SURVEY AND ALIGNMENT OF SLAC'S B-FACTORY

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Abstract

The survey and alignment of SLAC's B-factory injector and high energy ring will be complete in March 1997. Modern digital electronic surveying tools are contributing to new, efficient alignment procedures. A laser tracker was used to fiducialize almost 300 quadrupole magnets. Digital levels were used to pre-set base plate elevations. Theodolites with very accurate co-axial distance meters were used for everything from layout to 3D magnet positioning to network surveys, all in free stationing mode. A number of procedures and measurement results are outlined.

1 FREE STATIONING

Laser trackers and a new breed of "total station" are designed specifically for industrial metrology. They both combine arc-second angle accuracy with better than 100 micron distance accuracy in a package with co-axial optics. They are, essentially, portable coordinate measuring machines and have changed the face of surveying at SLAC. While the laser tracker's power and versatility is now familiar, most B-factory work was performed with the Leica TC2002 total station. The TC2002 is much more robust and portable, much less expensive, and ideally suited to discrete point measurements.

Total station technology was introduced by HP twenty years ago. The key to metrology application was improvement of distance meter technology. Unlike the laser tracker, which uses interferometry, this class of distance meter emits a modulated infrared signal that is reflected back to the instrument by a retro-reflective target. The differential phase angle between the exiting and returning signals yields a distance equal to a fraction of the modulation wavelength. The additional integer number of wavelengths comprising the distance is then determined by switching to a lower frequency to repeat the measurement. A few years ago the most accurate total station distance meters, after extensive calibration, could approach 1mm. Today, certain Leica total stations achieve 0.1mm right out of the box. Figure 1 shows differences between distances measured with four TC2002s and SLAC's interferometer. Distances from 1 to 30 meters were measured at one-meter intervals. Figure 2 shows a Fourier model of the differences between TC2002 and interferometer distances measured at intervals of 0.1 meter over 6 meters. The model reduced the measurement standard deviation from 73 to 52 microns.[1]

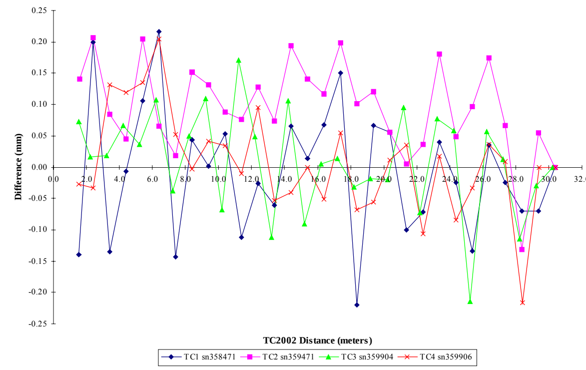

Figure 1 TC2002 vs. Interferometer

The total station allows dramatic changes in routine surveying procedures. Formerly, special forced-centering hardware was erected and centered over floor monuments to receive separate angle and distance measuring instruments. Distance measurements were very slow, many minutes per observation, and differential leveling was required to deliver the third dimension. With the total station, activities ranging from network data collection to bolt pattern layout are conducted in "free stationing" mode. Free stationing means that the instrument is not force-centered over a monument, but located in a general area where all points of interest are visible. Monuments are no longer confined to the floor, but more conveniently located on walls and even ceilings. Monument designs vary, but all are some form of cup made to accept sphere-mounted

