High-precision survey and alignment techniques in accelerator construction

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ABSTRACT

Basic concepts of precision surveying are briefly reviewed, and an historical account is given of instruments and techniques used during the construction of the Proton Synchrotron (1954-59), the Intersecting Storage Rings (1966-71), and the Super Proton Synchrotron (1971- ). A nylon wire device, distinvar, invar wire and tape, and recent automation of the gyrotheodolite and distinvar as well as auxiliary equipment (polyurethane jacks, Centipede) are discussed in detail. The paper ends summarizing the present accuracy in accelerator metrology, giving an outlook of possible improvement, and some aspects of staffing for the CERN Survey Group.

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Over the last two decades, particle accelerator energies have grown from several tens of GeV to several hundred GeV, and unavoidably accelerator diameters have similarly increased by a factor of ten, from two hundred metres to two kilometres. Despite this escalation, tolerances on magnet positioning have remained not only as tight as in the past, but have become even more exacting owing to the very survey results obtained.

The sequence of large projects undertaken by the CERN Laboratory, the 28 GeV Proton Synchrotron (PS, 1954-1959), the Intersecting Storage Rings (ISR, 1966-1971), and the 400 GeV underground Super Proton Synchrotron (SPS, 1971- ) has ensured continuity in the work of the CERN Survey Group, and each project has been in itself a major challenge. The Group has thus been constantly searching to improve the reliability and speed of measurement without sacrificing in any way the accuracy essential to proper accelerator operation.

1. BASIC CONCEPTS

An accelerator consists basically of magnets arranged in series according to a certain configuration. The magnets are separated by straight sections where there is no magnetic field, and form a lattice having a certain periodicity. The proton trajectory is not, therefore, a circle but a complicated curve which can be computed from the machine's parameters.

To an observer standing outside, the magnetic structure resembles an underground train in a circular tunnel. However, for the accelerated proton, which sees things from the inside, the picture is quite different. It has the sensation that it is running round a magnetic circuit, and this circuit must be as smooth as possible to ensure that no oscillations are induced which would broaden the particle beam to which it belongs. The protons are sensitive to any bumps occurring in the circuit; these bumps may be due to three causes, each independent of the other, but which have the same effect on the magnetic field that guides the beam around the machine. These are:

- slight movements of the foundation rock or of the concrete structures supporting the magnets,
- random errors in magnet alignment,
- errors in the beam guidance field itself.
In practice, it is smoothness rather than perfect circularity of a string of magnets which is important, but the "smoothing" distance is in the region of 100 m on a large accelerator.

For the PS, the task facing the Survey Group was to measure ground movements and the alignment of the magnets. In the case of the ISR, the Group dealt with magnet alignment. For the SPS, it carried out, during 1964-1970, ground stability studies on sites proposed in Europe for the 300 GeV project, with experts from Member States, especially in Belgium, France, Germany, Italy, and the United Kingdom, and is now working on magnet alignment. For the first time it was entrusted by the Magnet Group with building measuring equipment to determine the geometric shape of the pole-pieces of the quadrupoles.

Intuitively, it is not difficult to guess that the measurements which call for tight tolerances are those related to beam trajectories. The geodesist will observe angles, measure distances and tilts and, after least squares adjustment, provide the beam orbit specialists with the following values:

- \( dr \): the radial deviation of the magnet centre line,
- \( dz \): the vertical deviation from the mean plane selected for the closed orbit along which the accelerated protons circulate,
- \( dt \): the deviation in the transverse tilt of the magnets, which introduces coupling between the horizontal and vertical planes and makes orbit corrections difficult.

2. INSTRUMENTS AND TECHNIQUES AVAILABLE IN 1954

When the problem of aligning the magnets of a circular particle accelerator was met in 1954, following the decision to build a 28 GeV proton synchrotron in Switzerland, at Meyrin, the selection of survey instruments and, therefore, the techniques available for meeting the tolerances required, were fairly limited. At that time, the logical consequence was to use traditional geodetic methods in order to work out a possible approach to this problem. The estimated values of the achievable tolerances were introduced in the computations for the closed orbit, in order to define the size of the magnet aperture. This aperture determined the dimensions of the magnets and therefore the dimensions of the tunnel and, in part, the over-all cost of the accelerator. The geodesists were, therefore, part of the group of "pioneers". Their position was similar to that of the other specialists: they were working at the limit of the possibilities offered at that time in their own field.

