EURAMET project 1528
Pilot study
Calibration of Angle Encoder

Technical protocol

(rev1 – August 2024)

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Turin, 30 August 2024

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1 Document control

Version Draft A1 Issued on 30 August 2024;

2 Introduction

The metrological equivalence of national measurement standards and of calibration certificates issued by national metrology institutes is established by a set of key and supplementary comparisons chosen and organized by the Consultative Committees of the CIPM or by the regional metrology organizations (RMOs) in collaboration with the Consultative Committees.

At its meeting in October 2020, the EURAMET Technical Committee for Length, EURAMET TC-L, decided upon a pilot study for a comparison on angle encoders with INRIM as the pilot laboratory. The comparison was registered on the EURAMET website in June 2021, artefact circulation will start in September 2024 and will be completed in August 2025.

Angular encoders provide an electrical signal proportional to the angular position of a shaft and are key components of lots of instruments where accurate angular measurements are needed in different application fields like industry, science and medical equipment.

These devices are often integrated into rotary tables: thus, in that case the whole measuring machine has to be calibrated with respect to a reference angle standard by means of standard procedures. Viceversa, the calibration of individual angle encoder is much more tricky, since the mechanical coupling between the encoder and the reference standard is extremely delicate and can heavily affect the achievable calibration accuracy. Nowadays, only few NMIs in the world have a CMC for the calibration of angle encoders.

Hence, the increasing importance of these instruments and the need for their traceability support the motivation for this comparison.

The procedures outlined in this document cover the technical procedure to be followed during the measurements. The procedures are principally intended to allow for a clear description of the required measurements, handling and transportation of the circulating standards and to complete the comparison in the time scale provided for. This technical protocol was prepared following the layout principles of the documents for previous comparisons.

A goal of the CCL key comparisons for topics in dimensional metrology is to demonstrate the equivalence of routine calibration services offered by NMIs to clients, as listed in Appendix C of the Mutual Recognition Agreement (MRA). To this end, participants in this comparison agree to use the same apparatus and methods as routinely applied to client artefacts.

By their declared intention to participate in this key comparison, laboratories accept the general instructions and to strictly follow the technical protocol of this document. It is very important that participating NMIs perform their measurements during assigned dates. Participants should keep in mind that the allocated time period is not only for measurements, but for transportation and customs clearance as well. Once the protocol and list of participants has been agreed, no change to the protocol or list of participants may be made without prior agreement of all participants.

3 Organization

3.1 Participants

Participants are listed in Table 1.

Table 1. List of participant laboratories and their contacts.

RMO	Laboratory Code	Contact person, Laboratory	Phone, email
EURAMET	INRIM (Pilot)	Milena Astrua, Marco Pisani INRiM, Istituto Nazionale di Ricerca Metrologica, Div. Applied Metrology and Engineering strada delle Cacce, 91 - 10135 - Torino - Italy	Phone: +39 011 3919 963/966 m.astrua@inrim.it m.pisani@inrim.it
	CMI	František Dvořáček CMI OI Liberec Slunecná 23 460 01 Liberec - Czech Republic	Phone: fdvoracek@cmi.cz
	GUM	Dariusz Czułek, Piotr Sosinowski Central Office of Measures (GUM) ul. Elektoralna 2, 00-139 Warsaw – Poland	Phone: +48 22 581 9543 d.czulek@gum.gov.pl piotr.sosinowski@gum.gov.pl
	IPQ	Fernanda Saraiva Instituto Português da Qualidade Rua António Gião, 2 Almada 2829-513 CAPARICA – Portugal	Phone: +351 212 948 460 Fsaraiva@ipq.pt
APMP	NIMT	Ketsaya Vacharanukul 3-4/5 Moo 3, Klong 5, Klong Luang, Pathumthani 12120 Thailand	Phone: +66 25775100 ext. 1216 ketsaya@nimt.or.th
	NPL-I	Arifsanjid Arifsanjid LENGTH & DIMENSION STANDARDS National Physical Laboratory, Dr. K.S. Krishnan Road, New Delhi – 110012 - India	Phone: sanjid@nplindia.org

3.2 Schedule

The participating laboratories are asked to specify a preferred timetable slot for their own measurements. The timetable given in table 2 has been drawn up taking these preferences into account as much as possible. The programme is to start in September 2024 with measurement at the pilot laboratory. **Each laboratory has eight weeks** that include customs clearance, calibration and transportation to the following participant.

With its confirmation to participate, each laboratory is obliged to perform the measurements in the allocated period and to allow enough time in advance for transportation so that the following participant receives the standard in time. If a laboratory has technical problems to perform the measurements or customs clearance takes too long, the laboratory has to contact the pilot laboratory as soon as possible and, according to whatever it decides, it might eventually be obliged to send the standards directly to the next participant before completing the measurements or even without doing any measurements. The pilot laboratory will repeat measurements at the end of the schedule to check the stability of the artefacts.

