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DATUM DEFINITION PROBLEMS IN ACCELERATOR ALIGNMENT*

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-ABSTRACT

Any measurement task requires a fixed reference base (the datum°) from which measurements can be made and calculated. The linac was the datum to which all SLC components were aligned; although this reference existed as a physical object, the actual establishment of the datum and its transferral to datums that were more useful for the SLC installation challenged the technology and computational ability of the survey group. Once established, the maintenance of datums is not to be taken for granted, as demonstrated by the 1989 earthquake which destroyed all SLAC's survey datums.

1. INTRODUCTION

The Stanford Linear Accelerator Center (SLAC) is a research laboratory for high-energy physics funded by the Department of Energy and operated by Stanford University. The mainstay of SLAC is the two-mile-long linear accelerator (linac), constructed in the mid-1960s. In 1984 construction commenced on a new type of particle collider, the Stanford Linear Collider (SLC).[1] The SLC, which is entirely underground, consists of two semicircular arcs (each 1400 m in length) joined to the end of the linac (Fig. 1).

Bunches of electrons and positrons are accelerated down the linac and injected into the arcs: the electrons into the North Arc and the positrons into the South Arc. Approximately 460 eight-foot magnets in each arc steer the particle beams through to the Final Focus System (FFS) where they are prepared for their final collision. The north and south FFS regions are each about 200 m long and contain dozens of elements to focus, steer, monitor, and massage the beams. The beams enter with a cross section of 0.1 mm and emerge into the collision point focused to 4 μm.

The alignment of the SLC presented many challenges to the survey group which was set up specifically for the task.[2] This paper presents some of the problems and the solutions developed to cope with them, especially as they concern survey datums.

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o A survey or geodetic datum [plural datums] is a point or set of points used as a reference for the calculation of other points.

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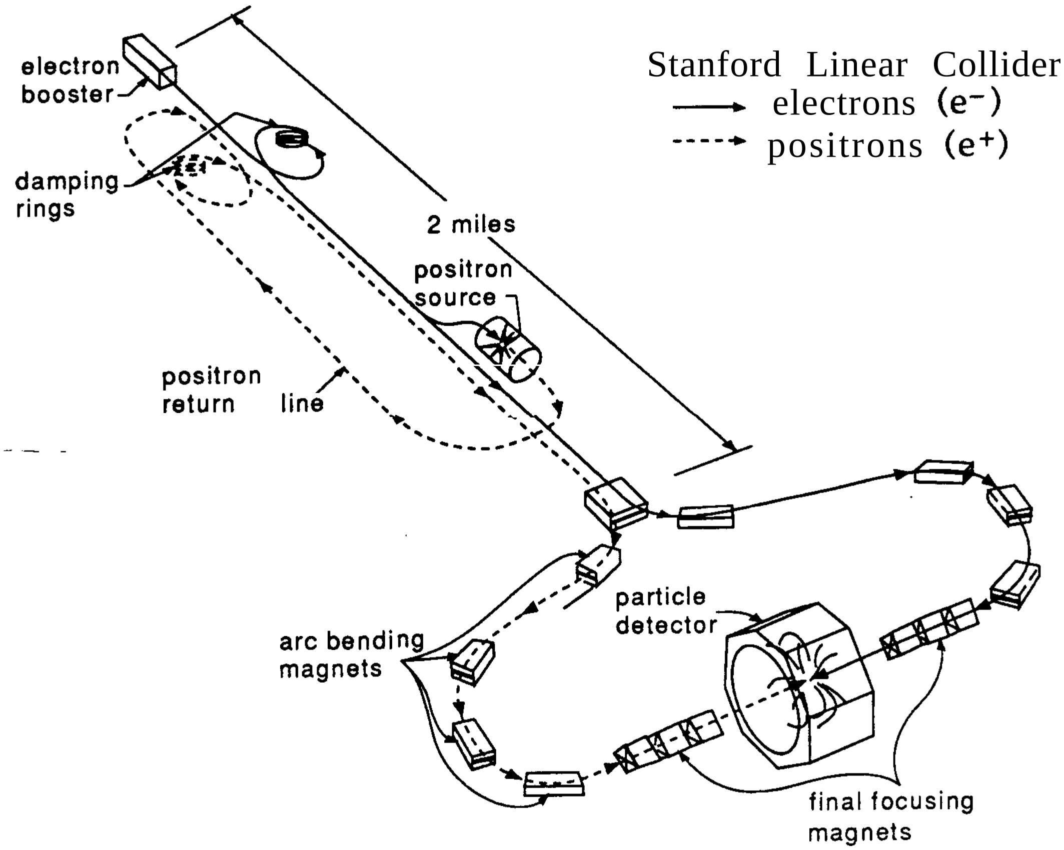

