GEODETIC METROLOGY OF PARTICLE ACCELERATORS AND PHYSICS EQUIPMENT

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Abstract

This paper presents a review of the instrumentation, techniques and processing methods used at CERN for the metrology of large scientific equipment (from a few metres to several kilometres), the positioning of which requires high accuracy. Some specific features of tridimensional geodesy and comparative surveys of such objects are treated and illustrated.

I. INTRODUCTION

Since the construction of the first particle accelerator at CERN, in 1954, the Applied Geodesy Group has gained great experience in the metrology of large or very large objects. This initial machine was the largest in the world at that time, with its 200 m diameter. CERN has now built LEP (Large Electron Positron Collider), a new accelerator 27 km in circumference, for which the Geometrical tolerances have been tighter : a relative accuracy of 0.1 mm all along the machine and the best possible absolute accuracy with respect to the theoretical geometry.

To achieve such requirements, many specific devices and methods have been developed at CERN. Most of them have been widely described in various articles and the purpose of this paper is mainly to give a review of the more recent developments in instrumentation, techniques and processing methods, with emphasis on some particular problems related to the exceptional size of such machines. More detailed information on all these topics may be found in CERN bibliography.

II. GEODETIC METROLOGY OF LARGE OBJECTS

II. 1. PARTICLE ACCELERATORS

The search for accuracy in geodetic metrology demands that the processing of the data always remains rigourous, and takes into account any factor which can affect the exactness of the measurements or that of the results. For each project, the size of the new accelerator to be built has led to the reconsideration of several aspects of the methodology.

Major changes in geodetic concepts have been introduced in designing the SPS (2.2 km diameter) and LEP (8.6 km diameter) control networks.

First, in both cases, the computation of the theoretical XYZ coordinates of the machine has resulted in increasingly precise considerations of the geometry of the earth. For the SPS, a spherical approximation was sufficient to express the effects of the earth's curvature in computing the Z ordinates, correcting the vertical *descent* of geodetic points down the shafts or properly tilting the magnets, in order to obtain a real plane in space. With the LEP accelerator, which partly lies under the Jura mountains, a further step has been to determine the vertical deflections generated by gravity disturbances, and then to express the separation between a reference equipotential surface and a reference local ellipsoid (see IV.1). This knowledge provides the necessary corrective factors to convert measured altitude into ellipsoidal heights in 3-D computations (see IV.2), to correct the coordinates of bottom points from the effects of vertical deflections, or to reduce the gyro measurements.

One other change in the methodology is that repetitive measurements of the SPS or LEP control networks could no longer be thought of, and managed as, *absolute* surveys. For such long and flexible ring-shaped figures, the variations of the coordinates issued from different sets of comparable measurements have no physical meaning for the particles. The trajectory of a beam within an accelerator is mainly sensitive to short-range errors. Misalignments of the components are thus seen as local imperfections of the guiding magnetic field. Long-range errors have less effect but are not negligible. Thus, the major requirement for the geometry of an accelerator is that relative errors must be as small as possible. In other words, the figure must be smooth. This smoothing concept is fundamentally involved in a particular refinement process which is used for the first installation of a large machine and for any new partial or global survey when a re-alignment of components is to be done (see chapter V).

A further consideration is the fact that certitude in any accuracy problem cannot be acquired without a thorough knowledge of the stochastic behavior of the measured networks. Although this statement sounds self-evident, it is in reality dependent on the method of estimating the actual errors and deformations which a network may undergo as a result of the random and systematic errors in the measurements. For this purpose, a simulation method has been developed at CERN on the basis of a statistical analysis under controlled perturbations (see IV.3.).

From another point of view, the considerable increase of accelerator size required an improvement in technical and economical efficiency of instruments, in-field measuring procedures, data logging, processing and data management.

For a 27 km long machine, with more than 4500 functional elements installed in a tunnel, about 32000 measurements have been carried out, collected and processed at different stages of the project. Such a tremendous effort, involving many people, must be thought of in terms of management and technically organized in a reliable and efficient process.

This consideration required the implementation of the best operational procedures, both for civil engineering controls and metrology of accelerators (see chapter III).

II.2. PHYSICS EQUIPMENT

Particle accelerators are very particular, due to their exceptional size. Physics equipment (Fig. 1), brings us back to more common dimensions and the following considerations may apply to other industrial objects.

The main characteristics - in relation to their metrology - of the new generation of experiments at CERN are :

- currently, 1000 m^3 and 10000 tons of equipment,
- complex structure, with concentric assembly of parts,

- sub-millimetric accuracies required,
- high density of connected elements (many masks),
- confinement in caverns, with a gas-like property to completely fill the available volume.

These features give a first idea of the technical and environmental difficulties of the task.

