Tunnel Surveys for New CERN Particle Accelerators

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Key words:

Engineering surveys, gyro measurements, plumbing techniques, tunnel surveys

ABSTRACT

At present extensive underground construction works take place at the European Organization for Nuclear Research (CERN) in Geneva, Switzerland. In the context of the Large Hadron Collider project (LHC), connecting tunnels between the existing ring accelerators LEP and SPS are built on the one hand. On the other hand further tunnels are constructed for the CNGS project (CERN neutrinos to Gran Sasso). Already for the excavation works highest accuracy demands were stated. Thus, the real axis of the tunnels must be centred within a 50 mm radius circle in the theoretical axis. The main difficulty from the point of view of surveying is the orientation transfer from the surface reference network to the tunnels, since tunnelling is started from shafts. A further crucial aspect of the survey are lateral refraction effects due to the small diameters of the tunnels (3 m). Grunder Ingenieure AG based in Hasle-Rüegsau, Switzerland, were mandated to carry out survey checks of the contractor's primary survey. Controlled traverses in the tunnels and trigonometric networks in and around the shafts are measured. Further, the plumbings in the shafts are independently controlled by an optical plummet. The height transfer in the tunnels is done by high spirit levelling. In order to fulfil the tolerance, the orientation transfer has to be carried out by gyroscopes, this being performed by the Institute of Geodesy, Bundeswehr University Munich.

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1. NEW CERN PARTICLE ACCELERATORS

1.1 The CERN LHC project

The European Organization for Nuclear Research (CERN) is in the process of replacing the Large Electron Positron Collider (LEP) by the Large Hadron Collider (LHC). The superconducting magnets that accelerate and direct the beam of subatomic particles will be placed into the existing LEP and SPS rings, but new underground halls and tunnels are required to house the detectors and to connect both rings. Dipole magnets are used to keep the particle on a circular orbit in a ring-shaped vacuum chamber. Quadrupole magnets are used to focus the particles. Due to switch on in 2005, it will be possible to collide beams of protons at an energy of 14 TeV. This will allow physicists to penetrate still further into the structure of matter and recreate the conditions prevailing in the early universe.

