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The NIST 66 m Ball Range

A One Dimensional Artifact to Test Three Dimensional Imaging Systems

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National Institute of Standards and Technology
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Bruce Borchardt, Craig Shakarji, Large Scale Metrology Group

Abstract

NIST (the National Institute of Standards and Technology) has instituted a 66 m long range for testing of distance-measuring systems using noncooperative targets. The range consists of titanium balls mounted along a line on stands at unequal intervals. This paper describes this range, including the uncertainty of the calibrated ball positions. The range has been shown to be sufficiently stable and repeatable that it, when calibrated from day to day, is capable of being used as a workable test range. The overall array of kinematic nests holding titanium balls can be used as a facility for performing range tests of three-dimensional imaging systems with uncertainties in the test distances of (10 + 1.1 L) µm, where L is the distance in meters. Continued monitoring of the positions has shown some interesting systematic behaviors that do not interfere with using the range for its intended purpose.

Background and History

While still at the Van Ness Street site in Washington, DC, NBS (The National Bureau of Standards, since renamed NIST, the National Institute of Standards and Technology) built a tape tunnel in order to meet the demand for the calibration of metal tapes. The facility was reconstructed in Gaithersburg between 1964 and 1965. Tapes were the primary method of measuring long distances, and included surveyors' "chains" used in geodesy and all types of surveying. Until 1960, the base length unit of the SI was the physical meter bar at BIPM (Bureau International des Poids et Mesures) in Paris, realized in this country by an array of platinum bars directly traceable to that bar. The facility at NBS was designed to transfer the meter to a master tape to be used on a bench for comparing tapes.

The facility consisted of 22 microscope stands on piers. (These piers form the mounts for the current range as discussed later in this document.) The microscopes were used in the process of calibrating master tapes. The stands were laid out in a particular pattern. For metric tapes only, the pattern would have been fairly straightforward: a stand every 5 m, with one 5 m interval divided into 1 m sections. The 1 m section is needed to transfer a 1 m line standard to a 5 m standard. Complications arose from the need at the time to include 50 foot measured intervals for the calibration of 200 foot tapes in English (US customary) units. To cover 200 feet, four extra stands were required. Since 50 feet is exactly 15.24 m, the extra stands were put at multiples of 15.24 m from a reference point. To get the total number of stands: every 5 m from 0 m to 65 m requires 14 stands, plus 4 stands for the 1 m sections, plus 4 stands for the 50 foot intervals, making a total of 22 stands.

Table 1: Stand positions

Distance from end stand, m	Comments
0	End Stand, farthest west
5	Reference for English 200 foot range
10	
15	
20	
20.24	50 feet from 5 m stand
25	
26	1 m section
27	1 m section
28	1 m section
29	1 m section
30	
35	
35.48	100 feet from 5 m stand
40	
45	
50	
50.72	150 feet from 5 m stand
55	
60	
65	
65.96	200 feet from 5 m stand

The system of transferring to tapes from line standards remained in use even after the redefinition of the meter in 1960, since interferometry over long distances was problematic and the Krypton lamp was difficult to use as a working standard. Practical laser interferometers became commercially available in the early 1970s, and the microscope stands and line standard carriages fell into general disrepair, as the calibration of tapes was done on the tape bench with laser interferometers as standards.

Adaptive Re-use

In 2005, the need became apparent for a facility to test three-dimensional (3D) imaging systems such as Lidar. An appropriate range would consist of suitable objects at known distances. To test an instrument, a typical procedure would be to use it to measure the objects; the errors of the instrument would be reported as the result of the measurements minus the calibrated values. The uncertainty of the calibrated values would then contribute to the uncertainty of the test result.

The choice of a suitable object depends to some extent on the type of instrument. In general, the choice for traditional metrological artifacts would be well-finished hardened steel. However, the mirror-like surface of such an object is normally not suitable for any system relying on reflected light.

For this range, the objects chosen were titanium balls. Titanium was chosen because it can be made round to a high degree of accuracy, typically a few micrometers, and can at the same time retain a matte optical finish while having the added advantage of being relatively light in weight. The size of 101.6 mm was chosen as a compromise. Small spheres on the order of 20 mm to 30 mm would be easier to make and measure, but are less representative of typical objects measured by a scanning system. Larger spheres would be very expensive. The titanium spheres were obtained with a “satin” finish, which is optically diffuse. All of the spheres were measured for form and diameter. The results are summarized in Figures 1 to 3. The (k = 2) expanded uncertainty of the CMM that performed these measurements is 0.5 μm. The lack of repeatability of these numbers reflects the fact that for an imperfect object the choice of points influences the value obtained. The uncertainty budget includes a term to account for this effect.

Building the Mounts

Because the balls need to be continually mounted, dismounted, and remounted for the calibration process, kinematic seats were necessary. It has been shown that kinematic seats with hard, smooth surfaces can repeat at the nanometer level. A simple three-ball nest was chosen, since mounting a sphere needs only a three degree of freedom mount, i.e., the angular motion of the sphere does not change its center location (at the level of the sphere roundness). Figure 4 is a simplified drawing of a mount, and Figure 5 is a picture of a titanium sphere in a mount. The mounting points are hardened steel tooling balls, 9.525 mm in diameter, expoxied in place. The bolt circle for the mounts (78.5 mm diameter) was calculated to have the contact points subtend a 90° angle (measured as the cone angle at the sphere center). This gives both reasonable stability and access to some of the lower hemisphere.

The kinematic nests were mounted on two-axis stages previously used to mount the microscopes that were used in the line standard calibration process. The stages were in various degrees of disrepair, with about half missing the handwheels to make adjustments. Fortunately, replacement handwheels were readily available, and loosening the gibs and lubricating the stages made all of them usable. The connection to the microscope was through three threaded studs, arranged in an equilateral triangle.

To mount the kinematic nests, we used a simple triangular plate with three holes to match the studs. (See Figure 6.) There were two different patterns of mounting studs on the two-axis stages, for unknown reasons lost in history; the pre-existing bolt circle diameter for 15 stages was 125 mm, and for the other 7 stages, it was 88 mm. There was room inside the 125 mm circle for a 63.5 mm diameter column. We had on hand a supply of 63.5 mm extrusion suitable for these 17 columns. The space in the smaller bolt circle could only fit 50.8 mm columns, so these were made of solid aluminum stock with the idea to prevent, as far as possible, losing some stiffness otherwise inevitable with the smaller column diameter. Both types of columns were made 155 mm high. This value was chosen so that the centers of the 101.6 mm diameter balls were at the same height as the laser interferometer axis located above the tape bench on the other side of the room.

The plate, column, and nest are screwed together with M10 studs. The joints between elements have tapped holes on each side. A stud is screwed into the two holes on each side of the joint. Using this assembly method means that the angular position of the three ball kinematic mount is not controlled, but this does not affect its performance.

The assembled array with titanium balls mounted is shown in Figure 7.

The 101.6 mm diameter SMR (Spherically Mounted Retroreflector)

Generally, the plan for calibrating the distances between the titanium balls is to rest an SMR in the nests in place of the titanium balls and use a laser tracker to measure the distances from one location to the next.

Thus, the plan for calibration depended on obtaining an SMR with the same diameter as the titanium balls. After some difficulty, we found one manufacturer who was able to supply two of these vital items with acceptable specifications for diameter, roundness, and concentricity of the optical elements.

The SMR tolerance specifications were:

Diameter	2.5 μm
Roundness	0.4 μm
Concentricity	2.5 μm

There was one unforeseen complication when we actually put an SMR into our kinematic nest: it wasn't balanced. The weight of the SMR outside sphere is not symmetrically placed, so when it's in a nest and free to pivot, it turns so the retroreflector points up. This problem was solved by making a small clip that goes between the lower edge of the kinematic nest and the lip of the SMR and holds it close to horizontal. Precise horizontal alignment isn't needed, as long as the tracker beam can see the center of the retroreflector. (See Figure 8.)

Setup and Alignment of the Nests

At this point, the array of nests was ready for alignment and calibration. The actual positions were arbitrary, since they could not be set significantly better than ≈ 0.2 mm and needed to be calibrated with an order of magnitude better uncertainty. The two end nests were set to be near the middle of their travel in X, Y, and Z. X and Y travel were easy to set as this just required turning the handwheel until the carriage was in the right place. Setting the Z axis was harder, since it is necessary to loosen the three upper (locking) nuts, move the three bottom nuts to the right places, and re-tighten the locking nuts. During the Z axis setting procedure, a small bubble level was used to keep the top of the kinematic mount close to horizontal.

The laser tracker was set up along the center line, a few meters beyond the “0 m” nest, at the height of the center of an SMR. At this point, it was necessary to make the tracker start tracking on the 101.6 mm SMR. The normal procedure calls for putting a 38.1 mm diameter SMR into the home position (“bird bath”) of the tracker and then moving it, without letting the beam be interrupted, to all measurement points. Since the 101.6 mm SMR could not fit in the home position, an alternate procedure was needed.

The tracker has a method of searching near a previously defined location. We made a temporary nest that held the 38.1 mm SMR up in line with the 5 m nest so the center of the SMR was close to the center point of the 101.6 mm SMR when it was put into the nest. We measured the temporary point and stored it as a measured point. The small SMR was put back in the home position, and the large one was put on the nest. The tracker was then instructed to “go location” to the measured point; it found the large SMR in the nest and began tracking it.

