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ANGLE CALIBRATION OF ROBOTIC TOTAL STATIONS AND LASER TRACKERS

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Abstract – This paper presents the recent development of two angle standards used for the calibration of high precision spherical measurement systems. These systems are a family of instruments comprising robotic total stations, and laser trackers. It discusses the Horizontal Circle Comparator and the Vertical Circle Comparator, the way they function and are used, their uncertainty, and results of instrument calibrations.

Keywords : angle, calibration

1. INTRODUCTION

Spherical Measurement Systems (SMS) such as Robotic Total Stations (RTSs) and Laser Trackers (LTs) are used extensively in large scale metrology (LSM). They are able to 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, where LSM is used are particle accelerator alignment and aircraft, ship and car manufacture. [1]

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. Nevertheless, the principles and techniques discussed are applicable to the field of LSM and of interest to metrology in general.

1.1 The European Synchrotron Radiation Facility

The European Synchrotron Radiation Facility (ESRF) located in Grenoble, France is a joint facility supported and shared by 18 European countries. It operates the most powerful synchrotron radiation source in Europe. Approximately 600 people work at the ESRF and more than 6000 researchers come each year to carry out experiments.

Synchrotron radiation sources address many important questions in modern science and technology that 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 archaeology to mention just a few.

1.2 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 850 metre 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. [2]

To help obtain these results, the ESRF has and continues to develop calibration techniques for high precision motorized RTS instruments 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.

The ESRF has a modern distance meter calibration bench (DCB) used for the calibration of electronic distance measuring instruments (EDM’s). Since February 2001, this bench has been accredited under ISO/CEI 17025 for the calibration of EDM’s by COFRAC, (COmité FRançais pour l'ACcréditation) the French National accreditation body.

EDM calibrations can be made between 1.9 and 50 m with an expanded uncertainty (k=2) 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 RTSs used at the ESRF. 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 50 µm. [3-5]

At the limit of distance meter precision, the only way to improve positional uncertainty results is to improve the angle measuring capacity of these instruments. To this end, the ESRF ALGE group has embarked on the design, manufacture and installation of two instruments, the

Horizontal Circle Comparator (HCC) and Vertical Circle Comparator (VCC). They are used for the calibration of the horizontal and vertical circles of RTSs and LTs.

2. THE HCC AND VCC

The focus of this paper is the calibration of the horizontal and vertical angles of SMS instruments. Distance meter calibration is discussed in detail in [3].

Most systematic angle collimation errors can be reduced to second order or negligible levels by employing what is generally referred to as two face measurements. Two face (face left and face right) measurements are a pair of observations to the same fixed point made in the two possible instrument's positions. First a face left observation is made and then the instrument is rotated by 180º about the trunnion-X and vertical-Z axes and a face right observation is made. Errors associated with the ATR system or laser tracking instrumentation are determined by observing the laser spot in different positions of the instruments' CCD or PSD image sensor.

SMS errors are automatically corrected by onboard software using parameters derived from a series of manufacturers' recommended test measurements. Other errors linked to the servo motion of the instrument about its axes (e.g. wobble error) are corrected in real time with onboard inclinometers and compensators.

All errors with parameters that can be derived from self testing and onboard software are corrected to the level of instrument precision. Some residual errors do remain however. These errors have three sources. The first are simply random errors; the second are due to drifts in the parameter values during normal instrument operation and between self testing operations; and the third are uncorrected systematic errors. It is the characterisation of these latter type errors that is of interest here.

2.1 The HCC

Horizontal angles are calibrated against the HCC. 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 system or LEC (refer to Fig. 1). The reference plateau is fixed on the rotation table and rotates with it. The LEC is incorporated into the rotation stage.

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 Fig. 1, 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 in 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 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 Fig. 2. One of the main advantages of this method is that any angle displacement over 360 degrees can be investigated.

Distances between the instrument and SMR are typically in the order of 6 to 7 m. Refraction effects on observed horizontal angles over this distance and under the prevailing laboratory conditions are minimal.

