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Accelerator and Transport Line Survey and Alignment *

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Abstract

This paper summarizes the survey and alignment processes of accelerators and transport lines and discusses the propagation of errors associated with these processes. The major geodetic principles governing the survey and alignment measurement space are introduced and their relationship to a lattice coordinate system shown. The paper continues with a broad overview about the activities involved in the step by step sequence from initial absolute alignment to final smoothing. Emphasis is given to the relative alignment of components, in particular to the importance of incorporating methods to remove residual systematic effects in surveying and alignment operations. Various approaches to smoothing used at major laboratories are discussed.

1.0 Introduction

What is Survey and Alignment's role in building accelerators and beam lines? The most obvious task is the physical positioning of machine components, particularly magnetic quadrupoles, sextupoles and dipoles as well as diagnostic devices, collimators and the like according to a lay-out specification, the lattice and its tolerance list. This very general task description can be broken down into six major subtasks:

1. **Survey Reference Frame** The first step is to define and physically establish a survey coordinate system appropriate to the project site and size. Control monuments are established to represent this reference grid.
2. **Lay-out Description Reference Frame** The beamline is designed and specified in a lattice coordinate system. Coordinate transformations, including rotations and transformations, need to be defined to relate this to the survey reference frame.
3. **Fiducialization** The fiducialization of a component relates its effective magnetic or electric centerline to external mechanical points that are accessible to subsequent survey measurements.
4. **Absolute Positioning** Beamline components are positioned with respect to the global reference grid.
5. **Relative Positioning** Local tolerances are achieved by the relative alignment of adjacent components.
6. **Circumference Correction** Manipulate smoothness trend curve to meet tolerance.

Besides being part of the construction executive branch, the survey and alignment engineer provides expertise in other areas. Three important areas of design work in which he should be involved are: i) the negotiations of positioning tolerances between the theoretically desirable and the practically achievable; ii) discussions of positional stability as this might be affected by such factors as

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thermal stability and ground motion; iii) early and active participation in the design of support systems for machine components to ensure that these allow the components to be realistically aligned to required tolerances with a cost-effective effort on the part of the alignment teams.

2.0 Reference Frames

The goal is to define a computational reference frame, or in other words, a mathematical model of the space in which the surveyor takes his measurements and performs his data analysis. Transformation algorithms and parameters between the surveying space and the machine lay-out coordinate system need to be defined.

2.1 Surveying Space

The ancient civilizations, such as the Chinese and the Mesopotamians, seem to have realized that the earth is round, but their thoughts remain in the realm of prehistory. The historical development of geodesy begins with the Greeks. Several Greek thinkers believed the earth to be spherical, and Eratosthenes (born 276BC) made the first serious attempt to actually measure the size and shape of the earth.[1]

The earth is never the less a complex shape, the modelling of which is not easy. Three surfaces are of importance to the geodesist studying the shape of the earth:

i) The *terrain surface* is irregular, departing by up to 8000m above and 10000m below the mean sea level.

ii) The *geoid* is the reference surface described by gravity; it is the equipotential surface at mean sea level that is everywhere normal to the gravity vector. Although it is a more regular figure that the earth's surface it is still irregular due to local mass anomalies that cause departures of up to 150m from the reference ellipsoid. As a result, the geoid is non-symmetric and its mathematical description non-parametric, rendering it unsuitable as a reference surface for calculations. It is however the surface on which all survey measurements are made as almost all survey instruments are set up with respect to gravity. Even the satellites now used for GPS surveys follow orbits determined by gravity.

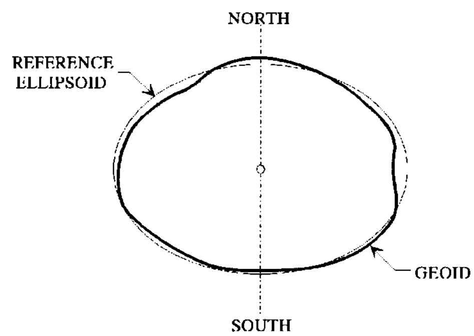

Fig. 1 Speroid (Ellipsoid) and Geoid

iii) The *spheroid* or *ellipsoid* is the regular figure that most closely approximates the shape of the earth, and is therefore widely used in astronomy and geodesy to model the earth (Fig. 1). Being a regular mathematical figure it is the surface on which calculations can be made. Nevertheless, in performing these calculations account must be taken of the discrepancy between the ellipsoid and the geoid. The deflection (or deviation) of the vertical is the angle of divergence between the gravity vector (normal to the geoid) and the ellipsoid normal (Fig. 2). Several different ellipsoids have been defined and chosen that minimize geoidal discrepancies on a global scale, but for a **survey engineering project it is sufficient to define a best-fit local spheroid** that minimizes discrepancies only in the local area. Whatever ellipsoid is chosen, all survey measurements must

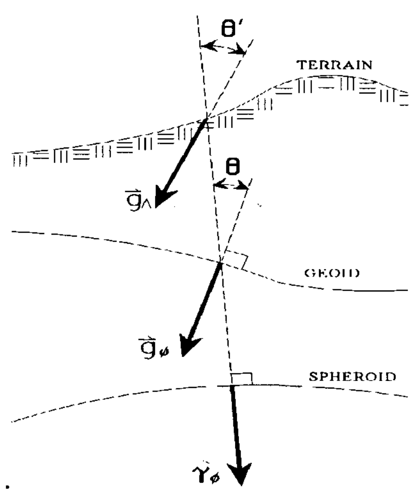

Fig. 2 Spheroidal Normal and Gravity

be reduced to the ellipsoid before computations can proceed. This reduction of observations to the computational surface is an integral part of position determination;[2] the equations can be found in most of the geodetic literature, e.g. in Leick.[3]

2.2 Surveying Coordinate System

Computations with spheroidal (geographical) coordinates latitude ϕ, longitude λ and height h are quite involved. Especially in survey engineering projects, coordinate differences should directly and easily translate into distances independent of their latitude on the reference spheroid. They are also not very intuitive: when using spheroidal heights, it can appear that water is flowing up-hill. Therefore, it is desirable to project the spheroidal coordinates into a local Cartesian coordinate system or, going one step further, to project the original observations into the local planar system to arrive directly at planar rectangular coordinates.

