THE CHESAPEAKE LASER TRACKER IN INDUSTRIAL METROLOGY*

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0. Abstract

In the summer of 1992, the survey and alignment team at the Stanford Linear Accelerator Center acquired a CMS3000 laser tracker manufactured by Chesapeake Laser Systems in Lanham, Maryland. This paper gives a description of the principles of operation and calibration of the tracker. Several applications are explained and the results shared.

1. Introduction

Until recently, the determination of coordinates in industrial metrology applications has usually required two instruments or two set-ups. In the most common triangulation approach, horizontal and vertical angles measured from at least two stations are necessary to determine object coordinates. The polar method which provides sufficient parameters from only one station was rarely used because prior to State-of-the-Art the laser tracker, two different instruments were required to gather the necessary observables, one instrument for angles, the other for distances. Traditional total stations did not meet the accuracy requirements of most industrial metrology applications. Promising solutions were not developed through to a commercial product.[1] The laser tracker is now a high accuracy total station combining horizontal and vertical angle measurements with interferometric distances, thus providing for real-time coordinate determination.

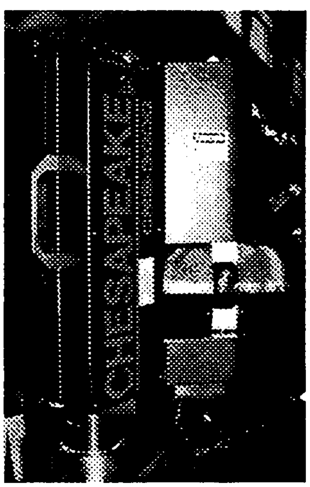

Fig. 1 Laser Tracker CMS-3000

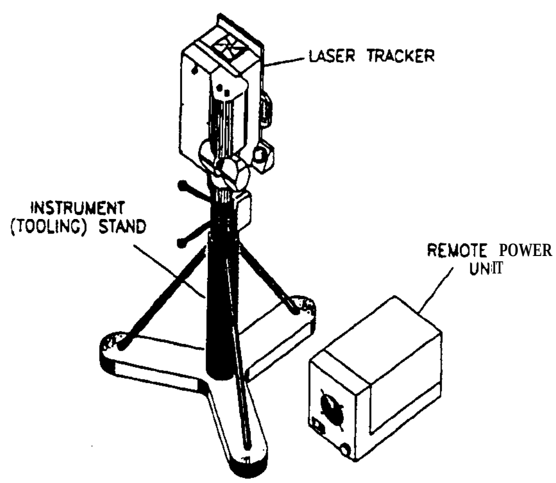

Fig. 2 Schematic of Tracker Set-Up

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The concept of laser trackers goes back to independent studies and efforts undertaken at the National Bureau of Standards (now NIST)[2], at Chesapeake Laser Systems[3], at the University of Surrey, England[4] and at the Fraunhofer Institut für Informations- und Datenverarbeitung [5]. From these studies, two products have evolved: the Leica SMART310 and the Chesapeake CMS3000.

The material below is based on the Chesapeake CMS3000 tracker, but in a general technical sense, it is applicable to the Leica tracker as well.

2. System Description

The Chesapeake Laser Systems (CLS) Coordinate Measurement System CMS-3000 (see Fig. 1) is a servo-controlled tracking laser interferometer measuring tool. The tracker follows a retroreflective target, providing real-time coordinate information of the target center location. A laser interferometer measures the linear distance to the target, and two angular encoders measure the azimuth and elevation angles of the laser beam. This gives the position of the target in spherical coordinates which are converted to Cartesian coordinates by the system computer. The tracker system comprises of 2 major components: the measurement head, and the controller with system software. The remote power unit and several accessories complete the tool list.

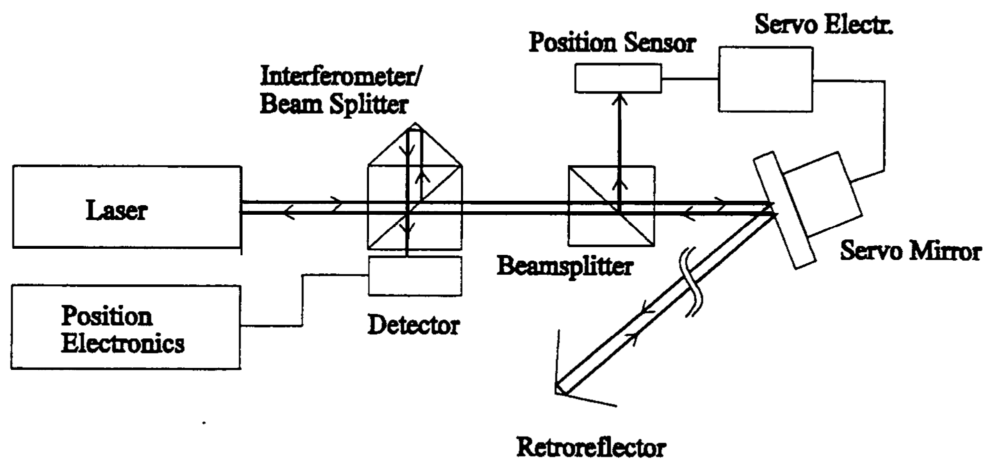

Fig. 3 Schematic of servo-controlled tracking System

2.1 Measurement Head

The measurement head acquires the raw angle and distance information. Like a theodolite, the tracking head provides rotation about two orthogonal axes. Attached to these axes are encoders for angle measurements. Both axes are driven by servo motors. To permit random motion of the target retroreflector, a servo control loop consisting of the tracking mirror and servo system with a position sensing detector is used. For simplicity in this explanation, the term “mirror” is used. However, the CMS-3000 employs a prismatic beam steering scheme which provides significant advantages. Fig. 3 shows the beam path. The laser beam passes straight through the interferometer optics to the servo mirror and hits the retroreflector. After reflection, the beam returns to the servo mirror and from there through a beamsplitter to the interferometer where it merges with the interferometer reference beam. The beamsplitter redirects 15% of the signal to a position sensor. If the laser beam strikes the retroreflector in its center, the reflected beam in a correctly calibrated system will focus on the zero position of the position sensor. Moving the retroreflector causes the reflected beam to move away from the center position. The position sensor measures the new beam position and translates the offsets into steering signals for the servo motors such that the laser beam will strike the retroreflector and consequently the position sensor in the center again. This correction process takes place up to 1000 times per second. The sensor resolution translates into a 1 arc second angular correction resolution at 5m range. The measurement head has a field of view of ±60° vertically and ± 135° horizontally. The mechanical arrangement of the axes permits plunge and reverse measurements without breaking the beam.

The resolution of the angular encoders is 1 arc second. It should be -pointed out that this angular resolution applies not only to the encoders and to the mechanical shafts they are mounted on, but applies directly to the horizontal and vertical angles of the beam itself This is possible because the unique optical design of the prismatic beam steering mechanism assures that the beam rotates in a 1: 1 relationship with both the encoders rather than the 1:2 relationship of a mirror based beam steering.

