METROLOGY FOR EXPERIMENTS

C. Lasseur
CERN, Geneva, Switzerland

ABSTRACT

This paper outlines the approach to metrology of the Experiments Section of the Applied Geodesy Group at CERN. This procedure has been developed to deal with the continuous evolution in size and complexity of modern particle physics experiments. The precision in construction and the resolution of these experiments necessitates the adoption of geodetic methods to achieve the required sub-millimetric positioning accuracies. The philosophy behind the adopted approach and the methodologies applied are discussed with respect to collider physics in general and the future LEP experiments in particular. The instruments employed are briefly outlined stressing the usage of a complete and versatile chain of data capture and calculation.

1. INTRODUCTION

In October 1984, the Nobel Prize for physics went to Carlo Rubbia and Simon van der Meer for the discovery of the W and Z bosons, which produced experimental proof of the electroweak theory. These discoveries rank among the greatest achievements in the history of science and were the climax of technological excellence and teamwork on a scale never before seen in the field of pure science. Among the many elements required to facilitate this discovery was the design and construction of a new machine, the Antiproton Accumulator, the adaptation of existing machines, namely the SPS and PS, to fulfil roles they were not designed for, and also the construction of general purpose detectors of hitherto unseen size and complexity.

The Applied Geodesy Group was fully involved at all stages of this challenging and exacting project; in the extension of the geodetic network required by the new works, in the civil engineering work both above and below ground, in the metrology of the accelerators new and old, and finally in the construction of the two new experiments UA1 and UA2 in underground caverns on the main SPS tunnel. These experiments had to be assembled with great accuracy (often sub-millimetric) in a confined space and this challenging precision was demanded for experiments of an unparallelled size and complexity; in the case of UA1, a large box 10 x 5 x 7 m which weighs over 2600 tons (Fig. 1), and for UA2 a mere 600 tons but more complex and innovatory in structure.
The purpose of CERN is to provide opportunities for research in particle physics. Accelerators give the particles the required kinetic energy (hence the name high energy physics) before being brought into interaction with other particles. The properties of particles are deduced by looking at the decays of collision by means of equipment called detectors. The experiments can be divided into two groups, following the way the accelerator is used (Fig. 2):

- fixed target experiments: beams are ejected tangentially from the accelerator and strike a target. The particles so produced continue (for the most part) in the same direction as the beam, hence the detectors are grouped downstream of the target;

- collider experiments: in this case two beams travelling in opposite directions are brought into collision. By this means, the highest collision energy ever achieved in controlled conditions is realised. The secondary particles produced in such a collision fly out in all directions, hence the detectors surround the interaction point.
The LEP project will operate in collider mode. The experiments under construction will surpass those of the SPS in size, accuracy and complexity. For example L3, a five storey structure weighting over 12000 tons and permanently placed on the LEP ring is predicted to produce a resolution of several hundreds of microns. The three other experiments (DELPHI, ALEPH and OPAL) will be mobile, less massive (around 10000 tons) but produce a similar resolution.
2. HOW EXPERIMENTS ARE CARRIED OUT AT CERN

To analyse what happens, the experimental physicist must be able to measure, with great precision, the properties of the particles emerging from the collisions, such as their direction, time of passage (speed), energy, electric charge and mass. A variety of techniques can be applied.

A selection of these is summarized in the following table:

<table>
<thead>
<tr>
<th>PURPOSE</th>
<th>TYPE OF DETECTOR</th>
<th>PROCESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time of passage measured to the accuracy of the best electronics (mm survey precision)</td>
<td>Scintillator</td>
<td>Charged particles produce tiny flashes of light when they cross blocks of plastic and this is detected by photomultipliers.</td>
</tr>
<tr>
<td>Direction/location accuracies of a few hundreds of microns (sub-mm survey precision)</td>
<td>Multiwire proportional chamber Drift chambers Time projection chamber</td>
<td>Ionisation caused by charged particles passing through a gas is picked up by an electric field between closely spaced planes of wires.</td>
</tr>
<tr>
<td>Mass/momentum sign of charge (mm survey precision)</td>
<td>Magnetic field (cryogenics) Magnet (a few tesla)</td>
<td>Magnetic fields curve the path of charged particles in opposite directions depending upon the sign of their electric charge. The amount of bending measures the particle’s momentum.</td>
</tr>
<tr>
<td>Energy (sub-mm survey precision)</td>
<td>Calorimeters (hadron and electromagnetic)</td>
<td>The energy deposited in a gas by a charged particle can be deduced from the amount of ionisation it produces. Iron plates can be interspaced with apparatus for measuring energy deposited by absorbed particles.</td>
</tr>
</tbody>
</table>

Every one of the CERN experiments involves complex detection systems of the types mentioned above; they surround the region where the collisions or the hits occur and record properties of the emerging decay particles. One can describe proton-antiproton detectors (UA1 and UA2) and the future LEP experiments as sets of Russian dolls, each being designed to detect a certain phenomena such as those described in the above table. Experiments of this type are designed to cope with large numbers of particles, collecting unbiased information from collision products collected over a solid angle as large as possible. UA1 contains 6000 sense wires, 30 km of extruded aluminium required by special positioning detectors; UA2 includes 240 cells pointing towards the centre of the interaction region and 5000 sense wires. To sift and analyse the massive amounts of data produced requires the speed and power of digital computers. The wealth of information recorded makes for prodigious data handling problems bearing in mind that each collision produces enough information to fill a telephone directory.
3. THE SURVEYOR'S ROLE

At the outset, the support given to the experimental teams in setting up physics experiments was purely empirical.

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 mandatory. Experience has shown that doing this using off-line alignment programs based on cosmic events or track fitting is tedious.

The large and complex structure of a modern physics experiment, made up of many individual modules, requires the use of a careful and systematic surveying and alignment procedure (often sub-millimetric) to derive the full benefit from the quality of the detector components and off-line software. The use of coordinates provided by the Experiment Section of the Applied Geodesy Group as approximate coordinates (raw data) in the off-line alignment programs allows a considerable saving in computer time.

