# Laser Tracker Measurements for Hydro Units: Benefits Evaluation and Sharing of Techniques

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## Abstract

This paper is a general discussion regarding the use of a laser tracker to build and assemble hydro units on-site. It presents the benefits and sometimes limitations of using a laser tracker. It also provides details about the hydro applications where they can be used. Examples are given from a few projects where Voith Hydro was building new turbine and generator units as well as a project with runner replacement and machining of the embedded turbine parts. The approach used for these projects was to own and keep a laser tracker on-site for the duration of the project so that it could be used anytime, as needed. The benefits have been assessed by comparing the laser tracker measurements with alternative conventional methods as far as ROI, time savings and quality of data and information derived from the system.

This paper also shares some techniques and methods that have been used on-site to ensure that the measurements are accurate. In some cases we needed to be able to prove on-site the accuracy of large dimension readings, and simple tests have been performed. Another interesting issue was the use of the integrated level which has a specified accuracy of 2 arc seconds. In some applications, we needed a level accuracy lower than 2 arcsec and we were able to demonstrate on-site that it was better than 2 arcsec and therefore adequate for our application. Many examples for using a laser tracker are shown. One of these examples is lifting a large component with a crane and monitoring its position with a laser tracker for lifting the component (a head cover) and passing around another piece (a shaft) with a small clearance. The method used is discussed in this paper. There remain some measurements not taken with the laser tracker, but for many measurements, the laser tracker is the best tool. The ROI and the overall benefits on a project are significant for both the customer and the contractor.

## Context of Presentation

Voith Hydro is an OEM company that strives for continuous improvement and product reliability. Over the last 3 years, Voith Hydro Canada and Hydro Expertise have worked very closely with specialists at Faro to develop processes and validation schemes in order to extend the range of applications of laser trackers in the installation of large size turbines and generators. The development of such applications entailed some risks that needed to be managed by thorough checks of the results and precision achieved every step of the way. This paper explains some key points of this journey.

## Description of the Laser Tracker Instrument

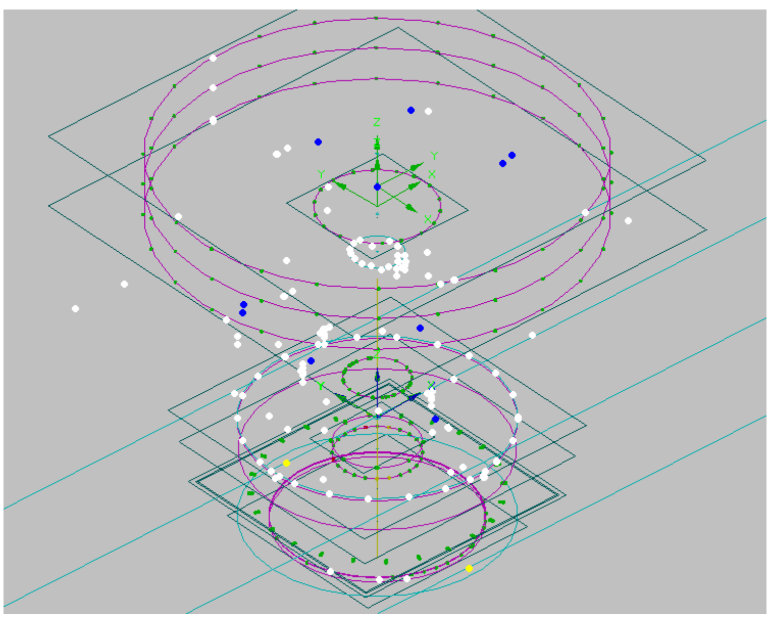
The FARO© laser tracker X is a portable, high accuracy, three dimensional (3D) coordinate measurement device. A combination of a laser based distance measurement systems, two rotary angular encoders, a fully-integrated weather station and an absolute distance measurement system (XtremeADM) report the position of the spherically mounted retroreflector (SMR) in real time up to

35 meters with a precision up to 0.02 mm. The XtremeADM also allows to laser beam to be recaptured in the air, without the need to go back to the laser tracker base (home). The device will calibrate itself with an automatic self compensation command to quickly ensure high accuracy. The tracker accurately measure parts and machinery across a wide range of industrial applications.


