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SETTING REFERENCE TARGETS[♣*]

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Abstract
Reference Targets are used to represent virtual quantities like the magnetic axis of a magnet or the definition of a coordinate system. To explain the function of reference targets in the sequence of the alignment process, this paper will first briefly discuss the geometry of the trajectory design space and of the surveying space, then continue with an overview of a typical alignment process. This is followed by a discussion on magnet fiducialization. While the magnetic measurement methods to determine the magnetic centerline are only listed (they will be discussed in detail in a subsequent talk), emphasis is given to the optical/ mechanical methods and to the task of transferring the centerline position to reference targets.

1 INTRODUCTION

Particles travel undisturbed on their design trajectory only when the magnetic axes of all beam steering components form a smooth continuous line in space. In addition, the axes of diagnostic instruments need to coincide with the particles' trajectory for good performance. Establishing these positioning conditions is the goal of the alignment process. The setting of reference targets is a key task in this process. These targets represent physically what otherwise cannot be accessed or referenced. In the task sequence of the alignment process, reference targets are used to represent the surveying coordinate systems (i.e. the surface net and the tunnel net), the geometric or electrical axes of diagnostic instruments, and the magnetic axes of the beam steering components.

The following definition conventions are used throughout the text: reference targets in the context of coordinate systems are referred to as *monuments*, and in the context of beam steering components or diagnostic components they are called *fiducials*. *Surveying* refers to measuring the position of an object, while *alignment* describes the action of adjusting an object's position.

2 REFERENCE TARGETS

Reference targets are used to represent virtual entities like the magnetic axis of a magnet or a coordinate system, which otherwise cannot be physically accessed. The design of the targets is a function of the survey and alignment instrumentation used with these targets, the placement location, the physical size of their host component if applicable, and the required measurement accuracy. In general, reference targets can be categorized by whether they are fixed installed targets or removable and by the number of degrees of freedom they reference.

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2.1 Fixed or removable fiducials

While fixed targets have an advantage in terms of accuracy, removable targets or fixtures can have a significant cost advantage. In beam lines where hundreds of structurally identical magnets are used, a limited number of fixtures can substitute for hundreds of fixed fiducials

2.1.1 Fixtures

Because of favorable magnetic properties, magnets are often constructed from stacked laminations. The same die is used to punch these laminations for all magnets, even for a large quantity. The dimensional features of the die can be machined to high accuracy, and are usually verified before and during use. Consequently, the mechanical dimensions of the laminations are very precise and their mechanical axis should coincide closely with the magnetic axis. Hence, it is possible to forego the fiducialization of individual magnets and instead reference the magnetic axis using clamp-on fixtures. These fixtures are seated in reference grooves and carry the actual targeting (see fig. 1, 2).

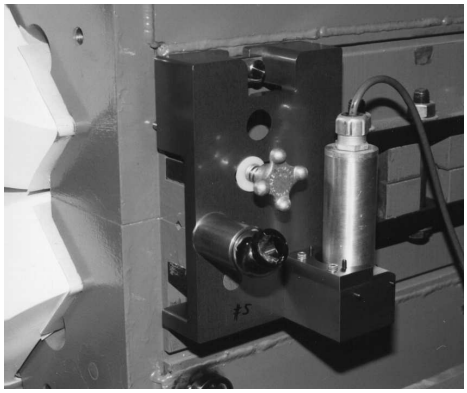

Fig. 1 Alignment fixture on quadrupole with reflector and inclinometer

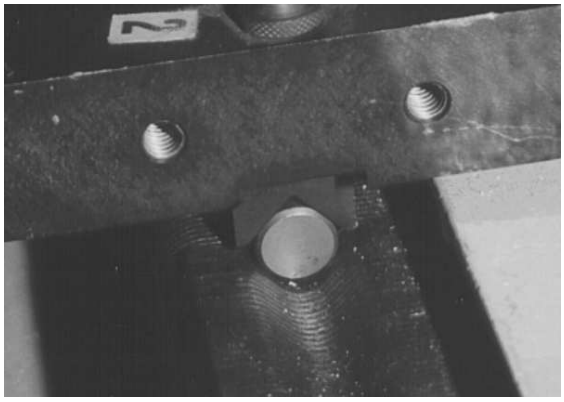

Fig. 2 Fixture referencing in lamination groove

2.1.2 Fixed fiducials

Usually, the fiducials are installed directly on the top or side of a magnet. While three fiducials, or two fiducials plus a roll reference surface are sufficient to reference all degrees of freedom, additional fiducials provide redundancy for error checking. If it is necessary to separate the fiducial from temperature caused expansion or contraction of the magnet body due to tight positioning requirements, the fiducials can be mounted on fiducial plates (see fig. 3). These plates, made of invar, reference to the split planes of the magnet. Since the split planes do not move due to temperature, and since invar has a negligible expansion coeffi cient, the fiducial position can be considered invariant with temperature.