The surveyor has two main responsibilities:

- towards the physics collaboration to ensure that the dimensional parameters of the experiment are fulfilled during fabrication and assembly and to give the final position once the whole detector is set in the particle beam (data-taking position).

- towards the machine group to ensure that common equipment (accelerator / experiment) such as experimental targets, magnets and virtual interaction points are positioned inside the required tolerances with respect to the theoretical beam position.

3.1 Geometrical approach of building a physics experiment

The use of increasingly complex detectors precludes a "Do it yourself" approach. For the physicist, the definition of the accuracy of the results is of primary interest. The global precision for an experiment is a combination of, firstly, the internal precision of each of the detectors and, secondly, the relative positioning accuracy. The surveyor's service is of importance in the second category.

The individual components of an experiment at CERN are rarely manufactured in the same place and are first fitted together on site during the final assembly of the experiment. Thus good accuracy of fit is required to avoid last minute machining and modification which is costly both in time and money.

There are a large number of measuring devices available for small items. When large objects have to be measured the erection or creation of large (often specialised) measuring devices has to be envisaged. These devices often require a considerable associated infrastructure, can be the cause of undesirable side effects (interference, work interruption, deformation) and do not give a global view of the object in its correct position.
The 3-D metrology method gives a picture of an object in a certain position at a given instant. This picture is defined in a referential frame whose main directions are known either in a general reference system or one related to the object itself and the coordinates so produced can be compared to the theoretical values, so ensuring that tolerances are respected. The method is both direct and of universal application; spatial coordinates of specified points on an object providing a suitable basis for the computation of spatial distances, body shapes and dimensions.

The methods and principles that will be explained here are, for the most part, based on our experience with UA1 and UA2 and our preparation for the LEP collider experiments. If we continue with the analogy of detectors as Russian dolls, the scheme of survey operations is that as each is inserted, one inside the other, their relationship is established geometrically. Once assembled, only the largest one is visible; the position of the smaller ones is reconstructed, assuming the geometrical relationship established during assembly is maintained.

The definitive precision of the experiment must include the various precisions in the geometrical relationship whose inaccuracies must be masked by the "noise" in the definitive precision in the working position. Reproducible accuracy (when remeasuring) must be equal to stability (of the object and the reference frame) accuracy, both of which have to be less than or equal to the relative precision between the components. This requires:

- the use of high precision instruments and methods at all stages (manufacturing, assembling, definitive survey).
- comprehensive surveying computation methods to determine an object by spatial coordinates.

We will particularly focus on these features of our work.

3.2 Necessity of good understanding

An agreement between the physicist and surveyor has to be built up from an early stage so that they understand the service we offer and, of course, the limits of that service. Basic working premises have to be clearly expressed, such as the global positioning precision required by the experiment, the precision and position of certain critical elements and, of course, working conditions. Every step should be defined in advance, in writing, and be included in the planning, from the initial to final stages. A comprehensive agreement has to be established covering all steps of the assembly and subsequent measurements. Any weakness in the overall project coordination can create problems, such as invisible references, means of adjustment unattainable, lack of preparatory measurements; the result being detectors either unmeasurable or only with reduced precision.

Prior to the installation of any element, be it a detector module or even a major support structure, it is mandatory that a computer file is prepared on the internal survey
data. This gives a complete description of the unit (position, shape, dimensions) with respect to a set of fiducial marks. The latter are physical and exterior points attached mechanically to the object itself, whose position (rectangular or polar coordinates) are known with respect to a reference of use to the physicist (for a wire chamber this could be the principle sense wires). There must be enough points to fully describe the detector.

The external survey data file is a set of geometrical parameters describing the spatial position of a detector with respect to the theoretical particle beam position when in the data-taking position. It is an adaptation of the internal survey data file following measurements when the experiment is on-line. The definitive document is called the external survey data-base and it is the surveyor's role to determine i.e. to provide the spatial coordinates of the whole set of fiducial marks. Therefore, for the surveyor, an experiment is a list of XYZ coordinates. He has to ensure the real significance of this data, keep them up to date and be able to define the quality of the results.

4. Surveying Procedure

The most frequently used procedure in surveying for the determination of spatial distances, body shapes and dimensions is the so-called micro triangulation-trilateration method. Theodolites or length measuring devices are set up at the end points of a baseline whose length and height difference are known to the required degree of accuracy. Precise measurements of the horizontal and vertical angles and/or distances permit determination of the X, Y and Z coordinates of the reference points on the object. If the measurements have to be repeated or if several sides of the object have to be surveyed (i.e. additional bases are necessary), it is worthwhile establishing a network of fixed points whose coordinates are known from a preliminary survey. Fixed points can be installed either as instrument stations, pillars, brackets on walls, or as sighting marks. The establishment of a network has the advantage that the location of the instrument can be freely selected, depending on the shape, size and position of the object to be measured.

To achieve sub-millimetric precision, the Survey Group has made certain choices with regard to instrumentation and methods. These include the intensive uses of distance measurements, calibrated instruments, force centring, well structured reference networks, redundancy, rigorous computer programs and a geodetic approach to the problem.

We will describe certain instruments and methods used by the CERN Survey Group: not all of them are universally applicable, indeed often they were specially designed for high-precision measurements in the experiments.

4.1 Precision requirements

The accuracy of the position of an intersected point depends on the accuracy of the calibration scale, from which the baseline data are derived, and from the observation
distances (when the coordinate computation is based on the measurement of angles). Further accuracy determining factors include the magnitude of the intersection angle, the quality of the object point marking, the stability of the instruments, illumination conditions and of course the shape of the object itself.

