The ESRF Calibration Bench Activities

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Key words: theodolite, EDM, angle, calibration

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. 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. In part to respect these tolerances, the ESRF has developed a 50m-long calibration bench. Originally conceived to calibrate invar wires, the bench has since been entirely redesigned to meet the demands of electronic distance meter calibration. Since February 2001, the ESRF calibration bench has been accredited by COFRAC under the ISO/CEI 25 and more recently the ISO/CEI 17025 standard for electronic distance measuring instruments. COFRAC is the French National accreditation body. This paper will discuss these activities as well as other developments undertaken in the domain of distance and angle calibration at the ESRF.

L'Installation Européenne de Rayonnement Synchrotron, European Synchrotron Radiation Facility (ESRF), est un accélérateur de particules situé à Grenoble, France, qui produit des rayons X de grande qualité utilisés par des scientifiques aussi bien européens que du monde entier. Le groupe "ALignment and GEodesy" (ALGE) de l'ESRF est responsable de l'installation, du contrôle et des réalignements périodiques des différents accélérateurs et expériences. Les tolérances d'alignement sont typiquement inférieures au millimètre et souvent de l'ordre de quelques micrométres. En partie pour respecter ces tolérances, l'ESRF a développé une base d'étalonnage de 50 m de longueur. Originellement conçue pour étalonner des fils invar, la base a depuis été repensée pour satisfaire la demande d'étalonnage de distancemètres électroniques. Depuis février 2001, l'ESRF est accrédité par le COFRAC au titre de la norme ISO/CEI 25 et récemment ISO/CEI 17025 pour l'étalonnage des appareils électroniques de mesure de distance. Le COFRAC (COmité FRançais pour l'ACcréditation) étant l'unique organisme français d'accréditation. Ce papier présente ces activités ainsi que d'autres développements entrepris dans le domaine de l'étalonnage des distances et des angles à l'ESRF.

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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, which can be compared to "super microscopes", reveal invaluable information in numerous fields of research including physics, medicine, biology, meteorology, geophysics and archeology to mention just a few. There are about 50 synchrotrons in the world being used by an ever-growing number of scientists.

The European Synchrotron Radiation Facility (ESRF) located in Grenoble, France — a joint facility supported and shared by 17 European countries — operates the most powerful synchrotron radiation source in Europe. Each year several thousand researchers travel to Grenoble where they work in a first-class scientific environment to conduct experiments at the cutting edge of modern science.

1.2 Alignment at the ESRF

The ALignment and GEodesy (ALGE) group is responsible for the installation, control and periodic realignment of the ESRF accelerators and experiments. Alignment tolerances are typically less than one millimetre and often in the order of several micrometers.

Until 1997, all planimetric measurements were made with two instruments developed at CERN (European Organization for Nuclear Research), the distinvar and the ecartometer. These two instruments are very precise but are time consuming and require special skills to use correctly. A typical survey of the ESRF Storage Ring would take up to 50 man-days to complete.

Shutdown periods when surveys can be made at the ESRF have become shorter and shorter. During these periods many activities including those of the alignment group must be performed in parallel. The Survey and Alignment group activities are rarely compatible with those of the other groups working in the tunnels. For these reasons a viable alternative to the distinvar/ecartometer pair was pursued.

Today, the ESRF Alignment group uses the Leica TDA5000/5 motorized theodolite with automatic target recognition (ATR) for all high precision survey work. This instrument provides an extremely high measurement rate accompanied by very good precision. Typically, three teams of two people make the full storage ring survey in one 8-hour shift (3200 angle and distance measurements). The standard deviation in the distance and angle measurements are typically 0.10 mm and 4.5 µrad (1 arcsec, 0.27 mgon) respectively. The error ellipse semi-major axes of the 384 points in the network are generally 0.15 mm. To achieve these results, great efforts have been made in the proper calibration procedures for this instrument.

Since February 2001, the ESRF has been accredited under the ISO/CEI 25 and more recently the ISO/CEI[1] 17025 standard for electromagnetic distance measuring instruments (EDM's). This ensures the greatest rigor in the determination of distance measurements made at the ESRF. More recently, attention has been turned to angle calibration.