We measured the two end points of the range. Using the tracker’s software, we defined a coordinate system whose X axis passed through those end points, with the Z axis vertical. At this point, it was just a matter of moving the SMR sequentially to each nest and adjusting Y and Z so the tracker Y and Z components of the measured position read a value near zero. The X readings were set to be close to the nominal values. For 18 nests, these were even meter values, but the 4 nests on 15.24 m (50 foot) centers needed to have meter equivalents calculated. At this time, we did not understand that the 5 m nest was meant to be the origin for the English ranges, so we set the 4 nests to an arbitrary value, making sure only that they were 15.24 m (50 feet) from each other. The first one was set to 20.2312 m from the end nest, and the others were set at 15.240 m intervals. To follow the designed intention, the first nest should have been set at 20.240 m and the others at 15.240 m intervals from there. This 8.8 mm maladjustment will be corrected the first time the nests are moved for any other reason; until then it’s not worth doing. It’s important to keep the positions fixed for as long a period as possible for the purpose of monitoring the history of their locations.

See Figures 9 and 10 for the approximate Y and Z values (as measured by a laser tracker) plotted for several calibration runs over a few week time period. Since the values of the Y and Z coordinates are not used in any report or analysis, uncertainties were not calculated. Judging solely by the repeatability values as shown, their uncertainties would be in the tenths of millimeters. On these plots, the end points are set to zero so that the other points will show the deviation from a straight line. Note that the Y values are closer to the nominal zero; this is because fine adjustment is much easier to do on the Y axis. Even so, only three nests are farther than 1 mm from a straight line in the Z direction. Nonetheless, for use as a ranging facility, the Y and Z deviations do not impact our uncertainty, because we only measure in the X direction. Furthermore, as a ranging test facility, we can calibrate the reference distances on the same day as a test, so effects that only occur over longer time periods do not affect the uncertainty of the reference values.

After we set the nest locations, the gibs of the stages were locked down tightly to minimize inadvertent movement. At this point, a casual tweak of any of the handwheels would no longer produce any measurable movement in the ball.

Using Trackers to Measure Nest Positions

A laser tracker when used as a linear interferometer has very small sources of error. In order to use a tracker in this mode, it must be set up in such a way that there are only small changes in the horizontal and vertical angles during the measurement. This normally means that the tracker is placed so it is in line with the line of measurement. (There are possible alternatives using one or more mirrors to direct the measurement line, but these are not relevant in this discussion.)

If the tracker is in line, the only significant errors are those of doing interferometry. These would include the laser wavelength, index of refraction compensation, and possible software errors that count the fringes incorrectly. ("Fringes" is used loosely; modern heterodyne laser systems have more subtle operating principles than the classical Michelson interferometer.)

Comparisons between two trackers

During the course of monitoring the 66 m range, two different trackers were used to measure the ball nest positions. The manufacturer's specifications are:

Tracker	Tracker 1	Tracker 2
Max Range	70 m	35 m
MPE at max range	70 μm	24 μm, from formula: 10 μm + 0.4 L (L in m)

(L is the measured length. MPE = Maximum Permissible Error- note these specifications apply to linear measurements and not to three-dimensional coordinates)

Because of the different maximum ranges, two different measurement plans were used for the two trackers. Tracker 1 was placed in line at the end of the row and the positions were measured directly. Since the maximum range for the tracker 2 is insufficient to measure the entire 66 m at once, this necessitated a modified plan. The tracker was placed in line between the 30 m and 35 m positions, and the nests on each side were measured from that point. Because of this technique, the distance from 30 m to 35 m was significantly less accurate. Measurements taken with a tracker in two opposite directions include twice the zero-point setting uncertainty. This is also called "bird bath error" because the physical point on the tracker where the interferometer starts counting is a shallow kinematic nest, vaguely resembling a bird bath.

The presence of zero-point error required a separate measurement of the 30 m to 35 m gap. The tracker was moved to approximately the 38 m point, and the gap was measured directly with the interferometer. This value was taken to be correct, and the positions of all of the nests from 35 m to 66 m were adjusted by the difference between the “true value” and the initial measurement (taken when the tracker was between 30 m and 35 m). For example, the first set of data (with the zero-point error included) might show the distance from 30 m to 35 m to be 5000.010 mm. The independent measurement of the gap would give 50000.030 mm. This is a better value, since it does not include any zero-point error. All of the X positions 35 m and above would have 0.020 mm added to them. This procedure adds some additional uncertainty that must be accounted for in the uncertainty budget.

Traceability of the Tracker Measurements

At intervals during the measurements, each tracker was compared with the reference interferometer used with the tape bench. The reference interferometer is calibrated using the iodine stabilized laser to realize the SI meter.

Although the comparisons with the reference interferometer are not completely stable, they are within acceptable limits for present needs. When Tracker 1 was sent back to the manufacturer for repairs, its error decreased significantly, so the current error budget can reflect a lower value for this term.

It should be noted that the two trackers have different procedures for correcting the effective wavelength for temperature and pressure. Tracker 1 requires the user to manually input values for temperature and pressure, and then calculates effective wavelength using some equation, presumably Edlén’s, but the process is hidden from the user. Tracker 2 has its own weather station, so it is important to put its temperature sensor at a point that approximates the temperature in the path of the laser beam.

The values used to correct Tracker 1 were taken from the reference interferometer’s extensive instrumentation, which includes 7 air sensors evenly spaced along 60 m of the tape bench. The average of those sensors is a very good estimate for the effective temperature along the bench. There is a known gradient from the bench to the line of nests of about -0.15 °C (i.e., the air above the nests is colder than that measured over the bench). This creates a bias in the measured lengths of about 1.4×10^{-7} m/m, or about 9 μm in the total length of 66 m.

Another factor which comes into play at these levels of accuracy is humidity. The Tracker-1 software assumes a constant relative humidity of 50 %. If the humidity is actually 20 %, as might often happen in the winter, the relative error is about 2.5×10^{-7}, with a direction sense making the measured length appear longer than actual. This value has been applied to the calibration of January 2009 in the table below. The appropriate adjustment has also been made to data taken after September 2008.

Table 2: Tracker range errors

Date (month/year)	Tracker	Relative error (max)	Comments
11/2006	1	$+7 \times 10^{-7}$	
4/2008	2	$+7 \times 10^{-7}$	
4/2008	1	$+5 \times 10^{-7}$	
6/2008	1	$+2.7 \times 10^{-7}$	before warmup
6/2008	1	$+1.5 \times 10^{-7}$	after warmup
1/2009	1	$+2.5 \times 10^{-7}$	with humidity correction

Results of Range measurements (uncertainty over the short term)

When using the facility to test 3D imaging systems, the procedure requires measuring the ball positions before and after the test. Therefore, the relevant factor to include in the uncertainty analysis would be the change in position from measurements taken before and after the 3D imaging test. Therefore, it's important to find out how much the positions change in the course of a day.

Short term changes of selected data are shown in Figures 11 to 21. (The runs were selected to highlight some significant aspects of stability.) For these plots, the time between runs was typically a day to several weeks. Error bars are not shown on these plots in order to make trends more visible. If they had been included, the uncertainties of all these values on these plots would be as calculated in the uncertainty budget below. The time periods are shown in the figure captions. There are several interesting features to notice in these plots. First, the changes are almost always linear; that is, the ball positions change proportionally with distance, subject to day-to-day random repeatability noise of about 5 μm. There are a few exceptions to this rule which will be pointed out later.

Figures 12 and 13 are plotted in a somewhat unusual way; the plotted values are all referenced to the 5 m point. Note that the 0 m point has a wide range of values, from -14 μm to 26 μm. During these runs, the weight of the tracker rested on the wood floor adjacent to the steel rails that the line scale carriage runs on. When the operator picked up the SMR from the 0 m pillar, it was necessary to walk on the wood floor. Consequently, the tracker would move slightly. Once the 0 m measurement was finished, no one walked near the tracker, and so after that the numbers became more stable and self-consistent. Once this phenomenon was recognized, a tracker mount that put the weight onto the steel rails was built, and the problem was corrected. The runs taken during the time the mount was less stable were plotted with the 5 m mount as the reference point.

Figure 12 also shows the biggest jump observed over the entire 4 years of measurements. Between runs 78 and 79, all of the positions moved significantly, even beyond the 0 m instability noted above. Every ball nest changed position by 10 μm to 35 μm. The two runs were on 26 May and 30 May of 2006, before and after the Memorial Day holiday weekend. We have no definite explanation for this unique behavior. Intriguingly enough, there was a major earthquake in Java, Indonesia, at about 7 pm on May 26. The longitude of the epicenter was at 110° East, about 173° of longitude from Maryland. This is unlikely to be a full explanation, especially since there were several significantly larger earthquakes elsewhere in the world over the time span of the data, and they didn't cause any noticeable changes. The unlikelihood of this explanation has been underscored by the occurrence of a magnitude 3.6 earthquake in Gaithersburg on the morning of July 16, 2010, which didn't cause any noticeable changes.

Figure 14 shows a small jump in the 20 m position; this change is only about 12 μm and may well be due to someone bumping into the pillar.

In Figure 19, a change with a known cause is shown. Just before run 470, it was found that the 20 m nest had come slightly unscrewed. The runs from 464 to 469 show the position was around +0.1 mm. For run 470, the nest was tightened down and the position shifted to -0.09 mm. Run 470 became the new reference, and subsequent runs are shown as the difference from that run.