4.1.1 Difficulties in measuring angles

The prerequisite for measuring angles is the absence of temperature gradients along the optical path; curvature of a light ray varies with the angle between its trajectory and the normal to the surfaces of equal temperatures: over a distance of 100 m and for a gradient of 1°C, it is deviated by 1 mm. Gradient of temperature, grazing sights and unequal lengths of sight all make optical measurements unreliable.

An ordinary theodolite telescope is unsuitable because of its unstable collimation which can change by as much as 30 seconds of arc throughout its range of focus, usually 1.8 m to infinity. When one seeks very high accuracies (0.1 mm or better), the position of the line of sight must be known very accurately with respect to some physical point. Moreover, the three axes, nominally orthogonal, do not, except by chance, pass through a common point. The optical tooling telescope seems to be essential for all serious accurate work (Taylor-Hobson: line of sight central to the cylindrical tube to an accuracy of 0.005 mm and collimation maintained within 2 arc seconds). However this equipment needs special features (top plates, trivet stands) which are not flexible enough for our purposes.

For all these reasons precise surveying networks have to be formed as much as possible of linear measurements.

Angle measurements are still used for the “details” in experiment metrology because the sighting distances are very short – a few metres and most of the halls at CERN have a temperature regulation system. Also in some cases, pure triangulation is the only suitable method because the object to be measured is not accessible directly or cannot be subjected to undesirable loads (deformations); the angle measurements made externally exert no influence on the structure and can be carried out on an object in use. Nevertheless, it is prudent to employ a combination of angle and distance measurements whenever possible.

4.1.2 Forced centring systems

To obtain high accuracy, and because of the short distances involved, it is obvious that the entire geodetic system must use forced centring systems. The standard socket used is machined to better than a few microns and the top of the socket can receive either a positioning cylinder (with which every instrument is equipped) or Taylor Hobson spheres. The bottom part of the system can be adjusted precisely in a given theoretical position, the reference being the centre of the 3.5 inch Taylor Hobson sphere set in the
cup. The top part can be adjusted to the vertical so that all measurements are processed in the horizontal plane.

4.1.3 Object point marking

The type of reference is crucial for the accuracy of the determination. If there are no well-defined points on the object, such as an edge, a corner or a punch mark, artificial marks must be added prior to measurement. In many cases the Taylor Hobson sphere is too big and heavy, and requires special additional equipment which renders it unsuitable for object point marking.

Precise reference holes of different diameters designed to receive plug-in target marks adapted to the measuring device (angles, distances) and easily visible from many directions are of more universal use. This system offers the most flexibility in the choice of measuring pattern because the forced centring disposition allows us to change the targets without affecting the repeatability of the measurement. Other possibilities are self-adhesive sighting marks (crosses, concentric rings, symbols taken from transfer films), while various target patterns are available for different conditions of sight distances and illumination. They do not require any special machining but only angle measurements can be made with them.

Sometimes it is impossible to make marks or attach references to the object. A possible solution is to use a laser whose beam is projected via the optical axis of the theodolite so that the target point thus created can be intersected by other theodolites.

Forced centring systems as developed at CERN appear to be the essential condition in high-precision measurement because of their reproducibility and flexibility of usage. They have helped us to perform measurements whose quality is similar to those achieved in laboratory conditions.

4.2 Technical surveying milestones of an experiment

4.2.1 Reference network

Setting up a micro reference network seems to be one of the more convenient ways to determine three-dimensional patterns. From the design stage up to normal running of the experiment, it ensures that the required accuracies will be attained. It is successively used for provisional installation, alignment of detectors within the tolerances, measurement of detectors in the data taking position. It also allows survey of the stability of these components; successive measurements, based on the network, attempt to maintain a correlation between the evolution of the components and of the geometry itself.

The network is really the fundamental frame of all survey activities. It acts as a stable and precise large calibration bench which surrounds the volumes to be measured so that the critical points are visible and accessible physically. This bench is defined by
pillars, brackets and/or rivets, whose positions must comply with a certain number of criteria:

- reference points must be easily accessible. The density of points has to be great enough to cover the objects to be surveyed.
- structure must allow simple, precise, easy and quick measurements of whatever kind on the points to be determined and between the reference points themselves.
- network structure must from the very beginning take account of the different steps of installation and be evolutionary enough for it to grow relevant to any future needs.
- key positions must be occupied in respect to the layout and be adapted to the point's projected usage (angles, distances, direct levelling).
- creation must be made as soon as possible and in one operation for the homogeneity to be maintained; completion in hindsight must be avoided.
- installation avoids unstable areas while allowing rapid measurements to be performed to detect and evaluate casual movements or accidents.

The assembly and positioning tolerances guide the homogeneity and the precision to be obtained when measuring and controlling the network, the threshold being given by the most sensitive elements of the experiment (which are generally the most difficult to reach practically). It is useful to attain the best possible accuracy under current conditions since even if this is not strictly necessary, it can be of great help in the future as the experiments evolve. Homogeneity means that the precision of the bench must be identical at any location of the network. Redundant measurements must be performed to ensure quality and uniformity of accuracy. These points must be considered when setting up the network since good homogeneity and density provide us a greater flexibility of methodology and control.

The form of the network depends on the type of the experiment. For fixed target experiments, the network consists of two lines parallel to each other and to the beam. The method of defining these lines depends on the precision required, for example, the line can be defined by survey sockets inset into the floor or, in a less demanding case, be simply drawn on the floor with several rivets placed along its length. For collider physics the network consists of several levels of references commanding both the maintenance and the on-line position of the experiment.

In the case of the UA1 and UA2 experiments, references are situated on three distinct levels (+ 6.0 m, 0.0 m, - 3.0 m with respect to the beam). The geometrical links between the floors were achieved using high precision verticality measurements. These were carried out between brackets on the same vertical (within several centimetres) for the case of UA1, whereas in UA2 sloping invar wires were used. The following results were obtained:

- UA1 : 38 brackets - 160 measurements - range of accuracy .08 -.17 mm
- UA2 : 56 brackets - 270 measurements - range of accuracy .08 -.18 mm
These results were only possible because all the requirements quoted above (length measurements preferable to angle measurements, forced centring) were met. Unfortunately, the network cannot always be established in its ideal form; it must be compatible with the other services such as ventilation conduits, cabling and cooling systems which greatly reduce the options available.