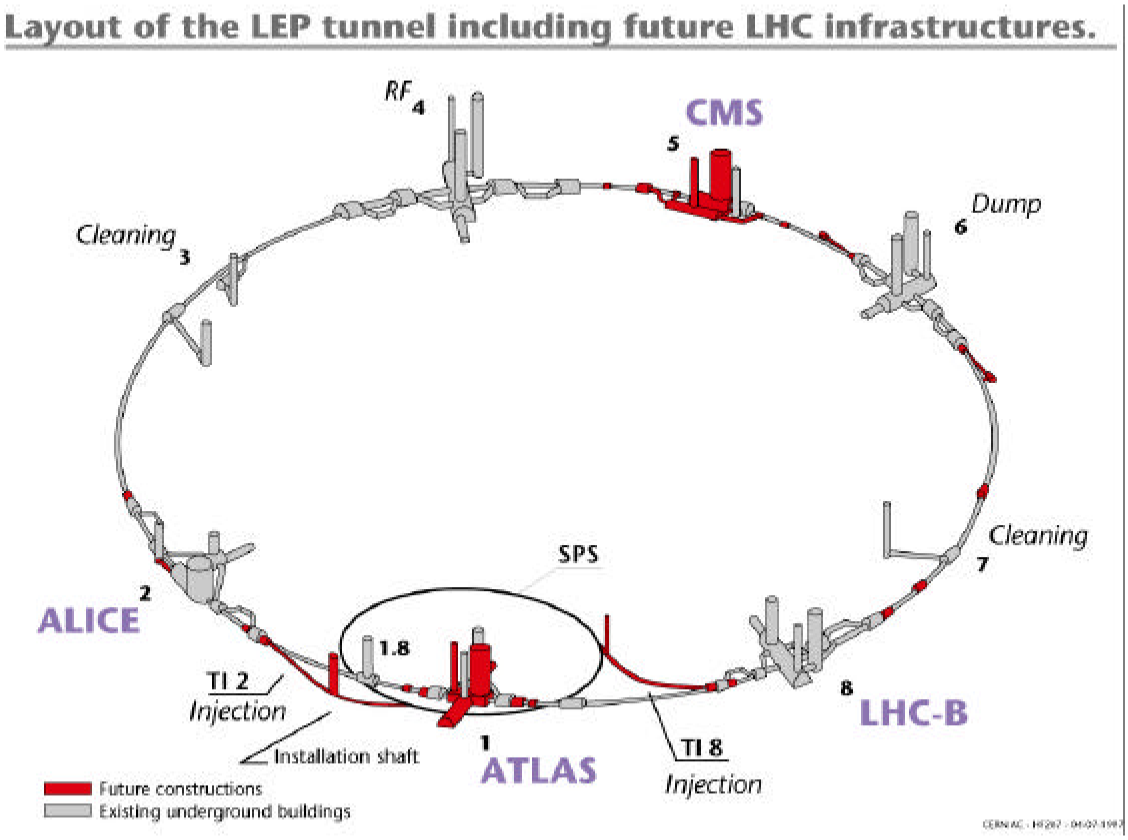

Fig. 1. Layout of the CERN ring accelerators
including the new connecting tunnels TI2 and TI8 (source: http://acwebimages.cern.ch/)

At the moment underground works at the Swiss-French border west of Geneva are in progress. The construction programme for the new facilities is divided into three segments: Segment 1 and segment 2 handle with the new detectors ATLAS and CMS where large caverns had to be excavated. Segment 3 involves work encompassing modifications to the existing structure and deals with new connections between the SPS and the LEP ring. Design engineering for the segment 3 is a joint venture of the enterprises Brown and Root, Leatherhead, United Kingdom, and Intecsa, Madrid, Spain. Grunder Ingenieure AG (GRIAG), Hasle-Rüegsau, Switzerland, act as consultants for surveying tasks concerning the staking out of the tunnels TI2 and TI8. Gyro measurements are carried out by the Institute of Geodesy, Bundeswehr University Munich, Germany. The Institute of Geodesy of the Swiss Federal Institute of Technology supervises the surveying work carried out by the project engineers.

1.2 The CNGS project

Aside from the extensive works for the LHC, another minor experiment is prepared. Tunnels are set out for the CERN Neutrino Gran Sasso (CNGS) project. Starting from 2006, it is intended to send a muon neutrino beam across the earth to the 730 km remote Gran Sasso laboratory. This laboratory is located at 150 km from Rome, Italy. There, it will be verified how many of the artificially produced muon neutrinos will have reached the detectors and how many will be transformed into tau neutrinos. This experiment should provide evidence for the so-called neutrino oscillation which states that at least one of the three neutrino types would have to possess a mass. The advantage over experiments with atmospheric muon neutrinos is that the intensity and the energy of the neutrino beam can be monitored.