What tools did the surveyor have at his disposal in 1954? Digital computers had only just made an appearance and adjustment computations had still to be made on calculating machines (Facit, Friden, Monroe, etc.). The direct consequence was that the geodetic reference figure had to be as simple as possible to avoid major adjustments which were always time-consuming with calculating machines. Figure 1 illustrates the octagon (P.1-P.8) with a central point (P.0), which was the basic network of the synchrotron's geodetic system. It also shows the elements \((r, \alpha, \omega)\) to be measured so that the magnets were properly aligned on the calculated orbit. The second consequence was that as calculations had to remain simple maximum accuracy had to be achieved in the measurements.

At that time geodesy relied essentially on angle measurement using a theodolite. Further improvements in accuracy could not be achieved by increasing the magnification of the
telescope or the precision of the graduations of the circle. Better accuracy could be obtained by using forced centring when locating the various instruments, and by building the sighting targets with the same precision as the reference holes of the forced centring system.

In addition to the need for forced centring, the other pre-requisite for measuring angles was the absence of temperature gradients in the synchrotron and radial tunnels, which implied installing a costly air conditioning system to satisfy, among other things, the survey requirements. The curvature of a light-ray varies with the angle between its trajectory and the normal to the surfaces of equal temperature. Over a distance of 100 m and for a temperature gradient of 1°C per metre, a light-ray forming an angle of 10 degrees with the normal is deviated by 1 mm.
The angles were measured with Wild T3 theodolites, each modified for forced centring, with a 30 mm diameter ball and equipped with a special target fixed directly over the rotation axis of the theodolite. With the method of direction and sixteen sets of measures, the standard deviation equalled 1 dmm (deci-milli-grade = 10⁻⁴). The resulting azimuthal positioning errors of the octagon monuments in relation to the central monument P.0, 105 m distant, were thus 0.166 mm.

Distance measurement was the second method available. In 1954, length measurement by electromagnetic methods was just making its appearance, with instruments such as the geodimeter or tellurometer. The original model of the geodimeter was tried out in 1947 with light modulated at 10 MHz. The standard deviation of this instrument (5 mm + 10⁻⁴ of the distance) makes it unsuitable for very short distances. The same also applies to the tellurometer, which is based on the use of transmitters and receivers operating on very short wavelengths (3000 MHz and above).

The only available tool was, therefore, the invar wire (or tape) used for measuring the bases at the end of a primary triangulation covering the whole country. It was Jäderin, from Sweden, who in about 1885 suggested measuring distances with wires in catenary hung at a constant tension, but this process could not be used until the discovery of the metal invar with almost zero expansion, thereby solving temperature difficulties.

The third of the three tools was the Wild N5 bubble level used with Taylor spheres placed on the bevel edges of the sockets. This method offers a standard deviation of 0.3 mm/km.

After the initial layout, it was necessary to be able to correct the position of the magnets according to the results of measurement. For this purpose, the magnets were installed on three jacks enabling movements in three directions (translation) and movements through three angles (rotation), corresponding to the six degrees of freedom of all non-deformable bodies.

3. RESULTS OBTAINED AT THE END OF 1959 WITH THE 28 GeV PROTON SYNCHROTRON AND THEIR CONSEQUENCES ON ACCELERATOR METROLOGY

When the synchrotron was first operated on 29 November 1959, there were no apparent problems due to misalignment. Because of the synchrotron's radial tunnels, it was possible to measure the radius between the central monument P.0 and the monuments at the top of the octagon; in this way the geometrical reference figure made it possible to determine eight points of the proton orbit facing the monuments with the accuracy of a single length measurement, i.e. 0.015 mm. In each octant, the further the magnets are located from the reference monument, the smaller the influence of distance measurement becomes, whereas the influence of angle measurement increases. The dr of a magnet, located at the centre of the octant, and measured from two monuments, depends solely on angular measurements. The standard deviation of these dr, calculated from a large number of measurements, is 0.15 mm. Figure 2 shows the distribution of the standard deviations of the dr and reveals a harmonic of order 8, corresponding to the number of monuments in the reference figure.