4.2.2 Detector assembly

Preparation phases.-

A detector is rarely a single unit. It is often divided into component parts which we can term sub-detectors which geometrically are considered as single, rigid and non-deformable units. Each assembly of sub-detectors is considered to produce another rigid object.

To plan the measurement procedures, it is of overriding importance that the steps of assembly are clearly defined, this normally being determined by the structure of the detector. Specific discussions can then start on any remaining ambiguities, and the following questions answered:

- is the detector a single unit or composed of several independent modules?
- is it rigidly mounted on another detector? How is the relationship between the two units to be made (mechanically or by means of surveying)?
- is its determination to be made sequentially (in a laboratory, in the experimental area)?
- have external reference marks to be created? If so how many and where?
- is there a supporting structure or a mechanical adjustment?
- has the detector (as a unit or modules) to be placed at a theoretical position, in respect to what (beam, surrounding detectors) and with what precision?
- what precision is needed for the different detectors relative to each other?

The surveying procedure can then be decided upon; the best place for reference marks, the redundancy required, the most suitable moment and place for the work during the assembly of the detectors, etc.

Steps of the geometrical determination.-

To obtain the final version of the survey data base, a cascade of operations is needed, from the first availability of individual objects up to the experiment’s data-taking stage. The steps of geometry result from principles whose sequence follows closely the following assembly phases.
Internal geometry.-

Each individual detector element (chamber or counter module) is equipped with fiducial marks defined in its own coordinate system (for example: the main axis of symmetry). They are deemed to be internal because they are part of the object. These marks can be the accessible sensing part of the detector, for example the cells of a calorimeter or wires directly visible from the exterior of the chamber.

Another possibility is reference marks directly connected to the sensing part of the detector; for example the pin holes used to centre planes of wires. Each plane is held within a frame and at each corner there is a reference hole whose diameter is precisely machined and whose position is known with respect to a wire (measurements carried out in the laboratory). If the chamber contains several planes of wires the relationship between each plane is assured by calibrated cylinders which fit precisely in the reference holes. From the measurement of the position of these cylinders, the position of each plane of wires and the position of each wire can be deduced.

Features of internal geometry are that it is carried out as an integral part of the manufacturing process and is used for geometry when easily, directly and permanently accessible. It is the preferable way of defining the geometry of the detector as a direct method of determination.

Link geometry.-

Measurements in this category are carried out for one of two reasons. Firstly, if the internal marks are not convenient for surveying, special survey references must be installed. These have then to be situated with respect to the internal geometry by geometrical, optical or mechanical methods, carried out in the laboratory, workshops or assembly halls before the definitive installation of the detector. Secondly, when a detector consists of several individual modules, then for reasons of economy (many sub-detectors), accessibility of the sub-detectors or to derive parameters for the physics data banks, link measurements between adjacent modules become necessary. These are related to marks (at least three) which will be accessible when the detector is in the data taking position and can be either visible internal reference marks or specially installed auxiliary references. The position of every element of the detector can then be deduced from the measurements of several references.

Features of link geometry are:

- the intermediate step required for the geometrical knowledge of a detector
- the difficulty to foresee whether it is really necessary since it is dependant on the environment (encumbrance of zone etc.)
- that auxiliary marks are not an integral part of the detector (link geometry has to be repeated or plug-in system foreseen)
- the use of mixed step link geometry, for example a mechanical plug-in system to extend internal reference marks

- that, if possible, it should be carried out with a precision greater than, or equal to, that of the original references; this is often not possible hence loss of precision.

Transformation geometry. -

Before being moved onto the beam line, the detectors are installed one by one in their definitive relative position. Due to the planning requirements, detectors can be assembled at different places in the mounting area before they are fitted together. This allows us to verify that the theoretical parameters of the experiment are respected, and to determine the relationship between different detectors which will later be hidden. An element unmeasured at this stage means that the position of one of the detectors will not be known when the experiment is on the beamline. Equally annoying is a relationship known with insufficient precision since all detectors internal to the one measured cannot then be located with sufficient accuracy.

Features of transformation geometry are:

- the establishment of the relationship between successive layers of detectors

- that, by this stage, the internal and link geometry of the individual detectors must be known (internal data base)

- the measurements are related to an assembly network during system assembly

- the relationships must be recorded at each step.

Definitive geometry. -

Once on the beam line, the visible references are measured from a network whose zero is the theoretical beam interaction point of the accelerator. Consequently, the position of all the detectors and sub-detectors can be calculated using transformation programs, whose truth depends on the care with which the measurement procedures were planned and the rigidity of the detectors. These results constitute the external survey data base required by the physicists.

The main feature of definitive geometry is that the position of all detectors is deduced from the measurement of the visible references of the experiment in the system of the machine.

The geometrical phases described above require much work and it is important that the number of cascaded operations should be reduced as much as possible. To this end non-essential movements of the experiment should be avoided as this requires new measurements and spatial transformation programs to determine the new shape and dimensions of the ensemble.
The final result, if it does not come from direct measurement, will be affected by the successive adjustments introducing slight differences due to the computations. To reduce this loss of accuracy, a high precision (homogeneity of network) in measurement is needed so that intermediate survey steps are not biased by successive determinations.

Possible geometrical method.

