Improved performance of a refurbished photoelectric autocollimator

IOP Publishing Measurement Science and Technology
Meas. Sci. Technol. **XX** (XXXX) XXXXXX https://doi.org/XXXX/XXXX

Improved performance of a refurbished photoelectric autocollimator

Milena Astrua[1] and Marco Pisani[1]

[1] INRIM, Div. Applied metrology and Engineering, strada delle cacce 91 – 10135, Torino, Italy

E-mail: m.astrua@inrim.it

Received xxxxxx
Accepted for publication xxxxxx
Published xxxxxx

Abstract

An old photoelectric Hilger & Watts autocollimator has been modified at INRIM to perform accurate angle measurements on two axes in a range of ± 250”. A CMOS camera was placed in the focus of the autocollimator’s optical system and a software implemented in LabVIEW processes on-line the image of the reticle projected on the camera. The data acquisition is triggerable at a selectable frequency up to some hertz to allow synchronization in critical applications. The autocollimator’s sensitivity was determined through a calibration with respect to the national angle standard. The combined standard uncertainty of the autocollimator calibration results to be equal to 0.035”.

Keywords: autocollimator, image processing, angle measurement

1. Introduction

Autocollimators (ACs) are instruments capable of making very precise and contactless measurements of the rotation angle of reflective surfaces. The resolution of best ACs commercially available is about ten nanoradians, while the accuracy is 50 to 100 nrad (0.01-0.02 arcsec). The measured angle traceability is guaranteed through the calibration of these instruments with respect to angle national standards, as described in [1]. ACs are widely used in many applications, from traditional angle metrology to industrial production. Recently they became fundamental for applications in the field of synchrotron radiation and X-ray free electron laser, since they can accurately measure the topography of beam-shaping optical surfaces [2-7].

Another recent and unusual application of ACs was the calibration of ISA accelerometers (Italian Spring Accelerometer) for ESA BepiColombo mission [8,9]. The calibration consisted in tilting the accelerometer of a known angle α, thus generating an acceleration $a = g_0 \sin\alpha$, i.e. equal to the projection of the gravitational acceleration g_0 on the measurement axis. The angle had to be measured with an accuracy level of 100 ppm by means of an AC aiming at a mirror fixed to the outer shell of the accelerometer. Moreover, the data acquisition need to be synchronized with the reading of the accelerometer in order to perform a calibration based on the spectral analysis of the data. These demanding requirements imply the possibility to trigger the angular measurement at a given rate (e.g. 5 Hz). The latter requirement is not commonly available on commercial ACs. This lead us to develop a new instrument devoted to this specific purpose. Hence, we decided to exploit and modify an old photoelectric Hilger & Watts AC no longer in service. In section 2 we present the main changes made to the instrument to fulfill the requirements. In section 3 we describe the characterization of the new autocollimator and the achieved performances. The uncertainty budget is reported in section 4 and conclusions are drawn in section 5.

2. Modified autocollimator description

The instrument to be modified is a photoelectric autocollimator, model TA5, built by Hilger & Watts in the 60s for the measurement of angles along one axis in an angular interval of 100” with an accuracy of 0.2”. Decades later, the optical part of the instrument, consisting in a reticle located in the focal plane of a series of lenses, a lamp and a beam splitter, is still fully functional and suitable for high resolution angular measurements. On the other hand, the detection system, made by a vibrating slit, a micrometer drum, a photodetector, a reading unit and an eyepiece, is obsolete and need to be upgraded. Therefore, the old detection system has been completely removed. In its place, we put a camera by means of a spacer made of steel in the focus of the optical system. Figure 1 shows a picture of the modified autocollimator.

Fig. 1 Picture of the modified Hilger & Watts autocollimator. In the foreground, the old detection system is visible. Behind it, there is the electric circuit of the IDS camera mounted on a steel cylinder used to keep it at the focal plane of the optical system. On top of the picture, the black knurled part is the shield of the lamp. The lamp is powered with a 4V DC source.

