GEODETIC METROLOGY FOR LARGE EXPERIMENTS

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1. INTRODUCTION

The importance of the role of geodesists in the alignment of particle accelerators is generally accepted, on the other hand their role in the alignment of the physics experiments themselves is less well known. The requirement for precise and rapid control of dimensions has stimulated a rapid development in both technology and methods of industrial measurement on this side.

This paper gives an overview of the survey work that is generally required for the installation and alignment of the collider experiments at CERN.

Several important trends of interest in these are highlighted and these together with the experience from the LEP installation allow us to draw certain conclusions for the alignment of the next generation of collider physics experiments.

2. SURVEY ALIGNMENT OF A PHYSICS EXPERIMENT

2.1. DEFINITION OF RESPONSIBILITIES

The responsibility of survey alignment for physics experiments is twofold :

- responsibility to experimental collaboration : that is to provide technical aid to the collaboration (verification of theoretical parameters) and to provide coordinates for the external survey data base (approximate values for alignment by track fitting).
- responsibility to experimental collaboration and machine : that is to assure the correct alignment of common elements of the accelerator, the most important being the experimental magnet.

2.1 MAIN ASPECTS OF THE METHODOLOGY (figures 1 & 2)

A detector is rarely a single unit and the components can be considered as sub-detectors or individual objects : each step of assembly produces another set of objects. In the case of collider experiments, the installation of a detector hides another; the structure of the ensemble can be compared to that of a set of Russian dolls and the technique developed for the alignment of large non-deformed composite objects of this type was christened “Russian doll metrology”. It is the establishment of a cascade of spatial relationships between parts of a modular object at various measurement and installation epoches, which allow the subsequent mathematical recreation of the complete object from the first availability of individual units up to the definitive installation.

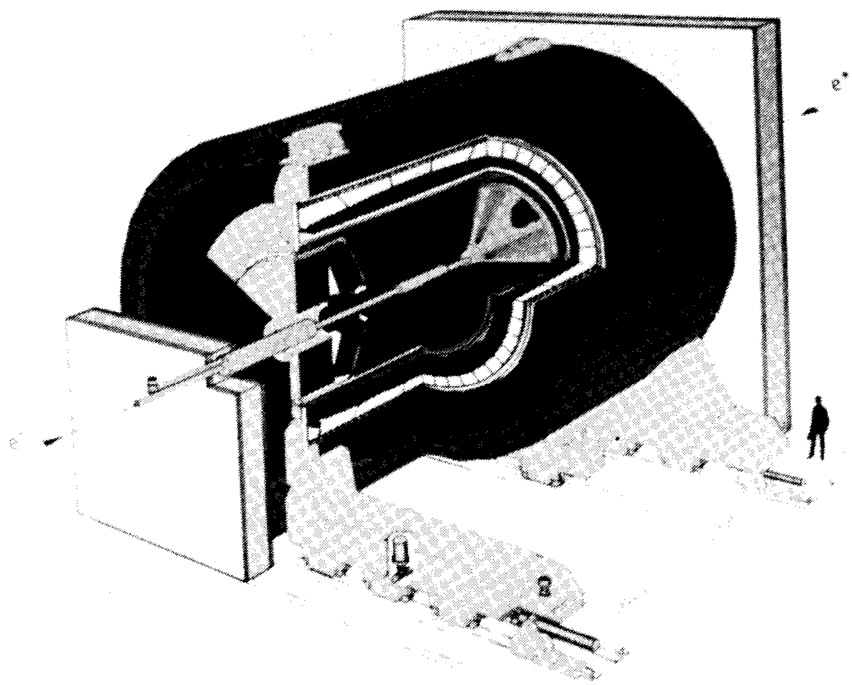

Figure 1: The OPAL experiment at LEP

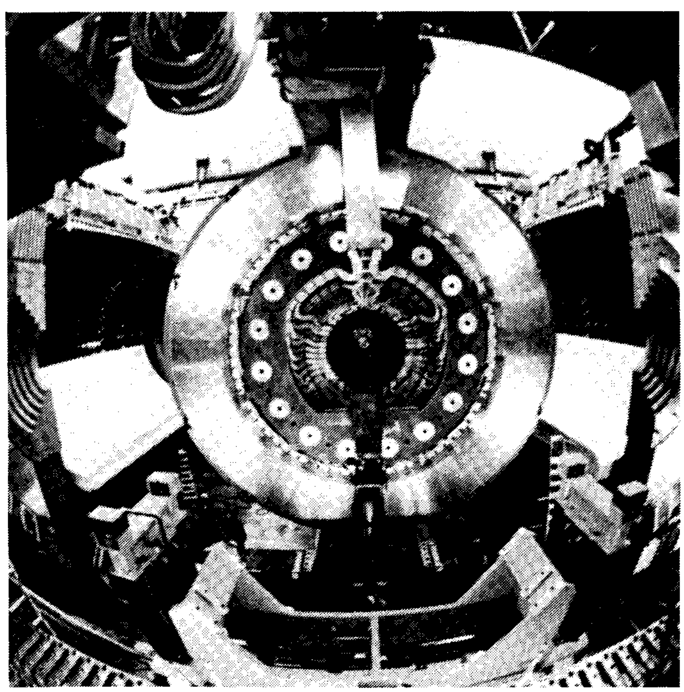

Figure 2 : OPAL before closure

Four levels of relationship can be distinguished.

2.2.1 **Internal geometry** : definition of the spatial relationship between the physics reference and the survey reference on each individual basic element of the detector.

2.2.2 **Detector geometry** : spatial description of a modular object featuring the detector by using the survey reference points.