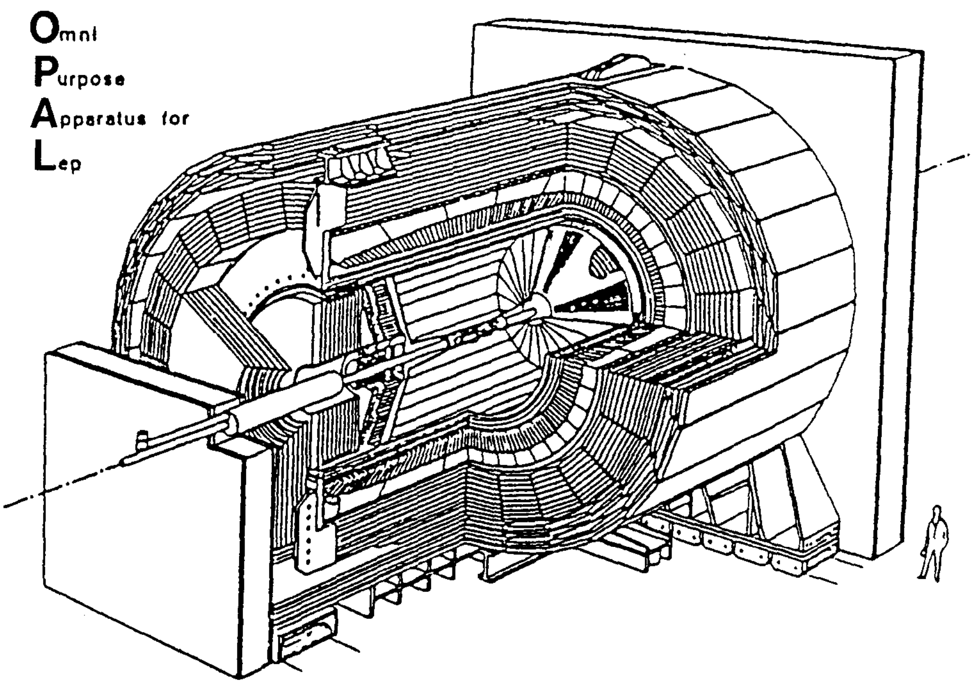

Figure I : Collider Experiment

One can describe modern experiments, specially the LEP ones, as a set of Russian dolls; each doll being designed to detect a certain physics phenomena. In order to obtain good results in the analysis of events (reconstruction of particle paths), a precise knowledge of detector positions, both with respect to the beam and respect to each other, is requested.

The modules are inserted one inside the other, the positioning relation being established geometrically. The biggest external one is the only one visible in the working position. The position of the smaller internal module can be reconstructed from the position of the largest, assuming that the geometrical relationship established during assembly is maintained. The assembly and positioning tolerances determine the precision to be achieved, the threshold being given by the most sensitive elements of the experiment.

To obtain the final coordinates of each detector of the experiment (alignment data base) a succession of survey operations is needed from the first availability of individual objects up to the data-taking position.

Each individual detector element is equipped with internal reference marks defined in its own coordinate system, with respect to a physical reference. In most cases, these internal marks are not convenient for surveying and special survey references must be installed. A first operation consists in realizing a *link geometry* - by either geometrical, optical or mechanical methods - which is carried out in the laboratory, workshop or assembly hall. For that purpose, a complete and mobile micro-geodetic process has been developed. This system makes use of clamped tripods, invar measurements, micro-triangulation with up to three electronic theodolites

KERN E2 connected to a portable computer (HEWLETT-PACKARD IPC), distance measurements on the object itself with an accurate micrometric bar, inclusion of known mechanical constants between parts or marks. Observations are directly processed *in situ*, where it is needed.

Then, before being moved onto the beam line, the detectors are installed one by one in their definitive (relative) position. This lengthy stage is subjected to successive geodetic controls by means of an assembly network, materialized around the mounting location. During this *transformation geometry,* external (visible) reference marks of the detectors are surveyed, before being hidden by the next layer (Russian dolls problem).

The final stage of that complex geodetic process is carried out when the whole experimental equipment has been drawn and aligned on the beam line. There again, a control network is used for the determination of a sufficient number of the visible reference marks located on the *outer skin* of the object. This network must be carefully linked to the geometry of the accelerator and its coordinates, expressed in the CERN reference system, can be converted into *beam coordinates.* Hence, in a backwards and recurrent loop of successive 3-D transformations, the final coordinates of all fiducial marks of all detectors are at last determined in the beam reference system. The exact location and accurate geometry of the whole equipment are then known.

In order to open the scope of measuring facilities in such complex configurations, the tridimensional adjustment program is able to process many kinds of observations (see IV.2). Beside horizontal and vertical angles, orientations, distances, off-sets and levelling measurements, the following measurements are allowed :

- spatial off-sets in any plane of the object,
- theodolite off-sets, i.e. horizontal distance to a vertical plane (theodolite sight),
- vertical off-sets, i.e. horizontal distance to a vertical (nadiral or zenithal sight, plumb-bob).

These facilities may give a powerful means to provide appropriate and significant binding measurements, thus ensuring the homogeneousness and reliability of the metrology.