The camera is an IDS model UI-1241LE (based on a Teledyne CMOS sensor 1280x1024 pixels, 5.3 µm pixel pitch), 8 bit and maximum frame rate of 25 frame/sec. It is connected to the PC via an USB cable. A program implemented in LabVIEW acquires and processes on-line the image of the reticle projected by a mirror on the camera, as shown in figure 2, and provides the x and y coordinates of the center of the reticle expressed in pixel. The communication between the camera and LabVIEW is allowed by the library “uEye_LabVIEW.dll”. The image provided by the camera is treated by the software as a matrix of intensity level values, $A_{ij,}$ with i=1,…,1024 and j=1,…,1280. The procedure to evaluate the y coordinate is articulated in the following steps. First of all, the mean value of the intensity level of the whole image, $\bar{A}$, has been calculated. Secondly, a selectable number of columns are averaged to obtain a vector t_i (1024 pixel long). Then, a new vector has been calculated as $y_i = \bar{A}-t_i$. This resulting vector is a bell-shaped distribution, generated by the shadow of the reticle wire. We have found that a Gaussian profile describes the profile satisfactory. Therefore we apply a Gaussian fit to that vector to finally obtain the coordinate of the peak, as shown in fig. 2. The software allows to select the dimension of the area to be averaged to obtain $y_{i,}$ according to the experimental needs. Indeed, if we select a small number of columns to perform the average, the frame rate acquisition will be fast at the expenses of the coordinate precision. For more precise tasks, instead, the whole image could be averaged, yet limiting the acquisition rate to about 2 Hz. The same procedure is applied to extract the coordinate on the other axis. The fitting procedure enables a sub-pixel subdivision of the CMOS matrix and limits the influence of random noise. In order to convert the coordinates expressed in pixel to angular values, an accurate calibration of the system with respect to an angle primary standard is necessary and will be the topic of the next section. Another important feature of the modified autocollimator, is the possibility of a triggered acquisition. Indeed, the data acquisition can be triggered by an external signal sent to the camera at a selectable frequency in order to allow a spectral analysis of the data. The frequency is limited to some Hertz because of the processing time needed by the CPU.

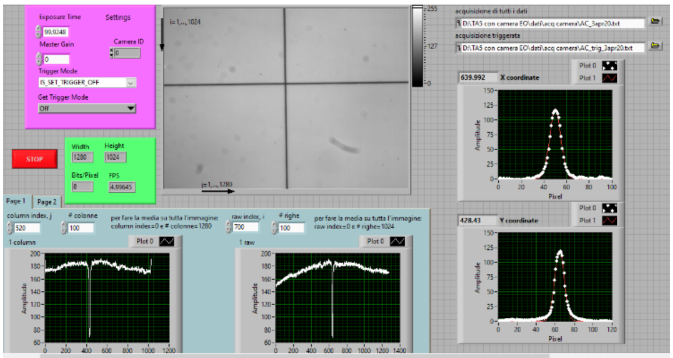

Fig. 2 graphic interface of the software for the image processing. On top left, the panel to select some parameters of the camera acquisition; on bottom left, the plots of intensity of one single raw and column. In the center, the image of the reticle on the camera. On the right, the two Gaussian fits to obtain the x and y coordinate.

3. Autocollimator characterization

The autocollimator was characterized by comparison with INRIM national angle standard REAC (Rotating Encoder Angle Comparator). REAC is based on a high accuracy angular encoder, model ERA 4200, manufactured by Heidenhain, which rotates continuously. The encoder is read by two heads: the first one is fixed to the reference frame while the second one is fixed to the moving table. Therefore, the rotation of the moving table is obtained by measuring the phase difference between the two heads' signals. The accuracy of the system proved to be at the level of hundreds of nanoradians. A detailed description of the facility can be found in [10,11]. The AC is positioned so that its optical axis intersects the rotation axis of the REAC table and aims at a flat mirror placed above the REAC rotating table, as shown in fig. 3. The image of the reticle projected by the mirror on the camera is centered on the y axis of the detector acting on the adjustment screws of the AC.

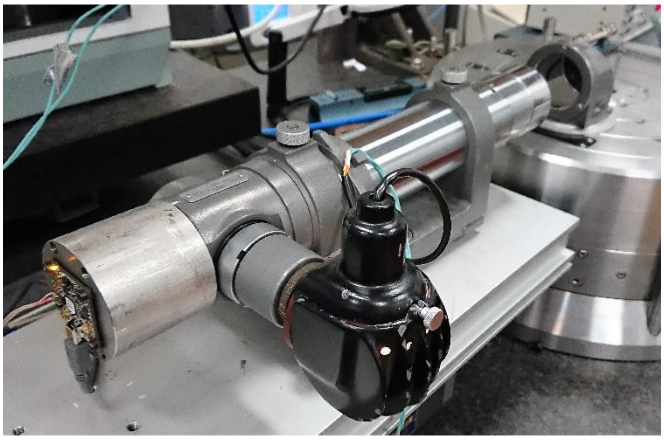

Fig. 3 experimental set-up for the AC calibration

Since REAC generates angles in the horizontal plane, the AC characterization should be performed one axis at a time. Thus the AC body must be oriented along the optical axis in order to avoid errors due to the coupling of the two axes. In the experimental conditions, the maximum error of the vertical coordinate was included within ± 1 pixel, for the entire field of view of the camera along the horizontal axis.

