« Ce besoin, cette hantise de devoir préciser son domaine, ses recherches ».
                                            Pierre BOULEZ

INTRODUCTION

In a recent conversation with Dr. J.B. Adams, Director-General of CERN Laboratory II, it was again stated that two fundamental problems must be solved in order to ensure correct operation of particle accelerators. It is essential firstly to ensure the stability of the foundations of the magnetic structure which guides the particles; secondly, to provide a magnetic confinement system in which the protons circulate for several seconds during acceleration. This calls for precise positioning of the components.

The geodesists intervene at the time of the construction to check the stability of the foundations, and during the installation, to carry out the fine adjustment of the magnets. This applies in the case of both combined and separated-function machines.

Geodesy is again taking up its place among the spearhead techniques, in a field which is far-removed from its own: accelerator construction. This science played a vital part in fundamental physics during the 17th and 18th centuries. It is to Abbé Picard that we owe the first accurate geodetic determination of the earth's radius in 1669, a little over 300 years ago. By means of triangulation Picard measured an arc of meridian between Sourdon, south of Amiens, and Mallevoisine, south of Paris. To determine the scale he used a geodetic base measured between Villejuif and Juvisy and observed astronomical latitudes. He obtained, on the assumption that the earth was spherical, a value of 57060 toises for the degree, which is quite remarkable for the time. The result was communicated to Newton in 1682 and provided him with the precise numerical data which he needed in order to prove his law of gravitation. The value which Newton had initially used for the earth's radius was so imprecise that the value he found for g — already quite well known — was too large by one sixth. Using Picard's figure, Newton found

that his theory agreed well with the experimental results. In 1687, Newton published his famous "Principia mathematica philosophiae naturalis" in which he set out his view of the world system. He proved Kepler's laws by means of the law of gravitation and calculated the flattening of the earth (1/231) assuming it to be a homogeneous body.

At the beginning of the 18th century there was still strong contention between the supporters of Cassini, who upheld that the earth was an elongated ellipsoid, and those of Newton who maintained that it was a flattened ellipsoid. Consequently, in 1735, at the instigation of the Académie française des Sciences, Chancellor Maurepas decided to send out two geodetic expeditions with the task of measuring a 1° arc of meridian in Lapland and in Peru. Maupertuis, Cleraut and Celsius made the measurements in Lapland using instruments designed by the famous English mechanical engineer Graham. Bouguer, Godin and La Condamine directed the operations in Peru. The results of these two expeditions confirmed Newton's hypothesis.

For geodesy, with the advent of artificial satellites, the future holds in store an unlimited field for experiment. It may be predicted that at one of the frontiers of science, geodesy and its natural extension, geodetic astronomy, will play the same part with regard to Einsteinian physics as Abbé Picard's measurements did for Newtonian physics.

If we turn to another frontier of science, fundamental research in particle physics, geodesy has reassumed the scientific importance which had become overshadowed by the progress of other sciences during the 19th and 20th centuries.

Geodesy and Large Particle Accelerators

J. Gervaise, CERN

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1. GEODESY AND ITS TECHNIQUES, WHY ?

"When FORTUNE magazine in the mid-1960's surveyed 1,003 young executives employed by major American corporations, it found that fully one out of three held a job that simply had not existed until he stepped into it. Another large group held positions that had been filled by only one incumbent before them. Even when the name of the occupation stays the same, the content of the work is frequently transformed, and the people filling the jobs change".

Alvin TOFFLER - "Future Shock", Bantam Export Edition, 1970

In the first generation of circular accelerators (28, 33 and 78 GeV), it was necessary, owing to their size, to adapt geodesy - in the sense of the above quotation - to suit the problems raised by these machines. This is no longer the case today: the diameter of the SPS is 2.2 km, which means that the magnetic confinement system has a circumference of 7 km and contains over 1000 bending and focusing magnets.

