

Large Scale Metrology for Research and Industry – Application to Particle Accelerators and Recent Developments

Michel MAYOUD, France

Key words: Micro-geodesy, engineering survey, large scale metrology, high precision measurements, monitoring, industry, research.

SUMMARY

For now about 50 years, CERN, the European Laboratory for Particle Physics, has always been more and more demanding for positioning the components of larger and larger particle accelerators, the biggest being 27 km circumference. A special “survey” group is therefore devoted to the geodetic metrology of particle accelerators (8500 surveyed components along nearly 63 km of beam lines) and their large detectors, within very tight tolerances - typically 0.1 mm r.m.s as relative accuracy over 100 m. The ongoing projects are even more and more demanding with regards to accuracy (sometimes a few micrometers), monitoring and remote control. Various high precision instruments and methods have then been developed for this special metrology, either at CERN or through R&D programmes with industry. This paper will shortly review the instruments and methods presently used, and then sketch the developments made for the micrometric metrology of future linear colliders – which will be designed for accelerating nanometric particle beams along twice 15 km long channels made of a 4mm diameter vacuum chamber.

Mots clés: Micro géodésie, topométrie d’ingénierie, métrologie des grandes dimensions, mesures de précision, télécontrôle, industrie, recherche.

RÉSUMÉ

Depuis bientôt 50 ans, le CERN – laboratoire européen pour la physique des particules - a toujours été de plus en plus exigeant pour le positionnement des composants d’accélérateurs de dimensions toujours croissantes, le plus grand faisant 27 Km de circonférence. Un groupe de géomètres est donc dévolu à la métrologie géodésique des accélérateurs de particules (8500 éléments, le long de 63 Km de lignes de faisceaux) et de leurs grands détecteurs, dans des tolérances très sévères - typiquement 0.1mm de précision relative (1σ) sur 100 m. Les projets en cours sont encore plus exigeants par endroits, en termes de précision (parfois quelques micromètres) et de télécontrôle. Divers instruments et méthodes de haute précision ont été développés pour cette métrologie spéciale, au CERN même ou en collaborations avec l’industrie. Cette communication passera en revue les moyens actuellement utilisés et présentera les développements faits pour la métrologie micrométrique des futurs collisionneurs linéaires, conçus pour accélérer des faisceaux nanométriques sur 2 fois 15 Km de machine, dans une chambre à vide de seulement 4mm de diamètre.

Large Scale Metrology for Research and Industry – Application to Particle Accelerators and Recent Developments

Michel MAYOUD, France

1. INTRODUCTION

"Engineering survey", "industrial geodesy" or "large scale metrology" are some terms used for the application of geodetic or photogrammetric techniques to the accurate measurement of large objects, when workshop tools are not appropriate to the problem. Many applications to industry and construction are well known, this sector of surveying activities is growing steadily, but research is also a very interesting sector of applications. Often ranked at an higher degree of requirements, the high precision metrology of large scientific equipments has induced various specific developments.

To that respect, the most demanding field is undoubtedly the alignment of particle accelerators, intended for high energy physics (HEP), synchrotron light (SL), nuclear research, industrial or medical use. Mastering alignments to within a few 0.1 mm over such long machines, or even a few microns for the future ones, is the major challenge in this field.

CERN, a European intergovernmental organization with 20 Member States, is the world's biggest laboratory exclusively devoted to fundamental research in particle physics. It has its seat in Geneva but straddles the Swiss-French border. Its objective is to provide for collaboration among European States in the field of high-energy particle physics (HEP) research and to this end it designs, constructs and runs the necessary particle accelerators and the associated experimental areas. At present more than 5000 physicists from research institutes world-wide use the CERN installations for their experiments.

The Large Hadron Collider (LHC) is the next accelerator being constructed on the CERN site. The LHC machine will mainly accelerate and collide 7 TeV proton beams or heavy ions. It will be installed in the existing 27 km circumference tunnel, about 100 m underground, which was housing the Large Electron Positron Collider (LEP). The LHC design is based on superconducting twin-aperture magnets which operate in a superfluid helium bath at 1.9 K.

Regarding Survey and Alignment, the LHC concentrates most of the activity of the "Large Scale Metrology" group - formerly named "Positioning Metrology and Surveying" group and always referred as "SU group" in this paper. The LHC project involves a lot of work for surveyors: 27Km (main ring) +2x3Km (transfer lines) =33 Km of new beam lines, 3000 new components to install and align from new metrological reference networks, 4 big experiments - of which 2 huge ones (CMS & ATLAS) - to assemble and align.

In addition to LHC construction and installation metrology and the maintenance metrology of the existing equipment, the other activities of the group are mainly dealing with the CNRS project (beam of neutrinos sent to Gran Sasso, at 730 km), the CLIC (Compact Linear Collider) development programme, plus a few new experiments.

Some outstanding developments and achievements are reviewed in this paper, with emphasis on the means designed or developed in the context of recent, present and future projects.

2. SPECIAL CERN INSTRUMENTS AND METHODS DEVELOPED IN THE PAST

Beside or before the adequate equipment which can be found now on the market (like precision theodolites or total stations, laser trackers, precision distancemeters, optical and digital levels, electronic inclinometers, etc.), some specific instruments and accessories had to be developed at CERN for matching in time the more and more severe requirements on larger and larger particle accelerators, or simply for increasing the efficiency of the alignment process. Most of these past CERN developments are widely described in professional literature (cf. Gervaise and Mayoud in bibliography). They are listed below for memory and some are illustrated in fig. 1.

- Accurate length measurement devices, like Distinvar (a few 0.01 mm accuracy) or in-situ interferometry with a self-aligning reflector;
- Special instruments for off-set measurements with respect to a stretched wire or a laser beam (a few 0.01 mm accuracy with optical sensors);
- Electronic inclinometers;
- Hydrostatic levelling systems (with contact sensor);
- Reference sockets (for instrumental set-up) and targets in accordance with requirements;
- Suitable movers (for positioning the measured objects within specifications)
- Suitable calibration facilities for all the above.