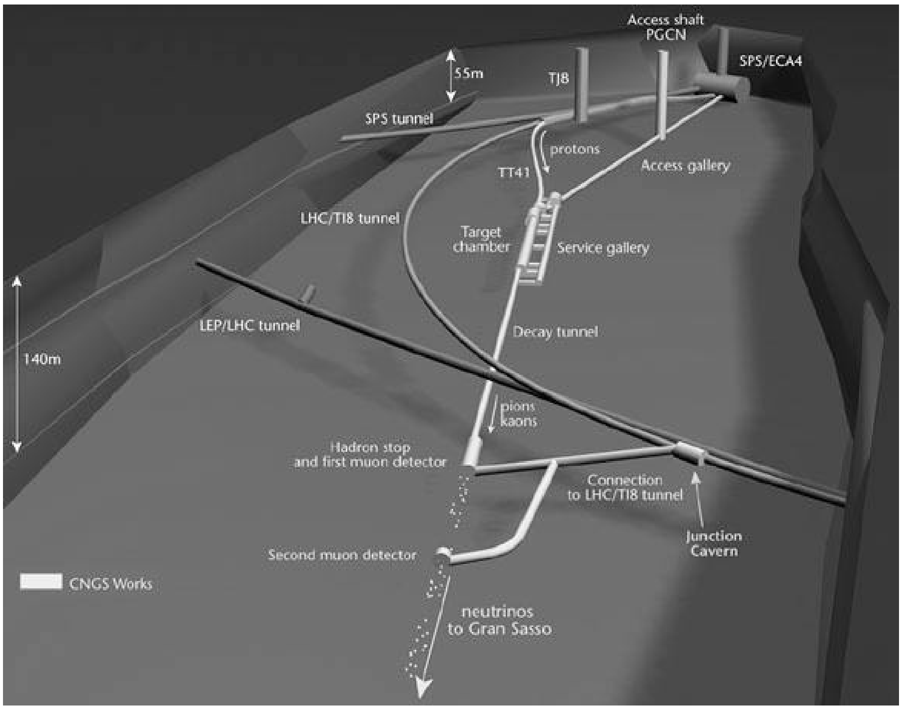

Fig. 2. Layout of the tunnels for the CERN Neutrino Gran Sasso project (source: http://proj-cngs.web.cern.ch/proj-cngs/)

The design engineering work in this project is managed by the enterprise Gibb, United Kingdom. Gibb works together with Grunder Ingenieure AG and the University Bundeswehr Munich as survey consultants. The survey consultants check the primary survey carried out by the contractors.

1.3 Excavation of the LHC and the CNGS tunnels

The tunnels are built in the sedimentary deposits of the Geneva Basin between the Jura mountains in the north and the Alps in the south. Drilling and blasting are not necessary in the smooth underlying molasse or in the upper moraine. On contract 3A of the LHC project, road headers were used for the 2.6 km long, 3.8 meter outer diameter TI2 tunnel. Two tunnels were driven from an oval-shaped shaft situated in the middle. In the 2.5 km long TI8 tunnel, excavation was done by a tunnel-boring machine. During the excavation of the TI2 and TI8 tunnels, care had to be taken not to disturb existing structures, especially when the LEP machine was still in operation. Before the breakthrough of the TI2 and TI8 tunnels to the LEP ring at the end of 2000, the LEP machine was shut down. Concrete lining in both tunnels was completed by the end of 2001.

In the CNGS tunnels, excavation is still in progess and will be finished by the end of 2002. Apart of road headers a tunnel-boring machine is used for excavating the proton beam tunnel and the decay tunnel.

Geology at CERN is far from being ideal. During the excavation of the TI2 tunnel, in certain sections a swelling and heaving reaction of clays and marls occurred when they were in contact with water [Pérez-Dueñas, 2000]. An uplift of the tunnel ground was the consequence. Rock falls were minimised with the installation of extra rock bolts in certain areas and with a thickening of the shotcrete primary support.

2. NETWORK LAYOUT FOR CHECKING CONTRACTORS PRIMARY SURVEY

For the alignment of the superconducting magnets, relative accuracies in the sub-millimetre range are required. Thus, very high accuracy demands are already stated for the excavation works. For the LHC tunnels, the real axis of the work must be in a 50 mm radius circle centred on the theoretical axis. The accuracy requirements to the decay tunnel in the CNGS project are identical. This leads to a maximum misalignment of the proton beam of 0.05 mrad which is 36 m off-axis at the Gran Sasso laboratory. According to physicists [Ball et al., 2001], this is sufficient for detecting neutrino events.