III. RECENT DEVELOPMENTS IN CERN INSTRUMENTS AND TECHNIQUES

III.1. UNDERGROUND CONTROLS

The tunnelling work, for a particle accelerator, must be carried out within very strict and tight tolerances. To avoid costly mistakes, conflicts or disputes, it is necessary to make controls at different stages of the construction, and to finally check the concrete lining of the galleries and caverns. For such a long and difficult task, the respective roles of firms and CERN surveyors were contractually defined and a close collaboration was established.

In that particular domain, some recent developments or refinements have been implemented, mainly in the vertical linking between surface and tunnel levels, the gyro measurements and profiling methods.

A convenient and reliable way to transfer points through deep shafts is shown in figure 2. This operation involves setting up three theodolites and their (calibrated) EDM, one MOM or WILD gyro, one WILD Na2 level and three special target or reflector holders (screwed on the pit curb-stone). All horizontal and vertical angles are measured, as well as distances, orientations and height differences. Observations are processed as a spatial block by means of the CERN 3-D adjustment program. Deflections of the vertical are taken into account to correct *gyro* measurements and to express the correcting vector due to the difference between the physical plumbline and the normal to the reference ellipsoid. For a pit as deep as 140 m, this correction can reach 6 mm. The accuracy of this operation is estimated to be $\sigma_{xy} \leq 1$ mm and $\sigma_H < 2$ mm.

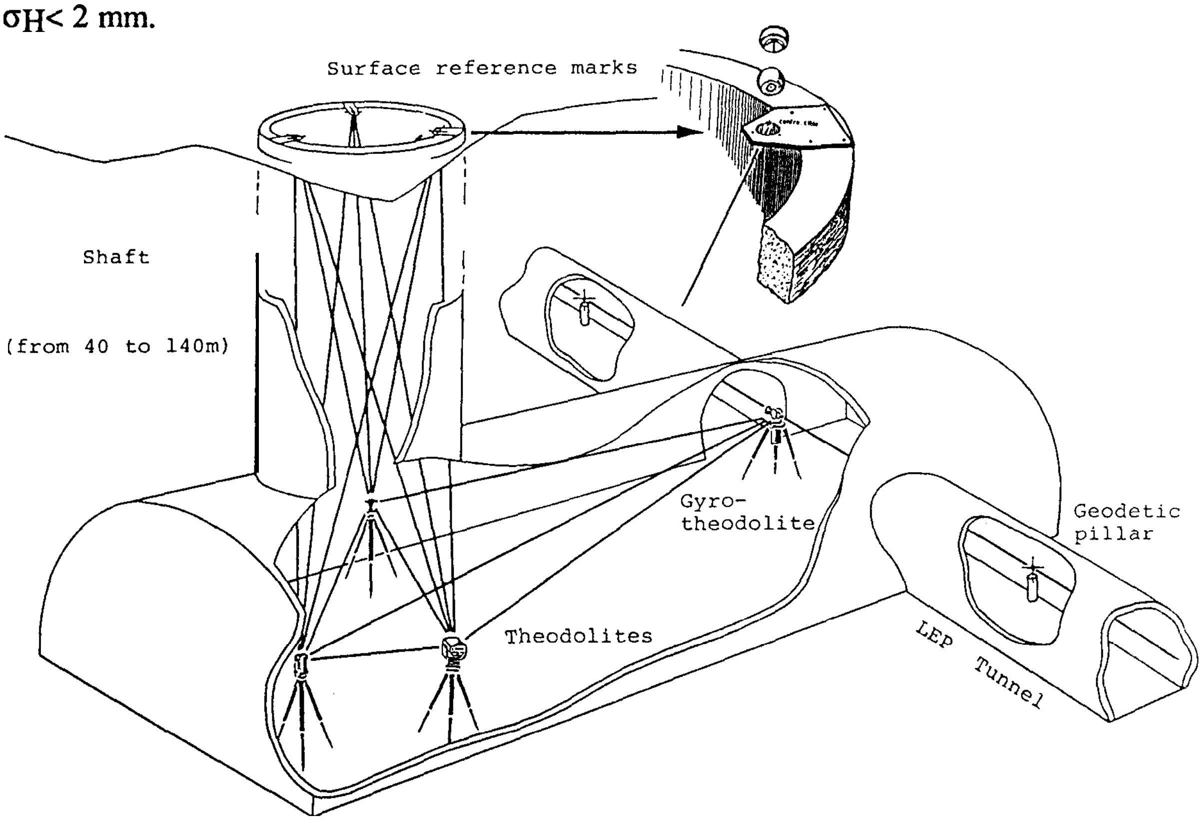

Figure 2 : Linking measurements at tunnel level

For the guiding of tunnels, after the experience gained for the SPS, LEP was a new challenge with its 27 km being cut in octants (3.3 km between control points). More than ever, gyro measurements were the only way to ensure minimum misclosures and a complete automation and computerization of the WILD GAKl Gyro has been undertaken, with a dedicated software for internal calibration, thermal corrections and North computations. The in-situ performances of the modified GAKl vary from 11 to 18 cc (1 σ) in a ZP-MOTOR-ZP-MOTOR-ZP sequence, framed by two outdoor calibrations.