One conclusion to be drawn from this information is that the individual ball positions are stable to approximately 10 μm over a short time interval (a day or two), with rare anomalies where greater changes are possible. Another conclusion is that the overall length of the range changes slowly over a time span of weeks to months, and that this drift is uniformly distributed along the 66 m length of the room.

Results of Range measurements (long term stability)

Even though we anticipate doing frequent recalibrations of the range so that the short term stability is the only important term, it is interesting to investigate the long term stability. Figure 22 shows all of the history of the values for the total length of the range (from the 0 m position to the 65.951 m position). Because we have shown that the positions move uniformly proportional to length, this plot is indicative of the scale changes of the whole range. To assure ourselves that the last ball is representative of the range, we have also checked the position of the 65 m pillar, and it tracks the changes in the 65.951 m position very closely.

Inspection of the plot shows some interesting features. The most obvious is the seasonal variation. Every summer the range gets longer, and every winter it shrinks again. The seasonal changes exceed 10 μm/m. This would require a change of 10 °C in air, and 2 °C in most types of rock. Since we continually monitor the tunnel, ensuring it to be 20.0 ± 0.2 °C during a measurement, this can be eliminated as an explanation, especially considering that the bases of the columns are five meters underground.

However, we note that temperature variations, when they occur, can produce the effect seen. This is underlined by the results from late 2009, after the February to September timeframe when the air conditioning system was undergoing extensive renovation, with the result that the temperature was entirely uncontrolled. During this time, the average air temperature frequently exceeded 25 °C and approached 30 °C. (No measurements were made during this time period.) When the air temperature was brought under control around September 11, the first check of the range was longer than the historical maximum, 0.7 mm longer than nominal. However, it began to shrink rapidly, and by December 10 it was down to 0.077 mm, in line with the previous year's values. The values continued to decline all winter, reaching a minimum on March 1, 2010. The minimum value, -0.428 mm from nominal, was the lowest value ever. By June 29, the range length had rebounded to -0.007 mm, and by October was up to +0.010 mm, entirely in accord with past history.

It appears that permanent mountings are not as permanent as one might believe. They need recalibration regularly; at the highest level, they must be calibrated before and after each use.

We have a very good site; it is underground, has had 40 years to settle, and the room has excellent temperature stability. Despite all of these factors, there are influences beyond our control. Given this data, a range with its pillars set in surface earth or sited out of doors could well be much worse than this.

A long-term study such as this is valuable to point out the necessity of monitoring things that one might not think need monitoring.

Uncertainty Budget

The standard uncertainty in the calibrated distances between the centers of mounted titanium spheres (when using Tracker 1) is given by the general equation:

$$u_{\text{cal}} = \sqrt{u_{\text{rep}}^2 + u_{\text{form}}^2 + u_{\text{reference}}^2 + u_{\text{tracker-comparison}}^2 + u_{\text{temp-gradient}}^2 + u_{\text{pressure}}^2 + u_{\text{humidity}}^2}\ ,$$

where the components have values as follows (length-dependent values use L, the measured length, in meters):

$u_{\text{rep}} = (3.0 + 0.3L)$ µm

Repeatability studies over very short intra-day time periods were performed as well as reproducibility studies over one-day and many-day time intervals in order to capture several effects including stand instability, SMR imperfections, drift, etc. For the short time periods, several distances (on every stand) were measured twice (with the SMR removed and then placed on the nest again) to capture the short term effect. For the longer time periods, reproducibility studies were performed over several one-day and multi-day periods (displayed in Figures 11 to 22). The formula for u_{rep} capturing these effects is given as $(3.0 + 0.3L)$ µm for time durations of one full day (including overnight). (The primary interest lies in time periods of one day or less, due to the time between measurement and performing a test under normal testing). Under normal testing, the distances between nests would be measured both before and after a test, virtually eliminating the chance that an undetected anomaly occurs (as is rarely seen in Figures 11 to 22).While it is possible this term is not completely independent of other uncertainty contributors, the inclusion of its full value leads to only a mild overvaluation of the uncertainty.

$u_{\text{form}} = 3.0$ µm — The form of the titanium spheres can affect the center location when seated in the kinematic nest. Simulations were run using the form magnitudes shown in Figure 1 to arrive at the value used here.

$u_{\text{reference}} = (2.5 + 0.2L)$ µm — The reference interferometer has been compared to an iodine-stabilized laser many times and is used as part of a ranging test facility having a well characterized uncertainty. See [1, 2]. The uncertainty of the reference is dominated by atmospheric compensation on the tape bench line, temperature gradients along the bench line, and the mechanical effects of the carriage (e.g., Abbe errors).

$u_{\text{tracker-comparison}} = 0.40L$ µm — The value for the back-to-back comparison between the tracker including atmospheric temperature compensation and the reference interferometer is based on the results shown in Table 2 converted to one standard deviation, taken to be large enough to cover all variations.

$u_{\text{temp-gradient}} = 0.2L$ µm — Computed from the Edlén Equation using the effect of a 0.15 °C mean difference between the temperature sensors on the tape bench and the actual ball range. The mean temperature difference will likely be reduced in future calculations due to upgrades to the thermal environment.

u_{pressure} (negligible) — The effects of pressure gradients (up to 0.02 hPa)—as calculated by the Edlén Equation—are dominated by other terms in this uncertainty calculation [2].

u_{humidity} (negligible) — The effect of a non-50 % humidity is corrected for in the calibrated value. The effect of the uncertainty of the humidity—as calculated by the Edlén Equation—is dominated by other terms in this uncertainty calculation [2].

Combining these terms gives:

$$u_{\text{cal}} = \sqrt{24.3 + 2.8L + 0.33L^2} \text{ µm.}$$

Or, written in a more understood way (mildly overvalued):

$u_{\text{cal}} = (5.0 + 0.57L)$ µm.

The expanded (k = 2) uncertainty is found as:

$U_{\text{cal}} = (10 + 1.1L)$ µm.

Using this budget, the k = 2 uncertainty for a 66 m range (our maximum) for a one-day duration is 83 µm.

Conclusions

The existing pillars and kinematic mounts have been shown to be sufficiently stable and repeatable and, if calibrated from day-to-day, are capable of being used as an accurate test range.

The overall array of kinematic nests holding titanium balls can be used as a facility for performing range tests of scanning instruments with an expanded uncertainty (k = 2) of (10 + 1.1 L) µm. To achieve this level requires checking the coordinates of the ball nests before and after the range test, preferably on the same day. If the time between calibrations is a few days to a week, data shows the uncertainty increases about 50 %. Data shown indicates that for time periods of six months or more, the uncertainty can rise several-fold.

We are continuing to monitor the ball nest positions, when circumstances permit.

Acknowledgements

The staff of the Large Scale Coordinate Metrology Group have given extensive help in this project. In particular Dan Sawyer and Tyler Estler were integral to setting up the range. They, in addition to Chris Blackburn, frequently measured the ball range to keep the data string as intact as possible. Steve Phillips oversaw the project and was responsible for funding the work.

References

[1] W.T. Estler, D.S. Sawyer, B. Borchardt, S. D. Phillips, *Large-Scale Metrology Instrument Performance Evaluations at NIST*, The Journal of the CMSC, Vol. 1, No. 2, Autumn 2006, p. 31.

[2] W.T. Estler, *Uncertainty Analysis for NIST Tape Calibrations*, NIST Large Scale Coordinate Metrology internal white paper, September 2008.

List of Figures:

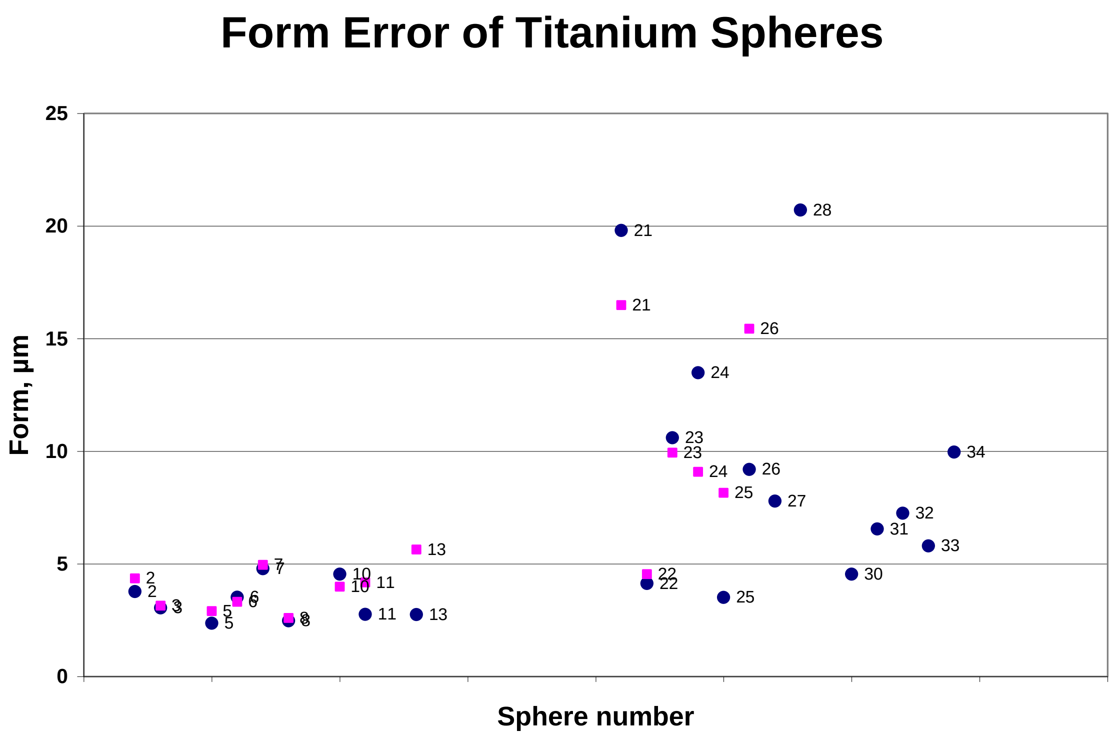

Figure 1. Form Error of Titanium Spheres as measured on the M48 CMM using 225 points. The second data points shown are repeated measurements. Note that not all spheres have repeated data. See text for a discussion of CMM uncertainty.

