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***Abstract* – Direct-current comparator bridges (DCC) are the working horse of primary resistance metrology in the intermediate resistance range. Having a ratio accuracy reaching 10^{-7} or better, they allow the realisation of resistance scales and the calibration of artifact standard resistors for customers. In this paper we compare the performances of three commercial DCC bridges, by performing measurements on decadal resistors ($1\,\Omega$ to $10\,\mathrm{k}\Omega$) of very high stability in a thermostated environment. The results show that the three bridges give mutually compatible results within the manufacturer specifications, therefore mutually validating the bridges; nevertheless, the readings time series show quite different statistical behavior, with internal correlations, making an evaluation of the Type A measurement uncertainty not trivial.**

I. INTRODUCTION

Direct-current comparator bridges (DCC) [1] are instruments which can measure the resistance ratio between two four-terminal resistance standards R_1 and R_2 with a base relative accuracy of 1×10^{-7} or better for the intermediate resistance range ($1\,\Omega$ to $10\,\mathrm{k}\Omega$), and are therefore suitable for the realisation of a primary resistance scale and to sustain a calibration service in National Metrology Institutes and calibration laboratories. Commercial, fully-automated bridges are on the market since more than 40 years.

Research is ongoing in INRIM to simplify and automate the traceability chain for the maintained resistance standard and to perform calibration for customers, and commercial DCCs are employed as a check of the scaling in the intermediate resistance range, and as a direct calibration instrument for the low resistance scale ($10\,\mu\Omega$ to $1\,\Omega$). Checking the measurement accuracy of the different DCCs employed is therefore a basic metrology verification requirement.

In this paper, we compare the performance of three different commercial DCCs in performing measurements on the maintained national standard of dc resistance, in the intermediate range.

II. DIRECT-CURRENT COMPARATORS

The direct-current comparator bridges (DCC) [2] measure resistance ratio between two four terminal-pair resistors R_1 and R_2. The resistors are energized by two current sources; the resulting currents I_1 and I_2 flow through two windings, having turns N_1 and N_2, wound on a ferromagnetic core. The magnetic flux in the core is given by $\mathcal{R}\Phi = N_1 I_1 - N_2 I_2$, where $\mathcal{R}$ is the reluctance of the core. Φ is measured by a fluxgate detector [1, 3, 4], whose output constitutes the error signal of a feedback control. The output of such control drives one of the two current sources (e.g., I_2) to keep $\Phi = 0$ and therefore the condition $N_1 I_1 = N_2 I_2$. The voltage difference $\Delta V = R_1 I_1 - R_2 I_2$ between the two resistors is measured, and the turns of one of the two windings (say, N_2) are also adjusted to set ΔV to a minimum. This second adjustment was manual in early bridges [1] and is presently also automated [5]. The readings of the bridge are the two values N_1/N_2 and ΔV, which give the measurement equation

$$\frac{R_1}{R_2} = \frac{N_1}{N_2}\left(1 - \frac{\Delta V}{R_2 I_2}\right). \tag{1}$$

During the measurement the currents I_1 and I_2 are periodically reversed to reduce the influence of voltage offsets.

The DCC bridge measurement accuracy [6] is limited by the sensitivities of the flux detector and of the voltage detector which sense ΔV, and by flux leakage in the magnetic circuit. Bridges measuring resistors in the $\mu\Omega$ to the $\mathrm{M}\Omega$ range are available; best accuracy is achieved for medium-ranged resistors ($1\,\Omega$ to $10\,\mathrm{k}\Omega$) and ratios within the $1:10$ range.

The DCCs under comparison are three different models from the Measurement International that acquired at different times. In the following, the measurements are labelled as follows:

6010B Measurement International model 6010B, serial 1020904, acquired in 2006.

6010D Measurement International model 6010D, serial 1104668, acquired in 2021.

6010Q Measurement International model 6010Q, serial 1100670, acquired in 2008.

Table 1. Measurements settings employed in the measurements of the 10/1, 100/10, 1k/100 and 10k/1kratios with the 6010B, 6010D and 6010Q DCC bridges.

	$I/\,\mathrm{mA}$	$t_{\mathrm{set}}/\mathrm{s}$	$Filter$	6010Q $\#ADC$
10/1	10	6	3	6
100/10	3	8	3	8
1k/100	1	8	3	8
10k/1k	0.1	12	3	12

III. THE MAINTAINED NATIONAL STANDARD OF DC RESISTANCE

The comparison of the three bridges required equipment consisting of a series of high stability standard resistors, a Guildline VT9732 oil bath, a Kambic TK-105 US air bath and a low noise switching system. The resistors used have nominal values in the $1\,\Omega$ to $10\,\mathrm{k}\Omega$ range, manufactured by Leeds & Northrup and Tinsley, all kept inside a constant temperature oil bath at a level of of $23\,°\mathrm{C}$ with a stability of $0.001\,°\mathrm{C}$. The measurements also involved two ESI SR104 resistors maintained at a temperature of $23\,°\mathrm{C}$ inside a Kambic air bath with a stability of $0.005\,°\mathrm{C}$. The bridges and the resistors are connected by means of an automatic Leeds & Northrup type rotary switch system with low thermo-electromotive forces (less than $5\,\mathrm{nV}$). The comparison of the bridges, whose measurements could not be made at the same time, was possible due to the high stability of the standards used both in short and medium term (about 1×10^{-7} per year), and of the influence parameters.

