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THE USE OF INTERSECTING LASERS IN THE ALIGNMENT OF THE NEW ELECTRON-POSITRON COLLIDER AT THE STANFORD LINEAR ACCELERATOR CENTER*

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ABSTRACT

At the Stanford Linear Accelerator Center (SLAC) a new project is underway to build an electron-positron collider, the Stanford Linear Collider (SLC). This paper gives an overview of the alignment procedure for this project, followed by a detailed description of the first step in the alignment. In this part of the procedure pedestals are set in pitch and yaw and brought into ±3 mm of their final three-dimensional position by use of two intersecting laser beams. The fixturing and instrumentation are described, together with the software and data-flow which are used. Finally, the results obtained with this method are discussed, and conclusions are drawn on its effectivness.

INTRODUCTION

The Stanford Linear Accelerator Center was established in 1962 and provides the U.S. with facilities for research into particle physics by means of its three particle accelerators. The first machine to be built on the site was a linear accelerator (linac) after which the laboratory was named. It was completed in 1966. This machine runs for over 3 kilometres west to east and is used both directly in experiments and to feed the other machines on the site. One of these is the Synchrotron-Positron-Electron Asymetric Ring (SPEAR) which is located at the eastern end of the linac and was completed in 1972. This machine is an oval ring approximately 200 metres in circumference and collides electrons and positrons at two points.

The third machine on the SLAC site is the Positron Electron Project (PEP) completed in 1980. This is also an oval storage ring but is much larger than SPEAR and has six experiment areas around its 2 kilometre ring.

The linac will also be used to feed the latest in the SLAC machines, the SLAC Linear Collider (SLC) (see Fig. 1). This machine is currently being built at the site and is unique in its design. The SLC will basically consist of two extension arms to the linac each of just over 1 kilometre in length. Each arm or arc will contain almost 500 magnets which will steer beams of electrons and positrons first away from the linac and then towards each other and into a head-on collision. Unlike the SPEAR and PEP storage rings in which the beams circulate and can be used over and over, the particle beams in the SLC will be used only once and then discarded.

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Due to the topographic and geological constraints of the site the SLC is not built in a plane, but has a path which follows the contours of the land such that a maximum slope of 10% is encountered. Each arc of the tunnel is divided into 23 achromats. Each achromat forms a plane and contains 20 magnets which are to be pitched and rolled. These factors pose unique problems in the alignment of the SLC.

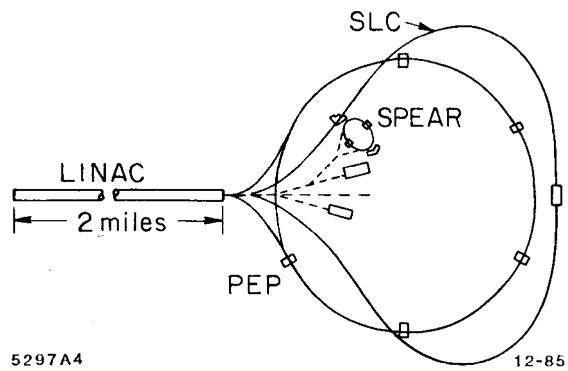

Fig. 1. A schematic of SLAC including the Linear Collider.

SURVEY TOLERANCES AND APPROACH

High absolute and relative accuracies are required in the SLC (Friedsam 1984). The absolute accuracy is important in two respects. First it is essential to ensure that the SLC arcs are consistant with the existing linac (Ruland 1985). Secondly, absolute accuracy is important in that it affects the overall length of the arcs and thus the timing of the particle collisions. However, it is the relative accuracy and above all the smoothness which are the chief concerns of the alignment, since pertubations in the beam path are unacceptable.

Some of the alignment tolerances demanded in the building of the SLC are given below:

— The length of the arcs should agree with the theoretical length to within 15 mm.

— The absolute magnet position should agree with the theoretical position to within 10 mm.

— The distance along the beamline between any two magnets should be set to within 0.5 mm

— The lateral offset between two magnets in any achromat should be set to within 0.1 mm

— The roll of the magnets should be set to within 1.0 mrad.

In order to achieve these accuracies a precise tunnel traverse is used. This traverse is supported every 200 metres or so by penetration points whose coordinates are determined by a surface net. Simulations have shown that this should produce traverse points with coordinates accurate to within 0.2 mm with respect to neighbouring points. Precise levelling is also carried out and bench marks are located at least every 20 metres along the tunnel.

Once the traverse is established a three step procedure is used to bring the magnets into their final positions. Step 1 sets the magnet support pedestals in pitch and roll and brings them to ±3 mm of their ideal position, at which point they are grouted in place. Step 2 measures the position of the pedestals and then adjusts them to within 0.5 mm using dialgages. The magnets are then mounted on the pedestals and the final step in the alignment is carried out. In step 3 the magnets are again measured and adjusted using dial gages. They are also set in roll and the magnet to magnet alignment is carried out (Friedsam 1985). It is the first of these steps, however, which shall be discussed here.

