Instrument Calibration at the ESRF

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SUMMARY

The European Synchrotron Radiation Facility (ESRF) is an accelerator laboratory located in Grenoble – France. It is a joint facility supported and shared by 18 European countries. The ESRF 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 exciting experiments at the cutting edge of modern science.

The ALignment and GEodesy (ALGE) group is responsible for the installation, control and periodic realignment of the accelerators and experiments at the ESRF. Alignment tolerances are typically less than one millimetre and often in the order of several micrometers over the approximate 1 km accelerator network. Typically, least squares survey network calculations give distance and angle residual standard deviations of 0.1 mm and 0.5 arc second respectively. The semi-major axis of the absolute error ellipses are less than 0.15 mm at the 95% confidence level.

To help obtain these results, the ESRF has and continues to develop calibration techniques for high precision Robotic Total Stations (RTSs) and Laser Trackers (LTs). Electronic Distance Meters (EDM) incorporated into RTSs and Interferometric and Absolute Distance Meters (IFMs and ADMs) used in LT instruments are calibrated on the 50 m long Distancemeter Calibration Bench (DCB). Recently two instrument standards, the Horizontal Circle Comparator (HCC) and the Vertical Circle Comparator (VCC), were developed to calibrate horizontal and vertical angles measured by RTS and LT instruments. These three instrument standards are accredited by COFRAC[1] under the ISO/IEC 17025:2005 *General requirements for the competence of testing and calibration laboratories standard*.[1]

This paper will present these standards and calibration results of LT and RTS instruments calibrated on them.

[1] The HCC and VCC are in the process of final COFRAC accreditation.

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1. INTRODUCTION

Robotic Total Stations (RTSs) [2] and Laser Trackers (LTs) are used extensively in large scale metrology (LSM). They determine three dimensional coordinates of a point by measuring two orthogonal angles (nominally horizontal and vertical) and a distance to a corner cube reflector; typically a spherically mounted retro-reflector (SMR).

LSM covers fields that require very high precision alignment over relatively large areas and volumes. Examples of LSM include particle accelerator alignment and aircraft, ship and car manufacture. [2, 3] The field of particle accelerator alignment is unique in so far as it overlaps both the fields of metrology and traditional surveying and geodesy. Standard measurement precision is typically sub-millimetric over distances ranging between several hundred metres up to nearly 30 km. Extremely specialised techniques and instruments are needed to guarantee that these requirements can be met. [4, 5]

2. ALIGNMENT AND CALIBRATION AT THE ESRF

For the ESRF accelerators and beam lines to work 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. Distance and angle residual standard deviations issued from the 842 metre long accelerator network are in the order of 0.1 mm and 0.5 arc-seconds respectively. Absolute error ellipses are smaller than 0.15 mm at the 95% confidence level. [6]

To help obtain these results, the ESRF has and continues to develop calibration techniques for high precision motorized RTS instruments. This type of instrument is the workhorse for all precision work made at the ESRF. At present, the ESRF Alignment and Geodesy group provides a full calibration suite for the calibration of distances and angles issued from RTSs and LTs. Distances are calibrated on the Distance Meter Calibration Bench (DCB). Horizontal angles are calibrated using the Horizontal Circle Comparator (HCC), and vertical angles are calibrated against the Vertical Angle Comparator (VCC).[7]

[2] Robotic Total Stations are total stations (i.e. a theodolite with an integrated distance meter) equipped with an automatic target recognition (ATR) system. They provide a degree of remote control of the instrument. For example, a survey operator can control the RTS from a distance using a wireless radio device. The operator holds the reflector and controls the total station from the observed point. At the ESRF, the RTS is controlled from a laptop computer to follow a pre-programmed measurements series.

2.1 The Distance Meter Calibration Bench

At the ESRF, distances are calibrated against the 52 m long DCB (refer to **Figure 1**). Since February 2001, this bench has been accredited under ISO/IEC 17025 for the calibration of EDM's by COFRAC, (COmité FRançais pour l'ACcréditation) the French National accreditation body.