Methods must be comprehensive enough to give a true 3-D picture of the object. The techniques used in most cases will be a mixture of the following: angles, distances (horizontal, vertical and spatial), offset measurements (optical or physical, in the horizontal or vertical plane). To the measurements made in the field can be added internal distances. That is, high precision values known from the manufacturing of the object or from calibration measurements performed in the laboratory. These values can be used in several ways:

- verification: to check that there has been no distortion of the object after movement (transportation, handling) by a comparison of the deduced internal distances and the known internal values. They can serve equally to verify the scale factor of the network (with an appropriate weighting). It could be envisaged to measure an object using auxiliary theodolite stations where the precise scale of the base is derived from the internal distances of the object.

- determination: these redundant distances are often known to a higher degree of precision than we can achieve in the field. They are also direct measurements made on the object itself. Thus, through their precision and their redundancy, they optimise the 3-D determination. In the case where points are unattainable or too numerous, internal distances between unobserved and observed points are a mean of deducing the unmeasured points.

Methods depend on the following considerations:

Characteristics of the object.— Its shape, dimension and behaviour (a priori instability in movement or a light structure).

Immediacy.— Because of fragility or limited availability of the object, rapid results may be required for verification.

Reference system.— When lab or preparatory works are necessary a local reference system is required. The choice depends on the spatial situation of the object and whether a direct knowledge of the parameters of the object are needed. Three cases can be distinguished for an object in any position:

- direct knowledge: the referential is directly linked to the object itself. The parameters are measured by trilateration or by triangulation but in the latter case the vertical axis of the theodolite must be parallel to the axis of the object;

- object can be adjusted and direct knowledge: it is obviously much more convenient to adjust the object, for instance with jacks, to produce a truly vertical axis;
indirect knowledge: the object is measured from a reference system unrelated to the object itself. To obtain dimensions and relations in the object reference system, a transformation is required.

Environment. For example not enough space around object for comprehensive coverage; the use of artificial lights with the risk of phase error; temperature gradient rendering triangulation unreliable.

Number, location, accessibility and type of survey marks used. Visibility and required accuracy determine the most suitable method. Standard multi-purpose targets appropriate to any kind of measuring are very useful in this type of work, especially when access is difficult or installation of the point has to be permanent. Pattern and dimensions must be chosen in respect of the length of sight and thus have important considerations for the network. Insufficient room around the detector means too many stations (time-consuming) or the need to use special lenses to allow focusing on the objects with consequent loss of precision.

Non-rigidity of the object. Unfortunately sub-detectors are not always rigid. This can be due to the environment of the object (local vibration) or just a weakness in the structure of the detector (the more sensitive detectors in particular are built with a minimum of material). The non-rigidity can be controlled either by using instruments like gauges, clinometers or by using geometrical methods. The former give punctual information of a high precision, can be placed at critical points, and are independent of the geometrical results. However, this information cannot be directly included in a 3-D determination; Moreover, that needs special equipment support and many instruments to give a complete picture. The geometrical method can provide a relationship between adjacent modules but requires a certain preparation and is relatively time consuming. It requires marks on the object which are not necessarily linked to the internal references. Adding marks in hindsight should obviously be avoided but because of the complexity of the detectors is sometimes the only solution.

The question of whether the detector or the network has moved is obviously a problem, in particular in underground experiment halls where movements of the order of mm's continue for many years after the completion of the civil engineering work. This requires periodic verification of the reference network, often in conditions less favourable than when the network was established (experiment and services in place, lines of sight blocked). Redundancy becomes more and more essential but less easy to achieve. In any case with the geometrical method it is impossible to determine the precise moment of the movement, the amount and direction at any given time to be allowed for in the calculations and the rotation/translation centre. To avoid some of these problems it is a good idea to use instruments giving punctual information, especially if used to furnish on-line information to monitor the situation. Once the deformation exceeds a certain limit a general geometrical survey can be made. All in all, it emphasises the need for a good preparation of the object, to detect at an early stage any possible movements and allow the possibility to install special equipment if necessary.
Special tools. – Precise extension plugged into reference socket, various shaped "jigs" or pins, plug-in brackets, adjustable supports, targets with scales, self-illuminating marks, ball bearing fitting system to measure a distance in any direction are all of considerable help. Precision of the machining, a rigidity of structure, adaptability, adjustable if necessary and simplicity of use are generally required.

4.2.3 Survey and assembly sequences

During installation, it is essential that coordination is established between surveyor and the person in charge of the installation to ensure timely interventions and that allowance will be made for the need for space and time for survey measurements. A communication system has to be arranged to allow a fast access to the survey data at all steps of the geometrical process. Hence possible inconsistencies between different measurements can be detected during installation so that measurements can be repeated if necessary. This survey file should be used to test off-line alignment programs between the modules already in place (e.g. by Monte Carlo simulations).

4.2.4 Data-taking period: diffusion of results

Survey measurements have to be repeated often because of position instabilities and movements on replacement of modules. The survey results must be entered as soon as possible in the experiment’s data-base. It is updated following the progress of the installation and must reflect any last minute changes or modifications. It can be considered as the definitive document between the surveyor and his customer. At the request of the latter, further information such as the precision of the results must be provided. Publication of the results must be meticulous, in particular when designations of the measured points are concerned. Graphics plotting in 3-D can help in the understanding of the results.

In fact we also need intermediate data banks – specially constituted by the link measurements – and we have to create an adapted computing chain that will be described later.

5. Means available in the field for the surveying of large physics experiments

5.1 Angle measurement

Theodolites (Wild T2 and T3, Kern E2) are used over short distances (a few metres) in conjunction with forced centring systems for detector assembly of medium accuracy, in particular when references are non-accessible or unreliable. Extensive use of vertical angles in conjunction with direct levelling improves the accuracy perpendicular to the base. Angles are also used in network observation when required to improve the strength of the geodetic figure.
5.2 Distance measurement

5.2.1 High precision (accuracy better than .1 mm)

The three main instruments for providing high precision distance measurements are listed below together with their relative merits and drawbacks.

