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In Search of the Next Micron?

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Biography

Dan Nelson is a registered Land Surveyor by the State of California. He has worked for Lawrence Livermore National Laboratory (LLNL) for twenty years. He has received an R&D100 Award, and the Recognition of Excellence Awards from both the Department of Defense and the Department of Energy. His assignments at LLNL have included projects in oil shale and coal gasification; development of multi gigahertz sensors and recording systems for hostile environments; micro assembly and alignment; conventional surveying and precision alignment.

ABSTRACT

Lawrence Livermore National Lab's National Ignition Facility (NIF) Project presents numerous measurement challenges and tasks, demanding an extremely high level of precision and accuracy. This paper discusses some of the efforts to optimize, and better understand the results and looks at some of the alignment tools tested to lay hold of this complex task.

The methodologies discussed were commonplace in the "good old days" of land surveying. However, with the introduction of high accuracy equipment many of those practices have fallen by the wayside. This paper looks at the results of a series of in-depth, comparison measurements using three different laser tracker measurement instruments.

In search of the next micron

When often confronted with the challenges to deliver increased precision, the available avenues are few. One is left with either to improve the techniques, equipment or both.

When challenged to increase the precision of measurements, improving the techniques was sought. A Land Surveyor is taught to 'wrap up' the measurements to correct for any errors in the instrument's manufacturing process. Multiple front and back sights are used to correct for sighting and calibration errors. Observations from multiple locations also help reduce the measurement uncertainty in the location of a point by taking advantage of measurement geometry and the instruments' strengths. It was decided to see if these techniques could be applied in the use of a laser tracker, and how much improvement in accuracy could be obtained. It should be noted that front and back sight observations from multiple locations for our critical features were always a requirement at LLNL. The question was how much more could be achieved, and at what price.

When a component is measured from a single instrument location, the only information regarding the precision of the measurement is the manufacturer's published information and personal experience. However, if the points are measured from more than one location and a least squares adjustment is performed, much more can be learned about the precision of the instrument, *and* where the points really are. For the single station measurement the accuracy must be predicted. For example, the published specification for the ADM (Absolute Distance Measurement) on the SMX™ 4500 is 20 microns + 1.1 microns / meter, and multiple station results can be calculated based on the actual shot data. The comparison between single and multiple station measurements are shown in figure 1. The single station data is the product of the published specification times the length of the shots taken in the test. The multiple station data is the delta between the actual shot and the calculated position of the measured point. What this shows is, if a data set contains a small volume the use of multiple stations will yield an improvement of 20 – 30%. However, also note that as the job volume increases, the improvement climbs to 80%.

