 4: Turbine pit measurement locations

**Analysis:** PolyWorks was able to determine a best-fit cylinder of the turbine pit wall and shaft. Results determined that the center of the turbine pit wall was 1.29 inches from the center of the shaft at  $236^\circ$  counterclockwise from the gallery wall.

This information was given to TSC crane engineers so this as-built offset could be compensated for in the design of the crane.

### Key Findings:

- 1) FARO's ability to automatically take distance- and time-based tracker measurements is a valuable tool to speed up measurements.
- 2) It is difficult to use the SMR on concrete due to the amount of surface imperfections.
- 3) Maintaining the SMR aperture pointing to the FARO tracker is difficult and a skill that is developed with practice.

## Unit Runner Interference



*Photograph 2: Unit runner and distributor*

**Background:** In June 2020, a replacement of unit wear plate was completed. Upon reassembly of the unit, an interference between the turbine runner's lower band and the distributor's new wear plate was discovered. This interference would not allow the unit to freely rotate. Laser tracker measurements were requested to map the implied asymmetries of these two components to visualize where interference was occurring and how much material would need to be removed from the new wear plate to fit the turbine runner.

**Procedure:** The use of laser scanning devices was successfully able to complete this task in a days' worth of scanning. The runner required three device positions and the distributor required two to adequately plot the desired surfaces. Both components were scanned using the FARO mounted on the tripod, as this study was completed prior to the purchase of the magnetic mount. Multiple SMR nests were glued around the work areas to accurately reference one location to another. The data detailed the contours of the runner's shaft journal, upper seal, and lower band by plotting points every half-inch as the SMR moved on the surface. The surfaces of the distributor's head cover flange, curb plate, and wear plate diameter were also defined.

**Analysis:** Point clouds were able to be analyzed and the deviation from maximum and minimum fits visualized as shown in Figures 5 and 6.

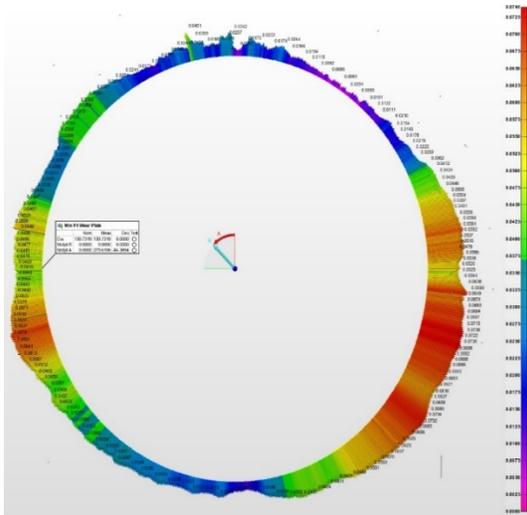


Figure 5: Wear plate minimum fit deviations

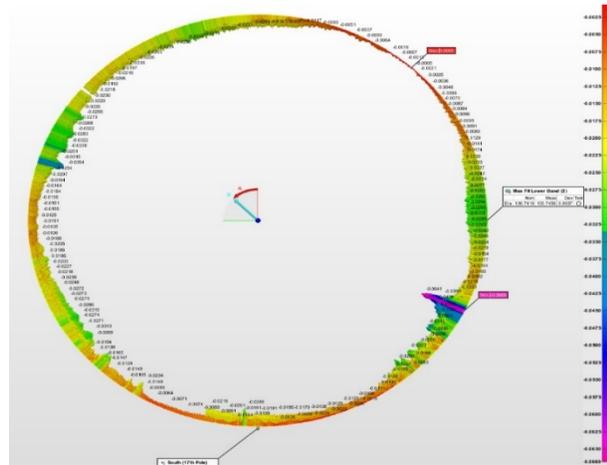


Figure 6: Runner band maximum fit deviations

Results of the laser measurements indicated that the minimum diameter of the stationary wear plate is 13.7 mils smaller than the maximum diameter of the rotating runner's lower band, if they were perfectly concentric. Therefore, an interference will exist between the two components.

Four monuments in the turbine pit at North, South, East, and West were measured. The intersection of these monuments represents the shaft's center when installed. By using these points to create a cylindrical coordinate system, these scans were able to be overlaid to observe the theoretical areas of interference. Figure 7 depicts the deviations of the wear plate's surface from the maximum fit of the runner band when the center of the shaft journal bearing is aligned with the center of the monument circle. Measurements noted as negative indicate areas of theoretical interference.

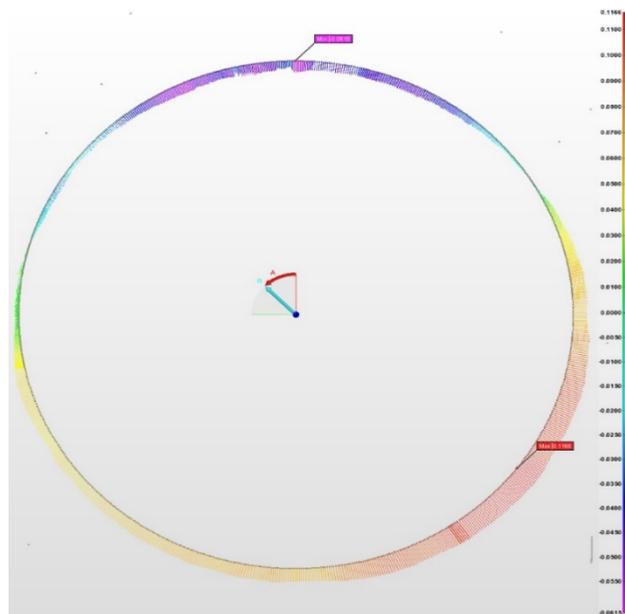


Figure 7: Wear plate deviations from max runner band

By gathering this data, area office personnel were able make educated decisions on how to machine the distributor's wear plate to align with the center of the runner. An in-place machining lathe was placed north of center to offset the interference shown in Figure 6. Upon reassembly of the unit, interferences were eliminated.

**Key Findings:**

- 1) The tracker can be used to accurately depict surface deviations from best-fit data averages. This data can be used to digitally verify the fit of two large components to ensure the desired clearance prior to the installation of components. This could eliminate complex and hazardous lifts if the desired clearances are not present.
- 2) The use of many reference points is critical in relating tracker locations. The more reference locations added, the easier it will be to localize additional locations.

## Unit Distributor Measurements



*Photograph 3: Distributor layout*

**Background:** The turbine runner of a powerplant's generator was being replaced by a contractor. Upon engineering evaluation by the contractor, it was determined that the pre-teardown measurements of the Unit 2 distributor, taken with a Brunson scope and invar scales, did not match the measurements of the length of the turbine shaft with the new runner. This indicated that the runner and shaft would not align properly to the turbine pit and distributor components without significant modification. To confirm this scenario, the FARO tracker was used to verify the field measurements of the Unit 2 distributor.

**Procedure:** Prior to the unit disassembly, a benchmark sticker was placed on the turbine pit wall that was used to reference the elevation of the turbine shaft coupling. The center punch adapter with transfer punch was used to accurately obtain the elevation of the benchmark sticker with the FARO tracker. The dataset utilized two device locations within the turbine pit, and one on top of the generator cover. All three locations used the FARO magnetic mount to secure the tracker head. Nests were strategically placed around the turbine pit to locate the multiple device positions. Four elevations and two diameters were measured of the distributor components.

**Analysis:** PolyWorks was able to run statistics and map surfaces as best-fit planes and cylinders as shown in Figure 8.

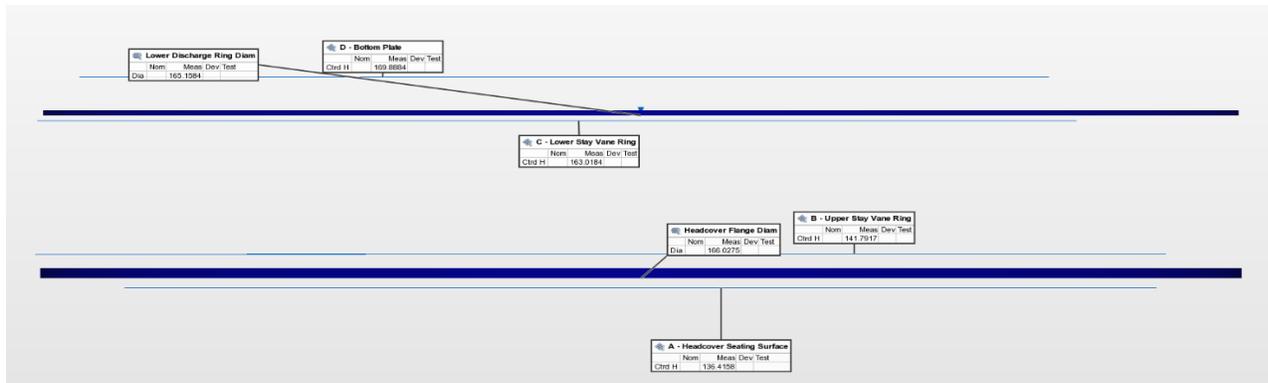


Figure 8: Distributor best-fit features

These best fit planes were then used to determine the elevations and distances between the respective surfaces. These results ultimately determined that the field measurements were within the margin of error of the FARO measurements as shown in Figure 9.

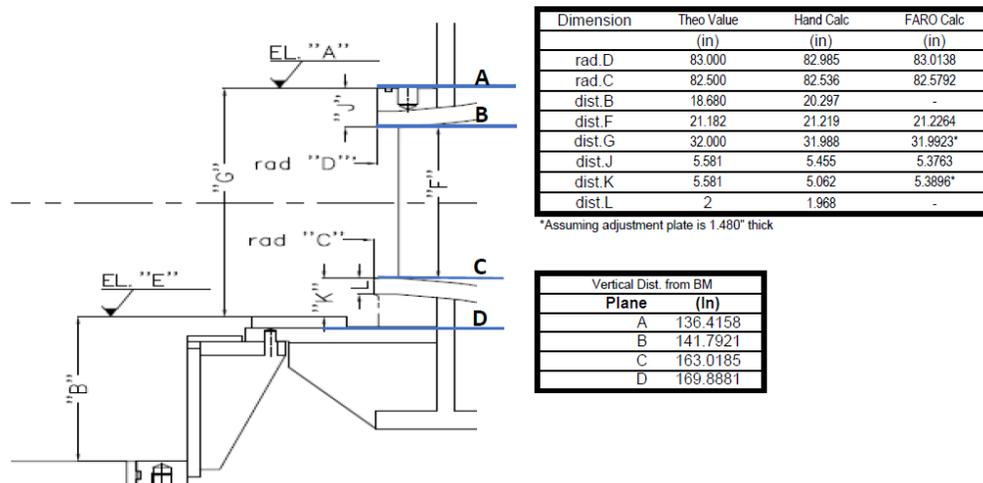


Figure 9: Final measurement results

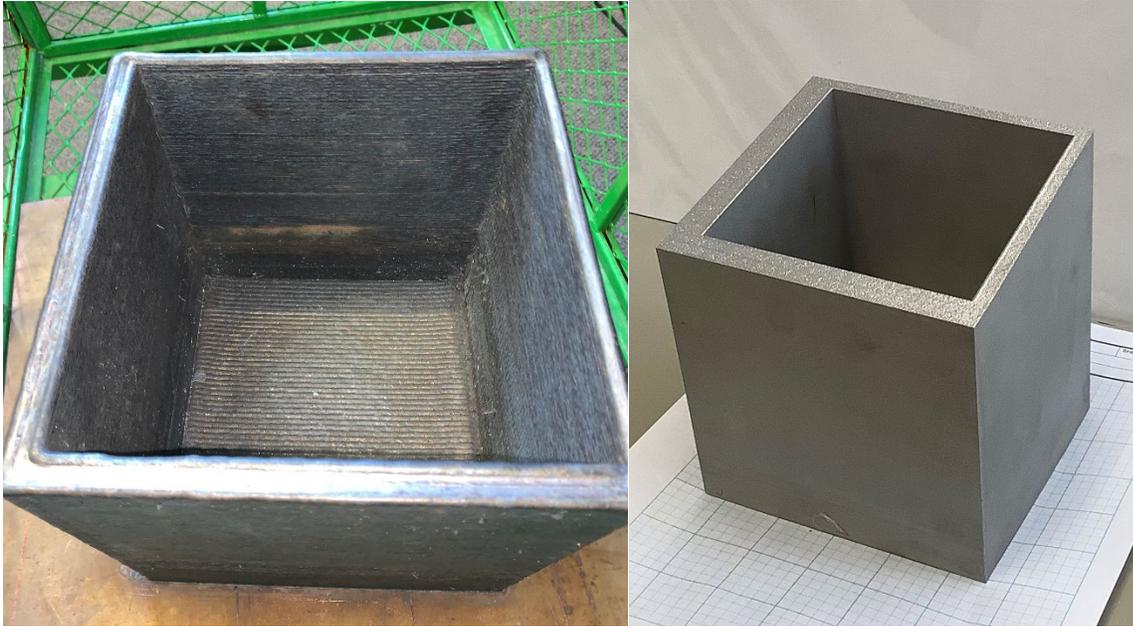
By gathering this data, area office personnel were able communicate to the contractor that the Brunson scope readings were accurate and that accommodations should be made for the theoretical gap.