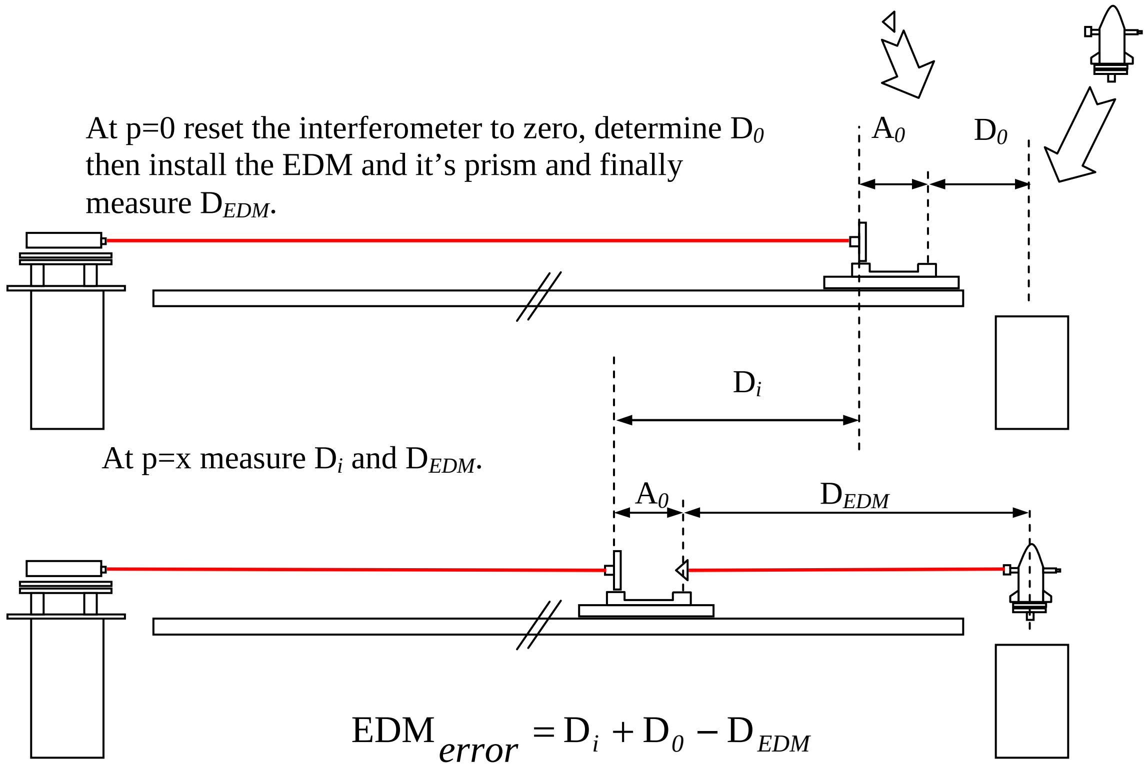


Figure 1 The ESRF calibration bench showing the EDM calibration process.

This paper will discuss calibration at the ESRF. It will also address the question of standards in survey measurements in general.

[1] ISO International Standards Organisation, CEI Commision Electrotechnique Internationale or International Electrotechnical Commision

2. INSTRUMENT CALIBRATION AT THE ESRF

2.1 The ESRF Calibration Bench

The ESRF Survey and Alignment group is equipped with a very modern calibration bench. This bench was originally conceived to calibrate invar wires used in the aforementioned distinvar/ecartometer survey. Quickly it was realised that the bench could also be used for the calibration of EDM equipment.

The 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, and as we shall see, certain distance dependant angle errors. The instrument set-up is shown in figure 1.