The representation of points on a spheroidal surface on to a plane requires the transformation of these points to points on the plane surface. Depending on the particular approach of projection, certain properties of relationship (distance, angle, etc.) of the original points will be maintained, others will be distorted. It is simply not possible to project a spherical surface on to a plane without creating distortions (see fig 3).[4] However, these distortions can be mathematically modelled. It is therefore possible to correct derived relationships such as distances, angles or elevations. This situation can be vividly shown on the example of the projection of leveled elevations on to a planar coordinate system.

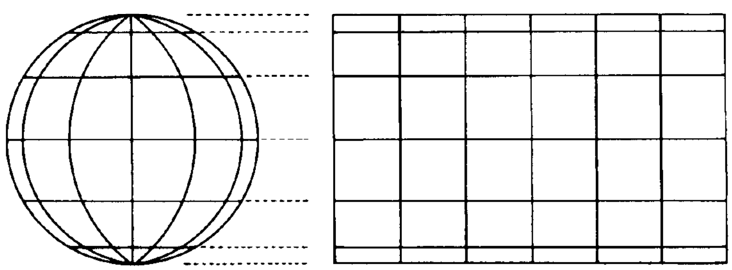

Fig. 3 Projection of Speroid on to a Plane

Since leveling is done with respect to gravity, the reference surface is the geoid. In our example, we have modelled the geoid with both a sphere and a spheroid (see fig. 4). Table 1 shows the projection errors as a function of the distance from the coordinate system's origin. Notice that for distances as short as 20m the deviation between plane and sphere is already 0.03mm.

Table 1: Curvature Correction, Plane to Sphere or Spheroid

Distance [m]	Sphere H_S [m]	Spheroid H_E [m]
20	0.00003	0.00003
50	0.00020	0.00016
100	0.00078	0.00063
1000	0.07846	0.06257
10000	7.84620	6.25749
25000	49.03878	39.10929

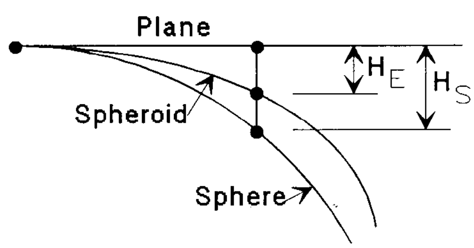

Fig. 4 Curvature Correction

2.3 Grid Systems

The surveying coordinate system is physically represented by monuments whose coordinates are determined using conventional trilateration or triangulation methods or for larger size projects satellite methods like the Global Positioning System.[5]

2.3.1 Surface Network In order to achieve the absolute tolerance and the circumference requirements, usually a surface network with pillar type monuments (see fig.5) must be established. Traditional triangulation and trilateration methods (see fig.6) or GPS surveys can be applied to determine the coordinates of the monuments and of tripods over the transfer shafts or sightholes. Differential leveling of redundant loops is the standard method to determine the vertical coordinate. Proper reduction of measured distances also requires accurate elevation difference data.

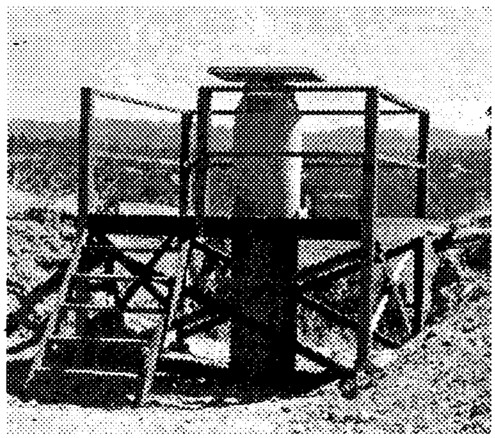

Fig. 5 SLAC-SLC Pillar Monument

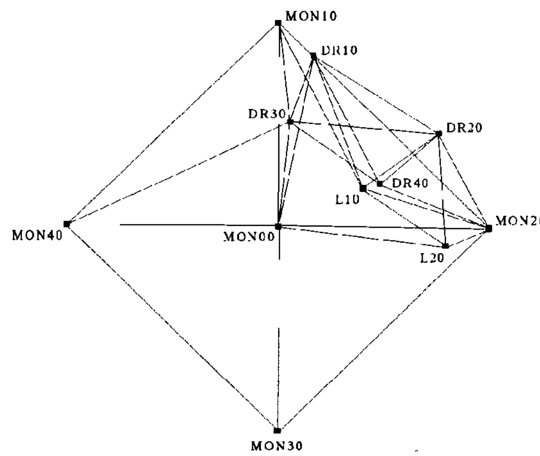

Fig 6 Example of Surface Network (Argonne ALS)

Using state-of-the-art equipment in a small trilateration network with good intervisibility of monuments can yield standard deviations for the horizontal coordinates in the range of 2mm + 1ppm. In medium size applications it has been shown that GPS, combined with terrestrial observations and a good control of the antenna eccentricities, (GPS, too, has its fiducialization problems) can yield 2mm range positional accuracies.[6] In large projects, like the SSC, preliminary computer simulations indicate 6 - 12mm type positional accuracies using two frequency receivers. Trigonometric and differential leveling are the only accurate methods to determine elevations; both methods yield the same accuracies: 1mm for networks below 2km extension, and 20mm for a SSC size network.