Table 2. Draft schedule of the comparison

RMO	Laboratory	Starting date of measurement
	INRIM (Pilot Lab)	September 2024
	GUM	October/November 2024
	NPL-I	December 2024/January 2025
	NIMT	February/March 2025
	IPQ	April/May 2025
	CMI	June/July 2025
	INRIM (Pilot Lab)	August 2025

3.3 Reception, transportation, insurance, costs

The standard will circulate within a box together with a copy of this protocol and an ATA carnet in case of circulating outside Europe.

Upon reception of the package, each laboratory has to check that the content is complete and that there is no apparent damage on the box or on the standards. The reception has to be confirmed immediately to the pilot with a copy to the former participant (sender), preferably using the form of Appendix A.

It is of utmost importance that the artefacts be transported in a manner in which they will not be lost, damaged or handled by un-authorised persons. Packaging for the artefacts has been made to be suitably robust to protect the artefacts from being deformed or damaged during transit. The packaging should be marked as ‘Fragile’.

Once the measurements have been completed, the package shall be sent to the following participant.

Each participating laboratory shall cover the costs of shipping and transport insurance against loss or damage. The package should be shipped with a reliable parcel service of its choice. Once the measurements have been completed, please inform the pilot laboratory and the following participant when the package leaves your installations indicating all pertinent information. If, at any point during circulation, the package is damaged, it shall be repaired by the laboratory before shipping it again.

The package is accompanied by an ATA carnet. Outside EU the carnet shall always be shipped with the package, never inside the box, but apart. **Please be certain, that when receiving the package, you also receive the carnet!**

4 Artefacts

4.1 Description of artefacts

The artefact to be calibrated is an incremental angle encoder, manufactured by HEIDENHAIN, model RON 786, with integral bearing and integrated stator coupling. It has a hollow through shaft for axial clamping, diameter 60 mm, 18000 lines and an accuracy level of ± 2”. It is equipped with an evaluation electronics, ND287. For more details, you can see the link: Product details | HEIDENHAIN

A picture of the standard is reported in figure 1.

Figure 1 – picture of angle encoder

The mechanical design is reported in fig 2.

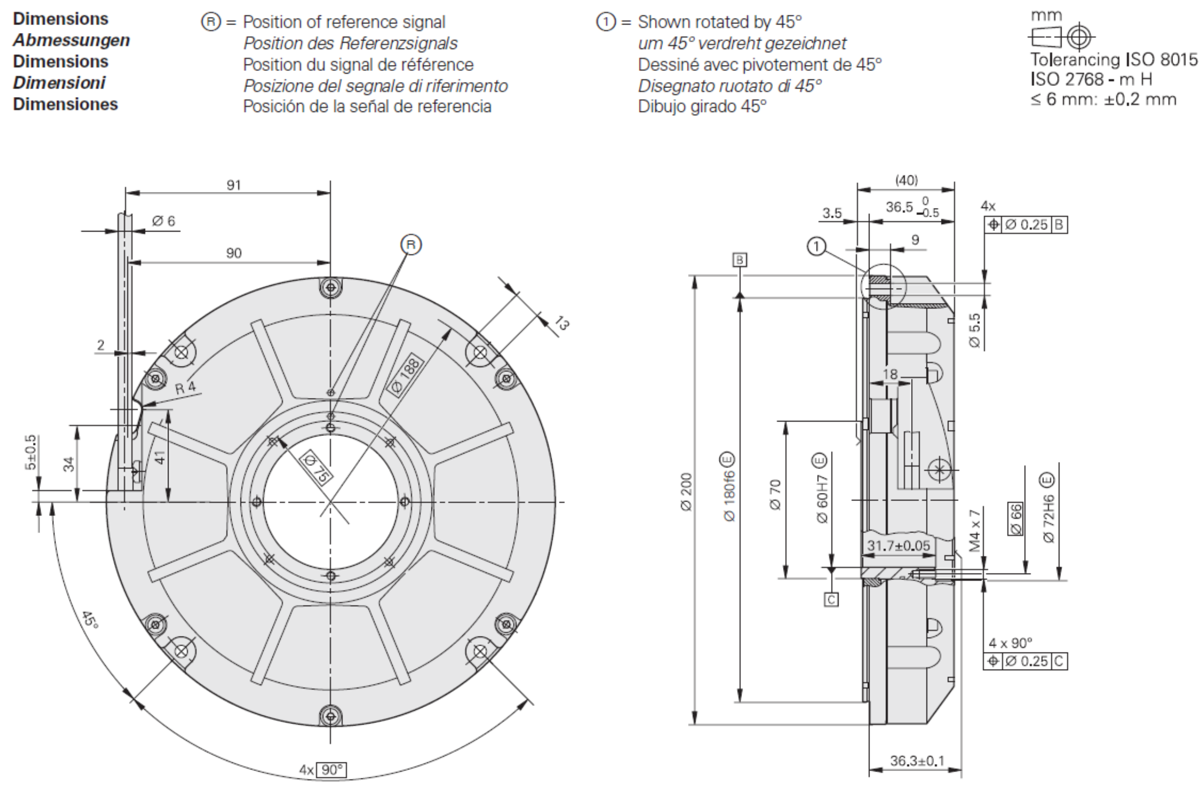


Figure 2 – mechanical design of angle encoder

The standard for this comparison has been chosen for the following reason:

1) The integral bearing minimizes the issues coming from the mechanical coupling between the encoder and the reference standard.
2) The device performaces are appropriate for the purpose of this comparison.
3) Heidenhain angle encoders in general are widely used all over the world for precision angle metrology in research and industry.