2.2 EDM Calibration on the ESRF Calibration bench

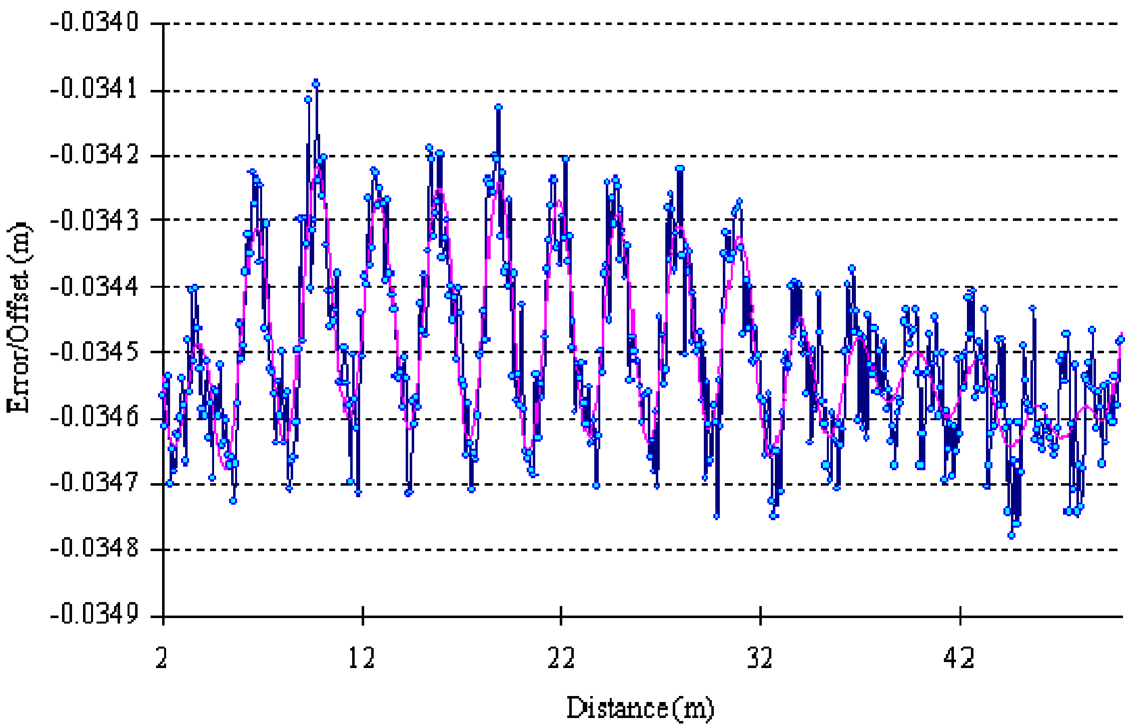


Figure 2 A typical calibration curve with superimposed Fourier series model produced at the ESRF calibration bench.

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 calibration curve as shown in figure 2. A Fourier series can model this calibration curve. Residuals with respect to a modeled curve are generally less than 0.1 mm and typically in the order of 0.07 mm. This curve can then be used to correct measured distances.

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 distance calibration is employed.

2.3 100 m EDM Calibration Development (Not accredited)

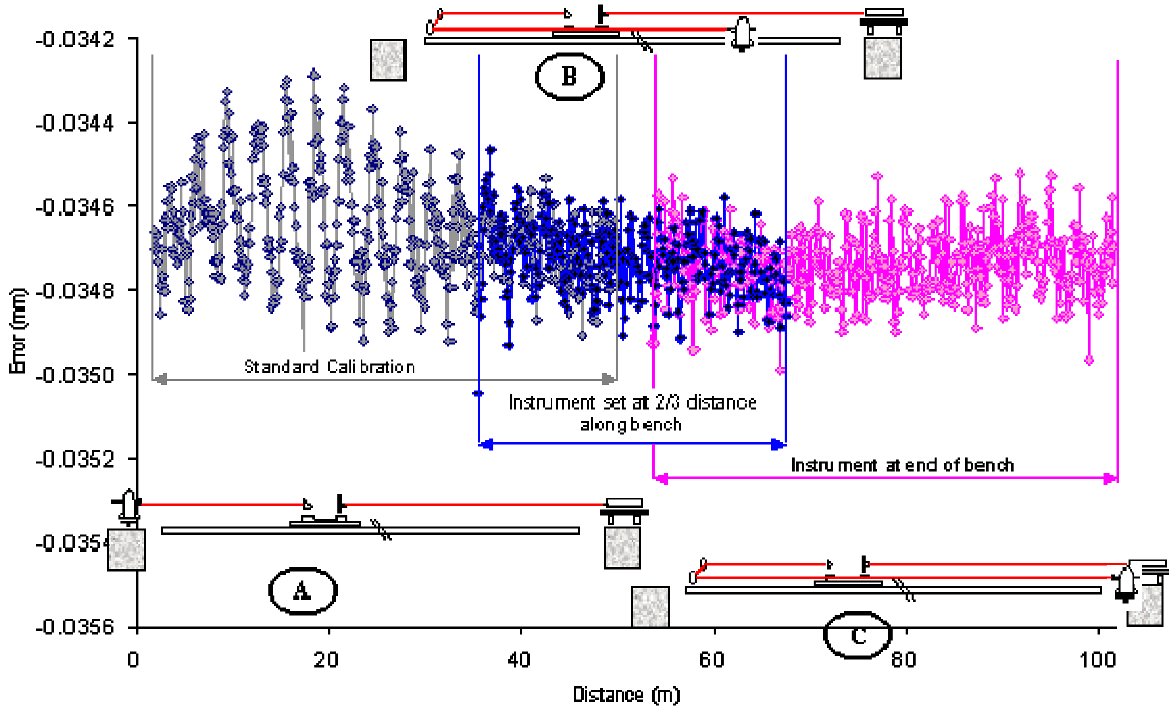


Figure 3 100 m EDM calibration curve showing the set-up for A the standard calibration curve, B the 35 to 68 m calibration curve and C the 50 to 100 m calibration curve.