In parallel, very good results ($\sigma \cong 7$ cc) have been obtained with the MOM Gi-Bll gyro in long sequences of eight independent measurements, framed by calibrations.

The control traverses in the tunnel, are a combination of gyro observations, short and long-side angular measurements, invar distances between pillars, long-range EDM measurements, direct and indirect levelling data. Before computation, gyro measurements are corrected for convergence of meridians and for the effects of vertical deflections. All observations are processed in the 3-D adjustment program. Over the eight 3.3 km octants so bored and measured, the r.m.s. radial misclosure has been 10 mm (1 σ) only.

About the profiling of cross-sections of the galleries, it is only worth mentioning that very good performances have been obtained with analytic photoprofiles - accuracy better than 1 cm (1 σ) - along with fast production rates (two minutes for full data acquisition of one station and eighteen minutes per profile for observation, computation and plotting). For large caverns, where photoprofiling is not suitable, a FENNEL profile scanner has been tested and used, producing good results.

III.2. AUTOMATIC INSTRUMENTATION AND ALIGNMENT CONTROL

Without changing their basic principles, deemed still good, all CERN instruments have been fully re-designed in order to implement a computerization of their functions and to make them able to work under digital control. The goal was to realize a complete computer-aided process for the measurement and alignment stages of the metrology of LEP.

The present range of automatic instruments is the following :

- Distinvar (counting unit 0.01 mm), for invar wire measurements from 0.40 m to 50 m;
- Laser interferometer with self-aligning reflector (counting unit 0.1 µm), for the in-situ calibration of invar wires with $\sigma \leq 0.01$ mm;
- Horizontal offset measuring device (counting unit 0.01 mm), with either a nylon wire or a laser beam reference line;
- Vertical offset measuring device (counting unit 0.01 mm) for direct geometrical levelling with a laser beam;
- Electronic inclinometer (counting unit 0.01 mrad) for the measurement of tilt angles.

All these instruments can be connected to a computer or a control box through a RS 232 line, and be digitally operated.

At the measurement stage, instrument control and data acquisition are made on small portable computers, like EPSON HX20 or PX4. Relevant Basic programs have been developed for each measuring procedure, guiding operations, collecting data, calculating statistics and formatting the data files.

For the alignment stage, a more powerful computer was required. Since no convenient one was available some years ago, it was decided to develop and build a field-computer, specially dedicated to this operation. Easily transportable, in a reasonable case, it is based on a MOTOROLA 68000 processor, can be powered by internal or external battery (or AC supply) possesses 1 Mb RAM and 1 Mb ROM memory, allows connection of five RS 232 lines, includes an additional support memory for 64 K RAM cartridges, has a 40 characters printer and incorporates digital transducers for temperature, humidity, pressure and battery control.

The computer-aided alignment of an accelerator component is conceived as shown in Figure 3. The control network is settled on plug-in tripods, and the coordinates of these reference points are derived from the previous stages of the metrology. The problem is then to carry out an accurate installation of an element - say a quadrupole magnet - at a pre-determined theoretical position.

A first pre-alignment step is realized, with help of an auxiliary hydraulic device, using a combination of length, offset, tilt and levelling measurements, controlled by the field computer. Then the quadrupole can be released on to its mechanical jacks, and the final positioning is carried out with, again, a full computer control of the operation. Real-time readings of all set up instruments permanently allows the program to compute the actual position of the quadrupole compared with theoretical coordinates and deduce the optimum moves to apply to the jacks.

Such computer-aided procedures have been repeated about 4500 times, around the 27 km of the accelerator.