2.2.3 **Relative geometry** : establishment of a cascade of spatial relationships between adjacent detectors.

Dimensional control such as the verification of certain parameters of objects in laboratory, workshop or factory (often carried out as part of an acceptance procedure) and geometrical calibration namely the spatial description of an object by survey measurements providing relationships between sensitive parts of the detectors and the outside survey reference marks are perfect examples of these steps.

2.2.4 **Definitive geometry** : measure of position of all detectors on beam-line deduced from above relationships.

Pre-alignment measurements before final installation, alignment improvement during installation and metrological measurements in the data taking position to provide definitive spatial coordinates for the external survey data base plus maintenance of the latter are also good examples of that step. Nearly 3000 reference points describe the detectors of the four LEP experiments.

Russian doll metrology is often the only means available to supply a complete spatial description of an experiment on the beam-line. It requires however a very important planning effort in particular for the definition of the timing of intervention and to assure that the common points necessary for the transfer of relationships are always visible. From the point of view of installation, it is advantageous, because most survey work is done before installation of the experiment on the beam line. However objects are assumed to have an unchanged spatial relationship through time which is often not the case. The truth of this assumption can be checked by appropriate and auxiliary measurements also by software criteria when items are remeasured but the final status is given by the alignment systems of the detectors themselves.

3. IMPLICATIONS OF SURVEY FOR INSTALLATION

3.1 SURVEY PREPARATION WORKS

3.1.1 Preliminary exchanges of information

Survey must be incorporated from the establishment of the collaboration and included in the working groups in order to explain what survey can do, can not do and has done. An introductory appraisal of the needs can be conducted by means of a simple questionnaire. It is also essential to have one representative for each detector, who is charged with the survey dialogue. Survey technical advice and requirements in calls for tender may be asked during manufacture of the detector. Moreover as the procedures used to align experiment and machine are very different the definition of role and responsibility is part of the dialogue machine and experiment.

3.1.2 Definition of survey reference marks

It is rare that survey measurements can be made directly on the detection part thus outside survey fiducial marks have to be created at a known position with respect to the physics reference system. It is better to establish this essential relationship during the manufacturing process as the fiducial marks are more readily accessible. The type and position of the survey reference is thus chosen before the survey procedure is finalized : precise holes allowing the inter-changeability of targets are generally requested for most detectors.

3.1.3 Precisions

Before any discussion of survey procedure, it is essential to have an idea of the precision required for survey measurements on a given detector and to understand the reasons for this request. Experts at this sort of surveying know that a sub-millimetric is generally required over very large volumes.

3.1.4 Definition of survey procedures

Theoretical studies and simulations play an essential part in the definition of survey operations because of the complexity of installation procedures and the limited optical access to survey fiducial marks. Certain problems may require development of special instrumentation and tests.

3.1.5 Definition of timing of intervention

Survey measurement must occur at the right place and time; so it must be included as a post with an allocation of space on the chain of assembly even in the most rudimentary plannings specially in tight schedules.

3.2 GEODETIC NETWORK

An indispensable element of the survey of a physics experiment is the geodetic network, a series of stable points at strategic locations, whose coordinates are known with respect to the theoretical beam to a few tenths of a millimetre and which acts as a large calibration spatial bench. It is the homogeneity, the precision and the continuity through time which determine the measurement accuracy between spatially separated detectors. The network evolves following the advancement of the installation and this must be taken into account for zone demarcation. The materialization of the network (survey brackets, pillars etc) require space, stability and optical inter-visibility. The definition of essential optical paths is required but any restriction to the optical accessibility reduces the possibility to meet unforeseen survey applications.

Regarding the main steps of mounting, the calibration measurements are also related to networks which have to be settled nearby the assembly locations. Nearly 40 of these ad-hoc local grids had to be arranged for the LEP experiments.

4. SURVEY TECHNIQUES

The needs for alignment of physics experiments require the use of a variety of techniques, not-always associated with those of surveyors - see figures 3 and 4.