An accredited interferometer is installed on a fixed pillar at one end of the bench and the instrument to be measured (RTS or LT) is installed on a fixed pillar or heavy tripod at the other end. The interferometer and instrument reflector are installed on a servo-controlled carriage. A calibration is made by first determining the zero error of the instrument reflector pair and then by moving the servo-carriage along the bench and comparing the displacements measured by the RTS or LT and the interferometer.

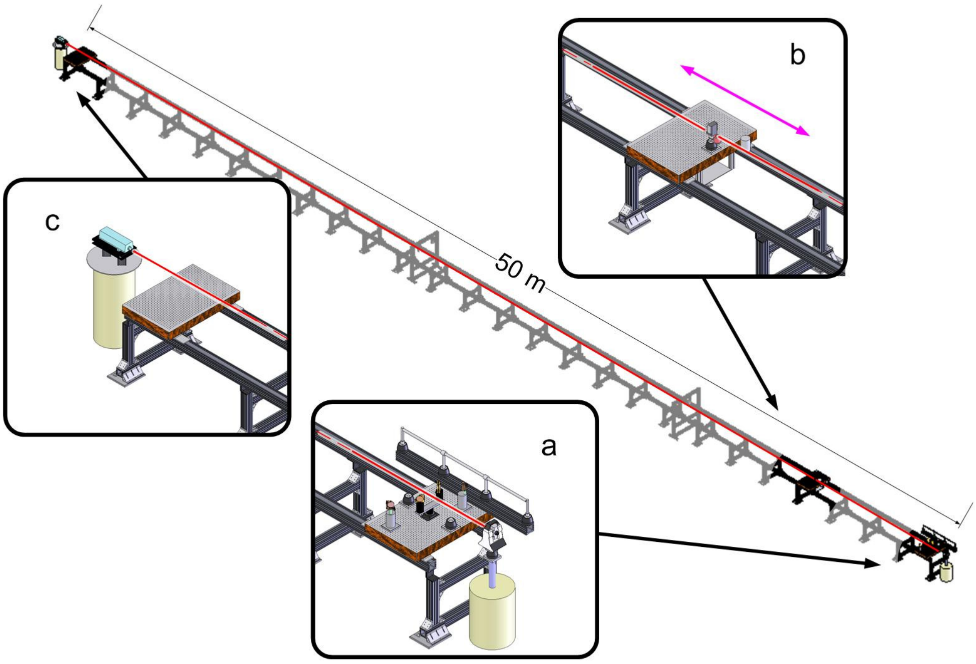


Figure 1 Schematic of the ESRF calibration bench. Zoom a) is the instrument station; zoom b) the servo carriage with the instrument and interferometer reflectors and zoom c) the interferometer station. After the zero error has been determined the servo carriage is moved in 10 cm intervals from 2 m to 50 m to determine the instrument cyclic (bias) error.

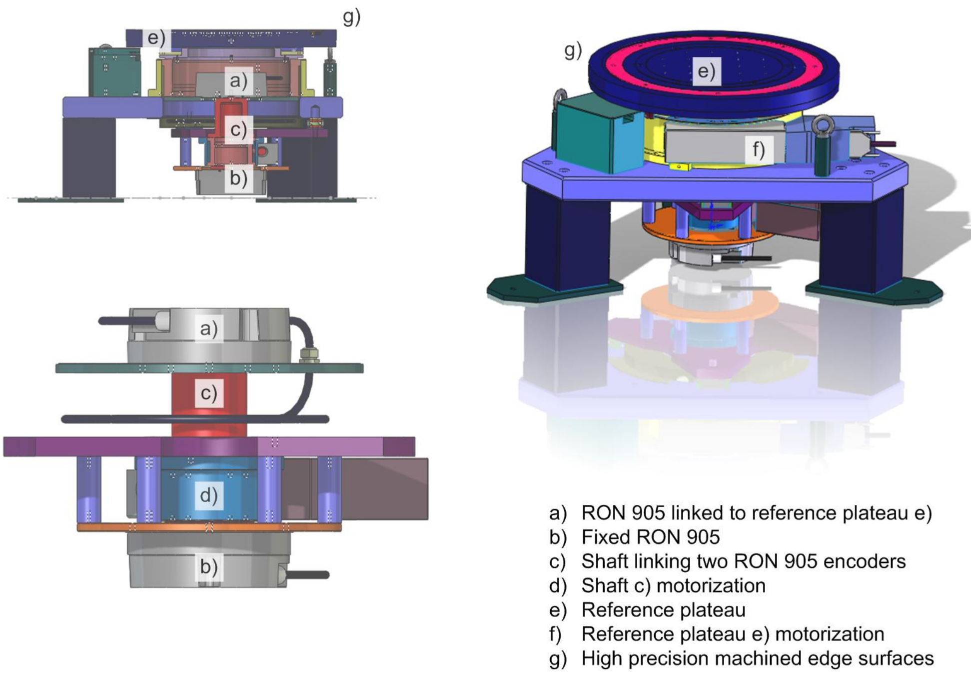
The bench is equipped with an accredited meteorological station which measures temperature, pressure and humidity. Additional temperature sensors are installed at regular intervals along the length of the bench to improve corrections for the variations in refraction along the line of sight. EDM calibrations can be made between 1.9 and 50 m with an expanded uncertainty[3] $(k=2)$ of $0.07\text{ mm} + 0.76q$; and from 1.9 to 113 m with and expanded uncertainty of $0.10\text{ mm} + 0.74q$. Here, q is the instrument resolution. It is 0.1 mm in the case of the