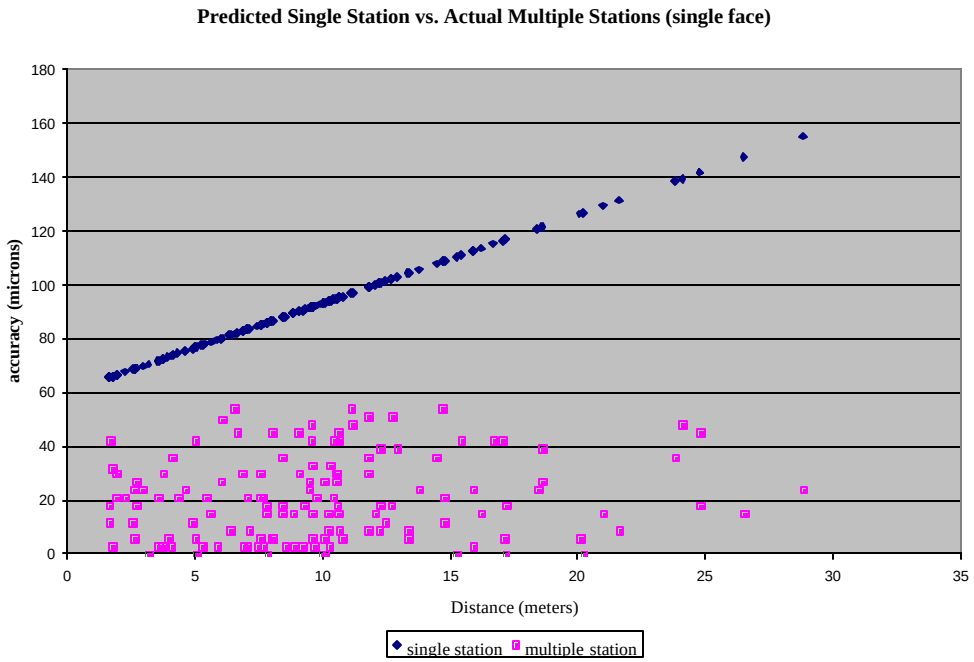

Figure 1

To determine how many times the points in the test area should be measured, points at 5, 10, 15, and 20 meters were selected. These points at these distances were measured in both front and back face, ten times. The standard deviation of the point was noted as the shot count increased. What was anticipated was an asymptotic curve revealing a clear point of diminishing return, which would be used in the next part of the test. As Figure 2 shows, the curve is there but not as clear as had been hoped. The curves suggest two to three pairs of observations per point will deliver fundamentally the same precision as ten.

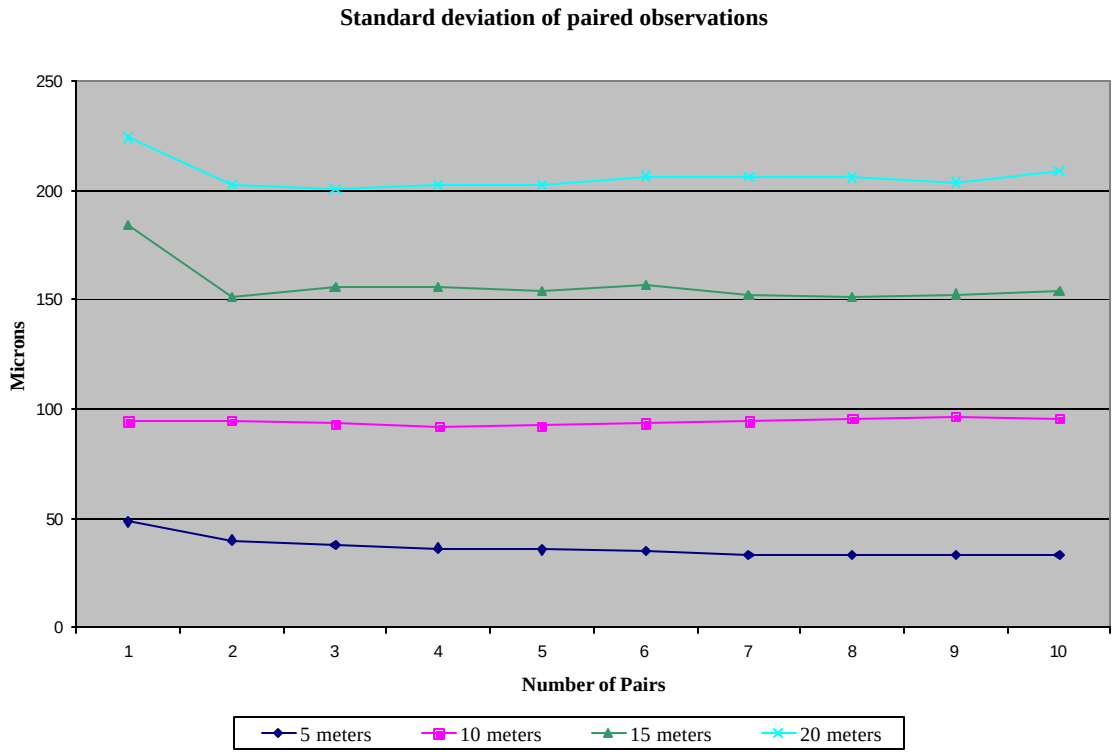

Figure 2

The next step was to try this on a real set of measurements. Since the measurements would be taken over a period of several weeks a stable location allowing a valid comparison of the test results was required. The tests were performed in the basement of the Target Bay at the National Ignition Facility (NIF). The temperature is controlled at 20°C ± 0.2. The concrete floor is 12 feet thick, and the available area is approximately 75% of a 30 meter diameter room with a 3 meter high ceiling.