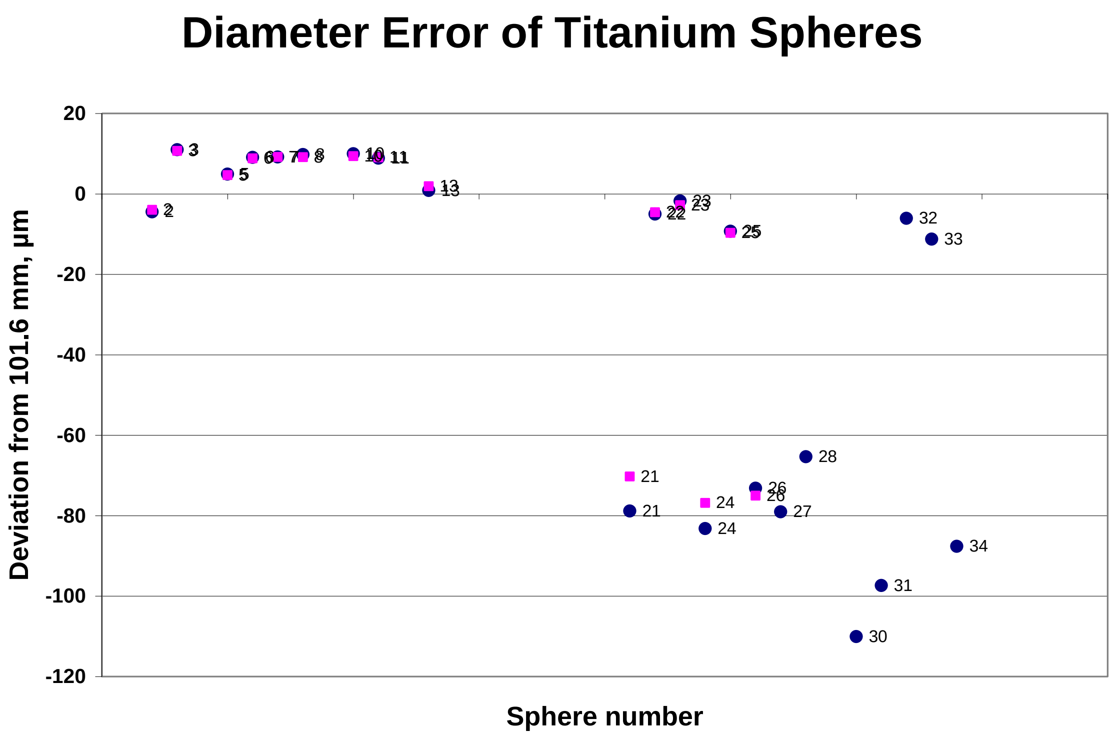

Figure 2. Diameter error of Titanium Spheres as measured on the M48 CMM using 225 points. The second data points are repeated measurements. Note that not all spheres have repeated data. See text for a discussion of CMM uncertainty.

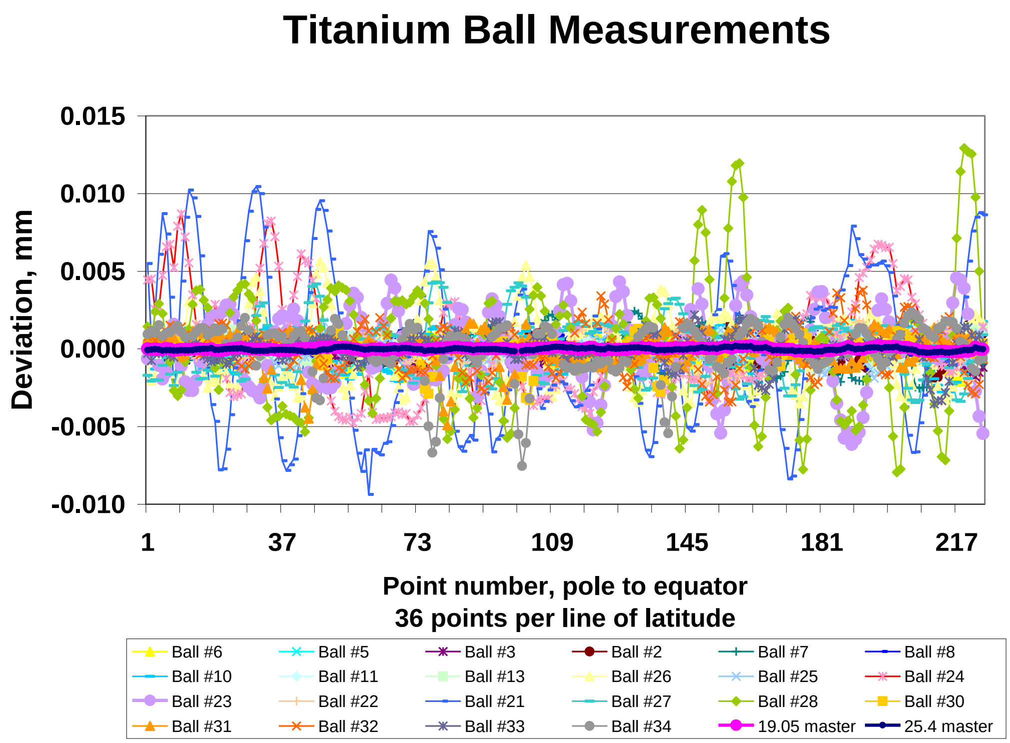

Figure 3. Titanium Spheres, all measured points. The point numbers increase from pole to equator, with 36 points per line of latitude. Note that only four spheres have data points outside the ± 5 μm lines: numbers 21, 23, 24, and 28. See text for a discussion of CMM uncertainty.

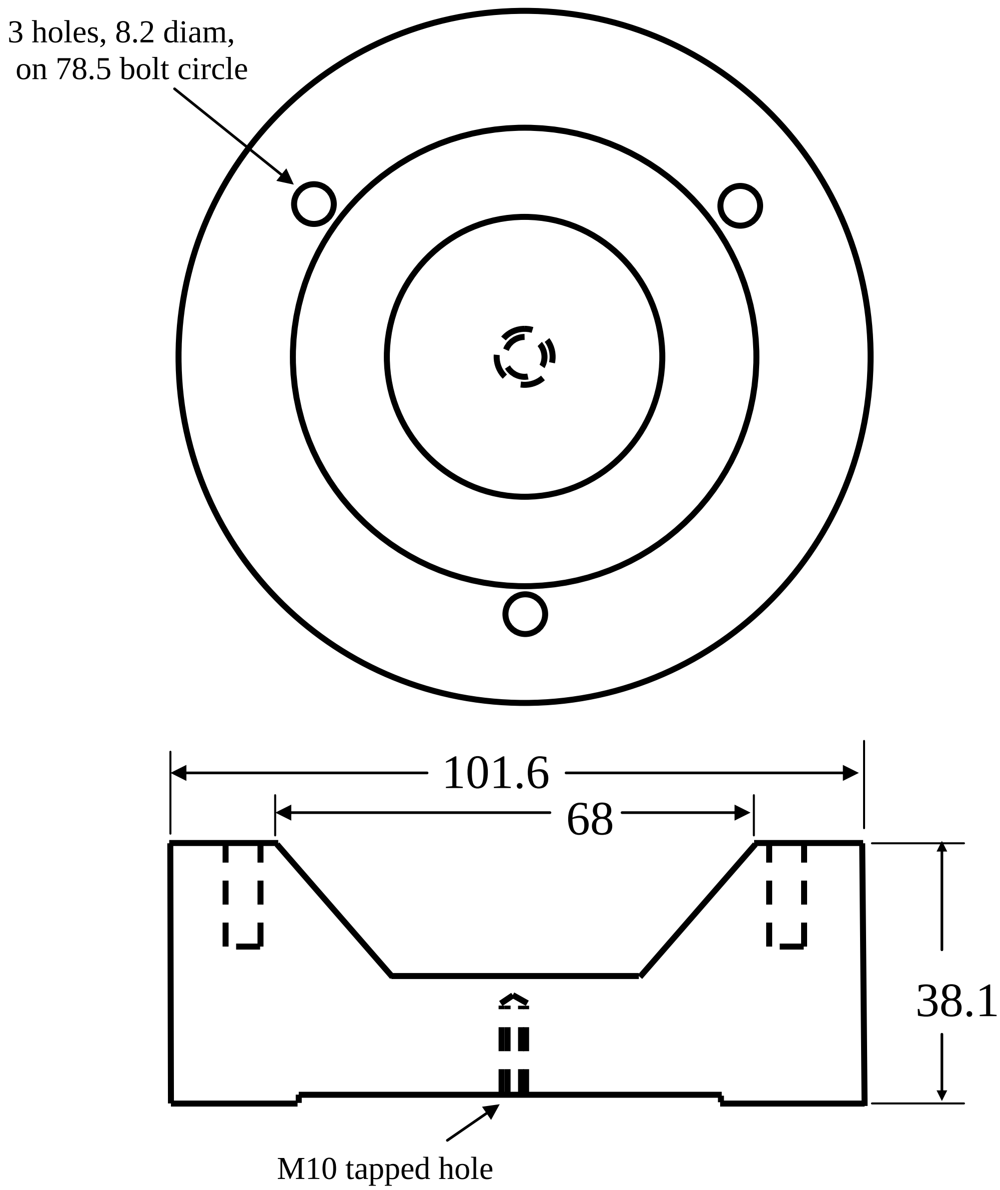

Figure 4. Drawing of kinematic mount (dimensions in mm)