IV. MEASUREMENT PROCEDURE

We define the ratios between $10\,\Omega$ and $1\,\Omega$, $100\,\Omega$ and $10\,\Omega$, $1\,\mathrm{k}\Omega$ and $100\,\Omega$, $10\,\mathrm{k}\Omega$ and $1\,\mathrm{k}\Omega$ as 10/1, 100/10, 1k/100 and 10k/1k, respectively. All the ratios were measured with the 6010B, 6010D and 6010Q DCC bridges in sequence by employing the same resistance standards, described in Section III., and the same measurement configurations, reported in Table 1. For all the bridges it is possible to set the desired current I for the highest resistor under test, the settle time $t_{\mathrm{set}}/$ between the current reversal during the measurement and the filter size $Filter$ corresponding to the number of averaged values ($Filter \times 10$) before each value is displayed. For only the 6010Q DCC bridge, it is possible to set the parameter $\#ADC$ representing the number of conversions of the analog-to-digital converters.

The three bridges were automatically controlled by the same software developed specifically for the comparison that ensures the same procedure and execution of the measurements with the same integration times.

V. RESULTS

Table 2 shows the results of an example measurement of each ratio performed with the 6010B, 6010D and 6010Q DCC bridges on 2 March 2022. For each measurement, the nominal ratio, the measured ratio (the mean of repeated measurements), the standard deviation, the applied current, the number of repeated measurements and the measurement time are reported.

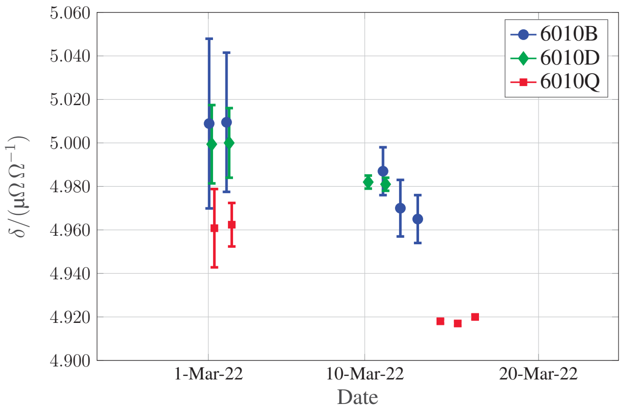

*Fig. 1. **10/1 ratio**. Relative deviations from the nominal ratio 10/1 for different measurements performed in about 20 days with the 6010B (blue), the 6010D (green) and 6010Q (red).*

Figures 1, 2, 3 and 4 show the comparison among the results obtained with the 6010B, 6010D and 6010Q DCC bridges in the measurements of the 10/1, 100/1, 1k/100 and 10k/1k, respectively. Each plot reports the relative deviation δ of the measured ratio from the nominal ratio obtained from several measurements performed in about 20 days. In all figuresbefore the 10 March 2022 the results are obtained from 100 repeated measurements, while after the 10 March 2022 the results are obtained from 800 repeated measurements. The uncertainty is calculated by applying the multiplying factor 2 to the standard deviation of the mean, as proposed in [7] for a similar experiment.

In fact, the expression of the type A uncertainty is non-trivial, since for all measurements the readings' time series display internal correlations, and therefore the standard deviation of the mean underestimates the real uncertainty. To support this, Figures 5, 6 and 7 show examples of a measurement acquisition of the 10k/1k ratio performed with the 6010B, 6010D and 6010Q bridges, respectively, in the same measurements conditions.

VI. DISCUSSION

Despite that the three bridges come from the same manufacturer and are realised with different technologies, the three time series of Figures 5, 6 and 7 have a different behaviour and show a different amount of internal correlations. This might be due to different raw data processing inside the bridge firmwares.

Table 2. Results of an example measurement of each ratio performed with the 6010B, 6010D and 6010Q DCC bridges on 2 March 2022. For each measurement, the nominal ratio, the measured ratio (the mean of repeated measurements), the standard deviation of the mean, the applied current, the number of repeated measurements n and the measurement time are reported.