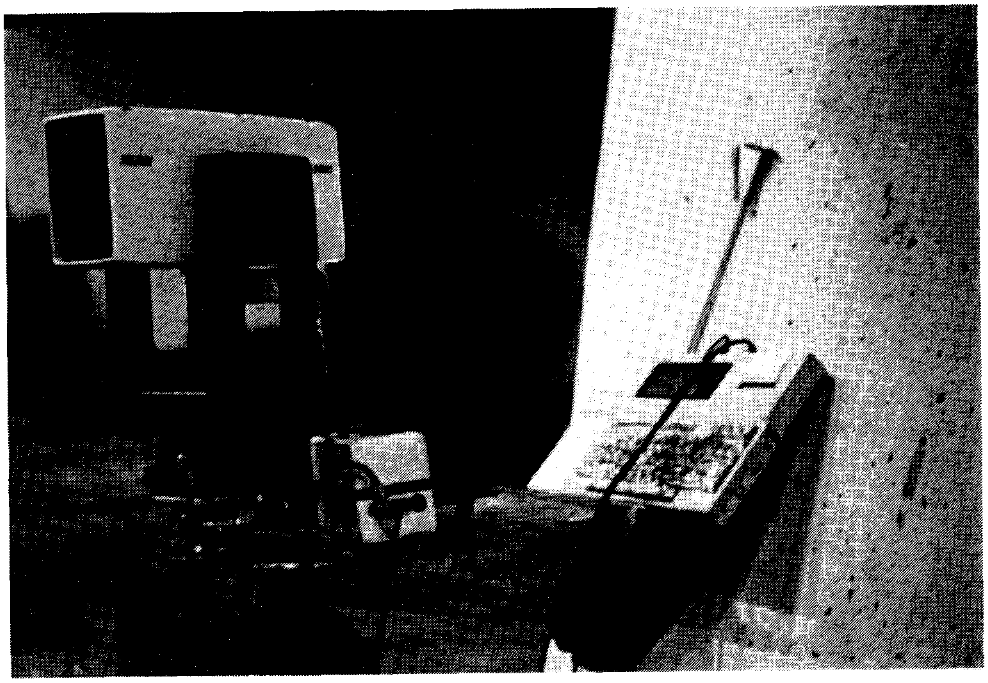

Figure 3 : The Mekometer ME 5000 plus PX4

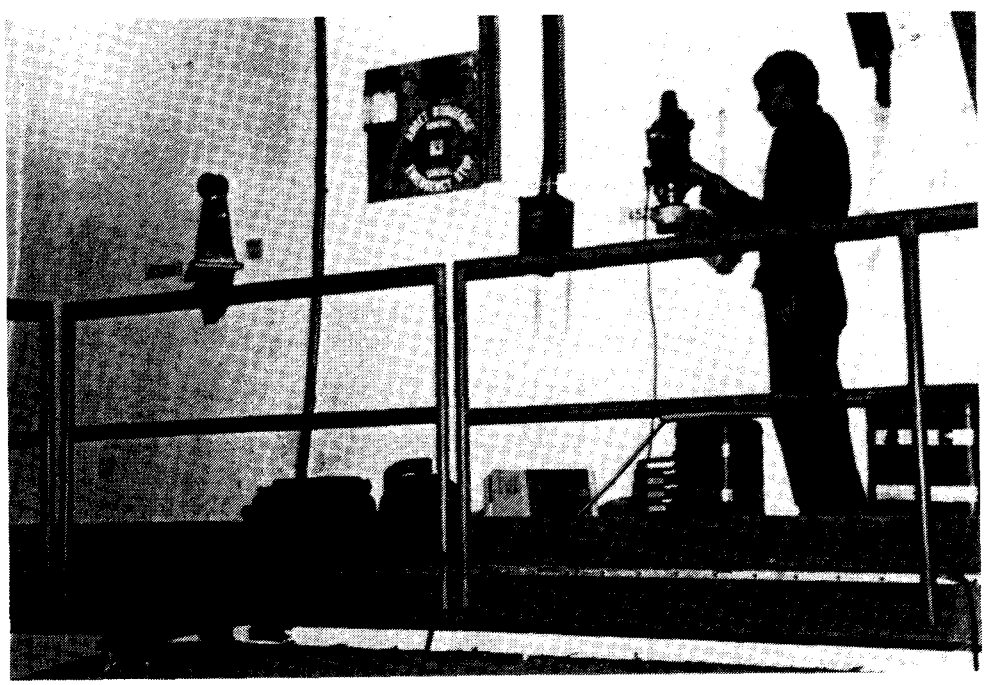

Figure 4 : The KERN E2 plus HP-IPC and network brackets

4.1 INDUSTRIAL TRIANGULATION AND SUBSEQUENT IMPLICATIONS

The method of the description of an object by coordinated points intersected from two or more electronic theodolites in a common reference system, has been largely adopted and adapted.

The use of surveying techniques gives the versatility plus mobility and adaptability of application, however the level of precision obliges the use of a high quality equipment such as electronic theodolites (Kern E2, Wild T3000 with on-line data capture, treatment and management facilities on portable computer), geodetic levels, electro-optical distance metres (Mekometer Kern and DI 2000 Wild) and an important computing effort such as:

- “in-field home-made ad-hoc facilities” developed on laptops;
- mathematical modellisation programs and routines (specially for curves, surfaces fitting and calibration model);
- exhaustive on-line 3D determination program with appropriate routines to short range geodesy (ponderation regarding the quality of the targets, special algorithm) firstly to facilitate and increase the speed of treatment, secondly for the rigourous bloc adjustment of various redundant measurements including distances and direct levelling with immediate controls and analysis;
- large core computer processing for data management (information system to and from a main survey bank), spatial adjustment programs for large 3D networks capable of handling the widest variety of observations and facilities of treatment (free adjustment - Meissl algorithm - 3D adaptation with identification of given discrepancies) plus analysis (on-line simulation, display of residuals, possible errors, confidence areas and displacement vectors) and graphics interfaces for most of the outputs.

4.2 SPECIAL TECHNIQUES WITH HIGH RESOLUTION INSTRUMENTS

4.2.1 Ability of the Kern ME5000 to short distances (Figure 5)

As the internal low range program presents some restrictions for distances below 20 m, it was necessary to well understand the limits as well as the calibration: a general program based on the recognition of two consecutive changes of slopes in between which a complete demodulation occurs and incorporating a quick and reliable procedure for short distances has been then produced.

The studies have been conducted on the baseline at CERN where any lengths up to 56 m can be created with an interferometric accuracy; from 21 to 4 m, a systematic survey of all possible minimums has also been carried out inside the working limits of the modulator (460-510 Mhz) and particularly inside the band of best efficiency (467-495 Mhz). It has been concluded that all the minimums outside this band provide measurements biased proportionally to the differences to these limits, the dispersion increases as the distances increases and the final accuracy is not significantly improved according to the number of possible minima corresponding to the distance. When only one minimum is possible, approximate value within 10 cm and the frequency corresponding are needed in order to see if it is inside the limits of optimum efficiency. If no minimum is available - or just in the limits - using a calibrated bar of nearly a quarter of wavelength (about 15 cm) readjusts the minimum in the best possible conditions of efficiency and then makes the process possible.