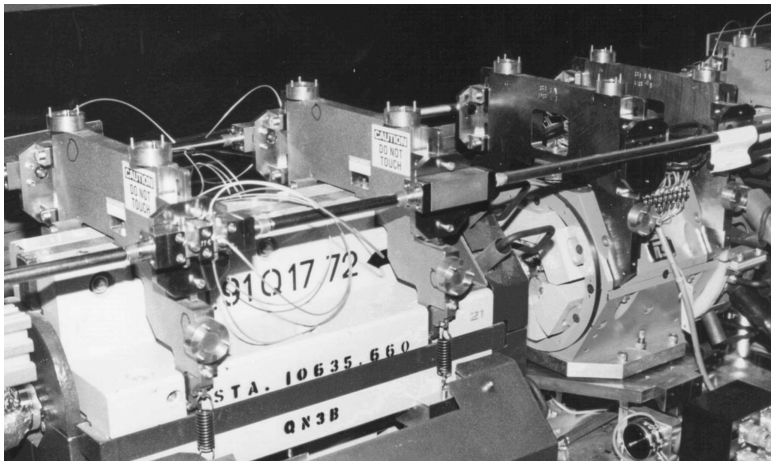

Fig. 3 Fiducial plates

2.2 Fiducial and Monument Designs

2.2.1 One-Dimensional Reference Targets

Traditionally, coordinate systems were represented by 2+1 D monumentation. Separate reference marks were used to represent the horizontal (2-D) and vertical (1-D) coordinate systems. Typical 1-D designs are rivets grouted into the floor (see fig. 4) or leveling bolts set into walls (see fig. 5).

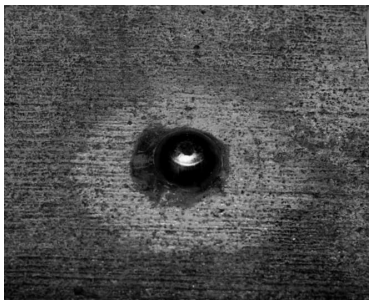

Fig. 4 Leveling rivet

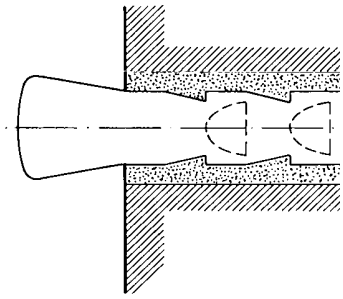

Fig. 5 Leveling wall bolt

Fig. 6 Scribe line

2.2.2 Two-Dimensional Reference Targets

The most basic 2-D reference mark can be scribe-lines on the floor (see fig. 6, 7) or stick–on targets. A variation is the SLAC SLC floor-marks; to protect the stick-on targets from traffic wear, they are mounted inside small metal cans which are grouted into the floor (see fig. 8). Other 2-D references are the standard Leica and Kern forced centering mounts. The Kern mount is commonly used on pillar monuments representing surface network points (see fig. 9).

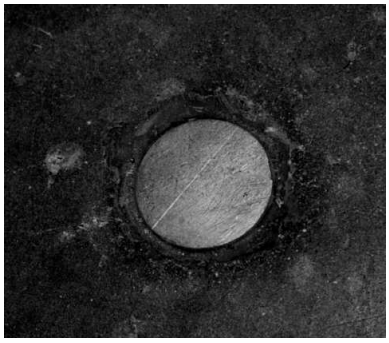

Fig. 7 Brass plug with scribe line

Fig. 8 SLAC 2-D target

Fig. 9 Monument centering

2.2.3 Three-Dimensional Reference Targets

3-D reference marks provide both horizontal and vertical reference.

