CONTROL SURVEYS FOR UNDERGROUND CONSTRUCTION OF THE SUPERCONDUCTING SUPER COLLIDER

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ABSTRACT

Particular care had to be taken in the design and implementation of the geodetic control systems for the Superconducting Super Collider (SSC) due to stringent accuracy requirements, the demanding tunnelling schedule, long duration and large size of the construction effort of the project.

The surveying requirements and the design and implementation of the surface and underground control scheme for the precise location of facilities which include approximately 120 km of bored tunnel are discussed. The methodology used for the densification of the surface control networks, the technique used for the transfer of horizontal and vertical control into the underground facilities, and the control traverse scheme employed in the tunnels is described.

1. INTRODUCTION

The Superconducting Super Collider (SSC) is being built by the U.S. Department of Energy at a cost of $8.4 billion. Situated near Waxahachie, 40km south of Dallas, the device will be the world's largest accelerator of sub-atomic particles. The main SSC ring (Figure 1) will be placed underground in a nominal 4.2m diameter, 87km long tunnel. Additional components, including boosters and injectors involve a further 9km of cut-and-cover excavation and 28km of bored tunnel. The main collider ring will be connected to the surface by clusters of vertical shafts which provide access for personnel, utilities, ventilation and equipment including the 17m long magnet cryostats. These shafts are located on the Service Areas at intervals of approximately 4.4km around the ring.

The main collider tunnel and the tunnels for the boosters, injectors and transfer lines must be positioned - in the horizontal and vertical dimensions - to within ± 8inches (200mm) of their designed locations. This tolerance includes ± 3inches (76mm) for surveying control with the remaining portion of the tolerance budgeted for tunnel boring machine (TBM) guidance variations. Tunneling will be accomplished using as many as six simultaneous TBM drives at different locations along the ring.

For design purposes, the given tolerance of 76mm for control surveys was taken as the maximum permissible error at the 99% level of confidence. The vertical accuracy requirement for the pouring of the final tunnel invert depends on such factors as the adjustment range of the magnet stands and on the degree of vertical 'smoothness' required for magnet alignment. The tolerance for relative vertical positioning is ± 0.5 inches (12mm).

2. SURFACE CONTROL NETWORKS

The horizontal surface control is provided by a Global Positioning System (GPS) network which was observed using dual frequency equipment and processed using the US Defense Mapping Agency precise ephemeris [7]. The GPS does not provide a stable reference frame because scale and rotational variations may occur over a long time period [3]. Therefore, at the SSC, the horizontal datum is realized by a fiducial network of massive concrete monuments. Owing to the problem of expansive soils in the area, these monuments are sleeved to sufficient depths to isolate the pillars from the soil. The majority of these monuments is anchored in competent bedrock. In addition, nine fiducial monuments are equipped with inverted pendula which provide independent checks on stability. This network consists of 22 points and is augmented by a number of similar monuments which serve as calibration lines for gyro-theodolites and EDM instruments (Figure 1). The network was designed to yield a maximum relative horizontal positional accuracy across the SSC ring - a distance of approximately 30km - of 15mm at the 99% level of confidence.

The primary vertical control network consists of 130 deep benchmarks, all of which are sleeved and grouted to competent bedrock. The network includes 600km of double-run leveling which was observed to slightly more stringent requirements than U.S. Federal Geodetic Control Committee (FGCC) First Order Class I standards. The network was designed to yield a maximum relative vertical height difference accuracy across the collider ring of 10mm at the 99% level of confidence.

3. CONTROL NETWORK DENSIFICATION

The possibility of the occurrence of temporal variations in the Global Positioning System coupled with the difficulty of finding stable locations for monuments has resulted in the development of a strategy for piecemeal densification of the fiducial networks [3]. Thus, control points are established in the vicinity of each shaft shortly before the start of the control transfer survey. Simple concrete monuments are used because stability is only necessary for a few days at most - the time needed for the densification and transfer operations.