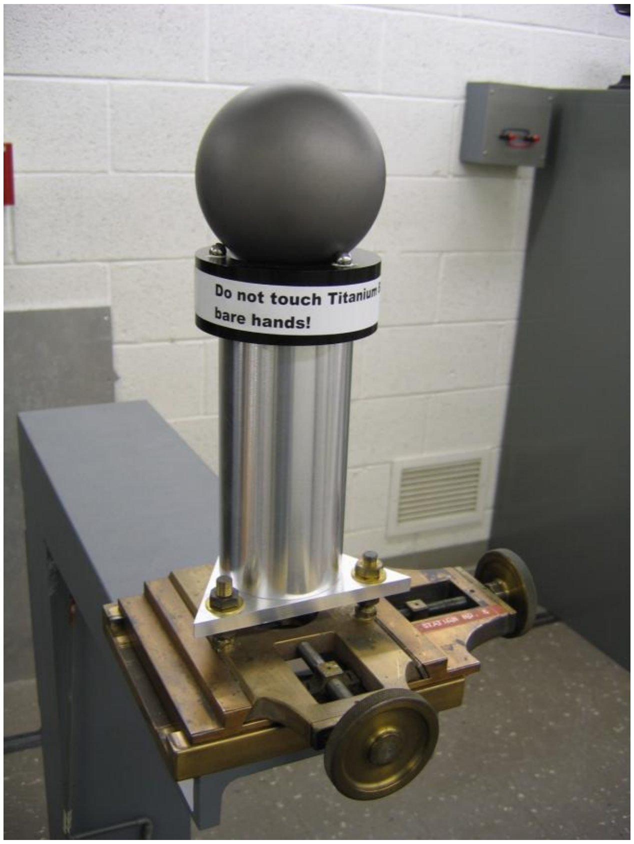

Figure 5. Photograph of kinematic mount with titanium sphere.

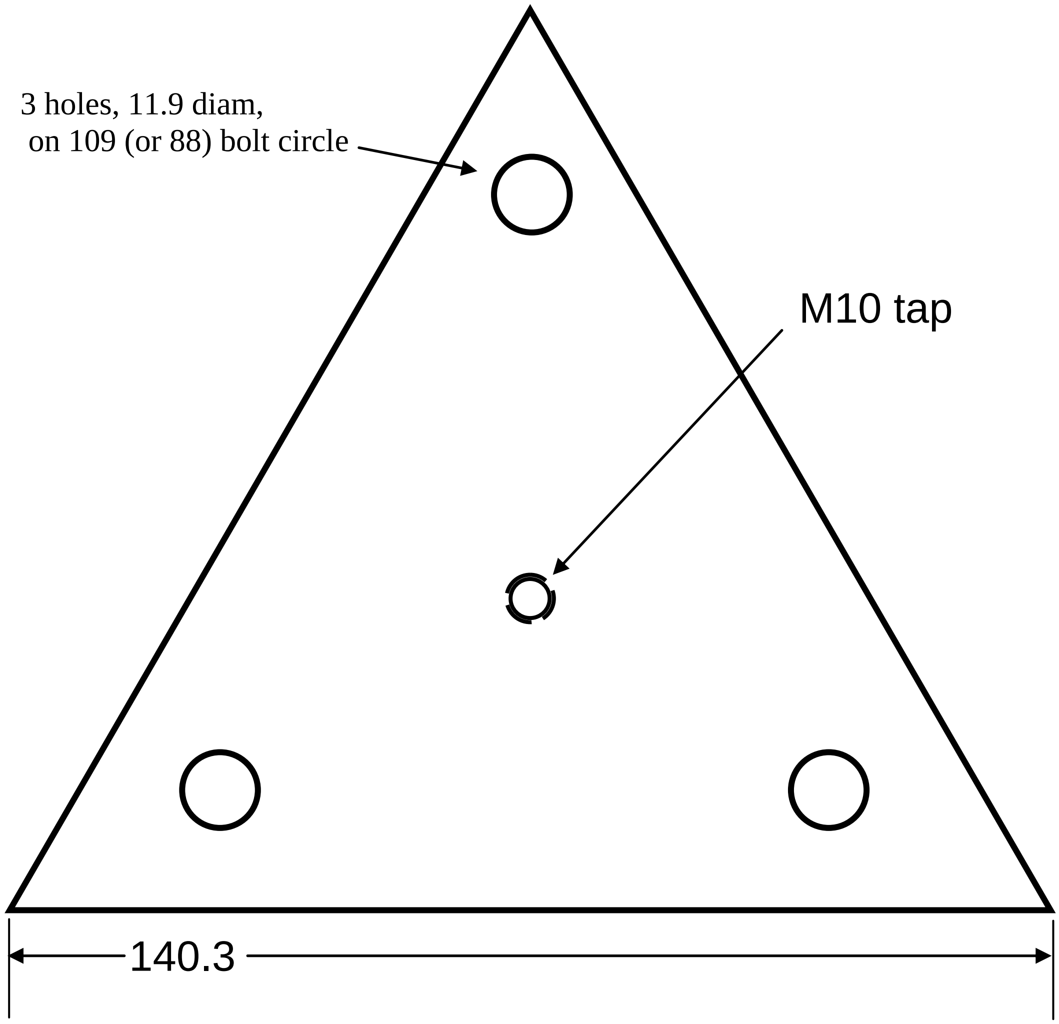

Figure 6. Drawing of mounting plate (dimensions in mm). Note that the two versions differ only in the size of the bolt circle of the three through holes. Plate thickness is 9.5 mm.

Figure 7. The array with all titanium balls mounted. The apparent varying tilt of the columns is an optical illusion exacerbated by the straight fluorescent lights.

Figure 8. Photograph of SMR holding clip.

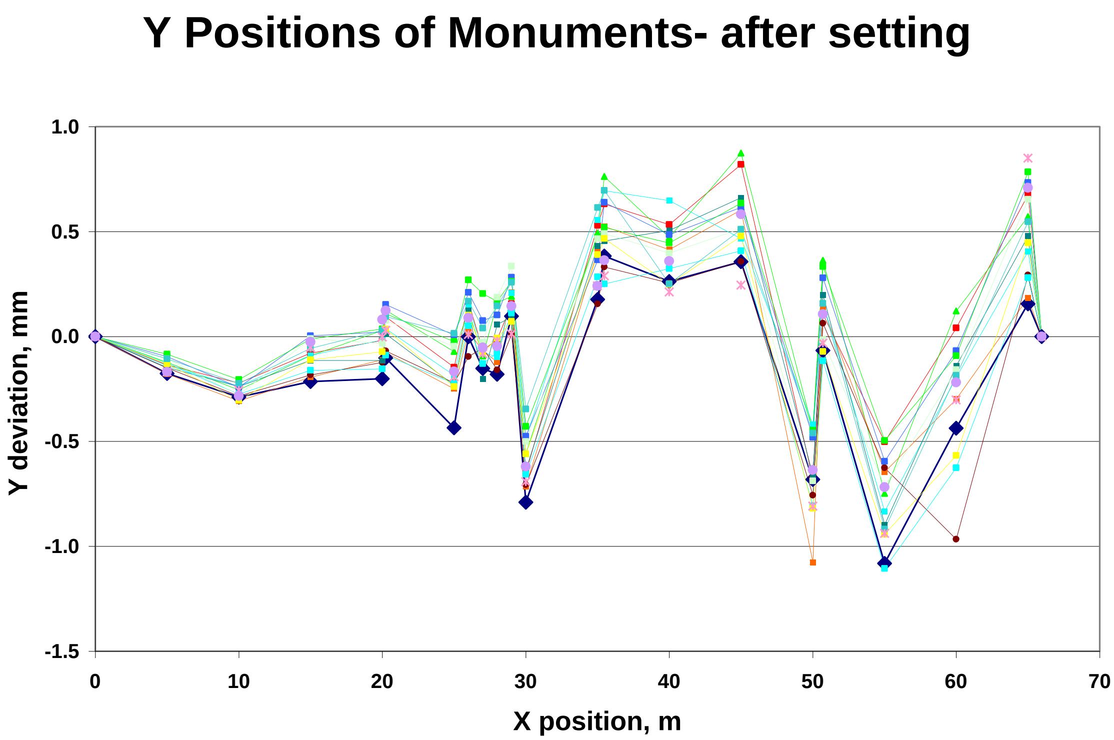

Figure 9. Y positions of monuments measured over a 14 week time period. Since the values of the Y and Z coordinates (Figures 9 and 10) are not used in any report or analysis, uncertainties were not calculated.

