TECHNOLOGICAL EVOLUTION OF MEASUREMENT TOOLS DILEMMAS, ILLUSIONS AND REALITIES

M. MAYOUD, E. MENANT, J.P. QUESNEL
CERN - European Organization for Nuclear Research
1211 Geneva 23 - Switzerland

1. INTRODUCTION

New instruments appeared recently on the narrow market of geodetic metrology, bringing replacement or complementary facilities to our specific problems - related to the alignment of the components of accelerators (experiments included). Before entering hastily the fatal cycle old ≅ classical ≅ obsolete, it would be judicious to make an objective inventory of our major tools - old and new - with their actual capabilities, limitations, drawbacks, etc.

This paper will therefore present a collection of reflections and facts on some basic elements of our methodology and instrumentation, based on CERN experience and mainly focussed on distance, angle and off-set measurements. It results from our own reflections, but also from the many questions coming from people recently involved in that field, who have to solve alignment problems. In both cases - for ourselves or when acting as a consultant - this deserves to make an objective analysis of the alternatives, and to bring clear and fair answers.

2. PANOPLY OF TOOLS

As a quick inventory of accurate instruments available for geodetic metrology, the following - and non exhaustive - list has been limited by two selection criteria : linear accuracy (1 σ) £ 0.5 mm, longitudinal, radial or vertical and angular accuracy (1 σ) £ 3 cc or 0.3 mgon or 1 arc-second.

Distances

- CERN Distinvar;
- Other invar wire equipments (KERN Distometer, various geodetic systems);
- KERN ME 5000;
- COMRAD Geomensor;
- WILD DI2000 (corrected);
- Short-range parallactic measurements (with a stadia);
- Special adaptation of linear sensors (e.g. SYLVAC/CERN equipment).

Off-set measurements

- Wire devices (CERN);
- Laser devices (CERN, TAYLOR-HOBSON, etc.);
- Optical systems with telescopes, scales, etc.

Angles

- CERN E2i theodolite with panfocal telescope;
- WILD T3000 theodolite with panfocal telescope;
- AGA, ZEISS, etc.

Levelling

- Many good and well-known instruments satisfy the criteria;
- A few automatic instruments exist : CERN Nivella, WILD Na2000.

3. BASIC METHODOLOGY

Supposing appropriate solutions for centring or targeting problems, man-related errors and levelling, assuming good least-squares adjustment programs with their statistical tools (stochastic analysis, simulations, optimization), the most critical elements to point out are the following :

- *Calibration facilities,* as essential tools for a full mastering of the accuracy and reliability of the instruments used,
- *Rigourous measurements procedures,* to ensure the quality of measured data;
- *Optimized control networks,* preserving a good geometrical configuration with respect to environmental and technical constraints - associated with an optimum set of measurements (regarding their nature, efficiency, accuracy, redundancy);
- *Good secondary/auxiliary points,* when supporting the main operation lines used for the alignment of critical components;
- *Smoothing,* as an essential scheme for the final checking and the refinement of the alignment process.

4. SEMANTICS, VOCABULARY, UNITS

As a reminder, it would be useful and quite on purpose to recall some definitions used in geodetic metrology :

- *Accuracy* : standard deviation (1 σ) of random errors;
- *Systematic errors* : additional, repetitive and cumulative errors resulting from instrumental defaults, centring or setting-up errors, technological limits;
- *Corrections* : parametric data needed for expressing the exact value of a given measurement, in relation with physical, mechanical or geometrical considerations (known systematic errors, refraction, projection, etc.);
- *Optimum accuracy* : accuracy obtained in very good conditions - calibration facility, laboratory, test area, etc, - from an optimum procedure of measurements;
- *Configuration and structuring* : geometrical shape and measurement scheme of a network, to ensure a satisfactory accuracy, coherence and homogeneousness in the 2D or 3D determination of its points with respect to specifications;
- *Redundancy* : overall factor, expressing the ratio between the number of measurements and the number of free parameters (unknowns of the least-squares adjustment);
- *Scaled estimates* : depending of the configuration, structuring and redundancy of a network, statistics on the residuals of a given group of measurements

(distances, angles, off-sets, etc.), or the estimates applying to a set of parameters (coordinates, etc.) are distorted. Only simulations made with controlled perturbations (Monte Carlo process) can indicate these distortions and provide the correction factors which will re-scale the statistical parameters of the least-squares adjustment;

- *In-situ accuracy* : a posteriori accuracy (1 σ) of adjusted measurements or parameters, resulting from scaled estimates of the global stochastic analysis (simulations, adjustment, statistics, correction factors).