Option	Resolution [μm]	Velocity [m/sec]
1	5.0	6.0
2	2.5	4.0
3	1.2	2.12
4	0.6	1.06

Table 1: Tracking Speed vs Resolution

The interferometer is of the single beam type. It uses a helium-neon laser with 632 *nm* wavelength. The maximum tracking speed at the highest resolution is 1.06 *m/sec.* The tracking speed is inversely correlated to the resolution (Table 1). Additional optical hardware can extend the resolution to 0.079 μm. The measurement range is 0.17 *m* to 40 *m*.

Mounted to the measurement head is the re-set or home point. The re-set point serves two purposes. Firstly, it provides a known offset distance from the inaccessible effective tracking head axis to an easily accessible reference point. The offset distance is used to set the interferometer's initial distance. Secondly, it provides for a convenient reference point on which to close measurement loops or from where to re-start an interrupted measurement

2.2 Controller with System Software

Data management and tracker control are executed on the same computer. The tracker system operates on a 286 or higher, MS-DOS based computer. One expansion slot is required to mount the proprietary communication interface card. 486 Portables with VGA color screen are preferred choices. TCHost is the standard DOS-based tracker system operating software. The program contains all of the functions required to operate the tracker and to collect data. The user views a screen which shows the x, y, z Cartesian coordinates of the target in real time, and data is saved to a file in response to a function key or remote push button. TCHost allows for the storage and export of data files in standard ASCII format which can be imported into most commercial spreadsheet programs, and in partial DXF format, which can be imported into commercial CAD software packages. The user can add labels and comments to the file during the data collection session for easy future point reference. Any beam interruptions, resets or error flags are automatically written to the file, giving an active history of the data collection session. A typical data file will contain the following information for each point.

Data index,
X, Y, Z Cartesian coordinates in user coordinate system and units,
Azimuth, Elevation angles in user selected units,
Interferometer distances, both absolute and relative in user selected units,
Tracker serial number and system number,
File header name, time and date when opened.

TCHost contains a command language which can be used to program the tracker to perform precise pointing, search patterns, change environmental compensation parameters or display diagnostic data. TCHost is also available as a function library. Based on this library, we have built our own front end running under Windows™. Fig. 4 shows a typical screen during the measurement process.

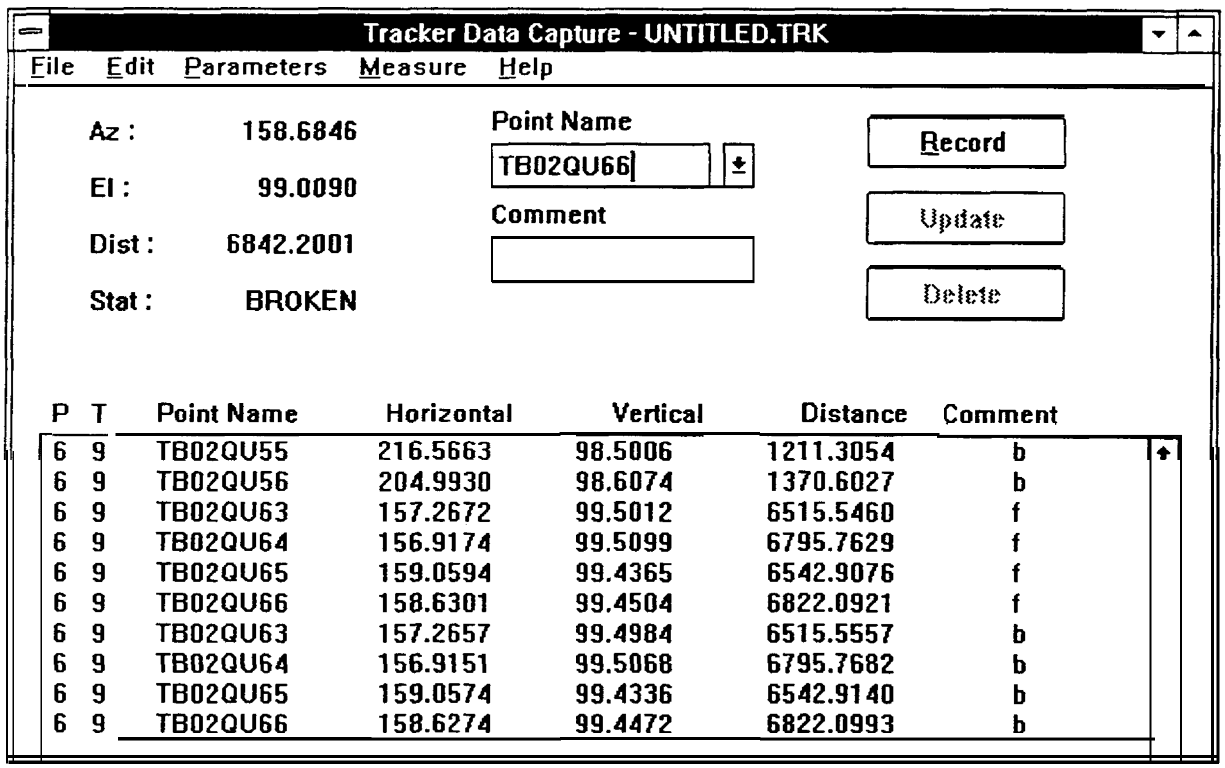

Fig 4 Data capture screen of SLAC control software

2.3 Remote Power Unit

The remote power unit conditions and supplies the required voltages to the tracker. An electronic barometer is built into the power supply housing to provide the barometric pressure information for the calculation of the velocity of light.

front surface again collimates the light. A field of view of 270º can be achieved. Therefore, retrospheres are used where a large angular field of view is required, e.g. if the target cannot be rotated to face the tracker.

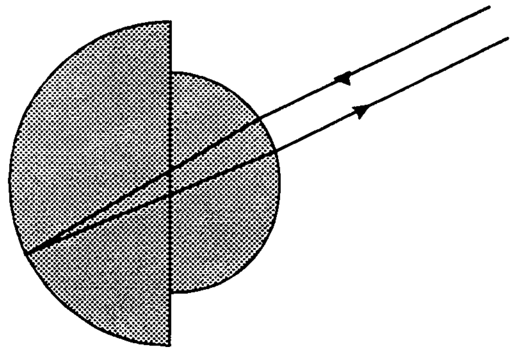

Fig. 7 Cat's Eye Reflector

- Magnetic Mount With Tooling Pin

  The magnetic mount with tooling pin is a magnetic mount as described above which has a shank precisely located in line with the center of the SMR. The shanks are available in different diameters to match the dimensions of tooling balls. This mount is useful for obtaining dimensions of the centers of tooling holes as well as for measurements of edges and bores.

3. The CMS-3000 Calibration Conditions

There are three major categories of residuals in the single beam tracker[6]:

1. Residuals in the measurement of the angular direction of the beam in the air.
2. Residuals in the determination of the center of the target with respect to the centerline of the beam, and of the centerline of the beam with respect to the pivot point of the beam steering mechanism.
3. Residuals in the measurement of the distance along the beam from the pivot point to the target.