The triangulation and trilateration dimensions for the 400 GeV synchrotron are of the same magnitude as those of third order networks performed in the industrialized countries. To establish the geodetic framework which covers the sites of Laboratory I, the SPS and the North Experimental
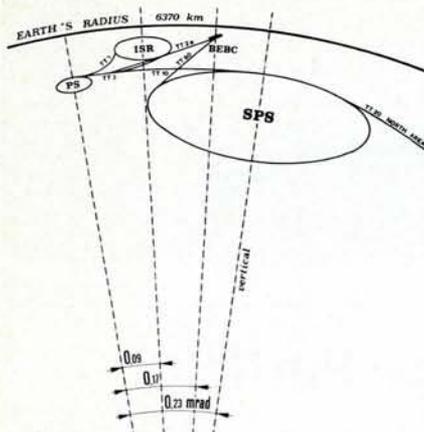
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Fig. 1 Influence of the earth curvature. The drawing shows the angles between the plane of the PS, which is the reference plane, and the planes of the ISR and SPS.

Area, it was necessary to measure distances up to about 7 km.

To reach the degree of precision promised by the geodesists it is necessary to apply to the measurements the first order geodetic techniques, the distances of which are generally 10 times greater than those of the CERN network.

The calculations must allow for the curvature of the earth. The distances measured must be reduced to sea level and it was even necessary to create a local projection system. The curvature of the earth poses unexpected problems in the levelling operations. If a plane cuts through a sphere the result is a circle. The orbit of the synchrotron is not a circular one but must remain in one plane. The orbit consists of six circular sextants with a radius of 947 m separated by six 250 m-straight insertions. In these long straight sections the deviation from the mean plane of the 1.1 km radius circumference is 2.3 mm, which is by no means negligible. Furthermore, as the ISR and

SPS are constructed horizontally to within a few tenths of a millimetre, the planes of these machines are not parallel to that of the 28 GeV synchrotron; the angles they form with it are 0.09 mrad and 0.23 mrad respectively (see Figure 1).

To avoid any error accumulation, the geometry of the SPS reference figure has been broken down into 32 m-sections. The sequences of magnet installation will be achieved sextant by sextant. When the last sextant has been installed, adjustment of the complete geometric figure will be made by the least squares method and the resulting matrix will be of the same dimension as those of the geodetic networks of European countries.

2. INVAR: A MODERN VERSION OF A TECHNIQUE DATING FROM 1900

The problem of the choice of instruments and of adapting them to the required measurement accuracy arose in 1954 at the beginning of the construction of the 28 GeV CERN proton synchrotron. This was the first major structure to call for such high-precision measurements. The same was also the case for the ISR and this is still true for the 400 GeV accelerator. The geodesist has few instruments which he can use in this range of measurement. It may even be said that all electromagnetic distance-measuring instruments are designed to provide maximum precision over much greater distances.

For distances of between 0 and 50 m, only invar wire has provided the necessary accuracy and reliability. The requirements of the CERN Survey Group have been such that more than 10 km of invar wire have been employed 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 105.85 and 81 m. It was necessary to use frictionless pulleys, because an excess tension resulted in a length variation 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 N. 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 Bureau International des Poids et Mesures in Sèvres (Paris) was immediately informed and as a result carried out a series of tests on a 24 m-length of invar wire which subsequently confirmed our results. Figure 2 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.
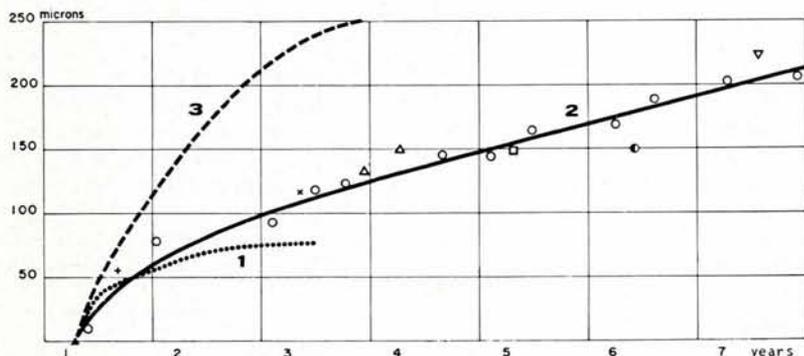
These phenomena were detected because CERN possesses a 64 m-bench for standardization of its wires, located between 1959 and 1969 in one of the radial tunnels of the synchrotron. After 1969 the bench was installed in a specially equipped tunnel near the ISR. Only the 4 m rule and the microscope were retained. The rest of the equipment was modernized and the latest refinements incorporated, such as a laser interferometer.

Invar wires used in an instrument developed at CERN, the Distinvar, are no longer a source of difficulty, and provide the only industrial method of obtaining a relative precision of 10^{-6} in the range of distances encountered in accelerator construction.