[3] The notion of expanded uncertainty is discussed in the Guide to the Expression of uncertainty in Measurement (GUM).

RTSs used at the ESRF. Therefore the expanded uncertainty for 50 m and 113 m calibrations are 0.15 mm and 0.17 mm respectively. In 2006 the ESRF accreditation was extended to laser trackers. The uncertainty $(k=2)$ for the calibration of LT absolute distance meters (ADMs) and interferometric distance meters (IFMs) over the range of 0.2 m to 48.2 m is 42 µm. [8-11]

2.2 The Horizontal Circle Comparator

At the ESRF, horizontal angles are calibrated against the HCC (refer to **Figure 2**). The HCC is composed of a reference plateau, a rotation table, and an angle acquisition system. The angle acquisition system is referred to as the Linked Encoders Configuration (LEC). The reference plateau is fixed on the rotation table and rotates with it. The LEC is incorporated into the rotation stage.



a) RON 905 linked to reference plateau e)
b) Fixed RON 905
c) Shaft linking two RON 905 encoders
d) Shaft c) motorization
e) Reference plateau
f) Reference plateau e) motorization
g) High precision machined edge surfaces

Figure 2 Schematic of the HCC assembly showing reference plateau e), the rotation table f) and the linked encoders configuration (LEC) a), b), c), and d).

The principal HCC movement is rotation about the main Z axis. However movements with the other five degrees of freedom are unavoidable. Twenty mm wide edges around the circumference of the plateau are high machined surfaces, shown at g) in **Figure 2**, that act as targets for capacitive probes used to determine the plateau x, y and z translation movements and rotations about the X and Y axes. The correction of these unwanted movements is important in the resolution of errors inherent to the HCC.

The RTS and LT horizontal circle calibration procedure consists of installing the instrument on the reference plateau; placing its SMR on a fixed socket located at nominal distance from the instrument and observing horizontal angles. After each angle observation, the HCC is turned through an angle θ_{HCC}; the instrument being calibrated is rotated back through the same nominal angle $-\theta_{RTS}$, and the observation procedure is repeated. The calibration consists of comparing the differences between the HCC angle readings and RTS or LT horizontal circle observations. The procedure is illustrated in **Figure 3**. Any angle displacement over 360 degrees can be investigated.