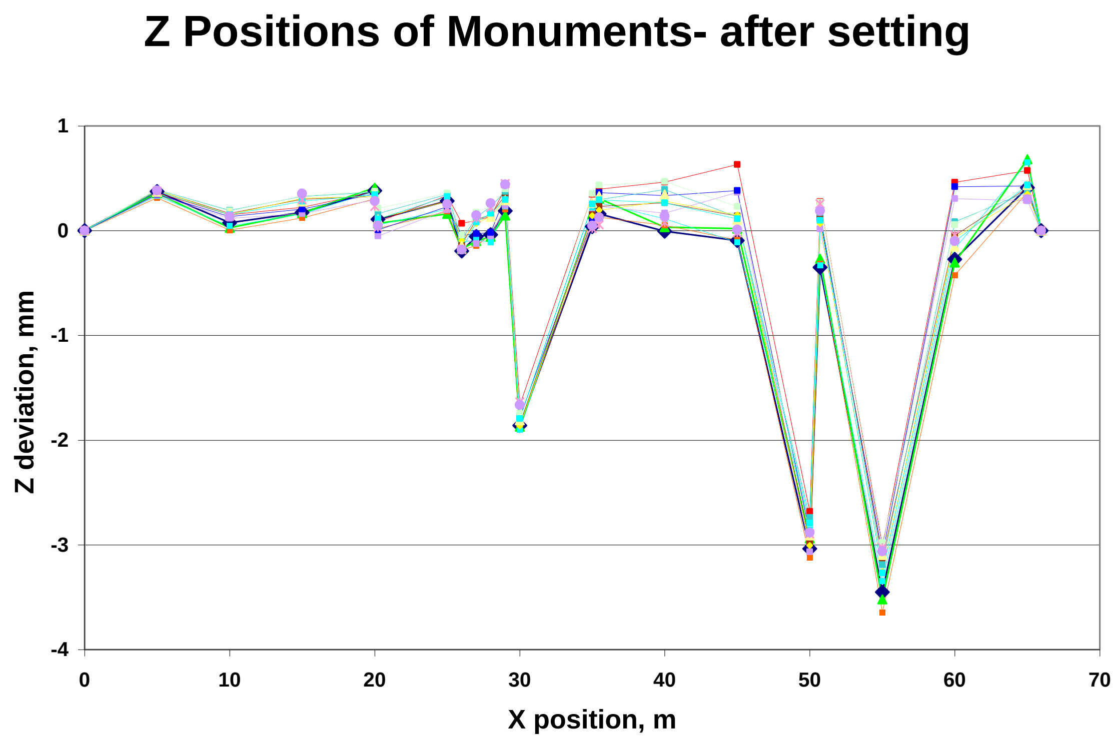

Figure 10. Z positions of monuments measured over a 14 week time period. Since the values of the Y and Z coordinates (Figures 9 and 10) are not used in any report or analysis, uncertainties were not calculated.

Figure 11. Runs 11 to 31 over 35 days: 23 January 2006 to 27 February 2006. Note that error bars are omitted from Figures 11 to 21 for clarity. If shown, they would follow the formula (10 + 1.1 L) μm (k = 2 expanded uncertainty; see uncertainty analysis).

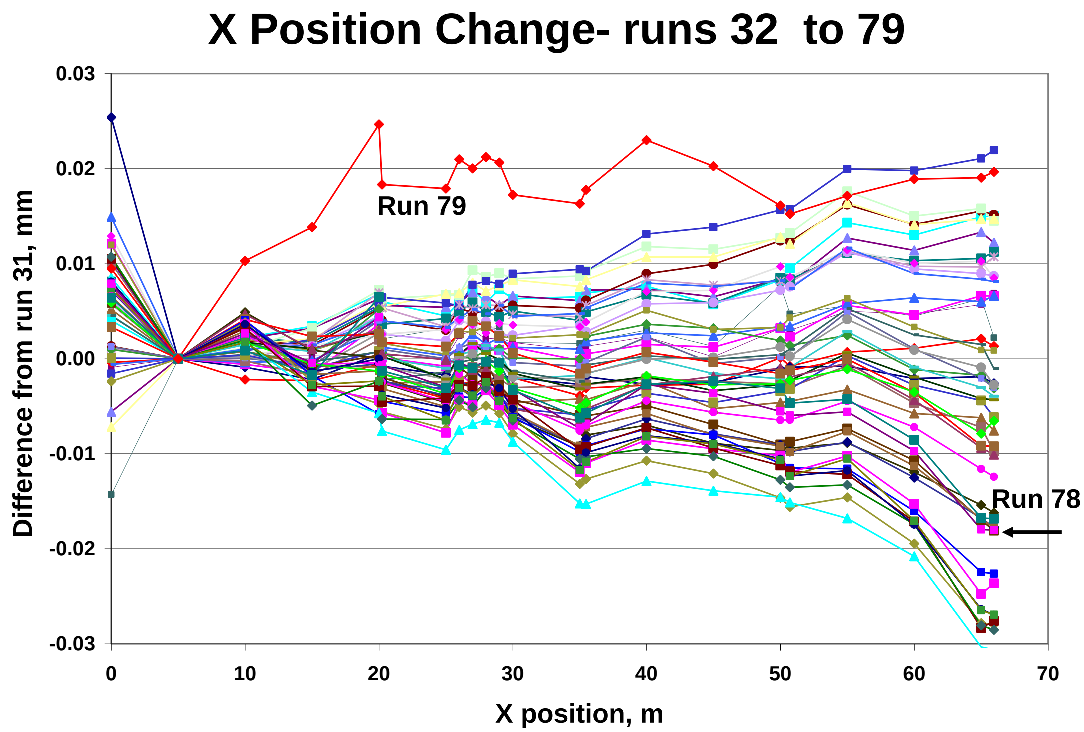

Figure 12. Runs 32 to 79 over 21 days: 9 May 2006 to 30 May 2006

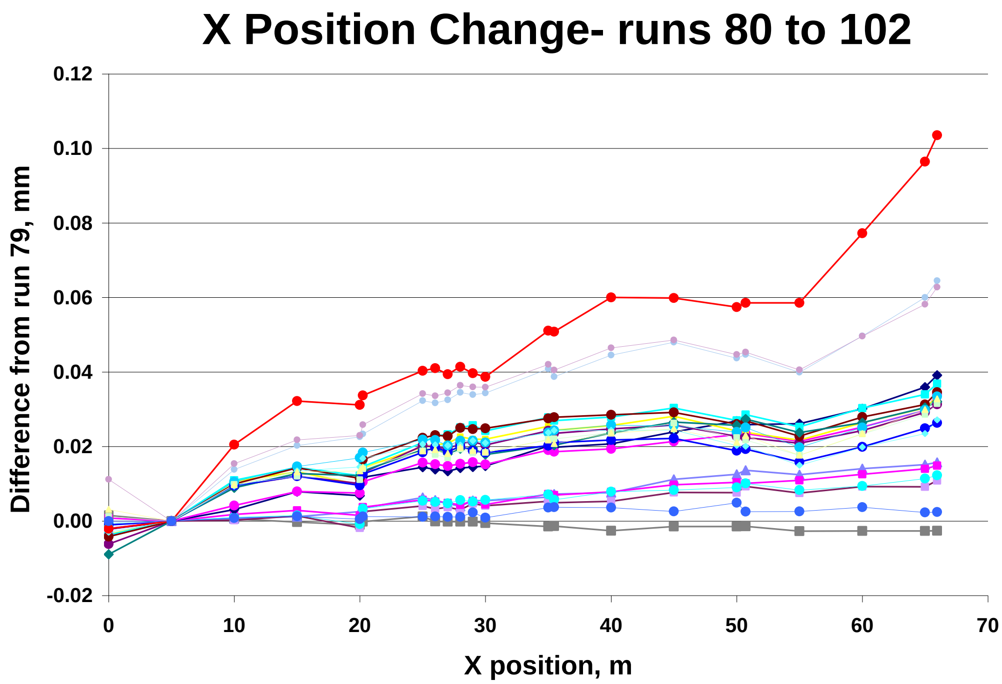

Figure 13. Runs 80 to 102 over 34 days: 30 May 2006 to 3 July 2006.