The intensive use of these investigations allows us to measure spatial distances as a standard deviation of 0.1 mm in the 3D networks of the experimental areas.

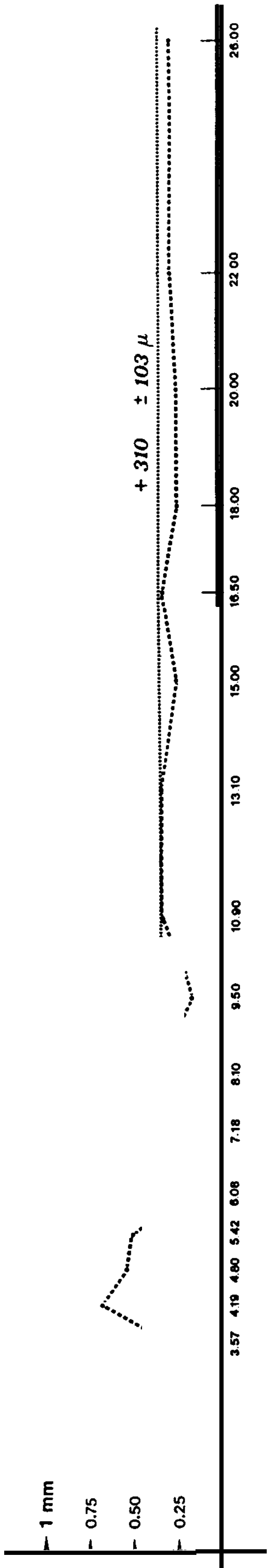

Figure 5 : Mekometer ME 5000
Results of calibration for short distances

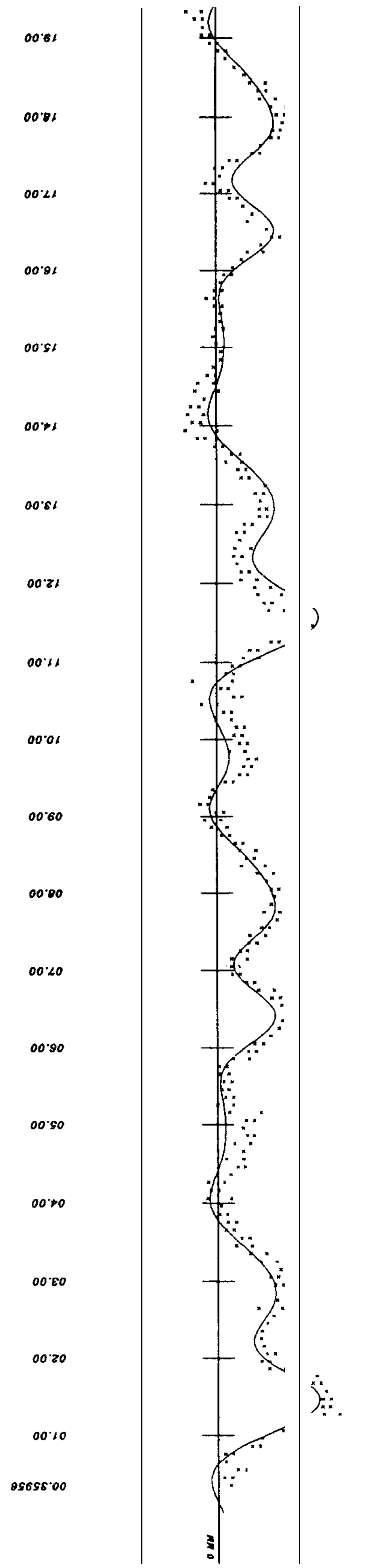

Figure 6 : WILD DI 2000
Results of calibration and modellisation (Fourier series)

4.2.2 Determination of polar coordinates (Figure 6)

After an exhaustive interferometric calibration, a complete modellisation of the performance of the Wild DI2000 (standard deviation of 0.2 mm after adjustment and perfect accord of the spread of the residuals with the expected cyclic errors) permits us to use this instrument, associated with the T3000, as a very accurate total station for setting auxiliary networks and, more often, for measuring marks on the detectors (calibration and data-base measurements).

4.2.3 Metrology on the object

A digital micrometer (Sylvac-bar - see figure 7) based on differential condensers and equipped with calibrated extensions up to 3 m plus suitable centring devices, was used to control magnetic cores (10 m in diameter) and large circular frames, both composed by individual units defined by fiducial marks.