First of all, we have to determine the focal length of the AC lens in order to place the camera in the right position. To this purpose, we initially mount the camera on a slide equipped with a micrometric screw approximately in the focal plane of the lens, so we can move the camera back and forth by fractions of millimeters. In each position of the camera, we measured the AC sensitivity in pixel/arcsec recording the x coordinate for some angular values of the REAC. This measurement was performed for different distances of the mirror as shown in figure 4. The absolute value of the sensitivity depends on the distance between the camera and the AC optical system. Moreover, a slight dependence of the sensitivity on the mirror position, of the order of $2{\cdot}10^{-5}$ pixel/arcsec/mm, has been observed for all the different positions of the camera with respect to the focal plane. Likely this effect could have been reduced by trimming some optics in the body of the AC, but we have chosen to leave the mechanical parts as they are. The final position of the camera was chosen to be the one where the image of the reticle wire was more focused. Although this effect is not so large, it must be taken into account for demanding applications where the distance between the AC and the mirror must be known with an uncertainty of 1 mm, as explained in section 4.

Then, a thorough calibration was carried out in steps of 30" over an angular range of 500". An average sensitivity equal to 1.6922 pixel/arcsec has been obtained. Fig. 5 shows that the AC residuals with respect a straight line with the average sensitivity are all well within ±0.04".

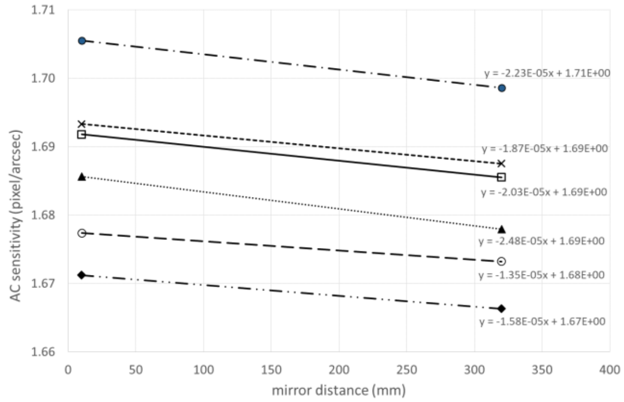

Fig. 4 AC sensitivity versus mirror distance. Each curve represents the sensitivity of the AC in pixel/arcsec for a given position of the camera with respect to the focal plane. We have chosen the distance where the image of the wires is more focused, corresponding to the continous curve. The sensitivity has been measured for different distances of the mirror from the lens. A slight change in sensitivity is observed.

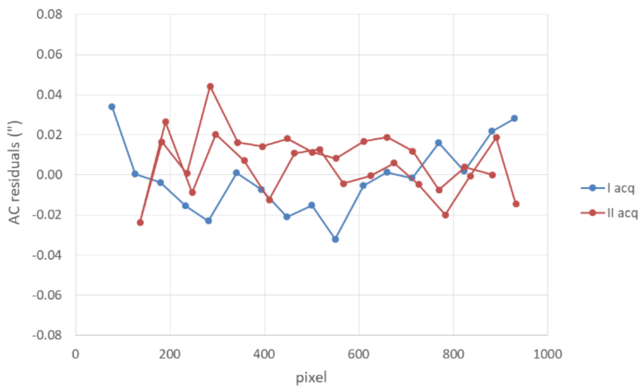

Fig. 5 AC residuals with respect a straight line with sensitivity equal to 1.6922 pixel/arcsec

Finally, to evaluate the stability of the autocollimator in the short and long term, the signals of the AC and REAC were acquired in stationary conditions (still rotating table) for several hours. Figure 6 shows the noise spectral density of the time series of the two instruments. The sampling frequency of REAC is limited to 0.5 Hz, while it is 2 Hz for the AC. The y coordinate of the AC was obtained by averaging the whole image (i.e. $y_i = \frac{1}{1280}\sum_{j=1}^{1280} A_{ij}$), while the x coordinate was obtained by averaging only a limited number of rows (i.e.

