ALIGNMENT OF THE STANFORD LINEAR COLLIDER ARCS —CONCEPTS AND RESULTS—*

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ABSTRACT The alignment of the Arcs for the Stanford Linear Collider at SLAC has posed problems in accelerator survey and alignment not encountered before. These problems come less from the tight tolerances of 0.1 mm, although reaching such a tight statistically defined accuracy in a controlled manner is difficult enough, but from the absence of a common reference plane for the Arcs. Traditional circular accelerators, including HERA and LEP, have been designed in one plane referenced to local gravity. For the SLC Arcs no such single plane exists. Methods and concepts developed to solve these and other problems, connected with the unique design of SLC, range from the first use of satellites for accelerator alignment, use of electronic laser theodolites for placement of components, computer control of the manual adjustment process, complete automation of the data flow incorporating the most advanced concepts of geodesy, strict separation of survey and alignment, to linear principal component analysis for the final statistical smoothing of the mechanical components.

INTRODUCTION The approximately 3000 m long Arcs of the Stanford Linear Collider (SLC) transport the electron and positron beams from the existing 2-mile linear accelerator to the straight sections on either side of the interaction point, called the final focus. Fig. 1 shows a survey set-up using an electronic theodolite in the south arc tunnel. It is this beam line, consisting mainly of over 900 2.5 m long spaghetti like high alternate gradient multifunction magnets (called AG magnets), which posed the greatest challenge in constructing SLC. Missing alignment tolerances by one standard deviation could make it impossible to achieve a practical luminosity[1], a situation very different from past experience of a slow degradation of luminosity with increasing misalignment. Alignment tolerances for future linear colliders with higher gradients and smaller beams are expected to be even more demanding.

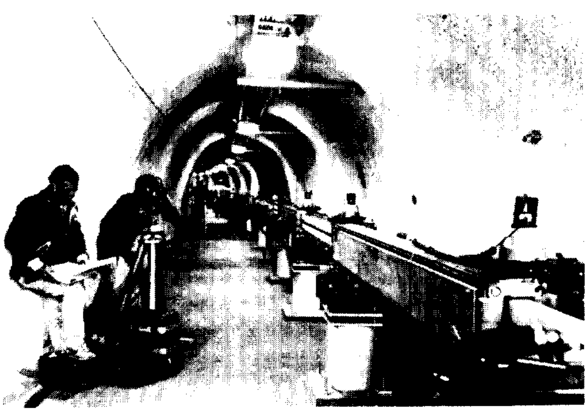

Fig. 1 Survey set-up in South Arc Tunnel

For the SLC Arcs, the survey problem is compounded by the coupling of tight tolerances with the topography of the SLC Arc site (Fig. 2). The beam dynamics requirements resulted in achromats with a phase shift of 6π containing 20 AG magnets each. In order to get from the accelerator to the interaction point the achromats have to lie in 46 different planes which are rolled up to 15 degrees and pitched up to 10% with respect to gravity. This makes all six degrees of freedom significant and inseparable. For example, to relate an upstream end of one AG magnet to the downstream end of its neighbor, 10 cm away, requires 18 translations and 12 sequential rotations in 3-dimensional space. Thus, for SLC a true coordinate measurement had to be devised, for which neither methods nor equipment were readily available and had to be developed, designed and fabricated.

In order to solve the conceptual and technical problems indicated above a survey engineering group of up to 30 people was created with a healthy mixture of mechanical designers, geodetic engineers, physicists, software engineers, survey engineers, and survey technicians, recruited from the US and Europe. The total costs were in the neighborhood of 4 M$ over a 4 1/2 year time span, including expenses for the final focus area.