NIF procedures were followed whenever possible during the tests. All trackers (SMX™ 4500, Leica™ LT800, Faro™ SI) were allowed to warm up for a minimum of 16 hours before calibration. All three instruments received a complete calibration when shipped and were not subjected to any unusual conditions. All three instruments used were held to the same operational requirements. (It is required to recalibrate when the back sight error reaches 20 ppm (0.005” in 20‘) and reject the calibration results if the error isn’t below 8 ppm (0.002” in 20‘)). For the ADM the recommended specification was used. The Leica did not receive a complete calibration because the required calibration tool was unavailable. However, after the interim calibration the Leica was able to meet the basic requirements. ATT metrologists (Redmond, WA) under direction performed all tests and calibrations. A large number of SMRs were also used to decrease the measurement time. Although, the optimum number of targets to use varies by instrument and location, it is found that 25 are about the largest group for practicality purposes.

The first test was performed using a LLNL owned SMX™ 4500. Thirty-seven monuments were measured from seven different instrument locations. Due to blocked lines-of-sight the actual number of stations able to observe every point varied from three to all seven stations. Each visible point was measured twenty times, ten with each face. This produced a total of 2780 measurements of the 37 observable points. All measurements were taken using the ADM function in an automated survey mode. The results were exported for post processing with the LEGO software package from Stanford Linear Accelerator complex (SLAC). Figures 3 and 4 show the calculated three-sigma uncertainty of the points. The uncertainty reduction with additional measurements from each of the stations is demonstrated by the reduced values for the multiple observation data sets.