Tooling Ball Reference The most inexpensive kind of a 3-D reference are tooling ball holes drilled into the bodies of components or tooling ball bushings tack-welded onto components (see fig. 10). Common tooling balls inserted into the hole or bushing (see fig. 11) provide an excellent reference for leveling mini-rods or optical tooling blades. For optical pointing, the tooling balls can be exchanged for targets with identical dimensions but with a cross hair or other target pattern at the

exact center of the virtual sphere (see fig. 12). For distance measurements, reflector tooling balls are available, which have glass or air cubes mounted into the sphere such that the optical center of the reflector coincides with the center of the sphere (see fig. 13). Commonly, tooling balls with either a 0.5 inch head diameter or a 0.875 inch head diameter are used.

Fig. 10 Tooling ball bushing

Fig. 11 Tooling ball in bushing

Fig. 12 Theodolite target

Fig. 13 TB mounted reflector

1.5 inch Sphere System The equivalent of the tooling ball bushing for the 1.5 inch sphere system is usually referred to as a nest. A three-point mount provides a kinematic centering for the sphere. Also used are mounts with conical surfaces (see fig. 14). As with tooling ball targets, the 1.5 inch sphere can be host to a variety of target patterns and applications (see fig. 15). A sphere-mounted reflector with front mirror surfaces (air cube) is the commonly used laser tracker reflector.

Fig. 14 Floor sphere mount

Fig. 15 1.5 inch sphere mounted targets

3.5 inch Sphere Target The 3.5 inch standard is the evolutionary ancestor to both of the other two target systems. These spheres are a traditional item in optical tooling based alignment. As with tooling ball targets and 1.5 inch sphere targets, the 3.5 inch sphere can be host to a variety of targets (see fig. 16, 17). However, because of its bulkiness, the 3.5 inch standard is rarely used anymore. A flavor of this size standard is the CERN socket (see fig. 18), where a sleeve clamps a 3.5 inch sphere with a 30mm bore onto a conical surface. This design provides the flexibility to adjust the sphere such that the bore is parallel to gravity. Using a special mounting adapter, targets and instruments can be mounted with reference to gravity on sloped surfaces (see fig. 19).

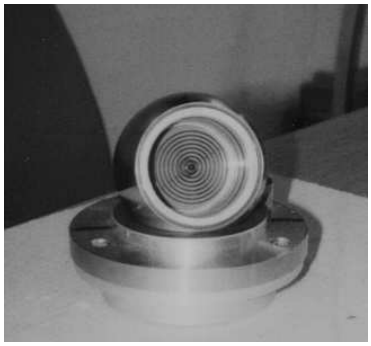

Fig. 16 Taylor-Hobson sphere

Fig. 17 TH reflector

Fig. 18 CERN socket

Fig. 19 CERN socket with E2

3. TRAJECTORY DESIGN SPACE

Three translations and three rotations define the position of any object in space with respect to a Cartesian coordinate system. These values are a function of the design beam trajectory, the position of magnetic fields along the trajectory, and of the placement of the trajectory on our earth.

3.1 Design Trajectory

Codes like MAD[1], NOMAD, or TRANSPORT[2] are used to trace the path of particles through idealized magnets. The particles' path is described by a sequence of beam elements placed sequentially along a reference orbit. The reference orbit consists of a series of straight-line segments and circular arcs. A beam following coordinate system describes the orientation of the beam at any point along its path through the accelerator (see fig. 20). This system remains tangent to the orbit with its positive z-axis pointing downstream. The system is rotated such that the positive x-axis generally points out from the bending arc and lies in the plane of the curve. The positive y-axis is oriented to complete the right-handed coordinate system for the local beam. To transform the local coordinates into the global system, three shifts and three rotations are applied. Care has to be taken with the sequence of the rotations and their signs (see Table 1).

