Calibration of Total Stations Instruments at the ESRF

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Key words: total station, EDM calibration, angle calibration, laser tracker, ADM calibration, standards, certification, ISO 9000

SUMMARY

The European Synchrotron Radiation Facility (ESRF) is an accelerator laboratory located in Grenoble, France which produces high quality X-rays for use by scientists from Europe and around the world. For the ESRF accelerators and beamlines to function correctly, alignment is of critical importance. The ESRF ALignment and GEodesy (ALGE) group is responsible for the installation, control and periodic realignment of the accelerators and experiments. Alignment tolerances are typically less than one millimetre and often in the order of several micrometers over the ESRF storage ring circumference. To help respect these tolerances, the ESRF has developed a 50m-long calibration bench. Since February 2001, this bench has been accredited by COFRAC under the ISO/CEI 17025 standard for the calibration of electromagnetic distancemeters (EDM). This work has recently been extended to the calibration of laser tracker Absolute Distancemeters (ADM's). Considerable effort has also been made to qualify the angle measuring capacity of Robotic Total Stations (RTS) and laser trackers; in particular the angle dependence on distance and the calibration of the angle readings with respect to a very high precision standard. This paper will present and review these activities.

SOMMAIRE

L'Installation Européenne de Rayonnement Synchrotron (ESRF) est un accélérateur de particules situé à Grenoble, France qui produit des rayons X de grande qualité utilisés par des scientifiques européens mais aussi du reste du monde. Pour que les accélérateurs et lignes de lumière de l'ESRF fonctionnent correctement, l'alignement est d'une grande importance. Le groupe ALignement et GEodesie (ALGE) de l'ESRF est responsable de l'installation, du contrôle et du réalignement périodique des accélérateurs et lieux d'expériences. Les tolérances d'alignement sont typiquement infèrieures au millimètre et souvent de l'ordre de quelques micromètres le long de l'anneau de stockage de l'ESRF. Pour arriver à respecter ces tolérances, l'ESRF a développé une base d'étalonnage de 50 mètres de longueur. Depuis février 2001, cette base est accréditée par le COFRAC suivant la norme ISO/CEI 17025 pour l'étalonnage des distancemètres électroniques (AEMD). Ce travail a été récemment étendu à l'étalonnage des distancemètres absolus (ADM) des lasers de poursuite. Un effort considérable a aussi été fourni pour déterminer les capacités angulaires de stations totales robotisées ainsi que de lasers de poursuite ; en particulier, la dépendance des mesures angulaires suivant la distance ainsi que l'étalonnage des lectures angulaires par rapport à un

standard de très grande précision. Ce document va présenter et passer en revue ces différentes activités.

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1. INTRODUCTION

1.1 The European Synchrotron Radiation Facility (ESRF)

Many important questions in modern science and technology cannot be answered without a profound knowledge of the intimate details of the structure of matter. To help in this quest, scientists have developed ever more powerful instruments capable of resolving the structure of matter down to the level of atoms and molecules. Synchrotron radiation sources, such as the ESRF can be compared to "super microscopes". They reveal invaluable information in numerous fields of research.

The ESRF is a European cooperation in science where eighteen nations work together to use the extremely bright beams of light produced by its high-performance storage ring to study a remarkably wide range of materials, from biomolecules to nanomagnets, and ancient Egyptian cosmetics to metallic foams.

1.2 Alignment at the ESRF

For the ESRF accelerators and beamlines to work correctly, alignment is of critical importance. Alignment tolerances are typically less than one millimetre and often in the order of several micrometers over the 844m Storage Ring (SR) circumference.
The ALignment and GEodesy (ALGE) group is responsible for the installation, control and periodic realignment of the ESRF accelerators and experiments. Typical distance and angle residual standard deviations over the approximate 1 km accelerator network are in the order of 0.1 mm and 0.5 arc-second respectively. Absolute error ellipses are inferior to 0.15 mm at the 95% confidence level [1].
To help obtain these results, the ESRF has and continues to develop calibration techniques for high precision Robotic Total Stations (RTS) equipped with Automatic Target Recognition (ATR). This type of instrument is the workhorse for all precision work made at the ESRF. Attention has been paid to both the angle and distance measuring components of these instruments.