2.3.2 Tunnel The tunnel horizontal net is usually tied to the surface net by optically or mechanically centering a tripod-mounted translation stage on the surface over a monument in the tunnel through a survey shaft. Tunnel horizontal nets will commonly be established as longitudinal networks like the one shown in fig. 7. Points beneath the shafts and connected to the surface net will be incorporated. As floor marks 2-D (horizontal only) or 3-D monuments can be used. Common designs are the SLAC

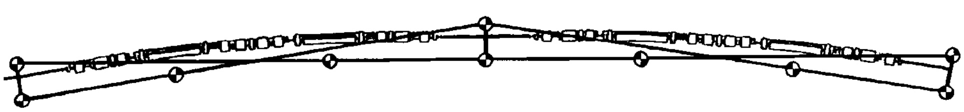

Fig. 7 Tunnel Network Lay-out

2-D marks or the Desy-HERA 3-D reference cups. Some kind of tripod or column-like monopod is used for the instrument set-up. The SLAC setup (see fig. 8) is designed to accommodate slopes of up

Fig.8 SLAC Tripod Set-up

Fig. 9 Self-Centering HERA Monopod

to 15°; the HERA design is more optimized towards efficiency in that it virtually eliminates the task of centering instruments and targets over monuments (see fig. 9 [7]). The elevation of the instrument above the 3-D reference cup is known very accurately, which facilitates 3-D mapping with theodolites.

3.0 Lay-Out Description Reference Frame

The lay-out description of every machine component is given in a document called the lattice or the "TRANSPORT"[8] run. The lattice defines every machine component and its ideal position.

3.1 Ideal component position.

For every new machine various computer programs are used to simulate the path of the particles. Model components bend, focus or defocus the particles as they traverse the electromagnetic fields they encounter. Component parameters are manipulated to keep them on the intended trajectory and to qualify the beam's characteristics. The result of such simulations is a sequential listing of the design components and their parameters. Most commonly, the coordinates for the beginning of the magnetic length of a component and for the beginning of the following drift space are listed in all six degrees of freedom **in a beam following coordinate system.** In addition, a magnet's field strength, and if applicable, its bending angle is given.

3.1.1 Tolerances. Based on experience and the results of lattice simulation runs, position tolerances are determined for each magnetic component and are attached to the lattice specifications. The individual specified parameters are usually the maximum permissible displacements in the direction of the three coordinates and the rotation around the longitudinal axis. The tolerance specifications usually distinguish between absolute and relative positioning. The absolute positioning tolerance defines a maximum global shape distortion by specifying how closely a component has to be placed on its ideal location, whereas the more important relative tolerance defines the alignment quality of adjacent components. The tolerance definition needs to state also the required level of confidence, and whether or not the random distribution is truncated.

Surveying measurements, if done carefully with well calibrated sensors, will show a typical Gaussian distribution including entries outside the 1σ confidence level. To achieve the equivalent of the mathematical truncation requires not only means to identify "outliers" but also to add independent redundant observations.

Traditionally, the stochastic computations in surveying are based on a 1σ confidence level. As a rule of thumb, one can assume that the surveying effort increases almost quadratically when trying to achieve the same quality results on a one step higher confidence level.

3.2 Connection to surveying reference frame.

The relationship between the surveying and lattice coordinate systems is defined based on project and topographical considerations. For small or even medium sized projects like light sources it is easy to define a common origin. For projects the size of the SSC it becomes more involved. Geological, geophysical, tunnel construction and also radiation shielding considerations enter into the definition process. But in any case the result is a definable transformation matrix.[9]

4.0 Fiducialization

Fiducialization is a fancy name for relating the effective electromagnetic axes of components to some kind of mark, that can be seen or touched by instruments. The alignment process is one in which we move a component's reference marks to its nominal coordinate. The beam, influenced only by the electromagnetic field of a component, knows nothing about fiducials. We have, therefore, to relate the magnetic axis to the fiducial marks with the same care if not greater, as we do the final positioning.

Magnets in accelerator beam lines have, for the most part, been made with ferromagnetic poles and traditionally these pole surfaces have been used as the references for external alignment fiducials.[10] This practice assumes that the magnetic field is well-defined by the poles (which fails in the presence of saturation). It also fails in the case of superconducting magnets, which have no tangible poles. There are other well-known difficulties: the poles of an iron dipole are never perfectly flat or parallel. Where then is the magnetic mid-plane?[11] The equivalent problem for qua-drupoles or sextupoles is that there is no unique inscribed circle that is tangent to more than three of these poles; this makes it quite difficult to describe where the centerline really is.