3.1 Angular Direction of the Beam

The angular direction of the beam is obtained by reading the two angular encoders. Errors therefore distribute themselves into the following categories:

1, Encoder error: Each encoder has a residual error which is directly measured with a calibration fixture and a traceable angular standard. Reported angular measurements are corrected in the software by means of a lookup table.

2. Coupling error: To the extent that the encoder reading does not represent the actual rotation of the shaft due to compliance, there will be a residual error introduced. The CMS-3000 tracker uses a precision ground shaft which carries both the optics and the encoder disk.

3. Alignment error: The system is designed to place the laser beam coincident with the axis of rotation of the beam steering assembly. This means that an observer attached to the beam steering assembly will see no change in the angle of the beam as the assembly is rotated. To the extent that the beam is not precisely parallel with the rotation axis, the observer will see the beam precess in a conical pattern about its ideal direction as the axis is

2.4 Accessories

Because the servo loop needs to receive part of the reflected beam, a suitable reflector is necessary as target. Two kinds of retroreflector are commonly used:

- Magnetic Mount for SMR

  In order to provide truly forced center position for the SMR in all three coordinate axes, a magnetic centering nest with a three point kinematic mount keeps the center of the SMR in the same accurate position (see Fig. 5). The kinematic mount is realized by either three conically shaped resting pads or by three pins. The position of the SMR in a centering nest is independent of the direction in which it is pointing. Centering errors do not exceed 5 μm.

- Spherically Mounted Retro-Reflector (SMR).

  Three mirrors are mounted orthogonally inside a 1.5” sphere. The standard SMR has a finished sphericity of less than 5 μm rms. Mechanical centering of the assembly is within 10 μm rms. The advantage of this type of mounting arrangement is significant. Since the outside surface is a sphere, there is always a known and constant offset between the actual point being measured (the center of the sphere) and the part surface in contact with the outside of the ball. The SMR field of view is approx. ±20º. Fig. 6 shows a picture of a SMR sitting in a forced centering mount. The total centering error budget using different spheres in the same nest is approx. 12 μm.

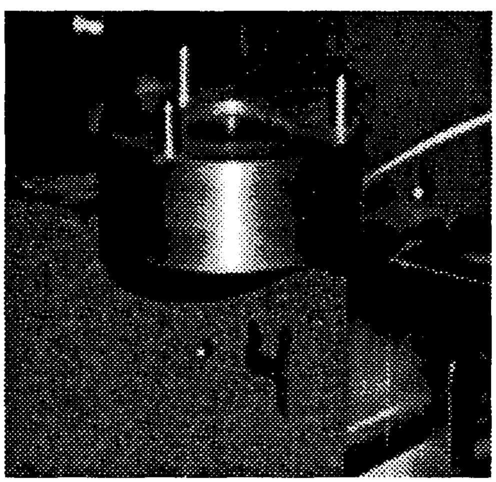

Fig. 5 Mounting Nest

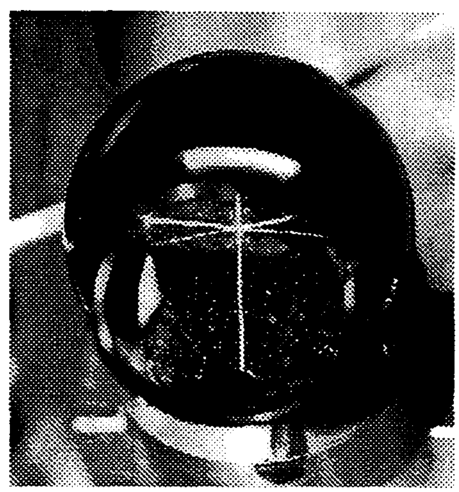

Fig. 6 Sphere Mounted Retrorefector

- Cat’s Eye Retroreflector

  The retroreflector consists of two glass hemispheres (see fig. 7). The bigger hemisphere is silver-coated, the smaller one is coated to minimize reflection. Parallel rays impinge on the front hemispherical surface. The focal length of the front surface accurately equals the distance from the front to the rear surface, causing the beam to converge to a point focus on the rear reflective surface and diverge back to original size as it returns to the front surface. Upon exiting the cat’s eye, the focal length of the rotated. This error can be determined by the simple procedure of plunge and reverse measurements of a series of fixed targets.

4. Mechanical runout: If the bearings on which the beam steering assembly rides are improperly aligned or are of insufficient quality, mechanical runout or bearing wobble will result. The plunge and reverse measurements will reveal if this is a problem, but it can be difficult to compensate for.

3.2 Target and Beam Centering

1. Target centerline: The position of the center of the target is determined by measuring the location of the centroid of the returning beam and comparing it with the ideal location. As the target is moved, there will normally be a small deviation in the center of the returning beam, and it is this deviation which provides a signal for the servo control system to follow the target. When the target is stationary, there will be a small "hunting" error of a few seconds of arc which is random. The actual displacement between- the target centerline and the outgoing beam is measured with a position sensitive photo detector.

2. Beam centerline: Just as a lack of parallelism between the rotation axis of the beam steering assembly and the centerline of the beam results in an angular runout, so does a lack of centering of the beam centerline on the axis of rotation result in a circular runout of the beam position.

3. Target centerpoint location: The precise location of the center point of the target must often be known with respect to the desired point to be measured. This offset can easily be determined for the spherically mounted retroreflector (SMR). Knowing the diameter of the ball, one may compute the location of the target center point with respect to any other mechanical feature of interest.

3.3 Measurements of Range

The laser interferometer is the most accurate component of the laser tracker. Nevertheless, there are still residuals which must be considered in evaluating its accuracy, and these come from environmental sources and from residual alignment errors and mechanical tolerances.

1. Environmental residuals: Since the range measurement is based upon the wavelength of the laser light and the wavelength in air depends upon the temperature and pressure of the air, compensation must be made for these parameters. The tracker contains temperature and barometric air pressure sensors, calibrated against NIST-traceable standards. Internal compensation for refractive index is automatic.

2. Deadpath: Range measurements are scaled by the appropriate factor to compensate for changes in the ambient temperature. A correction must also be applied for the change in the apparent range between the position where the interferometer reads zero and the actual location of the interferometer itself. This additional distance is referred to as the deadpath.

3. Thermal Expansion: Since the reset mount is used as a reference for the interferometer, its location must be precisely known. Thermal expansion of the tracking

unit with changes in the ambient temperature affect this distance to an amount measurable by the interferometer itself. The procedure to determine the reset mount position can be used to measure the actual condition.

4. Path Length Runout: Slight misalignments of the beam with respect to the axis of the beam steering assembly will result in a slightly longer or shorter optical path length as the beam steering assembly is rotated.

5. Coincidence of axes: The horizontal and vertical axes are constrained to intersect at the pivot point. Assembly techniques and subsequent precision measurement assures that this tolerance is held to within a few microns.