1.3 Calibration at the ESRF

The ESRF has a modern bench used for the calibration of electronic distance measuring instruments (EDM's). Since February 2001, this bench has been accredited under the ISO/CEI 17025 standard for the calibration of EDM's by COFRAC, (COmité FRançais pour l'ACcréditation) the French National accreditation body. Presently calibrations can be made between 1.9 and 50 m with an enlarged uncertainty of 0.09 mm + 0.75q; and from 1.9 to 113

m with and enlarged uncertainty of 0.13 mm + 0.7q. Here q is the instrument resolution. It is 0.1 mm in the case of the RTS's used at the ESRF.
This work has recently been extended to the calibration of laser tracker Absolute Distancemeters (ADM's). This is not yet covered by a COFRAC accreditation. Considerable effort has also been made to qualify the angle measuring capacity of Robotic Total Stations (RTS); in particular the angle dependence on distance and the calibration of the angle readings with respect to a very high precision standard. This paper will review these activities.

2. STANDARDS AND CALIBRATION

2.1 Introduction

Few people question that their banking card works at every money machine in the world, but this confidence could not be possible without standards. While driving we stop at hexagonal, not round or square-shaped stop signs. These are just two of the thousands of standards that impact on our everyday lives.

A standard is a rule or requirement that is determined by a consensus opinion of users and that prescribes the accepted and (theoretically) the best criteria for a product, process, test, or procedure. The general benefits of a standard are safety, quality, interchangeability of parts or systems, and consistency across international borders.

ISO (International Organization for Standardization) is a global network that identifies what International Standards are required by business, government and society, develops them in partnership with the sectors that will put them to use, adopts them by transparent procedures based on national input and delivers them to be implemented worldwide.[2]
The GIS/Geomatics profession is concerned by several series of ISO standards. There are the ISO 12858 series concerning ancillary devices for geodetic instruments; the ISO 17123 series field procedures for testing geodetic and surveying instruments; and the ISO 191xx series concerning geographic information. The FIG is very actively involved in standardization. For a good review of the merits of standardization in the field of surveying refer to the FIG web page dedicated to this subject (http://www.fig.net/standards_network/index.htm) [3].

2.2 ISO Standards

Often one thinks that employing standards and quality assurance will lead to more work. However, this is not the case at all. Standards and quality assurance management stripped down to the core are a set of simple common sense rules. Moreover their correct implementation is generally quite straightforward.

Typical goals in implementing a set of standards may be: to become more efficient and profitable; to produce products and services that consistently meet customer requirements; to achieve customer satisfaction; to maintain and/or increase market share; to improve

communication and morale in the organization; to reduce costs and liabilities; and to increase confidence in the production or service system.
The ISO 9000 family of standards represents an international consensus on good management practices aimed at ensuring that the business or organization consistently delivers products or services that meet the customer's quality and applicable regulatory requirements while simultaneously aiming to enhance customer satisfaction, and achieve continual improvement of its performance. These good practices have been distilled into a set of standardized requirements for a *quality management system* (ISO 9001:2000), regardless of what the organization does, its size, or whether it's in the private, or public sector.

Most people tend to think of their professional activity as being unique and so can legitimately ask: how does the ISO 9001:2000 standard accommodate the diversity of a small family run business enterprise on the one hand, and multinational firms, public utilities, and government administrations on the other? The answer lies in the fact that ISO 9001:2000 lays down the requirements that a quality system must meet. However, it does not dictate how they should be met in any particular organization. This leaves great scope and flexibility for implementation in different business sectors and as well as business and national cultures.

2.3 Standards in Surveying

In the modern world, there is and will continue to be pressure upon the GIS/Geomatics community to standardize. These pressures come from within to increase productivity, market share, etc...; and perhaps even more importantly from without, coming from government and clients.
For example in France, Electricité de France (EDF), the French public electrical utilities company insists upon ISO9000 certification for its contractors to perform topographic works [4]. Furthermore they require a COFRAC or equivalent certificate (when possible) for all instruments employed. Once again in France, a new law has been published concerning the precision of all surveys made for French governmental agencies LOADT (loi 95-115 d’orientation pour l’aménagement et le développement du territoire…).[5] This law explicitly forbids using a scaling factor on any measurements made. This is important insofar as the only way to ensure the scale of a survey network is through correct distance measurements.
An ISO 9001:2000 certification is considered proof of a supplier's capability to design, manufacture, and supply quality conforming products and services.