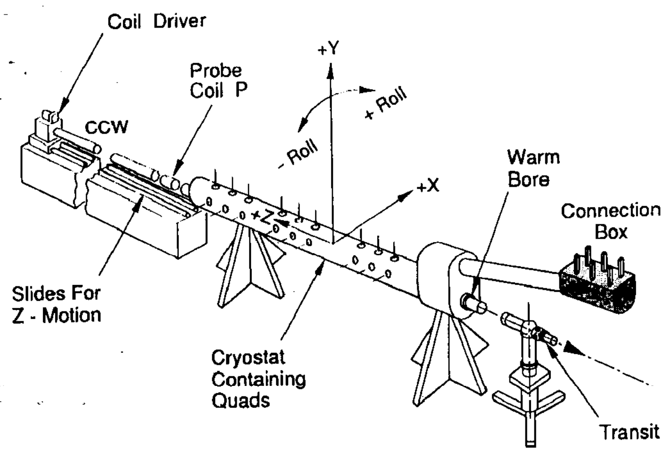

Fig. 10 Fiducialization set-up of superconducting triplet quadrupoles for SLC/SLD

The only way to avoid these problems, I believe, is to use magnetic field measurement to establish fiducials. This has already worked successfully for a number of projects like the alignment of multiple permanent quadrupoles in drift tube linac tanks in Los Alamos[12], the SLC/SLD superconducting triplet quadrupoles (see fig. 10), the HERA superconducting proton ring magnets[13] and is the method of choice for the Final Focus Test Beam project at SLAC.[14]

5.0 Absolute Positioning

Efficient computer-aided methods and procedures have been developed to increase positioning productivity, accuracy and reliability. These techniques have been tested and proved in the alignment of SLC[15], HERA[16] and LEP[17]. Consequently, for the absolute positioning task, a six step survey and alignment cycle is proposed:

Step 1	"Blue Line" Survey, on the tunnel floor,
Step 2	Prealignment of Component Modules/Girders,
Step 3	Rough Absolute Positioning of Components/Girders in Tunnel,
Step 4	Fine Alignment of Girder Components,
Step 5	Final Absolute Positioning of Girders,
Step 6	Quality Control Survey.

5.1 Blue Line Survey

In preparation for the installation of the support systems, a "blue line" survey will be performed to lay out the anchor bolt positions. This will be done from the tunnel traverse points using intersection methods. An accuracy of 5mm can be easily achieved.

5.2 Prealignment of Component Modules

A storage ring lattice is made up of cells, i.e. a sequence of dipole-quadrupole-sextupole patterns. Since the relative alignment of the adjacent quadrupole-sextupole pair has a significant impact on the machine performance, it is advantageous to combine both into a single mechanical unit. This is usually accomplished by mounting both components onto a common girder or by marrying the sextupole, which is usually much smaller than the quadrupole, directly to the quadrupole. In both cases the important relative alignment can be performed in a controlled environment rather than doing this critical task in the more hostile environment of the accelerator tunnel. However, since there is usually no provision to check their alignment status after they have been installed in the tunnel, the relationship must remain undisturbed during the transportation and installation operations. This requires that the mechanical design of the girder or frame must preclude any kind of non-elastic deflection. Traditional optical tooling techniques, industrial measurement system, or if necessary, coordinate measurement machine measurements can be employed to control the relative positioning.

For light sources the situation is different. In this case smaller components are dominated by a bulky vacuum/light chamber. Girders will be commonly used to support the components and the vacuum chamber. These girders will be loaded in an assembly factory before they are transported into the tunnel. A first prealignment will occur at that time. Since some non-elastic girder deflection is to be expected during transportation, a final fine position alignment is not warranted at this point. Consequently, this prealignment will only provide the position tolerance required for the assembly process, mainly for the insertion of the vacuum chambers. It can be assumed that 0.5 mm will suffice. Traditional optical tooling techniques or industrial measurement system measurements can easily provide the required accuracy. Once the component prealignment is completed, the magnets will be split and the vacuum chamber inserted. The chamber can be positioned using gauge blocks in respect to the magnet pole tips.

5.3 Rough Absolute Positioning of Components in Tunnel

After the blue line survey, the anchors are set and the prealigned monoliths or girders will be installed, but with the anchor bolt nuts only "hand tight". At this stage, the girders' adjustment systems are set to mid range; they will not be used for the rough positioning. A method designed and optimized to accomplish this task and particularly geared to machines built on inclined planes uses laser theodolites (see fig 11). Laser theodolites, set up on traverse points will visualize the virtual ideal position of reference marks. With inclinometers as roll control instruments, a girder or monolith with real reference marks attached will be tapped to a position where the real marks fall into the laser beam intersection.[18] 2 mm accuracy or better can routinely be achieved.

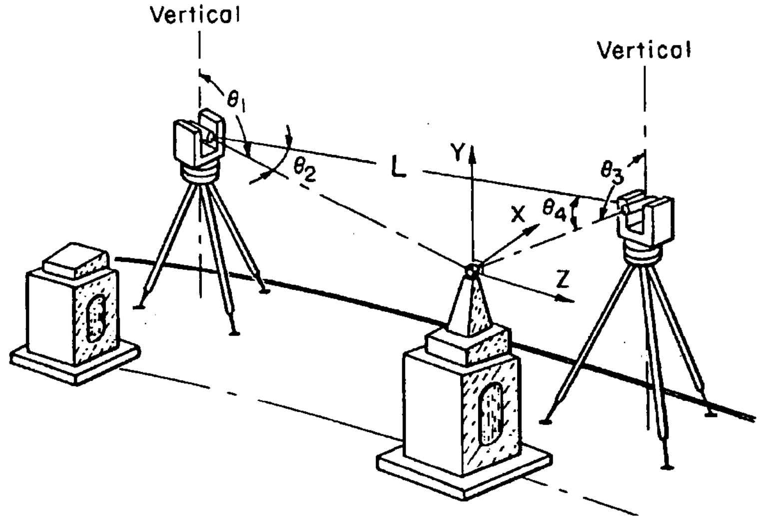

Fig. 11 Early Rendering of Lay-out Scheme

In many cases not every component or module needs to be subjected to this routine. Given, e.g., a dipole quadrupole-sextupole module type cell sequence, only the quadrupole-sextupole modules need to be rough positioned. The intermediate dipoles can be aligned in respect to the adjacent modules. Procedures following along this line are described by Schwarz[19] and Hublin.[20]