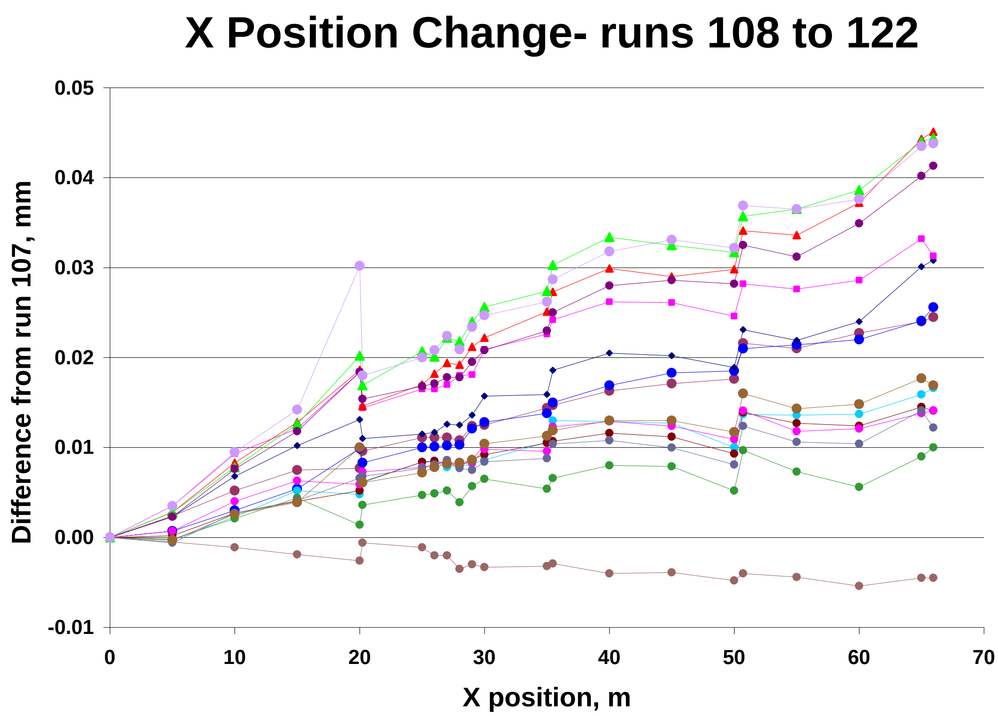

Figure 14. Runs 108 to 122 over 6 days: 26 July 2006 to 1 August 2006.

Figure 15. Runs 123 to 171 over 98 days: 1 August 2006 to 7 November 2006. There is a 64 day gap (24 August to 27 October) between the top group and the lower group of runs.

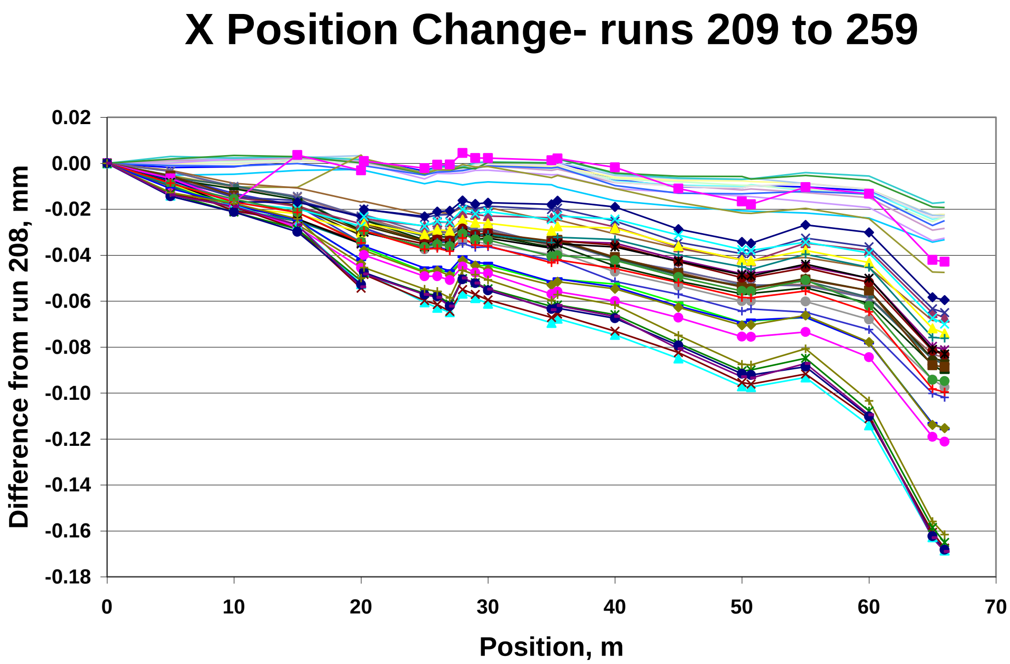

Figure 16. Runs 209 to 259 over 50 days: 13 December 2007 to 1 February 2008.

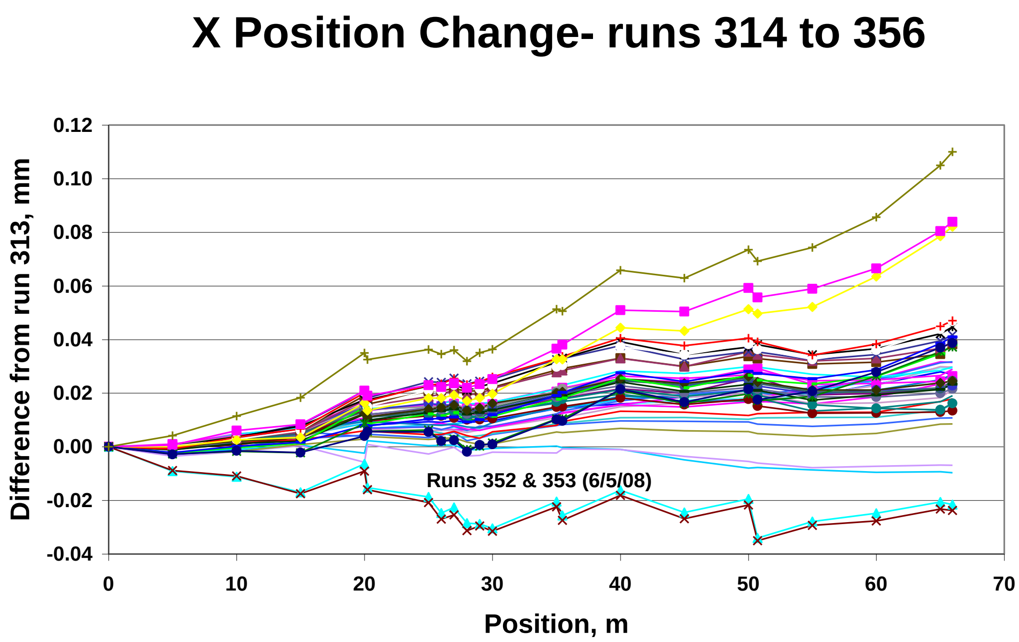

Figure 17. Runs 314 to 356 over 33 days: 7 May 2008 to 9 June 2008.

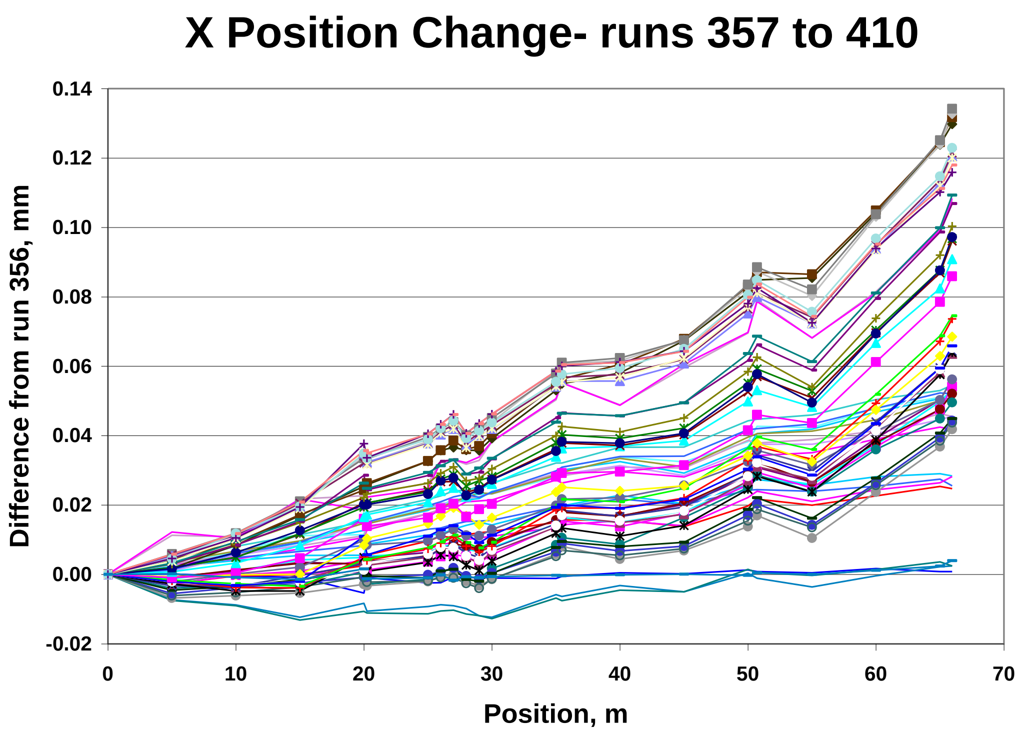

Figure 18. Runs 357 to 410 over 60 days: 9 June 2008 to 8 August 2008.