2.4 Calibration and Standards in Surveying

One common sense rule in the ISO 9001:2000 standard (chapter 7.6) concerns the control of monitoring and measuring devices. Specifically it requires that whenever necessary to ensure valid results, measuring equipment shall be calibrated or verified at specified intervals, or prior to use, against measurement standards traceable to international or national measurement standards; where no such standards exist, the basis used for calibration or verification shall be recorded.[6]

Surveyors have traditionally been very concerned about instrumentation, its functionality and performance. At one time instrument testing was second nature. Today, however with modern survey instruments and their associated complexity, there is a tendency, due to among other things the rapidity and simplicity of the measurement process, to assume the measurements are exempt of error.[7]

This of course is entirely false. In fact within our COFRAC EDM calibration activity we have found that somewhere between 2% to 4% of operationally employed field instruments sent to the ESRF for calibration exhibit suspicious behaviour or do not work correctly and have been found to give false measurements of up to several millimetres!

Many efforts have been made in the last few years concerning standards in surveying and in particular the elaboration of the ISO standard 17123 parts 1 through 4. These standards are largely derived from the Deustches Institut Fur Normung (DIN) 18723 norms parts 1 through 8. Instrument manufacturers when making reference to instrument precision often quote these standards.

Each of the ISO 17123 standards prescribes measurement procedures aimed at qualifying an instrument precision and performance. They also serve to verify if it is in correct operating condition. It is noteworthy that these are field test procedures and not an instrument calibration. The standard is entitled *Optics and Optical Instruments - Field Procedures for Testing Geodetic and Surveying Instruments.* These tests should be made on a regular basis. For example field tests can be made: at regular six month intervals; before and after a series of precision measurements; after a long period of inactivity; and after transport.[7]

Field tests should not be confused with an instrument calibration. They only address a part of the ISO 9001:2000 standard: namely the testing of instruments. Calibration links the instrument directly to international standards. Calibration is the act of checking or adjusting by comparison with a standard or reference the accuracy of a measuring instrument. A standard or reference is an instrument or method that will measure more accurately and precisely the desired quantity than the measuring instrument itself. For example a laser interferometer measures more accurate distances (relative displacements) than an EDM.

Calibration is generally performed less often than field tests. Frequently calibrations are made at one to two year intervals. There are many reasons to make a calibration. A calibration can be made if one is suspicious of results issued from an instrument. It might also be made after an instrument repair. An important reason to calibrate an instrument is to improve its precision by employing a calibration model to its measurements. This is the main impetus behind the development of the ESRF calibration bench activities.

A calibration is performed in an accredited laboratory. Laboratory accreditation is awarded from an internationally recognized organization such as France’s COFRAC or the United Kingdom’s UKAS, Germany’s DAR, Italy’s SINAL or Switzerland’s SAS to mention a few of the European national accreditation bodies. An accredited laboratory is required to follow the ISO/CEI 17025 standard *General Requirements for the Competence of Testing and Calibration Laboratories*.

This standard ensures the traceability of the calibration. In the case of the ESRF (COFRAC accreditation number 2-1508) measurements made on the calibration bench can be traced directly to the definition of the metre through the chain BNM (Bureau National de Métrologie or National Metrology Bureau) at the French national level, the BIPM (Bureau International des Poids et Mesure or International Bureau of Weights and Measures) and CIPM (Comité International des Poids et Mesures or International Committee for Weights and Measures) at the international level and ultimately to the CGPM (Conférence Générale des Poids et Mesures or The General Conference on Weights and Measures).

The method employed at the ESRF to calibrate an EDM can be considered a de-facto standard resembling closely the ISO 17123-4 standard. It is similar to methods employed at similar laboratories such as the LNE (Laboratoire National de Métrologie et d'Essais) and ESGT (L'Ecole Supérieure des Géomètres et Topographes) in France; or CERN (Conseil Européen pour la Recherche Nucléaire or the European Organization for Nuclear Research) in Switzerland, and SLAC (Stanford Linear Accelerator Center) in the United States, to mention only a few.

