

30
6/9/87 JJS

7-30808

SLAC-PUB--4208

0R0252-6

SLAC - PUB - 4208

February 1987

(A)

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

R. PITTHAN, B. BELL, H. FRIEDSAM, M. PIETFYKA, W. OREN, R. RULAND

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

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 in-

*Work supported by the Department of Energy, contract DE-AC03-76SF00516.

separable. 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 U.S. 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.

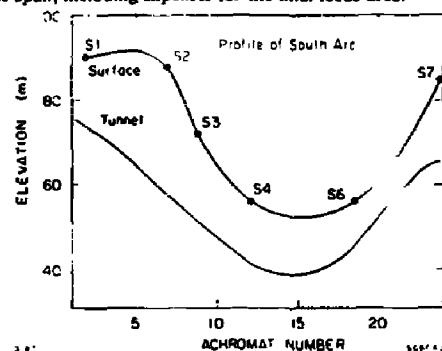


Fig. 2 Site topography. S denotes the vertical survey penetrations^[2,3].

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.

Presented at the Particle Accelerator Conference, Washington, D.C., March 16-19, 1987

EB
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

3. Breakdown of alignment into steps matched to the accuracy required and the methods applicable:

- 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).
- intermediate steps reference to the local tunnel net (0.3 mm rms).
- 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 100 μ m 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 30 μ rad 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).



beats in the machine lattice which can be very destructive if they are related to the Betatron wave length.

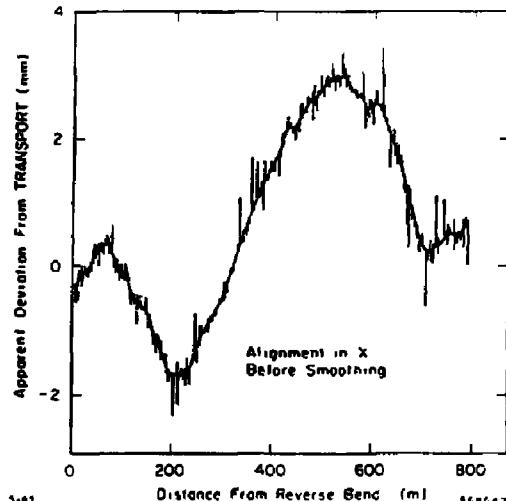


Fig. 4 Smooth curve fit with principal surface analysis

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 40 μ rad, corresponding to the requested 100 μ m 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.

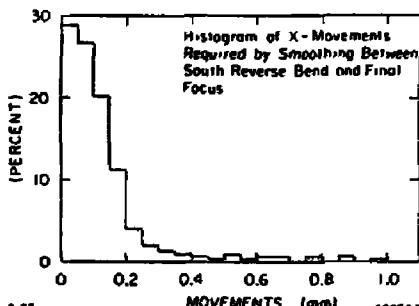


Fig. 5 Percentage of magnets requiring a certain movement to be on the smooth beam line

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 180 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 100 μ m 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.

ACKNOWLEDGEMENTS We are indebted to Trevor Hastie for his help in understanding and applying the principal curve analysis to our data, and for modification of his computer programs, and to Bill Davies-White and John Rees for their unwavering support of our efforts.

REFERENCES

1. S. Kheifets, T. Fieguth, et al.: "Beam Optical Design and Studies of the SLC Arcs", SLAC-PUB-4013, 13th International Conference on High Energy Accelerators, Novosibirsk, 1986.
2. H. Friedsam, W. Oren, M. Pietryka, R. Pitthan, and R. Ruland: "SLC Alignment", in: Stanford Linear Collider Design Handbook, SLAC 1984, pp. 8-3 - 8-85.
3. R. Pitthan and R. Ruland: "A Proposal for the Alignment of SSC", SSC-N-134, SLAC-PUB-383D, 1986.
4. W. Oren, R. Pushor, and R. Ruland: "Incorporation of the KERN ECDS-PC Software into a Project Oriented Software Environment", SLAC-PUB-4141, to be presented at the 47th ASP-ACSM Convention, Wash. D.C. 1987.
5. R. Ruland and H. Friedsam: "GEONET - A Realization of an Automated Data Flow for Data Collecting, Processing, Storing and Retrieving", invited paper presented to the XVIII FIG Congress, Toronto, June 1-11, 1986.
6. I. Burstedde: "Das Programmsystem GEONET zur Ausgleichung Geodätischer Netze", to be published in: Allgemeine Vermessungsnachrichten, May 1987.
7. I. Burstedde, and K. Cremers: "Zur Ausgleichung Geodätischer Netze nach der 1-Norm", Allgemeine Vermessungsnachrichten, 6/1986, pp. 228-234.
8. M. Pietryka, H. Friedsam, W. Oren, R. Pitthan, and R. Ruland: "The Alignment of Stanford's New Electron-Positron Collider", SLAC-PUB-3842, 45th ASP-ACSM Convention, Wash. D.C. 1985, pp. 321-329.
9. R. Ruland and A. Leick: "Application of GPS in a High Precision Engineering Survey Network", SLAC-PUP-3620, 1st Int. Symp. on Prec. Pos. with GPS, Rockville MD, 1985, pp. 483-494.
10. C. Curtis, W. Oren, and R. Ruland: "The use of Intersecting Lasers in the Alignment of the New Electron-Positron Collider at the Stanford Linear Accelerator Center", SLAC-PUB-3837, 46th ASP-ACSM Convention, Washington D.C. 1986, pp. 61-69.
11. T. Hastie: "Principal Curves and Surfaces", Stanford U. Ph.D. SLAC-276, STAN-LCS, 1984.
12. G.E. Fischer et al.: "Some Experience from the Commissioning Program of the SLC Arcs", this Conference, 1987.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.