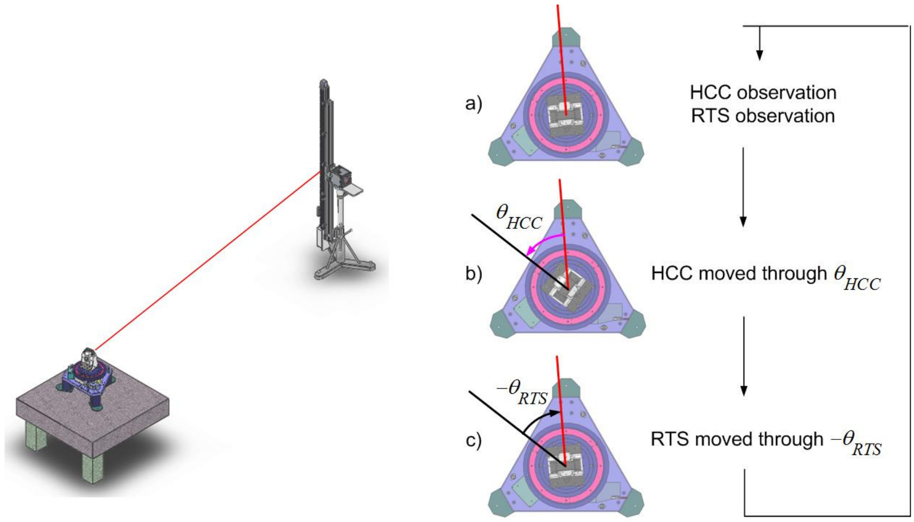


Figure 3 Observation procedure using the HCC.

2.3 The Linked Encoders Configuration

The HCC angle reference system is the LEC (**Figure 2**). The LEC consists of two Heidenhain RON 905 angle encoders mounted in juxtaposition. The body of one RON 905 is fixed to the main support assembly and does not move. The body of the second RON 905 is fixed to the main plateau and rotates with it. The two RON 905 encoders (rotors) are rigidly connected together in a precision alignment shaft assembly. The shaft and encoders are rotated continuously by a high-performance precision rotation stage (shown c) in **Figure 2**). The two RON 905 encoder positions are read out simultaneously and continuously. The LEC is used to reduce the influence of residual RON 905 encoder errors. [12-15] Comparative small angle tests made between the LEC and high precision capacitive probes measuring rotational movements of a 1 m long bar show that the LEC uncertainty remains below 0.05 arc seconds.

The HCC has been examined by COFRAC and is awaiting final accreditation. The expanded uncertainty $(k = 2)$ for HCC calibrations of RTS and LT horizontal circles is 1 arc second.[4]

2.4 The VCC

[4] As part of the accreditation procedure, an inter-laboratory comparison between the ESRF and the French National Metrology Institute, the Laboratoire National d'Essais (LNE) using a 12 sided polygon mirror was made. Values were compared using E_n numbers. The maximum E_n number was determined to be 0.44. Values of $|E_n| < 1$ provide objective evidence that the estimate of uncertainty is consistent with the definition of expanded uncertainty given in the GUM.

The VCC is composed of a motorized 2.5 m long linear motion guide with carriage fixed to a 3 m aluminium structural rail and an interferometer system (refer to **Figure 4**). The interferometer system is positioned at one end of the rail while the motorisation driving the carriage is at the opposite end. Its reflector is placed on the carriage. The full system is placed on a heavy duty adjustable height stand. The VCC system is interfaced to the stand with a system which permits it to be rotated in any orientation. When the VCC, a multipurpose tool, is oriented vertically it can be used to calibrate the vertical circles of RTSs and LTs.

Whereas it is important to examine the horizontal circle over the full 360°, this constraint is generally relaxed with vertical circles. First, no instrument available on the market is capable of observing a target directly over the full 360° vertical circle. For example its base prevents it from reading angles between approximately 150° and 210°. Often taking vertical readings near the zenith (i.e. 0º) is difficult as well. For the most part, the typical working range of the vertical circle of LTs and RTSs is within ±45° of the horizontal (i.e. vertical circle readings of 90°±45° and 270°±45°).

The VCC calibration procedure compares the SMS vertical circle readings with the vertical displacements of its SMR. These vertical displacements are measured by the interferometer system installed on the VCC. The determination of the vertical reference angle requires the simultaneous measurement of the distance between the instrument being calibrated and the VCC. Provided that the instrument (RTS or LT) distance meter is calibrated on the ESRF DCB, these distances are traceable with an assigned uncertainty and coverage factor.