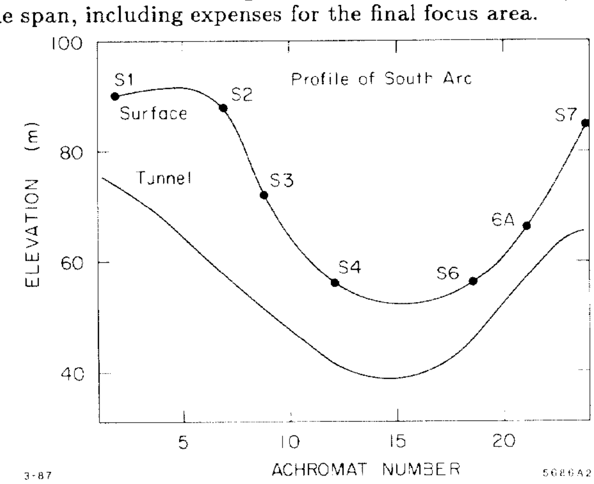

Fig. 2 Site topography. S denotes the vertical survey penetrations[2,3].

CONCEPTS The concepts implemented in the design of the survey and alignment system included:

1. Strict separation of survey and alignment, which is only possible when coordinates are measured. Reasons:
   a) allows mathematical analysis of data without time pressure, here: use of χ^2 techniques and of linear principal component analysis;
   b) allows relative smoothing of components without reference to absolute ideal coordinates, thus minimizing the numbers of elements to be moved and amount of mechanical movement in the very demanding final alignment step;
   c) allows mechanical corrective movement independent of the presence of a highly skilled survey crew and their expensive equipment. It also permits partial recovery from historical mistakes like magnet calibration errors without a new survey; allows movement under computer control with the help of electronic dial gages, thus reducing errors due to human mistakes.
2. Redundancy of measurements and methods. Reasons:
   a) accuracy is more economically improved by taking redundant measurements than by pushing the accuracy of each measurement;
   b) least square methods with error analysis and blunder detection are only possible with redundant information available.

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3. Breakdown of alignment into steps matched to the accuracy required and the methods applicable:
   - *a*) the initial placement requires reference to a SLAC-global coordinate system transferred into the tunnel (5mm with reference to the linac, 1mm with reference to the local net).
   - *b*) intermediate steps reference to the local tunnel net (0.3 mm rms).
   - *c*) final alignment references to a coordinate system determined by the neighboring magnets (0.1 mm rms, smoothing).

A further important contribution to success was the ability to influence design concepts of the magnet support structure, thus avoiding common errors like overconstrained adjustments or sliding metal surfaces, which can make fine adjustments below the 100μm range difficult, if not impossible, and close cooperation with the SLC beam dynamics task force[1] in order to establish practical machine tolerances.

DATA MANAGEMENT AND ADJUSTMENT The data taking in the field is designed around HP110 portable computers interfaced to instruments like theodolites, inclinometers, electronic dial gages etc.. Data collected are transferred at least once a day into a system of networked IBM-XT's, and immediately checked for measurement blunders. All data management, application of atmospheric refraction, calibration, and geodetic corrections, merging of files for least square adjustments and field applications, is handled on the 3Com linked network with the SLAC-designed menu driven GEONET Data Management System[4],[5].

The least square adjustment is done on an IBM mainframe, using the commercially produced GEONET Program System, tailored to the specific requirements of SLAC[6],[7]. The 3Com PC network and the mainframe are directly linked. GEONET allows free, minimally constrained, constrained, and connected adjustments of networks in 1, 2, and 3 dimensions, and accepts a wide variety of observables. The main advantages of GEONET are: it is menu driven, has a modular design, incorporates state of the art geodetic quality control and blunder detection techniques, and has professional consistency in programming standards which makes it easy to use and easy to modify.

SITE SURVEY To position the AG magnets in the tunnel, a network of nearby reference points is necessary[8]. Error analysis within the framework of free network theory shows that a traverse in the tunnel alone can not supply reference points within the required absolute accuracy (5mm on the 68% confidence level) without support from a surface network or high precision gyro-theodolite.

To meet a 30μrad launch angle tolerance, this SLC Arc (and final focus) net had to be oriented precisely to the same datum as the design coordinate system, which has the linac direction as the Z-axis. The unfavorable configuration of this system in the transverse coordinate for terrestrial observation is shown in Fig. 3, especially since linac station 0, 10, and 19 can only be seen from station 20 and 42. This was the situation when it was decided to try the satellite based Global Positioning System (GPS).