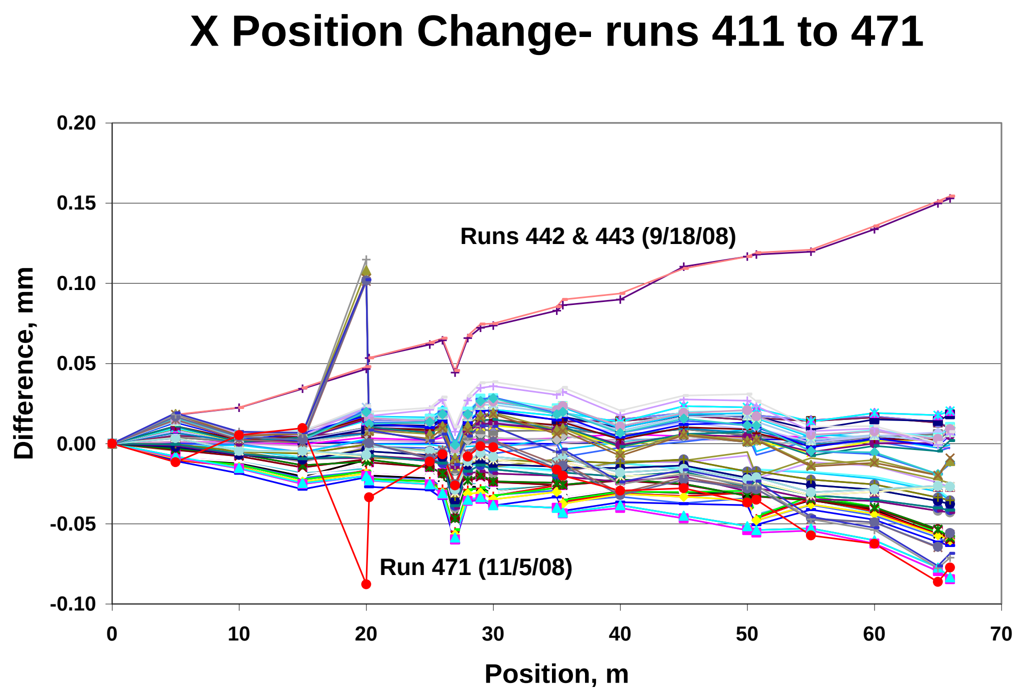

Figure 19. Runs 411 to 471 over 89 days: 8 August 2008 to 5 November 2008.

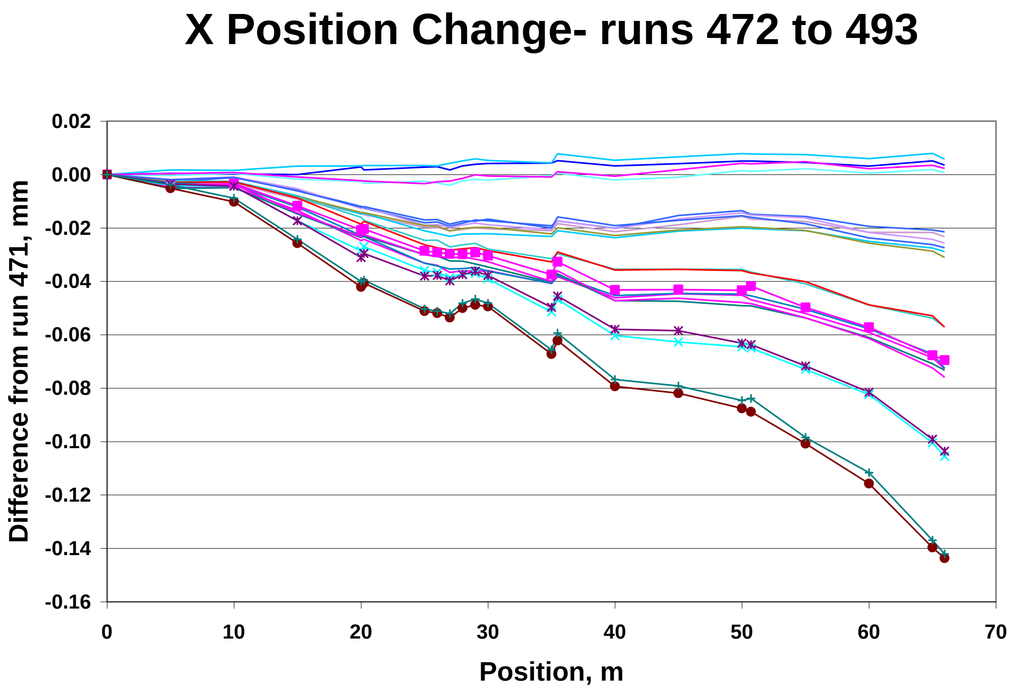

Figure 20. Runs 472 to 493 over 25 days: 11 November 2008 to 1 December 2008.

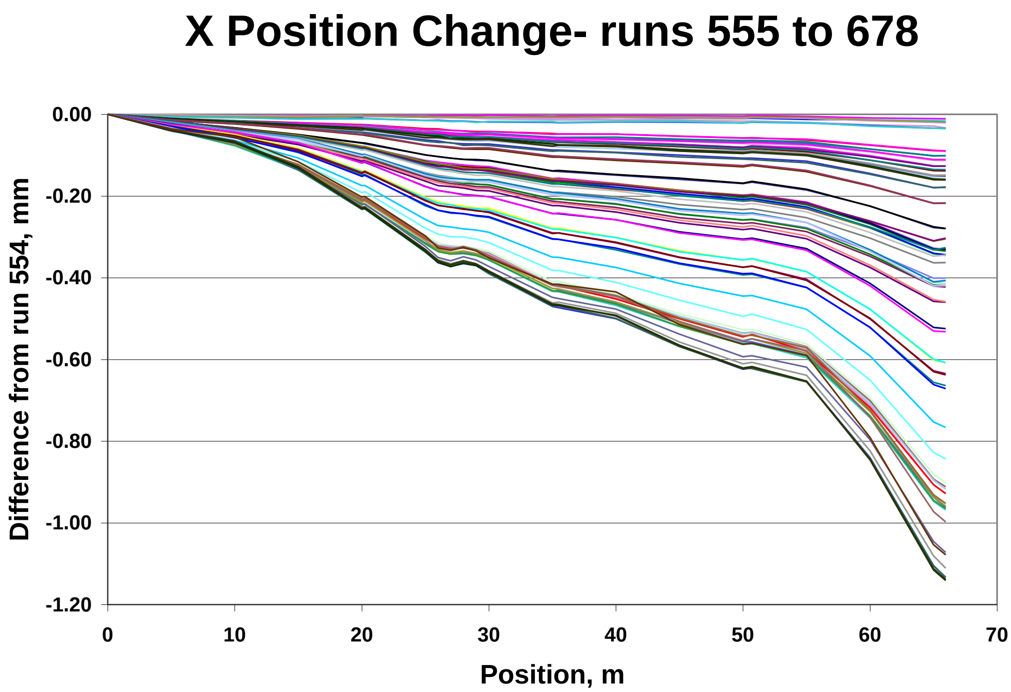

Figure 21. Runs 555 to 678 over 191 days: 21 September 2009 to 31 March 2010

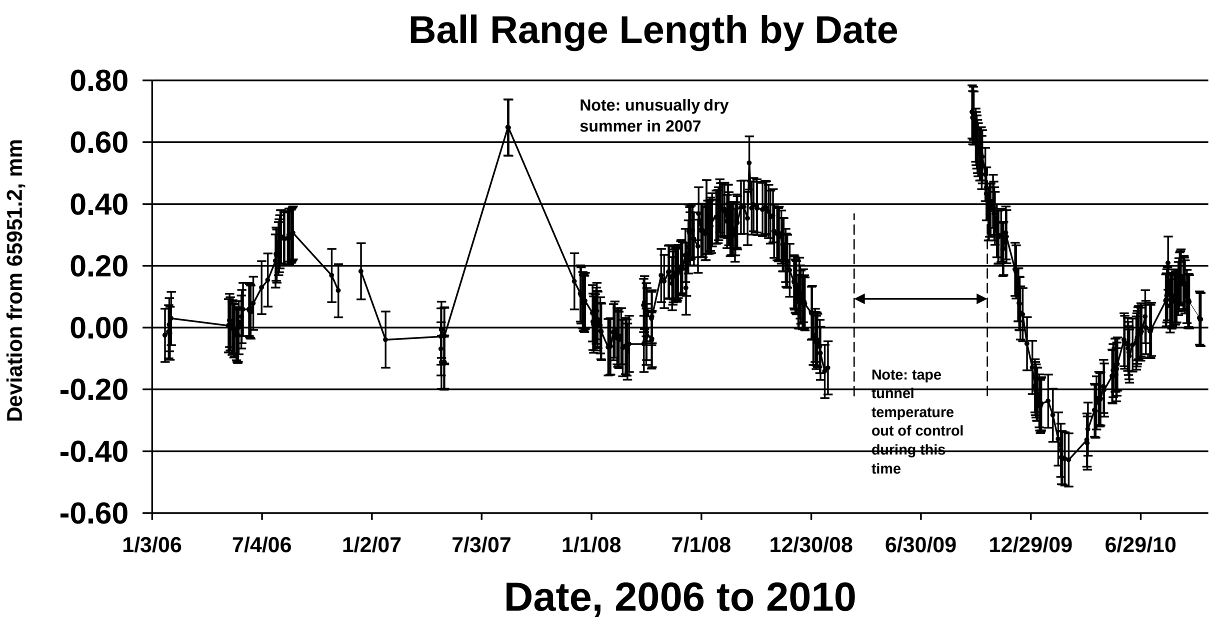

Figure 22. Change in the measured value of the 66 m length from 24 January 2006 to 6 October 2010. Error bars are k = 2 expanded uncertainty.