The VCC has been examined by COFRAC and is awaiting final accreditation. The expanded uncertainty $(k = 2)$ for VCC calibrations of RTS and LT horizontal circles is 1.65 arc seconds.

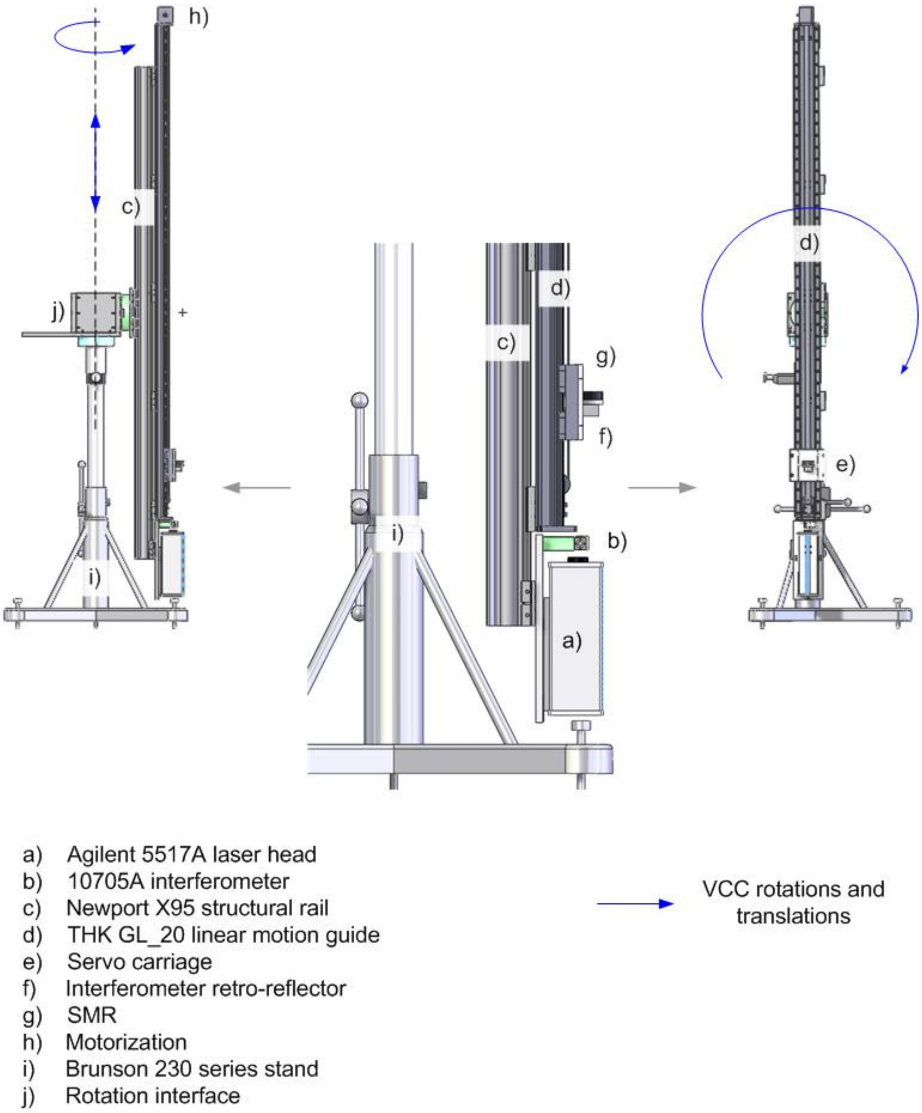


Figure 4 Schematic of the VCC assembly.

3. CALIBRATION RESULTS

Figure 5, **Figure 6** and **Figure 7** show characteristic results of calibrations made using the DCB, the HCC and the VCC respectively. All results show the difference between the distance or angle measured by the instrument being calibrated (i.e. LT or RTS) and the distance or angle determined using the DCB, HCC and VCC standards (i.e $x_{meas} - x_{ref}$). These calibrations ensure that all measurements taken with instruments calibrated at the ESRF are traceable to the metre.[5][16]

[5] Note that the radian, the official SI unit for angle, is a dimensionless unit defined using the metre as $m \cdot m^{-1}$.