Since tunnelling is done from shafts, the main difficulty in terms of surveying is the orientation transfer from the surface to the tunnels. Considering the required accuracies and the length of the tunnels, it is obvious that the tolerances only can be fulfilled if the orientation of the traverses is updated by gyroscope azimuths. In order to improve reliability, all traverses are observed with overlapping legs. The diameters of the tunnels including the lining lay around 3 m. Lines of sight closer than 0.50 m to the tunnel wall are avoided due to disturbing refraction effects. Thus, a circular profile of 2 m can be used for the tacheometric observations. This has to be taken into account in curves. Considering the TI8 tunnel axis radius of 1000 m, traverse legs of 120 m can be defined at most. For the overlapping method, every 60 m a station has to be established. In straight sections, traverse legs of 200 m are measured. Additional strength to the network orientation is given by the connections to existing structures with reference markers, such as in the access gallery for the decay tunnel where after 150 m a connection to the existing SPS ring is built. Besides, accurate traverse distances in curved tunnels slightly help reducing the lateral deviations caused by angular errors.

For checking the contractors primary surveys, Grunder Ingenieure AG have to design geodetic networks where lateral error must not exceed 50 mm on a 98.8 % confidence region (2.5 sigma). Since gyroscope measurements are the cost dominating part of a tunnel survey, error simulations were computed for each tunnel network, varying the number of gyro azimuths. For the TI8 an error simulation according to Monte Carlo methods was done. This approach has been used for years at CERN [Mayoud, 1989] and was recommended to the GRIAG surveyors for designing and optimising the networks. Its advantage over the conventional stochastic variance-covariance approach originates in the possibility of the simulation of different perturbations which can affect the network geometry. In addition to random errors, systematic effects can be added to the random process. Starting from theoretical coordinates, 100 measurement sets were produced adding random errors from a Gaussian generator scaled on the following a priori standard deviations:

- $\sigma_{\text{Directions}}$: 0.7 mgon
- σ_{Azimuths} : 1.5 mgon
- $\sigma_{\text{Distances}}$: 1 mm + 1 ppm
- σ_{SetUp} : 0.5 mm
- σ_{Plumbing} : 3 mm

Rather pessimistic a priori standard deviations were chosen, counting also for unknown systematic effects. For the TI8 tunnel, the error simulation yielded an appropriate solution with gyro measurements on every fourth traverse leg or every 480 m. Thus, the tolerance can be fulfilled at chainage 2090 where the network can be controlled independently by means of plumbing measurements through a borehole to the LEP tunnel. Figure 3 shows the trajectories of 100 traverses. The lateral deviation to the theoretical axis is scaled. For comparative reasons, 95 % confidence ellipses (dashed) are drawn. A histogram for chainage 2090 gives the distribution of the radial deviations of the proposed network. Similar strategies are applied for designing networks in the remaining tunnels.