**Key Findings:**

- 1) Mapping a unit's major measurements prior to teardown can provide vital information for reassembly. The elevation data for all critical componentry can be saved for future layout analysis and reference.
- 2) Reference nests can be permanently glued to the unit turbine pit for future reference if more FARO measurements are required.

## FARO Arm and Laser Line Probe Case Studies

### 3D Printed Parts Quality Control



*Photograph 4: Metal 3D printed boxes – DED left, PFB right*

**Background:** 3D printing is a relatively new manufacturing process that creates a part by adding material in a specific pattern to create a desired geometry. Depending on the type of printer and material being used, anomalies can form that were not a part of the design. A study was conducted that would detail these anomalies to see how well a printed part compares to its CAD drawing.

Both plastic and metal 3D printed parts were analyzed in this study. Acrylonitrile Butadiene Styrene (ABS) plastic is a common printable material that is relatively popular in the 3D printing community. The TSC has a 3D printer that can print ABS plastic parts via fused deposition modeling for research and laboratory purposes. Additionally, a separate research project explored the feasibility of utilizing metal 3D printing to manufacture hydropower parts. As part of this project, a FARO scan of the products was desired to quantify errors from the printing methods. Two different materials and 3D metal printed processes were analyzed, carbon steel via direct energy deposition (DED) and stainless steel via laser powder bed fusion (PFB).

**Procedure:** Physical and CAD models of each type of print were obtained. Their physical models were scanned with the FARO Arm and LLP to the best extent practicable. Reclamation had previously printed two parts in ABS plastic, a speece cone and a square-to-round transition piece as shown in Figure 10. The speece cone and transition piece required four and five partial scans respectively, to generate a complete model.

The 3D metal pieces, printed by outside companies, were scanned when received from the printer. The original file was a 9 x 9 x 9-inch cube. However, due to size constraints of the printing machine, the stainless-steel cube had to be reduced in size to 5 x 5 x 5-inches. This process also required the

box to be printed at a slope as seen in Photograph 4. Both boxes were generated in a single scan orientation.

These pieces were scanned with the FARO arm and LLP to compare to their CAD source file for comparisons as shown in Figure 10 and 11.

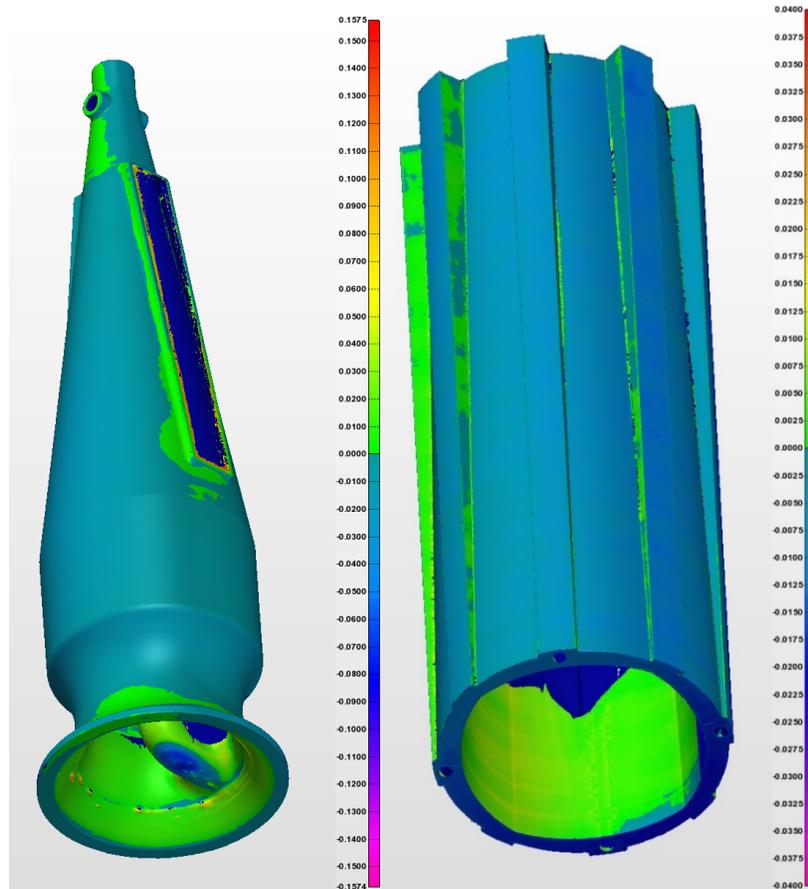
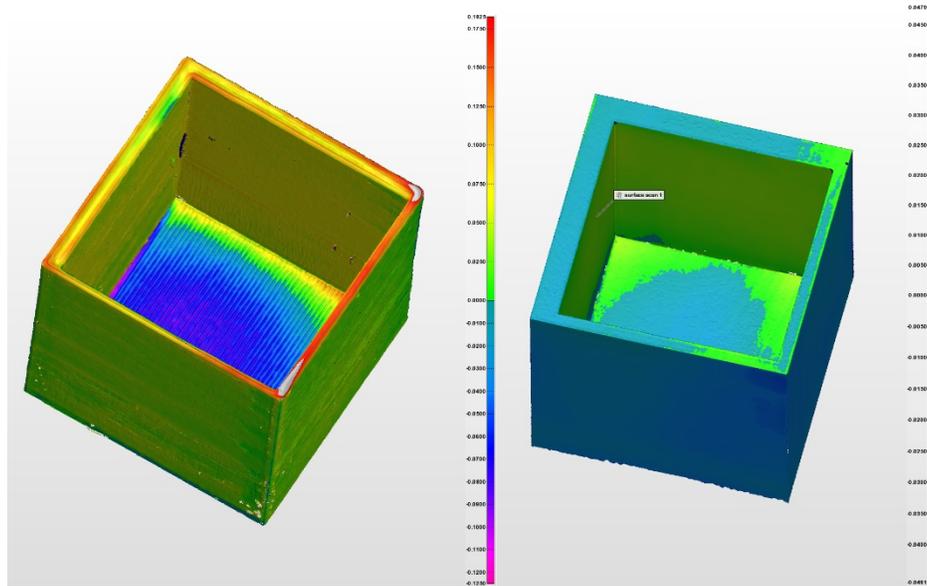


Figure 10: Printed ABS speece cone(left) and square-to-round transition (right) quality control



*Figure 11: Metal 3D printed boxes quality control*

**Analysis:** The ABS printed parts had geometry extremely close to their original geometry. The color map highlighted areas on the speece cone that showed printing defects on the underside of its base that deviated from the nominal drawing. A maximum deviation of less than 0.158-inch was found. The transition piece was found to be extremely close to the nominal CAD drawing with a max deviation of 0.041-inch.

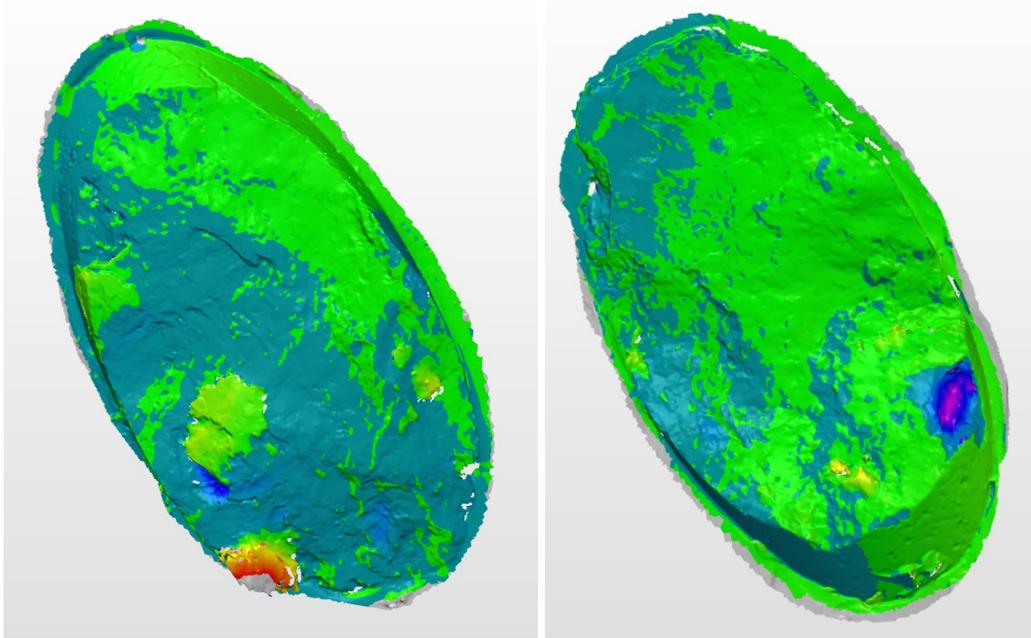
As shown in Figure 11, the direct energy deposition (left) print showed obvious inaccuracies and consistent deviations greater than 0.185-inch. A bowling effect of the lower surface was clearly seen in the colormap. The laser powder bed fusion print however, turned out to be extremely accurate with deviations less than 0.040-inch.