6010B					
Nom. Ratio $/\Omega\,\Omega^{-1}$	Meas. Ratio $/\Omega\,\Omega^{-1}$	St. Dev. $/\mu\Omega\,\Omega^{-1}$	I/mA	n	Meas. Time
10/1	10.00005010	0.016	10	100	15 min 44 s
100/10	9.99999868	0.008	3	100	18 min 13 s
1k/100	10.00008113	0.009	1	100	18 min 12 s
10k/1k	9.99995057	0.053	0.1	100	23 min 58 s
6010D					
Nom. Ratio $/\Omega\,\Omega^{-1}$	Meas. Ratio $/\Omega\,\Omega^{-1}$	St. Dev. $/\mu\Omega\,\Omega^{-1}$	I/mA	n	Meas. Time
10/1	10.00005000	0.008	10	100	12 min 31 s
100/10	9.99999867	0.004	3	100	12 min 30 s
1k/100	10.00008102	0.003	1	100	15 min 49 s
10k/1k	9.99995190	0.060	0.1	100	22 min 19 s
6010Q					
Nom. Ratio $/\Omega\,\Omega^{-1}$	Meas. Ratio $/\Omega\,\Omega^{-1}$	St. Dev. $/\mu\Omega\,\Omega^{-1}$	I/mA	n	Meas. Time
10/1	10.00004962	0.005	10	100	21 min 4 s
100/10	9.99999821	0.003	3	100	20 min 45 s
1k/100	10.00008150	0.001	1	100	20 min 59 s
10k/1k	9.99995003	0.010	0.1	100	40 min 39 s

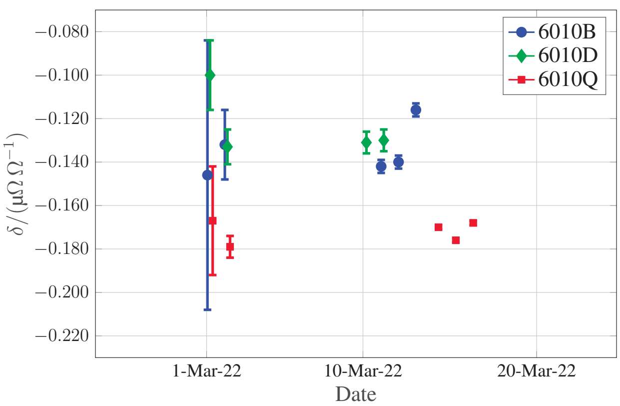

Fig. 2. ***100/10 ratio****. Relative deviations from the nominal ratio 100/10 for different measurements performed in about 20 days with the 6010B (blue), the 6010D (green) and 6010Q (red).*

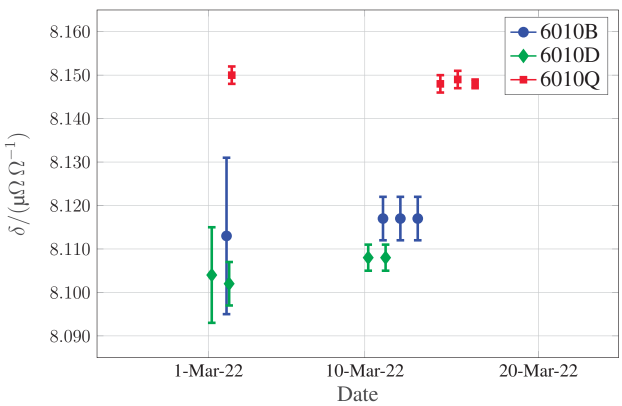

Fig. 3. ***1k/100 ratio****. Relative deviations from the nominal ratio 1k/100 for different measurements performed in about 20 days with the 6010B (blue), the 6010D (green) and 6010Q (red).*

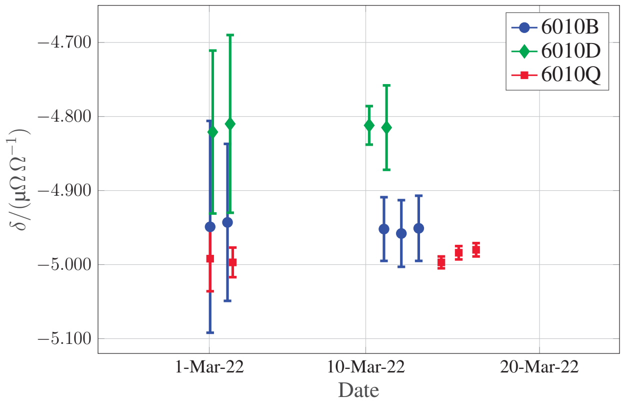

Fig. 4. ***10k/1k ratio****. Relative deviations from the nominal ratio 10k/1k for different measurements performed in about 20 days with the 6010B (blue), the 6010D (green) and 6010Q (red).*