$x_j = \frac{1}{100}\sum_{i=1}^{100} A_{ij}$). The effect is clearly visible in the region of higher frequencies. Indeed, for time intervals of the order of few seconds, the y coordinate of the AC demontrates a stability much better than 0.01”, limited by the noise of the camera. Conversely, the x coordinate stability is limited by a white noise due to a poorer statistics. For longer times, of the order of one hour or more, the stability of the AC is limited by the mechanical and thermal drift of the REAC structure and of the AC support, independently on the extension of the averaging area.

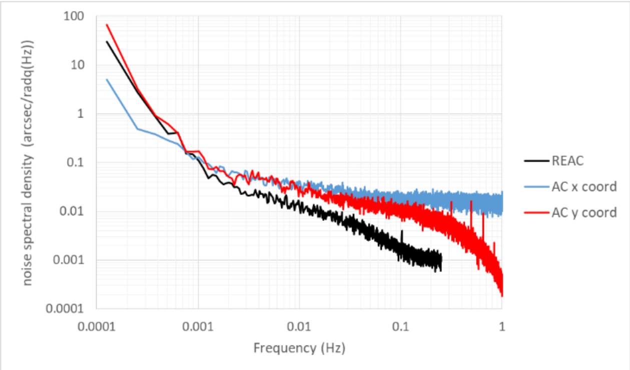

Fig. 6 Noise spectral density of REAC in black, x coordinate of AC in blue and y coordinate in red.

In order to prove the capability of a triggered acquisition, the mirror has to be place on a structure which is able to generate small angles driven by a periodic signal. Hence, the mirror is placed on INRIM nano-angle generator, NAG.

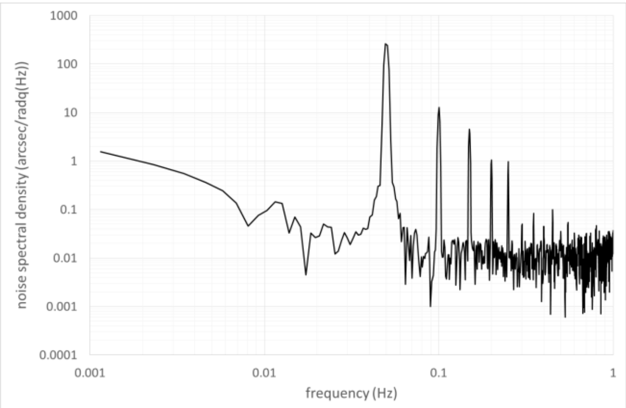

Fig. 7 Spectral analysis of the AC signal when the NAG is moved by a sine wave at 50 mHz generating a tilt 25” wide.

NAG is a sort of sine-bar with an elastic hinge to define the point of rotation ad a pivoting arm moved by a piezoelectric actuator. It can generate angles in a range of 25” with an accuracy of the order of few thousandths of arcsecond. Further details can be found in [12]. Figure 7 shows the spectral analysis of the AC signal when the mirror placed on the NAG is moved by a sinusoidal signal at a frequency of 50 mHz, which generates a tilt 25” wide. The peak corresponding to the fundamental frequency of the excitement signal is well recognized and its amplitude is about 4 order of magnitude bigger than the noise level, thus demonstrating the advantages of the triggered acquisition that allows the synchronization of the exciting source with the AC readings.

4. Uncertainty budget

In this section, the different sources of uncertainty for the autocollimator calibration are discussed and analyzed. The contributions from the reference standard and from the autocollimator have been considered.

4.1 Uncertainty due to the reference angular standard

The uncertainty of REAC is mainly due to noise, repeatability, systematic and interpolation errors. The uncertainty due to noise and repeatability of the REAC measurements has been evaluated equal to 0.02”. The REAC systematic error has been determined equal to ± 0.04” with rectangular distribution in ref [11]. Anyway, a minimum fraction of the entire range of REAC is used for the autocollimator calibration. Hence, in this case, the contribution of the REAC systematic error could be estimated equal to 0.01”. The uncertainty contribution due to the interpolation errors between two encoder graduation lines has been demonstrated to be negligible. Nevertheless, we take it into account and conservatively evaluate its contribution as 0.01”.

4.2 Uncertainty due to the autocollimator

The uncertainty components due to the autocollimator are the repeatability of the AC readings and of the sensitivity coefficient, the stability and errors due to the coupling between x and y axes or to the distance between the AC and the mirror. The autocollimator repeatability has been evaluated equal to 0.01” as the standard deviation of 10 sec measurements. The sensitivity coefficient repeatability has been evaluated about 20 ppm, thus contributing to the autocollimator uncertainty with 0.01”. Another important contribution to the measurement uncertainty is the stability. According to the noise spectral density plot of fig. 6, the autocollimator stability can be estimated equal to 0.02” for measurement carried out in a time interval of about 1 min. As explained in previous section, the coupling between the two autocollimator’s axes has been minimized to a level of $2{\cdot}10^{-3}$ (i.e. ± 1 pixel over 1000 pixel range). Hence, the cosine error due to this misalignment leads to a relative uncertainty of few ppm and can be neglected. Finally, also the uncertainty contribution due to the distance between the AC and the mirror is negligible. Indeed, if we assume an uncertainty of 1 mm on the measurement of the distance between the AC and the mirror, the uncertainty of AC sensitivity becomes about 10 ppm.