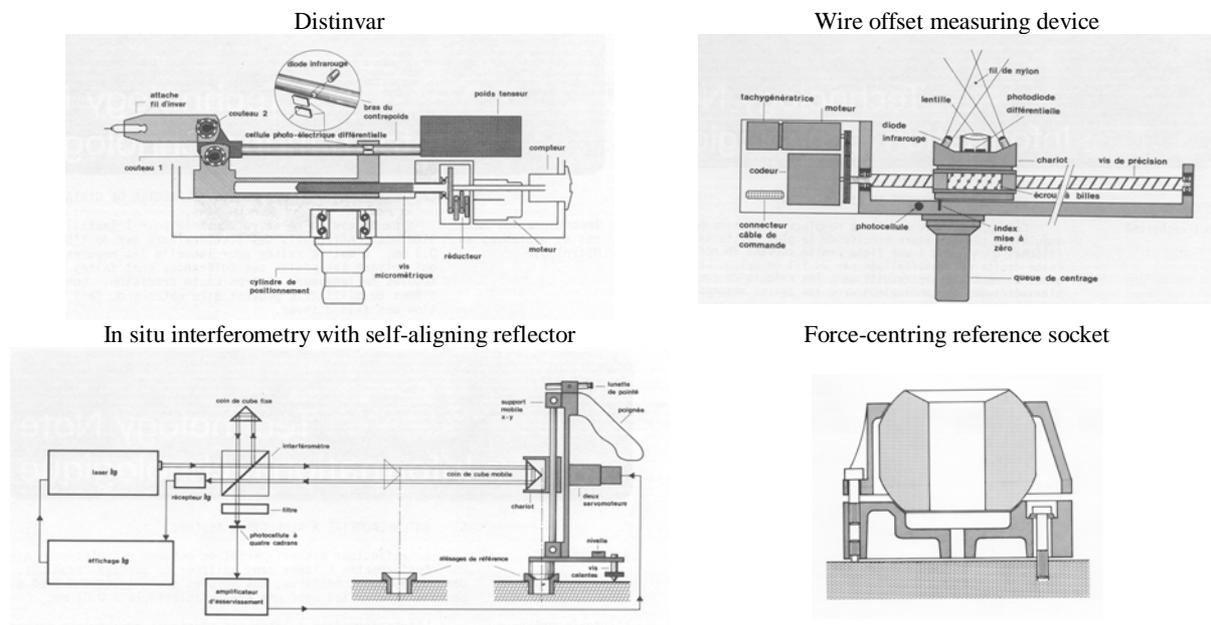


Figure 1: some past developments made at CERN

Regarding the methods, the main feature is that the size and geometry of the long curvilinear networks and machines to be measured, in good tunnel conditions, has led to give up angle measurements. Faster and accurate sequential offset measurements (figure 2) are taken, instead, with special instruments good to 0.01mm resolution. This has produced much better results in controlling the size and accumulation of radial errors along such networks and traverses.

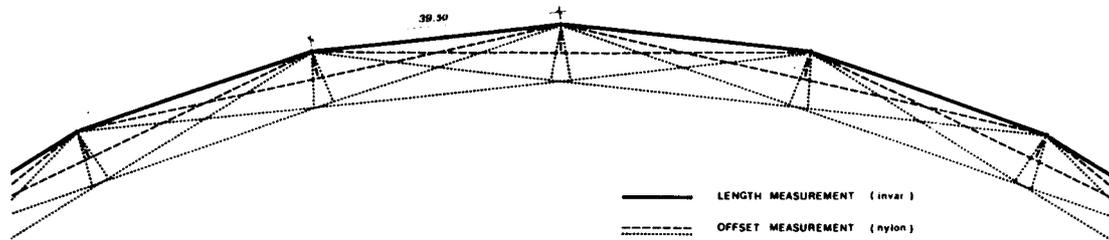


Figure 2: wire offset measurements along accelerators

A related feature is that the positions of the components have to be smoothed, both vertically and radially. When installing the components, the first determination of the control network gives the displacement vectors between their actual *rough* position and their theoretical one. The positions are spread around an unknown mean trend curve (one among an infinity) contained within the envelope of maximum errors. The polynomial degree of the curve depends on the redundancy and the overlap of measurements, and on the bridge distance between control points (figure 3).

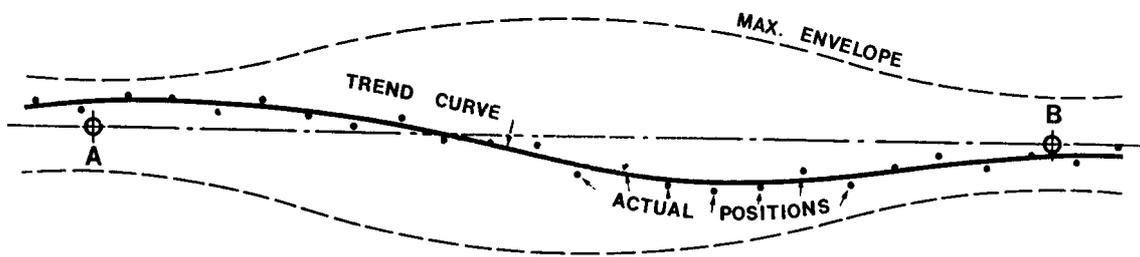


Figure 3: the smoothing concept around trend curves

The relative errors along a trend curve are a quadratic combination of those of the network itself and those of the positioning, i.e. installation, errors. The initial alignment consists in reducing this scattering to within the specification (0.10 to 0.15mm r.m.s) by moving selectively the misaligned components, and maintenance alignments aim to restore this situation at the optimum of functional values whenever needed. Smoothing algorithms can be parametric or non parametric, and data processing is made in a sliding window - with an adjustable threshold which optimally selects, from local fits and statistics, the components to move back to a better position.

3. INSTRUMENTS AND METHODS FOR MICROMETRIC REQUIREMENTS

When accuracies of 0.1mm were commonly mastered along accelerators, it did not take too long before that particle physicists came with machine components or detectors requiring a few hundredths of a mm, followed by others coming quickly to claim about microns... Such requirements were initially specified for controlling better the beams in the so-called low-beta sections by refining the alignment of these quadrupole magnets on both sides of the experiments.