The immediate consequence of this can be seen, namely that distance measurements with invar wire in a tunnel are ten times more accurate than angle measurements over the larger distances. Table 1 shows the results obtained compared with the standard deviations εr introduced into the calculations made when determining the dimensions of the useful aperture.
Table 1

<table>
<thead>
<tr>
<th>ε_t</th>
<th>PS diameter 200 m</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>1954 Project</td>
</tr>
<tr>
<td>dr x</td>
<td>0.6</td>
</tr>
<tr>
<td>dz ⊥</td>
<td>0.3</td>
</tr>
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</table>

This immediately calls to mind two fundamental problems.

Firstly, whether magnets which have been positioned with this degree of accuracy can maintain it over a period of time, and whether their supporting structures are able to provide a similar degree of stability. As the coefficient of expansion for concrete is $1 \times 10^{-5}/^\circ\text{C}$, a variation in temperature of only $1^\circ$ will lead to a 1 mm change in the machine radius, since the 200 m diameter toroidal concrete beam serves as the sole support for the synchrotron's 100 magnets. This would not be serious if the temperature variations were uniform around the accelerator's circumference. In the event of a lengthy shutdown, when

Fig. 2 Distribution of radial deviations $dr$ depending on the azimuthal position of the magnets (28 GeV Proton Synchrotron)
surveys are being carried out, all of the doors are open and the temperature is unevenly distributed. Measurements and realignments cannot be performed in the accelerator operating conditions, and it is virtually impossible for the beam orbit specialists to make precise correlations between the drift based on the survey and those supplied by the pick-up units, which measure the position of the circulating beam of protons at a limited number of points around the ring.

Over a ten-year period, repeated measurements of the monument positions in the PS reference figure showed the long-term consistency -- taking into account movement of the molasse, movement of the monuments, and random errors in measurements -- to be 0.1 mm per 100 m per year. A measurement carried out independently of any triangulation confirmed this figure. From 24 August 1965 to 13 February 1968 a pair of Marussi horizontal pendulums were mounted on the centre P.0 anchored in the molasse 10 m below ground level. These instruments measure the variations of their support in relation to the direction of the vertical, and therefore of the movement of the vertical axis of the 10 m pillar. Figure 3 shows that the over-all movement of the molasse, and of the monument itself, scarcely exceeded 0.15 mm in a north/south direction over a period of two and a half years.

The second matter to be considered relates to invar wire measurements. The requirements of the CERN Survey Group have been such that more than 10 km of invar wire have been used to date, probably the largest amount used in the world. When the PS was being built it was necessary to use wires having a length of 105 and 81 m. It was necessary to use frictionless pulleys, because an excess tension of 1 g on wires of such length resulted in variations dL of the order of 10 μm. The development of pulleys in which the ball-bearings were replaced by balance knife-edges enabled the excess tension to be reduced to 0.002 g. During microscopic measurements of the scales fixed at each end, it was noted that the wires were constantly becoming elongated under a tension of 196.18 N (Newton). As we were the first to use wires longer than 100 m with pulleys that were virtually frictionless, we were naturally in a position to detect this non-elastic elongation. The International Office of Weights and Measures in Sèvres (Paris) was immediately informed, and as a result carried out a series of tests on

Fig. 3 Over-all displacement of the centre monument of the PS according to measurements with two horizontal pendulums over the period 24 August 1965 to 13 February 1968.
24 m length of invar wire which subsequently confirmed our results. Figure 4 shows the elongation of invar wire and tape when subjected to tension for a prolonged period.