4.3 Standard uncertainty of the AC calibration

Eventually, combining all the different contributions, a standard uncertainty for the calibration of the AC calibration equal to 0.035" has been achieved. If we consider the entire range of the autocollimator as 500", the relative standard uncertainty of the AC calibration amounts to 70 ppm, which is a performance comparable to the accuracy of the best autocollimators currently on the market.

5. Conclusions

An old photoelectric AC manufactured by Hilger & Watts has been modified and upgraded at INRIM to perform accurate angle measurements on two axes in a range of ± 250". A CMOS camera was placed in the focus of the autocollimator's optical system and a software implemented in LabVIEW processes on-line the image of the reticle projected by a mirror on the camera. The mirror's tilt is converted in angular values through a calibration with respect to the national angle standard. The data acquisition can be triggered at a selectable frequency up to several hertz to allow synchronization with integrated acquisition systems in dynamic applications. Several tests have been performed to characterize the system. The combined standard uncertainty of the autocollimator calibration results to be equal to 0.035". The instrument described here has been developed to fulfill a special calibration need, but the same principle can be used to adapt any kind of similar old AC to a novel and efficient measurement instrument with a minimum effort. Also the camera can be changed either to increase the resolution, or the measurement speed or the measurement field. Future development will be devoted to enhance the frame rate of the triggered acquisition by improving the software efficiency to reduce the processing time. Finally, we plan to adopt the shearing technique [13,14] to investigate the potential errors of the instrument for small (sub pixel) angular intervals.

Acknowledgements

The authors would like to thank Emanuele Audrito for his valuable help in mechanical realizations.

References

[1] EURAMET Calibration Guide No. 22 Version 1.0 (07/2017) "Guidelines on the Calibration of Autocollimators"
[2] Geckeler R et al. "Use and traceable calibration of autocollimators for ultra-precise measuremenmt of slope and topography", Proc. SPIE **4401**, 184-195 (2001)
[3] Geckeler R et al. "Autocollimators for deflectometry: current status and future progress" Nucl. Instr. Methods Vol 616, 2-3, (2010), 140-146
[4] Geckeler R et al. "Aperture alignement in autocollimator-based deflectometric profilometers" Rev. Sci. Instrum. 87, 051906 (2016)
[5] Qian J et al. "Performance of the APS optical slope measuring system" Nucl. Instrum. Methods Phys. Res., Sect. A **710**, 48-51 (2013)
[6] Yashchuk V et al. "High precision tilt stage as a key element to a universal test mirror for characterization and calibration of slope measuring instruments" Rev Sci Instr 87, 051904 (2016)
[7] Yashchuk V et al. "Sub-microradian surface slope metrology with the ALS development long trace profiler" Nucl. Instrum. Methods Phys. Res., Sect. A **616**, 212-223 (2010)
[8] Pisani M et al. "Characterization of ISA - BepiColombo internal calibration source" 2016 IEEE Metrology for Aerospace (MetroAeroSpace), Florence, 2016, pp. 495-499.
[9] Pisani M et al. "On-ground actuator calibration for ISA — BepiColombo," 2015 IEEE Metrology for Aerospace (MetroAeroSpace), Benevento, 2015, pp. 312-317.
[10] Pisani M and Astrua M "Towards the realization of the new INRIM angle comparator" Proc of the 13th Euspen International Conference – Berlin – May 2013
[11] Pisani M and Astrua M "The new INRIM rotating encoder angle comparator (REAC)" Meas. Sci. Technol. 28 (2017) 045008
[12] Astrua M and Pisani M "The new INRIM nanoangle generator" 2009 *Metrologia* **46** 674
[13] Geckeler R and Just A "A shering-based method for the simultaneous calibration of angle measuring devices" *Meas. Sci. Technol.* 25 (2014) 105009
[14] Yandayan T et al "Application of advanced shearing techniques to the calibration of autocollimators with small angle generators and investigation of error sources" Rev. Sci. Instrum. **87**, 051903 (2016)