#### **Key Findings:**

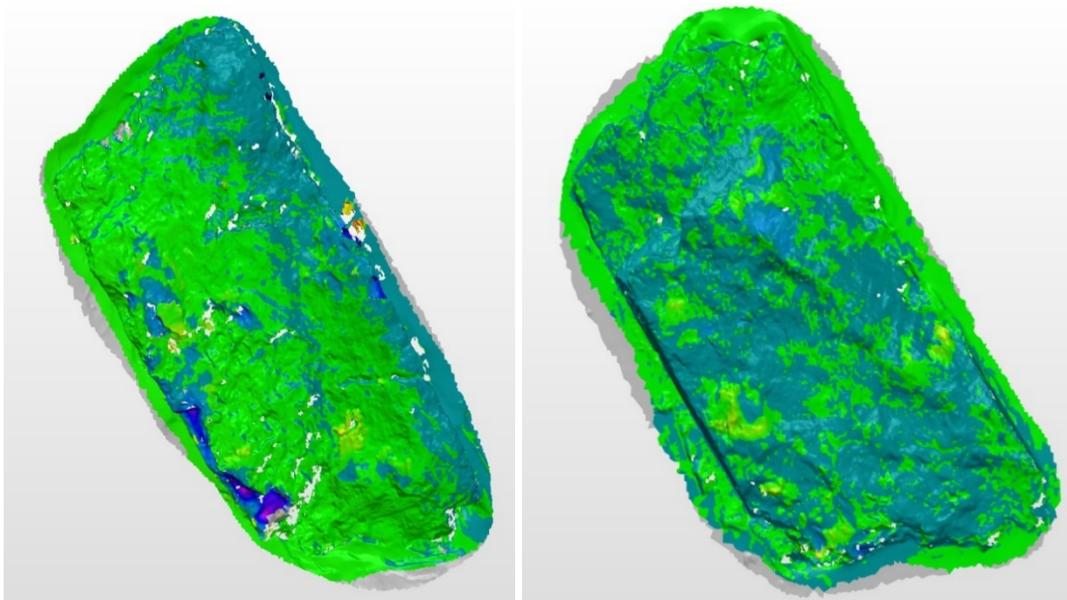
- 1) PolyWorks is a very useful tool for part quality control. This could be used to verify part's acceptability prior to installation.
- 2) Scanning items with lots of surfaces can be time consuming.
- 3) Minimizing the number of positions the part is scanned eliminates areas of possible error while meshing the scans together.

## Concrete Joint Analysis

**Background:** Geotechnical scientists requested scans of concrete joint specimens to compare the joint damage inflicted after subjected to a shear force in a testing machine. The ultimate goal of the study was to compare the two pieces before and after the shear tests were completed.



*Figure 12: Rock specimen 1 – shear test comparison*



*Figure 13: Rock specimen 2 – shear test comparison*

**Procedure:** Scans with the FARO LLP of each half of the two specimens were completed for before and after shear force tests. These samples were encased in a 1-foot diameter ring that were scanned and later cropped out of the data file.

**Analysis:** The scans were compared against each other to identify differences between tests. PolyWorks was able to best-fit the pre- & post-test scans to each other. The colormaps were able to highlight material that had transferred from one surface to the other or where pieces were missing from each surface. Figure 12 and 13 illustrate these analyses.

**Key Findings:**

- 1) The FARO LLP is efficient at scanning rough, small surfaces.
- 2) The LLP can be used to catalog samples as they undergo testing phases.

## Cavitation Volume Estimation

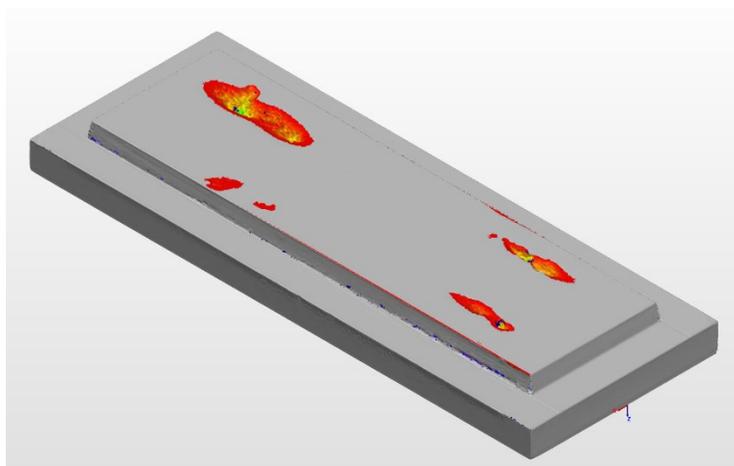
**Background:** Millions of dollars are spent every year repairing cavitation damage. Volume estimation of the existing damage needs to be determined to predict the amount of welding material that will be required. Currently this is done with clay by packing every crevice with clay, then removing it to measure its volume. Could this process be done faster and more accurately with the FARO LLP? This case study was created to answer this question.

**Procedure:** The sample examined was a flat piece of stainless steel seen in Photograph 5 with cavitation created with a pressure washer. Four areas of the steel sample were subjected to the pressure washer jet at varying degrees of time and injection angles. The sample was scanned with the FARO LLP to create a detailed point cloud of the damage. The scanner had a hard time detailing the deeper pits of the sample because of the narrow pits made.



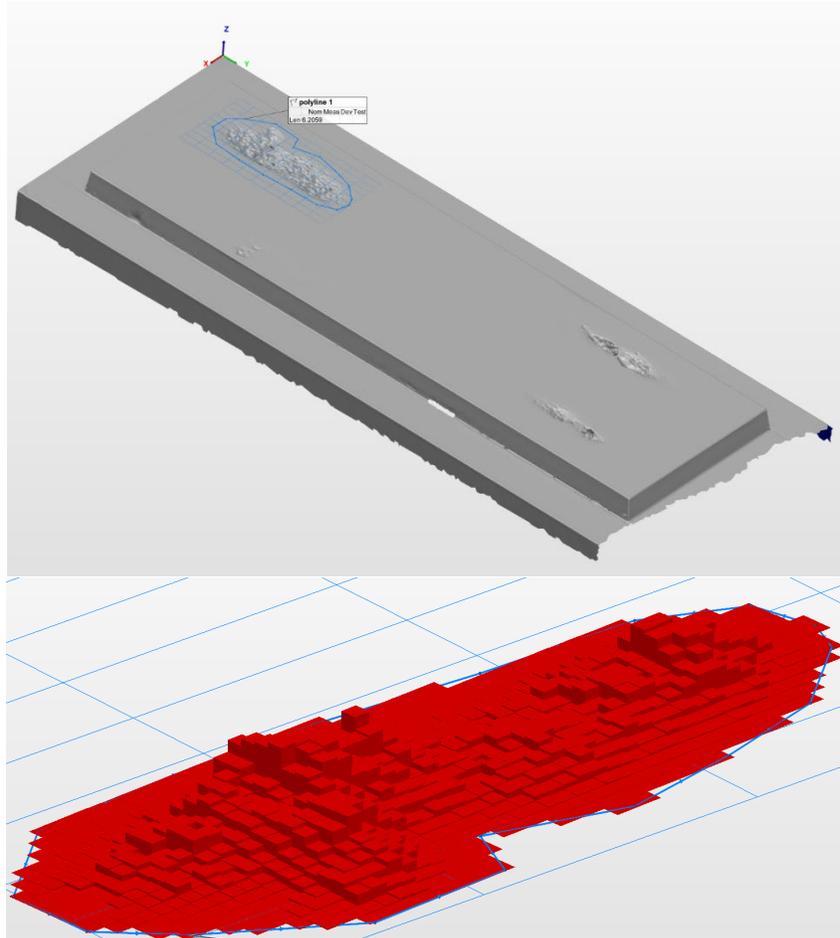
*Photograph 5: Cavitation sample*

**Analysis:** A colormap was made to identify the deviation of the damaged areas from the original sample surface. The extents of the damage were highlighted as shown in Figure 14.



*Figure 14: Cavitation sample scan deviation colormap*

The boundary of the damaged area was then outlined to limit error, as PolyWorks calculates the volume of the measured surface to the outlined plane seen in Figure 15. PolyWorks measures volume by using extruded squares of a set dimension to fill voids much like a pin board. This feature is extruded from the reference plane to the measured surface and the sum of the Length<sup>2</sup> x Height of all boxes is calculated.



*Figure 15: PolyWorks volume calculation visualized*

This damage was found to have a volume of 1.00 mL. Conducting a physical experiment by weighing the amount of water the void can hold, the volume was found to be 1.11mL. The error may be explained by the inability of PolyWorks to deal with undercut features. On a larger scale, these undercuts are unlikely to make up a large enough portion of the damaged area to represent significant error. However, the speed in conducting this analysis could be detrimental. While PolyWorks does allow for this analysis to be completed on a curved surface such as a turbine blade, recreating the nominal condition to compare the volume against could be time-consuming.

Grand Coulee Powerplant was scheduled to conduct runner cavitation scans, utilizing a custom-made FARO arm mount designed and manufactured by Coulee personnel. However, due to the Coronavirus pandemic, the scheduling of this work was disrupted and was unable to be conducted during an available outage. It is recommended that this type of study be conducted when cavitation volume estimation is next completed.

**Key Findings:**

- 1) PolyWorks can be utilized to measure the volumes of defect size. This has the potential of significant financial savings from traditional volume measurements.
- 2) More analysis of large runner cavitation damage should be conducted when the opportunity arises.
- 3) This volume analysis requires all holes in the feature to be filled. Polywork Modeler is useful in completing this task if a full scan is not obtained. This could potentially be a time-consuming task.

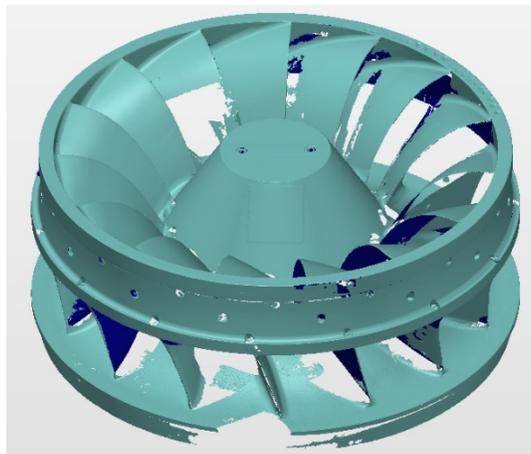
## Reverse Engineering a Miniature Turbine Runner



*Figure 16: Actual runner vs. final CAD part*

**Background:** An initial goal of obtaining the FARO equipment was to be able to reproduce parts that do not have CAD drawings. Once parts are in CAD, they can be easily replicated and analyzed by engineers as needed. PolyWorks will enable the user to convert scanned geometry into a CAD software file. Turbine runner blades, for example, are often proprietary designs not released by the manufacturer but provide a critical function to the performance of a hydro generator. A study was desired to determine how well the FARO equipment and PolyWorks could reproduce complex geometries. This study focused on the replication of an entire turbine runner.

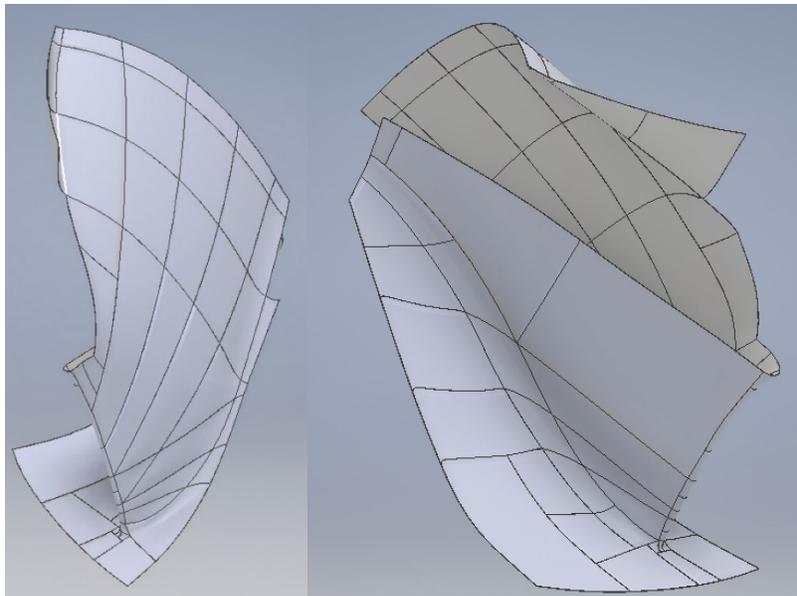
**Procedure:** A scaled version of a turbine runner, approximately 14 inches in diameter and previously used in a model simulation in the TSC Hydropower Labs, was used for this study. The FARO LLP was used to scan the runner to the best of its ability. Due to the size of the runner and distances from one blade to the other, a full scan of a single blade was not able to be obtained. The final scan ended with about 2.25 million points collected. Figure 17 depicts the areas scanned of the turbine runner.