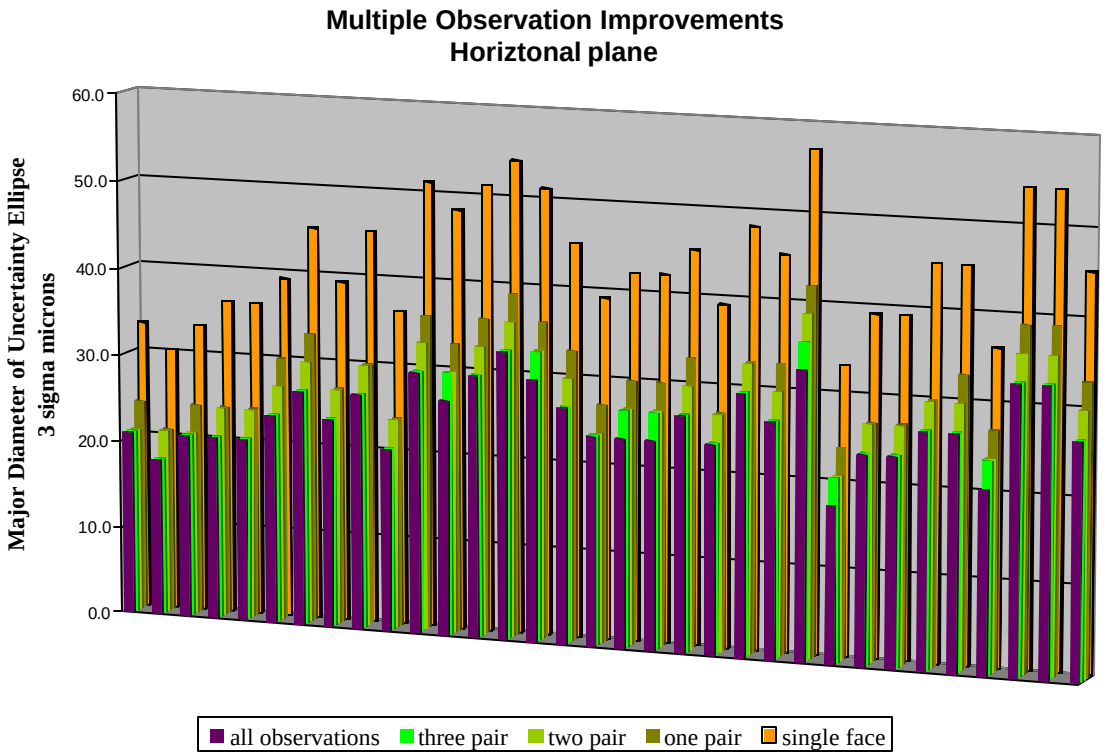

Figure 3

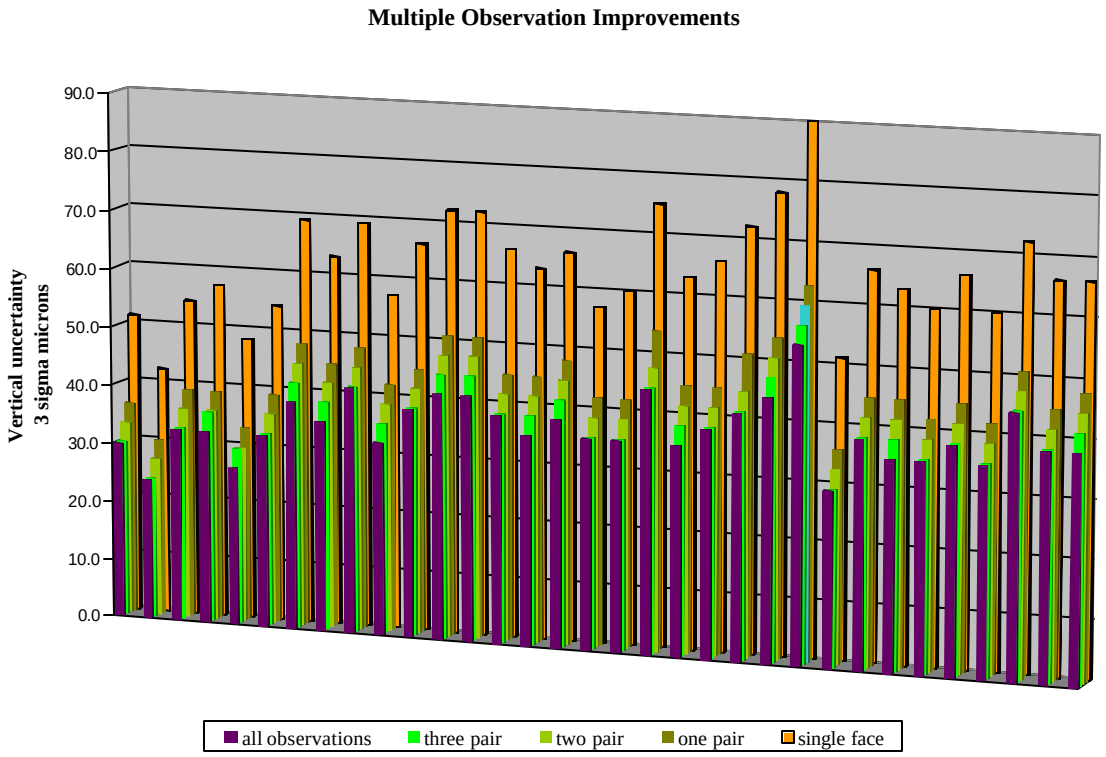

Figure 4

An uncertainty reduction of 29% was achieved with just 1 front - back sight observation pair versus a single front sight observation. An additional 5% was achieved with two pair, another 4% with a third pair and only an additional 2% from a total of ten pair.

The improvement from three sets of observations, from multiple stations, can yield improvements of as much as 90%. This would of course be from a comparison of a large volume job measured from a single location and the same job measured from multiple stations with at least three pairs of observations from each station.

The improvement in the measurement quality is partially dependant of the measurement geometry. Ideally, each point would be measured from stations equally spaced around it. Since this is impractical, an effort should be made to obtain the best geometry time and space would allow. This need for improved geometry also applies in the vertical direction. It is often difficult to obtain much vertical separation of the stations. However, even varying the height of the instrument by three or four feet provides a noticeable improvement.

Experience has shown additional improvement in the vertical axis can be realized by incorporating high accuracy level data with the tracker measurements. Also, for large-scale measurements the addition of data from an instrument capable of high precision measurements over longer distances will help highlight possible tracker measurement

problems. These measurements should span the volume of several tracker stations. For example, the Leica TC2002 is excellent for these measurements.

The control network at the NIF is an example of how the tracker, level and total station measurements can be combined to provide a high precision control network. Laser Bay One is approximately 140 meters long (460 feet), 30 meters (100 feet) wide and the network has a vertical spread of 10 meters (30 feet). There are almost 1000 monuments in this room alone. When this portion of the network was established all points were measured from at least three stations with two pairs of front and back sight measurements. The TC2002 was used to measure the visible monuments from ten locations around the perimeter. The Leica NA2002 digital level was also used to measure the elevation differences of many of the floor monuments. When complete the maximum three-sigma uncertainty in the network yielded only 158 microns.