5 Measuring instructions

5.1 Handling the artefact

The standard should only be handled by authorized persons and stored in such a way as to prevent damage. Before proceeding with the calibration, familiarize yourself with the functioning, handling and features of the encoder by consulting the manual supplied with it.

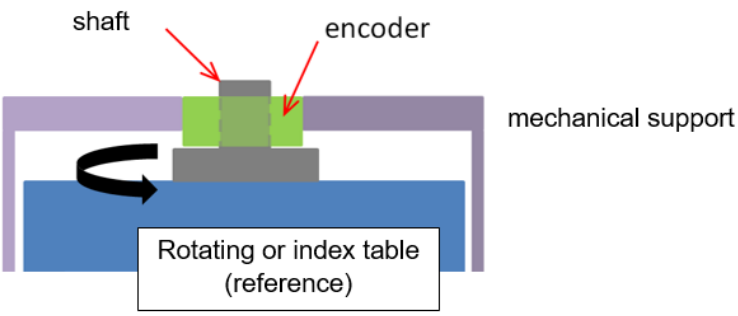
Before switching on the encoder, plug in the connecting cables. Then, check the operability of the encoder.

Ensure that the content of the package is complete before shipment. Always use the original packaging.

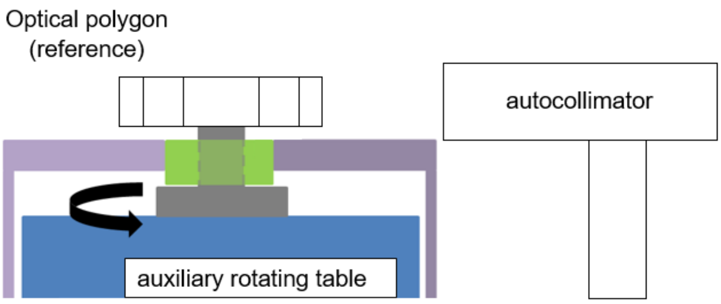
5.2 Measurement methods

The calibration of angle encoders in large range is usually performed by direct comparison against reference angle standard such as optical polygons, indexing or rotary tables or angle encoders. Details about different methods are reported in Ref [1]. The following figures show some examples of possible schematic set-up for different calibration methods.

a)



b)



c)

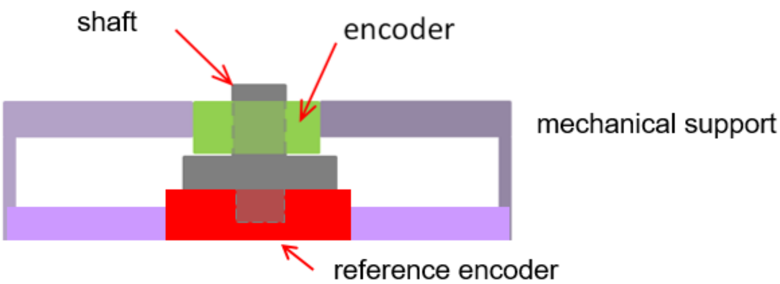


Figure 3 – different calibration methods of angle encoders: a) calibration with respect to rotating or indexing tables; b) calibration with respect to a calibrated optical polygon; c) calibration with respect to a reference encoder.

Participants are encouraged to use their own method. Please, note that in any case the test encoder needs to be fixed on a mechanical structure and coupled to the reference standard through the coupling shaft because of the presence of integrated bearing. The mechanical interface shall be compliant with the quotes and the tolerances given by the manufacturer (see chapter 5.3)

Since angle encoders cover the full 360° angle with a resolution of the order of the nanoradian, we recommend two different measurement ranges for the comparison:

- Measurement range 1: 360° in step of 5°
- Measurement range 2: 1° in step of 10”

If possible, measurement should be performed at the specified value as indicated by the angle encoder. If calibrations are not possible at all specific measurement points (e.g., calibration with respect to a reference polygon) participants are allowed to calibrate at a selected subset of points. In this case, please choose a step which is multiple of the recommended step.

5.3 Requirement for the mechanical coupling

Connect the encoder with the reference angle standard by means of a shaft coupling manufactured according to the mechanical design sketched in figure 4.