Then came the first ideas about some possible technologies for future accelerators, one being particularly promising but extremely demanding: the CLIC (Compact Linear Collider) development programme. Such powerful linear colliders will be made both sides of kilometres of small accelerating cells driving very dense (ultra-focussed) electron beams to collide. In order to increase the collision rate, beams will be reduced to a cross-section size of a few nanometres, and all the monitored alignment system has to be designed for maintaining critical components to a stability of a few micrometers all along the machine, and possibly better at the final focus section - where fast correctors of any kind must ensure the collision of these nanometric particle bunches arriving at light speed!

The needs for such requirements have fostered new R&D and collaborations in various HEP and SL laboratories, and the CERN SU group made the choice of very accurate capacitive sensors, based on the exclusively patented ones from FOGALE-NANOTECH (France). A new range of instruments, intended for this micrometric metrology (Table 1), has been first refined on test benches and finally set up on a real CLIC test facility, succeeding in monitoring automatically the positions of the cells to within 3 micrometers (cf. Becker et al.).

<p><u>Wire Positioning System (WPS)</u></p> <ul style="list-style-type: none"> - One or two axes - Measurement range : $\pm 5\text{mm}$ - Resolution: $0.1\ \mu\text{m}$ - Repeatability: $1\ \mu\text{m}$ - Bandwidth: 0-10 Hz 	<p><u>Hydrostatic Leveling System (HLS)</u></p> <p>Measurement range : 5 mm Resolution : $0.2\ \mu\text{m}$ Repeatability : $1\ \mu\text{m}$ Bandwidth: 0-10 Hz</p> 
<p><u>Tilt Meter System (TMS)</u></p> <ul style="list-style-type: none"> - Biaxial measurement of tilt and acceleration - Measurement range : $\pm 10^{-2}$ radian - Resolution : 10^{-7} radian - Repeatability : 10^{-6} radian - Bandwidth : 0 to 100 Hz 	<p><u>Actuators</u></p> <ul style="list-style-type: none"> - Stepwise motorization - Length at mid course : 155mm - Diameter : 60mm - Travel : $\pm 4\ \text{mm}$ - Resolution : $0.2\ \mu\text{m}$ - Repeatability : $1\ \mu\text{m}$ - Maximum load along the trust axis : 400 N

Table 1: instruments for monitored micrometric alignment

The set up of such instruments on the machine is shown on figure 4 below.

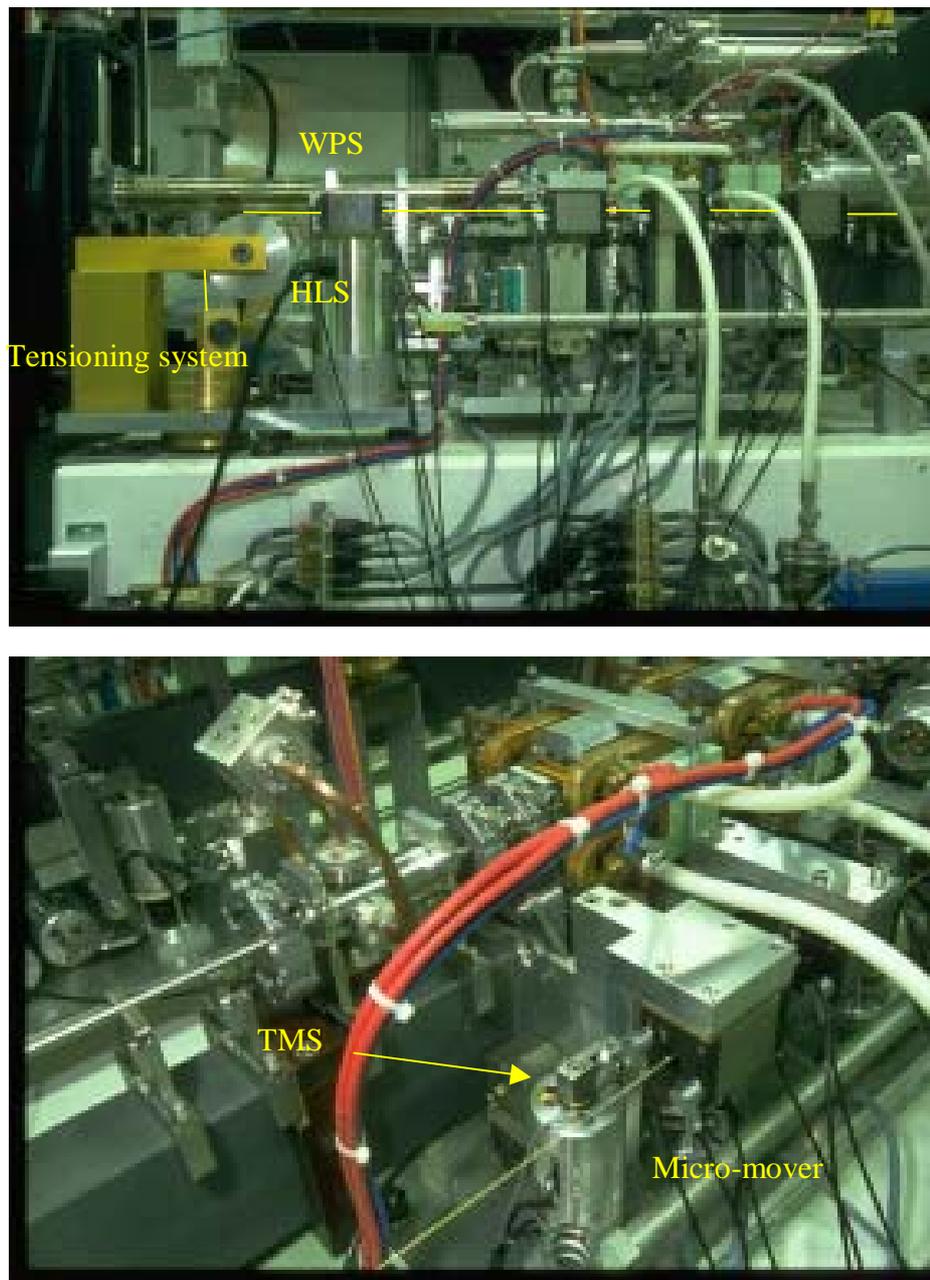


Figure 4: Set up of alignment devices on CLIC test facility

Beside their use in particle accelerators, such advanced developments have found - or may find - applications on special metrological problems:

- Alignment and online control of a large set of converging power laser beams, focussed on a deuterium/tritium target for atomic fusion and thermonuclear simulations - like MEGAJOULE project in France (240 laser beams, each 100m long, 1.8 megajoules, 500 terawatts) or NIF project in USA (192 Beams);
- Alignment and cyclic control of rails for high-speed scale models of trains ("Swiss Metro") or fast boats in R&D test facilities – which has led to a "metrological train" probe concept (figure 5), able to integrate all relevant geometrical data along a track from overlapping measurements sequences taken at successive stops of the whole carriage;
- Online or cyclic control of the stability of engineering structures, mechanical or optical components, etc.