3. ESRF COFRAC ACCREDITED EDM CALIBRATIONS

3.1 Introduction

The ESRF Survey and Alignment group is equipped with a very modern calibration bench. This bench was originally conceived to calibrate invar wires [8]. Quickly it was realised that the bench could also be used for the calibration of EDM equipment. Since February 2001, the ESRF has been accredited by COFRAC to make EDM calibrations. The ESRF is accredited to make two types of calibrations under COFRAC accreditation number 2-1508. The first is for calibrations between 2 and 50m and the second for calibrations between 2 and 113 m.

The ESRF calibration bench is 50 m long. A laser interferometer is installed on a concrete pillar at one end while the theodolite/total station is installed on a concrete pillar at the other end. The interferometer prism and EDM reflector are installed on the motorized carriage that is moved along the bench. This configuration permits the determination of distance errors, and as shall be shown, certain distance dependant angle errors (see section 4.1 below).

The ESRF calibration bench is used to determine the zero and cyclic errors of EDM instrument/reflector pairs. The zero error, or the offset between the distance measured by the instrument and the true distance, is first determined. The instrument prism is then moved along the bench and distances are measured by the EDM. These distances are compared to simultaneously measured interferometer distances. The results are a typical EDM calibration curve are shown in Figure 1. A Fourier series (or other mathematical model) can be used to model this calibration curve. Residuals with respect to a modeled curve are generally less than 0.1 mm. This curve can then be used to correct measured distances and improve survey results.

When these corrected distances are used in the least squares adjustment of the ESRF machine network there is a net amelioration in the distance standard deviation from 0.18 mm to 0.10 mm. Furthermore, the distance residuals become more normally distributed when the calibration model is employed.

3.2 Calibration to 50m

The 50m calibration employs a direct line of sight comparison of measured EDM distances with those measured by an AGILENT 5519A laser interferometer. The enlarged uncertainty is 0.09 mm + 0.75q. Here q is the instrument resolution which is 0.1 mm in the case of the total stations used at the ESRF. In other words the uncertainty in any distance measured between 1.9 and 50 m with respect to the definition of the metre is 0.165 mm. Results for a typical 50m calibration are identical to the first part of the curves shown for the 113m calibration curve shown in Figure 1.

3.3 Calibration to 113m

The 113m calibration employs mirrors to make the comparison of measured EDM distances with those measured by the laser interferometer. First a standard 50m calibration is performed. Second a first series of mirrors are employed which permit comparative overlapping measurements between 32m and 80m. Third the first set of mirrors is moved out of the way and measurements are made with a second set of mirrors located further along the bench. This gives overlapping distance measurements between 65m and 113m. A schematic of this set-up and process is shown in Figure 4 at the end of this paper. The enlarged uncertainty for this calibration is 0.13 mm + 0.75q. The uncertainty in any distance measured between 1.9 and 113 m with respect to the definition of the metre is 0.20 mm. Results for a typical 113m calibration are shown in Figure 1.