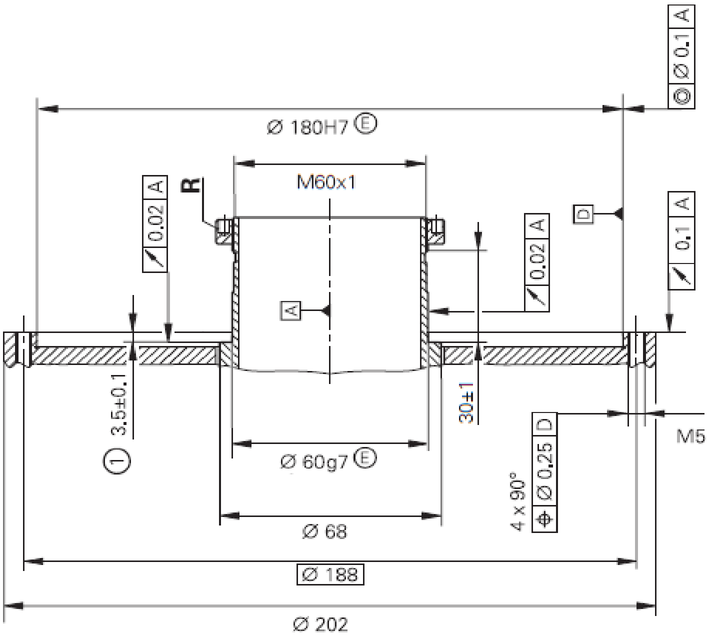
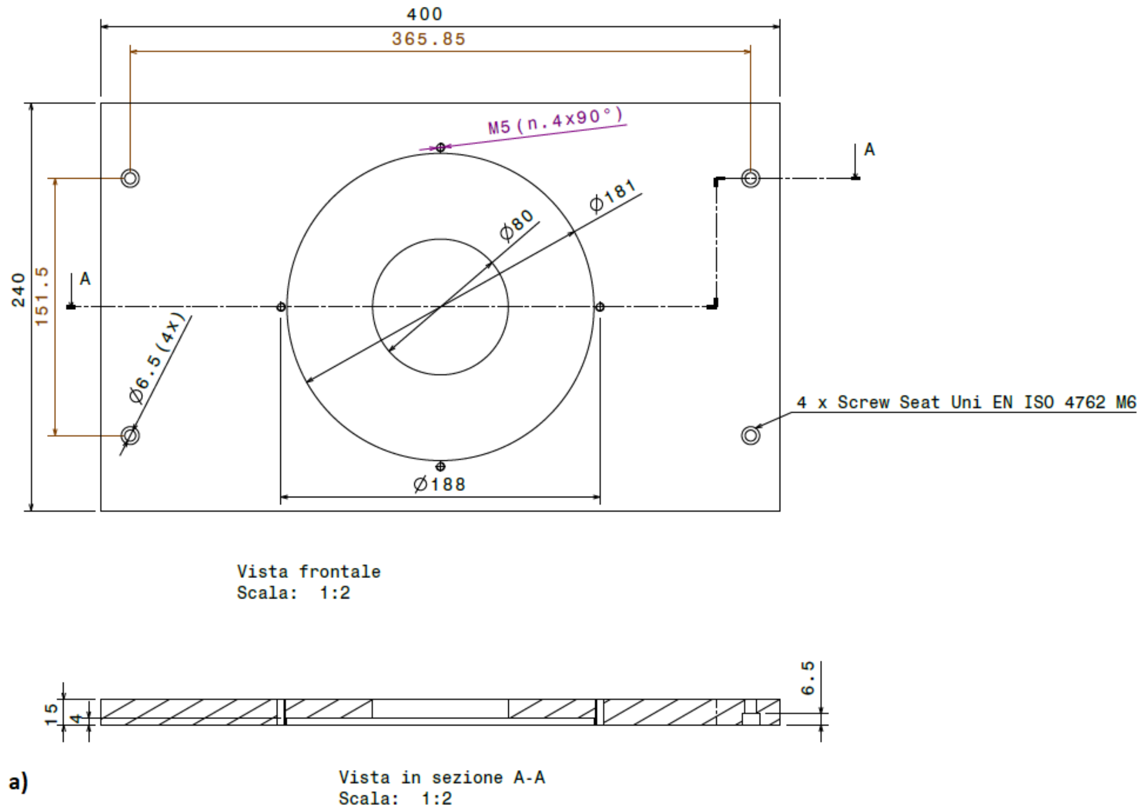