3. EARTH TIDE MEASURING EQUIPMENT USED FOR THE SYNCHROTRON

In addition to the traditional geodetic measurements, horizontal pendulums were used to check the stability of the molasse and of the CPS reference monuments.

Over a ten-year period, repeated measurements of the monument position in the CPS reference figure showed the long-term consistency — 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

1 Invar wire BIPM of 24 m (No. 796), tension 98.09 N
2 Travelling tape BIPM of 24 m (No. 2), tension 98.09 N
3 Invar wire CERN of 24 m, tension 196.18 N

Travelling tape measurements made at

O Bureau International des Poids et Mesures, Sèvres   Δ Institut Central de Recherches Scientifiques de Géodésie, Moscou
▲ National Bureau of Standards, Washington   □ Physikalisch - Technische Bundesanstalt, Braunschweig
+ National Physical Laboratory, Teddington.   ◉ Institut Géodésique de Finlande, Helsinki
× National Standards Laboratory, Chippendale   ▽ Geographical Survey Institute, Tokyo

Fig. 2 Elongation of invar wire and tape as a function of the number of years use.

of Marussi horizontal pendulums were mounted on the centre pillar 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 overall 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.
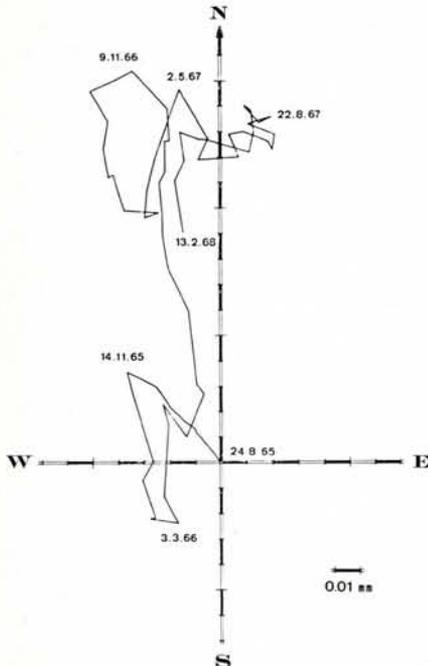

Fig. 3 Over-all displacement of the centre monument of the PS according to measurements with two horizontal pendulums over the period 24 August 1965 to 13 February 1968.

4. A GYROSCOPE TO GUIDE THE BORING MACHINE

As remarked by Dr. J.B. Adams during the Meeting on Technology arising from High-Energy Physics, Geneva 1974, "the technology of accurate tunnel boring which we had to learn and perfect in the last two years is one of the most fascinating technologies in the project".

The geological studies of the site showed that the same rock also existed below the site of the projected machine and allowed a 2.2 km-diameter synchrotron to be built adjacent to the existing CERN Laboratory. The PS and the ISR were surface structures built by the "cut and fill" method with prefabricated concrete tunnels. Unlike the FNAL 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 entirely covered with woods. For ob-

vious economical reasons, 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 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.

The initial civil engineering work started by digging six vertical shafts spaced at equal intervals around the 7 km-circumference. When making the underground traverses which were to guide the Robbins machine, it was physically impossible for the geodesist to measure any azimuthal bearings at both ends of one sextant, as he is normally required to do.

At the very beginning, an additional shaft was drilled directly above the

Note: 1 dmg equals 10⁻⁴ grade

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injection tunnel at 200 m from shaft 1. Between these two shafts a tunnel was bored to set up the Robbins machine. It could have been used to provide a starting azimuth. The usual practice of angular measurement could have been used for the successive bearings needed to guide the Robbins. In such a traverse the errors are cumulative. Using this method it would have been very difficult to guarantee the proper positioning of the tunnel to within a few centimetres after boring over a distance of 1.2 km to the next shaft, where a check could be made 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 pillars were built in the molasse and at each of these the geographical North was 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 gyroscope 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 dmg to 30 dmg in site conditions, when operated manually. At the same time, an automatic measuring system was developed for this gyroscope; although this system did not make a substantial improvement in the overall 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 traverses of the first three sextants were carried out manually with the gyrotheodolite starting from shaft 1. After boring 1.2 km, the transverse deviation of the axis of the tunnel was only 23 mm at shaft 2, 19 mm at 3 and 14 mm at 4. The traverses of the other three sextants were carried out with the automatic gyrotheodolite. The transverse deviation of the axis of the tunnel was 10 mm at shaft 5, 26.4 mm at 6 and 1.5 mm at 1.