*Figure 17: Scanned runner mesh*

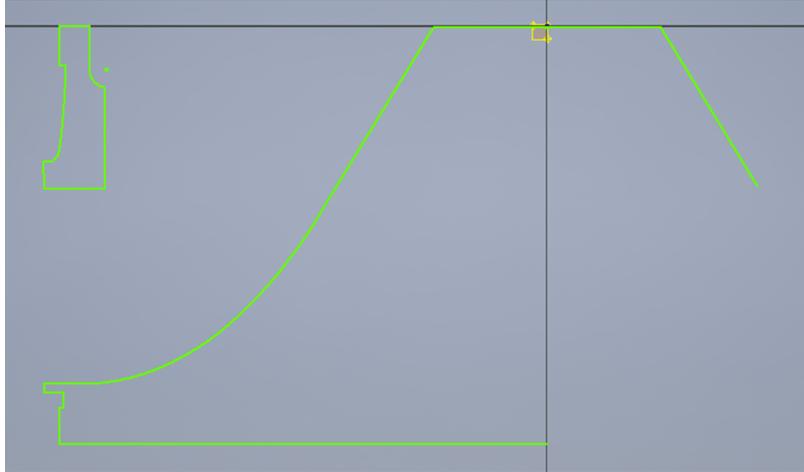
**Analysis:** With PolyWorks Modeler Premium software, cross-sections of scanned parts can be traced and sketches can be imported directly into CAD software for reverse engineering purposes. Complex surfaces can also be extracted to recreate a part. A turbine runner or pump impeller, for example, is often made up of a specific blade profile that is a swept feature made up of a series of complex curvatures extremely difficult to reproduce with traditional measurement methods. PolyWorks, however, can aid in the reverse engineering of this part through its many modeler features.

Despite not having a full scan of a single blade, PolyWorks was able to take two sides of different blades and mesh them together and fill holes of many unscanned areas. PolyWorks was then able to create Non-Uniform Rational B-Spline (NURBS) surfaces that match the geometry of the blade. A large portion of the blade's inside surface was unable to be fit due to the lack of data. The surfaces that were able to be fit were exported and thickened to create the blade's surface in AutoCAD as shown in Figure 18.



*Figure 18: Runner blade surface*

In addition, a cross section of the runner was outlined to trace the geometry of the runner's other components, such as the nose cone's angle and the band geometry as seen in Figure 19.



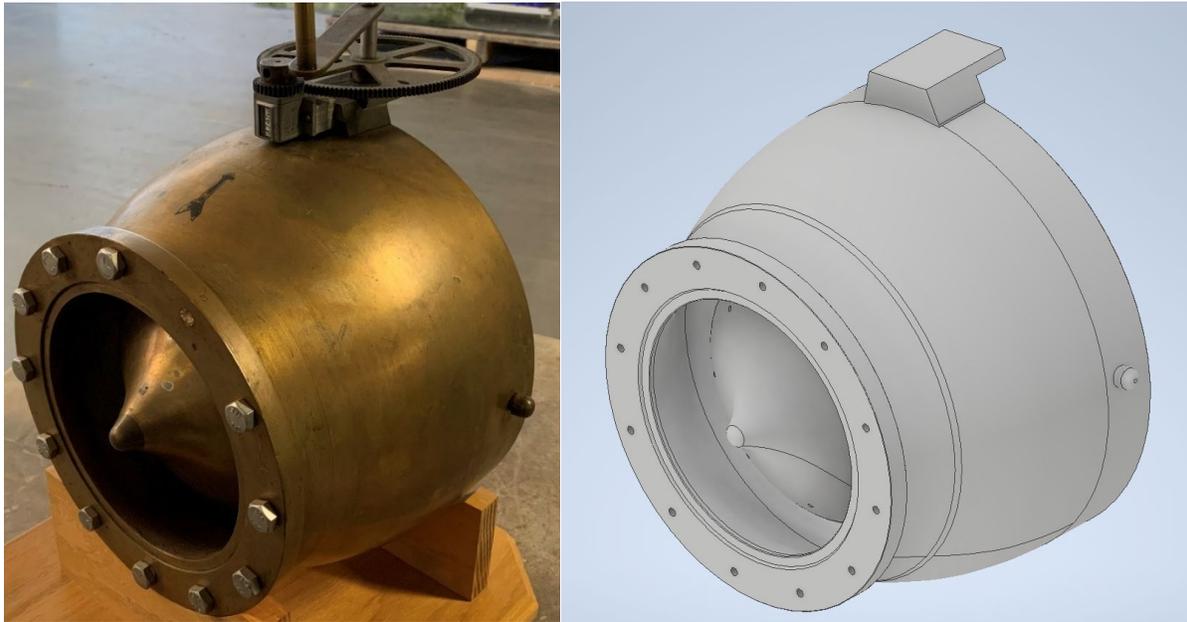
*Figure 19: Runner crown and nose cone cross-section outline*

These sketches were imported to AutoCAD Inventor and revolved to create the full nose cone and band structure. The CAD blade was multiplied and revolved around the runner axis and the two CAD parts were then combined into an assembly to recreate the full turbine runner seen in Figure 16.

#### **Key Findings:**

- 1) PolyWorks Modeler is a powerful tool that can reverse engineer even the most complicated geometries.
- 2) It is critical to scan a surface as much as possible to minimize error when filling holes in the model.
- 3) A large limitation of the FARO LLP is the standoff distance required to accurately scan a surface. This makes gathering data between two close features difficult.
- 4) A piece subject to reverse engineering should be scanned to the fullest extent possible to mitigate interpolation from PolyWorks Modeler software.

## Reverse Engineering a Jet Valve



*Figure 20: Actual 6-inch jet valve vs. final CAD part*

**Background:** The version of PolyWorks Modeler used to reverse engineer the runner blade was a trial license of PolyWorks | Modeler™ Primium. Prior to making the decision to purchase Modeler Premium, a trial was conducted to determine the difficulty of reverse engineering an item without the features of Modeler Primium.

**Procedure:** A 6-inch jet valve model was selected to be modeled due to its unique housing and needle shape. The part was scanned with the FARO LLP. Two scan positions were utilized and meshed together in PolyWorks. Cross sections of the scanned data were then extracted and traced to the best extent practical within Inventor. The scan required three scanning positions to be meshed together to get a full model. The mesh is comprised of 1.8 million data points.

**Analysis:** A cross-section of the scan was extracted that represented the curvature of the needle and valve housing. Unlike Modeler Premium, Modeler Lite is unable to create polylines generated from the scanned data. Instead, the cross-section was exported into Inventor and traced with the available tools as shown in Figure 21. These lines were not able to be anchored to the cross-section geometry and therefore minor errors exist. Once traced, the geometry was revolved to create the valve body and needle seen in Figure 20. A couple of additional features were extruded and cut to match other valve features.

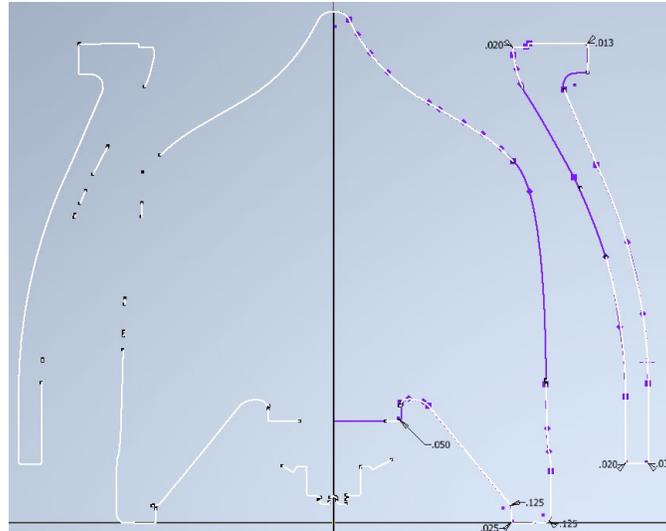
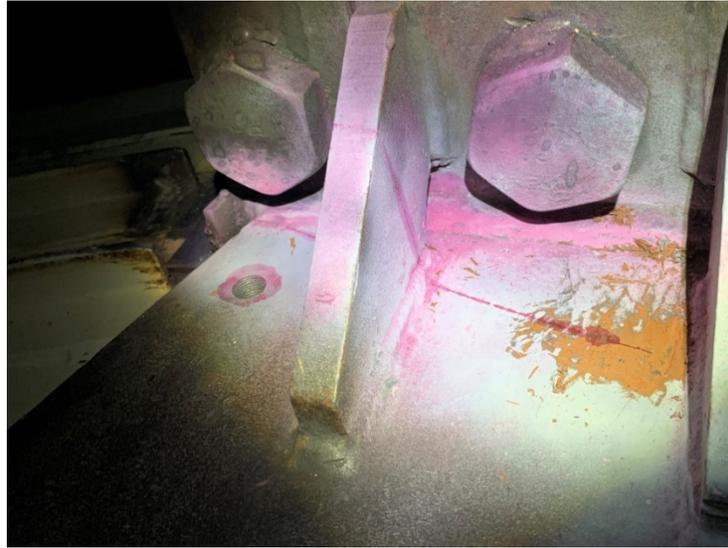


Figure 21: Tracing valve cross-section

**Key Findings:**

- 1) PolyWorks Modeler Lite is severely limited in the ability to reverse engineer geometry. The functionality of Modeler Premium is far superior and is worth purchasing for this purpose.