The ESRF calibration bench is 50 m long. However, efforts are being made to extend its usable length to 100 m using mirrors. At present this is done in a three-step procedure. First the classical calibration is made up to 50 m. Then the instrument is set up at a position approximately 2/3 of the distance along the bench and a calibration is made over the distances 35 to 68m. Finally, the total station is setup at the end of the bench and distances from 50 to 100 m are calibrated. The three calibration curves are superimposed to give the final calibration curve for 2 to 100m. The final curve is show in figure 3. The difference standard deviation between the established calibration and the new 100 m calibration in the overlap zones is better than 0.08 mm. This is equivalent to the difference between two independent calibrations for the same instrument.

This method of three instrument set-ups is cumbersome. However, it is necessary at present to avoid the mirror set-up on the motorized carriage. The calibration bench is not rectified so when the mirrors are installed on the carriage they must be very precisely servo-controlled so as to keep the EDM line of sight centered on the reflector. A second method is under test at the time of the writing of this paper that could permit the installation of the mirrors on the carriage and dispense with the three instrument set-ups.

It is the intention of the ALGE group to extend the present COFRAC accreditation for EDM instruments for distances up to 100 m.

2.4 Catalogue of Errors Associated with Angle Measurement in Theodolites

There are several well-identified errors associated with theodolites. These errors affect all types of instruments from the simplest traditional optical instruments through to modern electronic theodolites.

A theodolite has three axes: the vertical axis (also called primary, main, standing or rotation axis), the trunnion axis (also named secondary, transit or horizontal axis), and the collimation (or telescope or sighting) axis. The vertical and the trunnion axes should be perpendicular. The trunnion and collimation axes should also be perpendicular. The three axes should intersect at the same point.

Theodolites, like all instruments, are susceptible to errors of construction and adjustment. Furthermore the instrument can change and evolve over time. Below is a catalogue of errors associated with theodolites. Averaging the readings at both telescope positions theoretically eliminates the majority of these errors. In modern electronic theodolites most errors are compensated for by onboard software.

2.4.1 Collimation Axis Error

The line of collimation must be perpendicular to the trunnion axis. The axis has to move in a plane at right angles to the trunnion axis while tilting the theodolite telescope. If this condition is not fulfilled, a collimation axis error exists. The collimation axis error is composed of two parts, the horizontal collimation and vertical collimation axes errors. The effect of a vertical deviation of the collimation axis is constant. It is impossible to determine separately a vertical collimation axis error and a zero error of the vertical circle. Thus, the term collimation error refers only to the horizontal deviation of the collimation axis, while the vertical deviation is a component of the zero error of the vertical circle. Averaging the readings at both telescope positions and/or onboard software eliminates the horizontal collimation error.

2.4.2 Zero Error of the Vertical Circle

A zero error of the vertical circle occurs if the reference direction of the theodolite vertical circle (corresponding to the zero point) is not parallel to the vertical axis. This error will cause all zenithal angles to be measured too small or too large according to the sign of the error. Averaging the readings at the two telescope positions and/or onboard software eliminates this error.

2.4.3 Trunnion Axis Error

The deviation of the trunnion axis from a plane perpendicular to the vertical axis is known as the trunnion axis error. The vertical circle will no longer be in a vertical plane and angles will be measured with respect to a false zenith. Averaging the readings at the two telescope positions and/or onboard software eliminates this error.

2.4.4 Vertical Axis Error

The vertical axis error is not an instrumental error, but indicates an incorrect set-up. This occurs, when the vertical axis is not precisely vertical. Modern theodolites with built-in compensators eliminate the influence of a vertical error.

2.4.5 Line of Sight Error

The telescope line of sight of axis has to intersect the trunnion axis. If this condition is not fulfilled, an error is present. Averaging the readings at the two telescope positions and/or onboard software eliminates this error.