**Laser Tracker Applications in Hydro Power Plants**

The laser trackers usage in the hydro generation industry goes from engineering support, final machining verification, and thorough QA support to installation or refurbishment of turbine-generator. The particular context of measurements in hydro power plants requires attention and caution since high accuracy is targeted. Operators can be confronted to vibration due to machines in operation in existing plants, dusty environment, coordinates systems and benchmarks used over many weeks, large machine dimensions as well as interference from other workers on site. The following examples illustrate applications of the laser tracker in the hydro generation industry.

**Verification of the alignment of the stator, thrust block, bottom ring, head cover and stay ring.**

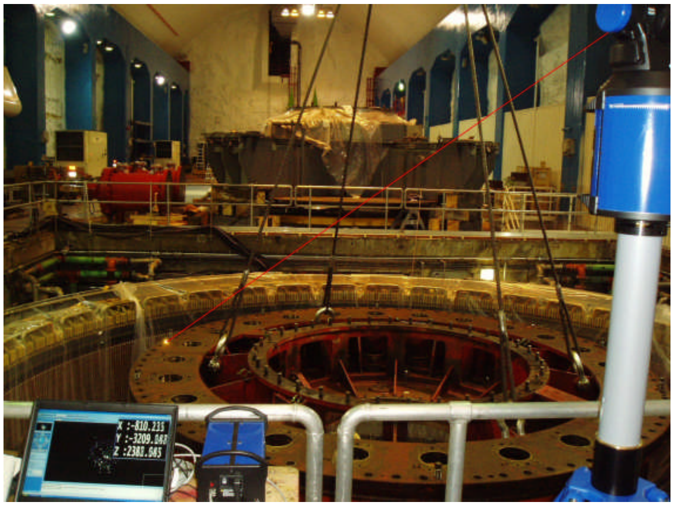


In the process of disassembling a hydro turbine-generator, it is convenient to measure the position of the rotating and stationary components in order to know what corrections need to be done before and during the reassembly. In the figure above, measurements taken on a vertical unit are represented by simple figures. The three upper circle represents the stator measured at three elevations, the smaller circle at the same elevation represents the thrust block on which was supported the rotor. Measurements go down to the bottom of the unit with readings on the head cover, stay ring and bottom rings. The data for all these readings is available in one single file, with all points having x,y,z coordinates using a common coordinate system. Characteristics like the circularity of the components, their best centre, the flatness and inclination of planes are all easily available in one file for analysis.

**Installation and verification of embedded parts**

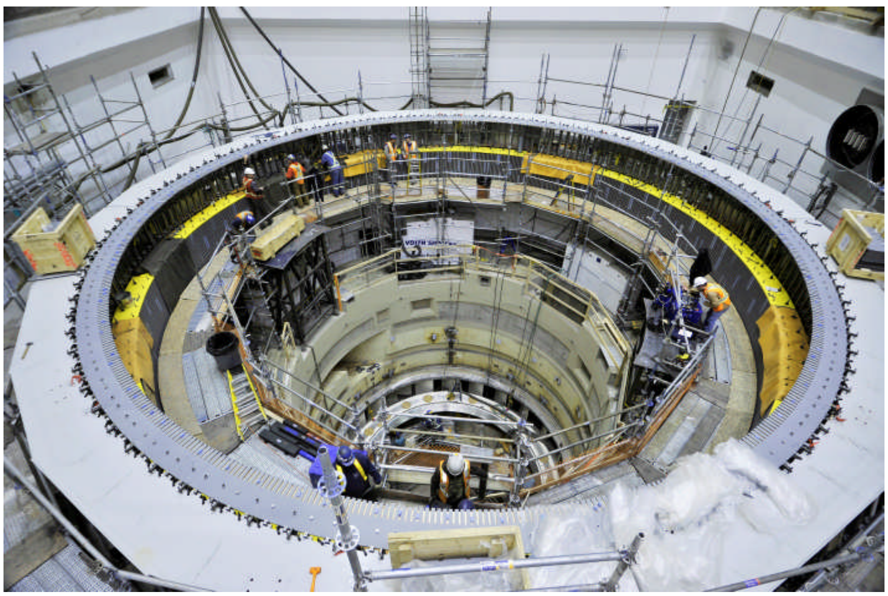
The laser tracker provides great advantages in the erection of a new hydro-generator. Employed to ensure the embedded parts will fit with existing implanted components like penstock, draft tube cone and pipes, the tracker is used for the assembly, the positioning and levelling of all embedded parts (cone, pit liner, stay ring, spiral case, servomotor soleplate) as well as finding unit best centre and relating it with penstock. It also help define cuts in parts that required cutting, monitoring level, circularity of assemblies and marking references.