The points are connected to at least five fiducial stations and they are distributed in such a way that they provide good positional and azimuthal control in the vicinity of each shaft. The densification networks are measured by means of GPS using procedures similar to those employed for the mensuration of the fiducial network.

The integrity of the fiducial network is checked prior to adjustment. The validation process follows five distinct steps. The stability analysis methodology is described in [2]:

1. The re-observed portion of the fiducial network is adjusted with minimum constraints by holding the original coordinates (x_0, y_0) of one of the re-observed fiducial stations fixed. A

set of displacements (dx, dy) between the original and re-adjusted positions of the stations is obtained.

2. A stability analysis is performed using an Iterative Weighted Similarity Transformation (IWST) of the displacement components to test the relative stability of the existing fiducial points used in the densification survey. In order to perform the IWST, the original variante-covariance matrix of the fiducial stations is transformed to the new datum (origin at x_0, y_0).
3. From the trend revealed in the second step, one of three models can be adopted to describe the behavior of an existing fiducial point:

   - There is no significant single point movement and no significant change in datum, i.e., for each point:

   $$dx = 0 \qquad dy = 0 \tag{1}$$

   - There is a datum change between the recent and original measurements. This may include a scale change, κ, emanating from (x_0, y_0) and a rotation, ω ,centered at (x_0, y_0), i.e., for each point:

   $$\begin{aligned} dx &= (1-\kappa)(x-x_0) - \omega\,(y-y_0) \\ dy &= (1-\kappa)(y-y_0) - \omega\,(x-x_0) \end{aligned} \tag{2}$$

   - Single point movement a_0, b_0 reflecting the instability of a fiducial monument combined with a datum change:

   $$\begin{aligned} dx &= (1-\kappa)(x-x_0) - \omega\,(y-y_0) + a_0 \\ dy &= (1-\kappa)(y-y_0) - \omega\,(x-x_0) + b_0 \end{aligned} \tag{3}$$

   while, for all other points, model (2) is adopted. The unknown parameters, κ, ω, a_0 and b_0 are estimated, together with their variances and covariances, by means of the least squares fitting of the model to the calculated displacement components.
4. A global statistical test on the model fitting is performed at the 95% level of confidence and the significance of individual model parameters is computed. If the global test fails and/or if the significance (1 - α) of any parameter is smaller than 70%, a new model - without the insignificant parameter - is adopted and model (2) is repeated.
5. The new GPS surveys are corrected for scale and rotation, if applicable, and the new data are adjusted together with the stable fiducial points which are entered into the adjustment as weighted stations so that their original variance-covariance matrix is propagated to reflect the true uncertainty of the new points. The coordinates of the fiducial points are not updated if they have been found to be stable. Fiducial points which have been identified as being unstable are treated as new points in the densification network and their new coordinates are determined together with those of the densification points.

4. CONTROL TRANSFER

On the main collider ring, the underground control will be connected to the surface control through a number of vertical shafts which, on average are spaced at intervals of 4.4km. Thus, this distance is the maximum length of an open-ended traverse network. The entire SSC complex will contain approximately 45 vertical shafts which vary in depth from 20m to 80m. The large number of shaft transfers and short turn around time for the subsequent calculation results has led to the evolution of efficient plumbing procedures which are depicted in Figures 2 and 3. Vertical plumbing is accomplished using a precision zenith plummet mounted underground on a pair of translation stages. The points at the top of the shaft are defined in three dimensions by the centers of Taylor Hobson Spheres which are mounted on survey brackets included in the basic shaft collar design. The spheres accommodate either concentric ring targets or retro-reflectors. It is possible, therefore, to make direction, zenith angle and distance measurements directly to the center of the sphere. Thus the spheres can be set in any arbitrary orientation without introducing an eccentricity: they can be set in a vertical position for vertical distance and horizontal centering (plumbing) measurements from the bottom of the shafts, and they can be rotated into any other orientations for surface measurements.