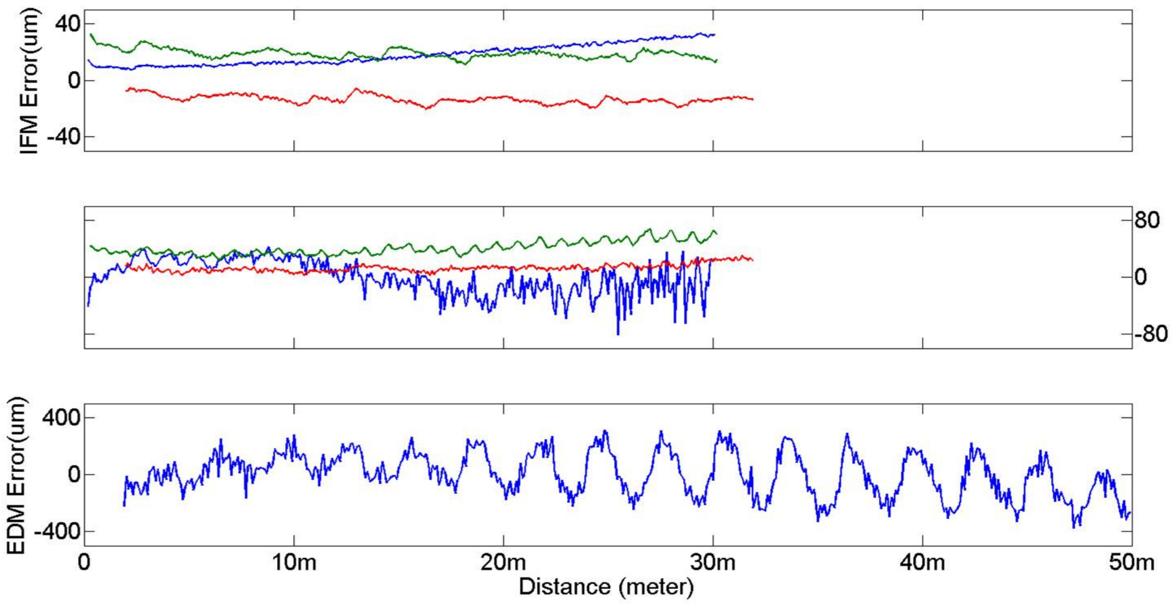


Figure 5 Typical IFM, ADM and EDM distance error curves derived from calibrations made on the ESRF DCB. The ADM and IFM curves are from three different instruments and manufacturers. The expanded uncertainties $(k=2)$ for these calibration curves are 0.042 mm for the IFM and ADM curves and 0.15 mm for the EDM curve.