Fig. 1. The Stanford Linear Collider.

2. ALIGNMENT OF THE SLC ARCS

2.1 Alignment Tolerances

The beamline of the SLC was designed by physicists using a computer simulation package.[3] The output given to the surveyors includes x,y,z coordinates for each component in the beamline plus tolerances on absolute and relative alignment. The tolerances include the following[4] :

(a) the length of each arc relative to its theoretical length is 15 mm;

(b) the absolute location of each magnet with respect to its theoretical position is 5 mm;

(c) the relative alignment of adjacent magnets is 0.1 mm in vertical and transverse alignment, 0.5 mm in longitudinal alignment; and 40 μrad angular alignment in yaw and pitch.

Both the absolute and the relative alignment tolerances of the SLC arcs are very tight. Since an error analysis showed that it would be impossible to obtain the required accuracy from a tunnel traverse alone, a hierarchy of networks was established beginning with a first-order geodetic network on the surface and ending with a local survey of each magnet in the tunnel.

Two decisions were made concerning the philosophy of measurement:

(1) There was a strict division between survey and alignment: all elements were surveyed to determine their actual location; comparison with ideal coordinates provided the offsets used in the alignment process.

(2) The horizontal and vertical nets were kept separate both in measurement and in computation. The vertical network was measured using conventional high-order spirit leveling above and below ground. The horizontal survey consisted of the following hierarchy: primary and secondary surface nets, a tunnel traverse, and a magnet survey.

2.2 A Hierarchy of Networks

Primary Surface Net

The primary network contains 16 stations, 13 around the SLC and three along the linac (Fig. 2).

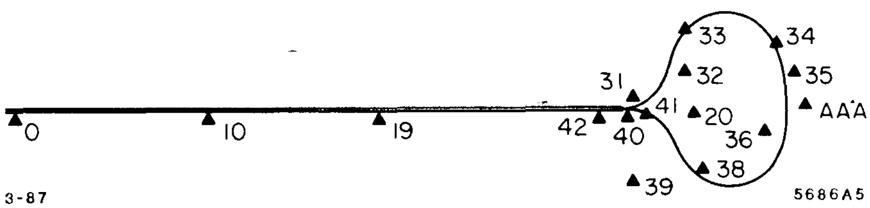

Fig. 2. The primary geodetic network for the SLC.

The stations of the primary net are all permanent double-walled monuments, with the exception of one tower on a hill in the center of the site (20) and three towers along the linac (0,10,19). The network was measured at night with E2 theodolites and a DM503 distance meter, the latter specially selected for a performance twice as good as Kern's specifications. The SLC portion of the network has a strong geometry, but the connection to the linac is poor since the three linac stations can be seen from only two SLC stations (20 and 42). In order to provide the correct launch angle, the alignment of the SLC arcs to the linac is critical, with a tolerance of 30 μrad. Since it would have been difficult for conventional survey methods to provide a sufficiently tight join between the linac and the SLC, a GPS measurement campaign was undertaken.[5] Nine stations were measured and the results used to orient the SLC network onto the linac. A comparison with the terrestrial measurements showed an agreement of 1.5 ppm.

Secondary Surface Net

Spaced approximately every 200 m along each arc is a penetration, a 1 m shaft from the surface to the tunnel; there are eight penetrations in each arc. For the secondary surface net, towers were set up over the penetrations and a point plumbed directly above a monument in the tunnel floor beneath. Measurements were again made with the E2 and the DM503, but the method of adjustment was different. The network was computed as a "connected net" with the monuments allowed to float a little so as not to distort the network. The monuments were weighted using error information taken from the variance/covariance matrix of the primary network.