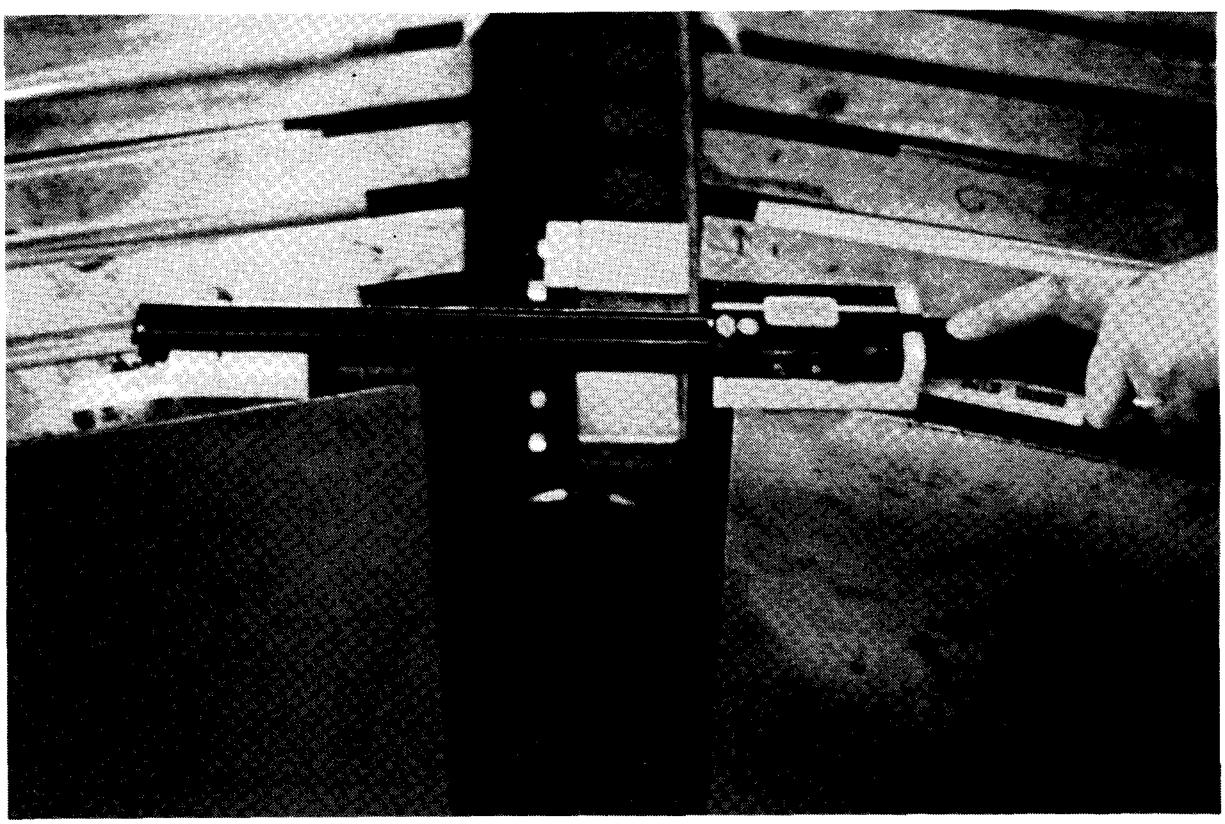

Figure 7 : The Sylvac-bar

A regular and redundant observation scheme in the vertical position was achieved - see figure 8. The definitive coordinates were obtained from a free network adjustment and the overall precision was within 0.2 mm partly due to the precautionary cares of measuring such as frequent comparisons with a calibration bench in the working area specially monitoring of the non linearity of the electronic device and taking into account the gradients of temperature.

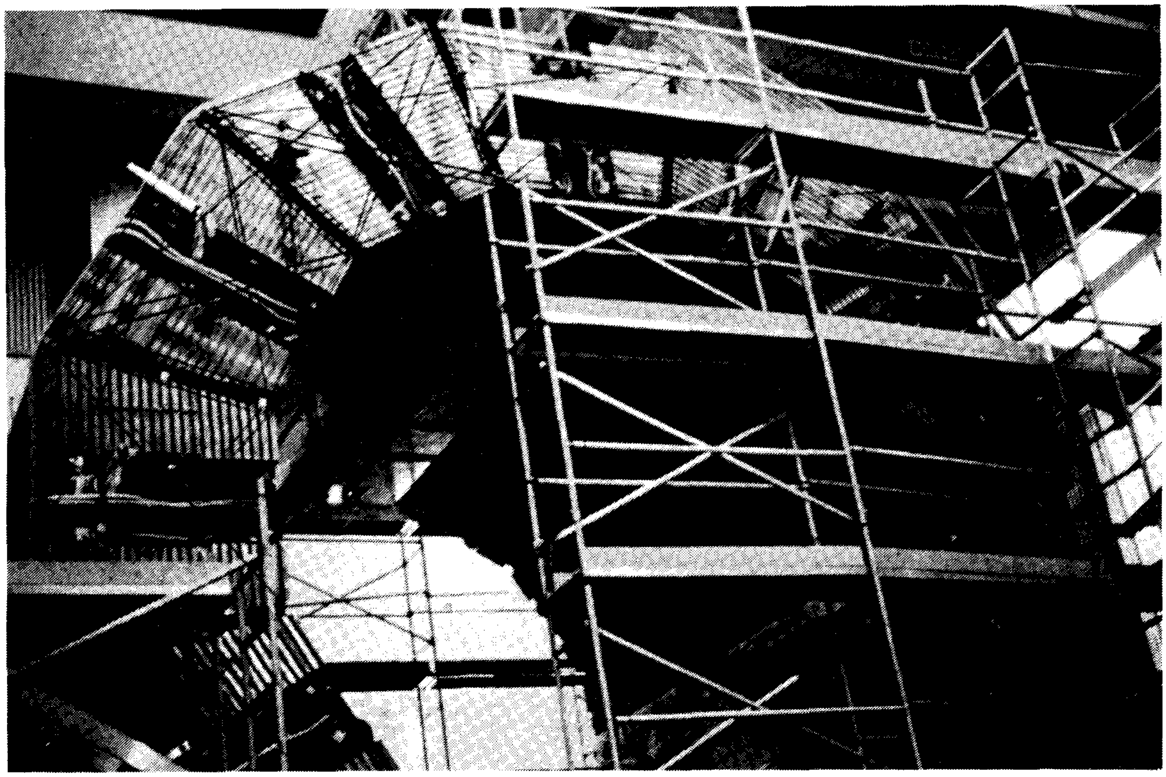

Figure 8 : Sylvac observations scheme for a magnetic core

4.3 SURVEY ALIGNMENT AND MECHANICAL ALIGNMENT

Survey and mechanical alignment should be seen as two complementary techniques requiring a careful adaptation of method to application. Cross-checking between the two is always desirable, it increases confidence and avoids misunderstanding or mistakes.