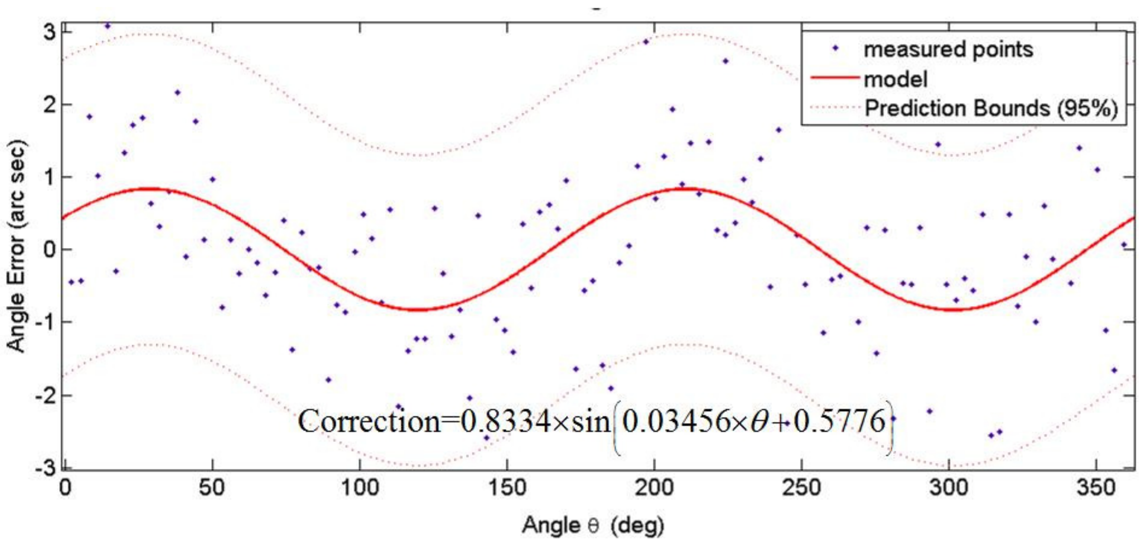


Figure 6 Results of a LT calibration made on the HCC. The heavy red line is a model for the horizontal angles issued from a LT. The RMSE of this model is 1.07 arc seconds. The expanded uncertainty $(k=2)$ for this calibration curve is 1.0 arc seconds

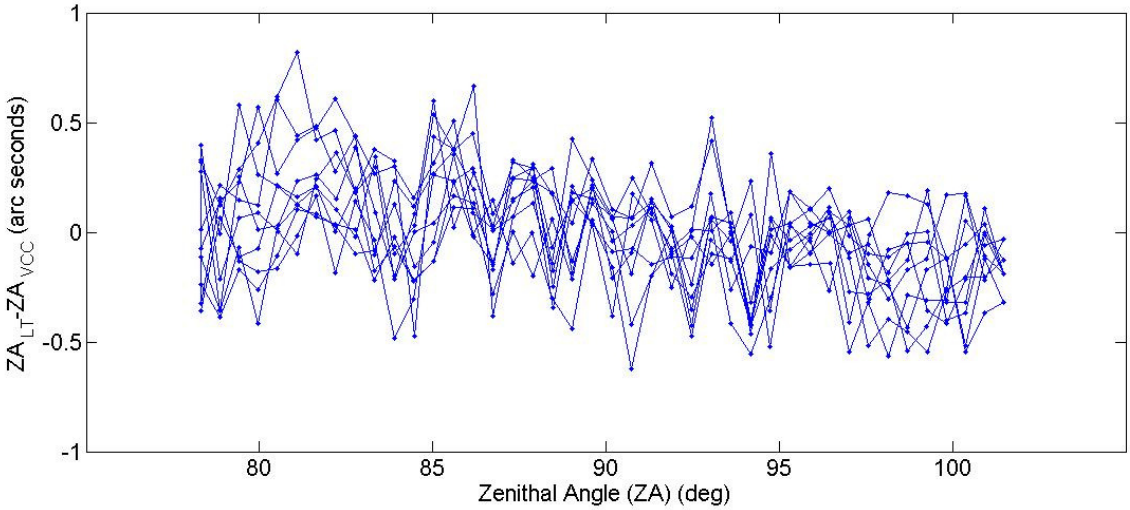


Figure 7 Results of a LT calibration made on the VCC. The expanded uncertainty $(k = 2)$ for this calibration curve is 1.65 arc seconds

4. CONCLUSION

This paper has presented three instrument standards developed at the ESRF used to calibrate the distances, and the vertical and horizontal angle readings issued from RTSs and LTs. The main reason for the development of these standards has been to provide assurance in, and ultimately improve the quality of measurements made on the ESRF survey networks. The improvement of measurement quality is achieved by developing mathematical models through calibration to compensate distance, and horizontal and vertical angle systematic reading errors.

All three of these standards have been, or in the case of the HCC and VCC are in the final process of being accredited under the ISO/CEI 17025:2005 *General Requirements for the Competence of Testing and Calibration Laboratories* standard.[1] This ensures that all measurements issued from instruments calibrated at the ESRF are traceable to the metre.

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BIOGRAPHICAL NOTES

David Martin is head of the ESRF Alignment and Geodesy Group. He holds an MSc in Land Surveying from the Department of Geomatic Engineering, University College London and a PhD in Engineering from the University of Warwick in the United Kingdom. He is the chair of FIG Standards Network and FIG Working Group 5.1 Standards, Quality Assurance and Calibration. He has published a number of papers concerning accelerator alignment, survey instrument calibration and hydrostatic levelling systems.

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