The next step was to look at the available laser trackers with ADM capability at the time of the test. The goal of this test was to take an independent look at the three trackers using LLNL people, techniques and stable conditions. The instruments used were a SMX 4500 owned by LLNL, the Leica LT800, and a Faro SI. The API tracker was not available at the time of the test. When time permits, a plan to look at one is definite.

One of the considerations when choosing an instrument is the time required for setup and calibration. The times mentioned here are those required to keep the instruments within operational specifications after the initial calibration. The SMX 4500 required a TAC1 every 3.5 hours on average and a TAC2 at least once a day. Time for calibration and operational checks for the SMX™ 4500 averaged one hour and 25 minutes per eight-hour day. The Leica LT800 required four interim calibrations in the five days it was used. Total calibration time for the Leica was one hour and 50 minutes during the week of testing. The Faro SI required three self-calibrations, two TAC1 and one TAC2 calibrations during the week it was used. However, one of the calibrations needed to be repeated to bring the results under the post calibration threshold. Time spent calibrating the SI was one hour and 35 minutes during its week of use. The time spent collecting the data for the uncertainty comparison was a little less than one and a half days for the Leica and the Faro, and just over two days for the SMX.

The manufacturer's software was used for data collection. This prevented collection of back sight measurements using the Leica. Leica has since then released a patch to permit automated two face measurements.

Since an automated two face measurement using the Leica was unavailable, the SMX™ and Faro data was processed using only the front face data. The resulting three-sigma uncertainty for the monuments is shown in figures 5 and 6.