Distinvar.--

This instrument can measure from .02 m up to 50 m with a rms error of .05 mm; due to the instability of the invar alloy, the elongation is directly proportional to usage, hence for work of the highest order the wire must be calibrated before and after measurement on a precise bench. The invar exerts a force of 15 kgf on an object being measured so the structure has to be rigid and requires a standard forced centring socket. It can be utilized on slopes up to 11%. It is rarely used on detectors unless prior provision has been made to accommodate it. Its main use in metrology for experiments is in the measuring of reference networks.

Self aligning interferometer.--

It is used for distances of .1 m to 60 m with an accuracy of .01 mm and does not apply traction to the detector but requires a free path and accessibility between reference sockets. It cannot be used for distances on slopes. More time is necessary but the instrument has the advantage of requiring straight line access rather than the catenary curve which may prohibit use of the distinvar.

The self aligning interferometer system is used for in-field auxiliary bases or for measuring high-precision networks when the reference points are all at the same height and freely accessible (linear network).

High precision bar.--

This new device (A digital micrometer based on differential condensers) will be used for distances up to 2 m and the accuracy expected is .05mm. Any mechanical adaptation can be fitted to make measurements between any kind of reference holes and in any plane, so that is is possible to increase length using precise extensions. Because of its light structure and easy handling, it does not deform the object.

This device is still under development and is expected to be of great use for precise micro-trilateration, in particular for link geometry in the metrology of experiments.

5.2.2 Medium precision (several tenths of a mm)

A stadiometric method has been developed which, although not of the accuracy of the devices mentioned above can cheaply produce good accuracy (.04 mm/m for distances up to
15 m and slopes of up to 20\%). It consists of a 3 m invar tape mounted on an H bar. Four accurately aligned marks act as references on the tape, the distance between these points being known from a laboratory calibration. A staff is held vertically in a reference socket, vertical angles being observed to the marks. From these observations (vertical angle resection) can be calculated the distance between the sockets, difference in the height (bottom of staff and theodolite) and the non-verticity of the staff. Corrections can be calculated from the latter. The main attractions of this method are the versatility (especially when working in bad conditions) and the possibility of calculating the distance in the field using a pocket calculator.

5.2.3 Millimetric precision

This is usually achieved by electronic distance measurement (EDM) using, for example, the Kern DM 502/4 instrument. Its main features are an accuracy of 1 mm rms for distances up to 15 m and that it can be used to determine approximate coordinates or 1-2 mm metrology, while Kern mirrors can be adapted to fit any reference holes.

To benefit fully from the EDM, frequent calibration is required (bench or an invar network) in the range of the measured lengths. The instruments used are adjusted at the factory to reduce phase errors over short distances, analysis of calibration measurements having confirmed this for distances up to 30 m. Thus, using linear regression, the zero constant and the scale error can be calculated. Calculation of the standard errors of the zero constant and the scale error allow estimation of degree of confidence. Important points are:

- the calibration constants can be calculated using a pocket calculator (though attention must be paid to rounding errors)
- additional information about the zero error can be gathered from residuals computed and plotted with respect to distance
- it is important to calibrate often since the zero error changes with time and rough handling
- the possibility to use self-adhesive "scotchlite" tape (up to 15 m) is very advantageous
- the absolute rotation angles of a large object (verticity, perpendicularity) can be obtained by means of differences in distances.

5.3 Levelling

Here we use an automatic high-precision levelling instrument such as Zeiss Ni2 with the limitations that long traverses cannot be made and intensive use is required of redundant measurements (nodal points) while frequent calibration is necessary since sights rarely of equal length. For convenience a vertical translation stage is used to measure directly on the point without using a staff though for experiments the large height differences often encountered require the use of 3/4 m staffs or vertical invar tapes.
5.4 Special instrumentation

5.4.1 Offset measurement

The offset is designed to replace angular observations by the precise measurement of the shortest distance (offset) from one point to a straight line defined by a nylon wire. Offsets of up to 500 mm can be measured in this way with an accuracy better than 0.1 mm. The method can be applied over large distances (up to 100 m) but requires stable air conditions, i.e. no draughts.

This instrument is used in conjunction with distinvar and/or interferometer measurements for the determination of linear networks and we intend to use it over short range and in any plane, in particular for redundancy in link measurements when they are combined with spatial distances done on the object itself. However, this special application will demand adaptation of the forced centring device.

For optical offsets a vertical plane is described by a theodolite telescope and an offset reading is made on a ruler which is approximately perpendicular to the plane. These measurements are used to give the verticality of an object and/or redundant measurements. The precision achieved is of the order of 0.3 mm over short distances.

An active system using a laser has also been used when turbulent air conditions prevent the use of a nylon wire. A rms error of 0.1 mm over 100 m is possible but this precision decreases rapidly over shorter distances.

5.4.2 Clinometers and hydrostatic levels

Clinometers give an accurate measurement of tilt angles in one direction and the value can be read by remote control. Accuracy is 0.01 mm/m and tilts of up to 2 mm/m can be measured.

The hydrostatic level is designed to measure the difference in height between several stations. The instrument installed on each station can be operated and read either directly or remotely and can be controlled either manually or by computer. The accuracy is of the order of 0.05 mm over distances of several tens of metres.

These instruments give periodic or permanent survey of altimetry, deformations or micro-movements. However, they require auxiliary equipment for their installation while generally their size and weight limit their application.

5.4.3 Vertical lines and plumbing methods

When a network is composed of several distinct levels it is necessary to find a way to transfer coordinates between floors. This can be achieved using the distinvar if the
slopes do not exceed 11%. In other cases the transfer is done using vertical lines between stations which are on approximately the same vertical using for example:

- a plumb-bob damped in an oil bath
- a specialized optical instrument: precision nadir plummet with mercury horizon (Wild GLQ)
- a nadiro-zenithal telescope
- optical methods using special adapters such as:
  - the diagonal eye piece for measuring zenithal distances in several planes between the vertical line of the theodolite and the point but only possible if measuring upwards.
  - the pentaprisms which when fitted to the telescope of a theodolite describes a plane perpendicular to the optical axis. Observations (horizontal and vertical angles) describe planes whose intersection give the observed point coordinates. For good accuracy, the height difference between the points must be known precisely and the planes described must be well distributed.