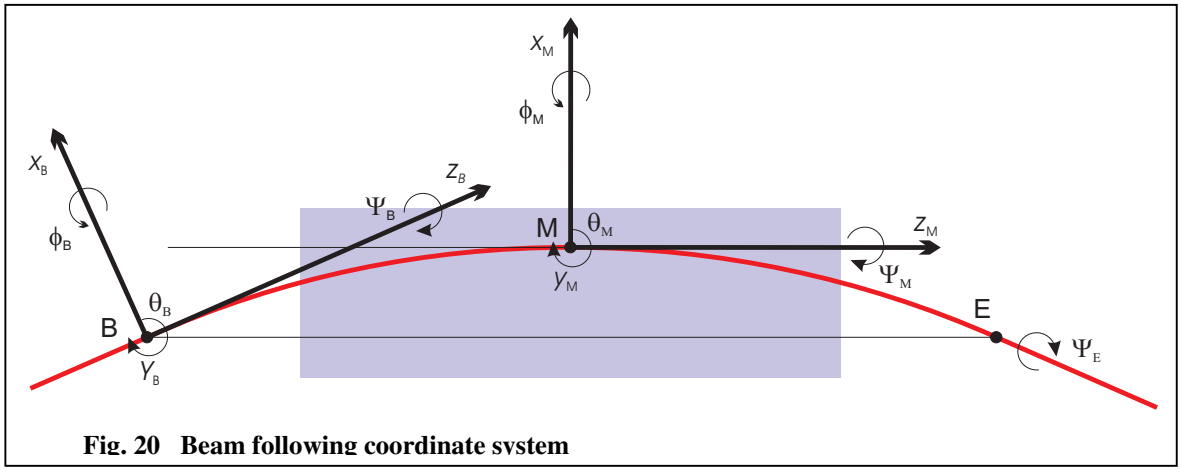

Fig. 20 Beam following coordinate system

	MAD	TRANSPORT	Alignment
Yaw, around y-axis θ	Positive, when z-axis turns towards x-axis	Same as MAD	Same as MAD
Pitch, around x-axis Φ	Positive, when z-axis turns towards y-axis	Same as MAD	Opposite
Roll, around z-axis Ψ	Positive, when x-axis turns towards y-axis	Same as MAD	Same as MAD

Table 1 Rotation sign definitions[3]

The output of the above mentioned codes gives three coordinates and three rotations for the beginning and end of each straight section and arc in the beam following system. It is now the magnet engineer's job to design a component, which replicates its virtual cousin's parameters.

3.2 Magnet Reference Target Parameters

3.2.1 Magnet Coordinate System

The parameters of the reference targets of a magnet are defined in the magnet's local coordinate system. The u, v, w coordinate axes form a right-handed Cartesian system. The positive orientation of the axes is defined in the same way as for the x, y, z beam-following local coordinate system. The datum of the u, v, w system relative to a magnet is not universally defined. While the w coordinate axis is usually coincident to the magnetic axis and the u-w plane parallel to the zero roll plane, there are differences in the definition of the origin. Often, the origin is placed where the beam enters the magnetic field. This is a virtual point and requires entering empirical data into the fiducialization

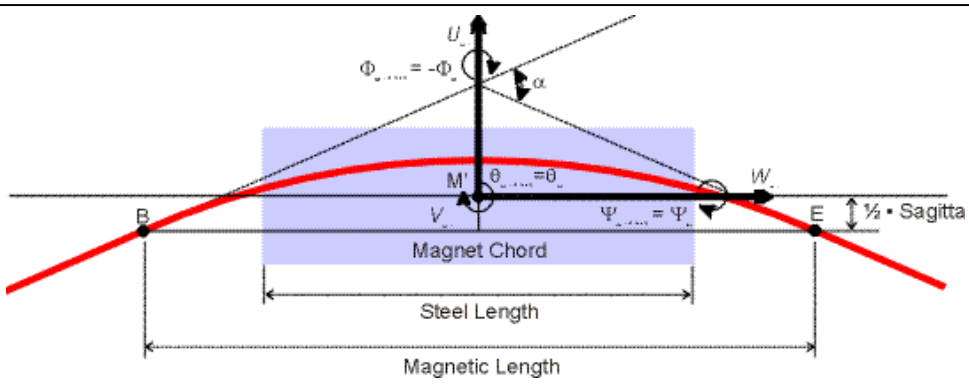

Fig. 21 TRANSPORT magnet geometry

process. At SLAC the midpoint of the magnet is the origin (see fig. 21). Since the midpoint of the magnetic length usually coincides with the midpoint of the steel length, the origin can be physically determined without knowing the difference between magnetic and steel length.

3.2.2 Roll

The split planes of magnets are often accepted as the zero roll planes. However, if necessary, zero roll planes can be determined to better accuracy with magnetic measurement methods. A dipole's roll can be measured by running a horizontal wire in a vertical plane. No voltage is induced if the magnetic field is oriented perpendicular to this plane. Hence, by adjusting the magnet's tilt around the w-axis until no voltage is induced, the zero roll position can be determined. In the case of a quadrupole, no voltage is induced if a wire moves radially relative to one of the poles. If, e.g., a quadrupole's pole design position is at a 45º angle, this method allows determination of the true 45º-field plane. From there it is straightforward to determine the zero roll position.