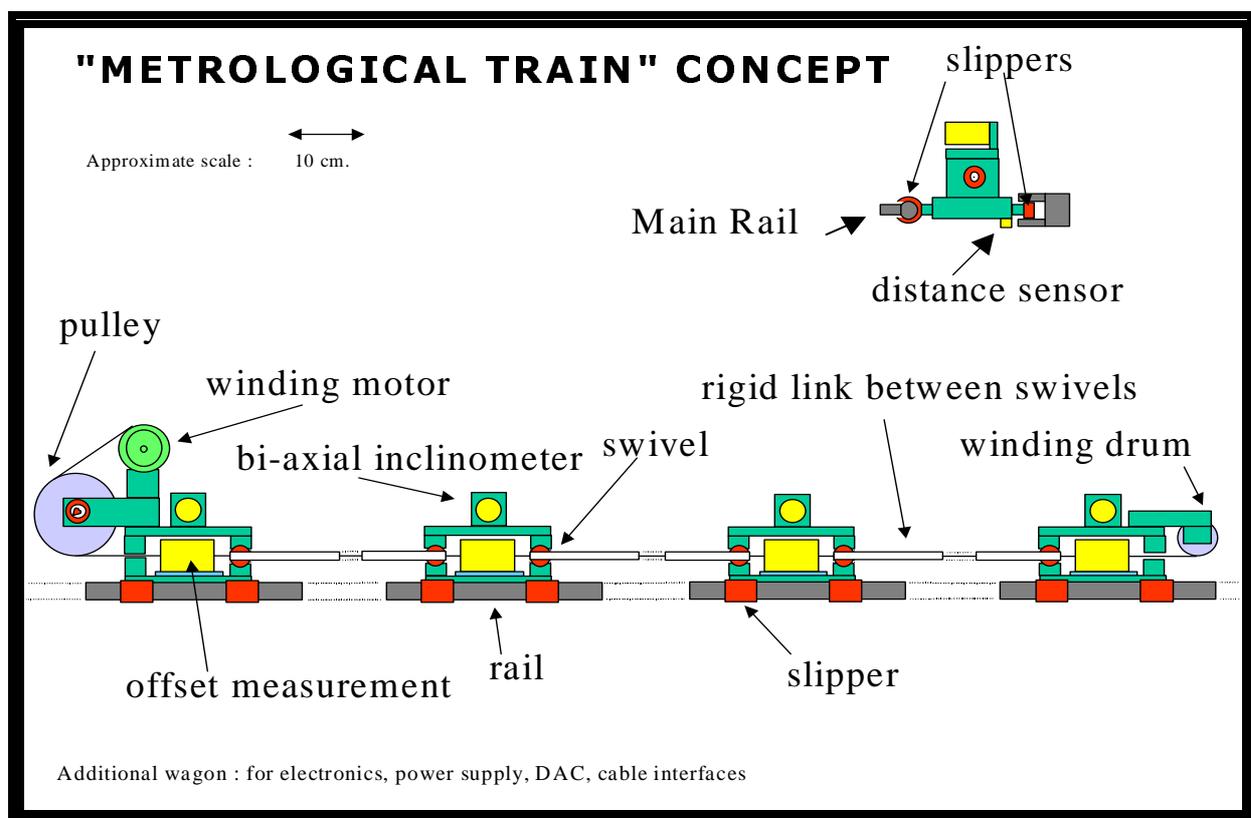


Figure 5: "metrological train" concept

Another efficient set up of WPS devices has been made on the so-called LEP spectrometer (figure 6), designed for measuring very accurately some possible slight changes of the beam position monitors during operation of the accelerator, with the following features :

- Required accuracy for the relative movements of the BPM's : $\pm 1 \mu\text{m}$
- Reproducibility of WPS measurements: $\pm 0.2 \mu\text{m}$; Range : $\pm 2.5 \text{ mm}$

- Wire: carbon fibre with Kevlar coating
- All elements are settled on 6 marble blocks
- Both BPM and WPS reference instruments are in temperature-controlled containers
- Wires are contained in a stainless steel pipe
- All sensors and electronics are shielded against radiation