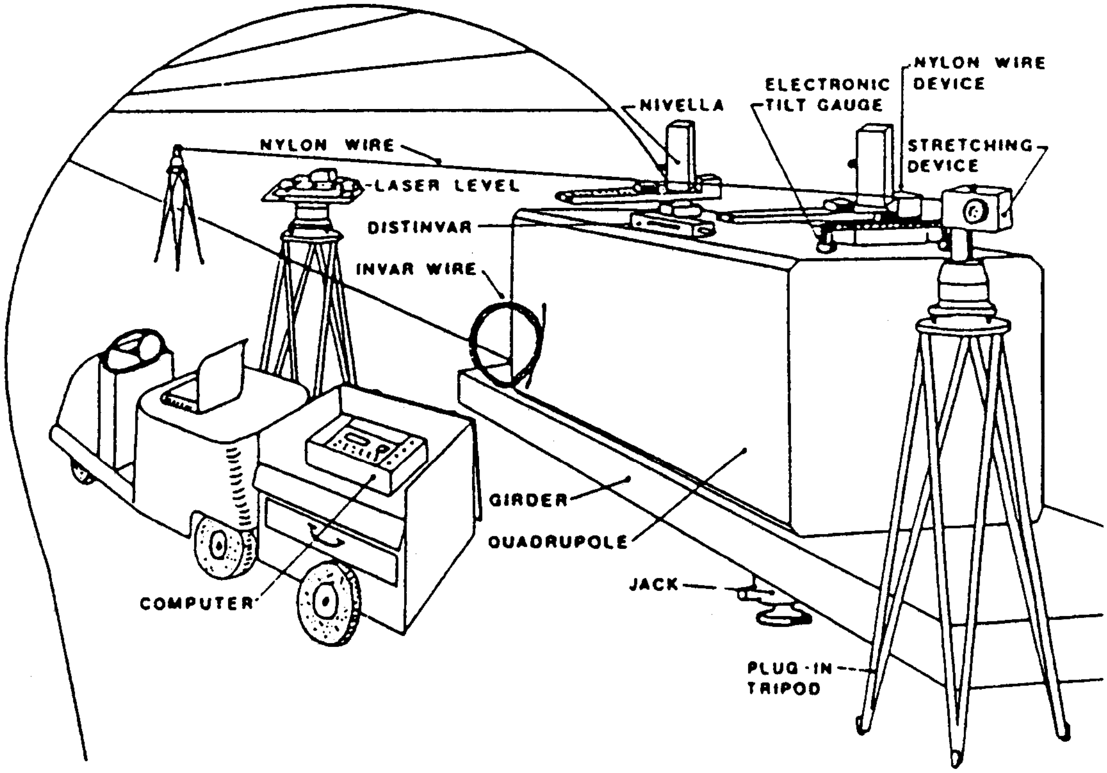

Figure 3 : Quadruple alignment arrangement

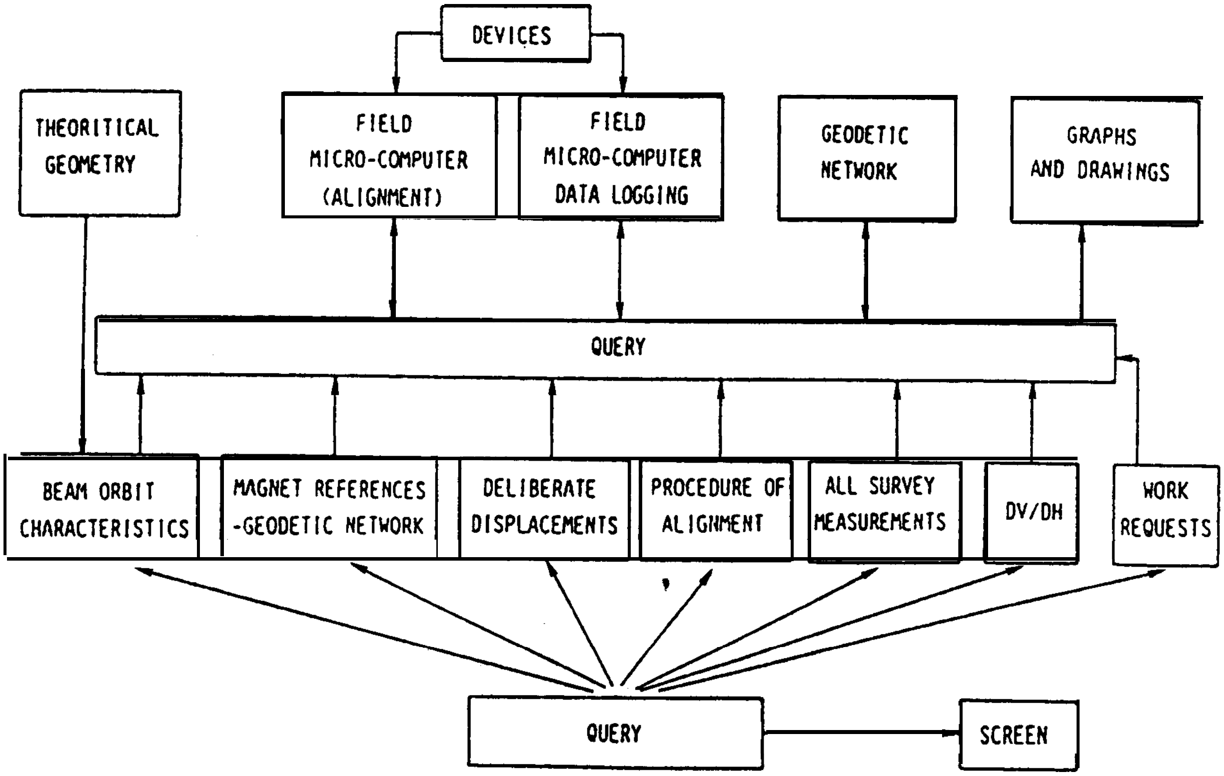

Figure 4 : Organigram

III.3. DATABASE MANAGEMENT

Beside LEP, other CERN accelerators and their transfer lines already represent more than 8000 elements laid along 20 km of beam lines. Each of them involves several metrological parameters : position of reference sockets, theoretical and actual coordinates, measuring procedure, use of special gauges, etc. Depending on beam orbit problems, they are regularly surveyed. Then some elements can be re-aligned due to local unstabilities, or they are deliberately displaced in order to act as correctors of the beam orbit.