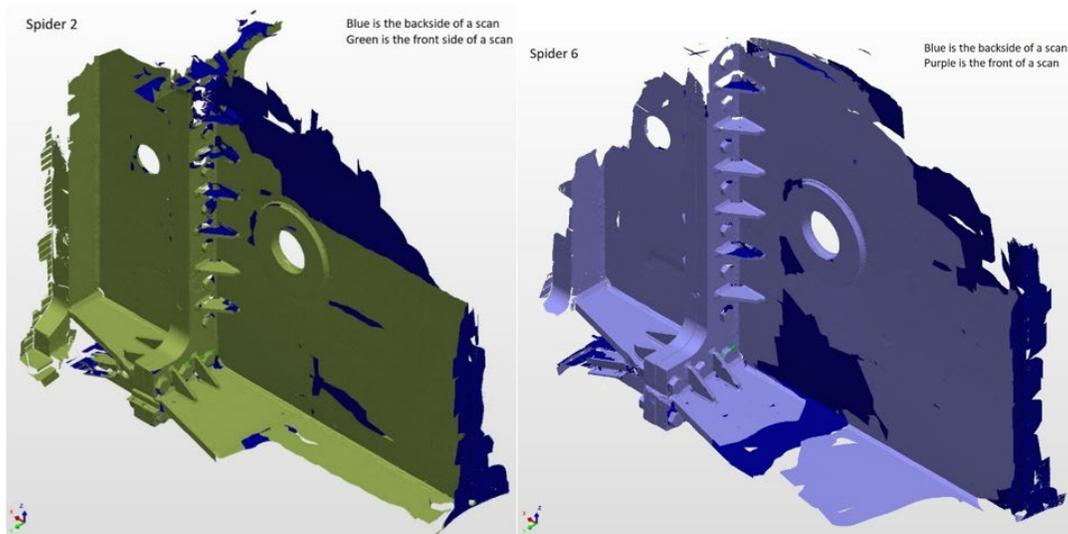
## Unit Rotor Crack Analysis



*Photograph 6: Spider arm rotor crack*

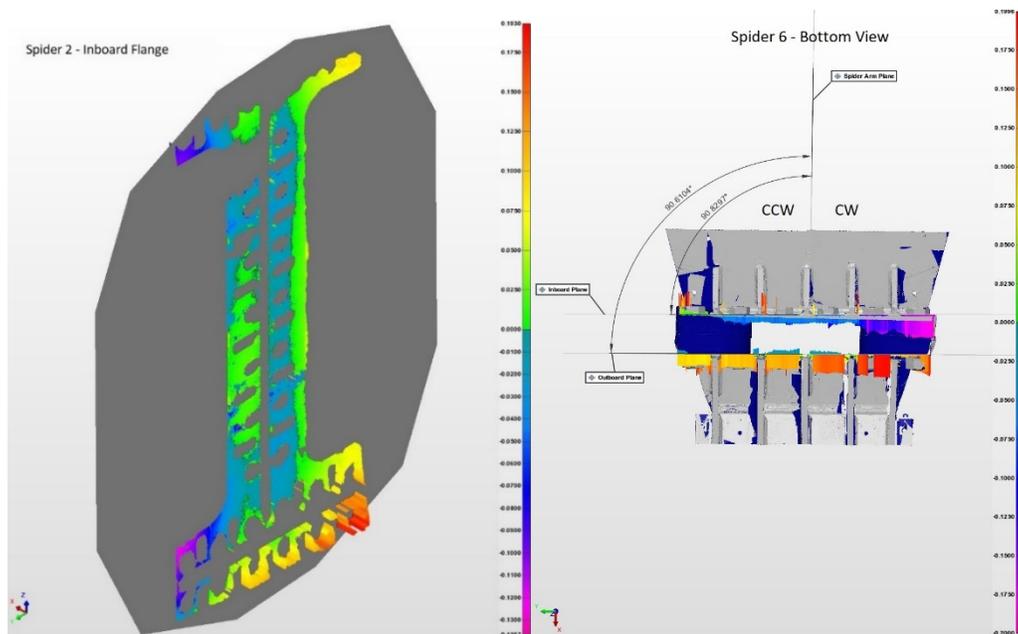
**Background:** A crack in a spider arm flange shown in Photograph 6 was found during an annual outage. Local area office engineers requested FARO scans of the two spider arms with bolted joint connections to analyze flange deflection. Both flanged joints on this unit have had cracks develop. The crack on Spider 2 has been previously repaired.

**Procedure:** The FARO LLP was used to scan the two spider arms. Due to the large size of the spiders, multiple device locations were used at each joint and spliced together. The FARO magnetic mount was set up in the various locations around the spider arm. Each scan shown in Figure 22 was made up of 30+ million points.



*Figure 22: Full spider arm scans. arms 2 (left) and 6 (right)*

**Analysis:** An analysis of the joint was conducted by calculating best fit planes for the inboard and outboard flange surfaces. Data from the flange faces in the middle of the spider arm were used to create a best fit plane. This plane was then used to compare displacement values on the lower section of the flange. The deflection was displayed in a series of whisker plots similar to the ones in Figure 23.



*Figure 23: Flange deflection spider plots*

In addition to the deflection data, it was requested that this data be used to measure the change in flange gap between an unbolted and bolted state in order to calculate bolting torque. A few scans were taken of the unbolted flange and the caliper tool within PolyWorks was used to determine the estimated flange deflection. This is illustrated in Figure 24.

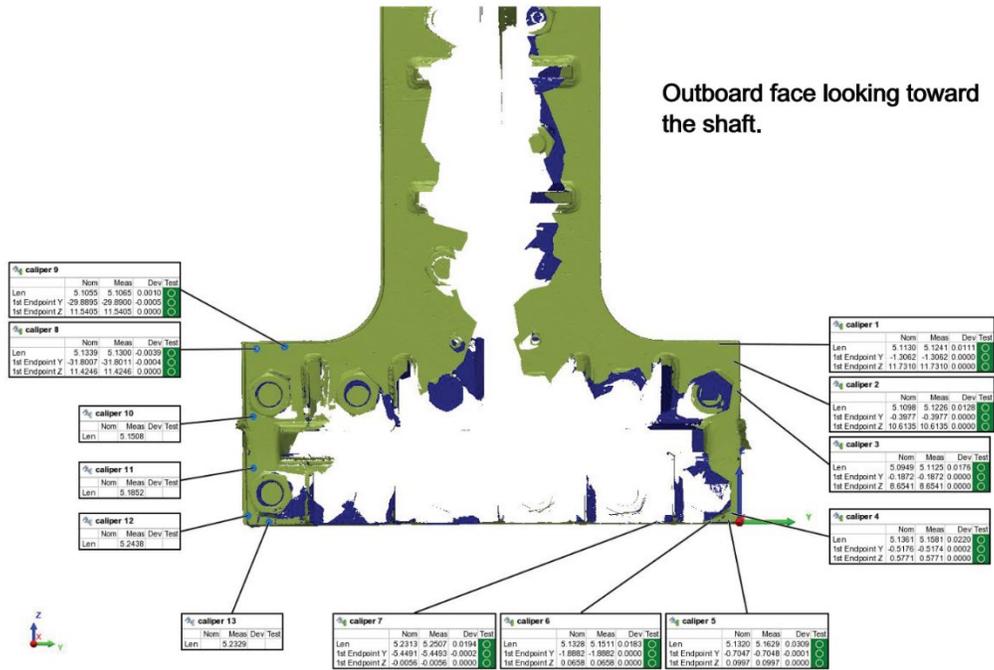


Figure 24: PolyWorks caliper determining deviation

### Key Findings:

- 1) Scanning large swaths of surface area can be cumbersome when conducting post-processing analysis. The large file size of the point clouds creates a lot of data for a computer to manipulate and analyze.
- 2) The magnetic mount is very useful for scanning areas around the generator unit due to all the structural metal within.

## Diversion Dam Model Embankment Variation



*Photograph 7: Diversion Dam Model*

**Background:** A large model of a diversion dam, shown in Photograph 7, was installed in the Hydraulics Investigations lab. One goal of this model is to observe how the embankment of the diversion dam changes after periods of time at various flow rates. A FARO scan was desired for an approximately 10 x 10-foot area in front of the diversion dam to observe these changes in the embankment. Previous models have used photogrammetry to complete these types of tasks, but this method was reportedly too slow for the lab's use.

**Procedure:** The FARO Arm was mounted to a pier with the magnetic mount. No other mounting locations were feasible for the scanning area. The FARO LLP was connected to the arm and the area around the FARO Arm was scanned to the extent of the arm capability. The scan included approximately 180° of the 4-foot radius focused on the quadrant of sand at the diversion entrance. A full scan of the area desired to be analyzed was not able to be completed due to the limitations of the mounting locations. A scan of roughly the same area was taken after the model had been run for a set amount of time at 3000 cubic feet per second (cfs). Both scans contained approximately 300 million points of data.

**Analysis:** An analysis of the area was conducted by comparing the two scans. A colormap of the surface deviation is shown below: A large amount of sand build-up was apparent. The highest of these points was about 3.5 inches higher than the original scan. The colormap also highlights the area of removed sediment, shown in blue and purple in Figure 25.

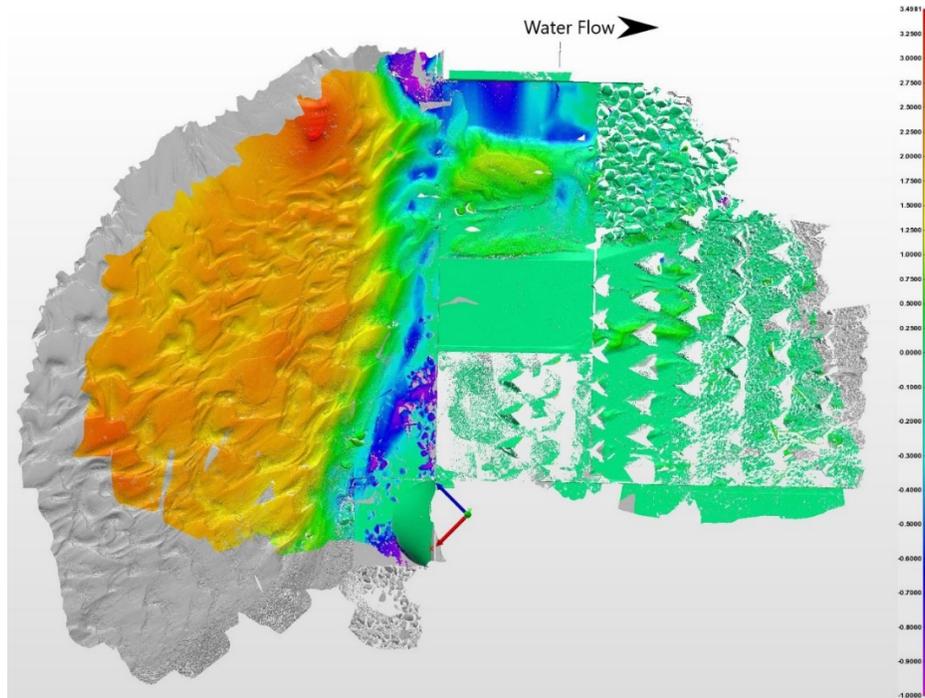


Figure 25: Diversion Dam 3000 CFS Colormap

The FARO Arm and LLP were able to produce a high-resolution model for the area that was able to be scanned. Additional scanning areas would be needed to scan the entire area desired. FARO offers another type of scanner that may be better suited for this type of job such as the FARO Focus Laser Scanner. The Focus Laser Scanner can map a large area into a point cloud without the use of the FARO arm. This sacrifices accuracy for the benefit of detailing large areas.

#### Key Findings:

- 1) The FARO arm is severely limited in scanning large open areas without locations to mount the FARO arm.
- 2) The LLP has trouble scanning some reflective surfaces such as white fiberglass.

## Conclusions

The FARO Tracker, Arm, and LLP have many uses around reclamations dams and powerplants. This complex equipment requires skilled users who have experience working in PolyWorks and understanding the best practices of taking measurements.

Uses in the powerplant, laboratory, and geotechnical applications have been proven throughout this research to help quantify and analyze deviations, interferences, or changes from previous conditions.

Despite the advantages the FARO equipment has over traditional measuring techniques, the devices do have some inherent disadvantages that limit the effectiveness and usability of the equipment. The advantages and disadvantages of these equipment are listed below:

FARO Tracker Advantages:

- Long range capability to accurately track large objects.
- Accuracy greater than any traditional method available.
- Ability to leave permanent reference points around a facility for future measurements.

FARO Tracker Disadvantages:

- The need for line-of-sight to the SMR; increasing the device positions for full measurements.
- The need for an off-network computer to use the device due to IT security policies.
- Post processing time can slow workflow down versus reading dial indicators.
- Narrow window of SMR operability.
- Inability to scan an object, only track features of an object with the SMR.

FARO Arm and LLP Advantages:

- Ability to scan objects in high detail.
- Ability to catalog condition of parts or specimens.
- The Arm allows for measurements that may not be in line-of-sight of the base.

FARO Arm and LLP Disadvantages:

- The equipment needing a sturdy base; limiting locations where they can be set up.
- The arm's limited range.
- Scanning large areas takes significantly more time than would be obtained with other FARO scanning products.
- The LLP's standoff distance: making it difficult to scan tight areas.
- High resolution of the LLP creates large files difficult to transfer to clients.