In some instances, a geometrical correction to the design program's roll value for dipoles needs to be applied. The w-axis of dipoles does not coincide with the x-axis of the beam-following coordinate system. Hence, if the origin of a dipole's coordinate system has been fixed where the beam enters the magnetic field, the roll value from the trajectory design program does not reflect the correct dipole roll angle (see fig. 22). A correction, which is a function of half of the dipole's bending angle, needs to be applied. However, if the magnet's coordinate system originates at the midpoint, then the design program's beam-following roll at the midpoint is the correct physical magnet roll

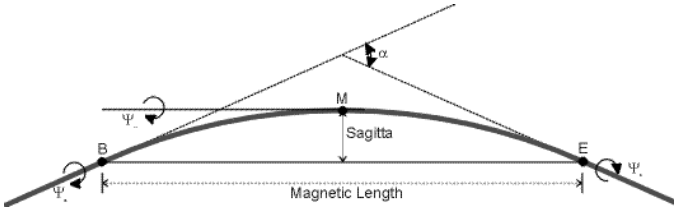

Fig. 22 Transport geometry

Larger machines need to take into account the convergence of the gravity vectors (see fig. 23) While in circular machines magnets at diametrically opposing locations are at the same elevation, their ideal roll values need to be corrected. E.g. for PEPII the correction amounts to about 0.15 mrad, SSC magnets would have needed a 1.5 mrad correction. Also, other geodetic corrections related to the beam line's geometry may apply (see following chapter).

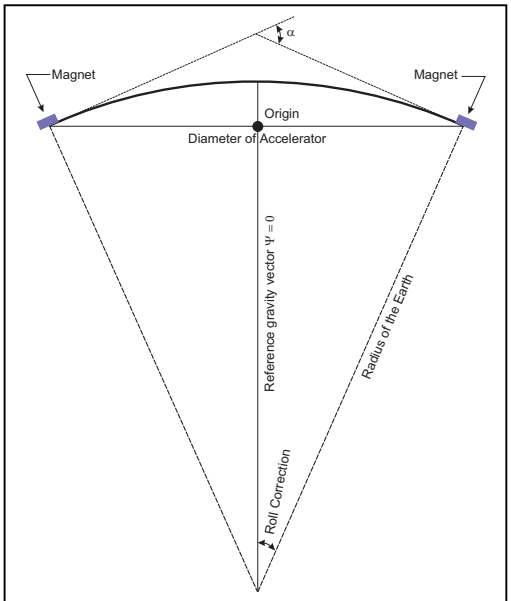

Fig. 23 Roll correction

3.2.3 Sagitta

In the dipole case the magnet is usually not centered at the midpoint, but shifted by a fraction of the sagitta height (see fig. 21 above). This shift minimizes the necessary aperture to accommodate a straight beam pipe, and moves the beam into the homogenous field region of the magnet. The amount of the shift varies. It is typically set to half of the sagitta, but two thirds are also not uncommon.

3.3 Global Reference Points

Global reference points are used to determine the overall shape of an accelerator. With the exception of small machines, these points represent the global coordinate system in the form of pillar monuments on the surface and floor marks in the tunnel.

3.3.1 Shape of the Earth and Survey Reference Frames

The goal is to define a computational reference frame, i.e. 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 layout coordinate system must be defined.

Ancient civilizations realized that the earth is round, and geodesy was born when the Greek Eratosthenes (born 276BC) first attempted to determine its size.[4] The earth is actually of a more complex shape, the modeling of which is not easy. Three surfaces are of importance to the geodesist studying the shape of the earth:

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

- *Geoid* 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 than the earth's surface, it is still irregular due to local mass anomalies that cause departures of up to 150 m from the reference ellipsoid. As a result, the geoid is nonsymmetric and its mathematical description nonparametric, rendering it unsuitable as a reference surface for calculations. It is, however, the surface on which most survey measurements are made as the majority of survey instruments are set up with respect to gravity.

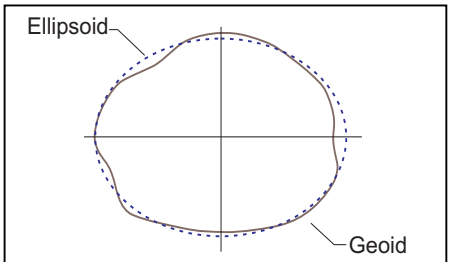

Fig. 24 Ellipsoid and geoid

- *Ellipsoid* 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. 24). Being a regular mathematical figure, it is the surface on which calculations can be made.