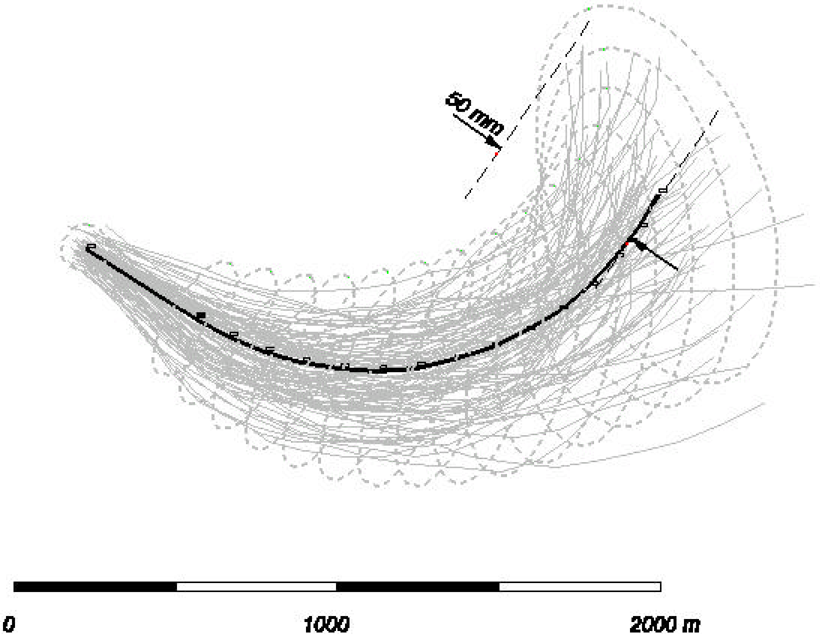

Fig. 3. Error simulation for tunnel TI8

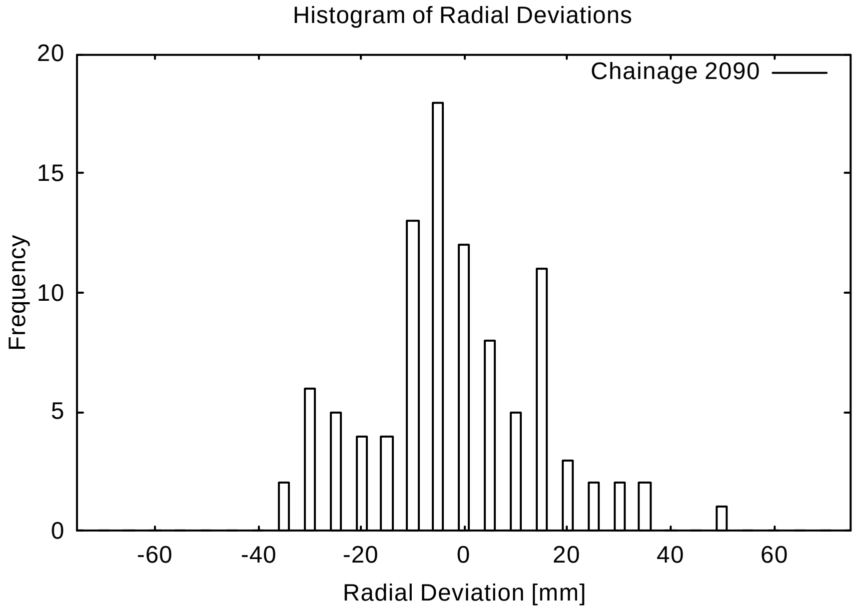

Fig. 4. Distribution of simulated radial deviations at borehole after 2.1 km of tunnelling

3. SURFACE NETWORK

The CERN surface network was established for the construction of the LEP in the nineteen eighties by the CERN metrology group. The network consists of pillars equipped with a forced centring system. Originally, distances were measured by means of two colour EDM. For the LHC project, some pillars were reoccupied by GPS [BLAUDET, 1998]. This network was provided to the design engineers at the beginning of the projects. The reference network of the constructions wherein the tunnels end as well as the Gran Sasso reference points are assumed as error free within the contractors' assignments. GRIAG had to control the contractors' markers and pillars around the shafts. Besides, CERN pillars used for orientation measurements were checked as well. For the surface work, Trimble 4000 SSi two-frequency GPS receivers were used applying double-difference techniques to the carrier phase data. Tacheometric measurements were carried out on pillars and on markers next to the shaft where the GPS measurements were potentially affected by multi path effects.