5.4 Fine Alignment of Girder Components

This step is only applicable if components are mounted on a girder which does not behave like a rigid monolith but is subject to non-elastic deformations during transport from the prealignment area to its final resting place. It more or less duplicates the previous prealignment of component module step. However, this time the components will be aligned in the girder coordinate system to achieve the final tolerances for component to component and component to girder. The first task will be to precisely level the girder; then the magnets will be brought to their ideal elevations and at the same time their pitch and roll values are set to zero using differential leveling techniques. Following the vertical alignment, the horizontal positions of the components will be set relative to the girder coordinate system. Thirdly, the vacuum chamber will be positioned.

5.5 Final Absolute Positioning of Girders/Modules

In this step, the girders/modules will be moved to their nominal position to within the prescribed tolerance. To avoid the accumulation of errors in positioning girders, the girder fiducials should not be used as a reference but rather fiducials of the two major components on the girder. Since the quadrupole/sextupole modules can be regarded as a monolith with an integral fiducial system, any suitable fiducial can be used. The first task will be to adjust the girders/modules to their ideal elevations and set their pitch and roll values to zero using differential leveling techniques. Then the horizontal positions of the girders/modules will be mapped relative to the traverse points using intersection methods. The mapped positions will be compared with their ideal values to determine the required mechanical adjustments.

5.6 Quality Control Survey

After the absolute positioning of components is completed in some logically functional section of the machine, a complete re-survey of this section should be conducted to verify the results. Quality control is better achieved by the use of independent procedures rather than the repetition of the same procedure by different teams, since data gathering with todays electronic instruments and field computers is to a large extent error-free due to on-line data validation, thereby eliminating the personal factor.[21,22]

6.0 Relative Positioning (Smoothing)

6.1 Philosophy

The absolute accuracy obtained in the absolute positioning step is the quadratic sum of many random errors (surface network, transfer of control through penetration shafts, tunnel control, magnet fiducialization, magnet lay-out, *etc.*) plus the linear sum of any residual systematic errors (instrument calibration, forced centering, set-up over control points, velocity correction of light, horizontal and vertical refraction, *etc.*). The typical error envelope for the absolute alignment of a beamline is cigar-shaped; it is a minimum (but never zero) at the control points and grows to reach a maximum midway between two successive control points (Fig. 12). The measured reference line oscillates somewhere within this error envelope. Its absolute position cannot be pinned down any more precisely than the size of the error envelope, and deviations within this envelope are statistically insignificant. However, within this absolute error envelope, relative errors between adjacent magnets should be smaller: the major error sources affect equally the positioning of adjacent components with the result that relative alignment accuracies are significantly higher than absolute alignment accuracies. Consequently, successive surveys will reveal reference lines of different shape whose absolute position floats around randomly within the cigar-shaped error envelope. An important implication of this is that the *absolute* comparison of independent surveys "would be a nonsense"[23] when trying to evaluate differences smaller than the width of the absolute error envelope. If attempts are made to proceed with final absolute alignment, the "nonsense" is that successive rounds of survey and alignment do not converge, *i.e.*, do not result in reducing the magnitude of the misalignments. All that is happening in this case is that the components are being moved back and forth within the error envelope.

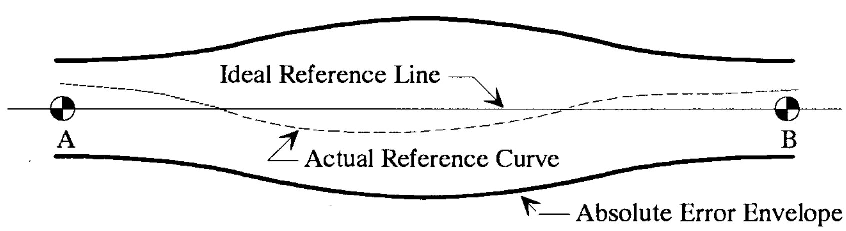

Fig. 12 Absolute Positioning Error Envelope

Because of these problems, the absolute positioning technique is not well-suited to achieving a final position tolerance. This problem was first recognized when the size of machines increased rapidly, stretching the distance between first-order monuments from 30m (CERN-ISR) to 1200m (CERN-SPS), thereby magnifying and rendering visible this effect. To overcome this problem, techniques were developed to separate relative displacements from the absolute trend curve - techniques which we now refer to as "smoothing". After the smoothing is carried out, the distribution of residuals needs to be examined by Fourier decomposition type analyses to ensure that no significant amplitudes occur at the betatron frequency.

6.2 Smoothing at DESY

6.2.1 The Evolution of Smoothing at DESY It is common survey practice to repeat elevation runs to check for ground motion on at least an annual basis. Following this practice, bench marks in the

PETRA tunnel at DESY were monitored. While comparing these type of measurements, the surveyors noted that the calculated height differences exceeded by far the expected deformations. A closer examination of the data indicated that it was contaminated by mainly two effects.

The first biasing effect was caused by the datum definition. The most common way to solve the datum problem in leveling reductions is to hold one point fixed and subsequently connect all the measured height differences to this datum point. The advantage of this method is that repetitive elevation runs can be readily compared. However, it assumes that the datum point has not moved in the mean time. Secondly, unavoidable systematic errors, mainly caused by vertical refraction, can bias differential leveling significantly.