STEP 1 ALIGNMENT

Rationale

Since the arcs of the SLC are sloping and the pedestals pitched, it became apparent that a simple layout scheme for the pedestals would not be possible. Uncertainties in the exact elevation and slope of the floor meant that a way needed to be found to position pedestals using known points at the height of the beam rather than at floor level. A computer program called TRANSPORT (Brown 1973) is used to compute the positions of all the elements of the SLC. Amongst the points computed is one known as the vertex point which is located between each magnet. Since each pedestal supports the ends of two magnets then the vertex point falls directly above the pedestal (see Fig. 2). It is this point, therefore, which is used to set out the pedestals and thus avoid projection errors.

Various approaches to the step 1 alignment have been considered, including in-place measurement and then iterative adjustment, and standard setting out procedure from two theodolites. It is only by using lasers, however, that it is possible to avoid time consuming iterative procedures and at the same time maximise manpower efficiency.

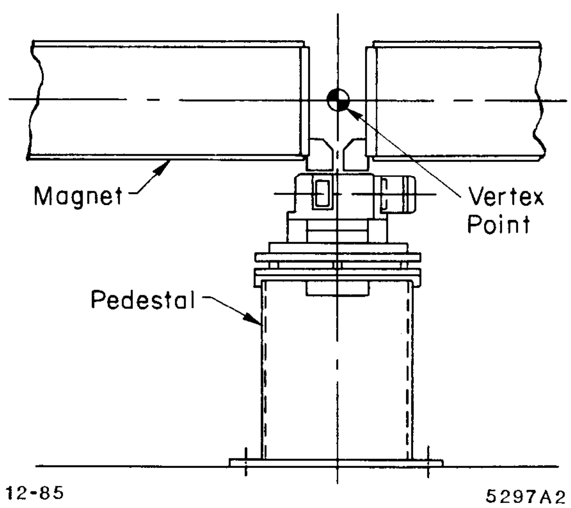

Fig. 2. Location of the vertex point.

Method

The step 1 procedure which has been developed uses two Kern lasers attached to two Kern E2 theodolites via laser eyepieces. With correct focussing a beam of approximately 1 mm in diameter can be obtained. The instruments are set up over traverse points located every 13 metres in the tunnel. Five pedestals lie between every pair of traverse stations. To orient the instruments two backsights are taken at each station onto two other traverse points, one located upstream and one downstream. Thus, four traverse points are generally used in the set up. The height of each instrument is obtained by setting the telescope at 100 gon and shooting onto a level rod. Observations are fed into a HP 110 computer which calculates the required horizontal and vertical directions for the pedestal (more about this will be said later). These are then passed back to the theodolites and displayed on the two spare windows of the E2, thus removing any transcription errors. The theodolites are then moved to the correct positions such that the laser beams intersect at the vertex point (see Fig. 3).

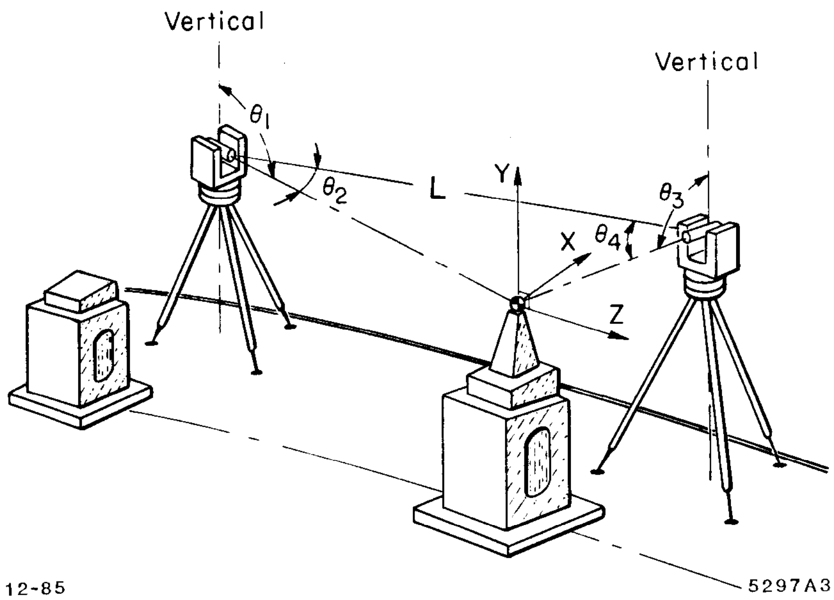

Fig. 3. An early interpretation of the Laser alignment technique.