Both the pentaprisms and diagonal eye-piece methods use redundancy in the determination which can be calculated with a pocket calculator. Accuracies of better than .2 mm have been achieved over distances of up to 20 m.

6. COMPUTER PROCESSING

6.1 Importance to metrology

The variety of measurements and the redundancy, the number of points to be handled mean that least-squares adjustment programs are an essential instrument for calculating definitive coordinates. All surveying operations in metrology depend on this since the calculation gives the observed object as a truly geometrical figure. The definitive form is the one which fits most closely to the observations. Some differences will remain because of the inaccuracy of the methods used but the resultant form is the most probable (statistically speaking).

The following features are essential for a least-squares program adapted to the metrological method:

- capable of handling the wide variety of observations such as horizontal and vertical angles, horizontal, vertical and spatial distances, offsets in any plane, punctual information given by non-geometric instruments (autocolimation, clinometer etc.)
- of sufficient size to adjust the largest data set in one go
- do not influence the method in the field
- give statistical analysis of the results including redundancy factor, standard error a posteriori of the measurements, error ellipses, residuals after compensation, criterions of homogeneity (relative error ellipses)
- independent weighting of variables
- good, clear presentation of the results (histograms, plotting etc.).

6.2. **In-field programs for metrology**

A chain of programs has been developed to aid the work in the field; their simplicity and versatility of usage being a considerable asset. These programs were first developed on HP41 calculators but the increasing availability of portable computers such as the Epson HX20 has allowed the development of more comprehensive and versatile complementary programs. For example, the determination of one point in X and Y by least squares (resection, intersection, distances and angles) can be programmed easily. This possibility of field computing offers a flexible setting out method which can be adapted to the working conditions.

6.3 **Data capture and computation programs**

When a large number of points have to be measured in a limited time, automatic recording programs become almost obligatory. They reduce operator strain and the possibility of error both in data taking and in subsequent manipulation of the data, and ensure data is taken in a consistent way. The connection of a portable computer to an electronic theodolite means that angles (and distances) pass directly to the computer, the data is then checked (verification, between two pointings, collimation of the instrument) automatically and directly. In the case of error the operator has the possibility to verify and correct the observation.

An extension of this idea is to calculate automatically (intelligent recording program) the results in the field (distance/bearing, intersection, resection, levelling), which are then stocked in the memory of the computer. This is used when there is little or no redundancy, and means that no computing is required in the office. If the measurements are periodic the previous values can be stored in the memory thus allowing a direct check before replacement by the new value. Observations or coordinates are then transferred to a larger computer for distribution and eventual further calculation.

6.4. **Main core compensation programs, specific concepts**

6.4.1 **XYZ determination**

Comprehensive planimetric, altimetric and spatial compensation programs have been developed over many years and are being continuously updated to take account of future needs. All are based on the variation of coordinates algorithm and specially cater for:

- offset measurements in any plane defined by the three connected points and offsets taken from a theodolite set on a given bearing
- gyroscopic bearings
- plumb-bob observations
- computation of any network as a free network (one fixed point and one specified direction), thus a minimum of constraints
- correction of distances by a scale factor or by a systematic constant after calibration
- the a posteriori transformation of angle residuals into radial vectors which are much more appropriate to short distance determination
- tracing of remaining mistakes by entering approximate coordinates as fixed points, big discrepancies between observed and calculated values highlight problems.

6.4.2. Simulations

The possibility of simulating future survey operations is intensively used (especially for the preparation of the LEP experiments). The methodology is established (set of measurements, choice of points), the program then calculates the theoretical measurement and adds an appropriate error calculated from a random number table and the a priori weight of the observation. The "observations" are then adjusted and the results calculated. The program repeats this several times (normally 10 is sufficient) using different random numbers. The precision of the definitive network can be seen plus the range of values for the definitive coordinates. If the program is used on several possible data sets, the most favourable pattern can be found and it can be seen if the required accuracies can be achieved. This allows planning and equipment requirements to be established in a rigorous way and well in advance.

6.4.3 Spatial-adjustment program

Spatial-adjustment programs are imperative in metrology since they give the complete set of coordinates even if only some points are remeasured from a previously established relationship and the possibility to change the reference system following needs (providing the relationship between the main axes is known). To define a coordinate system without ambiguity seven coordinates distributed among three points are needed (i.e. X1, Y1, Z1; X2, Y2, Z2 and Z3). Alternatively, six coordinates and a distance constraint have the same effect. In all of these cases, the relative geometry is not distorted and observation residuals are always the same. In an over abundant situation the network will be adjusted after the principle of least squares; this will produce inevitable inconsistencies in the residuals of the observations though these will be small or negligible. A set of three points known in X, Y and Z constitutes a redundant control set.

The decision to use minimal or redundant control should be based upon confidence in the control coordinates versus that in the measuring system and has important implications for the definition of methodology. If an item (network, detector) is periodically remeasured, then two cases are possible. First, all the points are used to fix the parameters of adjustment and the residuals dx, dy and dz prove the item to be stable or not. Second, due to changes in the environment the quality of the measuring method can not be maintained so that the relationships established from a previous measurement (in better conditions) have to be imposed to improve the quality and reliability of the
results. However, in an over abundant situation the distortion of the results by nonconform points is always a danger (micro-movements, instability). An a priori limit has to be defined to allow the rejection of suspect values which would otherwise bias the adjustment parameters (translation, rotation in the three planes and scale). Thus stable points can be selected and new coordinates computed for passive points.