Survey seems particularly appropriate for the non-contact measurements moreover treatment and redundancy give information of the quality of the final results. The setting of zero's with reference to a non materialised coordinate system and the final spatial determination are also well adapted to the survey technique.

On the other hand mechanical alignment may be suitable for various insertion operations (direct and trusted by engineers) and leaves little room for error if the reference is well chosen. But specially in the cases of possible mechanical changes after loading and definitive fitting, a verification by survey means is useful then generally accepted and applied.

5. NEXT GENERATION COLLIDER PHYSICS EXPERIMENTS

5.1 PRIMARY AND SECONDARY GEODETIC NETWORKS

The primary network is a priori to provide a link to the machine reference system and to provide a basic coverage of the area; the points must be at the same height as the machine survey reference plane and the reciprocal visibility between such points is critical and must be preserved.

Points in the secondary network are positioned for specific measurements on the detectors. The design will thus evolve following the definition of survey procedures and the stage of installation. Means have to be found to approach the secondary survey points towards the detectors such as temporary survey stations on magnet or solid and plug-in supports. The advantage of this method is versatility of survey action and reduction of the number of network points. However this type of strategy requires the redetermination before each measurement of the survey station and has the inconvenience of requiring a longer measuring time and preservation of a complete optical access to points of the primary network.

5.2. ASSEMBLY PROCEDURE AND PREPARATORY WORKS

The outline of the assembly procedures of new more massive detectors - see figures 9 and 10 - and the short installation time suggest that the majority of survey work would be done on the surface as an integral part of the assembly line of the individual elements of the experiment (magnet pieces, muon chambers, hadron calorimeter) : that should be the case of the establishment of the internal relationship between physics and survey fiducial marks by surveying techniques. This discussion will not be treated lightly as it is fundamental to any further survey action on the detector. Introduction in the definitive position, after preparatory works, on precise aligned guide rails, girders or presurveyed positioning gears should be adopted as often as possible. This procedure is likelv to reduce the planning problem and sometimes takes survey off the critical path of installation.

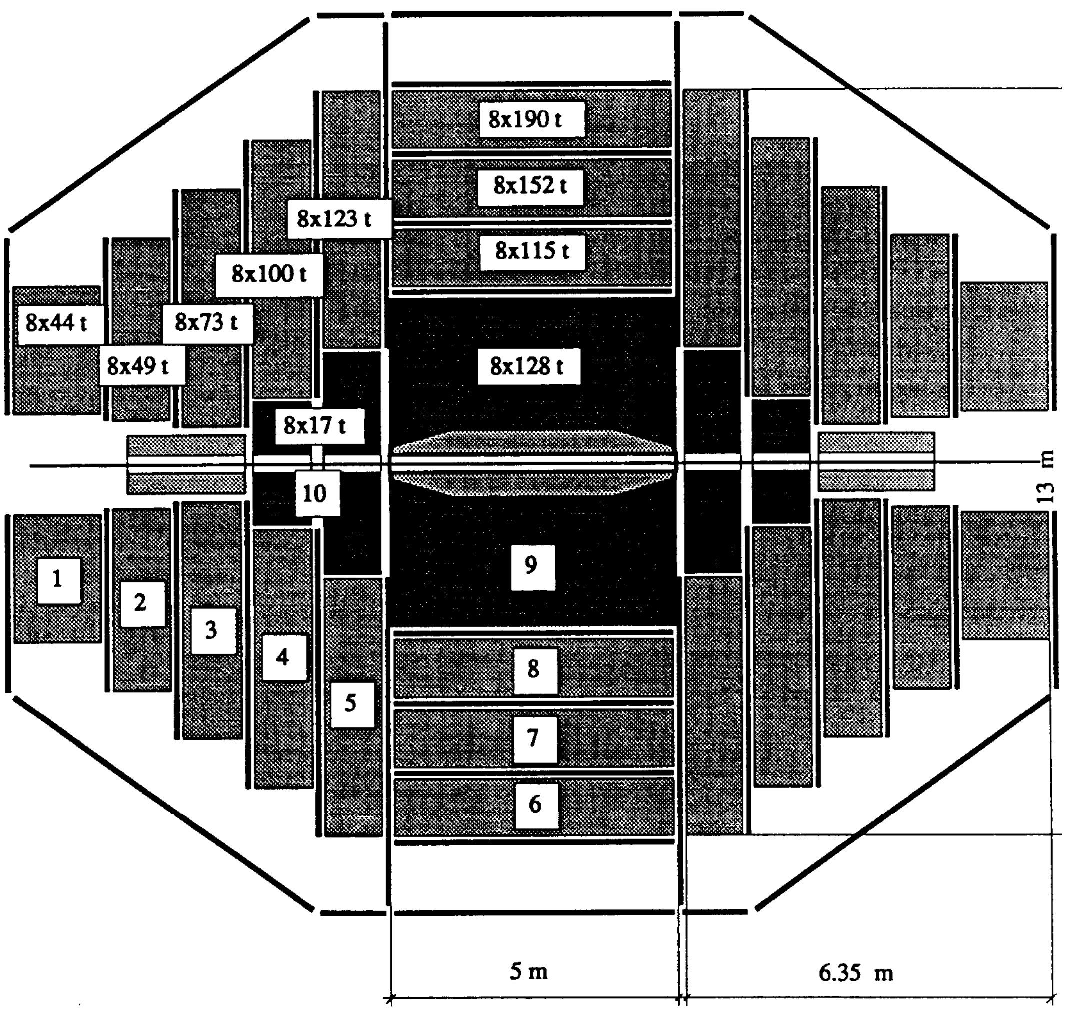

Figure 9 : LHC iron solenoid (8000 t)