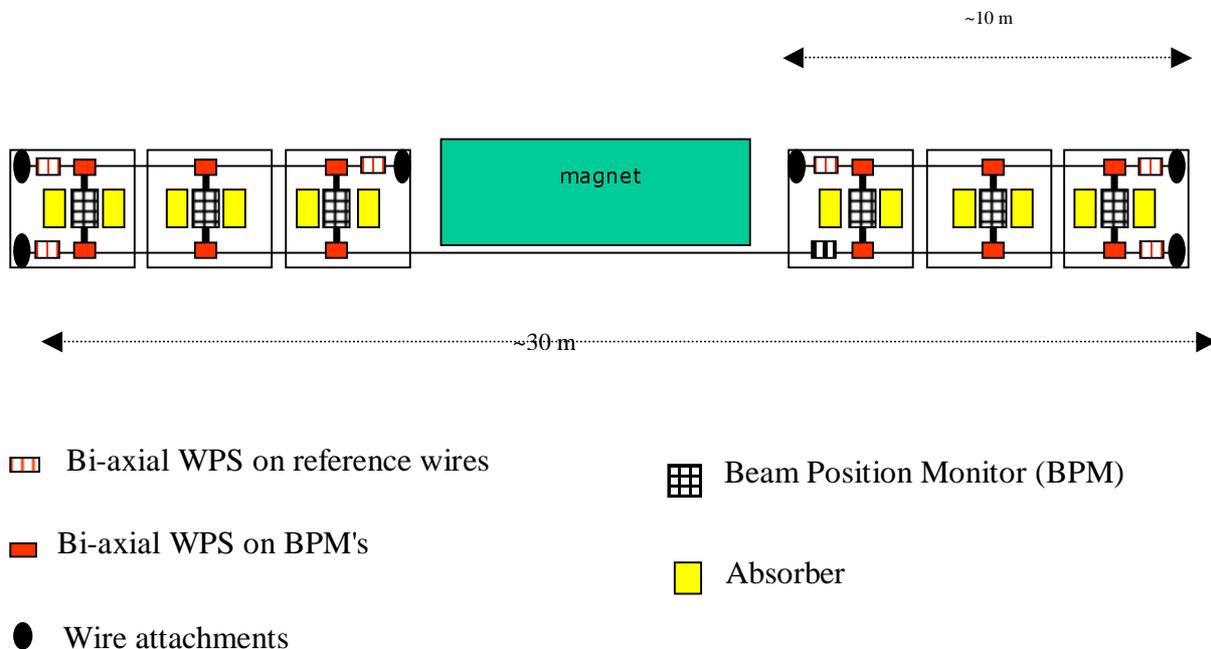


Figure 6: metrology of the LEP spectrometer

As for the set up of hydrostatic levelling systems, cares must be taken when designing the location of the vessels and the piping of the liquid – for not transforming the system in an awful combination of thermometer and barometer:

- avoiding up and down patterns in the geometry of the pipe path between vessels
- avoiding significant differences in temperature along the pipe and at measurement stands
- taking air pressure in only one inlet for the whole and piping for the link to the others, or using a single larger pipe for both water and air

If the configuration and environmental conditions do not allow height and temperature control along the pipe path, then a complicated circuitry must be designed for circulating the water of the HLS and reaching an homogeneous temperature before measurements. This happened for the monitoring of the low-beta magnets in the LEP accelerator (figure 7).

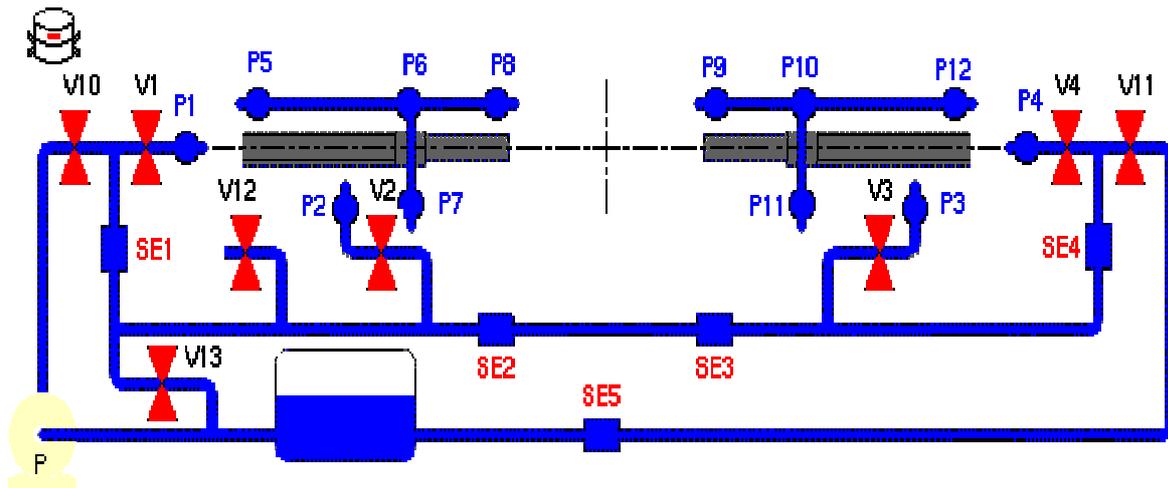


Figure 7: LEP low-beta areas: Temperature-Controlled Hydrostatic Levelling

Each of the four low-beta areas was equipped with three hydraulic circuits:

- A pair of static independent circuits, (p5, p6, p7, p8) and (p9, p10, p11, p12), one on each low-beta girder and acting like a bi-axial inclinometer. Each side, these vessels were connected by a single horizontal pipe for both water and air. Vessels p2 and p3 were also each on each low-beta girder, at a known height difference, but did not belong to these circuits.
- dynamic/static circuit (p1, p2, p3, p4), which ensured the link measurements between a reference vessel at each side (p1 & p4) and the low-beta girders (p2 & p3). All these vessels were connected by two different pipes, for air and water, separately. For topological reasons, these pipes could not be kept nearly horizontal in the environment (about 2m overall difference, plus local obstacles like doors), and the main problem was that the temperature conditions were not the same each side - for several degrees - in this complicated path. This did not alter the air pressure in the system but had significant effects on the height of the water column (local thermal expansions). The only solution was then to circulate the water through a large tank in order to quickly homogenise the temperature, and then to switch the system to its static configuration for doing coherent measurements. This was made by a pump and a set of servo-valves, and the whole process in computer-controlled.

Regarding the LHC project and its huge experiments, a very special scheme of measurements has been designed for linking both parts of the metrological network and the inner triplets of the accelerator. It consists in by-passing the detector through a parallel “survey gallery” which houses an offset reference line, for ensuring the alignment control of the very sensitive components located both sides. This special set up makes use of WPS devices, along the reference carbon wire, which are put at the end of orthogonal calibrated invar rods (figure 8), with capacitive (proximity) sensors at the other end for ensuring the link with the machine (cf. Mainaud-Durand in IWAA 2002).