**Monitoring the Position of a Component**

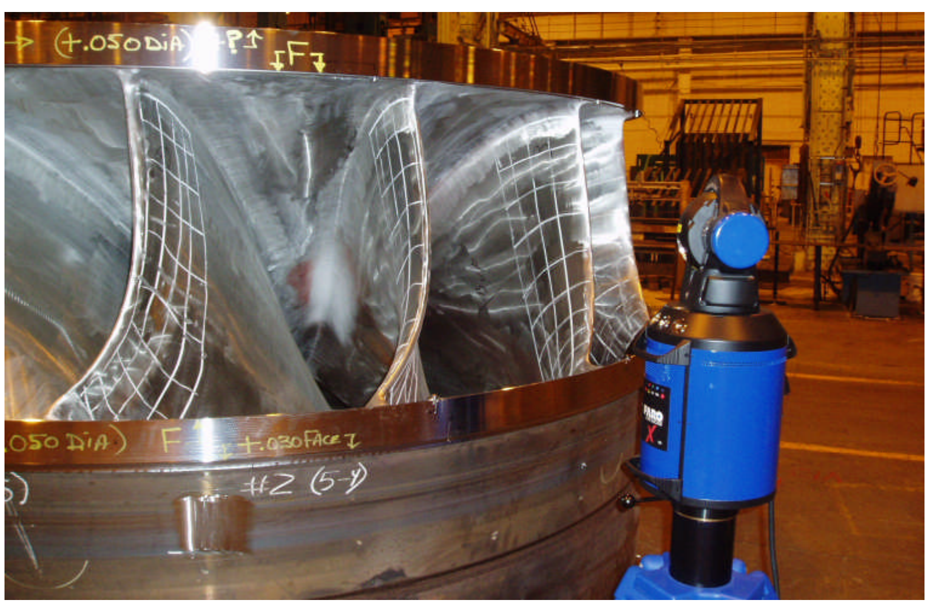


On the figure above, the head cover of the turbine is being lifted and moved out of the unit. The laser tracker was used to monitor the position of the head cover while being lifted. The clearance between the inner diameter of the head cover and the turbine coupling flange was only 1.5 mm (1/16”). Just prior engaging into the tight clearance, the lift was halted and the readings from two spherically mounted retroreflectors (SMR) previously installed on the head cover allowed the readjustment of the head cover position and then it was lifted safely without making contact with the shaft. Part of the preparation work for this operation consisted in measuring in advance the position of the shaft and positioning two pairs of SMRs on the head cover, each pair having SMRs mounted on opposite sides and at equal distance from the centre of the component. A minimum of three points measured on the head cover were necessary to monitor the change of inclination of the head cover when picking it up. After that the measurement of only one or two points were required to monitor the position. Two points are necessary when there is a possibility of a rotation of the component.