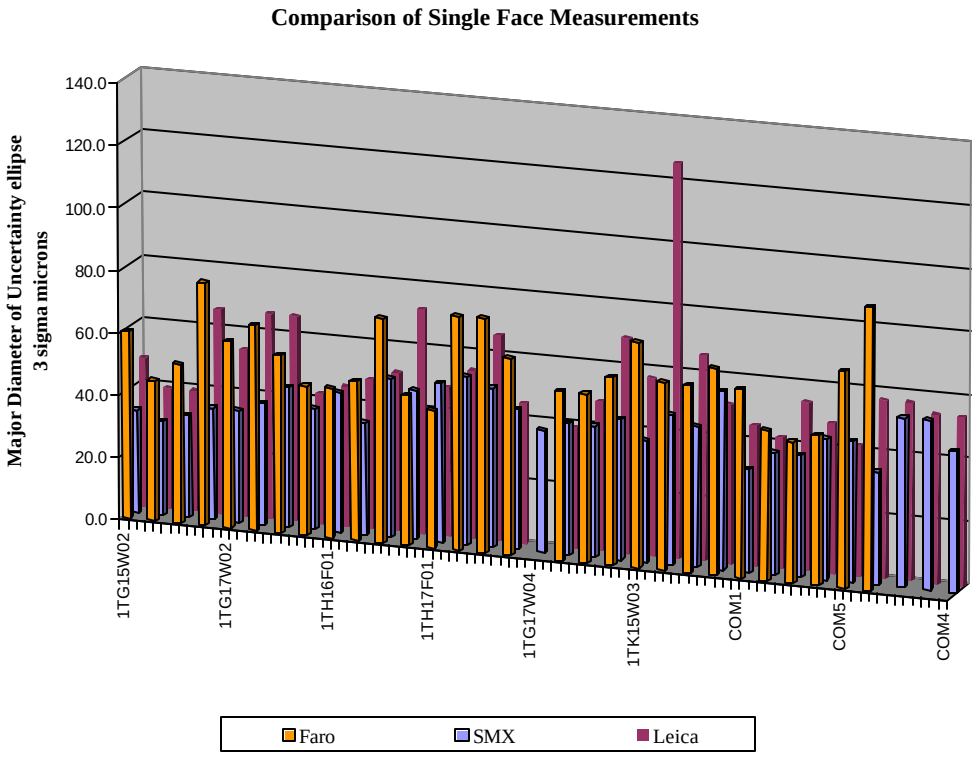

Figure 5

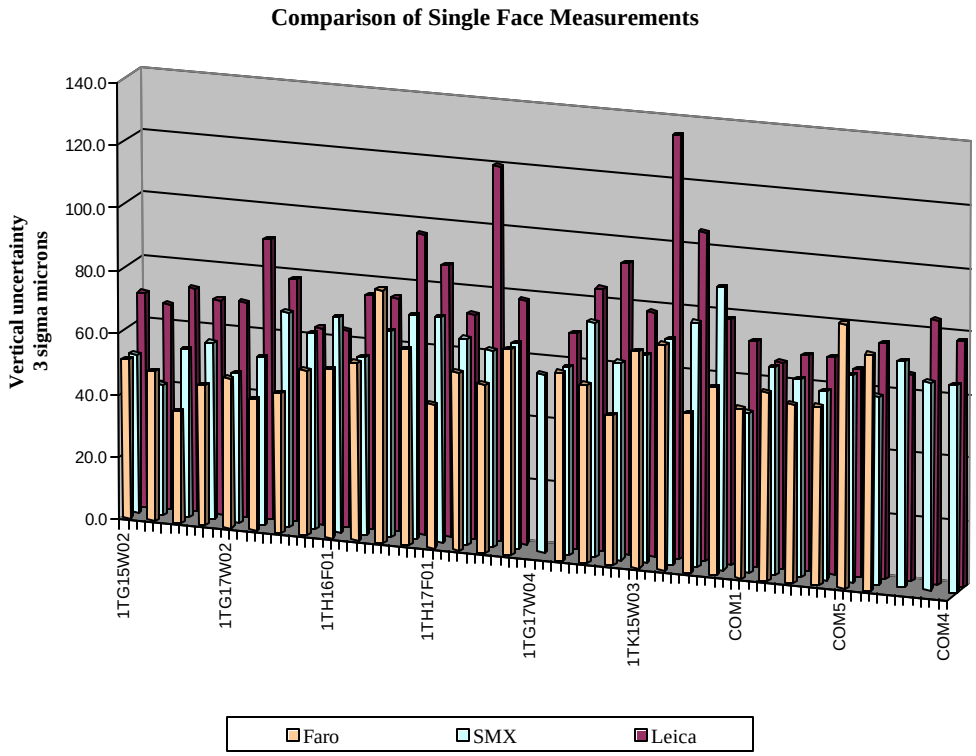

Figure 6

When comparing the single face measurements of the three trackers please note the increase in the reported uncertainty in the vertical direction of the Leica. This was believed to be due to the difficulty in varying the height of the instrument. The SMX™ performance is a little deceiving, because it required more calibrations; some of the observation sets were incomplete when the calibration was needed. This resulted in extra measurements of some of the monuments. These added observation sets serve to reduce the reported uncertainty.

The last step is to look at the analysis of all the measurements taken by the SMX and the Faro, Figures 7 & 8. (Note: Had the Leica been able to take the automated front and back sights the Leica data would of course have been included.) These data sets include ten observation sets of each monument, which could be seen from each station. Due to ongoing construction in the facility there were some points that could not be measured by the Faro. Also, the construction activities blocked some of the lines of sight, reducing the number of observable points from the different stations. The five points where the reported uncertainty for the Faro is considerably higher than that of the SMX were only measured from two locations.