Tunnel Traverse

The next level in the hierarchy of survey control is a tunnel traverse between the penetration stations, which are not intervisible; a control point is placed every 13 m, the spacing chosen after network analysis. These points are monumented by permanent targets in the floor over which tripods are mounted. Unfortunately the tunnel is not wide enough to allow these tripods to be left permanently in position, but the centering error is kept low through the use of well-designed translation stages and high-accuracy Wild optical plummets. The traverse was measured with E2 theodolites and with the Distinvar, an instrument that uses invar wires of predetermined length.

Magnet Survey

It was intended that the alignment of the magnets themselves follow a three-step procedure, using the traverse points as fixed control points in each step.

(1) In Step 1 the support pedestals were aligned using a pair of E2 theodolites equipped with lasers.[6] The pedestals were moved until the laser beams intersected on a target atop the pedestal. The aim was to achieve an alignment accuracy of 3 mm, but subsequent surveys showed that 1 mm was achieved for most pedestals. After alignment the pedestals were grouted to the floor.

(2) In Step 2 the s-y adjustment table atop the pedestal was aligned to 0.3 mm.

(3) After the magnets were placed in position on the adjustment tables, it was intended that Step 3 provide the final alignment of the magnets, both their relative and their absolute alignment. In practice it was found that two iterations of survey followed by alignment were necessary to obtain an accuracy of 0.3 mm.

2.3 Problems and Their Resolution

Two major problems concerning datums were encountered in this complicated measurement process: scale and relative alignment.

Scale Problems

The surface network featured long legs with an instrument of relatively low accuracy (l-2 mm for the DM503) and good geometry, whereas the tunnel network featured many short legs (13 and 26 m) with an instrument of relatively high accuracy (60-70 μm for the Distinvar) and the very poor geometry of a long thin network through which errors quickly propagate. Measurement conditions on the surface were ideal with all observations made at night, whereas conditions in the tunnel were much inferior with probable refraction problems due to temperature gradients, lines of sight passing close to walls, and ventilation. Furthermore the Distinvar pulls a tension of 15 kg on the wire, which certainly causes deflection in the tripods; a small error in the estimate of this deflection quickly adds up through the network. In order to provide orientation for the tunnel traverse, it was necessary to fix the network at the penetrations, but fixing it too tightly caused distortions. There is a scale discrepancy -between the surface and tunnel networks that has not yet been solved. To overcome but-not-to solve this problem, a scale factor was applied to the tunnel traverse to bring it into agreement with the surface network. In practice it is not serious that the scale be slightly wrong and that the SLC be built slightly too large or too small, provided that the shape is maintained. When the SLC was built, no distance instrument was available for use both above and below the surface; now the ME5000 Mekometer does offer this capability, but a complete survey would take many months and SLAC has neither the time nor the funding for this. A baseline was built with pillars spaced 50 m apart to allow a direct comparison of the DM503 and the Distinvar, but even this did not solve the scale problem.

Relative Alignment: The Need for Smoothing

The second problem concerned the magnet survey and alignment in Step 3. Because of the transfer and accumulation of errors, it proved impossible to obtain an accuracy of 0.1 mm in relative alignment by positioning the magnets in absolute space using the traverse stations as control points. The solution employed was to add a further alignment stage, Step 4, in which theodolites and the Distinvar were mounted directly on magnets to obtain relative positioning independent of the floor monuments. A nonparametric principal components smoothing program[7] was used to fit a smooth three-dimensional curve through the magnets, minimizing offsets while maintaining relative alignment tolerances.

Figure 3 shows the offsets from the ideal beamline of 300 magnets along a stretch of the North Arc as measured in Step 4. The sinusoidal bow may not represent actual misalignments but may be a mathematical artefact caused by systematic measurement errors and by the need to fix the network at each end. Note the discrepancy in scale: 800 m in the longitudinal, but only a few millimeters in the vertical and transverse directions.