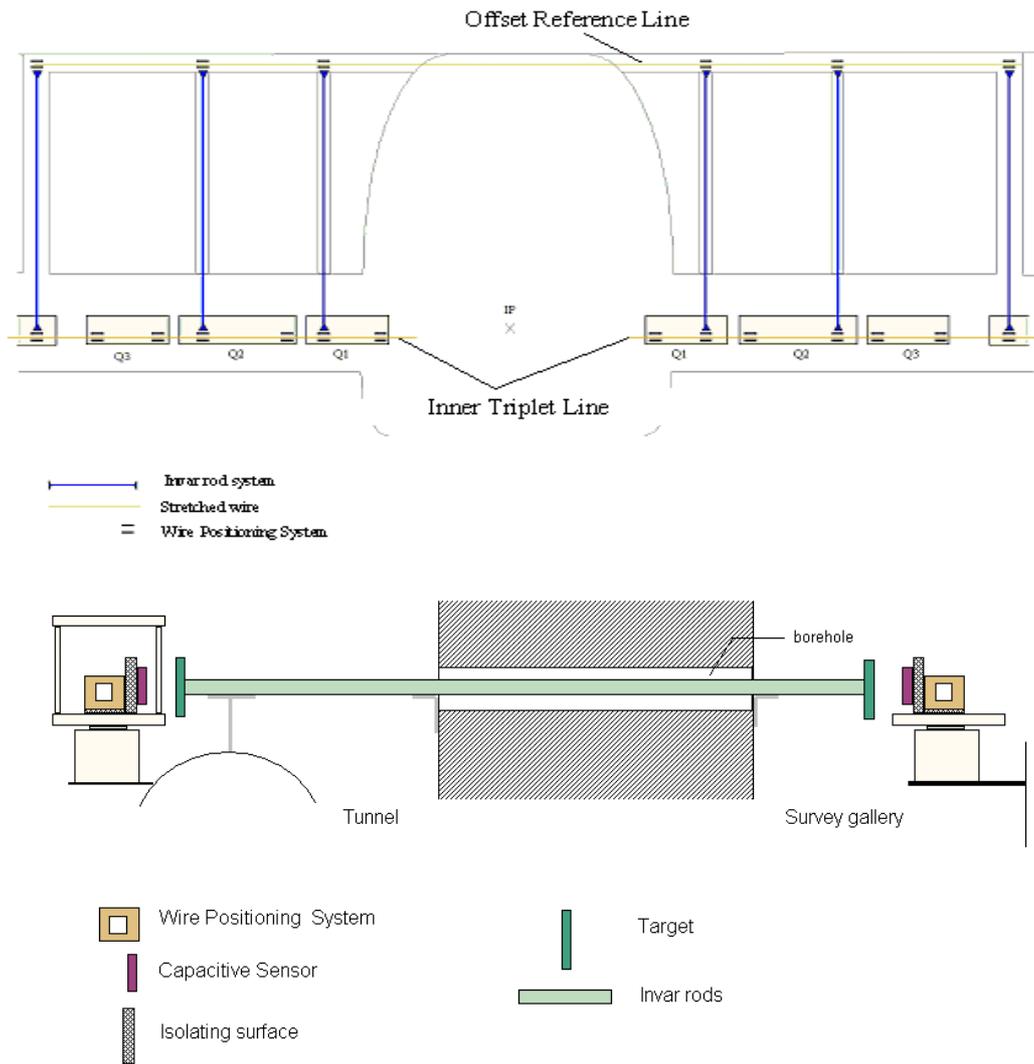


Fig. 8: radial remote control of the inner triplets of LHC in CMS and ATLAS areas

4. THE CERN CALIBRATION FACILITY

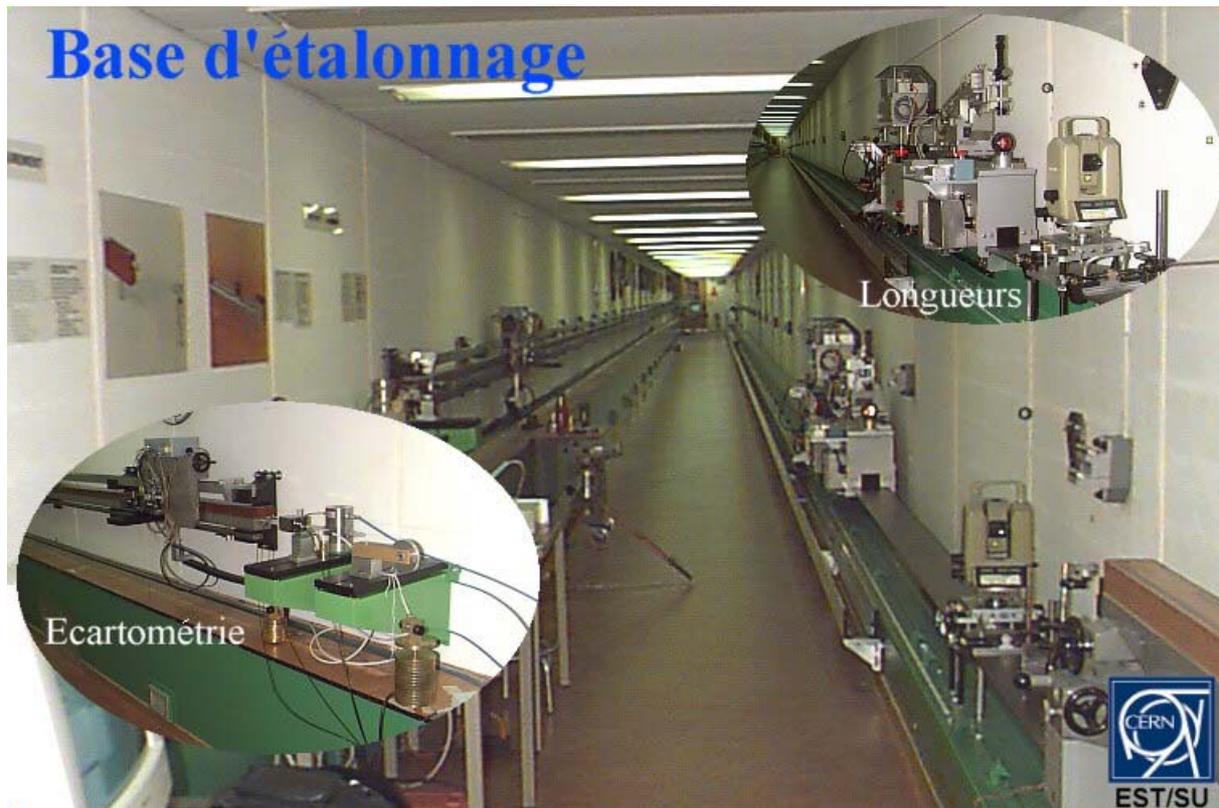


Figure 9: The CERN Calibration Facility

Such a facility is an absolutely needed tool when pretending to accuracy measurements, and CERN has implemented two ones, in relation with large projects. The present calibration facility (figure 9) is nearly 60 m long and is equipped with two benches for