2.4.6 Circle Encoder Error

Both the horizontal and the vertical encoders must be in a plane at right angles to the vertical axis and the trunnion axis. Furthermore the center of the horizontal encoder must be aligned with the vertical axis. Similarly, the center of the vertical circle must be aligned with the trunnion axis. If these conditions are not met, an error is introduced. Averaging the readings at the two telescope positions eliminates these errors. Modern electronic theodolites permit a complete scanning of the circle. Two simultaneous readings on the circle shifted through 90° eliminate the error due to the non-perpendicularity of the two circles. The circle scanning system eliminates encoder errors.

2.4.7 Wobble Error

The rotation of the theodolite around the vertical axis causes a wobble error. In relation to the measured object, the inclination of the primary theodolite axis changes for each sighting. For precise angular measures, the wobble error has to be measured simultaneously with the direction measurement, and of course eliminated by adding this above measure to circle reading. Unlike most mechanical errors, observing in two telescope positions cannot eliminate the wobble error. In modern electronic theodolites, the compensator eliminates the wobble error.

2.4.8 Automatic Target Recognition (ATR) Error

The automatic target recognition system usually presents an offset between the center of the prism and the cross hair. The system of ATR transmits an infrared laser beam that is reflected by a prism and received by a built-in CCD camera. The position of the received light spot is computed. This gives two computed offsets that are used to correct the horizontal and vertical angles. Automatic target recognition errors are eliminated by internal software

2.4.9 Focus Error

Theodolites are equipped with telescopes with a continuous range of lens settings to obtain sharp images of close and distant targets. Due to the movement of the internal focusing lens, the geometrical and optical characteristics of the telescope change with respect to the focus setting. For instance, when the focusing lens is moved, different components are changed notably the image scale, the optical distortion, and the collimation axis.

2.4.10 Alidade and Tribrach Error

When the theodolite vertical axis is not aligned with the center of the tribrach axis, a default exists. It is an assembly error and cannot be compensated.

2.5 Angle Error Compensation and Elimination

In modern electronic theodolites and total stations, the systematic mechanical errors are corrected by onboard software. Several constants are determined by procedures defined in the instrument user manual and then stored in the theodolite memory. An internal software program using these constants then adjusts the raw horizontal and vertical circle readings. There is a constant for each error that can be eliminated.

The circle readings in two telescope positions are unnecessary if the theodolite corrects measures by internal software. Nevertheless, the constants should be updated and checked regularly.

Table 1 Compensation constants determined for the instrument software corrections

Error	Leica TDA5005 (µrad)	Wild T3000 (µrad)
Collimation mean ε	17.3	-3.1
Collimation SD σ_ε	4.6	4.9
Trunnion mean τ	15.7	17.3
Trunnion SD σ_τ	17.7	29.7
Vertical circle mean i	-25.1	-17.3
Vertical circle SD σ_i	5.5	11.2

SD=standard deviation

In practice, however there is a residual error associated with the compensation schemes whether by averaging the readings in the two telescope positions or by employing onboard software. A series of tests were made to determine these residual errors with three instruments used at the ESRF. The results for the TDA5000 and TDA5005 are equivalent.

The calibration compensation procedures were effectuated ten times each by four different operators on each of the instruments under stable laboratory conditions. The results are summarized in Table 1. There is no statistical difference between the results of the different operators. However, there is a statistical dispersion for the different correction constants. This dispersion in the correction can be integrated into an incertitude calculation as shown in table 2.

2.6 Angle Calibration Development

Considerable improvement has been made in the distance standard deviation at the ESRF by employing rigorous calibration techniques. Being at the limit of the TDA5000/5 distance measuring capacity, one can only expect improvement in the network precision by increasing the accuracy of the angle measurements. At ESRF, there is a very strong incentive to improve the angle measuring accuracy. One method of improving angle precision is to calibrate the angle encoders as is done at Leica with the Theodolitprüfmaschine (theodolite-testing-machine). Several other methods have been elaborated in the literature for angle calibration and testing.

At the ESRF an angle dependence on distance has been observed[2]. Given the need to improve angle accuracy steps have been taken to model this dependence. This angular dependence has

[2] The manufacturer of this instrument LEICA recommends it be used in ATR mode at distances greater that 6 m. This error concerns principally distances inferior to this limit.

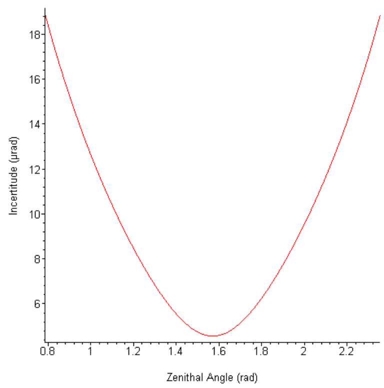
been clearly evidenced by least squares calculations made on the ESRF Storage Ring network. Among other things, the angle residuals issued from the least squares adjustment are not normally well distributed.