These results are substantially better than those promised by the geodesists in the Survey chapter of the 300 GeV Programme Report (CERN/1050, January 1972). Once the tunnel had been completed, the gyroscopic traverse was calculated over the whole length of the circumference, without taking into account the references from the surface geodetic system. After 7 km of underground traverse, starting from shaft 1 and returning to the same point, the closure vector is only 70 mm. This would have been sufficient for the civil engineering requirements, but in 1971 no-
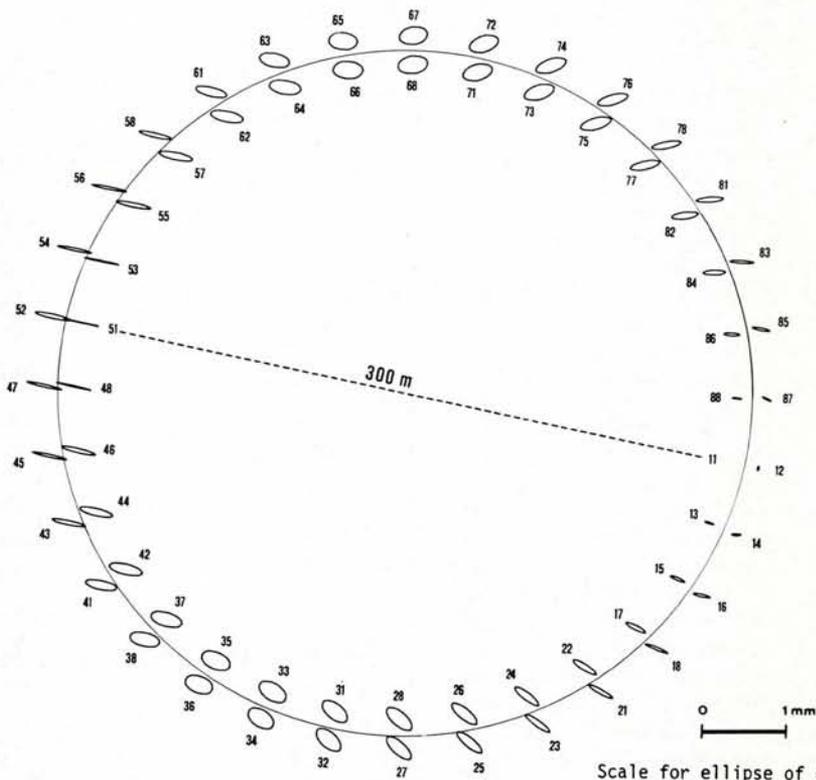

Fig. 4 Ellipses of errors computed when taking monument 11 as the starting point and direction 11-51 as orientation vector. They show the way in which errors accumulate around the Storage Ring's circumference.

one would have taken the risk of being without a surface geodetic network and relying solely on the gyro-theodolite.

5. LARGE CDC COMPUTERS SATURATED
BY GEODETIC CALCULATIONS

Surprises always come from where they are least expected. None of the senior computer staff ever thought to ask the geodesists what computer capacity was needed for carrying out geodetic adjustments.

The geometric reference figure was broken down into sections to avoid error accumulation. Once a section has been measured — generally a braced quadrilateral — a check can be made that no errors have crept in. On the contrary the calculations of the coordinates of the geometrical reference figure surrounding the magnetic confinement system of the SPS have to be carried out as a whole. It is only to match the planning that a provisional adjustment is made sextant by sextant.

This means that it will be necessary to carry out, by the least squares method, the adjustment of a network consisting of 864 unknowns and 1728 observation equations, one for each measurement.

As the 400 GeV proton synchrotron is a separated-function machine, the components which have to be positioned with a maximum accuracy are the quadrupoles located at each half period of the accelerator lattice, namely every 32 m.