4. PLUMBING AND HEIGHT TRANSFERS IN SHAFTS

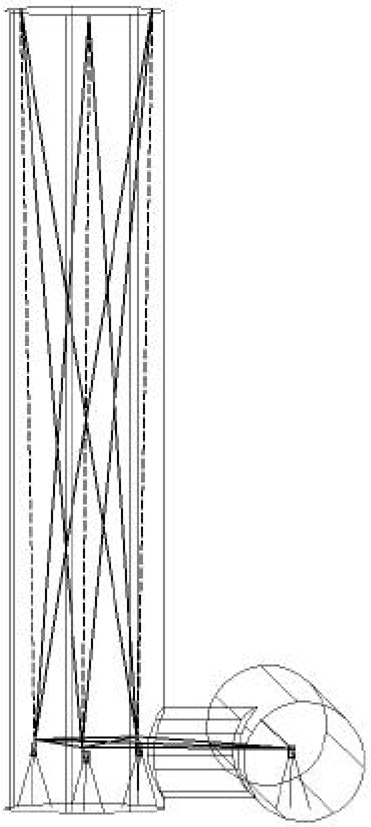

Fig. 5. Connecting measurements from surface to tunnel level

In both projects surface points had to be plumbed from the surface through around 50 m deep shafts to the tunnel level. This was done using the automatic WILD ZL zenith plummet. In figure 5 these measurements are represented by the dashed lines. Targets at the top of the shafts were well defined borings. The accuracy of WILD ZL is specified by the manufacturers as 1:200'000. However, the plumb lines are affected by refraction since they are close to the pit walls. Therefore, reflectors were attached round the shaft top and determined tacheometrically from the bottom. Due to the very inclined lines of sight, measurements in both tacheometer faces are indispensable in order to eliminate the influence of the axis errors. For correcting the directions, the component of the inclination of the vertical axis across the line of sight has to be measured. Care has to be taken with tacheometers performing an automatic correction of the inclination of the vertical axis. Most tacheometers "freeze" the amplification term for the correction at vertical angles larger than 80 gon. Figure 6 shows this effect of a badly levelled tacheometer on the direction for different height angles. For better results, the cross component of the vertical axis has to be written down manually and the correction term has to be applied. However, this procedure lacks of the exact assignment of the inclination during the angle measurements. Therefore, apart from a stable instrument set-up, several angle sets have to be measured.

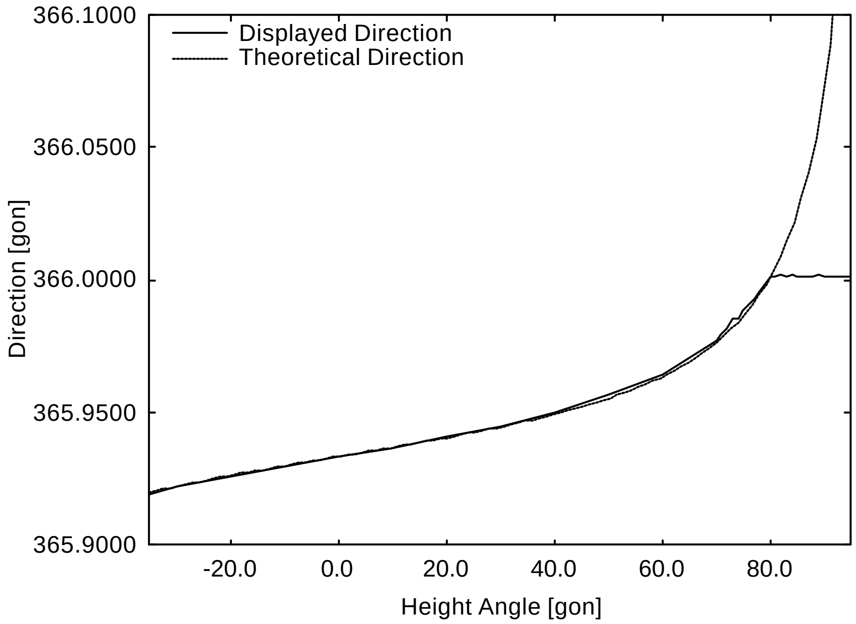

Fig. 6. Influence of compensator "freezing" on horizontal angle for a badly levelled tacheometer. The cross component of the inclination of the vertical axis is 20 mgon.

Directions with very inclined lines of sight have to be weighted carefully for further computations. The accuracy of the inclination measurement is limited not only to the compensator's centring but also to the trunnion error of the vertical axis. For the LEICA TCA2003, both error sources permit a compensator index determination with an accuracy of 0.3 mgon. This factor is amplified by the tangent of the vertical angle.