6. Location of the reset mount: The tracker mounted reset point is the alternative reference in lieu of the inaccessible true zero point, the intersection of the horizontal and vertical axes. The reset mount location (see fig. 8) may be determined by a simple field procedure.

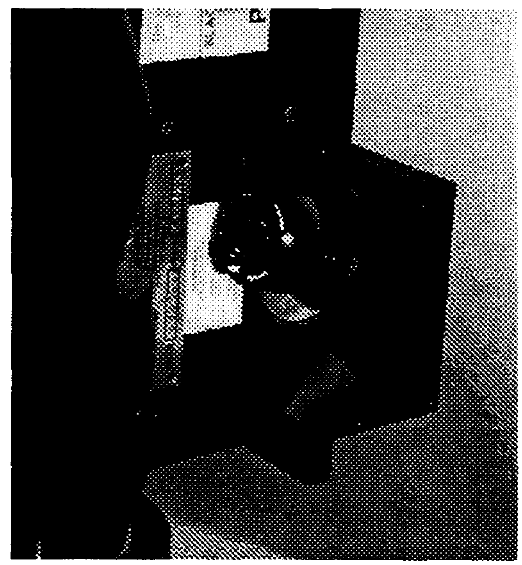

Fig. 8 Tracker Mounted Reset Point

4. The CMS-3000 Self-Calibration Routine

The tracker is designed to minimize all errors due to the geometry of the equipment and the optical alignment. Nevertheless, even the best of mechanical tolerances and most careful alignment procedures will result in angular errors of at least a few seconds of arc and displacement errors of at least several microns over an arc of 180°.

It is necessary to have a method for the determination of the magnitude of these residuals in order to assure confidence that the instrument is measuring accurately. It is also important that the user can utilize simple methods to verify the calibration condition of the instrument. To obtain such verification, a calibration process has been developed that will let the user measure and correct for nearly every systematic error present in the equipment.

The first step in developing the calibration procedure was the definition of a mathematical model describing the beam path. It was found that three groups of four parameters each define the beam path characteristics. The first two groups describe the possible two rotational and translational conditions of the laser beam as it enters the prismatic assembly in both the Azimuth and Elevation plane. The third group describes the collimation condition, i.e. the collinearity of the laser beam axis with the axis of the optical components. Two additional parameters, defining the quad cell centering, complete the mathematical model.

Like a theodolite, plunge and reverse techniques are employed to determine the observables of the calibration verification problem; the CMS-3000 tracker has been designed specifically to permit plunge and reverse techniques for both angular and range measurements without breaking the beam. Five targets in four vertical planes distributed evenly around the horizon are measured in both positions, plunge and reverse. Additionally, every target is also measured with a Sphere Mounted Mirror (SMM); this observation type yields a very accurate collimation measurement. This measurement sequence produces a total of 80 observations, which are then used to solve for the 14 unknown calibration condition parameters.

These 14 parameters, some basic constants, and the interferometer offset value are stored in the tracker configuration file.

Once the calibration parameters are known they can be used to correct the raw observations. Inverting the mathematical model equation yields the correction equation.

5. Coordinate Measurements

Trackers, in their present designs, cannot be used in a forced centered set-up. The basic tracker observables are the azimuth [Az] and elevation [El] angles and the radial distance [d] (see fig. 9). Furthermore, the radial distance in effect is only the radial difference from the previous point (see fig. 10). At the beginning of a measurement set this is the tracker reset position or afterwards the last measured point. The tracker control software takes the raw readings, applies all the required offsets and corrections, and converts the spherical coordinates into Cartesian coordinates in the local tracker coordinate system. It is possible to intercept the corrected spherical parameters. The tracker has been interfaced to our Stanford Industrial Measurement Software (SIMS). This allows us to integrate measurements from different stations into one least squares bundle solution, and also to combine additional theodolite observations, distance measurements, leveling data and hydrostatic height differences into the solution.

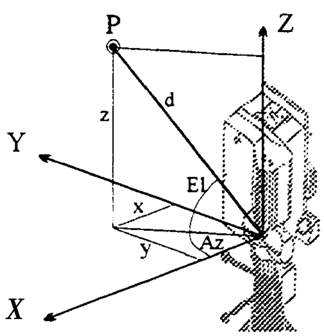

Fig. 9 Tracker Observables

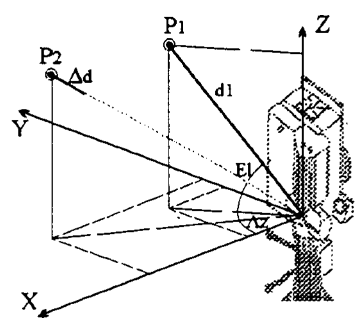

Fig. 10 Radial Distance Measurement Principle

In preparation for a measurement session, the tracker should be set up close to the object in the most appropriate vertical orientation; it does not need to be leveled. For measurements in the micron domain the floor must be absolutely stable. Before starting the measurement sequence, it should be verified that all points can be reached without breaking the beam. If necessary, offset bars should be used. We find that a scale bar should always be integrated into the set-up.

All tracker measurements should be started from the re-set position. This will set the absolute distance and lock the laser beam on to the SMR. Now the SMR is moved to the first object point with the beam tracking. For point measurements the SMR is centered on to a point by e.g. setting it into a magnetic mount. There, it should be carefully pointed towards the tracker. To randomize the SMR internal systematic alignment residuals, the SMR should be rotated around the beam axis without lifting out of the mount in about 4 increments while taking readings in each position. If the laser beam is interrupted, the interferometric fringe count is lost, and measurements must be re-started from the reset point. It is possible to define any object point as reset point.

For dynamic continuous measurements, the data rate needs to be selected and start/stop commands will control the measurement sequence.

6. Measurement Results

The following results have been obtained with a CMS-3000 tracker with was updated to the latest revision in March/April this year. The modifications yielded a significant improvement in measurement accuracy.

6.1 Warm-up Test

After turning the tracker on, it should warm up for at least 120 minutes. Fig. 11 shows the variations in azimuth and elevation caused by thermal changes over a five hour period. Fig. 12 shows the changes in distance of the same run. For very high precision measurements, a warm-up software control routine was developed. It monitors the variation of the tracker observables and determines against pre-set thresholds when thermal stability is achieved.