- Calibration of lengths (interferometric bench)
 - Reference: interferometer ($\sigma < 0.1 \mu\text{m}$)
 - Carriage: manual or automatic mode
 - Calibrated instruments: invar wires, electro-optical distance-meters (for constant & cyclic errors), passive or active linear gauges, engraved tapes, scale bars, levelling staves

- Calibration of alignment systems (bi-axial offset bench)
 - High precision capacitive sensors and inclinometers
 - Vertical reference line: hydrostatic levelling ($\sigma = 2 \mu\text{m}$)
 - Horizontal reference: stretched wire ($\sigma = 5 \mu\text{m}$)
 - Carriage: manual, with all position parameters measured
 - Calibrated instruments and systems: wire or laser offset measuring devices, telescope & target alignment systems, optical polar systems (theodolites/total stations, laser trackers)

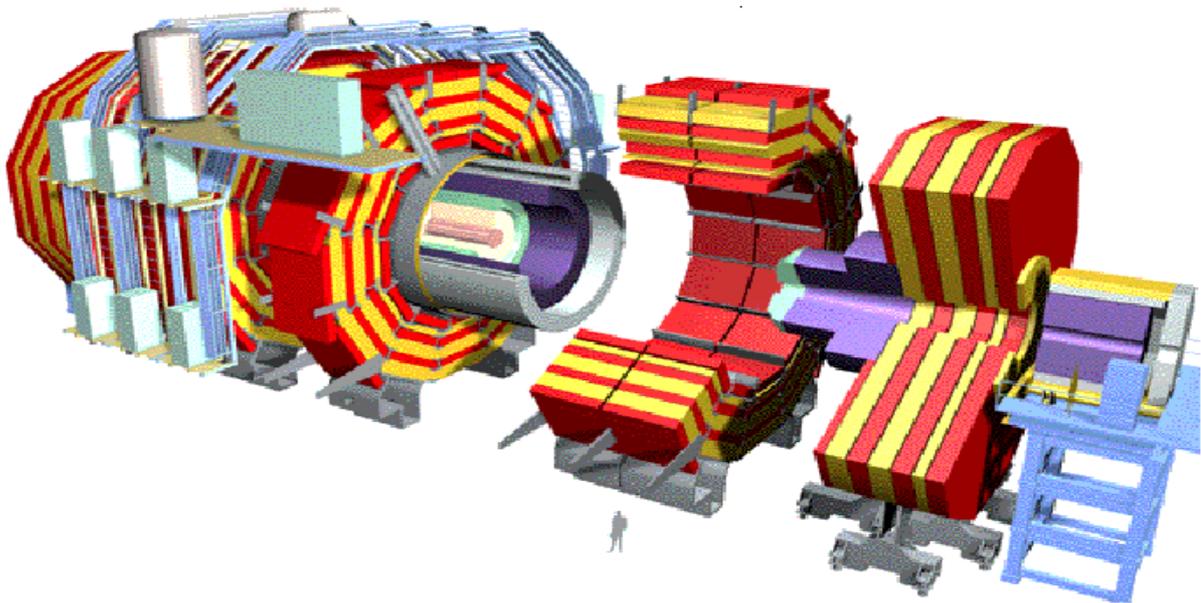
The moon & sun semi-diurnal forces have visible effects on the offset bench – as a combination of earth and hydraulic tides on the system – with amplitudes reaching 5 μm .

A device for calibrating digital levels and staves (cathetometer) is also installed in this facility, as well as a pillar and two stable points at 60 m for checking the constant parameter of gyro-theodolites. Another part of the facility is equipped as an indoor test network for some special tests or calibrations, and with a collimator for optical levels.

5. A GLANCE ON THE USE OF DIGITAL PHOTOGRAMMETRY AT CERN

Four large physics detectors, ALICE, ATLAS, CMS, LHC-B, will be installed at the four interaction points of the LHC (Large Hadron Collider), and new survey requirements had to be taken into account, together with new spatial and time scale constraints.

These detectors aim to study very high energy collisions of proton beams with the best precision possible and will be built from many separate pieces of structure, from central tracking units, to end caps closing the magnetic system and both detector heads. The typical onion layout for the CMS (Compact Muon Solenoid, diameter: 14.60 length: 21.60 m, weight: 14600 tons) is shown in figure 10. The performance of the particle tracks reconstruction depends on the intrinsic precision of sub-detectors and of their positioning. The requirements of the new LHC experiments for the object co-ordinate's precision vary from 0.05 mm for medium size objects up to some tenths of a millimetre for large size objects



(cf. Lasseur, FIG WW 2003)

Figure 10: CMS experiment

At CERN, a digital photogrammetry system consisting of several DCS460 cameras and the Rollei-CDW software has become the main tool for solving the geometrical positioning demands, the dimensional quality and the deformation analysis controls. Large objects, from

15 m to 20 m high, must be measured in their entirety at distance of only a few meters because free and available space is generally small and cramped, with multiple obstacles, and the interventions had to interfere as little as possible with the construction schedule. Digital photogrammetry appeared quickly to be the most convenient method at all respects – as easily adapted to such environmental constraints and after checking, on a scale model, that it could satisfy the various accuracy requirements for all dimensions to be processed for LHC detectors.

6. GEODETIC PARAMETERIZATION OF LARGE ACCELERATOR PROJECTS

Since the LEP collider (27 Km circumference), not only the local earth curvature was taken into account but also the local deflections of the vertical – generating a model of the local geoid in the CERN Cartesian three-dimensional system (cf. Bell, 1985; Mayoud, 1994. This was made necessary for correcting the gyro measurements around the ring and the vertical transfer of points from surface to tunnel level (a depths reaching 140m), and also for making sure that the accelerator be effectively defined in a real plane of space. The nearby mountain range of the Jura had indeed significant influence in these parameters.