Figure 4 shows the smooth curve that was fitted through the data. The residuals from this curve indicate the amount by which the magnets needed to be realigned; few adjustments exceed 0.3 mm. Sample check surveys afterwards showed that Step 4 was successful in aligning the magnets onto a smooth curve, with very few misalignments exceeding 60 μm.

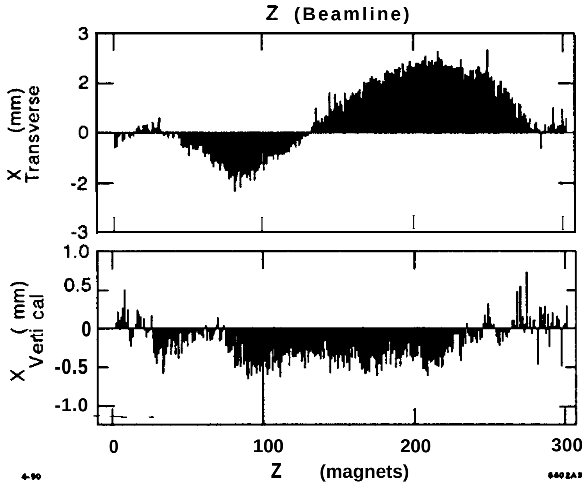

Fig. 3. Step 4 offsets.

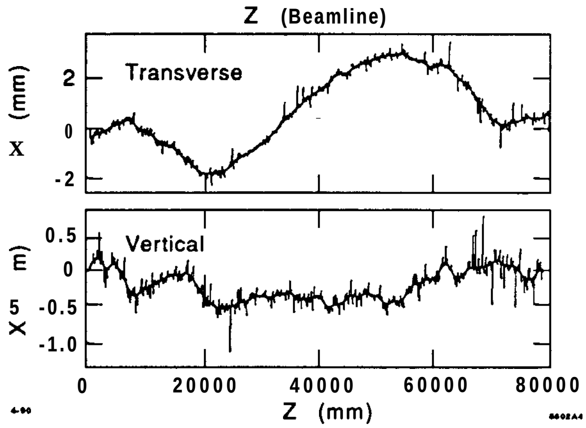

Fig. 4. The smooth curve.

3. ALIGNMENT OF THE FINAL FOCUS SYSTEM (FFS)

Like the arcs the FFS is long and narrow, so that the geometry of the survey network is poor, but the FFS is far more complicated than the arcs because it contains a high density of elements and no two elements are alike. Because this section is continually being upgraded frequent surveys have been made; but it has not been possible to measure the network the same way twice, due to the loss of lines of sight,, Again faced with the problem of orienting the network without distorting it, the adjustment method chosen was a completely free net, unconstrained in any manner, whereby it is the differences between the approximate coordinates and the adjusted values that are minimized. From among the points with the smallest change from the previous epoch, a couple of points were chosen to fix scale and orientation, but these datum points were not necessarily the same ones that were used in the previous survey, nor those used in the next survey. The adjustments revealed differences in the location of every element from one survey to the next, but it was difficult to distinguish real movements indicating misalignments from apparent movements caused by the different observation plan or by the adjustment itself. Although the problem is similar, the analytical techniques used in deformation analysis are not suitable for at least three reasons:

(a) The geometry is very poor.

(b) Alignment tolerances are so tight that the level of change looked for is below the borderline of significance in the deformation analysis.

(c) The requirements for deformation analysis software are too restrictive, as exactly the same network must be measured in the two epochs; this has not so far been possible in the FFS.

As in the arcs, smoothing was used to overcome but not to solve this problem.

4. EFFECT OF THE 1989 EARTHQUAKE

SLAC suffered a severe shaking at the hands of the magnitude 7.1 Loma Prieta earthquake that rocked the Bay Area for 15 seconds at 17:04 on October 17, 1989. The epicenter of the quake was 40 miles from SLAC and the San Andreas Fault passes within one mile of the start of the linac. As a result of the substantial ground motion that occurred throughout the site, all absolute references, datums and networks have been lost. Absolute alignment is no longer possible, but indications are that the absolute alignment tolerances are still met.