A graphical representation of the preliminary reduced data showed some kind of a harmonic curve with its symmetry axis offset from the zero axis. It became obvious that this systematic bias can easily exceed random errors by an order of magnitude or more. As a consequence, the results from different leveling runs were not comparable. To obtain the wanted ground motion information, the biasing effects need to be removed from the signal. Among several approaches, a harmonic decomposition analysis proved successful. Complete details are given in Löffler.[24] Figure 13[25] shows the results of three annual level runs after the systematic effects had been removed. The close correlation of the ground settling trends shows clearly the successful segregation of trend and signal.

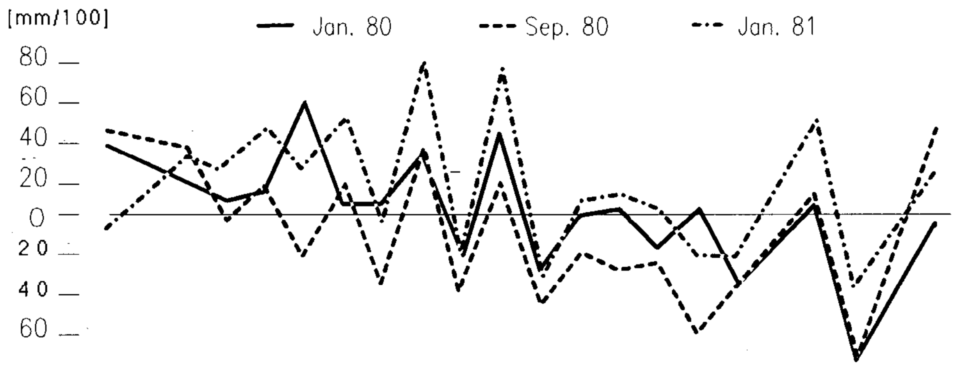

Fig. 13 Elevation Data after Removal of Systematic Effects

6.2.2 The HERA Approach In the design of the alignment procedure it was recognized that the fine alignment of HERA would require a more sophisticated smoothing process incorporating the radial position of components. To estimate the trend curve the application of polynomials, Fourier function

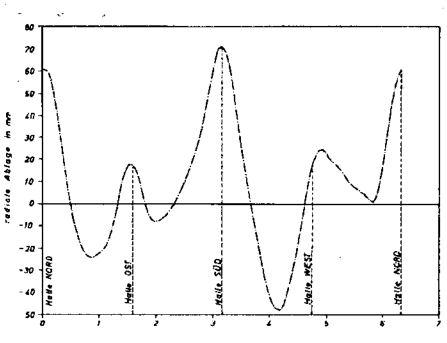

Fig. 14 Absolute radial offsets

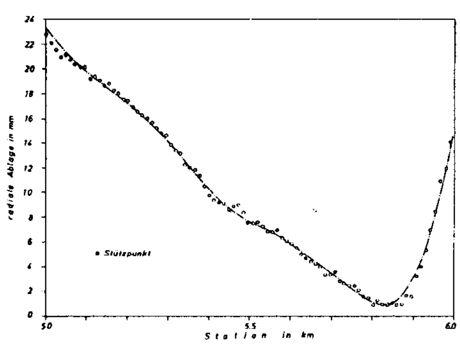

Fig. 15 Trend curve modelling of section 5 - 6km

or cubic splines were considered. Polynomials were rejected because low order polynomials do not model the short wave length behavior of the trend curve well enough and higher order ones tend to create sine wave type resonance oscillations. Fourier functions determined by spectral analysis or Fourier transformation decomposition were found suitable but too cumbersome to use.[26] The method of choice was cubic spline functions combined with an additional target function to incorporate the smoothing goal.[27] Figure 14[28] shows the computed actual radial offsets; these offsets show rather large values where the tunnel intersects the experimental halls. Since significant temperature differences had been measured between the tunnel and these halls, it can be assumed that horizontal refraction of the angle measurements caused the large amplitudes. In figure 15[29], a magnified view of the section between km 5.0 and 6.0 is shown after modelling the computed radial offset with the spline function. It can be clearly seen how well the spline modelling segregates the systematic biases. Only the differences between the computed points and the spline function will be taken care off by moving components.

6.3 The CERN Approach to Smoothing

6.3.1 Early Methods The first accelerator constructed at CERN was the Proton Synchrotron (1954-59) with a radius of 100m. Eight horizontal shafts radiating from a central survey monument at the real or actual center of the ring gave access to the beamline. The error envelope for the ring was cigar-shaped with a harmonic of order 8. Radial errors ranged from a minimum of 0.015mm at the 8 control points to a maximum of 0.15mm midway along each octant. Due to the small size of the ring and the direct access to a physical monument at the real center, this error envelope was sufficiently small for the alignment tolerances to be met by absolute alignment.[30]

The next accelerator, the Intersecting Storage Rings (1966-71), had a radius of 300m and possessed only a virtual center, i.e., no point or survey monument marked the center. During the alignment of the ISR angle measurements were replaced by offset measurements.[31] Again, absolute alignment was sufficient to meet the position tolerances, but the problem of "superimposition of successive measured figures"[32] already became controversial.