These results were taken from the reports of meetings of the International Committee of Weights and Measures (49th, 51st, and 52nd sessions held in 1960, 1962, and 1963 respectively).

These elongations were detected because CERN possesses, for standardization of its wires, a 64 m bench constructed by the Société Genevoise d'Instruments de Physique and located, between 1959 and 1969, in one of the radial tunnels of the synchrotron. After 1969 the bench was installed in a specially equipped tunnel near the ISR. Only the 4 m rule and the microscopes were retained. The rest of the equipment was modernized and the latest refinements incorporated. Until the advent of laser interferometers, this standardization bench was the only one in the world capable of calibrating invar wires of any length between 0.40 and 64 m.

In brief, much was learnt from this initial metrology experiment applied to large engineering structures, and in particular that it was essential to fit the work into the overall project schedule as a dummy activity and exploit to the full the possibilities offered by applied metrology.

The first consequence of this was the need to develop a rapid and reliable distance-measuring apparatus using invar wire. As was remarked above, distance measurement using invar wire is ten times more accurate and a hundred times faster than angle measurement by means of a theodolite. To avoid any non-elastic elongation of the wire, it was necessary to ensure that the tension exerted by the equipment was less than 196 N. Furthermore, it was necessary to carry out the measurements in an extremely short time so that the wire was not left under tension for prolonged periods.
The standard of the measurements performed in the PS clearly had repercussions throughout Europe, since the reference survey figure as well as the instruments and methods employed were used in the two electron synchrotrons built subsequently: DESY (Deutsches Elektronen Synchrotron) in Hamburg, Germany, and NINA (Daresbury Nuclear Physics Laboratory), Daresbury, Warrington, England.

4. EVOLUTION OF INSTRUMENTS AND METHODS (1962-1971);
CONSTRUCTION OF THE ISR (1966-1971)

From 1962 onwards, CERN began to acquire a large variety of computers, namely a Mercury and an IBM 709 computer, and at the end of 1963, an IBM 7090. The use of computers for geodetic calculations made a fundamental change in the philosophy of measurement and, to a certain extent, in accelerator design.

The PS and the machines whose design was based on it were the last to have radial tunnels. The studies carried out at that time for the ISR (Fig. 5) and the SPS (Fig. 6) already illustrate a basic survey system based on a chain of braced quadrilaterals. In the case of the PS, the centre is real and physically exists, whereas in the case of the ISR and SPS the centre is virtual. It was therefore necessary to find a way of superimposing two sets of successive measurements. Furthermore, the elimination of all angle measurement and the sole use of distance measurement modified the observation equations in the computations, and obliged us to reconsider the entire problem of trilateration adjustments. The studies were carried out simultaneously for the ISR and 300 GeV Program. Today, Table 1 can be replaced by Table 2.

Table 2

<table>
<thead>
<tr>
<th>$\varepsilon_t$</th>
<th>PS dia. 200 m</th>
<th>ISR dia. 300 m</th>
<th>SPS dia. 2,200 m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1954 Project</td>
<td>1959 Results</td>
<td>1965 Project</td>
</tr>
<tr>
<td>$d_r \pm \varepsilon$</td>
<td>0.6</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>$d_z \pm \varepsilon$</td>
<td>0.3</td>
<td>0.12</td>
<td>0.15</td>
</tr>
</tbody>
</table>

How were these results obtained and what do they mean? For the PS, the results shown in Table 2 are not only those necessary for smoothing the curve but they also define the absolute spatial position of the magnets in a fixed system of coordinates. For the ISR, the standard deviations indicated are those of elements located inside two adjacent quadrilaterals. The orbit has a PODO structure consisting of 48 magnet periods divided into four superperiods, whereas the complete geodetic figure comprises 32 quadrilaterals. Figure 7 shows one of the eight octants of the over-all framework.