Table 2 Incertitude resulting from compensation constants used in electronic theodolites involving horizontal angles measured at different zenithal angles

	Collimation axis	Trunnion axis
Error	$f(\varepsilon) = \mathrm{Arcsin}(\frac{\sin(\varepsilon)}{\sin(z)})$	$f(\tau) = \mathrm{Arcsin}(\frac{\tan(\tau)}{\tan(z)})$
Incertitude	$E_\varepsilon = \left(\frac{\frac{\cos(\varepsilon)}{\sin(z)}}{\sqrt{1-\left(\frac{\sin(\varepsilon)}{\sin(z)}\right)^2}} \right) \times \sigma_\varepsilon$	$E_\tau = \left(\frac{\frac{1}{(\cos(\tau))^2 \times \tan(z)}}{\sqrt{1-\left(\frac{\tan(\tau)}{\tan(z)}\right)^2}} \right) \times \sigma_\tau$

Incertitude at a zenithal angle z $E(z)=\sqrt{E_\varepsilon^2 + E_\tau^2}$.

Incertitude between measures at zenithal angles z_1 and z_2 $=\sqrt{E(z_1)^2 + E(z_2)^2}$



For these reasons, recently a method using the ESRF calibration bench has been developed to determine the angular error of a theodolite as a function of distance.

The instrument set-up is the same as it is with the standard calibration shown in figure 1. The carriage is moved along the bench and observations are made to the instrument reflector in the case of the TDA5005 and a Taylor Hobson Sphere in the case of a T3000. Very precise measurements of the six degrees of freedom of the carriage are made as it is moved along the bench with the laser interferometer and four WPS (wire positioning sensors) installed on the carriage.

The WPS measures horizontal and vertical displacements with capacitive sensors. Measures are made with respect to a stretched wire reference. This instrument has a measurement precision better that 1 µm. It is capable of measuring absolute horizontal and vertical displacements with a precision of 14 µm and 50 µm respectively over the full length of the calibration bench. Local variations can be measured with a much higher precision.