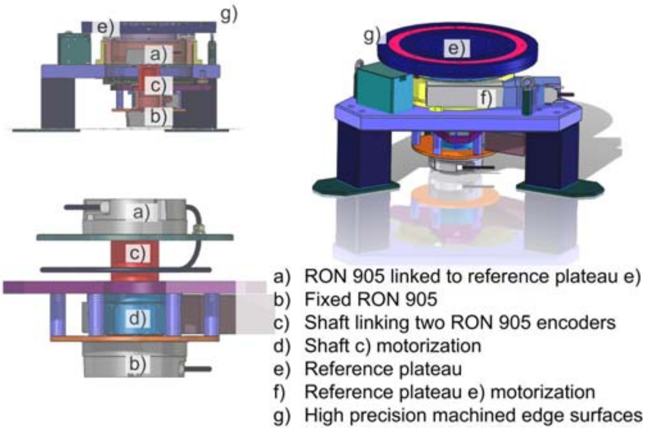

Fig. 1. Schematic of the HCC assembly showing reference plateau e), the rotation table f) and the LEC system a), b), c), and d).

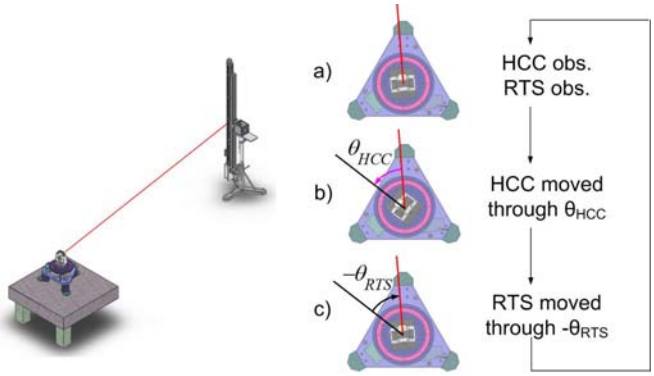

Fig. 2. Observation procedure using the HCC.

2.2 The LEC

The HCC angle reference system is the LEC (Fig. 1). 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 variable speed high-performance precision rotation stage (shown c) in Fig. 1). 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. [6-9]

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 over periods of up to 12 hours. The LEC uncertainty for more typical SMS instrument calibration periods of two hours is 0.04 arc seconds. Two hours is the time required to make an SMS instrument calibration with an angle step resolution of 1º on the HCC using the technique outline in Fig. 2.

2.3 The VCC

The VCC is composed of a motorized 2.5 m long linear motion guide with carriage fixed to a 3 m aluminium structural rail; an inclinometer mounted on the carriage; and an interferometer system. 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.

LTs and RTSs have their zero zenithal angle reading in the vertical direction; the direction of the normal to the gravity field. The direction towards the centre of the earth is at 180°. This orientation is generally only approximate for the 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.

3. UNCERTAINTY CALCULATION

The uncertainty of the HCC and VCC is presented in this section. The HCC uses the comparison of one rotation (i.e. the instrument being calibrated) against another rotation (i.e. the reference system). The VCC uses a sine method of comparison. Only the main uncertainty contributions are presented. Each main contribution can have several sub-contributions.

3.1 The HCC uncertainty

There are four main contributions to the HCC uncertainty. The LEC uncertainty is determined by direct comparison with capacitive probe measurements to a 1 m long bar. The probes are themselves calibrated against an interferometer. The LEC has temporal uncertainty dependence. The experimentally determined uncertainty $U\left(LEC\right)$ in Table 1 corresponds to a calibration period of 4 hours.

The expression of the effect of refraction on survey distance and angle measurements is expressed as C_d and C_α respectively and given in (1). [10-11] The evaluation of the refractivity N and the refractivity gradient $\frac{\delta N}{\delta z}$ over the path r of the observation is discussed in [12]. R is the path length.

$$\begin{aligned} C_d &= \int_{r=0}^{R} N dr \\ C_\alpha &= \frac{1}{R}\int_{r=0}^{R} r\frac{\delta N}{\delta z} dr \end{aligned} \tag{1}$$

The temperature of the angle calibration laboratory is nominally held at 20 Celsius. Temporal and spatial temperature variations are in the order of ±0.1 Celsius and ±0.9 Celsius respectively.

To evaluate the effects of refraction, thermocouples were placed at regular intervals in a three dimensional array; 4 m (length) by 4 m (width) by 3 m (height), within the laboratory volume. Pressure and humidity gradients in this volume were assumed to be insignificant. Refraction corrections were calculated from (1) and the uncertainty $U\left(E_{refraction}\right)$ derived.

Table 1. HCC Type B uncertainties.