5. DISTINVAR (CERN)

The whole set must consist of the reading unit, the invar wires, the attachment head and a necessary calibration facility, equipped with an interferometer.

5.1 LIMITATIONS, DRAWBACKS, CARES

The range is limited by the length of the calibration baseline, and also by the sag of the wires with respect to the nominal tension. The current range at CERN is from 0.25 m to 56 m - exceptionally 106 m with an intermediate pulley.

The accuracy is not limited by the reading unit but mainly by the physical behaviour of invar wires. The initial stability of the alloy depends on manufacturing conditions and may require improvement by means of beating operations. There is also an evidence of long-term elongation versus time and use, with fortunately an asymptotic trend. The rolling/unrolling modes, the handling and storage conditions may strongly affect the wire length. The measuring procedures must strictly take into account these parameters and ensure a sufficient number of cross-checks.

Pre, intermediate and post-calibrations are always necessary, combined with in-situ cross-checking, i.e. sequencing the operations with back-measurements. Away from the calibration baseline, secondary/auxiliary facilities must be provided, in order to make local calibrations by comparing three wires and keeping always one as a reference. Another solution is to use locally the CERN portable interferometric system, with its self-aligning comer cube.

The feasibility of Distinvar measurements can be also limited by the slope (maximum 12%), the lack of a sufficient free space between points, the stability of the measured object or support under a 15 kg horizontal tension.

Systematic errors induced by the mechanical play in the reference sockets must be cancelled by using centring *and* clamping fixtures under the instrument and the attachment head.

5.2. PERFORMANCES, FACTS, RESULTS

Within the range 0.25 to 56 m, the Distinvar is till the most accurate device for length measurements. The resolution of the reading unit is now better than 0.01 mm and the global in-situ accuracy can be as good as 0.03 mm (ISR and ADONE networks). More commonly, the average accuracy is easily kept below 0.1 mm and appears to be 0.05 - 0.06 mm in most cases (Marseille and Munford test-networks, PS and SPS). Even when some problems occur with repetitive measurements, it proves to be very reliable : the overall 27 km circumference of the LEP machine accurately measured with the RF ($\sigma \approx$ 2 mm) differs by only 1 cm from that resulting mainly from invar measurements, i.e. a relative precision of 4.10^{-7}.

Distinvar measurements have a low dependence on external conditions (temperature, draughts).

This instrument has been adopted as a secondary standard by aircraft industries in France (Aerospatiale) and is used for some other applications in geodetic metrology - when the best accuracy is required.

6. KERN MEKOMETER ME 5000

The whole set must consist of the instrument itself, a set of reflectors (at least the standard one), facilities for calibration - against interferometric or Distinvar truth - and for frequency control.

6.1. LIMITATIONS, DRAWBACKS, CARES

Short-range measurements are not possible below 17 m with the standard -instrumental software, or not below 12 m with the optional software. Improving the modulation frequency scanning and the search of minima (locking to an integer number of half-wavelengths), the CERN software allows measurements from 6 m onwards - and even less with one minimum instead of two *[T.W. Copeland-Davis, E. Menant : "The KERN Mekometer ME 5000 and short distance measurements", CERN LEP-SU, 1989-2]* This process is technologically limited within "windows" - between which measurements are not possible, or complicated by a necessary $\lambda/4$ shift of the comer cube.

Beside centring and setting-up cares, attention must be paid to the height and virtual plane of reflexion of the comer cubes when making accurate slope measurements.