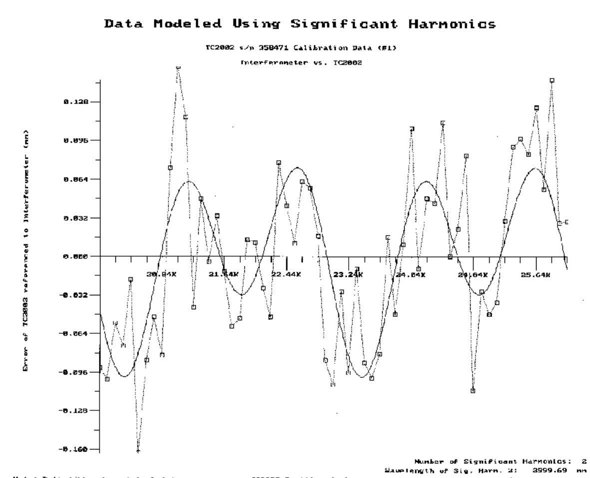

Figure 2 Fourier Cyclic Error Model

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targets(SMT) and retro-reflectors(SMR). Trackers and total stations both use commercially available 1.5 inch sphere targeting. The reference point is the center of the sphere in the monument. A much denser monument pattern can be installed since distances require only a few seconds each and measurements are taken in 3D. The instrument measures 3D vectors, horizontal angle, vertical angle, and distance, from its center of optics to each point of interest. For network or mapping surveys, the measurements are simply stored on the data collector for processing in the office. For alignment work, the surveyor first takes observations to several monuments, a data collector program solves for the instrument position and orientation, then component positioning proceeds.

2 HER QUAD FIDUCIALIZATION

The fiducialization measurements were performed with SLAC's CMS 3000 laser tracker. The liabilities of the tracker's 80-pound weight, large power supply, bulky cabling, and delicate nature are mitigated when it can be set up in a laboratory environment for gross data collection. An area in the magnet warehouse was cleared so that the tracker could be rolled on its stand all the way around the magnets. Monuments were installed in the floor around the perimeter of the cleared space. Six fiducial bushings were welded onto each magnet, four on the top and two on the aisle side, to accept removable magnetic mounts for 1.5 inch sphere targeting. The magnet engineer designed a one-meter-long mandrel that registered on two pole tips, projected through the magnet, and held a magnetic sphere mount on axis on each end.

The magnets were measured six at a time. They were arranged in a line, in three groups of two to facilitate mandrel handling, as shown in Figure 3. The tracker was situated adjacent to the first pair, on the "aisle" side, and measurements were recorded to all floor monuments, the fiducials and exposed lamination edges on magnets 1 and 2, and the mandrel in magnets 1and 2 in four different positions each. With bungy cords and shims the mandrel was forced into contact with each pair of pole tips for four different positions. In turn, the tracker was moved into position next to the aisle side of each magnet pair and then measurements were taken to the monuments, fiducials, and the mandrel positions. Then the tracker was rolled to the "wall" side and another data set was recorded next to each magnet pair. One surveyor in one shift measured this large, six-magnet data set. On the swing shift, another six magnets were moved into position to be measured the next day.

The day's measurements were processed in one big adjustment. The common monument observations made for a very redundant, geometrically strong network. The resulting coordinates were parsed into individual magnet data sets for further processing. Each magnet data set was used to generate magnet-centered fiducial coordinates. The beamline axis was defined by the axis of a best-fit cylinder through the mandrel coordinates, magnet center by the average of magnet end positions, and remaining coordinate axis orientation by a best-fit plane through lamination edge coordinates.

Figure 3 Six magnets ganged for fiducialization

3 TOTAL STATION WORK

To do alignment work with the total station, whether bolt pattern marking or component positioning, the surveyor arrives on scene with the instrument and a data collector loaded with surveyed monument coordinates and component ideal coordinates.[2] The instrument is set up on a portable tripod where several monuments and the area to be worked are visible. The monument positions are considered known and are used to solve for the instrument position. Distances and angles are measured to a number of monuments, some upstream and some downstream. While two monuments would give a unique solution for the instrument position, it is good practice to observe four or five monuments. This is enough data to identify possible problems with the monument coordinates and provide a redundant solution. SLAC's software displays measurement residuals and calculated standard deviations to help evaluate the quality of the solution. With a good solution in hand, alignment begins.

3.1 Layout and Stand Alignment

Some simple custom hardware facilitates layout and stand alignment. A layout block is a piece of steel 3 by 5 by 1 inches with a through-hole in its center. Pressed flush into one end of the hole is a drill bushing, while the other end is beveled to form a cup for the 1.5 inch SMR. The floor is marked by removing the SMR and inserting a center punch sized for the bushing. For stand alignment, special magnetic SMR cups were built to occupy critical component/stand interface positions. The surveyor enters the point name in the data collector and the position of the SMR in the block or cup is observed with the total station. For low precision work, it is adequate to aim the instrument at the apparent SMR apex and record a single measurement. The software computes a position and returns the difference between the observed and ideal positions. The difference cab be displayed in the beamfollowing coordinate system or in a system oriented to the line between the point and the instrument. The block or stand is moved toward the ideal position, perhaps aided by a pocket tape, and another observation is made. This process is repeated until the difference between observed and ideal is within tolerance, typically 1 or 2mm. If doing layout, the SMR is removed, and the center punch is inserted to mark the point. For stand alignment, there may be several points to check to verify stand orientation and special spirit levels can be very handy as well.