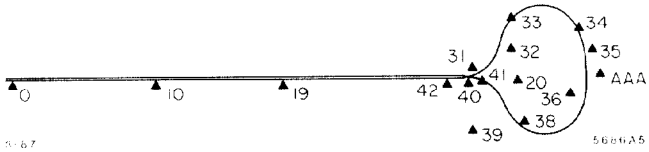

Fig. 3 Station layout for SLC Surface Survey

Since GPS measures vectors, redundant information is available, and a least square fit is possible. The result of the survey carried out on nine stations by GEO-HYDRO Inc. resulted in an overall error of 1.4 ppm (or a 2 mm closure error over 4 km), a result which was fully supported by subsequent conventional surveys with theodolites and electronic distance meters. Already at this time we had been able to apply blunder detection software and to detect a time bias error in the Geo-Hydro results, which greatly improved the final accuracy[9].

MECHANICAL ADJUSTMENTS As indicated earlier one of the main disadvantages of classical optical tooling techniques is the time consuming mechanical movement of the components (or attached targets) into the cross hair of an optical instrument. Since in our concept we measure coordinates, the movements of the magnets to bring them to the calculated (ideal or smoothed) coordinates is functionally independent from the survey.

The adjustments are monitored through generally at least six Mitutoyo Digimatic electronic indicators with a resolution of 1 micron and a range of 12 mm. The computer interface has been built at SLAC and contains the same NSC800 based single board microcomputer that is in use in several CERN and SLAC survey instruments like the CERN DISTINVAR and the SLAC precision inclinometers. It is able to handle 8 indicators. Programs are written in BASIC and stored in EPROM. Input and output data are stored in non-volatile RAM and downloaded from or uploaded to the GEONET data base. To enter additional operator observations, a mini terminal is attached to the box.

INITIAL MAGNET POSITIONING To minimize the number of iterations necessary to achieve a 0.1 mm rms error in the final alignment, the initial positioning had to be within 1 to 2 mm rms. In a horizontal tunnel where vertical (levelling) and horizontal (angles and distances) coordinates are separated this placement would be straight forward by applying conventional techniques. Roll and pitch of the magnets in a steeply pitched tunnel, coupled with a tunnel floor height tolerance of 2 inch made this impossible. Therefore, lasers were attached to two KERN E2 theodolites, the theodolites were pointed according to calculated values, and the appropriately targeted support structure was moved until the target coincided with the point in space were the two laser beams intersected[10]. The method proved to be reliable and fast; up to 30 supports were placed in one 8-hour shift. The next step in the alignment process, designed to bring the rms values down to 0.3 mm, showed that indeed a 1 mm accuracy in the component placement had been achieved. This next step still uses a tunnel traverse. Targets on top of the magnets (Fig. 1) are observed with a redundant observation plan and corrective mechanical movements are calculated and applied in a separate step with electronic dial gages under computer control.

SMOOTHING TECHNIQUES Down to an rms error of about 0.3 mm the SLC magnets were positioned in a coordinate system defined extraneously to the magnets, namely by the tunnel control net previously installed. The final smoothing step is designed to detect outliers and finally to move the magnets into a smooth curve rather than to ideal coordinates to minimize the survey and alignment effort. The horizontal observation plan used stations on top of the magnets only for instruments and targets and was optimized to provide tight control in horizontal x, whereas z had a relatively loose tolerance. Adjusted coordinates for each magnet were standardized by comparing to the ideal coordinates given by TRANSPORT, giving coordinate differences. The vertical y was determined by precision leveling.

The next task is to find a smooth curve best fitting these differences. Common methods for smoothing like a polynomial or spline fit all have one disadvantage: at the connection of adjacent fits an artificial discontinuity is be created, long wave length biases are introduced, and, most important, they are not robust, i.e., an outlier is not identified as such but biases the whole fit result. Worse, they may introduce model-dependent beats in the machine lattice which can be very destructive if they are related to the Betatron wave length.