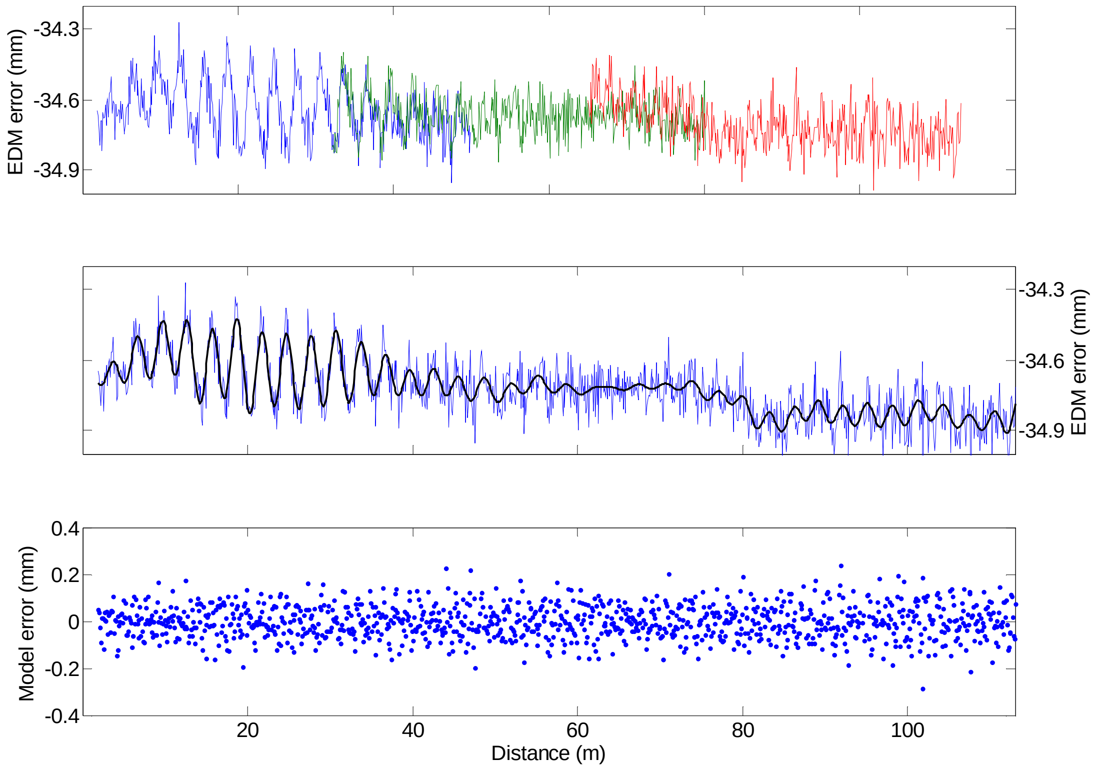

Figure 1 Typical 113m EDM calibration curve. The top graph shows results for the three sections of the calibration: 2m to 50 m, 32m to 80m and 65m to 113m. The middle curve shows the calibration results and a best model. The bottom curve shows residuals with respect to the model curve. The overall standard deviation with respect to the model curve is 0.07 mm.

4. ESRF NON-COFRAC ACCREDITED CALIBRATION ACTIVITIES

4.1 Introduction

The ESRF has an active program concerned with all aspects of survey instrument calibration. The impetus behind these calibration activities is to improve instrument performance. If an instrument has a systematic or repeatable error that can be modeled then the error can be corrected and the measurement results improved. We see this type of model used with EDM's in the middle graph of Figure 1. It is very important to note that this type of model is applied to perfectly functional instruments operating entirely within their manufacturers quoted precision and is used to improve upon the already excellent performance of these instruments.

Two examples of this type of work that has been carried out at the ESRF include RTS and laser tracker angle calibration as a function of distance and Laser Tracker ADM calibration. Several characteristic curves are presented below.

4.2 RTS and Laser Tracker Angle Dependence on Distance Calibration

Results in the ESRF network determination indicated that there were small systematic angle errors at short distances [1, 9]. These errors instigated an investigation into a systematic dependence of angles on distance. The results of some of these tests are shown in Figure 2.