4.1 Transfer of Horizontal Control

For horizontal control transfer, two or more temporary tripod points are located within 40m of the shaft collar. They are arranged in such a way that they form well configured Weissbach triangles with the Taylor Hobson Spheres (Figure 2). In addition they are located so that they are visible from several of the densification points. Direction, distance and zenith angle measurements are made to connect the spheres, temporary tripods and densification points. Wild/Leica TC2002 total stations are used for this purpose. The Kern centering system is employed providing forced centering in three dimensions. The following accuracies have been achieved:

- Directions: σ_δ = 7" for the mean 3 sets.
- Distances: $\sigma_s = \sqrt{(0.5\,\mathrm{mm})^2 + (1\,\mathrm{ppm})^2 S^2}$ measured in both directions with numerous electronic pointings.
- Zenith Angles: Measured in two sets to support the three dimensional adjustment.

Meanwhile, two tripod set-ups are established simultaneously at the bottom of the shaft. These incorporate pairs of translation stages which enable the plumbing to be performed with a resolution of 0.01 mm. A Wild/Leica ZL plummet is used for centering under the Taylor Hobson Spheres. Multiple micrometer readings are made in four orthogonal positions of the plummet and the stages are driven to the mean positions. The accuracy of this procedure is estimated to be better than 0.5mm in the deepest (80m) shaft if the effects of refraction are ignored.

As soon as the plumbing operation has been completed, the plummet is removed and replaced by a total station, and control is extended from the plumb points through the connecting adits and into the tunnel where connections are made to the permanent tunnel brackets. Temporary - forced centered - tripod points are used for this purpose.

4.2 Transfer of Vertical Control

The vertical control transfer technique may be used for shafts of any depth. In this case the method is an integral part of the horizontal transfer procedure (Figure 3) and is usually performed immediately after the completion of the horizontal plumbing operation when the plummet is replaced by the Wild/Leica TC2002. The procedure has three distinct components:

1. Transfer of control from surface benchmarks to the centers of the (bracket mounted) Taylor Hobson Spheres. This is accomplished using a precise level with a parallel plate micrometer, and requires a tripod with an elevating head to enable the level to be raised or lowered so that the sphere center is within the range of the micrometer. The accuracy is estimated to be σ_1 = 0.3mm.
2. The vertical distance between the bottom and top of the shaft is measured using the coaxial electro-optical distance measuring instrument (EODMI) which is integrated into the TC2002. A Taylor Hobson Sphere with a precise prism insert serves as the retro-reflector. The accuracy here may be estimated using $\sigma_s = \sqrt{(0.5\,\mathrm{mm})^2 + (1\,\mathrm{ppm})^2 S^2}$.
3. The final step involves the transfer from the trunnion axis of the total station to several nearby benchmarks. This is performed in a fashion similar to that used in the first step of the procedure. The accuracy here is estimated to be less than σ_2 = 0.4mm.

The estimated accuracy for the deepest shaft is thus: $\sigma_v = \sqrt{\sigma_1^2 + \sigma_S^2 + \sigma_2^2}$ which amounts to σ_v = 0.7mm for the deepest shaft.

5. TUNNEL CONTROL NETWORKS

A typical cross-section of the main collider ring is shown in Figure 4. The nominal diameter is Superconducting Super Collider (SSC) project 4.3m, although several tunnel contracts include bores of up to 4.9m. Pre-analyses were undertaken to determine a suitable network configuration and observation scheme. The influences of both random and systematic errors were assessed. A length of 150m was eventually selected for the primary traverse legs. This provides a reasonable compromise between the accuracy requirements and conditions such as station intervisibility. The primary network comprises two zig-zag traverses through pairs of points as indicated in Figure 5.

The cost of installing several thousand precisely machined survey brackets would be prohibitive. For this reason, de-mountable brackets installed on permanent backing plates were designed and utilized. A special version of the bracket was made to accommodate the DMT Gyromat 2000.