Concerning meteorological corrections, one has to remind the non-standard atmosphere in tunnels (due to the dust content) and the unavoidable approximations made for long-range measurements, without intermediate meteo data.

As a consequence, the calibration scheme on outdoor baselines would better be processed according to the multipillar concept - with overlapping measurements and a linear proportional factor *k* as a free parameter, for checking the reliability of meteo data.

6.2. PERFORMANCES, FACTS, RESULTS

The Mekometer ME 5000 is certainly the best EDM instrument - the most accurate, without cyclic errors - but we have not experienced any comparison with the Geomensor (from Comrad). It also allows sloped measurements up to vertical, and this is a great advantage over invar wires.

The optimum accuracy (between 12 m and 50 m) proves to be better than 0.1 mm. Several calibration results show a dispersion of 0.06 mm (1 σ) with respect to interferometric truth, within that range.

It may replace Distinvar in some control networks - according to feasibility, required accuracy, slope. It can be also a useful additional means (e.g. in LEP) for providing redundancy and cross-checking in length measurements, as a complement to Distinvar. In that latter case, one has to optimize the number and length of the overlapping chords to be measured, in order to avoid precision conflicts and local distortions along the traverse.

The results obtained in several control networks around CERN accelerators (PS, LEAR, LEP) or experiments (ALEPH, L3, OPAL) show that the in-situ accuracy tends to be 0.2 mm (1 σ) in the following conditions : distances from 12 m to 106 m, indoor environment, careful measurements with good centring, reiterations (forward and backward), etc.

7. WILD D12000

This phase-measuring EDM instrument proved to be a very good one, and it is worth mentioning in this review.

Given for a nominal accuracy of 1 mm + 1 mm / km, it shows a repetitive pattern of cyclic errors - which can be analytically removed after an appropriate calibration process, thus leaving an optimum accuracy of 0.17 mm (1 σ) around Fourier fitting.

Mounted above a theodolite (which implies corrections with slope...), it allows very short-range measurement - up to contact - and can be very useful for the pre-alignment phases on accelerators or experiments, installation of transfer lines, non-critical distances between components, etc.

In such applications, the field measurements proved to be good to σ £0.5 mm, as in-situ accuracy.

8. WIRE OFF-SET DEVICE (CERN)

The whole set consists of the measuring unit (now automatic), the nylon or Kevlar wire, the attachment heads - with or without a rolling and stretching system - and a very simple calibration stand for adjusting or checking the zero reading.

8.1 LIMITATIONS, DRAWBACKS, CARES

The range of the off-set measurements is limited by the size of the measuring unit : 0 to 58 cm for most of them (screw-drived type) or 1 m for a prototype of another type (linear encoder and CCD array).

The range of the reference line (wire length) is limited by the practical and environmental conditions of the measurements. The maximum length experienced at CERN is 120 m, in the LEP tunnel - stretching Kevlar wires with a tension of about 3.5 kg. For such long wires, cares are to be taken against draughts - if they affect significantly the measurements : increase of random errors (oscillations), appearance of systematic errors (bending effects). In that case - e.g. for some critical measurements in the SPS and LEP networks - the ventilation must be cut and removable plastic doors may be installed in the area.

However, in all other cases, the normal conditions allow good measurements without any of these special cares - like for the SPS or LEP smoothing, alignment of the components, transfer lines, etc.

The mechanical and encoding errors of the carriage can be neglected and the orthogonality is easily obtained, by seeking the minimum reading. For thigh accuracy measurements, corrections for temperature (thermal expansion) may be necessary. In any case, the zero reading must be regularly checked, using a small portable calibration stand.

8.2. PERFORMANCES, FACTS, RESULTS

The resolution of the measuring unit is 0.01 mm and theoptimum accuracy can be as good as 0.02 mm.

The whole off-set measurement process - along accelerators, transfer lines, traverses - is fast, efficient, accurate. In such repetitive sequences of overlapping measurements, it is much faster and significantly more reliable than any of the other means providing curvature (radial) data - i.e. angles with theodolites or long-chord measurements with E.D.M. instruments. This fact has been even once checked in a smoothing scheme, opposing theodolite and off-set measurements.