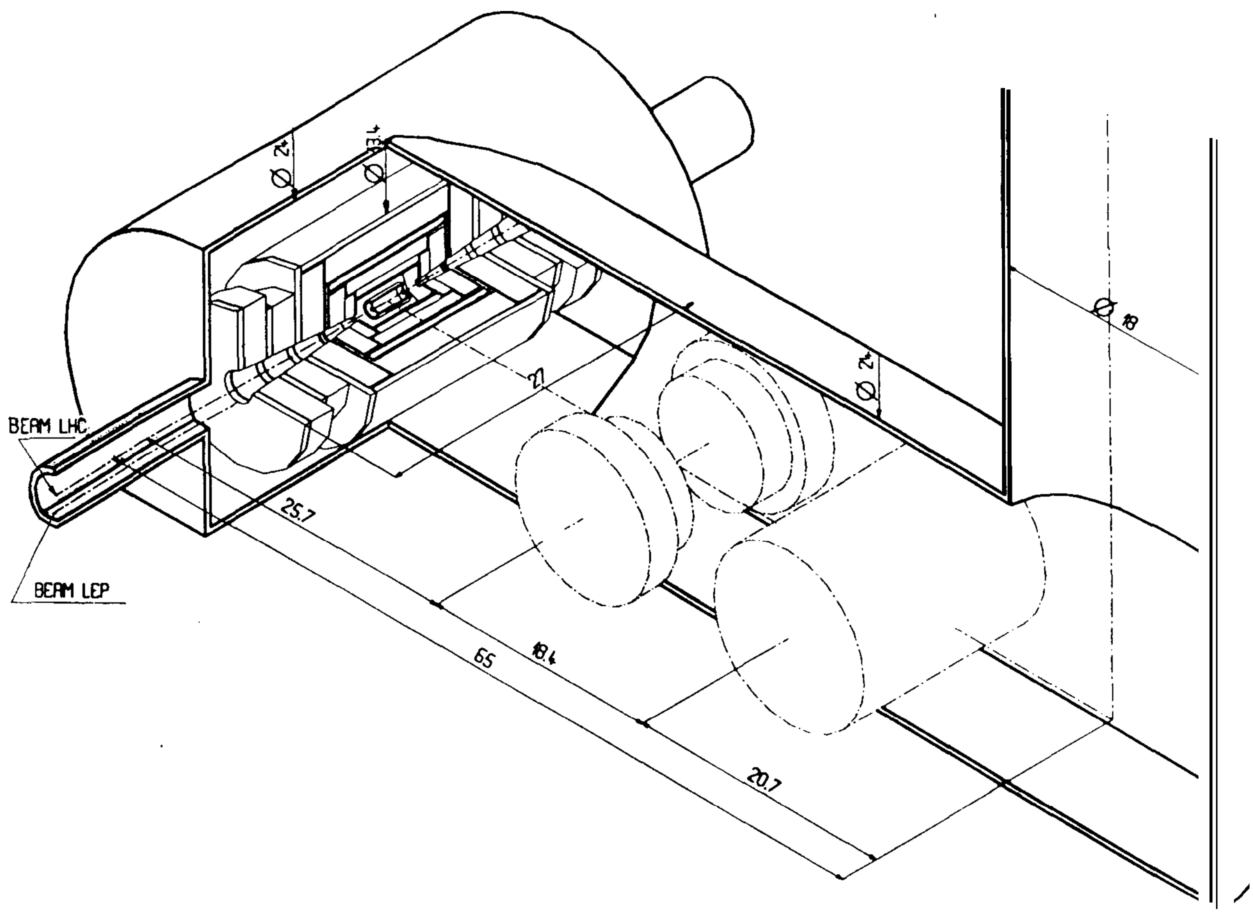

Figure 10 : LHC muon solenoid

This technique may be easily improved by the permanent inclusion of remote read out measuring and micropositioning devices as part of the detector - ref. W.Coosemans - the setting of the zeros before the insertion would be part of the data-base survey measurements of the detector itself and continuous measurements of position during and after installation could be filed.

The development of specialised graphical programmes, such as Autocad, are of interest for the survey preparation works because they should allow the direct inclusion of geometrical needs such as reference marks or optical paths in central drawing banks, facilitate preparation studies and keeps trace of survey implements for future considerations.

5.3. SURVEY DEVELOPMENT FOR THE FUTURE EXPERIMENTS

The continuing needs of industrial measurement have produced an enormous development in high accuracy non-contact measurement and analysis criteria which will influence directly the new prospects of massive experiments surveying.

Industrial triangulation seems to be the best compromise versatility, accuracy/ measurement time providing an on-line redundant solution. Remote measurement (theodolites and CCD camera) with remote guidance or automatic image recognition associated to motorisation angular movement allows rapid data capture and treatment and would permit the continuous profiling of smooth surfaces: reference surfaces could be added to reference holes and the spatial topological knowledge of the detector would be a far better physics parameter than a punctual information ; possibility of permanent monitoring gives evident and unequalled opportunities of applying the system. As a definitive gain in precision for the more conventional theodolites, the calibration bench Wild TPM1 produces a true resolution of 10-6 radian: the centesimal second is now a reality !

The appearance of precise total stations producing the spatial position of an object by polar coordinates, is certainly to be considered because the geometry for good intersections in experimental environment is rarely ideal. High precision total station with distancemetre included in the optics of the theodolite and with interferometric resolution (SMART 310 Kern) is certainly the next must of the experiments surveying.