Starting from one monument as reference, the ellipses of errors were calculated for each monument up to those diametrically opposite (Fig. 8). In this way, it is possible to judge the distortion of the reference figure. The value of the semi-major axis of the largest ellipse of errors is 0.2 mm for a probability of 0.40. For a probability of 0.99, this value must be multiplied by three, which gives a figure of 0.6 mm for the semi-major axis.
Fig. 5 Layout of survey monuments in the PS/ISR complex

Fig. 6 Layout of survey monuments for the SPS

Fig. 7 Reference braced quadrilaterals in octant 5 of the ISR
Fig. 8 Ellipses of errors computed when taking monument 11 as the starting point and direction 11-51 as orientation vector. They show the way in which errors accumulate around the Storage Rings' circumference.

This means that from one set of alignments to the next, the variation dr in the radius of the orbit is of the order of 0.08 mm in relation to the theoretical orbit, but its position in space has a 99% chance of being inside a circle of errors of 1.2 mm in diameter. The virtual centre of the ISR is therefore located in its horizontal plane inside a 1.2 mm diameter circle, i.e. with a relative precision of $4 \times 10^{-6}$, whereas the precision in the position of a magnet in relation to another one, inside two adjacent quadrilaterals, is better than 0.1 mm.

In order to achieve this, it was decided to eliminate systematically all angle measurement and to make all trilateration adjustments on our CDC 6000-series computers. At present, this is being done on a CDC 7600. The distances were measured with invar wire, using a new instrument developed at CERN: the "distinvar" (see Fig. 9 and Technology Note P14). It has been universally used for measuring the reference geodetic figure and for positioning the magnets. Only two days were needed to measure the 32 quadrilaterals of the reference figure and to calibrate the invar wires before and after measurement in the ring.
On top of each ISR magnet, which is supported by three jacks for fine position adjustment, there are two reference sockets precision-machined to within a few microns. The socket directly above the single jack at one end is brought into position by referring to the two closest monuments. The second socket of this magnet is aligned in relation to the straight line between the first socket of this magnet and that of the next magnet, using the nylon wire alignment equipment described in Technology Note P15 (Fig. 10). In this way the curve can be smoothed out and kicks on the proton are avoided between one magnet and the next.

The nylon wire alignment equipment has been extremely widely used for the layout of the operating components in the transfer tunnels between the PS and the ISR (see Fig. 5). These tunnels are more than 2 km long and have as many dipoles and quadrupoles as the ISR. Nylon wire was chosen because it is very easy to handle and is inexpensive. Furthermore, it has a very low density and a high tensile strength. When using a 0.2 mm Ø nylon wire, the maximum tension required is only 1.5 kg in order to reduce the sag to a minimum. Long-distance alignments are measured by determining the deviation between the broken line formed
by joining up the pre-aligned reference sockets and the straight line given by a stretched nylon wire. These deviations are processed by the least squares method, and the sockets are moved accordingly in order to construct the straightest possible line. Two, and in exceptional cases three, sets of measurements and calculations are sufficient to arrive at this result.

In the transfer tunnels between the PS and the ISR a concrete monument has been installed every 27.69 m. These monuments have the same sockets as those fitted to the monuments of the geodetic reference figure in the ring. After the tunnel ventilation system has been shut down to eliminate draughts, the nylon wire is stretched between monuments 1 and 4, over a distance of 83 m. Measurements are made of the offsets of sockets 2 and 3 in relation to the straight line given by the nylon wire. The wire is then fitted to monuments 2 and 5, and the offsets of monuments 3 and 4 are measured, and so on until the last monument is reached. Every offset is therefore measured twice, except in the case of the second and the last but one. An additional measurement is made with the wire stretched between 1 and 3 for socket 2 and between n-2 and n for socket n-1. The histogram (Fig. 11) shows the distribution of the deviations for a set of 173 measurements made with an early prototype in which the readings were made without a microscope. The arithmetic mean is 0.00 and the standard deviation is 18 μm.
One of the first prototypes of the distinvar was used in NINA, Daresbury, and another at the electron synchrotron at Frascati, Italy. The distinvar and nylon wire alignment equipment were successfully used for alignment work in the cyclotron of the Swiss Institute for Nuclear Research (SIN) at Villigen. The aircraft industry showed interest in the distinvar for measuring a calibration base for the triangulation of aircraft wings (Marcel Dassault). The distinvar and nylon wire alignment are now regularly used for verifying the stability of the Emsonn dam. It has also been used in Belgium at Redu for the Satellite Tracking and Remote Measurement Station and is also being used in France by the Centre d’Etude des Tunnels (CET) for measuring the stability of road tunnels.