6.3.2 Radial Offset Smoothing The Super Proton Synchrotron (1971-76) presented major new challenges. The SPS was housed in an underground ring of 950m radius. Six penetration shafts enabled the transfer of survey control from the geodetic network on the surface. The absolute error envelope ranged in size from 1.3mm at each of the six control points to 2.5mm midway along each 1152m-long sextant, far exceeding the 0.15mm radial alignment tolerance. A procedure of radial smoothing was developed to achieve a relative alignment within this tolerance. Measurements were made directly from magnet to adjacent magnets with no reference to the control monuments mounted on the tunnel walls (see fig. 16[33]). This gave overlapping measurements of local curvature which were then entered into a least squares adjustment, minimizing the sum of squares of both the residuals and the radial offsets.[34] A relative alignment tolerance of about 0.08mm was achieved using this method. Vertical alignment was undertaken as a separate process, using standard leveling practices for both absolute and relative vertical alignment.[35]

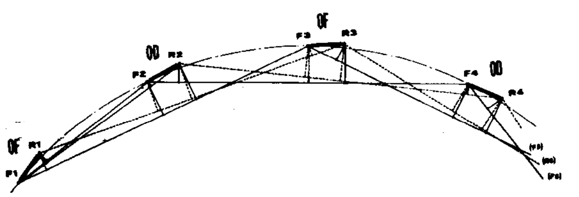

Fig. 16 Radial Offset Measurements

The same method was used for LEP (1981-89) only on a larger scale for a machine of 27km circumference within 3332m-long octants.[36]

6.4 Smoothing Techniques used at SLAC

6.4.1 The Linear Accelerator For the alignment of the 2 mile linear accelerator, a unique alignment system was developed and integrated into the accelerator support system. Approximately 300 Fresnel zone plates mounted in a 2 mile long 60cm diameter vacuum vessel provide absolute straightness information with 0.2mm accuracy.[37] However this system is not well suited for circular machines. The problem of smoothing arose for the first time at SLAC during the construction of the PEP ring, approx.. 2km in circumference.

The original PEP survey and alignment scheme is a combination of conventional surveying with computerized optical tooling type procedures.[38] The horizontal reference network in the tunnel was measured with traditional methods; the magnets are surveyed and aligned with computerized laser offset measurements. Since it was believed that the transfer of coordinates from control points to beam line components involved negligible error, a smoothing procedure, to remove systematic effects, was only applied to the control point measurements.

6.4.2 Smoothing of the SLC arc magnets The alignment tolerances set out for the SLC show how smoothness is more important than absolute positioning for beam transport.[39] For this machine, a global positioning envelope is set to ±5mm for every arc magnet, while the relative alignment of three adjacent magnets should be within ±0.1mm.

The pitch and rolled sausage-link beam line formed by the arc magnets makes this modelling particularly difficult. The absolute design shape of the path is a series of curves and straight sections in pitched and rolled planes. This form does not readily lend itself to fitting with polynomials or splines. The large coupling of the horizontal and vertical also prevents the separation of smoothing operations into two components.

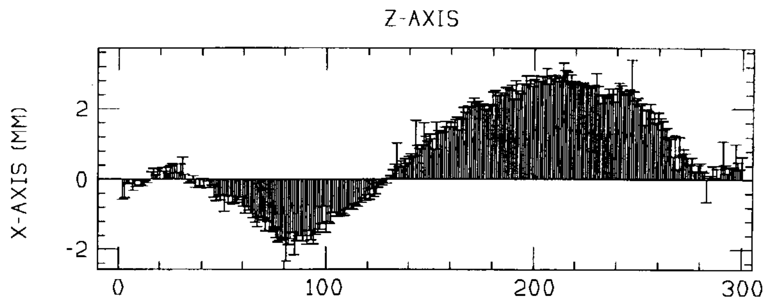

Fig. 17 Residual absolute misplacements perpendicular to beam direction

The complication of an irregularly shaped beam line was eliminated by subtracting out the actual size and shape of the beam line, leaving a series of residual misplacements for a string of magnets (see fig. 17); however, this step does not remove the correlation between the horizontal and the vertical components. Therefore, a spatial fitting routine was asked for; Principal Curve Analysis[40] was chosen to simultaneously pass a one-dimensional curve through the horizontal and vertical residual misalignment mapped out along the Z axis (beam direction). This curve will pass through the middle of the data set such that the sum of the squared errors in all variables are minimized (see fig. 18). The curve is **non-parametric** with its shape suggested by the data.

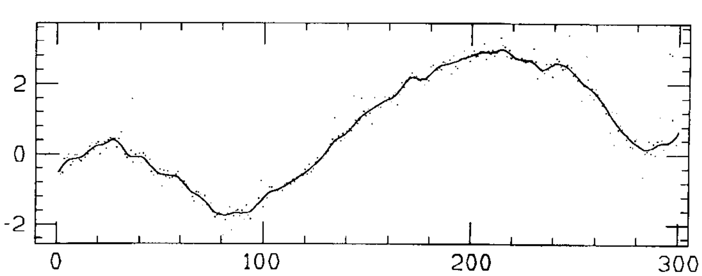

Fig. 18 Trend curve fitted through absolute misplacements

The smoothing algorithm provides the options to minimize movements of the magnets on to a smooth curve and to identify outliers. If an outlier, e.g. erroneous measurement, exists, it may artificially bias the fitting routine and draw the curve away from the general neighborhood trend. For this reason a robustness estimator is included in the modelling program to weight out these points.

One improvement was suggested through experience. This involved the independent weighting of points, so that a small area of magnets can be "patched in" to existing elements. This technique proved tremendously helpful when recovering from the effects from the 1989 earthquake (see fig. 19).[41] Another improvement made it possible to deal with irregularly spaced and patterned beam line lay-outs.