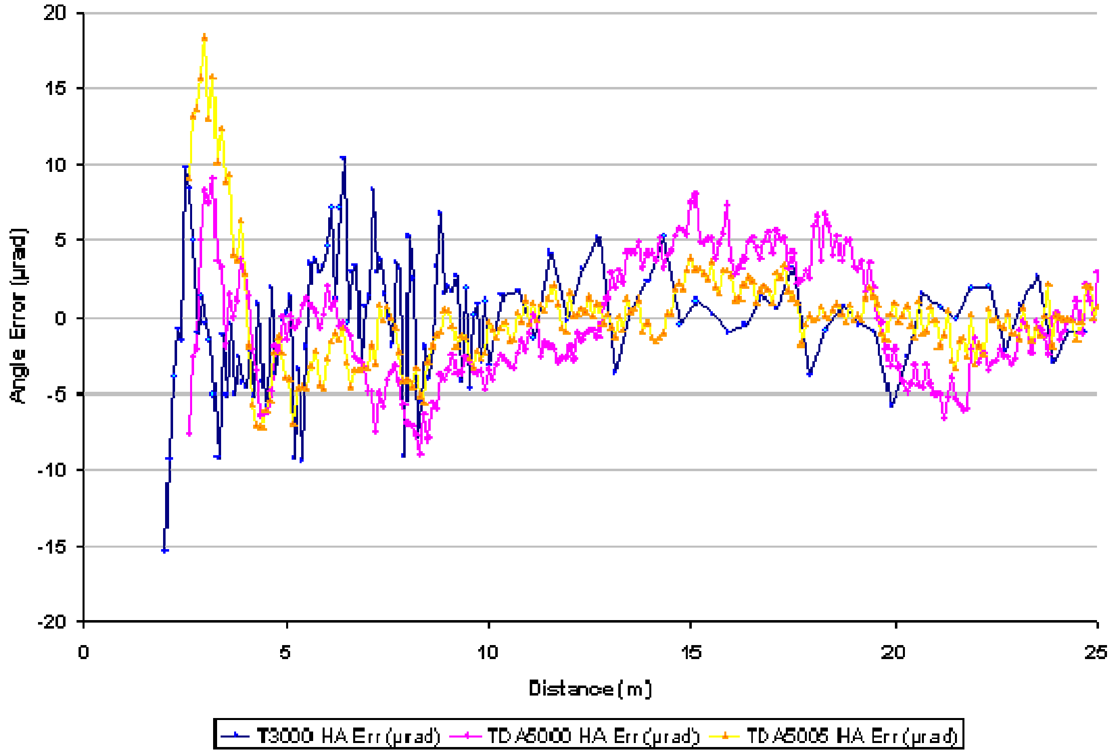


Figure 4 Calibration curves of horizontal angle as a function of distance for a Wild T3000 theodolite, a TDA5000 total station with ATR and a TDA5005 total station with ATR.

Several calibrations have been made. Figures 4 and 5 show horizontal and vertical angle calibration curves as a function of distance for an ESRF T3000, a TDA5000 and a TDA5005. This method appears to work well and will be fully exploited in an effort to improve the angle measurements precision.

3. STANDARDS

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 the world's leading developer of International Standards. It is a global network that identifies and delivers international standards required by business, government and society.

ISO standards are developed with the consensus of manufacturers, vendors, users, consumer groups, testing laboratories, governments, engineering professions and research organizations. They employ industry wide global solutions to satisfy industries and consumers worldwide. International standardization is market-driven and therefore based on voluntary involvement of all interests in the marketplace. ISO is an accepted and established authority for standards.

There is strong pressure upon the GIS/Geomatics profession to standardize. These pressures come in a number of guises. First is the pressure from within to increase personal productivity. More importantly is the pressure from without coming from government and in particular clients. For example in France, Electricité de France (EDF) insists upon ISO9002 certification for its contractors to perform topographic works [2]. Furthermore they require a COFRAC or equivalent certificate (when possible) for all instruments employed. This pressure will only increase over the coming years. It is possible, if not likely, that in order to survive economically in the future, surveyors will be required to standardize. It is entirely appropriate that they employ the ISO standards.

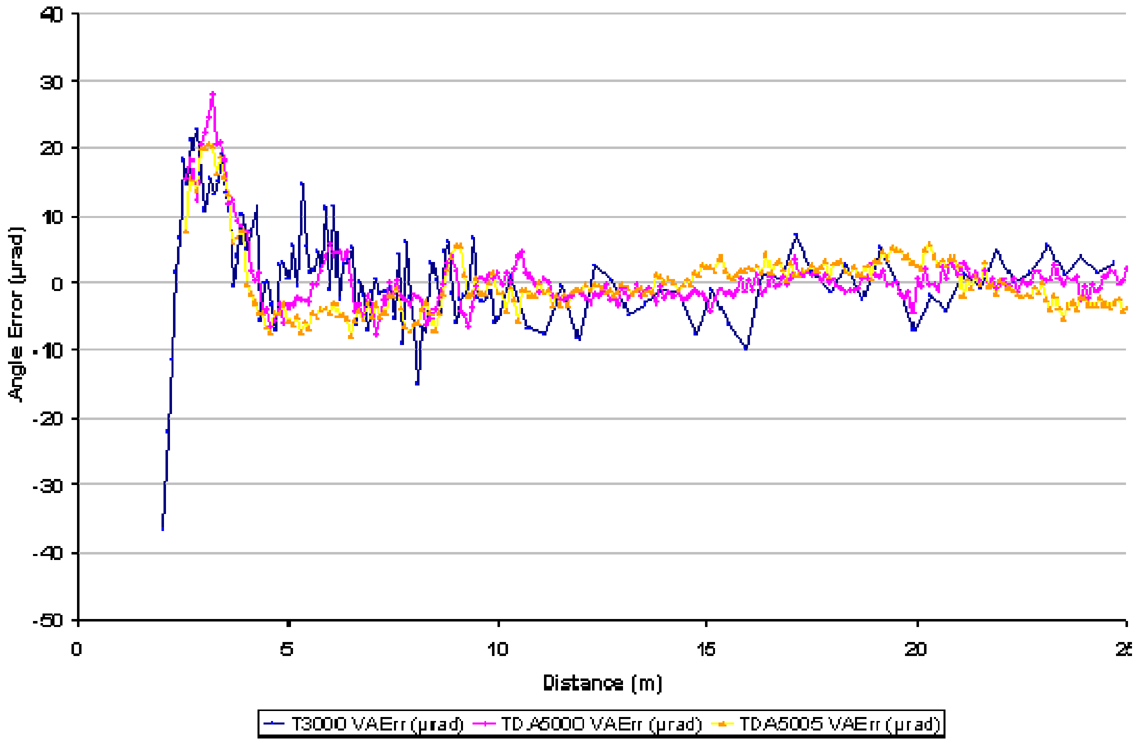


Figure 5 Calibration curves of vertical angle as a function of distance for a Wild T3000 theodolite, a TDA5000 total station with ATR and a TDA5005 total station with ATR.