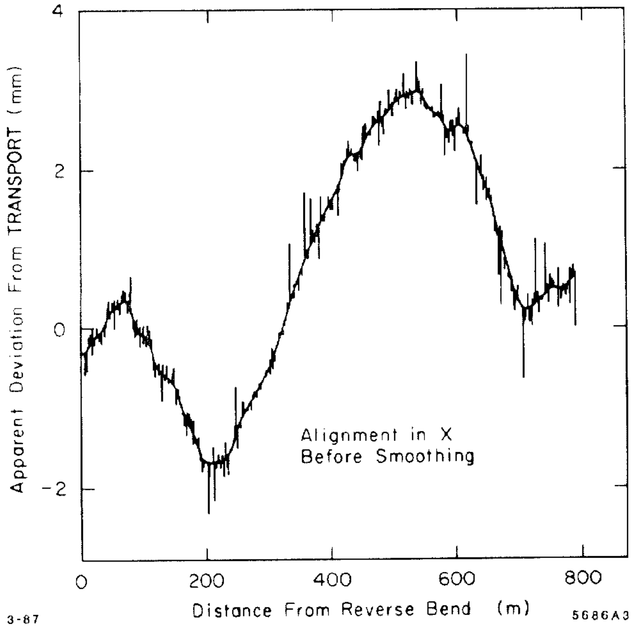

Fig. 4 Smooth curve fit with principal surface analysis

Therefore, the concept of principal surface analysis was chosen[11]. A principal surface has the property to pass through the middle of the three dimensional data cluster minimizing the distances between data points and the smooth curve. The data themselves define the path of the curve in contradiction for instance to a polynomial fit which assumes a deterministic behaviour of the data.

A modified version of the program described by Hastie[11] was used to determine the end of the iteration process. The iteration was ended when the angle included by three adjacent curve points were less than 40μrad, corresponding to the requested 100μm perpendicular tolerance for adjacent magnets. All fits were done with a kernel smoother and the robust option[11], which means that outliers did not affect the shape of the curve in their neighborhood, i.e., the further away a point is from the smooth curve, the less weight it carries. Figure 4 shows the apparent deviation of the magnet positions from TRANSPORT data.

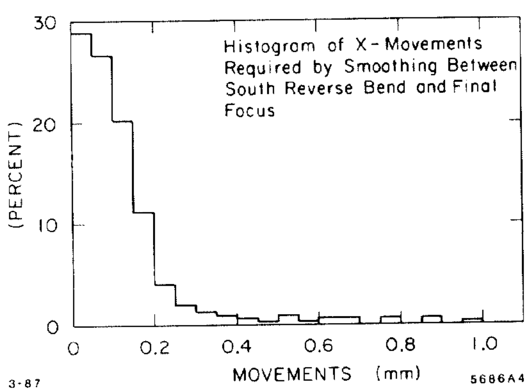

Fig. 5 Percentage of magnets requiring a certain movement to be on the smooth beam line

The very long wave length oscillation is a mathematical artifact and must not be interpreted physically. In any case, it corresponds to less than 1/40 of a betatron oscillation.

Finally, the distances between the data points and the smooth curve are translated into the beam following coordinate system. Figure 5 shows a histogram of the distances found. Movements less than 0.06 mm were not applied, while all other magnets were moved to their position on the smooth curve, which means that less than half the magnets were touched in the critical final alignment step.

RESULTS At the time of this writing the beam has been brought through the complete North Arc. For the last third of the North Arc two out of 150 correctors were used initially. Since correctors and beam position monitors form a 1:1 system one can estimate from the corrector strength the initial misalignment. The indication is that the goal of a 100μm rms initial mechanical alignment of the AG magnets was achieved. Unfortunately, we are too well aware of the constant movement of tunnel floors, which from PEP experience on SLAC soil can be larger than 0.5mm per year, thus requiring ever again new re-alignment when the misalignments exceed the corrector strength. The latter happens when the rms misalignment exceeds 0.3 mm.

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