PolyWorks Advantages:

- Computer based software allows for storage of data for future reference and an archive of part condition.

- Powerful user interface allows for complex measurements and visualizations.
- Ability to measure complex shapes for reverse engineering.

PolyWorks Disadvantages:

- Polywork's complexity to obtain FARO measurements.
- High functionality requires an experienced user to extract pertinent information from scans.

A large demand for this service was found throughout Reclamation facilities. In many cases, the speed, accuracy, and digital format of these measurements makes these methods highly desirable and useful in the hydropower industry. The continuation of FARO work within Bureau of Reclamation facilities is recommended to continue as a service provided by the TSC.

## References

- Different Types of Encoders and Their Applications*. (2019, June 12). Retrieved from Heidenhain: <https://www.heidenhain.us/resources-and-news/types-of-encoders-and-applications/>. Date Accessed 08/07/2020
- Interferometry explained*. (n.d.). Retrieved from Renishaw: <https://www.renishaw.com/en/interferometry-explained--7854>. Date Accessed 08/07/2020
- Wheeler, A. (2017, March 19). *3D Scanning: Understanding the Differences In LIDAR Photogrammetry and Infrared Techniques*. Retrieved from Engineering.com: <https://www.engineering.com/story/3d-scanning-understanding-the-differences-in-lidar-photogrammetry-and-infrared-techniques->. Date Accessed 08/07/2020

## Appendix A – Equipment Purchased

There are many different manufacturers of laser metrology equipment. FARO Technologies was ultimately selected due to their competitive prices, equipment specifications, and their use in other government departments.

The high accuracy laser metrology equipment purchased for this research included the following items:

### Tracker Equipment

1. **One Tracker Vantage E** – iADM Laser Tracker IP52 instrument with precision level and integrated Weather station, Cable Kit with 10m Communication Cat6 Cable and 3m Remote Air Temp Sensor Cables, Cable Case, Calibration Tripod, Lightweight quick release mandrel, Tracker Case, Mobile Device, Documentation, Power supply, USB Flash Drive with Utility Software, Glue gun and Glue Sticks. One-year manufacturers guarantee included. Tracker specifications are located in Appendix A.



*Photograph 8: FARO Laser Tracker Vantage E Head*

2. **One AC Power Cable** – 2.5 Meter, IP52 rated cable.
3. **Two 1.5 inch Standard Accuracy Break Resistant SMR** – Features a single element retroreflector with a gold coating and a black ring. The vertex is centered within  $\pm 0.0003''$ .

4. **One 1.5 inch Standard Accuracy Break Proof SMR**– Break proof solid construction. Vertex is centered within  $\pm 0.0005$ ".
5. **Two 0.5 inch Standard Accuracy Break Resistant SMR** – Features a single element retroreflector with a gold coating and a black ring. The vertex is centered within  $\pm 0.0005$ ".
6. **Ten 1.5" SMR Drift Nests** – Hard coat anodized Aluminum nests used for permanent placement into facilities.
7. **FARO SMR Case Kit** – Rugged storage case for FARO SMRs. Holds up to 3 SMRs of various sizes. (Required with any SMR order)
8. **RF Remote** – RF Remote features four programmable buttons to start commands in measurement software, mouse pointer control with left and right buttons, and a laser pointer. Operates up to 150 feet at 2.4 GHz.
9. **Target Tooling Kit, Soft Case** – Set includes:
  - a. (10) 1.5" SMR Drift Nests
  - b. (2) 1.5" Pin Nests NEG 1/8" & 1/4" Pin
  - c. (1) 1.5" Shankless Nest with Negative Cut
  - d. (1) 1.5" Large End Adapter
  - e. (1) 5" Bar Extension
  - f. (1) 10" Bar Extension
  - g. (1) Hard Point
  - h. (1).5" Construction Ball with .25" shank
  - i. (1) Tooling Ball Adapter
  - j. (1) Pin Nest for Bar Extension with .25" shank
  - k. (1) Offset plate 3"x2"x.25" with .25" Dia Hole
  - l. (2) 1.5" Negative Drift Nest
  - m. (1) Center Punch Adapter with Transfer Punch
  - n. (1) Pole Adapter
  - o. (1) Magnetic handle for .5" SMR



Photograph 9: Tracker Tooling Kit

## Arm Equipment

1. **Quantum S 2.5m 7 axis FARO arm** – FARO's most accurate and robust portable metrology device. Quantum S, 2.5m 7 axis includes Arm, calibration kit, base, plate, 3mm probe, 6mm probe, cables, heavy-duty case, rechargeable battery and One (1) year manufacturer's warranty. See the tech sheet below.



Photograph 10: FARO Quantum Arm

2. **FAROBlu HD Laser Line Probe** – FARO's most advanced handheld laser scanning probe. Features High-Definition scanning technology with superior accuracy, greater coverage and the highest speed and resolution. Ideal for non-contact measurement applications, inspection and reverse engineering. For use with a FARO Quantum Arm. Includes: Laser Line Probe, calibration kit, case and 1-year standard warranty.



Photograph 11: FAROBlu HD Laser Line Probe (LLP)

3. **Track Arm Kit** – PK1 Probe Interface: Includes case with a 7/8" SMR, two 7/8" calibration spheres, 7/8" drift nest, 7/8" SMR mount for Gen 5 arm and hex key. Compatible with Gen 5 Arms and all Laser Trackers.

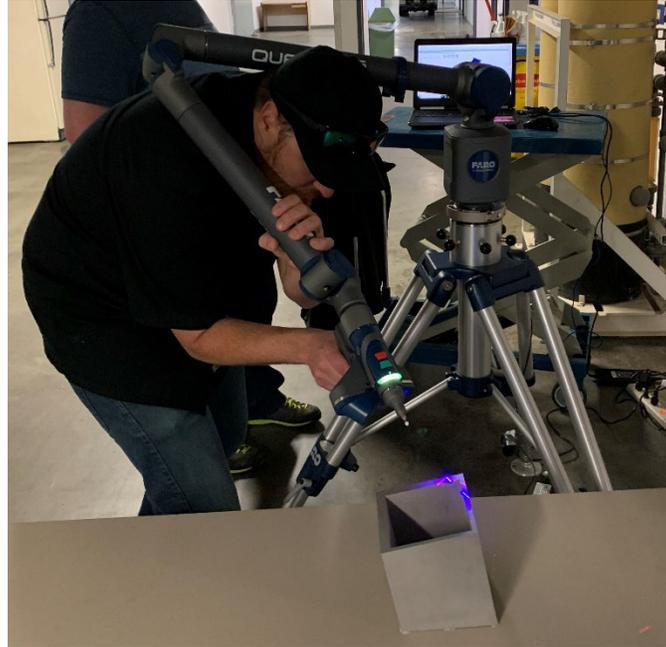
## Shared Equipment

Mounting equipment works for both the Tracker and Arm. Both systems utilize a 3-1/2" threaded ring commonly used metrology equipment.

1. **Laser Tracker Portable Folding Stand** – Folding stand compatible with all FARO laser trackers. Features easy height adjustment and an instrument adapter. Provides excellent stability and easy portability. Includes heavy-duty shipping case and wheeled soft carry bag. Height 28.5" - 42" (0.7 - 1m), weight 29 (13kg) lbs. Maximum load 150 (68kg) lbs
2. **FARO Arm Portable Folding Tripod** – Designed specifically for the FARO Arm, the folding tripod includes stabilizing struts that mount to the actual work surface, retractable wheels, ring mount for FARO Arm, wheeled soft bag and heavy-duty shipping case. Dimensions: Height 31" to 41" (0.7m to 1.0m), maximum spread 54" (1.4m).
3. **Magnetic Mount** - Gen 3+ arm – Magnetic mount allows any arm, or laser tracker to be mounted to surface plates, tool beds and other ferrous surfaces. Includes: (1) 150.0 mm diameter magmount, (1) hex wrench, (1) test certificate, (1) operating manual. Dimensions: Diameter=150mm (5.9"), Height=76mm (2.3"). Weight: 7.5Kg (16.5lbs.)
4. **Vacuum Mount** – Large vacuum mount designed for the Arm and Laser Tracker. Includes mount, hand pump, oil and case. 3.5" ring mount. Dimensions: Diameter= 10.75" (273mm), Height=1.75" (44.4mm).

# Appendix B – Quick-Start Guides

## FARO Tracker Quick-Start Guide



### Packing List

- FARO mount (Tripod, Vacuum Mount, Magnet Mount)
- Tracker Head and associated cords
- Presentation Remote
- Camera Tripod
- Glue Gun
- SMR Attachment Kit
- **PolyWorks Dongle**
- USB hub

## Set up



It is important to note that the FARO tracker should be given time to warm up and reach steady state. This could take about an hour. Because of this, it is recommended that the setup be done as soon as you get on site to minimize the overall time the measurements will take.

- 1) Set up the FARO Mount.
  - a) This can either be the magnet mount, vacuum mount, or the tripod. Ensure it is on a sturdy surface if using the tripod (preferably concrete). Tripod feet are prone to flip up; make sure they are completely flat and are clear of debris that may obstruct its surface connection. If using the magnetic or vacuum mount, ensure the magnets are set or the vacuum is secure prior to placing the head on the mount.
- 2) Attach the threaded collar onto the mount.
- 3) Place the tracker head onto the collar and close the collar lever.
- 4) Connect the tracker head to power and turn on the tracker.
- 5) Connect the thermometer and WIFI antennas if connecting to the tracker via WIFI.

## Connecting to the Tracker

- 1) Make sure you are using an off-network computer.

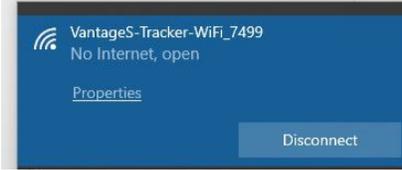
The FARO tracker will not be able to connect to your government issued computer because of the firewalls that are installed through the network.

- 2) Connect the PolyWorks dongle to the computer.

The dongle stores the keys and rights to PolyWorks. Without it, you will not be able to access any PolyWorks files. If the computer that you are using had never been used with the tracker or arm, the Polywork keys will need to be set up.

- 3) Make sure the WIFI functionality (button below the power button) is turned on and connect the laptop to the tracker by clicking the WIFI icon in the bottom right of the computer desktop.

- 4) Connect to the Tracker's network labeled "VantageS-Tracker-Wifi\_7499".



- 5) Open PolyWorks.

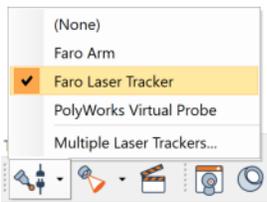


PolyWorks starts in the project view. This is where all scans for one project should be held.

- 6) Save this project as a unique name in a location you can find by clicking **File>Save as...** and navigating to the location you want to save.
- a) Once the project is saved, you can open an Inspector project by clicking the orange keyhole icon. PolyWorks Inspector is where you will scan the data.

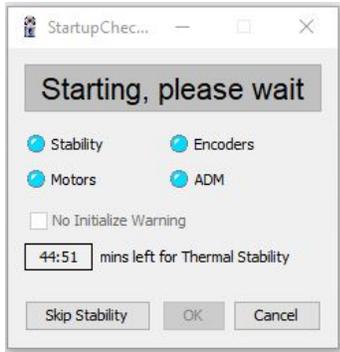


- 7) In the lower left-hand corner of the Inspector screen, select the drop-down arrow near the plug icon and click **FARO Laser Tracker**. Click the plug icon to connect. The icon of the plug will close when the tracker is connected.