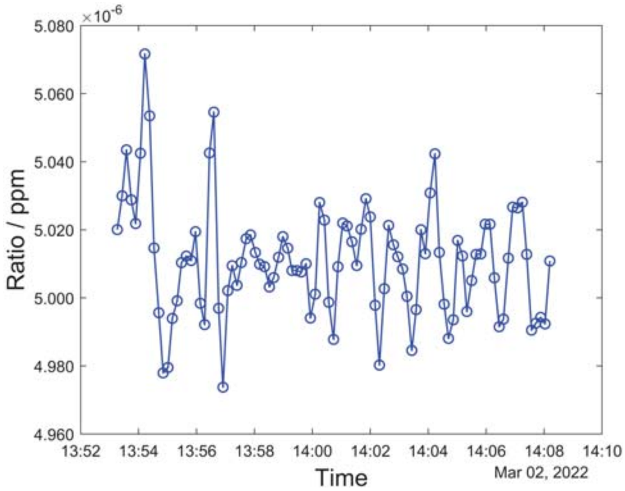

Fig. 5. Example of a measurement acquisition of the 10/1 ratio with the 6010B DCC bridge (100 repeated measurements).

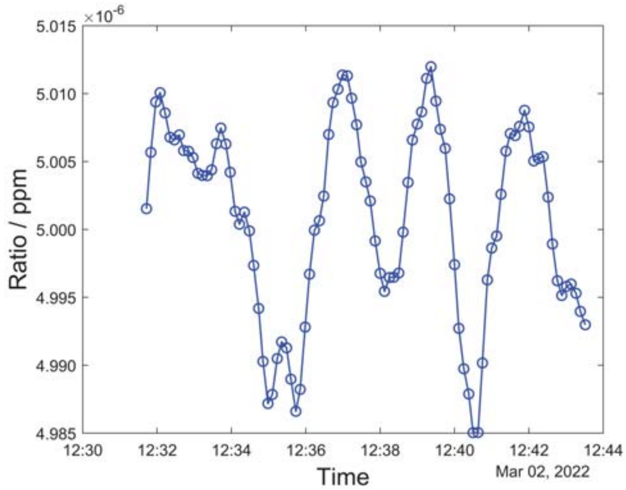

Fig. 6. Example of a measurement acquisition of the 10/1 ratio with the 6010D DCC bridge (100 repeated measurements).

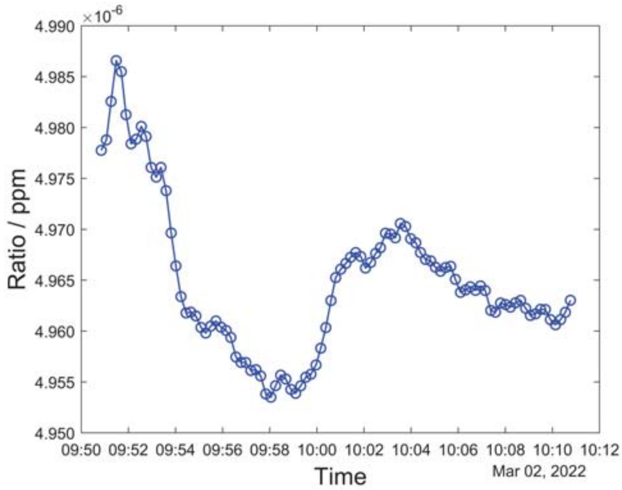

Fig. 7. Example of a measurement acquisition of the 10/1 ratio with the 6010Q DCC bridge (100 repeated measurements).

The short-term stability of the resistors due to drift and temperature variations can be estimated to be better than 3×10^{-10} over a day, hence the deviations between the readings of the three bridges are related only to the reading noise and bridge ratio errors.

It must be stressed that the error bars reported in the Figures 1, 2, 3 and 4 correspond to a (rough, to be improved) evaluation of the sole statistical uncertainty, and do not consider any Type B uncertainty. The visual effect is an apparent incompatibility of the results. The reported differences between the different estimates, however, match the manufacturer specifications of the relative errors of the bridges (of several parts in 10^8 for each bridge); the measurements, therefore, provide a mutual validation of the three bridges.

A better evaluation of the type A uncertainty can be approached by considering the Allan deviation [8] or the autocorrelation function [9, 8] or the series. For the moment, we performed a rough estimation by applying a multiplying factor to the standard deviation of the mean, as proposed in [7] for a similar experiment. A proper evaluation is ongoing and will be presented at the Conference.

The bridge ratio errors can be determined in an absolute way by comparing their readings with those of a cyrogenic current comparator [10], which allows measurements accuracies of parts in 10^9 and thus in this sense can be considered a perfect reference. A comparison experiment is under planning.

VII. ACKNOWLEDGEMENTS

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VIII. *

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