The intersection of the laser beams can not be seen under normal conditions. A target is used which provides both a screen onto which the image of the beams can be seen, and also a reference point which is to be moved to the ideal position. The target screen is made of a black plastic disc 0.75 mm thick, with a cross etched at its center. The fixture which supports the target consists of an aluminium base-plate underlying a pipe which acts as a spacer in order to mount the target to the height of the vertex point. The base-plate is used as a reference on which to measure pitch and roll. This is carried out using a Sperry digital inclinometer, which reads to 0.01 degrees.

Extending approximately 30 cm from the target fixture in the direction of the beam, is a bar which is used to set yaw (see Fig. 4). One theodolite is set parallel to the yaw of the pedestal and offsets are measured with a steel tape

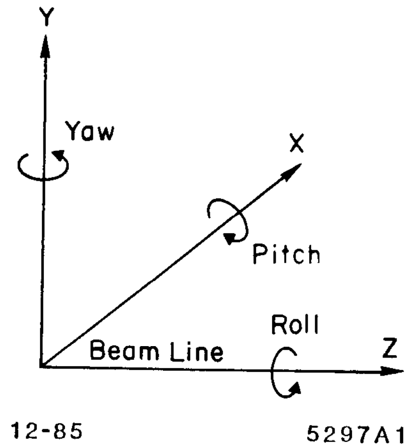

Fig. 4. Diagram showing yaw, pitch and roll.

from the center of the fixture and from the end of the bar. Using this method yaw can be set to within 3.5 mrad (0.2 degrees).

The two laser beams form dots of approximately 1 mm in diameter on the target screen. When the dots from each laser merge together into one, then the pedestal is in the correct position along the beamline (Z coordinate). The X (horizontally perpendicular to the TRANSPORT beam) and Y (vertical) coordinates are set when the dot appears at the center of the target.

It has been found that operations are speeded up if a pre-alignment step is carried out. In this step the pedestals are set in pitch and roll using an inclinometer and are also set in Y using an automatic level. Not only does this speed up the step 1 alignment, but it also serves as a useful trouble shooting exercise locating faulty pedestals.

Computation and Accuracy

As mentioned earlier, the TRANSPORT program provides the coordinates of all the elements in the SLC arcs. The coordinate system used by TRANSPORT is a cartesian system with its origin at a point known as station 100 at the eastern end of the linac. The direction of the beamline at this point defines the Z axis (positive east), while the Yaxis is defined by the direction of gravity (positive up). The X axis is perpendicular to the other two axes and completes the right-handed system (positive north).

Before the Y coordinates of the vertex points can be used in the step 1 alignment procedure, they must first be transformed into a geodetic system (Oren 1985). Were this not done, an error of up to 2 mm could occur in the elevation of a pedestal. This corresponds to the worst case separation of the vertical (20″) over a 20 m level shot.

Once this transformation has been completed, the coordinates for the vertex points together with those for the traverse stations and the elevations of the bench marks are downloaded into a HP 110 computer (Friedsam 1986). This machine has a storage capacity of 144 K bytes, but even so, with almost 1000 vertex points together with over 150 traverse stations and bench marks, it would be too time consuming for the routines in the program to search through all of this data. Therefore for practical purposes more managable units of say 4 to 5 achromats are stored in the computer.

This data is then used in a Basic program run on the HP 110 which is interfaced to both theodolites. The program first prompts for a level shot onto a bench mark in order to determine the height of the instruments. Tests have shown that with a single shot onto a rod, an accuracy of 1 mm can be achieved over the distances commonly used in the tunnel (approximately 10 m). Since heights of both instruments are determined independently then the resulting accuracy for the determination of the height of a pedestal should be in the order of 0.7 mm.

Once the heights of both stations have been established, two traverse stations are observed in order to provide the horizontal reference. The program uses both observations in determining the orientation of the theodolite circle. The azimuths between traverse stations are computed using the stored coordinates. Each sighting is then subtracted from the azimuth to give a constant. The constants for both sightings are then meaned and applied to the computed azimuth of the vertex point, giving the direction at which the theodolite should be set. This procedure not only improves the accuracy of the reference pointings, but also guards against gross error since both constants are compared and only accepted if they lie within 1.0 mgon.

Only one sighting is made to each of the traverse points. However, if one assumes an accuracy of 1.5 mgon for a single pointing with an E2, then at the maximum sighting distance of 15 metres the error would be 0.4 mm which is consistant with an overall accuracy requirement of ± 3 mm.

Once the theodolites are set to the direction of the vertex point the pitch of the pedestal is displayed on the computer. The yaw is computed as an azimuth in the geodetic system and then converted into a direction as shown above. This is then displayed on the theodolites when requested by the operator. During the operation, the computer periodically "reads" the directions set on the theodolites so as to guard against movement.