**Installation of key bars and stator piling**

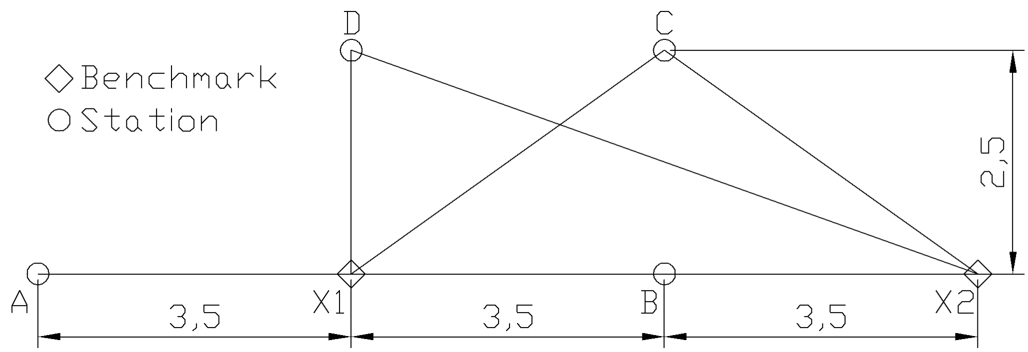


**Runner measurements during and after machining:**



When it comes to validation of engineering values on a runner, either for single dimensions or complex profiles, the laser tracker is often useful. Measurements can be taken during and after machining for validation and also for approval by quality control department. Parts can also be measured on site to ensure correctness of specific parts after transportation. The laser tracker can also be used for measurement of existing runner as a reverse engineering tool. The laser tracker brings accuracy measurement of complex components to an accessible level.

## On-Site Tests for Large Distances




| | Results : X1 to X2 measurements (mm) | Variation from average (mm) |
|---|---|---|
| Station A | 7175.010 | 0.009 |
| Station B | 7175.015 | 0.014 |
| Station C | 7174.986 | -0.014 |
| Station D | 7174.992 | -0.009 |
| Average | 7175.001 | |

In one instance, the validity of the readings of a large dimension of approximately 7 metres needed to be verified since it was not coinciding with the results obtained with a micrometer. A set-up was made to measure a distance of 7 meters from different tracker locations and the results were compared. Knowing that the laser tracker use different methods to measure distances when aligned with the two points (ADM system) and when looking at the points from the side (ADM and angular encoders measurements), the fact that the results from all tracker locations were practically identical as seen in the table above reassured the operator and the customer about the validity of the readings. The accuracy of the readings was later confirmed during the installation of the components which fitted properly with other components. There is a standard test included in the laser tracker software called Pointing compensation which does a similar test (ADM) with different tracker locations. This compensation procedure determines and corrects for backsight errors and errors in the angular encoders. When the test is passed, accurate readings can be taken from different locations.

## On-Site Verification for Accuracy of Level Readings

One easy method for demonstrating to a customer or proving to ourselves on-site that a laser tracker gives accurate level readings is to compare the results with another accurate instrument that is proven such as an electronic level. On a project located in British Columbia, we measured the inclination of a thrust block with the laser tracker and concurrently with an electronic level. The thrust block is similar to a coupling flange and has approximately 3 metres in diameter. The electronic level was placed in radial direction in 18 positions between the coupling bolt holes. With radial inclination in 18 equally distributed locations, the resultant inclination of the plane was calculated. For the laser tracker a plane was measured using also 18 points between the coupling holes. The results for both methods gave inclination value of 0.060 and 0.061 mm/m. We do not expect results to coincide so well every time, but it was nevertheless reassuring to see results being so close knowing that this component and many others need to be levelled within a tolerance of 0.02 mm/m (0.00024 in/ft) at reassembly.

The specified accuracy of our laser tracker model X is +/- 2 arc seconds which correspond to an inclination of +/- 0.0097 mm/m (1 arcsec = 0.004848 mm/m = 0.00005818 in/ft). The specified accuracy of +/- 0.0097 mm/m is approximately half of the smallest tolerance of 0.02 mm/m that we used during the assembly of hydro-generators. So in order to level a component within 0.02 mm/m we need to take particular cares on-site in order to meet the expected results. It means that before taking critical readings, the user must make sure that steps like warm-up time, self-compensation, angular checks and level checks have been performed. Also the coordinate system being used should be freshly established. After taking level readings on a component, one way of ensuring valid results is to re-measure the level of one component with a new set-up of the instrument and a new coordinate system. This is not normally required but can be helpful for removing doubts on critical measurements. Finally, it is our experience that with care, we can efficiently level components within the tolerance of 0.02 mm/m.