To efficiently handle such a considerable amount of data, a specific database has been established with the Oracle system (Figure 4).

This development is now fully operational and it constitutes a very clear and powerful means to manage all stages of the survey process.

IV. DATA PROCESSING IN A 3-D LOCAL SYSTEM

IV.l. LOCAL EVALUATION OF THE GEOID

For the evaluation of equipotential surfaces under the area covered by LEP, CERN has made use of the large mass model (510 x 410 km) realized in Switzerland and completed with additional data.

Taking into account both the numerical integration in this mass model and several surface measurements of vertical deflections, the collocation program developed at Bern (Gurtner, 1978) allows the computation of equipotential surfaces at any altitude. A 10 x 10 kilometric grid has been used for the estimation of the Geoid and vertical deflections at different levels over the LEP area. All the data has been related to the local origin of the CERN system, in order to express the parameters of relevant corrections.

Starting from a method developed at Bologna (Achilli et al, 1982), CERN has also experimented with a computation of gravity components in a limited portion (70 x 50 km) of the mass model, restricted to the topography from level zero upwards. Although referred to the same local origin, the results show a kind of systematic gradient difference from those of the Bern program. The cause of this is probably the absence of any external constraint (no *absolute* surface measurement of ξ, η) and the non-consideration in the model of the remote influence of some high Alpine mountains. Expressed in vertical deflections, these differences range from -1.7 to 0.6 arc seconds.

Finally, in order to make an independent check on these estimated values, astrogeodetic measurements were carried out on eight points, using the zenithal camera of the Institute of Geodesy of Zurich (Burki et al, 1983). This camera, developed at the University of Hannover, has a 1 m focal length, two high-precision Talyvel automatic levels and its operation is fully computer-controlled. Six plates were taken per station and the measurements and computations have been made at the University of Hannover. The standard errors on computed geographic coordinates were quoted as 0.3 arc second (0.9 cc).

The comparison between the resulting observed values of the deflections and the predicted ones was remarkably good. The residuals are generally less than 1 arc second. The standard errors of this comparison are :

- $\delta\xi = 0.55''$ $\delta\eta = 1.03''$ for the Bern mass model,
- $\delta\xi = 0.57''$ $\delta\eta = 0.56''$ for the CERN limited mass model.

Being more confident in the BERN program, the results of the large model computations, combined with astrogeodetic measurements, were retained. The search for a surface fitting the 121 + 8 point estimates of the grid called for the following considerations :

- the prism spacing (500 m) of the mass model induces small relative errors;
- at such a large scale, an equipotential surface is more likely to be smooth than wrinkled;
- for sake of simplicity, a *light* parameterization would be more convenient.

For these reasons, polynomials or piece-wise functions (like 3-D splines) were rejected and a canonical trend surface was looked for. The best least-squares fitting was a paraboloid limiting errors to less than 1 arc second in deflection, with respect to grid values.

IV.2. THE TRIDIMENSIONAL ADJUSTMENT PROGRAM

Many adjustment programs have been successively written to satisfy the geodetic needs for CERN accelerators : planimetric (XY) or altimetric (H) programs, tridimensional adjustment strictly limited to micro-geodesy, processing of large matrices, Helmert transforms, etc.

The size of the LEP project called for a new and rigorous computational tool, fully adapted to the processing of all kinds of geodetic data in a local system and whose main features are the following :

- local 3-D adjustment on the ellipsoid GRS80;
- altitudes are referred to the known local geoid and are subsequently converted into ellipsoidal heights;
- generalized least-squares processing of all types of available data, some kind being very peculiar to the metrology of experiments equipment;
- all angular measurements, observed relative to the local horizon, are re-expressed in the CERN Cartesian system through an appropriate rotation matrix;
- direct levelling data is processed as vertical distances;
- various constrained/unconstrained computational cases are available;
- statistical and variance analysis of the results;
- generation of random and/or systematic perturbations for simulations;
- preparation of files for subsequent (weighted) Helmert transforms;
- free-formatting and intensive use of keywords for flexibility in data handling.

IV.3. THE CERN SIMULATION METHOD

Starting from the a priori standard deviations on measurements, derived from experience, the well-known tools of stochastic analysis are :

- unit weight variance : σ^2;
- covariance matrix : $C_x = \sigma^2 N^{-1}$, which gives expression of absolute and relative error ellipses;
- histogram of residuals, estimated accuracy of (groups of) observations, elimination or refinement methods;
- confidence intervals on estimates.