## Startup

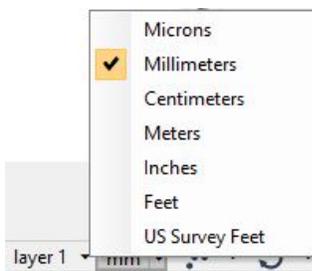
- 1) Once connected, an initializing window will appear displaying the estimated time until temperature stabilization.



- a) If taking quick measurements, this stabilization can be skipped by clicking **Skip Stability**. Otherwise, after the device has reached its steady state temperature, it will automatically go through an initialization process. Stay away from the tracker during this process.
- 2) Set up target nests.

While the tracker is warming up, it is a good time to place nests. If you anticipate needing to use multiple tracker locations to scan a single area you should set up monuments that will be able to see from all locations. **A MINIMUM OF 3 COMMON NEST LOCATIONS ARE REQUIRED TO LOCALIZE TRACKER LOCATIONS.** It is always better to attach more nests than needed in case some locations are out of sight of the tracker. The nests are magnetic and will attach to ferrous materials but will need to be glued to ensure they do not move. Use the glue gun to glue these nests to the desired locations. Make sure the surface is clean prior to gluing nests down to ensure proper glue adhesion.

- 3) Once the Tracker is initialized, click **OK**.
- 4) Select the measurement units you desire for the part in the lower right-hand corner of the window.



The tracker is now ready to compensate.

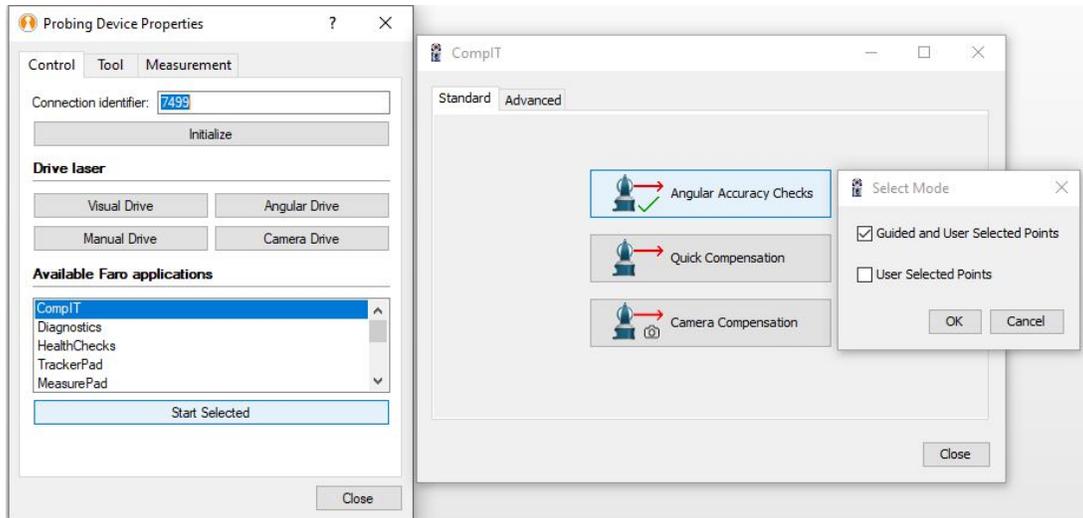
## Compensation

A full compensation of the tracker should be completed at the beginning of the project if it is being taken out of its case for the first time in a few days, or if you suspect the tracker head has been subjected to a jarring impact.

- 1) Prior to compensation, it is good practice to ensure the tracker is level if using the tripod. Open device properties  and click **TrackPad**. On here, click **bubble level**. It may take a couple

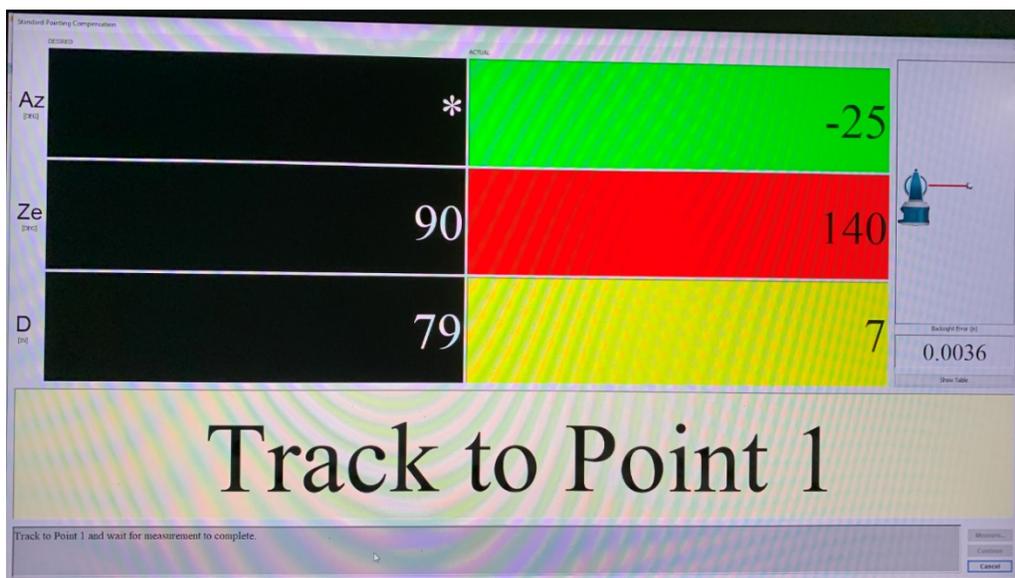
minutes for the level to appear. Once visible, use the tripod's adjustable legs to get the tracker head approximately level.

- 2) To compensate, click on **Device Properties>CompIt>Start Selected>Angular Accuracy**.
  - a) If using the tripod and have about 30 feet of clearance in one direction, select **Guided and Selected Points** and click **OK**. FARO will take you through points needed for the compensation.
  - b) If 30 feet is not available, select **Advanced>Setting** and change the range of the compensation.

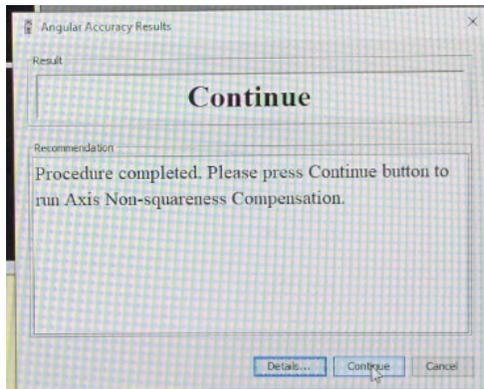


- 3) Move the SMR to the location that changes the colored boxes to green.

Use the camera tripod and SMR mount in the Tracker head case as needed. Once all three boxes are green, the FARO will automatically start its measurement. To change the Azimuth angle, you can loosen the collar lever and rotate the FARO tracker body as needed. Stay still if you are standing around the FARO or SMR.



- 4) After the compensation is completed, you can save the results of the compensation by clicking on **Details>Interim Test Deviations>Report** and save where you would like.
- 5) Click **continue** when you are ready.



The program will automatically take you through a few more types of compensations. Follow the prompts until you complete all compensations. A final window will appear with “Pass”.

- 6) Click **Update** to finish the compensation.
- 7) After this compensation, you are ready to scan your part. Exit all compensation related windows.

## Using the Remote

The remote is a critical tool for single-person operation of the tracker. It allows the user to place the SMR where desired and stop and start readings as desired despite being away from the computer.

- 1) If the computer has not been programmed with the remote before, a program will need to be downloaded at this website: <https://www.smklink.com/pages/downloads>
- 2) Plug the remote dongle into the computer.

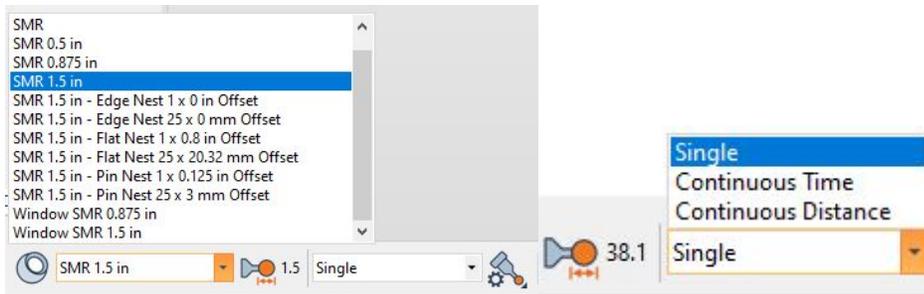
If the computer only has 2 traditional USB ports, a USB Hub will need to be used to accommodate your PolyWorks key, mouse, and remote.

PolyWorks uses the Insert and End key to start and stop measurements. These should be programmed as buttons 1 and 2 on the remote. Measurements can also be taken by clicking these keys or by using the buttons at the bottom of the screen.



## Taking Measurements

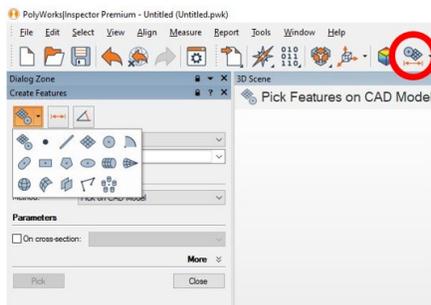
- 1) Verify that the correct SMR size, nest type, and desired measurement method are selected in the lower left of the PolyWorks window.



- 2) Define your target nests if you are using multiple device positions. To do that, click on the three target icons at the bottom of the screen

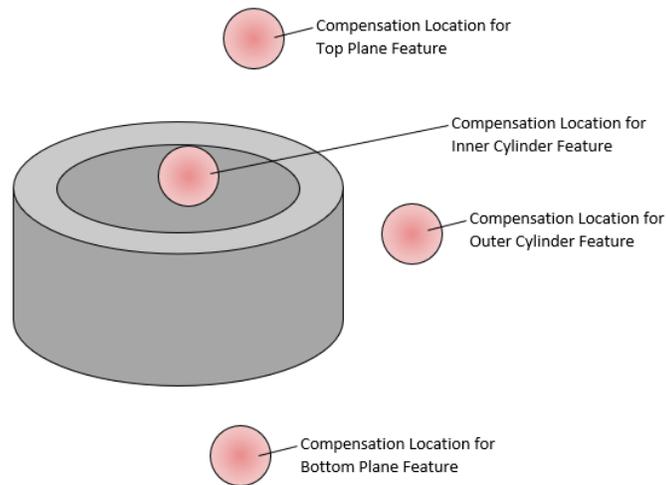


- 3) Place the SMR in the reference nest and take the measurement. The measurement method will need to be in “single” mode for this to work. Move to the next position and continue this process until all target nests have been measured. You will need a minimum of three common targets to localize the device after moving it. Press the end key or click **Close** on the dialog zone to continue.
- 4) To start measuring a part, you will need to create a feature. Go to the **Create Feature** button on the top of the screen and select the type of feature your part is in the dropdown of the dialog box.



- 5) Measure the feature with the SMR and measurement nests as needed. Once that feature is measured, you must compensate for the SMR size. Since the tracker is measuring from the middle of the SMR, a 1.5” SMR will have a 0.75” offset to compensate for. To do this, hold the SMR away from the surface measured in the opposite direction you wish to compensate for and click the End key, button 2 of the remote, or square at the bottom of PolyWorks.

For example, if measuring the top of a plane, you need to compensate with the SMR held above the plane. If measuring the bottom, you will need to hold the SMR below the plane. If measuring an outside diameter (OD), the SMR needs to be held outside of the part diameter and if measuring an inside diameter (ID), it needs to be held inside the diameter. The following figure illustrates this concept.