In performing geodetic 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. 25). Several different ellipsoids have been defined and chosen that minimize geoidal discrepancies on a global scale, but for a survey-engineering project, it is

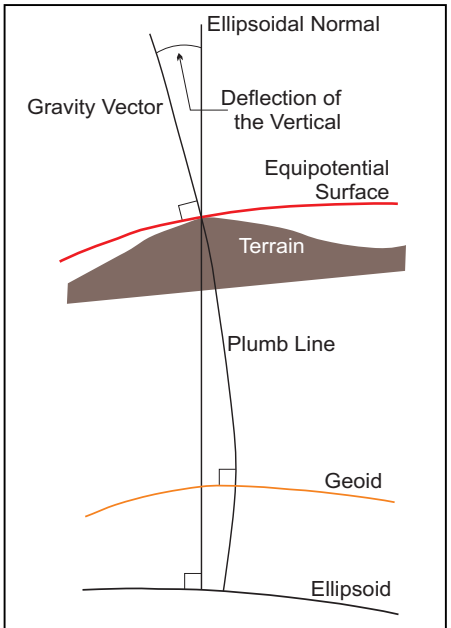

Fig. 25 Deflection of the Vertical

sufficient to define a best-fit local spheroid that minimizes discrepancies only in the local area. Whatever ellipsoid is chosen, all survey measurements must be reduced to the ellipsoid before computations can proceed. This reduction of observations to the computational surface is an integral part of position determination;[5] the equations can be found in most of the geodetic literature, e.g., in Leick.[6]

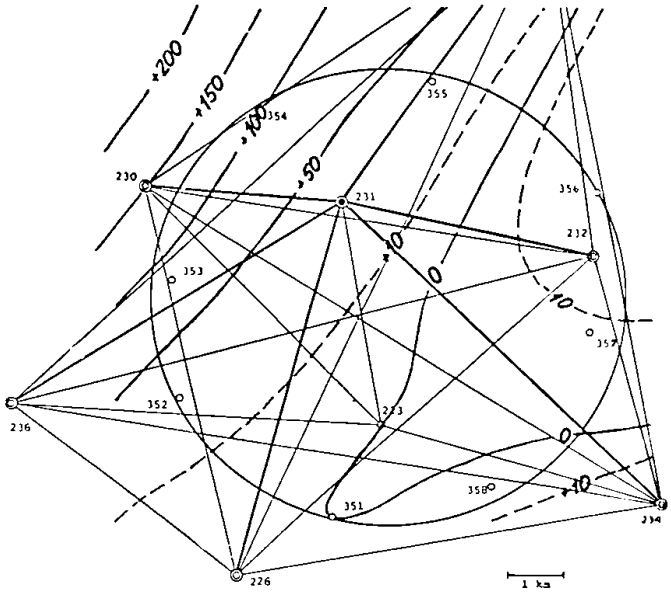

Fig. 26 LEP Geoid undulations (from [7])

For large projects, the magnitude of these corrections is significant. A geoidal height determination was part of the LEP surface net measurement plan. It was found that the vertical deflections approached close to 15 arc seconds, which resulted in a separation between the local reference ellipsoid and the geoid of up to 200 mm (see fig. 26). To nevertheless obtain a true plane in space, corrections varying between –40 mm and +100 mm had to be applied to the leveled elevations.[7]

3.3.2 Surveying Coordinate System

Computations with spheroidal (geographical) coordinates latitude ϕ, longitude λ, and height h are complex. They are also not very intuitive: when using spheroidal heights, it can appear that water is flowing uphill. Especially in survey engineering projects, coordinate differences should directly and easily translate into distances independent of their latitude on the reference spheroid. 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.

A transformation is required to project points from a spheroidal surface to points on a plane surface. Depending on the projection, certain properties of relationship (distance, angle, etc.) between the original points are maintained, while others are distorted. It is simply not possible to project a spherical surface onto a plane without creating distortions[8] (see fig. 27), but since these distortions can be mathematically modeled, it is possible to correct derived relationships, such as distances, angles, or elevations. This situation can be vividly shown in the example of the projection of leveled elevations onto a planar coordinate system (see fig. 28). Table 2 shows the projection errors as a function of the distance from the coordinate system's origin. Notice that the deviation between plane and sphere is already 0.03 mm at 20 m.