The effect of lateral refraction is well known but remains an intractable problem especially in a tunnel environment. As Chrzanowski (1981) has pointed out, even a very small lateral temperature gradient can produce a severe error if it prevails over the length of a line-of-sight. Heister (1992) provides a thorough theoretical analysis of the effect of lateral refraction on different traverse designs, leading to the conclusion that a zig-zag traverse with reciprocal gyro-theodolite measurements on every leg provides the best insurance against the accumulation of refraction errors. **A** similar assessment was reached at the SSC, where it was anticipated that the zig-zag traverses and reciprocal gyro-azimuths will ameliorate the refraction problem. The underground measurements and their accuracies are summarized below:

- Azimuths: measured twice in both directins for every leg of one of the zig-zag traverses and assumed to have accuracy of $\sigma_\alpha = 3.0''$ for a single measurement.
- Directions: σ_δ = 0.7" for the mean from 3 sets.
- Distances: $\sigma_s = \sqrt{(0.5\text{mm})^2 + (1\text{ppm})^2 S^2}$ measured in both directions with several electronic pointings.
- Zenith Angles: Measured in two sets to support the three dimensional adjustment.

6. SURVEY RESULTS

The primary horizontal and vertical surface control surveys have been completed. The primary vertical network which included 600km of double run precision leveling to standards slightly more stringent than U.S. Federal Geodetic Control Committee (FGCC) First Order Class I work. For single run sections an accuracy of 1mm $\sqrt{K}$ was achieved. See Figure XX This translated to a worst case accuracy across the extent of the main collider ring of 5mm at 99% level of confidence. The primary horizontal control network was established using GPS and yielded an accuracy better than that defined for FGCC Order A $\sqrt{5\text{mm}^2 + 0.1\text{ppm}}$. See Figure 6.

The first three half sector break-throughs of the main tunnel between two shafts, 4.3km apart, have been completed and yielded excellent results (Table 1). The results validate the designs of the surface and underground networks, as well as the observation procedures adopted. All data acquisition was carried out in a framework of strict geodetic protocols and computations completed according to a strict QA/QC system. All project activities were documented in a series of published Standards and Specifications and Field and Office Procedures.

Table 1. Tunnel Breakthrough Results.

Half Sector	Length (km)	Lateral (mm)	Longitudinal (mm)	Vertical (mm)
N25-N30	4.3	12	5	6
N40-N45	4.3	18	1	3
N20-N25	4.3	13*	-	13*

* Breakthrough computed onto Tunnel Boring Machine. Survey breakthrough not yet available.

7. CONCLUSIONS

With approximately 115km of bored tunnel, with as many as 6 concurrent tunnel drives, and with stringent accuracy requirements, the SSC is, by any standard, a very challenging surveying project. Great care has been taken with the design of the surface and underground networks and monumentation, and the field and office procedures have been given similar attention. The installation of very accurate, stable surface reference networks combined with precise transfer operations and extensive underground control consisting of dual zig-zag traverses with reciprocal gyro-theodolite measurements has enabled the design accuracy requirements to be met.