- 6) Scan as many features of the part as necessary to gather the information desired. If you need to move the device click the **Move Device** icon in the lower ribbon.
  - a) Under Alignment Method, ensure **Targets** is selected.



- 7) PolyWorks will then prompt you to remeasure your target nest locations. These do not need to be measured in the same order as before, PolyWorks will automatically recognize each location after 3 locations have been measured. Once completed, close the dialog zone, and continue measuring features.

## Shut Down

After finishing measurements, ensure the file is saved and turn off the Tracker head by pushing the power button on the head. Unplug all cables and fit everything back into their cases.

## FARO Arm and LLP Quick Start Guide



### Packing List:

- FARO mount (Tripod, Vacuum Mount, Magnet Mount)
- FARO arm box
- FARO LLP
- Glue Gun
- **PolyWorks Dongle**
- USB Hub

### Set up. 10 minutes:

1. Set up the FARO mount.
  - a. This can either be the magnet mount, vacuum mount, or the tripod. Ensure it is on a sturdy surface if using the tripod (preferably concrete). Tripod feet are prone to flip up; make sure they are completely flat and are clear of debris that may obstruct its surface connection.
2. Use the levers on the arm collar to snug up the threaded connection.
3. Connect the arm to power and turn on the arm.
  - a. The FARO arm does have a battery that will allow the arm to be used without the AC power adapter for 2 hours if needed.
4. Attach the desired sized point and Laser Line Probe to the end of the arm.

- a. To attach the probe point, open the probe locking lever on the pointer head, line up the arrows on the arm and probe, then insert the tab and close the lever.
5. Attach the Laser Line Probe (LLP) to the arm if scanning a part.
  - a. To do this, remove the cap on the end of the arm by loosening the handle locking collar. Insert the front edge of the LLP into the slot and flush up the connection. Retighten the collar until you hear a click, indicating that the screw is fully engaged.

## Connecting to the Arm

An on-network computer will work with the FARO Arm and LLP, however, a dedicated customized computer has been purchased for use with the FARO LLP. This computer can process higher-definition scans because of its improved graphics card. The PolyWorks dongle will need to be connected to the computer. The dongle stores the keys and rights to PolyWorks. Without it, you will not be able to access any PolyWorks file.

The arm can be connected to the computer directly with a USB cable, Bluetooth, or WiFi network. If you are using the Laser Line Probe, use the USB cable to connect to the device. If only probing with the arm, Bluetooth or WIFI will work fine.

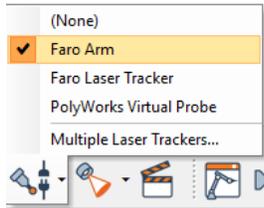
1. Open PolyWorks.



- a. PolyWorks starts in the project view. This is where all scans for one project should be held.
2. Save this project as a unique name in a location you can find by clicking **File>Save as...** and navigating to the location you want to save.
  - a. Once the project is saved, you can open an Inspector project by clicking the orange keyhole icon. PolyWorks Inspector is where you will scan the data.



3. In the lower left-hand corner of the Inspector screen, select the drop-down arrow and click **FARO Arm**. Click the plug icon to connect. The icon of the plug will close when the arm is connected.



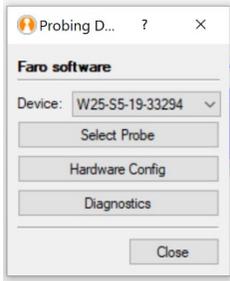
## Compensation

Once connected, compensation can start.

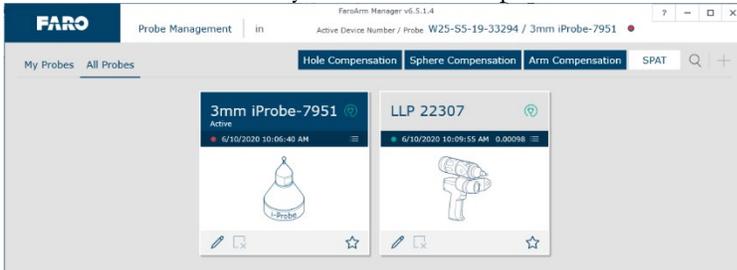
1. Click **Device Properties**.



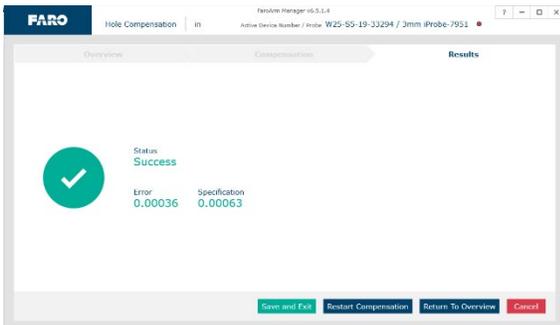
2. In the popup window click **select probe**.



3. Attach hole compensation piece to a sturdy surface using hot glue or a clamp.
4. Click on the Probe you want to compensate then select **Hole compensation**.



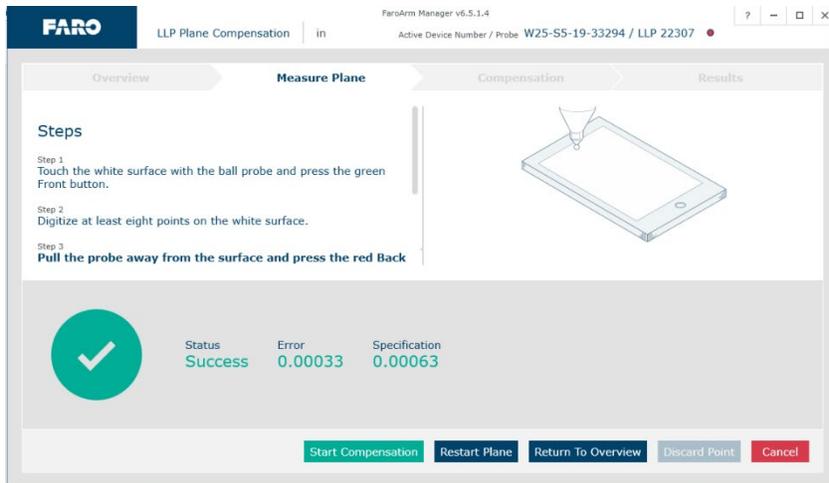
5. Go through the hole compensation procedure, this video will demonstrate this procedure in the first few seconds. <https://youtu.be/NZHC0dYXIUM>
  - a. If you are struggling to complete the compensation requirements, make sure the surface the compensation piece is attached to is ridged. Any movement of the piece will result in errors.



6. Click **Save and Exit** once successful.
7. Select the LLP probe and click **Plane Compensation**.

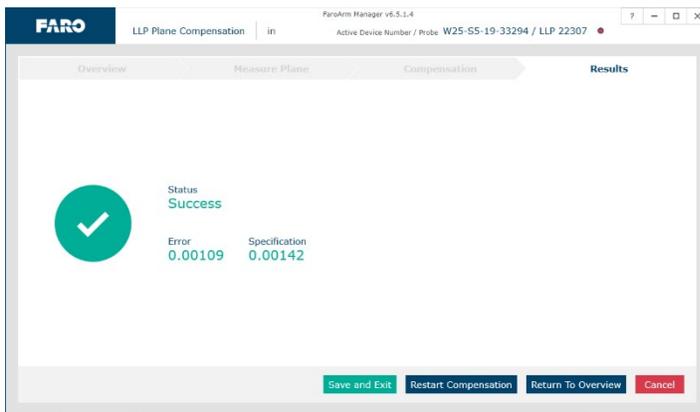


8. Remove the white sided metal piece located in the LLP case. **DO NOT TOUCH THE WHITE SURFACE** as it needs to be clean for accurate measurements.
  - a. Complete a plane compensation as directed, probing 8 locations around the perimeter of the piece.
  - b. If you are unable to successfully complete this compensation, move the piece around your table and make sure its bottom surface is clean from debris.
9. Click **Start Compensation** when passed.



10. Compensate the LLP.

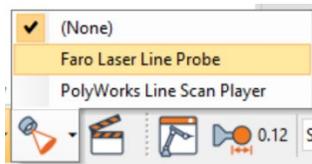
- a. It can be tricky to get all angles correct for the compensation to work. Watching the above video will give a good idea on how to complete this.



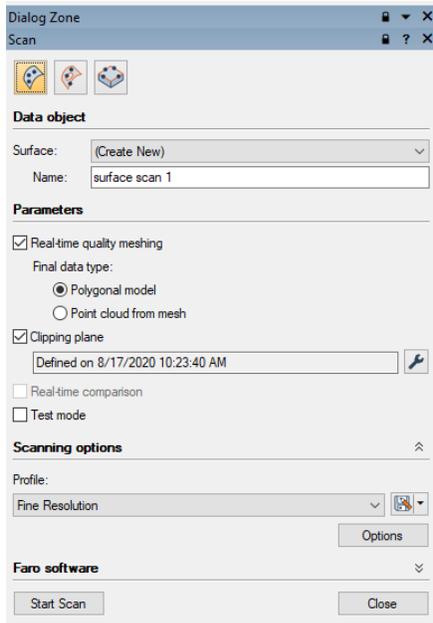
11. Once completed, click **Save and Exit**.

## Scanning

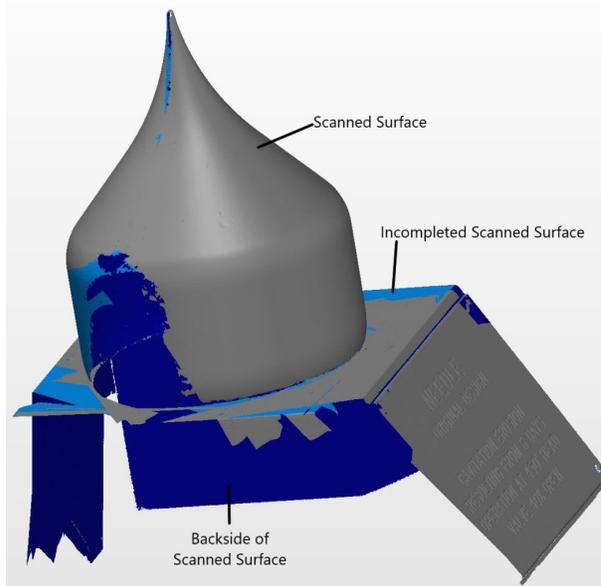
1. When you are ready to scan, connect to the LLP by clicking scan button and selecting **FARO Laser Line Probe** to connect.



This window will appear in the dialog zone on the left side of the screen:



- a. If your piece is sitting on a surface, a clipping plane will eliminate any scanned surface below that plane. Define this clipping plane by selecting the wrench to the right of the clipping plane field.
2. Click **Probe** and probe the clipping plane if necessary.
3. Begin the scan by choosing a resolution and selecting **Start Scan**.
4. Click the green trigger on the LLP and begin making passes of the piece with the laser.
  - a. To take a break, click the green trigger again. Repeat until you are satisfied the to coverage of the scan area. Any light blue area seen on the screen means you need to scan the area at a more perpendicular angle. Dark blue signifies the backside of scanned data.



- b. Clicking the Red trigger will finish the scan and do some calculations to make the scan a mesh.
5. To change the position of the scanned object or the arm, click **Move Device** on the bottom tab.



- a. Under Alignment Method, select **Custom**. This will allow you to proceed with scanning and align the data scans in post processing.
- b. Rescan the object, repeating Step 4 above until you believe you have full coverage of the scanned parts. If the previous scans get in the way of properly viewing the new scans, you can turn these views off in the treeview of the part.

## Shut Down

After finishing scans, ensure the file is saved and turn off the arm head by pushing the power button on the head. Unplug all cables and fit everything back into their cases.