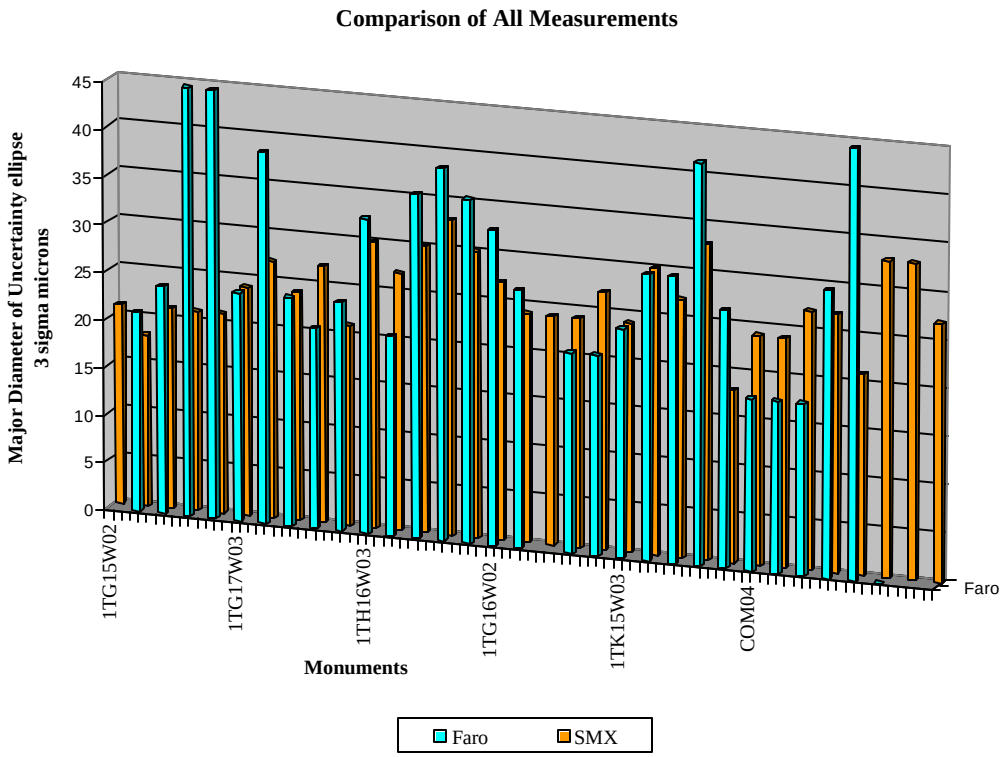

Figure 7

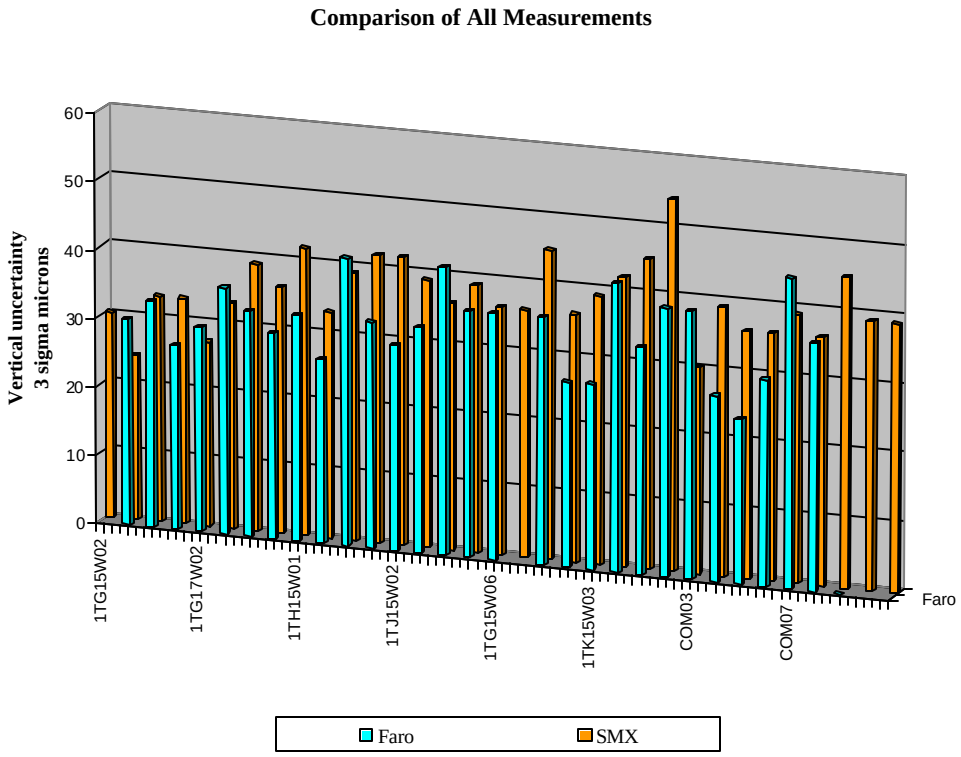

Figure 8

Summary

In regard to the instruments. Each of the new trackers tested performed at or above the published specifications. Each instrument has specific areas where it outperformed the other (I.e. calibration time; calibration frequency; accuracy; the amount of time to take the data, and ease of use.)

With regard to measurement uncertainty. Significant improvements in the uncertainty of the measurements in support of the various projects can be realized through the use of improved procedures and equipment. The tradeoffs are very familiar; time, cost, and quality.