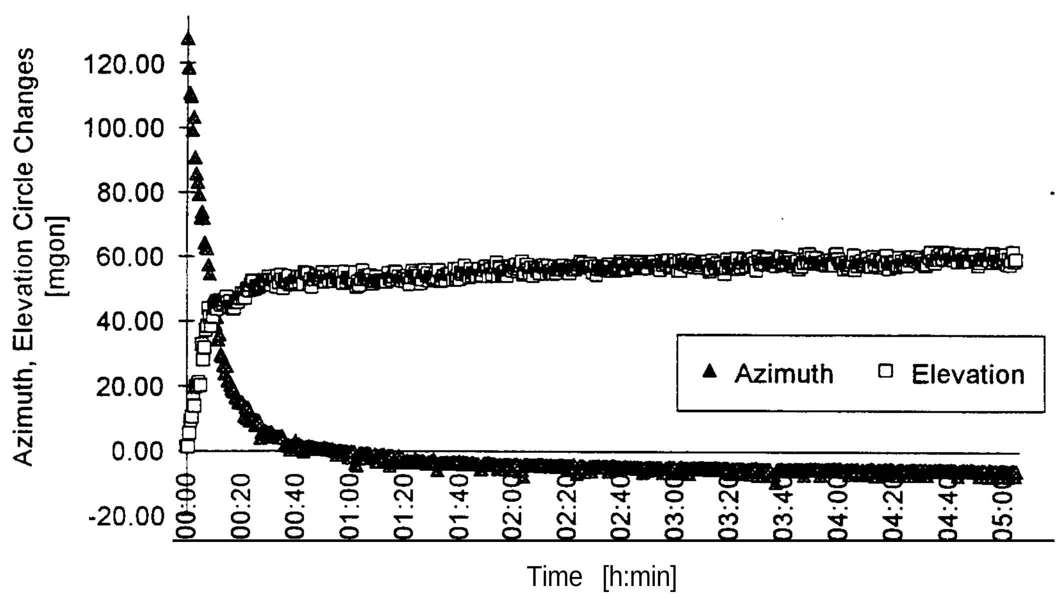

Fig. 11 Azimuth and Elevation Angle Changes during Warm-Up

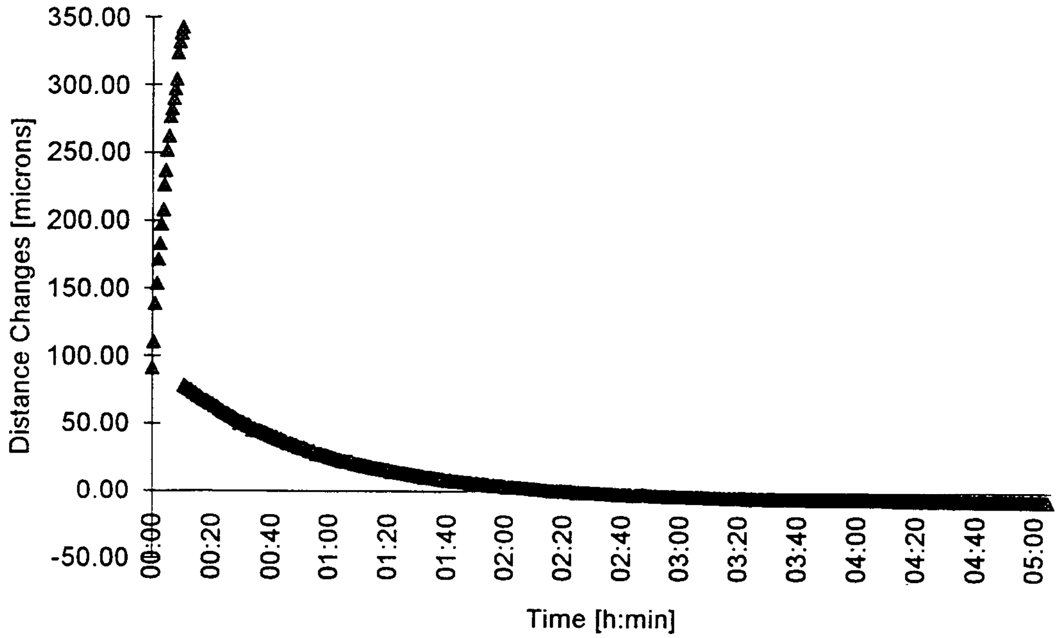

Fig. 12 Distance Changes during Warm-Up

6.2 SMR Centering

The SMR centering budget has three entries: the SMR's internal alignment, the SMR sphere's sphericity, and the centering in the mount. Measurements on a Leitz CMM with a certified accuracy of 0.6 μm were performed to check the sphericity of SMRs. It was found that the sphericity of earlier SMRs was out of specifications. the sphericity along the equator was within 5 μm, whereas the sphericity along the main meridian was distorted by up to 18 μm. However, the latest generation of SMRs has overcome this machining problem; their sphericity variation is less than 3 μm. To distinguish between the internal alignment effect and the centering effect, we first used the CMM again to measure the centering accuracy of the SMR in the mount. The SMR position was determined by probing the coordinates of 10 points on the sphere surface of the SMR and subsequently performing a sphere shape fit through these points. The SMR was removed and re-mounted 20 times. The sphere fits had standard deviations of less than 1 μm. Fig. 13 shows the variations in the sphere's center point coordinates. Then we repeated the removing and re-mounting sequence under the control of the tracker. Fig. 14 shows these results. The standard deviation of the error vector between the true position of the center point to its actual position is 12 μm. From these test we deduct that the internal centering of the SMR is in the order of 10 μm. This is certainly a significant contribution to the overall tracker measurement error budget. It is our hope that the mechanical centering technique can be improved to bring this number into the low μm range. In the meantime, the only remedy available is in trying to randomize this centering error by measuring the same point with the SMR in different rotational orientations.