Quantity	σ *(arc second)*
LEC $U\left(LEC\right)$	0.044
Refraction $U\left(E_{refraction}\right)$	0.011
HCC collimation correction $U\left(CE_{HCC}\right)$	0.012
HCC induced horizontal angle collimation correction $U\left(CE_{SMS}\right)$	$\frac{0.046}{H}$

For rotational movement about the principal Z axis of the HCC, there are coupled unwanted translations along the x, y and z axes and rotations about the x and y axes. These unwanted motions affect the reference position of the instrument axes and so introduce so-called HCC induced collimation errors CE_{HCC} into the instrument observed horizontal angles. These CE_{HCC} errors must be corrected. The HCC error motions are determined using capacitive probe measurements to machined surfaces on the edge of the HCC plateau (g in Fig. 1). The uncertainty in the determination of these movements and their influence on the instrument horizontal angle observations is given by $U\left(CE_{HCC}\right)$ in Table 1.

A related SMS instrument collimation error (CE_{SMS}) is introduced into the measured horizontal angles due to a combination of the offset of the instrument's principal axis with respect to the HCC Z rotation axis (i.e. the instrument eccentricity), and the variation of tilt along the axis orthogonal to the observed direction. These tilt movements are once again due to the unwanted motion of the HCC plateau as it rotates about its Z axis. The magnitude of this error and its uncertainty $U\left(CE_{SMS}\right)$ depends upon the height of the instrument H above the HCC plateau.

The Type B uncertainties in Table 1 must be combined with the random measurement uncertainty of the process. The calibration of the instrument presented in Fig. 4 indicates a Type A uncertainty of 0.47 arc seconds. The expanded uncertainty following the GUM [13] is given by:

$$\begin{aligned} u_c &= \sqrt{\sum(\text{Type B})^2 + \sum(\text{Type A})^2} \\ &= \sqrt{0.04^2 + 0.01^2 + 0.01^2 + \left(\frac{0.05}{0.41}\right)^2 + 0.47^2} \\ &= 0.49 \text{ arc seconds} \\ \text{U} &= \pm 2\text{u}_\text{c} \\ &= \pm 0.98 \text{ arc seconds} \end{aligned}$$

3.2 The VCC uncertainty

The principle of the calibration is illustrated in Fig. 3. The VCC functional model is given by equation (2). In the model, va' is the measurand. The instrument being calibrated also measures distances d_0 and d_1 and the difference Δha between two horizontal angles measured to the SMR in position 0 and position 1 (Fig. 3) at the same time as the vertical angle is measured. The difference between the horizontal angles Δha represents the inclination of the VCC and instrument with respect to one another in the xz plane. It is always very much less than 1 degree. D_I is the measured interferometer distance between the carriage in SMR position 0 and SMR position 1.

$$va' = \sin^{-1}\left(\frac{z_0 - \Delta z}{d}\right)$$

where

$$\begin{aligned} \left(x_0, y_0, z_0\right) &= d\left(0, \cos\left(va_0\right), \sin\left(va_0\right)\right) \\ \Delta x &= d\cos\left(va\right)\sin\left(\Delta ha\right) \\ \Delta y &= y_0 - d\cos\left(va\right)\cos\left(\Delta ha\right) \\ \Delta z &= \sqrt{D_I^2 - \left(\Delta x^2 + \Delta y^2\right)} \end{aligned} \tag{2}$$

One remarks that the measurand appears on both the left hand (va') and right hand (va) sides of the functional model given by equation (2). This is unusual but can be justified. Its influence is very small. Even with an uncertainty $U\left(va\right)$ in the order of 1000 arc seconds, the contribution to $U\left(va'\right)$ is only 0.1 arc seconds. Typical values for $U\left(va\right)$ are generally less than 1 arc second.

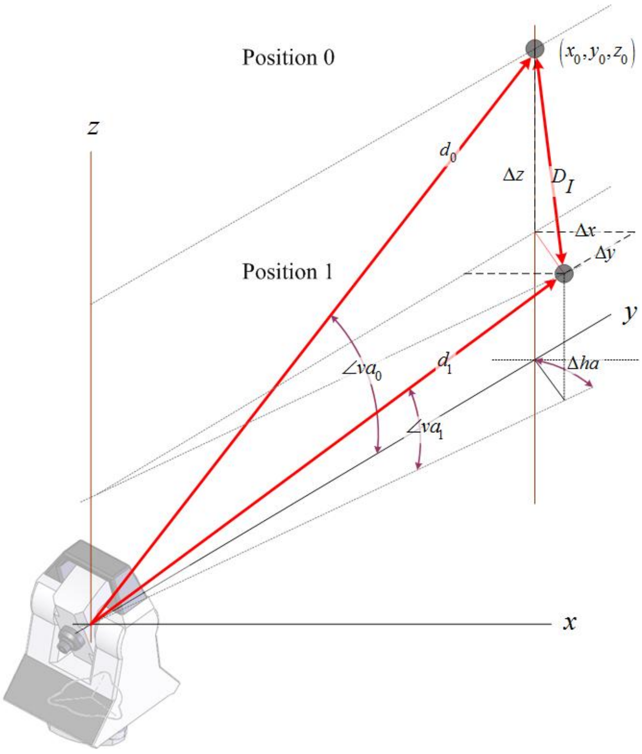

Fig. 3. Measurement scheme of the VCC.