Good results can only be obtained if these facts are considered. The accuracy of plumbed points is estimated to be 1 mm.

Furthermore, the observations have to be corrected due to the difference between the physical plumb line and the normal to the reference ellipsoid. For the 50 m deep TJ8 shaft, this correction reached 3 mm. The curvature of the physical plumb line along the shaft can be neglected.

The height transfer by EDM distances and vertical angles was independently checked by a calibrated steel measuring tape. Temperature dilatation was taken into account (11 ppm / °C for steel). In order to avoid vibrations by the shaft elevator influencing the measuring tape set-up, the readings were done simultaneously with two levelling instruments.

5. ORIENTATION TRANSFER AND TUNNEL NETWORKS

The orientation transfer by means of the plumbed baselines of 6 m to 10 m length would lead to unacceptable orientation errors in the range of 10 mgon. Reasonable accuracies can only be obtained by means of gyroscope measurements. The University Bundeswehr Munich, Institute of Geodesy acts in both project as a sub-consultant of Grunder Ingenieure AG and carries out the gyroscope measurements.

The University Bundeswehr Munich uses a Gyromat by DMT (Deutsche Montan Technologie). The principle of measurement is an electro-optical integration of a complete period of swing of a freely swinging gyro rotor. The centre of oscillation can be derived from these data. The accuracy is specified by the manufacturers as 1 mgon. The University Bundeswehr Munich regularly carries out several lab checks like functioning tests, calibration-value determinations on an astro-geodetic reference line and calibration-value determinations in the laboratory. The lab calibration value-determination is not of interest for the orientation transfer, since azimuths are referred to a calibration line in the CERN network. The time consuming determination of the temperature correction is carried out once a year [Heister, 2000].

Around the CERN sites, a calibration line was established in order to determine the local calibration value of the Gyromat. In addition to a regular pillar of the CERN network, a 5 m tall survey beacon was to be used for the calibration line. Although this survey beacon is deeply founded, natural oscillations of the beacon prevented from the zero tape determination of the gyroscope. Thus, an ex-centre was set up and linked to the CERN network. The length of the calibration line is 490 m. It is situated one to four kilometres away from the construction sites.

During a survey check, the following observing procedure is applied [Heister, 2000]:

- Determination of the local calibration value on the reference line. Three gyro azimuths are observed in forth and back direction.
- Gyro measurements in the tunnels. Three forth and three back azimuths are observed per given traverse leg.
- After the tunnel measurements the calibration line is re-observed according to the identical observation scheme controlling and determining the local calibration value.

Six gyro campaigns have been carried out yet. A skip of the calibration value of 4 mgon could be observed between the fourth and fifth campaign. Furthermore, on the calibration line, small refraction influences could be found analysing the differences of forth and back measurements reaching up to 2 mgon. However, constant refraction errors are minimised by averaging the reciprocal observations.

The measurements in the tunnels have to be carried out on tripods. Brackets cannot be mounted because of the narrow diameters of the tunnels. The University Bundeswehr Munich uses heavy KERN tripods with a special adapter for the DMT Gyromat. For setting up the instrument over a mark, a KERN centring pole is used. The centring accuracy of the pole can be specified with 0.5 mm. This leads to an orientation uncertainty of 0.3 mgon for the shortest traverse legs (120 m) which are situated in the curved TI8 tunnel. However, forced-centring is used for linking the azimuths with the traverses.

Before adjustment, gyro measurements are reduced for the instrument induced corrections which are the local calibration value and the reduction on a reference temperature. Furthermore, the measurements have to be corrected for convergence of meridians and for the effects of vertical deflections. Vertical deflections can be derived from the CERN geoid model [Bell, 1986]. This geoid model is represented by parabolic surfaces on different levels. The surfaces were deduced from grid values computed with the Swiss Geoid model containing mass models and astro-geodetic measurements. The accuracy of the h component is estimated to be 0.3 mgon.