A new project has triggered recently a careful refinement of both geodetic and gravity parameters of the CERN 3D reference system. The CNGS (CERN Neutrinos to Gran Sasso) project aims to investigate the 'oscillation' of neutrinos. A beam extracted from the CERN SPS accelerator will produce a beam consisting uniquely of muon-type neutrinos that will be directed to their destination, the underground Gran Sasso National Laboratory (LNGS) in Italy, 732 km from CERN.

For this project it is evident that our knowledge of the relative position of the neutrino target at CERN and the detector at Gran Sasso, is essential. Up until the CNGS Project the position of the CERN accelerators on a global scale has not been critical. Two GPS campaigns carried out in 1998, have now resolved this question to a high degree of accuracy, and a GPS survey campaign at Gran Sasso has provided us with their relative position.



Fig. 11: Scale of the CNGS Project

The geodetic problem is complicated by the fact that only one underground point, near the origin, can be directly linked to the surface network through a shaft. As a consequence, the final azimuth of the beam will rely upon 2 Km of accurate gyro measurements, and altitude and final slope parameters keep dependent on the knowledge of the local geoid.

Consultation with the national surveying bodies in France (IGN) and Switzerland (OFT) showed that the geoid model used for the LEP would probably need to be updated for the alignment of the CNGS accelerator components.

Based upon the 1998 Swiss geoid model (CHGEO98) a new model of the geoid and technique for its exploitation has been implemented at CERN (CG2000). This optimal local model appeared indeed to be in very good agreement with the European Quasigeoid EGG97, hence a safer expected correlation with the Italian Geoidal heights. The parameters establishing the position of the CERN Laboratory together with those of the CNGS beam line have now been refined again. This new geoid model is incorporated into our various algorithms (cf. Jones in IWAA 2002).

7. CONCLUSIONS

The considerations and examples given in this paper come from a long experience, over the 50 years of existence of CERN, in accurate measurements of scientific equipment in the domain of high energy physics. Due to the severe level of requirements and the specificity of the means to be designed in this field, such works and their related R&D were often made by “in house” geodesists and surveyors, integrated in such scientific institutes and laboratories. But commercial instruments have evolved, efficient collaborations can be settled with universities and private companies, and solutions may come more and more from industry and services. In any case, it requires a close collaboration between scientists and engineers, with multidisciplinary R&D on special measuring and monitoring tools whenever needed. Communication and exchange in this field exist through the series of International Workshops on Accelerator Alignment (see IWAA references), open to external audience, and within some special working groups of IAG and FIG (in commission 6).

As already stated at the Melbourne FIG congress (1994), surveying for research works generates research works for surveying, and it has to remain as long as possible a surveyor's concern.

BIBLIOGRAPHY

- Proceedings of the CERN Accelerator School on Applied Geodesy for Particle Accelerators, 14-18 April 1986, CERN, 87-01
- Proceedings of the IWAA series (International Workshops on Accelerator Alignment) in HEP laboratories : SLAC (USA, 1989), DESY (Germany, 1990), CERN (Switzerland, 1993), KEK (Japan, 1995), APS (USA, 1997), SPring-8 (Japan, 2002)
- http://iwaa2004.web.cern.ch/IWAA2004/previous_iwaa_proceedings.htm
- Becker, Coosemans, Pittin, Wilson : An Active Pre-alignment System and Metrology Network for CLIC – CERN CLIC note 553, January 2003
- Bell B. : A Simulation of the Gravity Field around LEP, CERN/SU internal note, 1985
- Gervaise J. : Applied Geodesy for CERN Accelerators (Part I), Seminar on High Precision Geodetic Measurements, Facolta di Ingeneria di Bologna, October 1984, Bologna, Italy

Gervaise J., Mayoud M. : Geodesy for Particle Accelerators, Advances of Accelerator Physics and Technologies - Chapter 16, Editor : Schopper H., Advanced Series on Directions in High Energy Physics - Vol. 12, World Scientific, 1993
Lasseur C. : Digital Photogrammetry Applied to Large Physics Detectors - Some examples - Original approach - Specific tests and conclusion, FIG WW 2003, Paris, France
Mayoud M. : "Specific Aspects of the Geodetic Metrology of Large Particle Accelerators", FIG XXIth Congress, 1998, Brighton, UK
Mayoud M. : Computing and Analysis Methods (Part II), Seminar on High Precision Geodetic Measurements, Facolta di Ingeneria di Bologna, October 1984, Bologna, Italy
Mayoud M. : High Precision Metrology of Large Scientific Equipment, FIG XXth Congress, 1994, Melbourne, Australia

BIOGRAPHIC NOTES

Michel Mayoud

Geodetic & Surveying Engineer diploma from ESGT, Paris, France, 1970

Post-graduate diploma in photogrammetric engineering from ITC, Delft, Netherlands, 1971

Professional experience:

* 1971-1974 - Société Française de Stéréophotogrammétrie (SFS, Paris): Aerial and terrestrial photogrammetry, geodesy, general and construction surveying, high precision measurements on dams, nuclear plants, ships, industrial and research equipment

* Since 1974 - "Applied Geodesy Group" of CERN; Deputy Group-Leader in 1982; Head of this group (renamed "Positioning Metrology & Surveying" and then "Large Scale Metrology") since 1986; Involved also, in this special expertise, as consultant, partner of collaboration agreements or occasional adviser for various research projects or achievements in Brazil, China, Germany, India, Italy, France, Japan, Portugal, Russia, Switzerland, Taiwan, United Kingdom and United States of America.

CONTACT

Michel Mayoud,

CERN

CH-1211 GENEVA 23

SWITZERLAND

Tel. + 41 22 767 3007

Fax + 41 22 767 3456

Email: Michel.Mayoud@cern.ch

Web site: CERN: <http://www.cern.ch>

Web site: SU Group: <http://ts-dep.web.cern.ch/ts-dep/groups/su/su.htm>