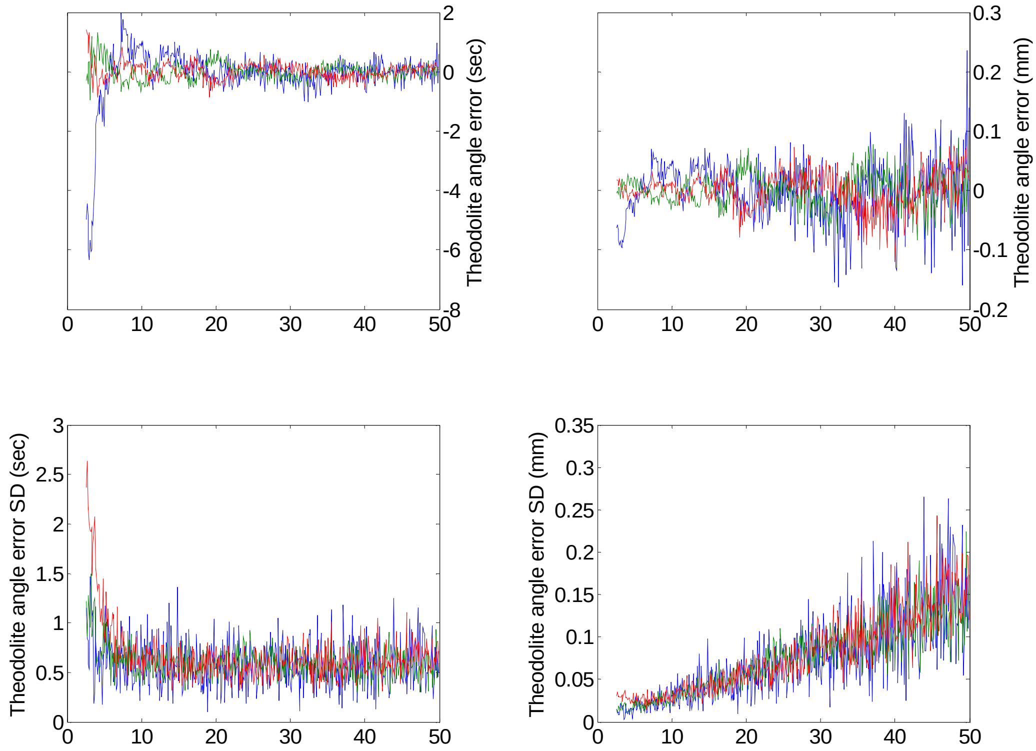

Figure 2 Results of angle dependence on distance for three RTS instruments of the same model type. Each instrument was calibrated 15 times. The top left graph shows the error with respect to the mean angle reading in arc seconds. The top right graph shows the same but reduced to an offset distance (i.e. $y = d \sin \alpha$). The bottom graphs show the standard deviations for the fifteen measurement series in arc **seconds (left) and mm** (right).

Results of angle dependence on distance for three RTS instruments are shown in Figure 2. All of the results are within the manufacturers quoted specifications. Nevertheless, there are very clear systematic tendencies in these curves. Using a model developed for the instruments shown in Figure 2 improves the overall results in the least squares network calculations.
Not shown in figure 2 are very similar results for a laser tracker angle dependence on distance. Once again the systematic errors can be modelled and employed to improve overall results.

4.3 Laser Tracker Absolute Distancemeter Calibration

A second example of instrument calibration which recently started at the ESRF is the calibration of laser tracker ADM instruments. This technique also permits the verification of the laser tracker interferometer. It cannot serve as an interferometer calibration which is typically done using a frequency comparison.