Unlike radial data resulting from theodolite measurements, the actual accuracy of an off-set measurements is not linearly dependant on distances. The in-situ estimates - issued from many networks with various measurement conditions - are often ranging from 0.03 mm to 0.09 mm, with an average trend at 0.06 mm (1 σ). Of course, long-wire measurements (i.e. 120 m) - when considered separately in the statistical analysis - show a larger dispersion. But they are necessary for a good structuring (redundancy, overlap, stiffness), and their adjustment with the other off-sets made on the same point provides the most reliable solution.

When used for positioning magnets or components, off-set measurements are straightforward and provide rather homogeneous data all along the reference line, as explained above. This is not true with a theodolite, opening a single sight at a given direction reading and aiming at a target (cf. following chapter).

9. ELECTRONIC THEODOLITES

These instruments are well known and we will only give several comments about those used in geodetic metrology, i.e. the WILD T3000 and the KERN E2i. They are both equipped with a panfocal telescope which better preserves the axial stability of sights - in relation with the focussing carriage. But nothing is perfect and if some instrumental errors are technologically eliminated or corrected, some others still remain and must be cancelled by corrective procedures.

The optimum intrinsic accuracy is claimed to be 2 cc - i.e. 0.2 mgon, 0.7 arc second or 3.2 p.rad - but this is not straightforward. The in-situ accuracy is limited by centring and pointing errors (short-range), atmosphere (long range), and is depending on measurement procedures.

Under good targeting and sighting conditions, 2 cc can be approached but hardly obtained - like for instance in the PS primary network (maximum sight length : 106 m) with an eight-rounds procedure. Let us remember that, in the same network and with a similar scheme of measurements, the old WILD T3 could produce 1.2 cc (1 σ) results. Beside this, other CERN examples - with easier conditions - show that a 3 cc (1 arc second) accuracy can be obtained with a four-rounds procedure.

No longer discussing in terms of angular accuracy, these few examples prove that a transverse accuracy of 0.1 mm on a remote target is not an easy goal with a theodolite. Taking for instance the 3 cc (1 arc second) threshold - obtained from a rather heavy and redundant process - our 0.1 mm goal will be lost over 21 m.

We, still use theodolites in control networks when they are efficient, i.e. compatible with the distance and off-set measurements. It depends on the configuration, the links with control points, etc. Their use tends to be kept at a minimum, in that particular case. But this instrument is of course the key one for 3D triangulation of object points, mainly around detectors and experiments : calibration of fiducials, assembly control, final positioning.

Beside that, theodolites are often used for alignment of intermediate components, where a second-order accuracy is sufficient, or for the installation of transfer lines, when off-set measurements are not possible. We have also experienced - as a test - their use for the alignment of main components. Under good conditions, i.e. very short sights, nearly axial operation lines and an accurate measurement of each radial distance, a single theodolite with its appropriate distancemeter could operate a complete positioning with a satisfactory result : 0.1 / 0.2 mm transverse accuracy (radial and vertical), quick setting-up and good control of the process, via a hand-computer.

10. CONCLUSION

An optimum design for the alignment of an accelerator is always a combination of tools, methods, cares - in relation with specifications, experience, technical conditions, processing means, available software, schedule, money, etc.

Nevertheless, the 0.1 mm accuracy threshold is a strange border : few instruments, methods or measurement schemes achieve this, more are just two or three times worse. But, in that case, a good smoothing and refinement scheme may still retrieve the situation and provide the necessary final corrections - with more time spent in this ultimate step before commissioning.

All the above considerations tend to guarantee that a final alignment relative accuracy of 0.1 mm is obtained - as requested - just before the commissioning of the accelerator. This allows machine physicists to tune the many other sensitive parameters of the machine - without caring too much about the small imperfections of its initial alignment.

ACKNOWLEDGMENTS

The authors would like to thank their colleagues M. Hublin and C. Masseur for the useful ideas, results and data provided for this paper.