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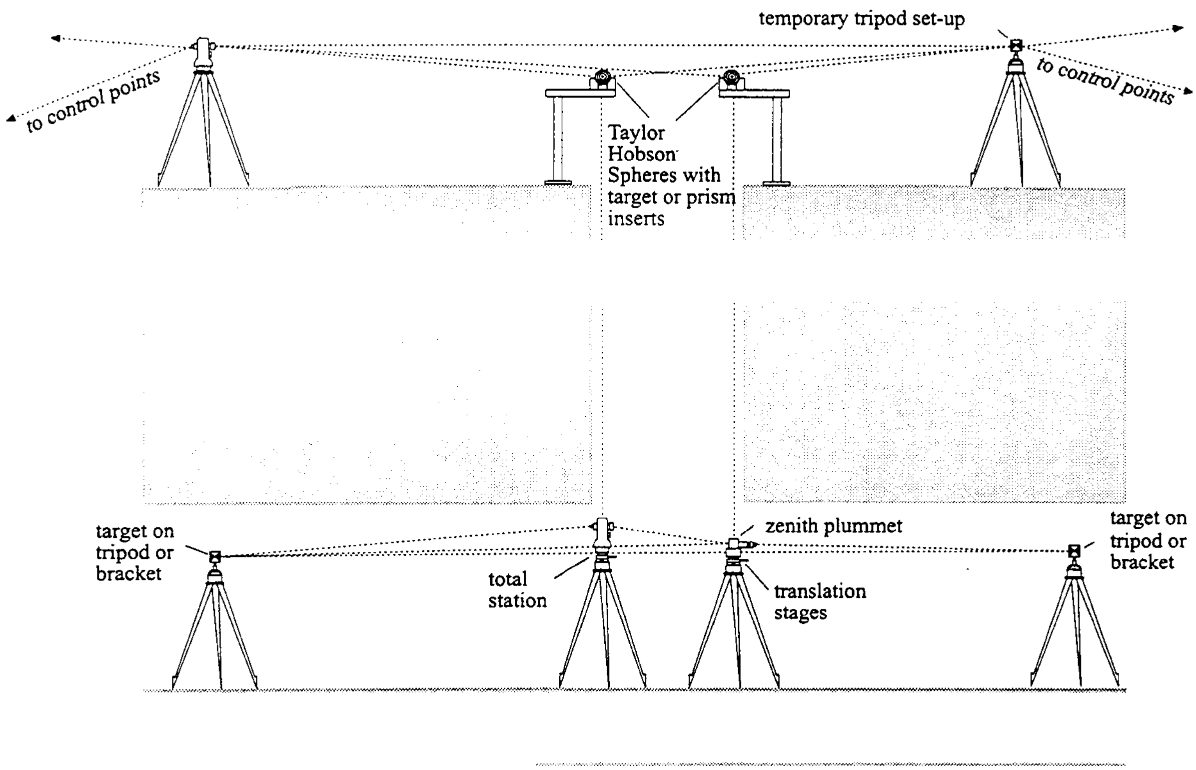

Figure 2. Transfer of horizontal control.