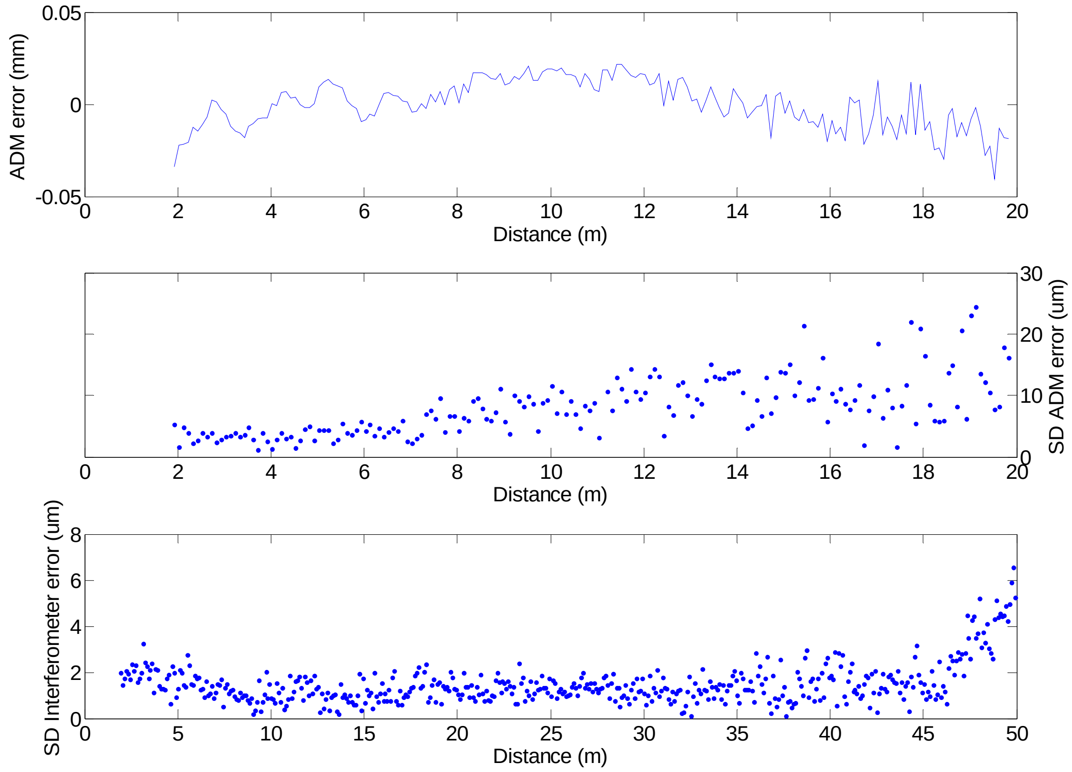

Figure 3 The top graph shows calibration results for a laser tracker ADM as between 1.9m and 20m. The middle graph shows the standard deviation (i.e. repeatability) for the 4 calibration series of laser tracker ADM. The overall standard deviation is 20 um.The bottom graph shows the standard deviation of the laser tracker IFM (interferometer) between 1.9m and 50m for 4 calibration series with the same laser tracker. The overall standard deviation is 2 um.

4.4 Theodolite Angle Calibration

A development program concerning theodolite angle calibration against an angle standard has been instigated at the ESRF. The aim of this program is to characterize theodolite angle errors as close to their normal operational conditions and over the instruments full circle.
The cornerstone of this program is very precise rotation stage coined TMM for Theodolite Measuring Machine. This instrument, in combination with several other instruments and techniques comprises the angle standard and can be employed for the calibration of theodolite angles.

The TMM incorporates two HEIDENHAIN RON 905 angle encoders mounted in juxtaposition to each other. One RON 905 is fixed to the main support assembly and does not move. The second RON 905 is fixed to the main plateau and rotates with it. The two RON 905 encoders are linked through a precision alignment shaft assembly. The shaft and encoders are rotated continuously by a variable speed precision rotation stage. The two RON 905 encoder positions are read out simultaneously and continuously. This configuration permits the elimination of residual encoder errors[10].

To calibrate the Theodolite on the TMM; a target located at approximately 6m is sighted; the TMM is turned through an angle; the theodolite is rotated back through the same angle; the target is re-observed; and the results compared. One of the main advantages of this method is that any angle displacement over 360° can be investigated.

At present this is an ongoing project. Nevertheless, the TMM has been shown to be capable of discriminating angular movements on its main rotation axis better than 0.05 arc-seconds. A system of capacitive probes is used to correct for parasitic movements on the other 5 degrees of freedom of the TMM. They have demonstrated that it is possible to make a simultaneous determination of the three translation and two tilt motions of the TMM with uncertainties of less than 50 nm and 0.1 arc-seconds for translational and rotational movements respectively[10].

5. CONCLUSION

No one can doubt the importance of standards in the modern world. It is remarked that surveyors are becoming more and more involved in the standardization process. This is clearly underpinned by importance standards have taken on in surveying profession and the FIG today. One important aspect of standards is the periodic testing and calibration of survey instruments. The ISO standard 17123 *Optics and Optical Instruments - Field Procedures for Testing Geodetic and Surveying Instruments* is concerned with survey instrument testing.
However, it is important to not confuse instrument testing with calibration. The ESRF calibration bench is accredited by COFRAC under the ISO/CEI 17025 standard to issue calibration certificates for electronic distance measuring instruments in the range of 2 to 50 m and 2 to 113m. The enlarged uncertainty for these calibrations is 0.09 mm + 0.75q for 2m to 50m; and 0.13 mm + 0.7q for 1.9m to 113 m. Here q is the instrument resolution. A system is presently under development to extend these activities to laser tracker absolute distance measuring instruments.
Systematic errors with angle residuals were observed in the least squares calculations issued from the ESRF Storage Ring survey network. This has led us to investigate the possibility of angle error dependence with distance. Several tests have been made on the ESRF calibration bench which shows that there indeed exists such dependence with both theodolites and laser trackers. Other tests of angle errors over the full theodolite circle with respect to a very high precision standard are also under investigation.

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BIOGRAPHICAL NOTES

David Martin is head of the ESRF Alignment and Geodesy Group. He received a MSc in Surveying from the Department of Geomatic Engineering, University College London, England. He spent two years at CERN (European Organization for Nuclear Research), followed by a short time at TRIUMF (Tri-universities Meson Facility) at University of British Columbia, Canada. He has worked for the last sixteen years at the ESRF. He has published a number of papers concerning accelerator alignment, survey instrument calibration and hydrostatic levelling systems.