By a stroke of good fortune, a complete survey of the linac had been made just weeks before the earthquake hit. A new survey immediately after the earthquake revealed significant movements (Fig. 5).

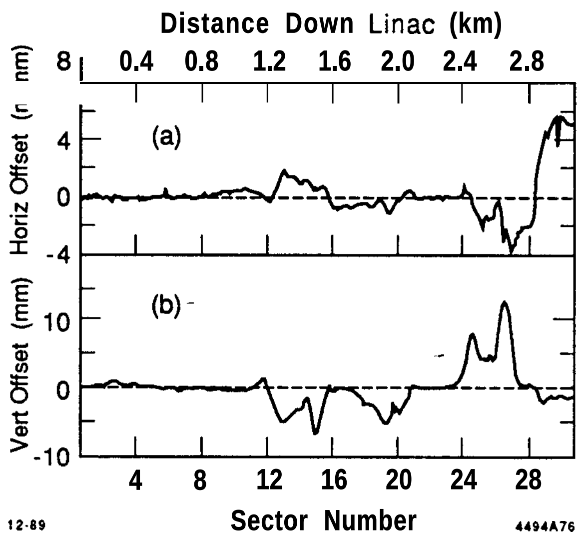

Fig. 5. Misalignment of the linac caused by the 1989 earthquake.

Major movement occurred at Sector 14, where the linac is built on landfill, and at Sector 28, where a minor fault is crossed. The linac is surveyed using a laser beam in an evacuated tube on which the accelerator rests. Every 10 m a fresnel lens can be swung into the path of the laser to form a diffraction pattern at the detection station at the far end of the linac. There are 300 targets along the accelerator. As everything had moved in the earthquake, it was difficult to know what to use as the two fixed points to define the line onto which the linac would be aligned, but once this new line was defined the first 28 sectors were quickly realigned. The fault at Sector 28 was more problematic as everything east of this break-the last two sectors of the linac and the entire SLC-had moved relative to the first 28 sectors of the linac. A complete realignment being impossible, a smooth curve was defined to bridge the discontinuity.

Another major break was found in the North Arc at the so-called Walker Fault just upstream of the North Reverse Bend, with offsets of up to 1 cm (Fig. 6). In the linac it was possible to realign the accelerator onto a common straight line as defined by the laser alignment beam, but in the arcs all the absolute reference points had been lost. A smooth curve was defined with constraints imposed to minimize the adjustment of five difficult elements.

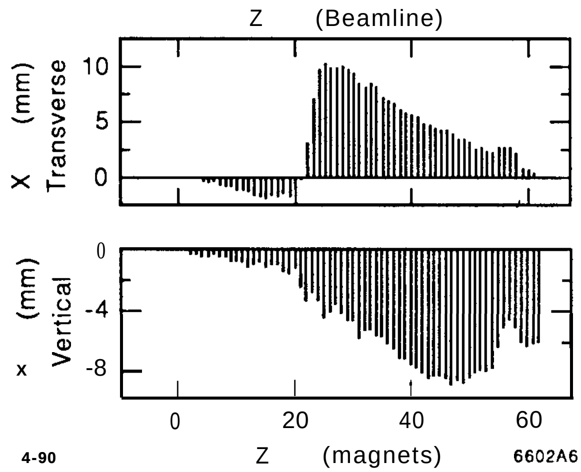

Fig. 6. Misalignmentsin the North Arc caused by the 1989 earthquake.

5. CONCLUSIONS

Even with the most rigorous measurement procedures and least-squares adjustments, the definition and maintenance of datums has been problematic. Tolerances are so tight that systematic errors on the level of even 10 μm are serious (for example, a 100 μm centering error in the two Wild T3000 theodolites rendered the measurements useless). A variety of methods has been used to overcome these datum definition problems: (a) GPS provided the connection between the linac and SLC datums; (b) a scale correction brought the tunnel datum into harmony with the surface datum; and (c) datums were ignored altogether in using smoothing techniques to overcome the propagation of errors caused by measurement hierarchies, systematic errors and mathematical artefacts of least-square adjustments. The development of smoothing to provide relative alignment has proven especially fortuitous, as all datums were destroyed by the recent earthquake.

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