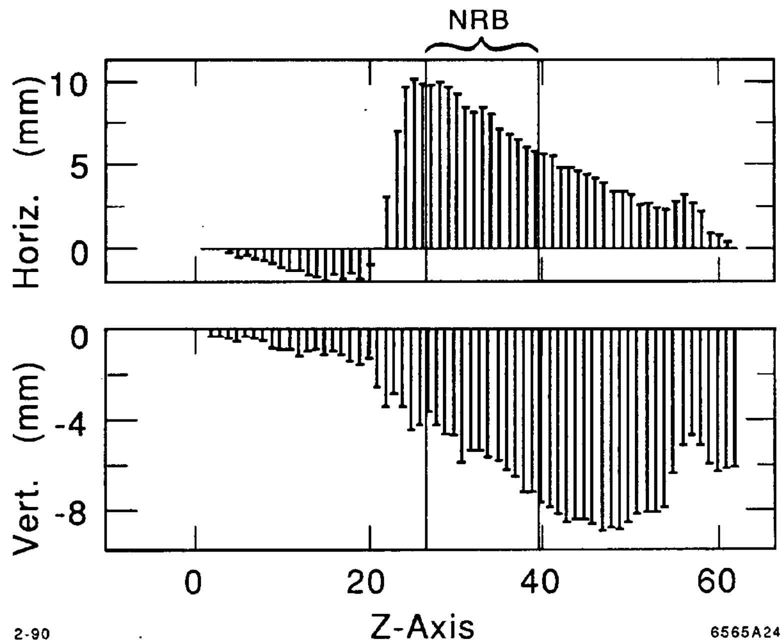

Fig. 19 Radial displacement of 12mm caused by 1989 earthquake

6.5 Smoothness Criteria

There are two major questions to which we only have tentative answers.

The question: "What is smooth?" must be answered. If the data suggests the form, then there is the hazard of too closely fitting the misalignments and not smoothing enough. We need to pursue discussions with lattice physicists to see whether beam modelling data from computer simulation programs can help with this problem.

Smoothing is our tool to achieve **relative** alignment. But how is **relative** defined?[42] The measure by which the survey and alignment engineer judges whether an alignment operation has achieved its goal, is the standard deviation of the determined parameters. The standard deviation in fact is a product of the same least squares adjustment as the parameter itself; it is computed from the coefficients of the variance/co-variance matrix. The variance/co-variance matrix is directly related to the normal equation of the least squares operation and hence to the network configuration. If one changes e.g. the datum definition, the shape and the size of the error ellipses changes. It would therefore be desirable to define a datum-independent measure of accuracy. So far there seem to be two approaches to solve this problem. Schwarz[43] suggests using the standard deviations of the calculated perpendicular distances of magnets from a common reference line. These values could be calculated

as a function of the unknowns in the same least squares routine which is run to reduce the data. At SLAC, we have for testing purposes integrated into data reduction programs a procedure suggested by Chrzanowski[44]. He developed an algorithm to compute relative error ellipses independent of the datum definition for a better prediction of break-through errors in tunnel construction.
Unfortunately, these problems have not found wide recognition and will require considerably more study.

7.0 Circumference Correction

With the latest generation of machines, especially with "multi ring circus" type machines, the circumference tolerances have become very tight. Very often, the absolute positioning step cannot yield these tolerances. Therefore, correction methods have been developed at DESY and SLAC, to cope with this situation. However, it should be pointed out, if the ring has a distribution of rf cavity systems, distances between the cavities should be appropriately adjusted.

7.1 DESY's Circumference Correction Method

After the smoothing step of a logical unit, one sextant or octant, is completed, a longitudinal distance survey over magnets is performed yielding, after reduction, the distances between vertex points. An integration of these distances will show the actual circumference. Comparison with the design value will give a proportional difference. The correction is created by inserting artificial smooth bumps to lengthen the circumference or by shortening the radial coordinate of a section of the ring to reduce the circumference. The spline trend estimation is applied to these sections to ensure local smoothness.[45]

7.2 The Approach at SLAC

The SLAC approach is very similar to DESY's. The only difference is that the circumference reduction is incorporated into the smoothing process in such a way that the smoothing alignment correction already includes any circumference correction.

8.0 Conclusion

The survey and alignment tasks described above pertain to a static situation. Under the assumption that the components are not moving significantly due to ground motion or thermal expansion of the supports or tunnel/building, then the described approach will satisfy the requirements. However, if significant position variations are to be expected, then a dynamic survey and alignment system may be called for. An example is the dynamic vertical survey and alignment system for the ESRF storage ring which is presently under construction.[46] Geophysical investigations showed that the poor soil conditions most likely would not provide the stability for a successful operation of the light source. The next generation of linear colliders will require a fully dynamic vertical and horizontal survey and alignment system. Already movements caused by daily temperature variation are expected to impede the performance of these new machines. Therefore, the FFTB project at SLAC will for the first time incorporate a dynamic horizontal and vertical survey and alignment system designed to hold the relative position of sensitive components stable to 5μm and the absolute position to better than 30μm.[47] It is my belief that the dynamic alignment systems will become an every-day part of survey and alignment systems as positioning and stability requirements are tightened and the technology becomes more widely available.

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It is a pleasure to be able to acknowledge discussions with Gerry Fischer and Bernard Bell at SLAC and Horst Friedsam's, (SLAC), support in running the computer simulations. Thanks also to Franz Löffler, DESY, Michel Mayoud, CERN, and Will Oren, CEBAF, for sharing their thoughts on smoothing.

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