The problem with distance remains the retroreflector generally bulky, impossible to fit to any structure and unsuitable for precise angle measurement. High resolution comer cube, precisely centred and embedded into a small sphere (40 mm in diameter) and easy to adapt to any kind of fiducial marks (via magnetic cup for the sphere and high precision centring for the reference hole) has been developed at CERN: in addition to conventional use with the distancemetres mentioned above, this type of sphere has made possible the accurate measure of vertical distances with the Mekometer - see figure 11.

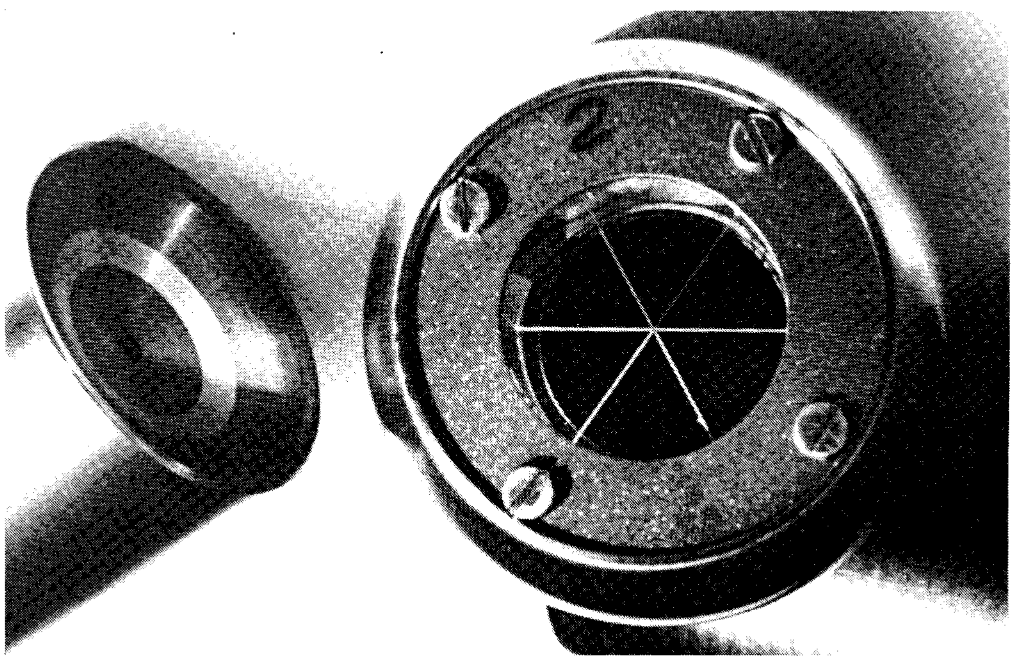

Figure 11 : Comer Cube in a sphere with magnetic cup

Cat-eye retroreflector, however larger and heavier than a comer cube will offer a wider working range and once fitted onto a mechanical centring device should ease precise trilateration from EDM or interferometric distancemetres even if disposed in no good location for accurate determination. It is worth noting that adhesive reflective material “scotchlite” produces a sufficient precision (sub-millimetric) for certain applications.

The last bastion of pure manual data- capture has finally dropped and the first digital level NA2000 Wild complements advantageously the fully automated survey equipment; tests has proved that, from 40 m, this instrument gives better results than conventional level.

Digital recognition far better than the human eye and nearly absolute precision distancemetres at long range particularly when no cyclic errors occur, prevail new concepts of surveying namely there is no need being close to the object for a high accuracy - to some extent, it is better operate far from the object. That allows the “experiments” surveyors to select the survey points more comfortably regarding their needs: everybody knows how crammed is the nearby environment of big detectors !

Industrial photogrammetry seems worth further investigation for regular inspection. Precision, however related to object form and size, of better 100 microns is apparently possible on objects of medium dimensions in conjunction with statistical refinement programs. The interest remains the rapidity of data-taking and the existence of a permanent record which can be reanalysed with hindsight.

Once the calibration errors have been modellised, the influence of the environment, optical medium included, is finally the limit on the possible precision of industrial survey specially concerning the question of datum when changes in position, shapes and dimensions are the most probable. The high quality of modem instrumentation subsequently the results of monitoring (object network and reference network) enhance the need of computational strategies and statistical methods for the determination of displacements and deformations such as testing of observations (data-snooping plus internal and external reliability), testing of stability of reference points and of single point and testing of deformation models between epoches using multi-dimensional and one-dimensional tests.

Geometrical data can then be used to compare predicted and actual displacements if the acting forces are known or they are used in the mechanical interpretation of the deformation phenomena.

6. CONCLUSION

Geodetic metrology of large experiments implies a quite continuing R and D: the detectors are not of standard features and the specificity of the operations need distinctive and unique options both for software and equipment.

That also requires skilled and qualified staff aware of a priori unexpected problems and capable to perform solutions on the spot.

The ransom of high quality instrumentation is the prospective development of dedicated analysis programs which will help for a better understanding of our task namely for a better service.

Bibliography

C. Lasseur : *Methods and Results of Three Dimensional Metrology* - UCL 1988.

T. Coppeland-Davies, E. Menant : *The Kern Mekometer 5000 and Short Distances Measurements* - CERN 1989.

J.P. Quesnel, C. Steel : *Etalonnage des EDM* - CERN 1989.

W. Coosemans, I. Wilson : *Experimental Approach of Micropositioning Problems on Future Linear Colliders* - DESY 1990