The HER quad raft installation required a second layout step. The hole patterns were drilled, the threaded anchor studs and steel mounting plates were installed, the surveyors leveled the plates, and the plates were grouted. The second layout was for mating pins in the mounting plates. The same procedure was used, but with a 0.5mm tolerance. After the surveyors punch-marked the steel plates the ironworkers followed with a magnetic base drill to make the mating holes. The mating pins controlled a quad raft's position and orientation. Table 1 displays how effective this scheme proved to be. The left side shows the surveyed positions of quads in region five before alignment. The residuals represent the sum of errors resulting from mating hole marking and drilling, and quad raft assembly.

Quad	DZmm	DXmm	Dymm	DXmm	DYmm
1	-0.15	-0.31	-0.29	-0.03	-0.12
2	-0.40	-0.27	-0.03	0.01	0.06
3	-0.18	-0.52	-0.36	0.10	0.14
4	-0.45	-0.47	-0.02	0.10	0.01
5	-0.19	-0.62	-0.11	0.04	0.04
6	-0.01	-0.38	-0.73	-0.39	0.20
7	-0.99	-0.37	-0.13	-0.18	0.13
8	-1.01	-0.36	-0.43	-0.10	-0.04
9	-0.43	-0.55	0.13	-0.22	0.11
10	-0.10	-0.65	-0.12	-0.23	-0.02
11	-0.62	-1.07	-0.37	0.07	-0.15
12	-0.79	-0.35	-0.23	-0.10	0.04
13	-0.61	-0.37	-0.18	0.02	0.03
14	-0.31	-0.53	-0.21	0.19	-0.13
15	-0.15	-0.19	-0.01	0.11	0.08
16	-0.78	-0.68	-0.04	0.07	0.20
17	-0.33	-0.99	-0.15	0.13	0.08
18	-0.47	0.07	-0.77	0.10	0.11
19				0.09	0.07
20	-1.06	-0.62	-0.06	0.24	-0.04
21				0.19	0.08
22	-0.21	0.05	0.37	-0.01	0.01
23	-1.07	-0.51	0.30	0.04	0.00
24	-0.94	-0.28	-0.13	-0.01	0.02
25	-0.62	-0.16	-0.02	0.02	0.02
26	-0.79	-0.38	-0.04	0.03	0.01
27	-0.33	-0.02	0.41	-0.14	-0.10
28	-0.25	-0.52	0.48	-0.07	-0.01
29	-1.34	0.00	0.25	-0.03	-0.01
30	-0.16	-0.16	0.09	0.07	-0.08
31				0.05	-0.01
32				-0.06	0.06
std. dev.=	0.36	0.28	0.30	0.13	0.09

Table 1 Region 5 Residuals Before and After First Alignment

3.2 Magnet Alignment

At a glance, the magnet alignment procedure looks the same as that for layout or stands. The tighter tolerances dictate a few refinements, however. First, the single set of monument observations is replaced by two or three sets to better determine the optical center. This yields benefits not only statistically, but also mechanically by compensating for instrumental errors. Second, it is more accurate to aim at a separate sphere-mounted SMT and then switch to the SMR for distance measurement. Finally, the light hardwood tripod is replaced by a heavy optical tooling-style stand, which is rolled from place to place.

Magnet fiducial observations started with single pointings to SMRs; no sense looking for microns until the millimeters were worked out. In the HER, the surveyors shot the four top fiducials first to get a look at magnet orientation. They adjusted pitch and roll to zero to de-couple orientation and translation, then worked Z, Y, and X struts to bring the magnet into position. Typically, this took several iterations of survey and alignment. The SMT and reverse pointings were not brought into play until the magnet was very close to its ideal position, say 100 to 200 microns.

After all HER quads were aligned, the tracker was used to map the quads and BPMs. This was another great application for the tracker; gross data collection in a protected environment where it could be rolled from magnet to magnet all around the ring. The right side of Table 1 shows results of that map. The residuals are from a smooth curve fit through the differences between surveyed and ideal magnet centers.[3] They represent the sum of errors from the monument network and the total station measurement procedure.

4 ACKNOWLEDGEMENTS

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