Nevertheless, this classical way of analysis may leave some interpretation problems on mixed networks. Significant distortions can occur on a posterior-i estimates and it is difficult to appreciate the relative *strength* of each group of observations. Furthermore, no signal is given to detect the systematic errors, which are not modelled in this process. This kind of simulation does not give a clear view of the behavior of a perturbated network and one must remain rather wary when interpreting the resulting statistical figures.

A pragmatic way to obtain a picture of the true situation is to simulate on a computer all the perturbations which can affect the geometry of a figure : Gaussian errors in measurement, artificial generation and addition of systematic errors, controlled constraints, etc.

For this purpose, the provisional coordinates (or theoretical ones for accelerators) are taken as ideal. Measurements are supplied in the input file as for a normal computation of the network. The program computes the ideal measurements and a gaussian generator adds random errors scaled on a-priori variances. The data is then processed as usual. Repeating these operations gives a *Monte-Carlo* generation of *'n'* sets of hypothetical measurements of the same network.

Empirical statistics carried out on the results give very interesting estimates to be compared with the known (and controlled) a priori values of the variance of each group of observation or, even, to allow a direct analysis of the effect of errors on the coordinates. Tests can also be made to appreciate the agreement of actual results with predicted values. Such a method gives a clear idea of the response of a complex network to random errors and provides some corrective factors to apply to the various estimates in order to make a correct scaling of the predicted errors.

When adding systematic errors and/or controlled constraints, the simulations also give a true image of the distortions suffered by the network. The effect of each constraint can then be evaluated. The resulting shifts of the mean values of the residuals, with respect to any selected systematic error in each group of measurements, gives an idea of the *warning lights* to watch for when actual measurements are to be processed.

This pragmatic method has been used for years at CERN and it is a very helpful tool for the engineer who needs a real knowledge of the network he has to design and optimize, and then observe and compute.

V. SMOOTHING AND COMPARATIVE SURVEYS

When installing the machine components, the first determination of the control network gives the displacement vectors between their actual *rough* position and their theoretical one. In fact, magnets are positioned 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 redundancy, overlap of measurements, and the bridge distance between control (fixed) points. The final relative errors are a quadratic combination of those of the network itself and those of the positioning, i.e. installation errors. Their statistical nature is essentially gaussian : the aligned elements are randomly and normally distributed around this mean trend curve (Figure 5).

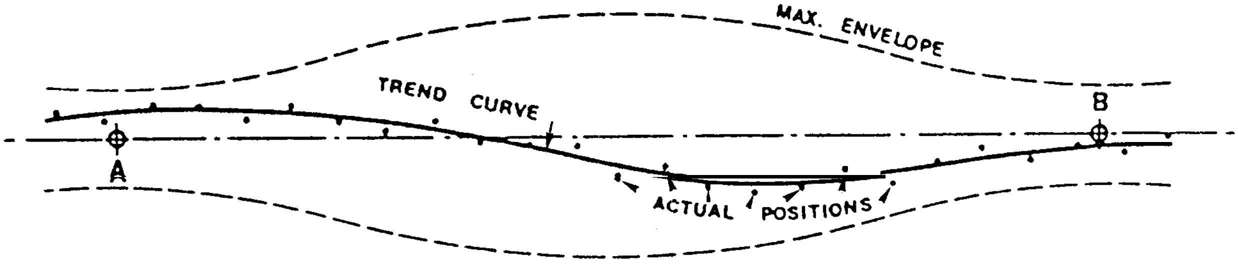

Figure 5 : Position of magnets with respect to theoretical orbit

As the major requirement for the geometry of an accelerator is that the relative errors must be very small ($\sigma \leq 0.1$ mm), an obligatory step for surveyors is to check the installation by measuring and - if needed - improving the smoothness of the machine alignment.

Another important consideration is that, when making successive surveys of long and flexible figures, absolute comparisons would be a nonsense. The difference between trend curves, corresponding to each survey, must be analytically eliminated without inducing systematic or harmonic errors, which are critical for an accelerator.

This mathematical problem is not trivial and different methods have been evaluated for the separation of absolute and relative discrepancies. Polynomials were rejected due to the inner constraints generated between data points when increasing their order. The Fourier decomposition was rather dangerous with respect to the harmonic sensitivity of beam orbits. Therefore, a special smoothing algorithm has been developed in order to process the local data in a purely relative way, e.g. without any absolute involvement in coordinates.

The smoothing process consists of a set of radial or vertical measurements (Fig. 6) which are treated in the following way :

$$(1/1+k)\ dRh - dRi + (K/1+k)\ dRj + St - Sm = vi$$

where :

H, I, J, are three successive points,
k = proj (I-U) / proj (HJ) along HJ
dR = unknown radial discrepancy with respect to mean curve
St = theoretical sagitta in point I, with respect to HJ
Sm = measured sagitta
vi = residual of the measurements

Each point receives three overlapping measurements resulting in a good redundancy. Nevertheless, these measurements only cover six points (i.e. three quadrupoles) and the global system would be rather poorly conditioned if a determination of coordinates was required. But as the purpose is to get local and purely relative information, this fact is not critical if the normal system is solved under the double condition $\|dR\|$ and $\|v\|$ minimum.