5. THE 300 GeV PROGRAM -- AUTOMATION OF THE EQUIPMENT SINCE 1971

On 27 January 1971, beam collisions were produced for the first time in the ISR. On 19 February the construction of the SPS was approved by the majority of Member States. This was straight away a new challenge to the CERN Survey Group. The PS and the ISR were surface structures built by the "cut and fill" method with prefabricated concrete tunnels. For this to be possible, it was necessary to raise the mean plane of the ISR 12 m above that of the PS. Unlike the NAL site (Batavia, USA), which is horizontal, flat, and free from vegetation, woods or forest, the new CERN site has a variegated topography, with a separation of 50 m between the highest and lowest points on the circumference of the tunnel, and the surface is almost completely covered with woods. For obvious reasons of economy, the SPS tunnel could only be located underground and bored with a special machine in the Chattian molasse plateau of the Geneva basin.

The quality of underground geodesy depends directly on the accuracy of the surface triangulation-trilateration framework. All traverses made in the main tunnel must close on geodetic points once they have been transferred down to the floor of the accelerator.

In the triangulation, all angles were measured with T3 theodolites, whereas in the trilateration all distances were measured with an NA 100 tellurometer. We have just received from NAL the geodolite which served for the survey of their accelerator. NAL claim that they have attained, with this instrument, an accuracy of 1 mm over a distance of 1 km. This equipment will be extremely useful for long-distances measurements, particularly for those relating to the North experimental area.

The initial civil engineering work started by digging six vertical shafts spaced at equal intervals around the 6911 m circumference. When making the underground traverses which were to guide the Robbins machine, the geodesist could not measure an azimuthal bearing at both ends of one sextant.
At the very beginning, an additional shaft was drilled directly above the injection tunnel at a distance of about 200 m from shaft PP1. A tunnel was bored between these two shafts, which could have provided a starting azimuth. As the errors in such a system are cumulative, it would have been difficult to guarantee that the tunnel would be in the right position to within a few centimetres after boring over a distance of 1.2 km to the next shaft, this being the only point where a check could be made of its position from the surface. An absolute reference of some kind had to be found. As the magnetic north would not have been sufficient for this purpose, the axis of rotation of the earth was chosen as a reference. A gyrotheodolite was used for measuring the bearings of the traverse. The legs of the traverse are all equal. Every 32 m a monument was built and the geographical north determined, thus avoiding any cumulative errors. This traverse ensured that the laser beam used to guide the boring machine was positioned in the right direction.

It took two years to become fully familiar with the operation of the gyroscope, a Wild GAK 1 mounted on a Wild T2 theodolite, and to solve the series of difficulties which had discouraged many surveyors from using it. With the experience gained, the standard deviation specified by the manufacturer was halved, thus reducing the figure of 60 dgm to 30 dgm in site conditions, when operated manually. At the same time, the Mechanics and Electronics Section of the Group was developing an automatic measuring system for this gyroscope; although this system did not make a substantial improvement in the over-all accuracy when working in tunnel conditions, it nevertheless enabled operators to leave the gyroscope to carry out the work automatically and record the transit times on tape. The automatic gyrotheodolite is shown in Fig. 12 and is described in Technology Note P17.

The traverses of the first three sextants were carried out manually with the gyrotheodolite. This system has worked remarkably well. After 1.2 km of boring, the transverse deviation of the axis of the tunnel was only 23 mm at shaft PA2, 19 mm at PA3, 14 mm at PP4, and 10 mm at PP5.