Figure 4 – Heidenhain mechanical design of the coupling

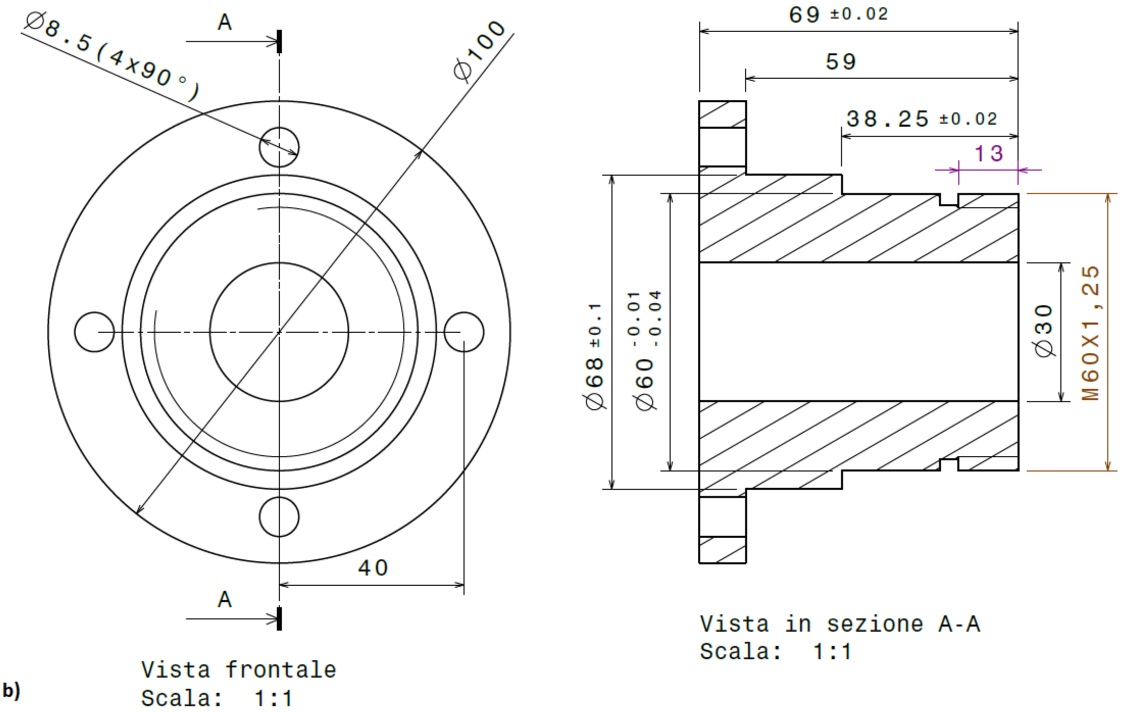
The mechanical interface realized and used at INRIM will be provided for the comparison to the convenience of the participants, but it is not mandatory to use it. Participants can realize their own mechanical interface paying attention to respect the quotes as in figure 4.

5.4 Accessories

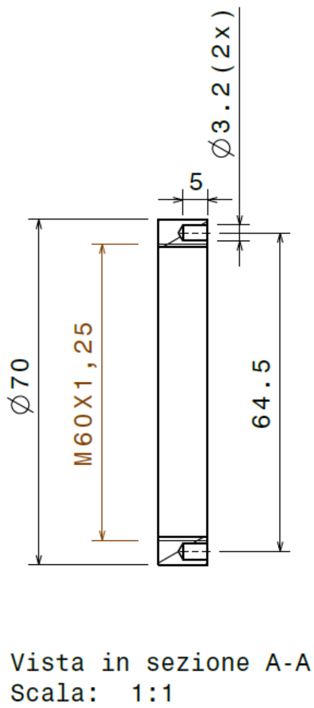
The mechanical drawing of the interface designed and manufactured at INRIM is in figure 5.



a)



b)



c)

Figure 5 – design of the mechanical interface designed at INRIM: a) mounting plate; b) shaft coupling; c) ring coupling

5.5 Mounting the artefact

Here is described the procedure followed by INRIM to align and mount the encoder on our reference angle standard. This procedure can be adopted as a hint for the participants, but it is not binding.

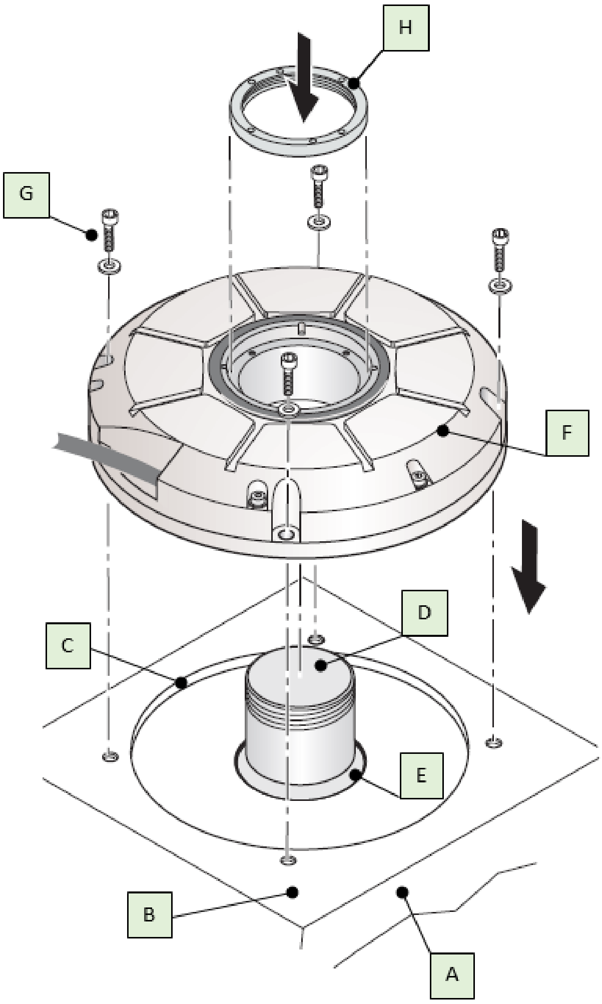


Figure 6 – mechanical design of encoder and shaft coupling

A	mounting plate
B	mounting surface for the encoder
C	encoder centering edge
D	shaft coupling
E	tooth bearing the encoder rotor
F	encoder
G	fixing screws
H	ring coupling

Mount and align the encoder according to the following steps:

1) mount and centre the shaft coupling D on the reference table so that the shaft axis is concentric and coaxial with respect to the reference table within ± 0.01 mm
2) place the mounting plate parallel to the reference table upper surface, paying attention to the height between the tooth bearing the encoder rotor and the encoder centering edge: this height should be 3.5 mm ± 0.1 mm
3) set the encoder centering edge C to be concentric with respect to the rotation axis of the reference table within ± 0.1 mm
4) couple the encoder and the reference table by fixing the encoder body to the mounting plate with 4 M5 fixing screws
5) align the reference marks on the encoder body and on the bearing, as shown in fig. 1 (denoted by R)
6) bind the shaft to the rotor by means of the coupling ring

It is recommended to calibrate the encoder in different relative angular orientation with respect to the primary standard in order to detect possible errors due to the mechanical coupling.

In figure 7, the measurement set-up for the calibration of angle encoders against the primary angle standard of INRIM, REAC, is presented. Here it is possible to see the accessories listed in chapter 5.4. Moreover, a mirror was placed on the mounting surface in order to measure by means of an autocollimator and correct for the small rotations of the plane induced by the shaft drag.

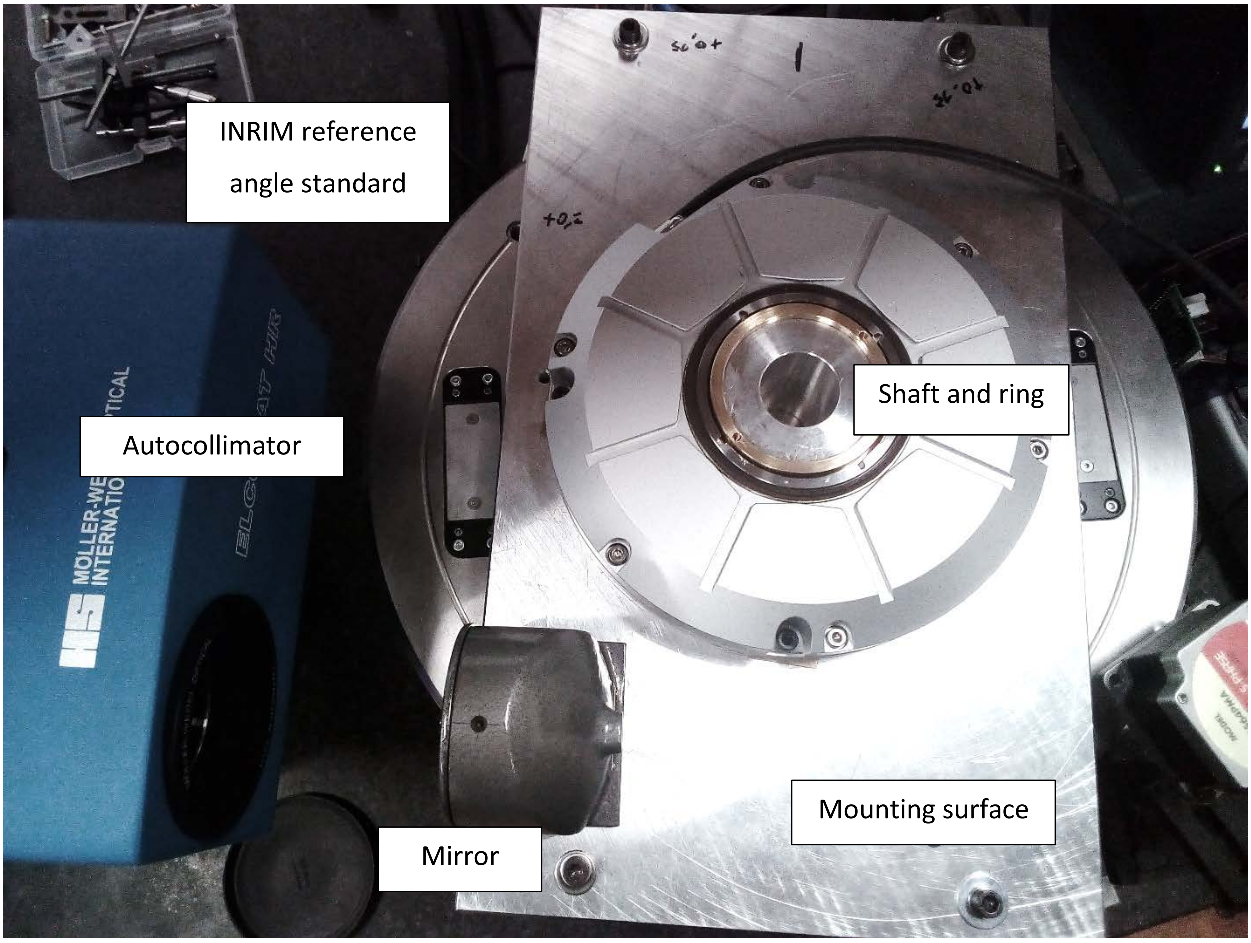


Figure 7 – set-up for the calibration of angle encoder at INRIM

5.6 Traceability

Plane-angle measurements should be traceable to the simple fact that one revolution equals either 2π radians or 360 degrees.