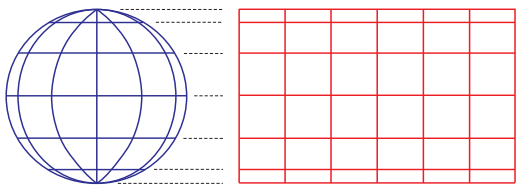
Fig. 27 Mapping distortion

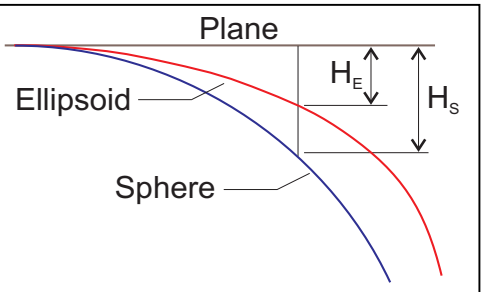

Figure 28 Curvature Correction

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

Table 2 Effect of Earth Curvature

3.3.3 Survey Networks

Monuments physically represent the surveying coordinate system. The coordinates of these monuments are determined using conventional trilateration or triangulation methods or, for larger size projects, satellite methods like the Global Positioning System.[9]

Surface network In order to achieve the absolute tolerance and the circumference requirements, a surface network (see fig. 29) with pillar-type monuments (see fig. 30) must usually be established. Traditional triangulation and trilateration methods or GPS surveys can be applied to measure 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 coordinates. Proper reduction of measured distances also requires accurate elevation difference data.

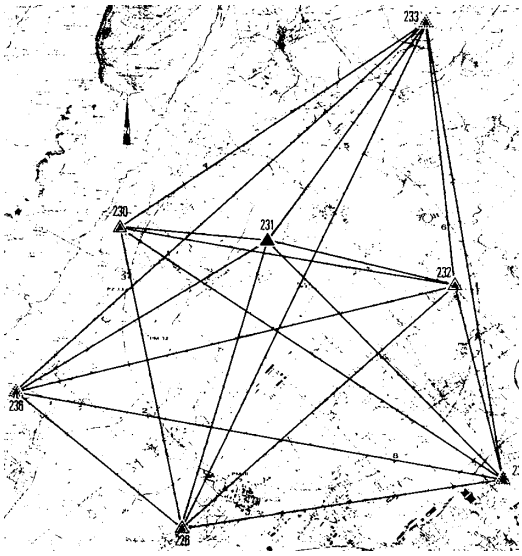

Fig. 29 LEP Surface network

Fig. 30 Monument pilar

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 2 mm + 1 ppm. In medium size applications, it has been shown that GPS, combined with terrestrial observations and careful control of the antenna eccentricities (GPS, too, has its fiducialization problems), can yield positional accuracies of about 2 mm.[10] In large projects, like the SSC or LEP, positional accuracies of about 10 mm can be achieved using two-frequency GPS receivers. Trigonometric and differential leveling are the only accurate methods to determine elevations; both

methods yield the same accuracies—approximately 1 mm for networks smaller than 2 km, and 20 mm for a SSC size network.

Tunnel Tunnel networks are usually long and narrow (see fig. 31), and incorporate points beneath the shafts as connections to the surface net. The monument system can be 2-D (horizontal only) or

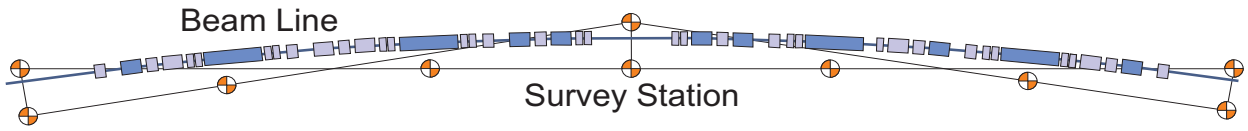

Figure 31 Tunnel network

3-D: common designs are the SLAC 2-D marks, the DESY-HERA 3-D reference cups or the standard 1.5 inch floor cups and magnet mounts (see fig. 11 in 2.3.2). Some kind of tripod or column-like monopod is used for the instrument setup. The SLAC setup (see fig. 32) is designed to accommodate slopes of up to 15°; the HERA design is more optimized towards efficiency, virtually eliminating the task of centering instruments and targets over monuments (see fig. 33).[11] The elevation of the instrument above the 3-D reference cup is known very accurately, which facilitates 3-D mapping with theodolites. Both set-up types are forced centered over known points. Laser tracker and the more recent generation of Total Stations allow the efficient use of the free stationing method (see fig. 34).