Another application where utmost care needs to be taken is when we use readings simultaneously at high and low elevations and particularly when these readings are used to centre stationary components. Hydro turbine and generator units may often have a height of 15 meters or more, a small inclination error of the coordinate system in the order of 0.01 mm/m creates an uncertainty of 0.15 mm (0.006 in). Therefore before taking such measurements, one has to ensure that the coordinate system is levelled. If not creating a new coordinate system, the user should execute the Measure Level command and read the i, j, k vectors of the newly created Level Plane with 6 decimals. For example if the i or j vectors equal to 0.000010, it indicates that the inclination of the X or Y axis are 0.01 mm/m. Then the user may decide to continue using the actual coordinate system or update it depending on the precision required. One common mistake is to assume that our nests (fixed reference) mounted on walls or surrounding equipments remain stable with time, thus ensuring that the coordinate system remain unchanged and precise. Especially with measurements that require to be taken over long period of time, the level of the coordinate system should be rechecked every day or before any critical measurement.

Another verification that we performed on-site was to verify the repeatability of the Level Plane created by the laser tracker with the command Measure Level. This test was repeated as an experiment and is explained below.

## Experiment to Determine the Level Accuracy

In order to determine the level accuracy of the laser tracker, we designed a test that was performed at different times and locations with different laser trackers, of the same model described before. The test is divided in two parts.
Part A, to validate the repeatability of the Plane Level created by the integrated precision level of the instrument.
Part B, which consisted of repeating elevation readings on two points apart approximately 15 m apart (50 ft) similar to a peg test normally done on optical precision levels.

For the first test Part A, it was conducted twice with two different laser trackers. The test consisted of creating 5 level planes to observe the variations between each plane. After creating a reference system with 8 nests surrounding the area of measurement, the laser head was rotated by 180 degrees. The nests were re-measured to reuse the same coordinate system as before the rotation, and then 5 new level planes were measured. The new 5 planes were also compared to each other to verify the variations. The average inclination of these 5 planes was compared with the average of the 5 planes taken before the rotation. This verification was done for detecting any influence of the laser head position, which could induce a systematic error on the level plane. The same exercise was repeated with the laser tracker head positioned at 90 and 270 degrees. The results of these tests are summarized below.

- Using two laser trackers, a total of 40 level planes have been created
- For any group of 5 level planes created in the same conditions, the variation of inclination in each axis is normally within 0.006 mm/m (+/- 0.003 mm/m). Only two planes indicated a variation up to 0.010 mm/m (+/- 0.005 mm/m) which correspond to a repeatability of the level plane within +/- 1 arcsec.
- The two level planes with most deviation from the average were the first two planes, suggesting than waiting a little longer for warming up the system help improve its accuracy
- By comparing the groups of level planes before and after the rotation of the laser tracker head, we observed no significant influence from the laser tracker head position. Therefore we have demonstrated that there is no systematic error related the laser tracker head position when creating a level plane.
- In conclusion for this test, we say that the laser tracker is capable of establishing a Level Plane within +/- 0.005 mm/m or +/- 1 arcsec. It could even be better if we would take the average of many level planes but it is not necessary for applications where the inclination tolerance is 0.02 mm/m or more.

For Part B of the experiment, 4 independent tests were conducted with 3 different laser trackers. The tests consisted of measuring the difference in elevation of two targets A and B separated by 15 m (50 ft). Like for a peg test for an optical level, the laser tracker was first placed in the center between targets A and B and then, it was moved to a new position at 3 m (10 ft) from target A. The elevation difference was measured again. This routine has been accomplished 5 times until a total of 10 readings have been collected. For each of the 10 positions, a new coordinate system was created using each time a Level Plane created by the laser tracker integrated precision level. Therefore the accuracy or repeatability of the results is a good indication of the accuracy of Level Plane and it may also include some reading errors that are not only coming from the Level Plane but from other source related to distance, vibrations or angular encoders error.

The 40 readings from the 4 tests are summarized below:

| | Test 1 - Elevation difference between target A & B (mm) | Variation in level from average (mm) | Test 2 - Elevation difference between target A & B (mm) | Variation in level from average (mm) | Test 3 - Elevation difference between target A & B (mm)* | Variation in level from average (mm) | Test 4 - Elevation difference between target A & B (mm)* | Variation in level from average (mm) |
|---|---|---|---|---|---|---|---|---|
| Position 1 | 114.57 | 0.01 | 59.25 | 0.02 | 106.96 | 0.04 | 8.22 | 0.05 |
| Position 2 | 114.66 | 0.09 | 59.18 | -0.05 | 106.93 | 0.01 | 8.18 | 0.01 |
| Position 3 | 114.58 | 0.01 | 59.14 | -0.09 | 106.94 | 0.02 | 8.20 | 0.03 |
| Position 4 | 114.63 | 0.06 | 59.18 | -0.05 | 106.88 | -0.04 | 8.11 | -0.05 |
| Position 5 | 114.47 | -0.10 | 59.25 | 0.02 | 106.88 | -0.04 | 8.21 | 0.05 |
| Position 6 | 114.61 | 0.04 | 59.31 | 0.07 | 106.91 | -0.01 | 8.13 | -0.04 |
| Position 7 | 114.52 | -0.05 | 59.31 | 0.08 | 106.93 | 0.01 | 8.17 | 0.00 |
| Position 8 | 114.45 | -0.12 | 59.29 | 0.06 | 106.91 | -0.01 | 8.13 | -0.04 |
| Position 9 | 114.57 | 0.00 | 59.18 | -0.05 | 106.97 | 0.05 | 8.20 | 0.03 |
| Position 10 | 114.61 | 0.04 | 59.21 | -0.02 | 106.90 | -0.02 | 8.12 | -0.05 |
| Average | 114.57 | | 59.23 | | 106.92 | | 8.17 | |

1) Distance between targets A & B were set at 15 m (50 ft) for all tests.

2) * Tests no. 3 and 4 were done using Laser tracker self-compensation after every displacement of the Laser tracker resulting in better accuracy.

We observe that the maximum variation from average is 0.12 mm during test no.1. Over a distance of 15 metres, it represents a variation of 0.008 mm/m (1.6 arcsec). This is within the equipment level specification of +/- 2 arcsec. It is to be noted that the variation between readings would be less if all readings were taken in the same coordinate system but this test was intentionally conducted using a new coordinate system for every position. One way to reduce the errors and increase the repeatability was to perform the laser tracker self-compensation and level check for every position, just like we should do when we create a new coordinate system. With this added precaution step, the maximum variation that we recorded for Tests no. 3 & 4 was +/- 0.05 mm which for 15 metres represents a variation of +/- 0.003 mm/m or +/- 0.6 arcsec.

From all these tests, parts A and B, we concluded that with a few precautions we can trust the Level Plane reference given from the laser tracker as being well within 0.005 mm/m (1 arcsec). We can surely level components with a level tolerance as low as 0.02 mm/m. Re-measuring the level of a component with a different set-up is also an easy way to gain confidence in the level of the component and is very time efficient by comparison.

## Sharing of Techniques, Good Practices, Tips

Actions and rigor are needed to achieve precision and accuracy. The setup of the laser tracker probably is the most important of the measurement process. The laser tracker requires time for warm-up and this step is also very important. Observations were made that the laser gives better accuracy after being on for more than one hour.
Multiple calibrations and check up can be done prior to measurements: Self compensation, angular accuracy check, pointing compensation, ADM interim test, level check. The angular check and the self compensation should be run at least once a day, before measurements, over the complete volume of the part to measure. Self compensation can be use more often if more precision is needed.
If returning in an existing coordinate system, ensure to check a few points to confirm the repositioning of the device in the previous coordinate system. Measure level and compare it with previous values to confirm proper repositioning.
Checking program parameter like probe setting, constraint values, acquisition rate, etc, will ensure good output and accurate readings.
It is highly recommended to record all calibration values, steps and operations of measurements in a notebook as well as naming the points to help in final analysis.
Keeping the nests (fixed reference) clean before each measurement will also help to reduce the risk of error as well as closing the reading by returning to a known reference. Never take for granted the accuracy or exactitude of values. Regular verification of the accuracy is a good practice.

### Evaluation of the Benefits and Limitations

The numerous examples of applications for the laser tracker speak for themselves when it is time to evaluate the benefits. Not only the time for taking measurements is reduced but also the accuracy of the readings is increased in most applications. The laser tracker also increases the capabilities of measuring various components in ways that were not possible without it, as for example checking the complex profile of a runner blade, or checking flatness of a surface on the field with great accuracy. More points can be measured than with traditional methods and scans can be performed.