Gilles Gatta is employed at the ESRF. He received his degree in Applied and Industrial Mathematics from the Université Joseph Fourier, Grenoble France in 1998. He is an active member in the calibration bench accreditation and research program.

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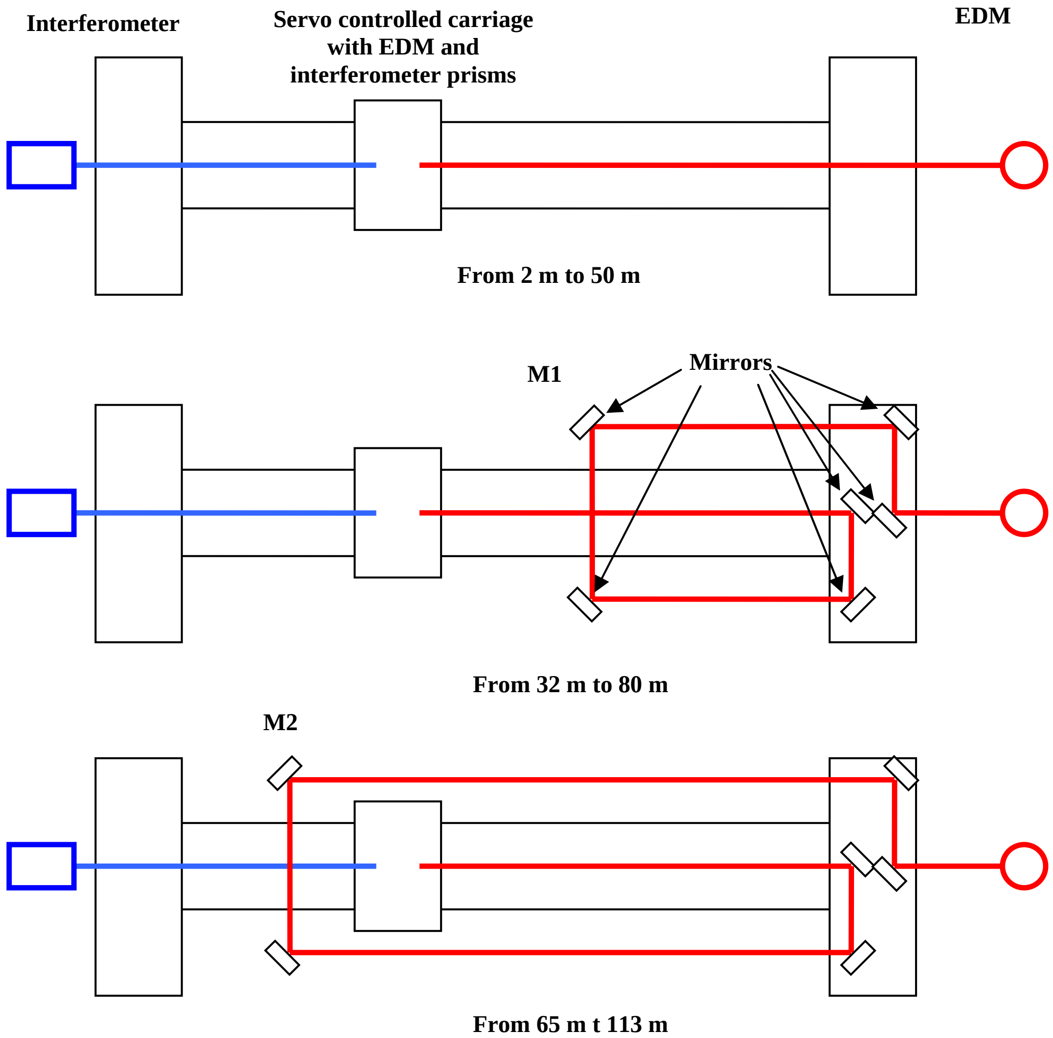

Figure 4 Schematic view of the 1.9m to 50m and 1.9m to 113m EDM calibration technique. For the 113m calibration, first a 50m calibration is performed. Second two mirrors (M1) are used for comparative overlapping measurements between 32m and 80m. Third mirrors M1 are move out of the way and measurements are made between 65m and 113m using mirrors M2.