The condition $\|dR\|$ minimum constrains the reference line of the ordinate dR to be the mean curve. This condition cannot be directly expressed in the adjustment. Neither can it be linearized since the differential increments, the unknowns dR, and the residual v are, nearly, of the same order of magnitude. The convergence would consequently be slow and the results uncertain.

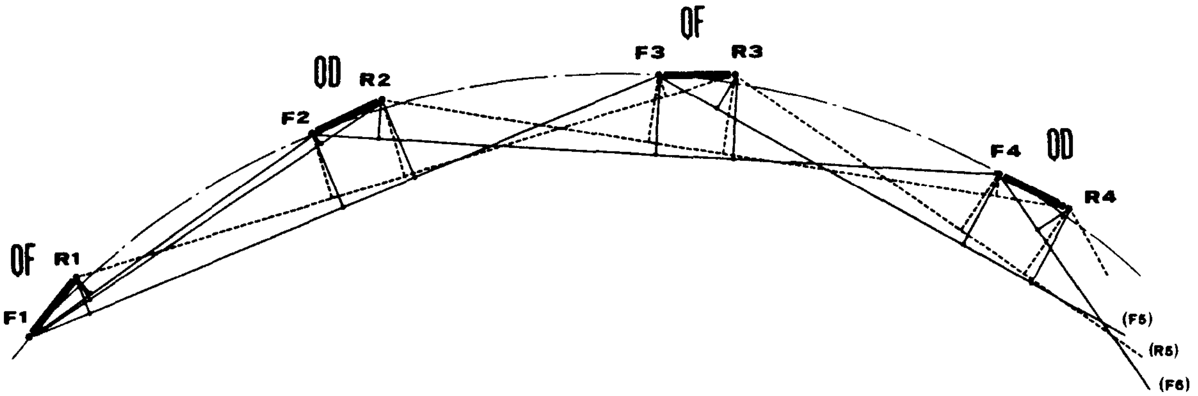

Figure 6 : Scheme of smoothing measurements

The only way which has been found for solving such a system is to move dRi onto the right-hand side of the equation, introducing for each central measurement on I a new observation equation :

$$1/\sqrt{3}\ (1/1+k\ dRh + k/1+k\ dRj + St - Sm) = dRi\ (+vi)$$

The weight $1/\sqrt{3}$ comes from the fact that each point receives three measurements.

The normalization of these additional equations is equivalent to $\Sigma(dr + v)^2$ minimum, i.e. :

$$(\Sigma dr^2 + \Sigma vi^2 + 2\ \Sigma dR\ vi)\ \text{minimum.}$$

Σvi^2 is set to its minimum by the normalization of the first equation, for each measurement. These residuals vi constitute a Gaussian distribution [0, σ_m] and the radial ordinates dR are also expected to be a set of Gaussian variates with, of course, a zero mean-value. Σdr^2 will consequently be a minimum if the quantity (Σdr . vi) tends to zero, this being the case for two Gaussian samples of the same dimension N.

If the sample V has dimension n = N/3, this is more difficult to prove. But it can be checked easily with a program using the computer's Gaussian generator.

This global procedure is a kind of compromise, which is not quite rigorous but nevertheless satisfactory. Simulations and real computations have given acceptable results both for checking the first installation and for successive and comparative surveys of the machines.

For vertical positions, smoothing has been first made *visually* by drawing a mean curve on a plot of differences H measured - H theoretical. A similar procedure has been tried by generating pseudo-observations of vertical off-set values, derived from adjusted altitudes, with the same overlap. Results here are also satisfactory :

- unfavorable sign sequences are located,
- outstanding dR values can be pointed out.

CONCLUSION

The very accurate instruments and sophisticated methods presented in this paper have been designed for obtaining the most precise knowledge of the shape, dimension and position of very large scientific objects. But it is also worth remembering that industrial and engineering surveys are performed in an industrial or scientific environment, where many topological problems occur in the installation of a very high density of various equipments.

For that purpose, digital cartographic systems - in connection with C.A.D. systems - are a powerful means to manage and maintain the survey data of complex and evolving industrial sites.

At CERN, a software package from INNOVAL (France) has been implemented for the complete management of the 1400 hectares of the site and the 500 000 m^2 of building floors, laboratories, galleries, halls, etc. All topographical, technical, management and administrative data can be entered in the Site and Buildings Databases, constituted with the *Espace* package, through graphical and standard alphanumeric terminals. In addition to its cartographic performances, such a system provides a very efficient way to correlate management information with the topographical location of any kind of equipment.

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