A simple model $va = \sin^{-1}\left(\frac{z_0 - D_I}{d_1}\right)$ in the presence of bias error is first invoked to determine the a-priori uncertainty $U\left(va\right)$. The inclusion of bias error in uncertainty calculations is discussed in [14] where it is argued that increasing the measurement uncertainty to allow for the uncorrected bias still results in an acceptable uncertainty statement. The a-priori value of $U\left(va\right)$ is then used in equation (2) to establish the final uncertainty $U\left(va'\right)$

Table 2. VCC Type B uncertainties.

Quantity	σ
Interferometer distance $U\left(D_I\right)$	10 µm
RTS distances $U\left(d_1\right)$ and $U\left(d_2\right)$	86 µm
LT distances $U\left(d_1\right)$ and $U\left(d_2\right)$	26 µm
RTS $U\left(\Delta ha\right)$	0.7 arcsec
LT $U\left(\Delta ha\right)$	2.8 arcsec
RTS $U\left(\Delta va\right)$	2.0 arcsec
LT $U\left(\Delta va\right)$	2.0 arcsec

The contributions to the VCC uncertainty are given in Table 2. The distance uncertainties for $U(d_1)$ and $U(d_2)$ for LT and RTS instruments are derived from their calibration on the ESRF DCB. [5]

Inserting the various contributions listed in Table 2 into equation (2), along with typical values for the working distance, d, yields the Type B uncertainty of the VCC. It takes essentially the same value, 0.6 arc seconds, for both RTS and LT instruments. The expanded uncertainty following the GUM [13] for the LT instrument with a Type A uncertainty of 0.31 arc seconds (Fig. 5) is given by:

$$\begin{aligned} u(va) &= \sqrt{(\text{Type A})^2 + (\text{Type B})^2} \\ &= \sqrt{0.31^2 + 0.6^2} \\ &= 0.7 \text{ arc seconds} \\ U &= 1.4 \text{ arc seconds } (k=2) \end{aligned}$$

4. EXAMPLE ANGLE CALIBRATIONS USING THE HCC AND VCC

Fig. 4 shows the results of 10 independent calibrations of a RTS instrument made on the HCC. Fig. 5 presents the results of 10 independent calibrations made on the VCC.

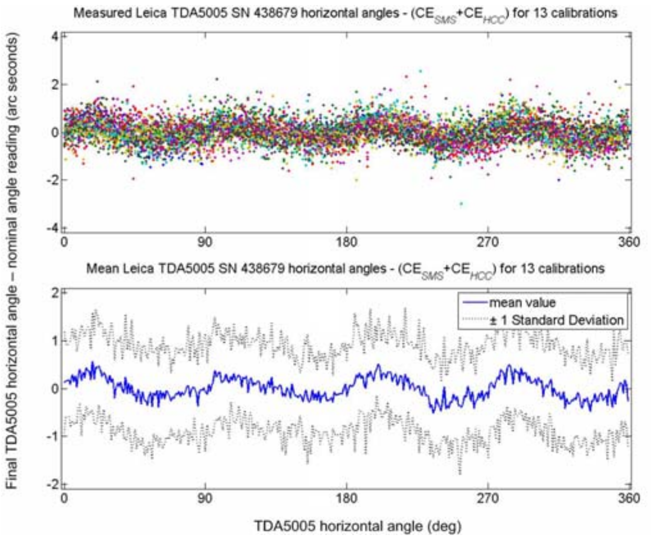

Fig. 4. Results of 10 independent calibrations of an RTS instrument made on the HCC. The bottom curve shows the mean values of the 360 sets of 10 measurements (i.e. one set per degree) and 1 standard deviation error lines

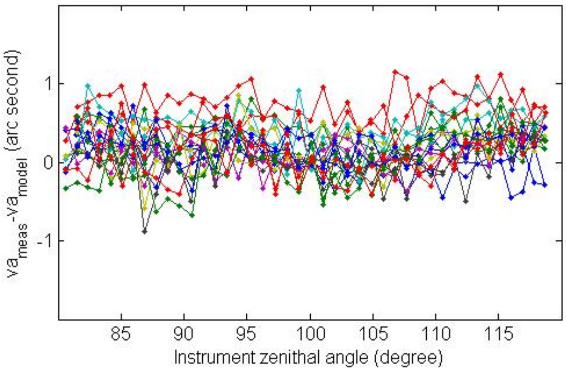

Fig. 5. Results of 10 independent calibrations of an LT instrument made on the VCC.