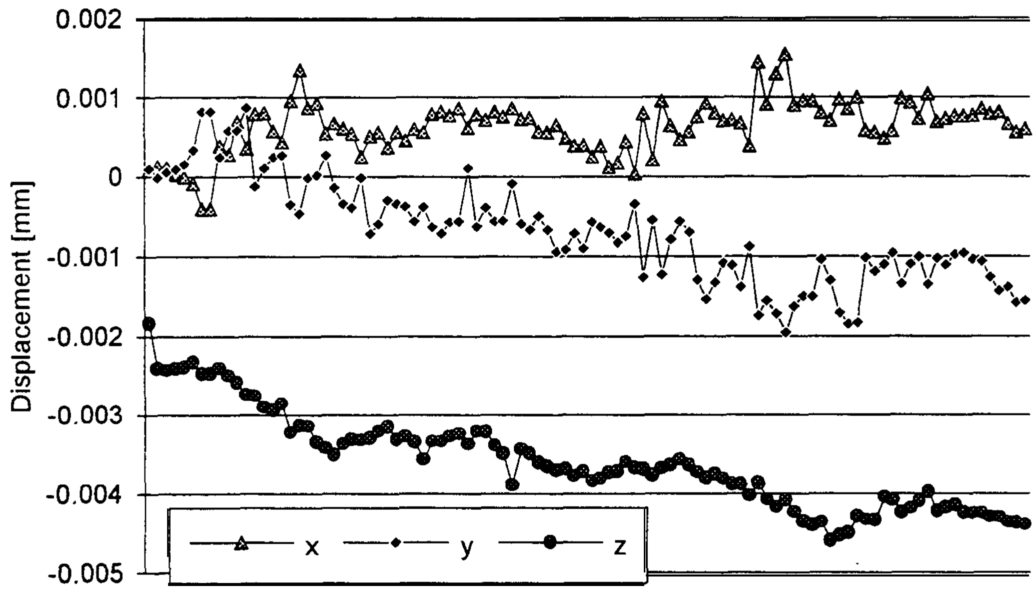

Fig. 13 Sphere Centering Test

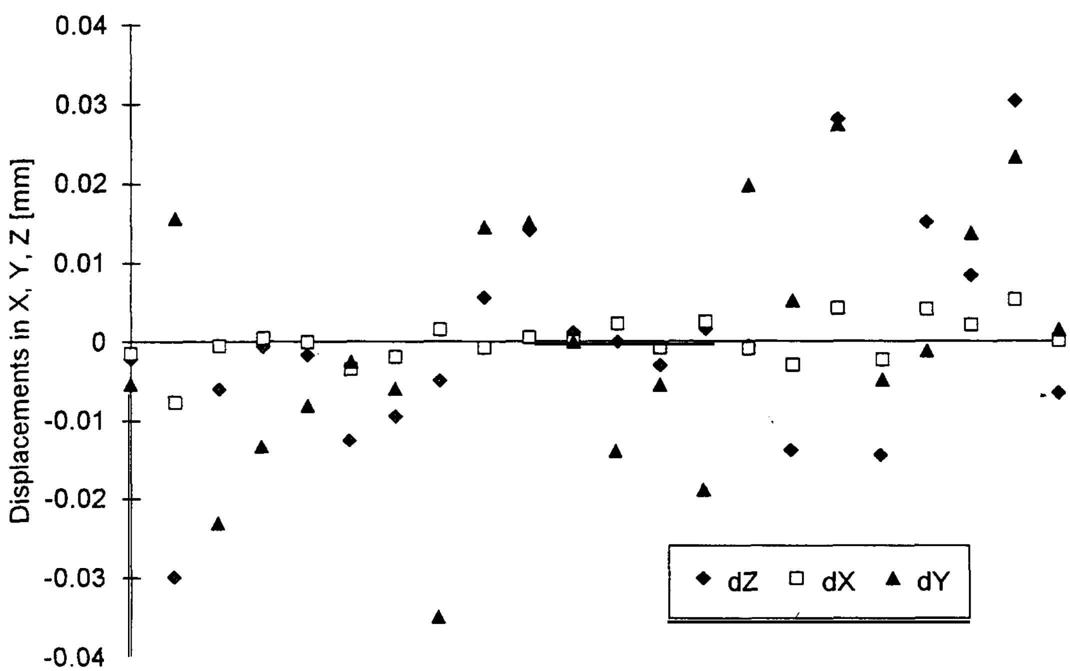

Fig. 14 SMR Centering Test

6.3 Interferometer Test

To check the distance measurement accuracy, tracker measurements were compared against interferometer measurements. In this test the tracker was carefully aligned with the measurement axis of a HP interferometer in order to avoid angular contributions to the distance readings. Fig. 15 shows the results. In summary, a negligible scale factor of 0.35 ppm was observed. It could not be determined whether the scale factor is attributable to the tracker or the interferometer measurements. After removing the scale factor, the measurement comparison carries a standard deviation of 2.5 μm.

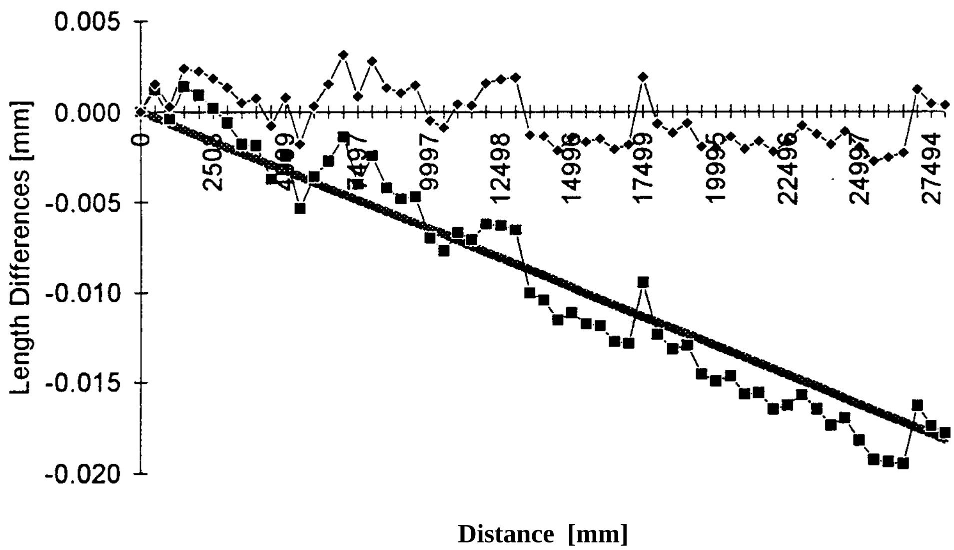

Fig. 15 Tracker versus HP Interferometer Distances

6.4 Single Face versus Two Face Measurement Test

It is well understood that in order to be able to determine horizontal and vertical angles with a theodolite, the horizontal axis/circle has to be horizontal, the vertical axis/circle has to be vertical and the collimation axis has to move within the vertical plane when tilting the telescope. The axes calibration conditions can be checked ‘using procedures based on plunge and reverse measurements. Since the construction principle of the tracker is very similar to that of theodolites, it can be assumed that the plunge and reverse behavior applies as well. To estimate the quality of the axes alignment of the tracker, we observed a test net first in a front face orientation, then in a reverse face orientation. Fig. 16 shows the results. The systematic appearance of the data is due to the arrangement of the measurement points in groups. From the data we can see that there remains a significant difference between the measurements in both faces even with the full data correction enabled. In comparison to the classification of theodolites[7], the tracker axes conditions are equivalent to the standards of high precision theodolites. Consequently, in order to determine accurate coordinates, all measurements should be taken in both faces.