6.5. Possible computable steps in metrology

6.5.1 Applications to periodic survey

In frequently repeated operations a methodology has to be developed to explain discrepancies in position. A comparison with the previous data set allows rapid detection of gross errors and gives an idea of possible discrepancies in position. Then computing a network as a free system (one fixed point one fixed direction) and adjusting the whole set of coordinates of the new network in relation to the old network is a possible way to detect stable points. The values of the residuals give a guide for introducing rejection criteria and give information on the accuracy; so a new adjustment (using so-called fix points) provides a direct comparison (absolute and relative positions).

Often the items to be measured are more stable than the network itself. This emphasises the need to use non-geometrical devices to control stability and the fact that a reference system related to the object itself (directly or through the use of internal distances) is often the most suitable way of obtaining true positions. When internal distances on the observed object impose unacceptable constraints the stability of the item or the so-called fixed points must be open to doubt (particularly if the network was not remeasured). Then, solutions have to be found to resolve the dilemma, such as computing network and object together (free calculation, one point fixed and one direction fixed) and processing successive spatial adjustment of the ensemble, taking different values of rejection criteria into account. The object may thus be used to relocate the network. After final adjustment the magnitude of the residuals dx, dy and dz gives an idea of the "exactness" of the final solution but, to envisage a solution along these lines, there must be redundant information otherwise casual deformations can not be brought into evidence. In any case these can only be detected if they are greater than the rejection value.

Example of link-transformation geometry adjustment.-

Let us consider the detector D3 which is part of the experiment UA2. The detector is composed of four identical modules each composed of four boxes containing three detector chambers: the physicists require the position of each of these 48 units. To achieve this, four distinct operations were required:

- laboratory measurements (carried out on a calibration bench) to an accuracy of a few hundredths of a mm (internal geometry),
- two separate operations of triangulation to establish link and transformation geometry,
- final triangulation to find position of the detector D3 in the experimental network (definitive geometry).
This entailed three successive adjustments, using the intermediate sets of coordinates, to provide the position of the detector chambers in the experimental network, the whole operation requiring more than 2700 angle measurements. However, in the following table, we can see that despite the number of operations, a sub-millimetric accuracy was still achieved.

<table>
<thead>
<tr>
<th>Measure 1</th>
<th>Measure 2</th>
<th>Measure 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>0.19</td>
<td>0.16</td>
</tr>
<tr>
<td>Y</td>
<td>0.05</td>
<td>0.17</td>
</tr>
<tr>
<td>Z</td>
<td>0.06</td>
<td>0.10</td>
</tr>
</tbody>
</table>

7. SPECIFIC FEATURES FOR THE LEP EXPERIMENTS

7.1 Computerisation

The size and complexity of the LEP detectors and the constraints imposed by the assembly and installation schedules require an extension of the geometrical methods. All relevant theoretical data and results files have to be available in the field, allowing a direct comparison of theoretical and measured parameters. Thus, the problem is one of data management rather than field technique and requires the use of a comprehensive system of data capture and calculation.

7.1.2 Features of the system

An internal disc drive allows permanent storage of theoretical parameters of an experiment (detectors, sub-detectors), coordinates of network, measurements and results. Use of the Unix system of exploitation enables logical subdivision into as many parts as there are units, while least-squares 3-D compensation and adjustment programs can be introduced into the computer.

The system can be interfaced with different configuration such as main frame computers, (IBM, VAX), electronic theodolites (master and/or receiver), and micro-computers (HP-IPC, Epson HX20 and PX4) used as data loggers. Multi-task functions allow the system to be used in a versatile way (acquisition, control of instruments, calculations, communication lines) to reduce data handling, while special routines and facilities help in producing comprehensive description and analysis of the results.

7.1.3 Expected benefits

Compensation and adjustment programs facilitate on-line comparisons either with internal fiducial-mark coordinates (theoretical values) or with previous results if the
current measurement reveals displacement. Since verification is made in the field, any
discrepancy (residuals given by the on-line capture and computations) can be checked, thus
giving greater confidence in the final results. This produces considerable time saving
since assembly, measurement, verification and correction are carried out simultaneously.

7.2 Instrumentation

The complete system consists essentially of two parts, namely electronic theodolites
and computer. The former is the Kern E2 (with DM502/504). It is used singly or in
combination (several E2s can be independently controlled through one interface RS232 and
via ASCII SINGLE BUS System). Readings are taken and the circle can be set remotely.
Computer equipment includes the data loggers and the central unit of management. The HX20
and FX4 will continue in their role as individual data loggers either remotely or through
keyboards. Their portability, robustness and practicality plus the battery of existing
programs make them ideal for data capture and simple calculations, both in the field and
in the office. The management unit will use the HP-IPC as its master unit. Its compact
design (internal disc drive, screen, printer), its capacity (1 Mbyte), its versatility
(programmable in BASIC, FORTRAN and C, system of exploitation UNIX, easily interfaced with
other apparatus) make it well suited for this role.

8. CONCLUSION

Progress at CERN is not limited to the domain of physics and the different methods and
instruments presented in these proceedings underline this. The rapid evolution of high
energy physics constantly poses new problems to the surveyor and in meeting this challenge
process is made. Metrology as described in this paper has benefited greatly from recent
advances in electronics, data handling and computing. The new automatic instruments
(theodolites and short distance devices) have greatly aided us. This however, has not
blinded us to less "glamorous" but sometimes more effective solutions. Organisation of
field and office work becomes more and more important in order to meet the needs of our
customers in a more efficient way. Full benefit from the possibilities of computing
requires considerable forethought, organisation and self discipline.

It is indispensable in our case to have a realistic idea of the precision (standard
errors, confidence limits). This requires redundancy of measurement and often the only
possibility of achieving this is by a mixture of "unusual" observations requiring
comprehensive and flexible compensation programs. To handle any wide ranging alignment,
portable computers are essential in order to manage the flow of data, calculate the
results and to stock the results in a data bank.

ACKNOWLEDGMENTS

The author would like to thank D. VEAL for his help and his large contribution to this
paper.