5.7 Measurand

The measurand is the deviation *Δα* of the angle measured by the encoder from the angle provided by the reference system according to the following mathematical model:

$$\Delta\alpha = \alpha_{CAL} - \alpha_{REF} + \sum_i \delta_i$$

Where:

Δα is the angle deviation of the encoder,

α_{CAL} *is the angle measured by the encoder,*

α_{REF} *is the angle measured by the encoder,*

δ_i *are the relevant components influencing the measurement*

5.8 Reference mark

The encoder's mechanical zero corresponds to the condition where the reference mark on the encoder body is approximately aligned with the mark on the bearing. Anyway, the zero condition could be changed in two ways:

1) using a second reference system with a different zero
2) or by pressing the button “ZERO RESET”

In the first case, the button “DATUM” allows to switch to a second reference system (from L01 to L02), then pressing the button “SET” it is possible to set the actual position as zero.

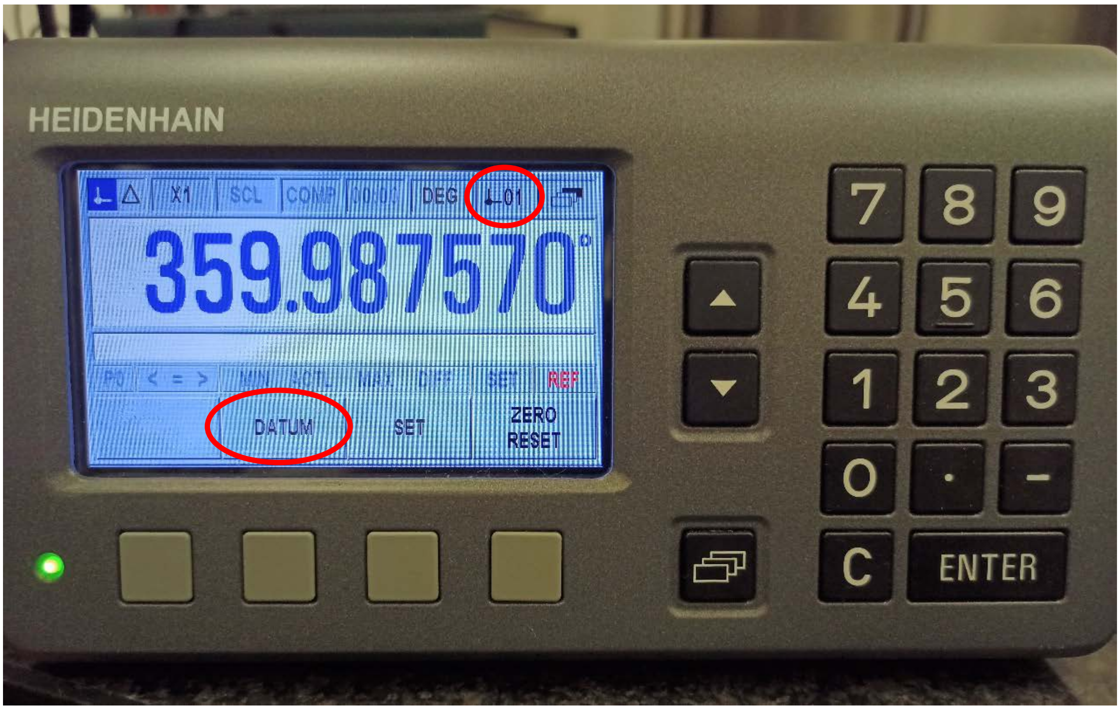


Figure 8 – ND 287 reading unit

Please, note that the new zero is kept in memory even if the unit is switched off. Press again the “DATUM” button, to come back to the original reference system, L01.

The second case is more drastic, indeed the button “ZERO RESET” would set the actual position as the new and permanent zero. To come back to the original mechanical zero, it is necessary to restore all the default settings through the “INSTALL SETUP” menu (see Appendix D for details).

5.9 Measurement uncertainty

The uncertainty of measurement shall be estimated according to the ISO *Guide to the Expression of Uncertainty in Measurement* [2].

All measurement uncertainties shall be stated as standard uncertainties. If appropriate, the corresponding effective degrees of freedom for each component should be stated by the participants. If none is given, ∞ is assumed. For efficient evaluation and subsequent assessment of CMC claims an uncertainty statement in a functional form is preferred, with indication of the factor k used, typically 2, or the one corresponding to a level of confidence of a 95 %, in case it was different.

6 Reporting of results

6.1 Results and standard uncertainties as reported by participants

As soon as possible after measurements have been completed, the results should be communicated to the pilot laboratory **within four weeks** at the latest.

The measurement report forms in Appendix B of this document should be used. It would be appreciated if the report forms could be completed by computer and sent back electronically to the pilot laboratory. In any case, the signed report must also be sent in paper form by mail or electronically as a scanned pdf document. In case of any differences, the signed forms are considered to be the definitive version.

Following receipt of all measurement reports from the participating laboratories, the pilot laboratory will analyse the results and prepare within 3 months a first draft A.1 report on the comparison. This will be circulated to the participants for comments, additions and corrections.