5. EXAMPLE APPLICATION OF HORIZONTAL ANGLE CALIBRATIONS RESULTS

The ESRF planimetric survey is based on a very regular network composed of 32 cells. The same observations are made in each cell. It is a long and narrow network typical of most particle accelerators.

The direction most sensitive to alignment errors is orthogonal to the travel of the accelerated electron beam. Because of the confines of the tunnel this direction is also the most sensitive to angle measurements. (Fig. 6) At present we are at the limit of the distance precision of the RTS used at the ESRF. Improvement in the survey results can only be gained through improved angle measurements. This can accomplished through calibration.

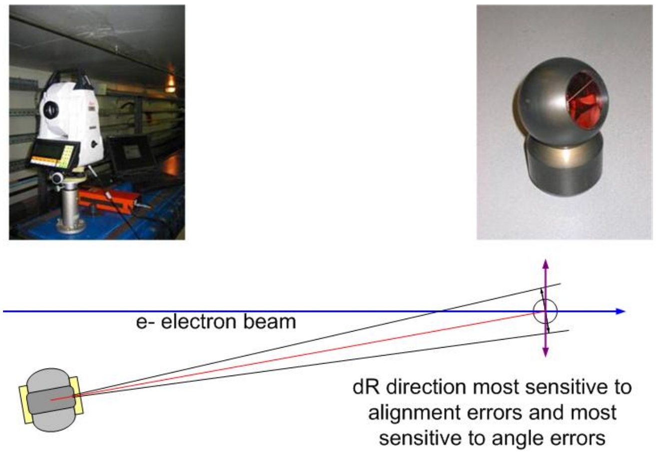

Fig. 6. At the ESRF, as with most accelerators, the directions most sensitive to alignment errors are those orthogonal to the direction of travel of the electron beam which is also the direction most sensitive to angle measurements.

It is instructive to examine what may be gained from using a model derived for the results of the calibration shown in Fig. 4. A study was made on the influence of distance and angle measurements on the ESRF survey network. [15] This study consisted of making a large number of simulations of the radial error issued from the least squares calculations of the ESRF survey network using different distance and angle measurement uncertainties. It was found that an improvement in $U\left(ha\right)$ of 0.1 arc seconds yields an improvement in $U\left(dR\right)$ of 11 µm.

Modelling the calibration results of an ESRF RTS gives the curve shown in Fig. 7. Employing this model improves $U\left(ha\right)$ by roughly 0.1 arc second. This translates to an overall gain of approximately 9% in $U\left(dR\right)$.

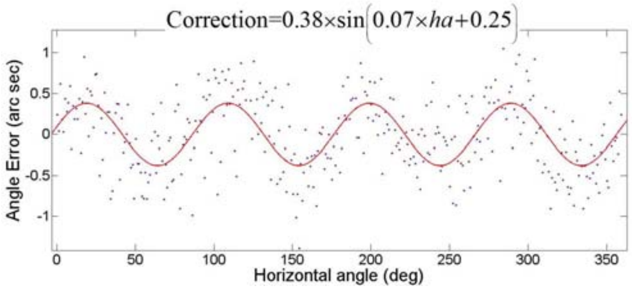

Fig. 7. Calibration curve using the data of Fig. 4.

6. CONCLUSIONS

This paper has presented two new standards developed at the ESRF to calibrate the vertical and horizontal angle readings issued from robotic total stations (RTSs) and laser trackers (LTs). These standards, the horizontal circle comparator (HCC) and the vertical circle comparator (VCC), in combination with the existing distance meter calibration bench (DCB) provide a full calibration suite for spherical measurement systems (SMSs). It is expected that these standards are relevant to metrology beyond the world of ESRF and accelerators. Aerospace and other manufacturing environments might not be quite as extreme in their current demands, but it can be anticipated that greater use of improved LTs and with the types of calibration developed here there may be economically significant opportunities for using long, thin networks to the advantages of factory efficiency (plant layout, lines of sight, etc.).

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