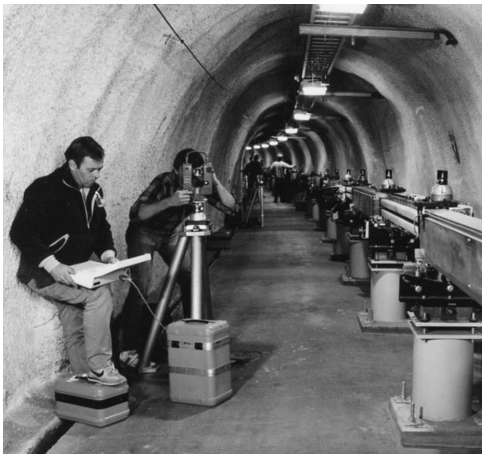

Fig. 32 SLAC instrument set-up

Fig. 33 HERA instrument set-up

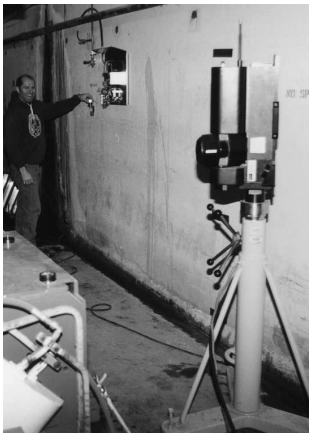

Fig. 34 Free stationed laser tracker

4 FIDUCIALIZATION

Fiducialization is a fancy name for relating the effective electromagnetic axes of components to some kind of mark which can be seen or touched by instruments. The beam, influenced only by the electromagnetic field of a component, knows nothing about fiducials. It is therefore of at least the same importance to accurately relate the magnetic axis to the fiducial marks as to correctly position the marks to their nominal coordinates. The term fiducialization is commonly also used to describe the task of relating the axis of mechanical components to their marks. These marks are then aligned to the nominal positions calculated with the information described in the previous chapters.

Fiducialization is a two step process: firstly, the axis of the component is determined, and secondly, the axis position is related to the fiducials.

4.1 Determination of Centerline

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 reference for external alignment fiducials. This practice assumes that the magnetic field is well defined by the poles. However, this fails in the presence of saturation and in the case of superconducting magnets, which have no tangible poles. There are other well-known difficulties: the poles of an iron magnet are never perfectly flat or parallel. Where is then the magnetic mid-plane?[12] The equivalent problem for quadrupoles 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.

While without a doubt the electro-magnetic determination of the centerline is the most accurate method, quite often, budgetary, time, or other constraints make it necessary to rely on mechanical means.

4.1.1 Mechanical Representation of Axis

Design Dimensions Magnets are often constructed from stacked laminations, what guarantees very repeatable dimensions. This permits the design of features into the shape of the laminations, which have a known and accurate relationship to the mechanical axis. Most commonly, these features have the shape of grooves or edges (see fig. 2 above). As already described in chapter 2.1.1, these features can be used to reference fixtures with targets, which then in turn will represent the centerline.

Bore Target and Mandrel If magnets could be machined perfectly, a bore target (see fig. 35) in the shape of a short cylinder with the nominal bore diameter would touch all four poles of a quadrupole. Since these required tolerances can hardly be achieved with affordable fabrication methods, the target is likely to touch only three of the poles. This method is therefore limited to lower accuracy applications, unless the typical method is modified. This improvement is accomplished by moving the target in the bore such that the target sequentially references different sets of poles. These four target positions, in case of a quadrupole, describe a circle. The center of this circle references the mechanical axis.

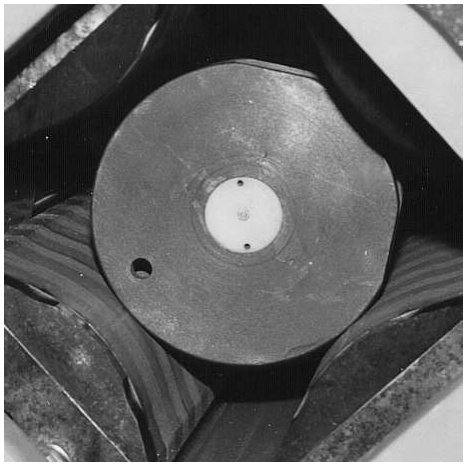

Fig. 35 Bore target