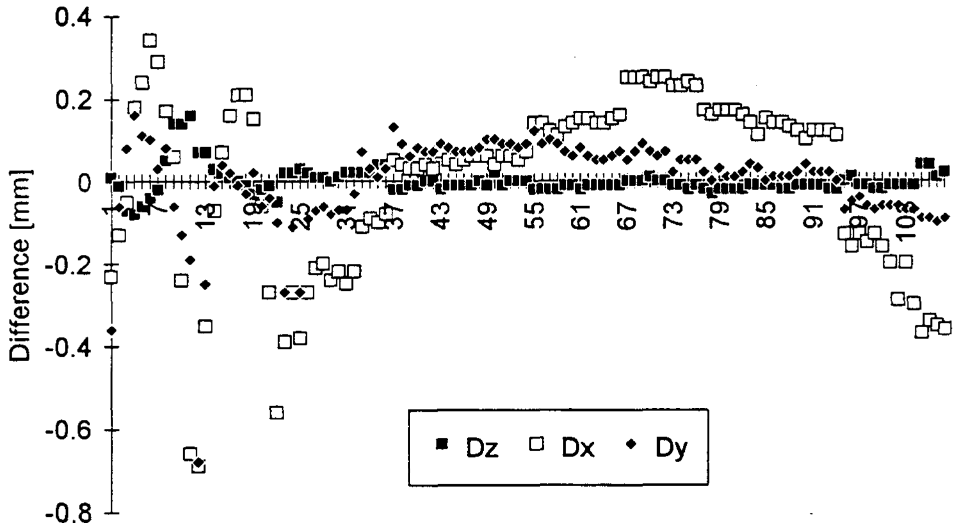

Fig. 16 Differences in Coordinates based on Sightings in Direct or Reverse

6.5 Test Net

The tracker was originally acquired as the necessary tool enabling us to achieve the positioning tolerances demanded by the Final Focus Test Beam (FFTB) project[8]. Consequently, we chose the FFTB as the accuracy test field. The test was conducted in two steps. Test 1 was designed to test the measurement repeatability. Fig. 17 shows the observation geometry. The measurements were repeated three times in exactly the same configuration by the same operators. Direct and Reverse sightings were taken and averaged before introduced into a Bundle Least Squares fit to estimate coordinates. To strengthen the geometry in the vertical plane, leveled height differences were included in the adjustment. All points were observed from at least three set-ups, thus providing ample

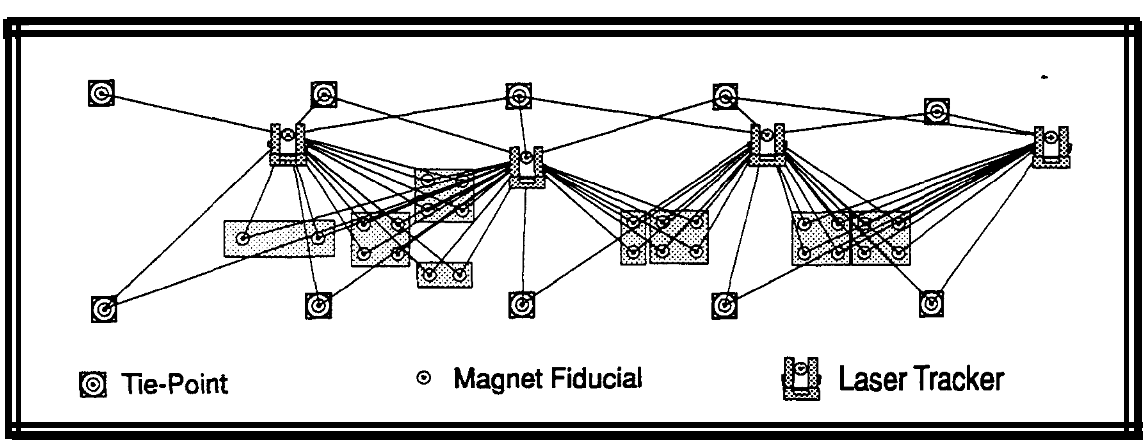

Fig. 17 Repeatability Test Observation Geometry

redundancy. Fig. 18 shows the coordinate differences between the first and the third data set. The histogram in Fig. 19 shows more directly that the majority of the resulting coordinates are less than 20 μm. From this we may deduct that the measurement precision is in the 20 μm range.

Fig. 18 Coordinate Differences between two Surveys with same Geometry

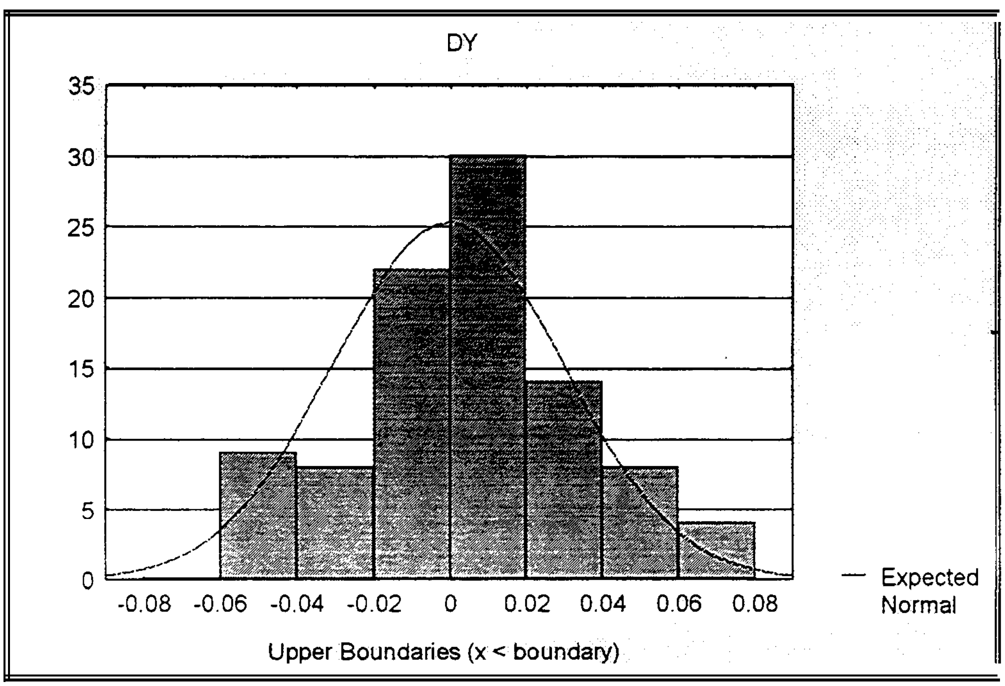

Fig. 19 Histogram of Coordinate Differences

Test 2 was designed to estimate the accuracy of tracker coordinate determination. We repeated the same survey again, but this time using different geometries insofar as possible within the constraints of the beam line housing. Fig. 20 shows the geometry of survey. The difference in geometry ensures that the observations are as much uncorrelated as possible while using the same type of instrument. Also included in this survey are two scale bar readings per set-up, and very accurate hydrostatic level measurements. These two additional independent observables act like an accuracy gauge; the indicator here is the chi-square test normalized over the degree of freedom.

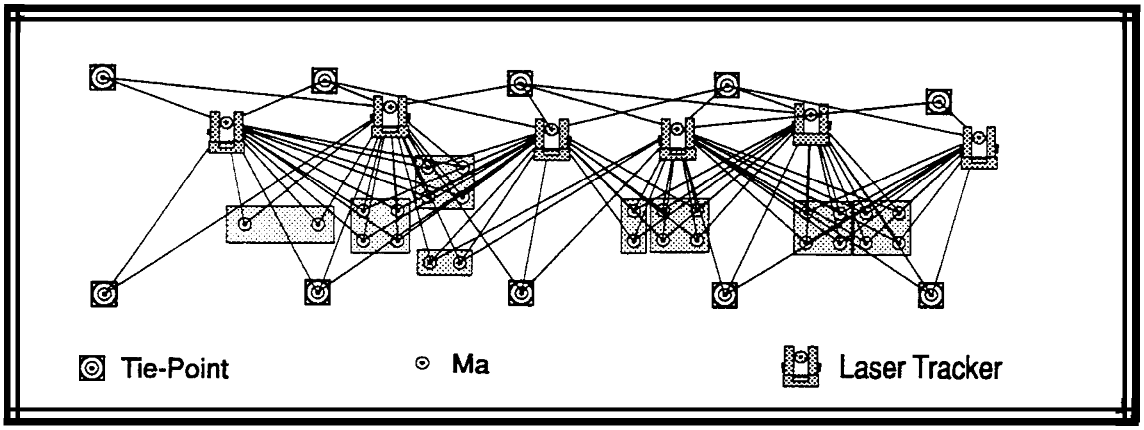

Fig. 20 Geometry Accuracy Test Observations

The bundle adjustment did not show any abnormal results, the normalized chi-square test yielded a value very close to one. Fig. 21 shows a graph of the coordinate differences between the survey 1 of test 1 and this new survey 6. Fig. 22 again shows a histogram Fig.