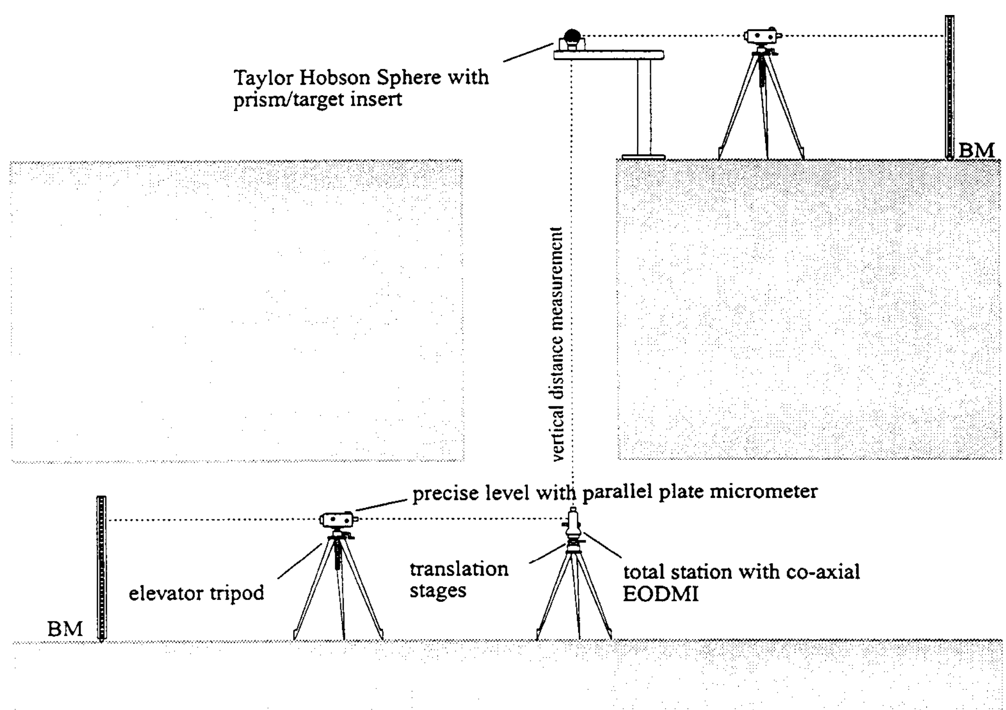

Figure 3. Transfer of vertical control.

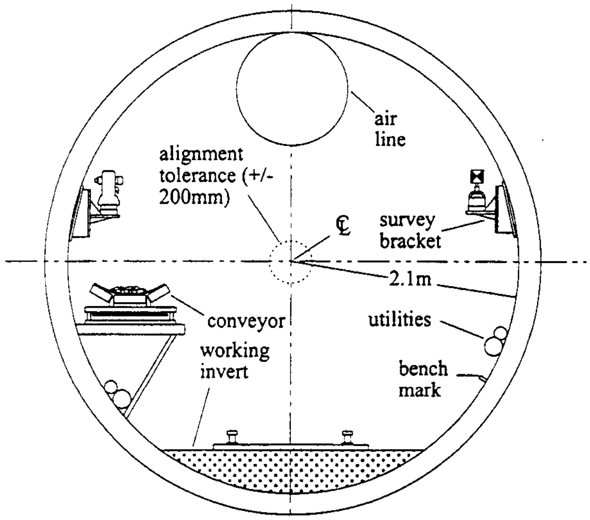

Figure 4. Typical tunnel cross-section.

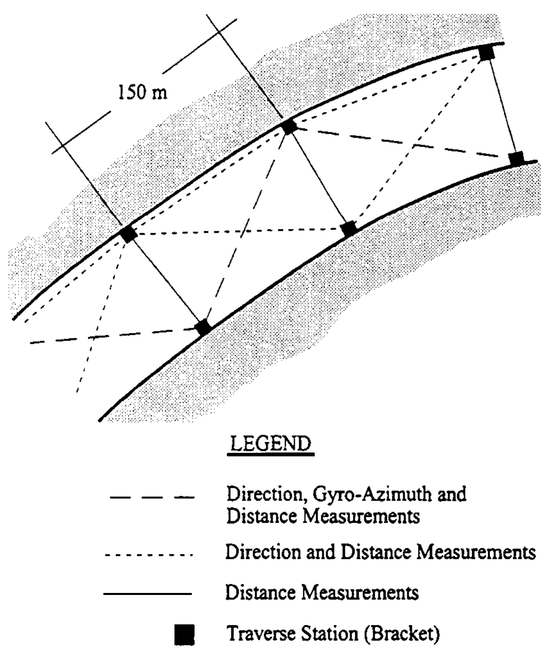

Figure 5. Transfer of horizontal control.

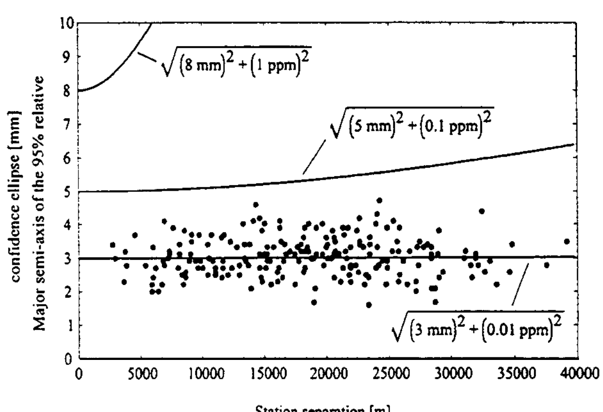

Figure 6. Relative uncertainty of Primary Horizontal Network.