In general, after 500 m of tunnelling a survey check is carried out for controlling the staking out of the contractors. For the gyro azimuths, a leapfrogging strategy is applied. One tunnel azimuth of the previous campaign is controlled and new azimuths are measured. For questions of reliability, traverses with overlapping legs are observed. Forced-centring is applied. The set-up over markers is done by using an automatic WILD NL nadir plummet. The markers possess a hole where a target with a millimetre grid can be inserted. Thus, in combination with a controllable centring device, a centring accuracy of 0.2 mm can be obtained. These markers can also be levelled. Special attention is given to lateral refraction. By means of the set-up of the markers on the tunnel axis in straight sections and the overlapping technique, care is taken to fight possible refraction effects. However, for safety reasons, ventilation has to be turned on during the survey checks. This causes temperature gradients mainly during winter time when cold air is pumped into the tunnels. Evidence for vertical temperature gradients was found for a TI2 campaign carried out in January 2000. Comparing the forth and back height angles, differences up to 10 mm could be found for lines of sight larger than 100 m. Indications for lateral refraction can be found by comparing reciprocal gyro measurements. Differences between forth and back measurements of the gyro azimuths in the tunnel do not exceed 2 mgon.

As explained in section 1.3, an uplift of the tunnel ground occurred due to swelling marls and clays mainly in certain parts of the TI2 tunnel. In order to monitor the stability of the tunnelling networks, some traverses including new gyro azimuths had to be re-measured starting from the shafts.

6. HEIGHT TRANSFER

Due to the good natured error propagation of levelled heights, the height transfer is under the prevailing tolerances not a very crucial point. High-spirit levelling is done only in forth direction since a control is given by the tacheometric heights of the traverses. A Zeiss DiNi10 is used. Regarding the considerably large height difference in the TI8 tunnel (70 m), care had to be taken of a possible rod scale factor. This error source was minimised by using calibrated invar rods.

7. DATA PROCESSING AND DATA MANAGEMENT

First data checks and blunder detection are done in-situ using the programme PreFilter. PreFilter clusters station sets by means of sequential Helmert transformations. Blunders are detected easily by data snooping. Apart of reduced angular and distance measurements, the programme provides initial coordinates for the final adjustment. Grunder Ingenieure AG use the adjustment programme LTOP. The planimetric adjustment is carried out in the CERN cartesian coordinate system. Angular measurements, observed relative to the local horizon, are rotated into the CERN XYZ system [Gervaise et al., 1976] counting for the convergence angles and the deflections of the vertical. Distances are reduced on the tangential plane in the fundamental point. The altimetric adjustment is done in the CERN XYH system. After each campaign, a new adjustment was calculated containing all measurements. The surface fiducial points were checked by applying loose constraints. The residuals of the gyro azimuths are in the order of 1 mgon and do not exceed 2 mgon. Three breakthrough events have taken place so far. The radial misclosures laid around 10 mm with standard deviations of 10 mm.

Data are maintained in the GRICAL data base. The point map production and the comparison between network versions can be generated automatically.

8. ACKNOWLEDGEMENT

We would like to thank Brown and Root/intecsa, especially MSc E. Pérez-Dueñas, Gibb and Prof. Heister of the Institute of Geodesy, University Bundeswehr Munich and his gyro group for the excellent collaboration.

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- Assignments for several projects in the context of the "Railway 2000" programme of the Swiss Federal Railways
- Assignments abroad (GPS consultancy in Monte Negro, geodetic volcano monitoring in Mexico, GPS and water vapour radiometry around the Mediterranean within the "Sea Level Fluctuation" programme of the European Union)
- Member of the STV/FVG, Swiss Technician Association, special group of surveying and geoinformation

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- Studies of geodesy at the University of Bonn, in 1984 received a Ph.D. for his thesis on "Development of Electronic Inclinometers" at the Institute of Geodesy, Bonn.
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