When the pedestal has been aligned the operator needs only to enter the name of the next pedestal for the computer to display the relevant data. At the end of the set up (every five pedestals) the reference directions are re-observed as a final check on theodolite stability. Before the program is shut down it writes an output file containing the various details of the set up. These are then printed out and kept as a record of the operation.

RESULTS

The first indications as to the accuracy of this method came when a sample group of five pedestals were aligned. The target fixturing was somewhat different to that used later on, but the procedure was basically the same. After aligning the pedestals using the lasers, their positions were measured by turning three direction sets with an E2 from three nearby traverse stations. The residuals from the ideal coordinates can be seen in Table I.

TABLE I. Residuals in metres from ideal coordinates after step 1 alignment (mock up)

POINT	DZ	DX	DY
XS0211PV	0.00090	−0.00030	−0.00020
XS0212PV	0.00050	−0.00090	−0.00030
XS0213PV	0.00050	−0.00030	0.00020
XS0214PV	0.00260	−0.00170	−0.00020
XS0215PV	0.00030	−0.00010	0.00030

From this it can be seen that the Z component has the worst determination. This is the direction along the beam and as such the geometry of the laser intersections is weak. Therefore, this result is to some extent to be expected. In the X and Y directions however, the results are satisfying, with only one of the X residuals greater than 1 mm and the Y residuals within 0.5 mm.

Although useful, these first results may not be typical of the general level of accuracy obtained under normal "production" conditions, when efficiency as well as accuracy must be considered. The effectivness of the technique under these conditions is easily seen since the first operation of the step 2 alignment is to measure where the pedestals are in space. Each pedestal is observed using three direction sets with an E2 from three traverse stations, and distances between pedestals are measured with invar wire. Precise levelling with a Wild N3 is also carried out. Therefore the determination is generally very reliable and error ellipses in the 0.1 mm range are obtained. A typical sample of these results can be seen in Table II.

These results show that the worst determination is again in the Z direction. Several of the residuals approach 3 mm and in fact two exceed it. Here again we see the effects of weak geometry. However, with each pedestal weighing approximately 200 lbs and with between ten and fifteen pedestals being aligned each day one should expect a few exceptions to the 3 mm limit. The X direction yields good results with residuals between 0.04 mm and 1.91 mm. The Y values, however, fall within 1 mm of the of the ideal position with the worst case being 0.87 mm. This not only shows a very good determination of the Y coordinate, but also supports our original assumption that the pedestal elevations would be set to an accuracy of ±0.7 mm.

Therefore, the results of the mock up were fairly indicative of the type of results seen under normal conditions. These can be summarised as a weak determination of the Z coordinate occasionally giving residuals in excess of 3 mm; whereas the X generally falls within 2 mm, and the Y is often within 1 mm. It can be seen, therefore, that the tolerance of ±3 mm has in most cases been achieved.

TABLE II: Residuals in metres from ideal coordinates after step 1 alignment (achromat 16 – production survey)

POINT	DZ	DX	DY
XS1601PV	−0.00294	0.00023	−0.00044
XS1602PV	0.00046	−0.00026	0.00022
XS1603PV	−0.00071	0.00093	0.00032
XS1604PV	0.00015	0.00027	0.00017
XS1605PV	−0.00388	0.00022	0.00018
XS1606PV	0.00287	−0.00031	0.00087
XS1607PV	−0.00170	0.00191	0.00041
XS1608PV	0.00239	0.00089	−0.00002
XS1609PV	0.00294	−0.00066	−0.00086
XS1610PV	0.00250	0.00048	−0.00047
XS1611PV	−0.00037	−0.00019	−0.00024
XS1612PV	−0.00218	0.00158	0.00045
XS1613PV	−0.00130	0.00153	0.00063
XS1614PV	−0.00023	−0.00016	−0.00013
XS1615PV	0.00036	−0.00004	0.00052
XS1616PV	0.00095	0.00019	0.00062
XS1617PV	−0.00187	−0.00122	−0.00019
XS1618PV	0.00152	0.00012	−0.00082
XS1619PV	0.00339	0.00062	−0.00061
XS1620PV	0.00168	0.00069	−0.00052

CONCLUSION

The alignment of the SLC pedestals using the intersecting laser technique began at the end of June 1985. Since that time the need to carry out survey tasks on other parts of the project has meant that only about fifty per cent of the time could be devoted to step 1 alignment. However, by the beginning of November, a total of 411 pedestals had been aligned by this method. This represents the majority of pedestals in the south arc, and a little over forty per cent of the total number. It is expected that all the pedestals will be aligned to step 1 precision by February of 1986.

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