7 Analysis of results

7.1 Calculation of the KCRV

The key comparison reference value (KCRV) is calculated as the weighted mean of the participants results [3,4]. The check for consistency of the comparison results with their associated uncertainties will be based on Birge ratio R_B. The degrees of equivalence for each laboratory with respect to the KCRV will be evaluated using E_n values. If necessary, artefact instability, correlations between institutes and the necessity for linking to another comparison will be taken into account.

7.2 Artefact instability

The instability of the standards must be determined in course of the comparison. For this check the measurements of the pilot laboratory are used exclusively, not that of the other participants.

In case of artefact stability, to avoid biasing the weighted mean, an average value of all sets of measurements from the pilot laboratory will be included in the reference value determination.

8 References

[1] Euramet Calibration guide 023

[2] ISO/IEC Giude 98-3:2008 'Guide to the Expression of Uncertainty in Measurements' (ISO: 2008) [REAC]

[3] M.G. Cox 'The evaluation of key comparison data' Metrologia 39 (2002) 589-594

[4] M.G. Cox, 'The evaluation of key comparison data: determining the largest consistent subset' Metrologia **44**, 187 (2007)]

Appendix A – Reception of Standards

To:	Milena Astrua Istituto Nazionale di Ricerca Metrologica (INRIM) Strada delle Cacce 91 10135 Torino Italy	Tel. +39 011 3919963 e-mail: m.astrua@inrim.it
From:	Date: NMI:	Name: Signature:

We confirm having received the standard for the EURAMET 1528 comparison on the date given above.

After a visual inspection:

☐ There are no apparent damages; their precise state will be reported in the form provided in Appendix B once inspected in the laboratory along with the measurement results.

☐ We have detected severe damages putting the measurement results at risk. Please indicate the damages, specifying every detail and, if possible, include photos. If it is necessary use additional sheets to report it.

Appendix B – Measurement Results

To:	Milena Astrua Istituto Nazionale di Ricerca Metrologica (INRIM) Strada delle Cacce 91 10135 Torino Italy	Tel. +39 011 3919963 e-mail: m.astrua@inrim.it
From:	Date: NMI:	Name: Signature:

Description of the measuring system and set-up

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Description of the method used

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Description of the procedure

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Environmental conditions

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CMC uncertainty for the service related to this comparison topic (if existing in the KCDB)

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(use additional pages as needed)

Measurement results

Table B2. **Measurement range 1: Results and uncertainties**

Nominal angle	Angle deviation (arc sec)	Expanded uncertainty (*k* = 2)
0°-5°		
0°-10°		
0°-15°		
…		
…		

Table B3. **Measurement range 2: Results and uncertainties**

Nominal angle	Angle deviation (arc sec)	Expanded uncertainty (*k* = 2)
10''		
20''		
30''		
…		
…		

Appendix C – Uncertainty of measurement

Table B4. Uncertainty budget of measurement

x_i	$u(x_i)$	v_i	$c_i = \partial y/\partial x_i$	$u_i(y)$

Combined standard uncertainty: $u_c(R)$=

Expanded uncertainty: $U(R)$ (k =) =

$U(R) = Q[a, bR] = \sqrt{a^2 + (bR)^2}$ =

Appendix D - ND 287 reading unit

When ND 287 reading unit is switched on, the display shows “0.000000°” and the red text “REF” blinks.

Then the encoder should be rotated by about ten degrees so that the reading unit can understand which is the physical encoder position. Now the instrument is ready to measure.

This reading unit is compatible with all Heidenhain encoders, so a number of parameters specific for our encoder was saved in the unit through the “INSTALL SETUP”.

In case of pressing the button “ZERO RESET”, the mechanical zero gets lost. The only way to restore it is to come back to the factory default: the “FACTORY DEFAULT” soft key appears in the COUNTER SETTINGS form, which is opened from the INSTALLATION SETUP. This soft key reset the configuration parameter to factory default, hence after that operation, it is necessary to insert all the specific parameters again.

INSTALL SETUP
Enter passcode: 95148

<u>Encoder setup</u>

Encoder type:	ANGLE
Encoder signal:	1Vpp
Signal period:	18000
Number ref. Marks:	36
External ref:	OFF
Count direction:	POSITIVE
Error monitor:	frq + contamination

<u>Display configuration</u>

Display resolution:	0.000005
Angle format:	360 degrees

<u>Counter settings</u>

Application:	1 axis
Keyboard:	release keypad
Second dec. Point:	ON
Power up screen:	ON
Display unit:	ND-287
Sw version:	V1.09 ID 646118-09

<u>Error compensation</u>

Error compensation	OFF

<u>Interface settings</u>

Serial port:	USB
Baud rate:	9600
Data bits:	7 DATA BITS
Stop bits:	2 stop bits
Parity:	EVEN
OUTPUT TAIL:	1

Software

A simple software written in LabVIEW to acquire the encoder's data through a serial COM port is available.

A picture of the software front panel is represented in the following figure.

On the left, there are the controls for the serial communication; on the rigth, different format of the encoder OUTPUT.

This software could be integrated in other LabVIEW based software, if needed.