As for every good tool, this instrument also has limitations. For large hydro turbine and generator units, the range of operation on a diameter of 70 metres is sometimes limiting. It may be necessary to make a few relocations of the laser tracker in order to complete the measurement tasks. When there are vibrations, the range gets reduced and it may be an issue when other adjacent units are generating power. But this can be worked around by selecting proper locations for the instruments or using supports that dampen the vibrations.

It may not be beneficial using the laser tracker in every possible application. For example shaft system alignment of a hydro unit is well done with rotational checks, micrometer readings and electronic level readings for verticality. There is not much gain trying to modify the method for using the laser tracker. But for many other applications the laser tracker is the best tool.

**ROI and Other Tangible Benefits:**

Faro Laser tracker documented Cost-Benefit by project

| PROJECT | DESCRIPTION | ALTERNATIVE USING CONVENTIONAL METHODS | Gain m-hrs % | Gain on Critical Path |
|---|---|---|---|---|
| GMS # 3: upgrade project | Unit baseline measurement at dismantling | Theodolite, Piano wire-micrometer and optical level | 75% | Significant |
| GMS # 3: upgrade project | Thrust bearing alignment | Piano wire-micrometer and optical level | 50% | Moderate |
| Rev 5: New construction | Embedded components alignment: Elbow, cone, spiral case, lower and upper pit liners | Theodolite, Piano wire-micrometer and optical level | 40% | Significant |
| Rev 5: New construction | Stator frame, core fabrication and alignment | Piano wire-micrometer and optical level | 60% | Significant |
| Rev 5: New construction | Distributor alignment: head cover, bottom ring, servomotors and wearing rings | Piano wire-micrometer and optical level | 30% | Significant |
| Rev 5: New construction | Lower bracket and thrust bearing alignment | Piano wire-micrometer and optical level | 50% | Significant |
| Rev 5: New construction | Upper bracket alignment | Piano wire-micrometer and optical level | 10% | Significant |
| Rev 5: New construction | Runner and shaft verification and installation | Piano wire-micrometer and optical level | 10% | Moderate |
| EM 1-A: New Construction | Embedded components alignment: Elbow, cone, spiral case, | Theodolite, Piano wire-micrometer and optical level | 40% | Significant |
| EM 1-A: New Construction | Stator frame fabrication and alignment | Platform & scaffolding , piano wire and support beam | 60% | Significant |

| **BENEFIT DRIVERS** |
|---|
| Greater margin driven by QA- Instrument tech productivity i.e significantly less hours than millrights instrument with micrometer and piano wire |
| Reduced labor cost due to less platforms and scafolding installation for piano wire installation |
| Fewer defects escaping upon inspection from suppliers where Faro Tracker used (runner and bearing fabrication) , resulting in less rework |
| Fewer defects escaping inspection during installation, resulting in less rework |
| Federal Research & Development Grant |
| **COST ITEMS** |
| Initial investment |
| Implementation cost |
| Maintenance, calibration, Faro accessories wear and tear and software upgrade cost |
| Training costs |
| Other costs |

| **ROI SUMMARY** | |
|---|---|
| Cost of capital used | 10.00% |
| Net present value over 5 years looking at 3 concurent sites per year | $1,102,324.47 |
| Payback (in years) | 0.92 |

Note for calculation of ROI:

- Change management progress: benefits estimated from 50% on potential to 100% over 2 years.
- Cost of training based on Faro and internal transfer of knowledge to increase by one technician operator staff per year.
- Cost of equipment maintenance, transportation, and annual calibration & certification going down after 2 years by developing internal procedure to be perform in-situ.
- Cost of upgrade and accessories mainly probes & nests replacement and assuming software upgrade every 5 years.
- R&D credits from Government Federal program granted on first year implementation.
- Gain on overall schedule and critical path activities not documented as tangible but having significant customer satisfaction impact.

## Conclusion

From our experiment, we demonstrated that the laser tracker is capable of establishing a level plane within +/- 0.005 mm/m or +/- 1 arc seconds. Based on this result and our own experience, we conclude that we can efficiently use the laser tracker for levelling components well within the most rigorous tolerance of 0.02 mm/m found in the hydro business.

As a general conclusion, we say that the overall benefits of using a laser tracker are very significant both for customer and supplier. It is a tool that is versatile, allows for very accurate measurements, and increases our measuring capabilities in comparison with conventional methods.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