Surveyors and companies providing Geomatics or GIS services fall under the ISO 9001 2000 standard. ISO 9001 2000 has replaced the ISO 9001 1994 standard. In addition, the ISO 9002 1994, under which Geomatics and GIS services formerly fell; as well as the ISO 9003 1994 quality standards have been discontinued and will become obsolete in December 2003.

Both the ISO 9001 2000 and the discontinued ISO 9002 1994 standards have subsections concerning instrument control, testing and calibration. Chapter 4.11 of the ISO 9002 1994 dwelt with Control of Inspection Equipment which applies to all survey instruments. Chapter 7.6 of the new ISO9001 2000 norm concerns Control of Monitoring Devices.

Many efforts have been made in the last few years concerning standards in surveying. In particular the elaboration of the ISO norms 17123 parts 1 through 4. These norms are largely derived from the Deutches Institut Fur Normung (DIN) 18723 norms parts 1 through 8. Instrument manufacturers when elaborating instrument precision often quote these norms. However, they only address a part of the ISO9001 2000 standard namely the testing of instruments.

Each of the ISO 17123 norms prescribes measurement procedures aimed at qualifying an instrument precision or testing if it is in correct operating condition. It is noteworthy that the norm is called *Optics and Optical Instruments - Field Procedures for Testing Geodetic and Surveying Instruments.* The precision issued from these techniques is typically a standard deviation at the 95% significance level. It is not an instrument calibration.

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.

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 norm *General Requirements for the Competence of Testing and Calibration Laboratories*. As part of this norm, the accredited laboratory must employ a quality assurance system. It must also provide an elaborate estimation of the uncertainty of the measures performed. Furthermore, all instruments used in the calibration process must have calibration certificates from a similarly accredited laboratory.

These requirements ensure 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. It resembles the ISO 17123-4 standard. It is similar to methods employed at similar laboratories such as the LNE in France or CERN in Switzerland to mention only two.

This is not the case with theodolite angles. Although several methods have been elaborated in the past to calibrate theodolite angles, in general they have either been unable to provide a reference significantly superior to the theodolite being calibrated [3] or they calibrate the angle encoders alone [1,8].

Finally, it should be stated that more often than not the EDM is treated as a separate entity to the theodolite. However, the ensemble is considered to be a *Total Station* and should operate as a whole. There is considerable evidence in calculations made at the ESRF that this is not necessarily true and could become the subject of future research.

4. CONCLUSION

I - GRANDEUR LONGUEUR - INSTRUMENTS DE MESURE

Domaine de mesure	Incertitude absolue	Méthodes et moyens mis en oeuvre
Distancemètre electronique Résolution q = 1 et 0,1 mm	± (0,14mm + 0,7.q)	*Comparaison interférométrique* Banc d'étalonnage de 50 mètres Interféromètre laser HP

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. Recently a method has been tested successfully extending this distance up to 100 m. An extension to the present COFRAC accreditation will probably be sought for EDM's in the range of 2 to 100 m.

There is clear evidence of problems with angle residuals 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 and show that there indeed appears to exist such dependence.

It is remarked that surveyors are becoming more and more involved in the standardization process. The GIS/Geomatics profession is concerned by the ISO9001 2000 norm. This norm requires both the testing and calibration of survey instruments. Testing as per the ISO17123 norms pertaining to survey instruments cannot be substituted for instrument calibration.

Although a de-facto norm exists for EDM calibration as is exercised at the ESRF and other similar laboratories, no standard has been widely accepted for theodolite angle calibration. Similarly, the question of *Total Station* calibration should be addressed.

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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 in 1986. 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 twelve years at the ESRF. He has published a number of papers concerning accelerator alignment and hydrostatic leveling systems.

Jean-David Maillefaud has recently received his Survey Engineering degree from ENSAIS, Strasbourg, France. He completed his thesis work concerning theodolite angle calibration at the ESRF. He is presently employed at the ESRF where he is continuing work on theodolite angle calibration and refraction characterization.

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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