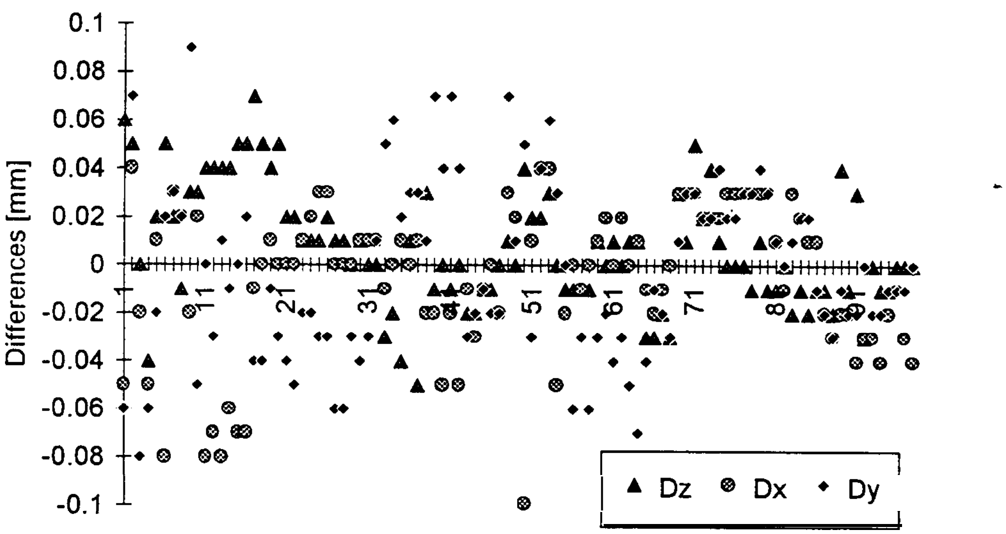

Fig. 21 Coordinate Differences between two Surveys with different Geometry

plot of the coordinate differences and the normal distribution at a 95% probability level. From the histogram we can see that the differences are normally distributed, indicating that the data is not systematically biased. From these results we can deduct that careful laser tracker measurements can yield coordinate accuracies in the 30 μm domain. However, we must note that a considerable number of points may carry offsets three times that amount. If these points cannot be tolerated, the observation plan and geometry has to be changed accordingly.

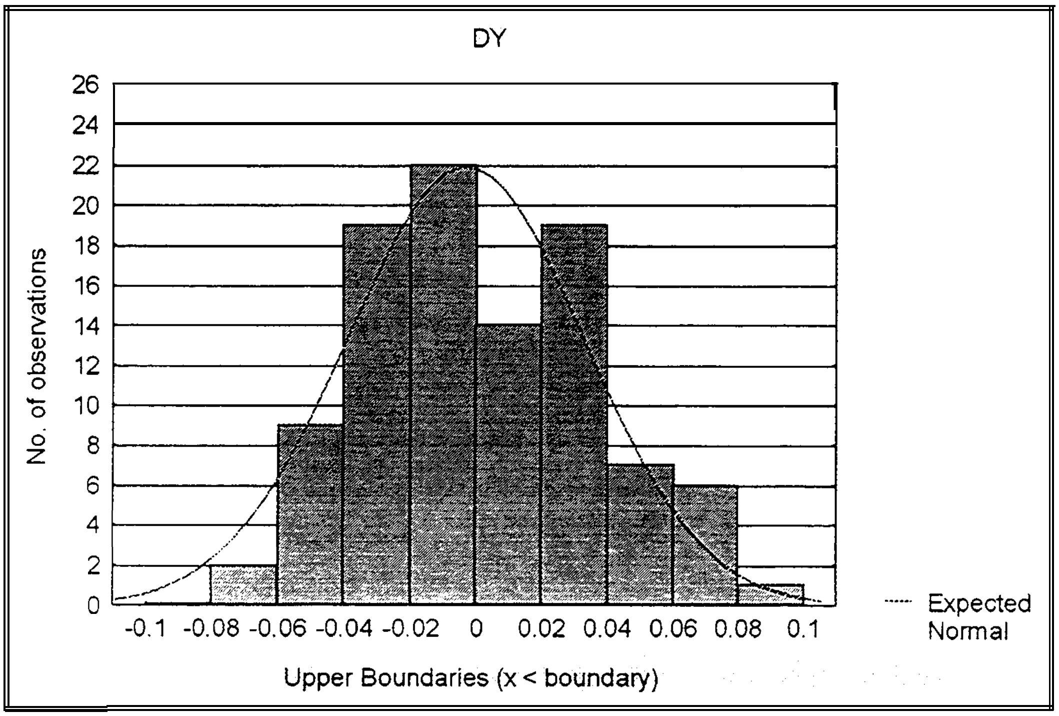

Fig. 22 Histogram of Coordinate Differences with different Geometry

7. Conclusion

The above described tests represent only a small subset of all the tracker surveys which have been performed over the last year at the Stanford Linear Accelerator Center to familiarize our survey staff with this new tool and to qualify itscapabilities. We feel that we now can routinely achieve results in the 100 μm range and with appropriate care and planning perform surveys at the 50 μm level. In this regard, the laser tracker has opened a domain which was in most cases not accessible with theodolite systems. The tracker also brought an increase in productivity. What used to take with a theodolite system two experienced theodolite operators one shift takes with a tracker 75% of a shift for one operator and a helper. However, all of the above does not mean that the theodolite systems have become obsolete. They might not longer be State-of-the-Art, but on the other hand a tracker requires the equivalent investment of two theodolite systems.

The Chesapeake tracker has seen almost constant improvement over the last years. Fortunately, we were able to have our model upgraded to the most recent version. But, as e.g. the plunge and reverse measurements indicate, there is still ample room for further improvements. Axis alignment conditions, thermal stability and weight are very high on our wish list. As a long range goal, I wish to see a substitution of the interferometric distance measurement with a method which can tolerate an interrupted beam.

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[7] In this context, horizontal and vertical do not necessarily refer to the direction of the vertical. Rather, they apply to the orientation of the local coordinate system in which the tracker is set-up.

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