It is therefore essential to adapt the metrology system to the periodicity of the quadrupoles. Two brackets will be placed opposite each quadrupole, one on the outer wall and the other on the inner wall. The reference figure will therefore be a chain of braced quadrilaterals, of which all the lengths will be measured with the distinvar. Between adjacent quadrilaterals redundant measurements will be made with nylon wire alignment equipment. In the adjustment of a sextant and, later, in the adjustment of the whole system, this will help to reduce the effect of the very unfavourable ratio between the width of the quadrilateral (3.40 m) and its length (32 m). In fact, it is the nylon wire alignments which will provide the rigidity of three successive braced quadrilaterals, thus allowing the transverse standard deviation of three quadrupoles of one period (QD-QF-QD or QF-QD-QF) to be 0.1 mm.

In 1965, these calculations had already been simulated. At the time, the CERN Survey Group had not yet developed the nylon wire alignment
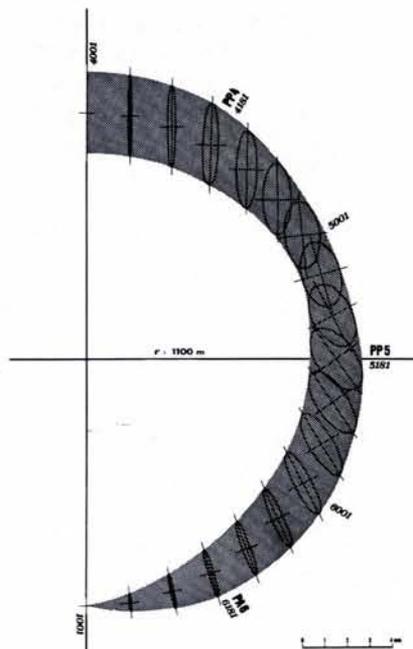
For memory, 1 dmg (10⁻⁴ grade) at a distance of 1 m equals 1.57 μm.

Fig. 5 Pattern of the ellipses of errors for half of the circumference of the SPS.

equipment. In the simulation calculations for a synchrotron of very similar dimensions (3.0 km) and with a very similar geometric lattice, (228 braced quadrilaterals instead of 216), only distance measurements were assumed to be used. The deformation of the geometrical figure was calculated for one half of the machine's circumference. Taking the standard deviation of invar wire measurement as 14.7 μm, the indeterminacy of two diametrically opposed points was 842 times the standard deviation of a single length measurement. This gave 12.4 mm. By connecting up adjacent quadrilaterals with nylon wire, this indeterminacy is only 1.8 mm. The gain in accuracy will be almost a factor of 10 on the absolute positioning of the accelerator. The rms value of the radial deviation of three successive quadrupoles will be less than 0.1 mm, whereas the distance between two diametrically-opposed points will not be known to better than ± 1.8 mm.

Since 1965, progress has been made in measurement and computation. The 28 GeV synchrotron measurements have been completely modified and adapted to the invar/nylon system. This adaptation was possible due to the advent of computers; there were none at CERN at the time when the CPS was built. The calculations which come closest to those of the new machine are those of the ISR. The sole difference is that owing to the width of the ISR tunnel, only invar wire distance measurements were performed. The least squares adjustment method remains the same; only the dimensions of the corresponding

matrixes are on a totally different scale.

Figure 4 shows the deformations of the ellipses of errors of the ISR reference pillars. Starting from one monument as reference, the ellipses of errors were calculated for each monument up to those diametrically opposite. 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 is 0.6 mm.

This means that from one set of alignments to the next, the variation of 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. In other words, the virtual centre of the ISR is located in its horizontal plane inside a 1.2 mm diameter circle, i.e. with a relative precision of 4.10^{-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.

These results were obtained from many sets of measurements in the ISR. Figure 5 is the result of a simulation and shows the pattern of the ellipses of errors for half of the circumference of the SPS.

The adjustment of the complete SPS reference figure has now been completely mastered and adapted to the capacity of the CERN computers.

CONCLUSION

After this review of some typical aspects of accelerator geodesy it is worthwhile for future users of CERN accelerators to remember the following data:

Calibration of a distance between two microscopes on the reference base, between 0.40 and 60 m . . 1-1.5 μm
Transfer of this length to between two forced centering sockets in the tunnel by means of the distinvar . . . . 10-15 μm
Combination of several length and alignment measurements in the reference geodetic framework; for example in braced quadrilaterals . 100-150 μm

To improve on the last two values by one order of magnitude would no doubt be possible, but only in laboratory conditions, or if laboratory conditions can be provided at the very point where the measurements are to be made. It can be predicted that certain special experiments will call for this level of accuracy. This will be a further challenge to geodesists in the near future.