Accuracy is controlled in a very simple manner (Fig. 13). At each station of the gyroscopic traverse, the bearings of two adjacent monuments are measured. For each side of the traverse, therefore, two totally independent values for the same bearings are obtained, since they originate from two different stations, each involving a determination of the meridian. The standard deviation, calculated over 107 differences, is 46 dgm. Figure 14 gives the differences between the direct and reverse bearings of the 36 sides of the sextant PP4-PP5, measured with the automatic gyrotheodolite.
Figure 15 shows the results of the determination of the geographical north using the transit method, without assistance from the operator and spread over a three-hour period; the theodolite is mounted with forced centring on a monument out of doors, and is not protected against atmospheric conditions. The mean difference between the theodolite's axis and true north is 67 dmg; the standard deviation is 6 dmg.

Fig. 13 Principle of gyroscopic traverse (GN = geographical north)

Fig. 14 Differences between direct and reverse gyroscopic bearings on the 36 sides

Fig. 15 Determination of the geographical north for calibration purposes
No doubt the work we have done at CERN will have dissipated the mystery surrounding the gyroscope. The results obtained prove the gyrotheodolite to be a reliable instrument which can be used without hesitation, provided due care is exercised.

There was another important check that could only be carried out early in 1974: when the 800 m injection tunnel was bored in a reverse direction to connect with the ISR transfer tunnel. Between the two theoretical axes of these tunnels, the transverse deviation was less than 1 cm. This figure proves that the new machine was correctly centred on the site with respect to the surface geodetic network.

The distinvar is gradually being converted to automatic operation. The latest prototype (Fig. 16) already offers increased reliability and easier operation. Development work is being carried out to display the results either on a digital voltmeter or on a print-out unit, or to feed them directly into an on-line computer.

The geodetic reference figure of the SPS is a modified version of that of the ISR. In the latter, because of the relatively favourable ratio between the width and length of a braced quadrilateral (1:2.5) distance measurements alone were used for the ISR framework consisting of 32 braced quadrilaterals. In the SPS, this ratio is approximately 1:10. To keep the deviation of the radius within the tolerances, the reference figure must be stiffened by measuring the offsets of the monuments of three consecutive quadrilaterals with the nylon wire equipment (Fig. 17). As the SPS is a separated-function machine, the components which must be accurately positioned are the quadrupoles situated at one end of each semi-period of the accelerator's lattice, every 32 m. In this case, therefore, it is necessary to adapt the metrology system to the periodicity of the quadrupoles. Opposite each quadrupole two brackets will be fixed, one on the outer wall, the other on the inner wall. In addition to the distance measurement of each braced quadrilateral, nylon wire alignment
inside three consecutive quadrilaterals will ensure the precise shape of the geodetic framework in each sextant, and it is expected that the radial standard deviation of three consecutive quadrupoles in one period will not exceed 0.1 mm.

Computation of the surface network shows that, for monuments built on two adjacent shafts 1.2 km apart, the semi-major axis of the ellipse of errors is 1.5 mm, namely a relative accuracy of $10^{-4}$. The underground invar nylon traverse over a sextant will reduce this value by a factor of 2, giving an expected accuracy of $5 \times 10^{-7}$.

In the ISR, the reference sockets mounted on the top of each monument were located in a pair of eccentrics in such a manner that they could occupy any position within a radius of 20 mm. In this way it was possible to build a geodetic framework that was as close as possible to the theoretical one. For economy reasons, and owing to the experience gained in working with computers, it was decided for the framework of the SPS not to use adjustable sockets but fixed ones. Consequently, after each set of measurements, it is necessary to compute the coordinates of the reference sockets and to use these coordinates when locating the quadrupoles.

To facilitate precise positioning of the quadrupoles, a new type of jack has been developed by the Mechanics and Electronics Section of the Group. The special feature of these jacks, shown in Fig. 18 and described in Technology Note P16, is that they have flexible polyurethane pads which allow horizontal and vertical displacements to within 0.01 mm. They are very easy to operate, since the maximum torque on the adjustment screws is less than 2 kg/m.

![Fig. 18 Polyurethane jacks](image)

For the first time, the Survey Group has dealt with a problem of workshop metrology involving the development of equipment known as the "Centipede" (Fig. 19) for measuring the geometry of the 3.6 m long pole pieces of the SPS quadrupoles.
This equipment is described in Technology Note P18. It is guided along a virtual axis between the four magnet poles provided by a laser beam aimed at a target consisting of four differential cells; the transverse tilt is measured by a newly designed automatic clinometer. The nodal point of the correction lenses ahead of the laser is 5 m from the target. In workshop conditions, it is impossible to ensure a reproducibility better than 0.05 mm. If it had been possible to use a nylon wire, accuracy could have been increased by a factor of 2.

6. CONCLUSIONS AND OUTLOOK

After this rather comprehensive review of the methods, instruments, and results of accelerator metrology, it is, in my opinion, important for the non-specialist to keep in mind the following basic standard deviations:

<table>
<thead>
<tr>
<th>Description</th>
<th>Deviation</th>
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<tbody>
<tr>
<td>Calibration of a distance between two microscopes on the reference base, between 0.40 and 60 m</td>
<td>1.5 μm</td>
</tr>
<tr>
<td>Transfer of this length to between two forced centring sockets in the tunnel by means of the distinvar</td>
<td>15 μm</td>
</tr>
<tr>
<td>Combination of several length and alignment measurements in the reference geodetic framework; for example in braced quadrilaterals</td>
<td>150 μm</td>
</tr>
</tbody>
</table>

Note: 1 dm (10^-4 grade) at a distance of 1 m equals 1.57 μm

To improve on these values by one order of magnitude would no doubt be possible, but only in laboratory conditions. The use of lasers both for distance measurement (interferometry) and for alignment in evacuated tubes (at about 10^-3 Torr) would probably provide a solution, but it would be complex and expensive.

An approach in this direction has been made in the alignment of the electron linear accelerator at Stanford (California), designed for an energy of 20 GeV. This 3000 m accelerator is housed in a straight tunnel 7.5 m below ground level. The electrons travel along a 10 cm diameter copper waveguide and are accelerated by electromagnetic waves produced by 240 klystrons. The smaller tube at the top of Fig. 20 is the one in which the electron beam travels. The large aluminium pipe underneath acts as a supporting structure; this tube is evacuated and a laser beam is sent through for alignment purposes. The accuracy achieved is 1 mm over 3 km length of the accelerator. The size of the tube containing the laser beam was determined on the basis of the maximum beam divergence. This solution is only possible because the linac's components are extremely light, quite unlike the magnets and lenses of circular proton accelerators.
As far as can be predicted, if it proves necessary to satisfy tighter tolerances, much more sophisticated and therefore more costly equipment will have to be built than that described in this paper, involving a measurement time which may be 10 to 100 times greater. It is quite possible that when setting up 300 GeV physics experiments in the halls, such equipment will be necessary, and metrology will thus have a further field in which exciting research can be made.

However, research in the field of accelerator metrology, as practised at CERN, has always been directed at developing and building equipment with increasingly better performance and suited to the exceptional size of the structures to be measured. This equipment has satisfied the accuracy requirements, whilst reducing the time required for initial positioning and re-checking the positioning of accelerator components.

At present, out of a total staff of 40 persons, about 30 are involved with geodetical and metrological work. For the future, it is essential to develop instruments which are both highly reliable and offer maximum ease of operation, because once the SPS has started to operate, a staffing problem will arise. As the PS is the sole injector for all the CERN machines, the Survey Group may well find that during prolonged shutdowns it is engaged in realignments in the PS, the Booster, the ISR and the SPS simultaneously. During the same period, the Group will be expected to set up experiments in the ISR intersection regions and in the SPS experimental halls. In order to cope with this type of situation, it will be necessary to form teams consisting of only one specialist from the Survey Group, CERN mechanics, and contract labour. This is essential if the staff number is to be kept at a reasonable level, but it also implies that increasing emphasis must be laid on the reliability and performance of the equipment, which should be constantly adapted to the requirements of the tasks to be carried out.