An international trilateral comparison among the newest generations of digital and Josephson impedance bridges

An International Trilateral Comparison Among the Newest Generations of Digital and Josephson Impedance Bridges

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***Abstract*— This work reports and thoroughly discusses the results of an onsite trilateral comparison between a dual Josephson impedance bridge developed by METAS and the electronic fully digital impedance bridges developed by CMI and INRIM-POLITO. The target accuracies of the bridges are at the level of 10^{-9} to 10^{-8} for the former and at the level of parts in 10^{7} for the latter. The bridges were tested with R:R and R:C standards, with nominal magnitudes of $12.9\ \mathrm{k}\Omega$, and with a quantum Hall resistance standard, in conditions suitable for the primary direct realization of the impedance units ohm and farad from ac quantum Hall resistance standards or from ac/dc calculable transfer resistance standards calibrated against dc quantum Hall resistance standards. The results were fully compatible at the expected level of uncertainty for what concerns the magnitude ratio, but phase measurements with R:C standards showed some incompatibilities.**

***Index Terms*— Bridge circuits, calibration, impedance measurement, Josephson effect, metrology.**

I. Introduction

IMPEDANCE bridges [1] of various constructions are used by national metrology institutes (NMIs) around the world to provide the traceability to the International System of Units (SI) of the units of impedance ohm, farad, and henry.

In recent years, there has been a progressive transition from traditional impedance bridges based on transformers or inductive voltage dividers to novel impedance bridges based on electronic or Josephson arbitrary waveform synthesizers. This transition has been stimulated by the fact that contrary to transformer-based bridges, electronic fully digital impedance bridges (FDIBs) and dual Josephson impedance bridges (DJIBs) with relatively simple architectures are capable of directly comparing impedances across the whole complex plane and operating over a wide range of frequencies. For instance, these kinds of bridges can directly compare like impedances (e.g. R:R or C:C) or unlike impedances (e.g. R:C or R:L), determining both magnitude (modulus) and phase angle (argument) of the complex ratio. FDIBs are also relatively affordable, easy to operate, and transportable but less accurate than DJIBs. The target accuracies are at the level of 10^{-9} to 10^{-8} for DJIBs and at the level of parts in 10^{7} for FDIBs. In the last decade, the transition from traditional bridges to FDIBs and DJIBs has been specifically promoted in Europe by a number of collaborating NMIs and universities through projects[1] funded by the European Association of National Metrology Institutes (EURAMET). Since the first prototypical FDIB [2], NMIs have been, thus, continually improving FDIBs and DJIBs such that these kinds of devices are currently mature enough for primary impedance metrology applications. Of particular interest is the application of FDIBs and DJIBs to the direct realization of the unit farad either from ac quantized Hall resistance (QHR) standards or from ac/dc calculable transfer resistance standards calibrated against dc QHR standards, thus avoiding the usage of complex transformer-based quadrature bridges.

However, the application of FDIBs and DJIBs to primary impedance metrology requires a careful assessment of their performances and their mutual compatibility at a number of relevant impedance ratios and frequencies. A first international comparison between FDIBs aimed at the calibration of secondary impedance standards was run from 2015 to 2018 [3]. For the assessment of FDIBs and DJIBs aimed at primary metrology applications, the Istituto Nazionale di Ricerca Metrologica (INRIM), Italy, the Federal Institute of Metrology

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[1]Namely, the projects AIM QuTE (2013–2016), *automated impedance metrology extending the quantum toolbox for electricity*, VersICaL (2018–2021), *a versatile electrical impedance calibration laboratory based on digital impedance bridges*, and GIQS (2019–2022), *graphene impedance quantum standard*.

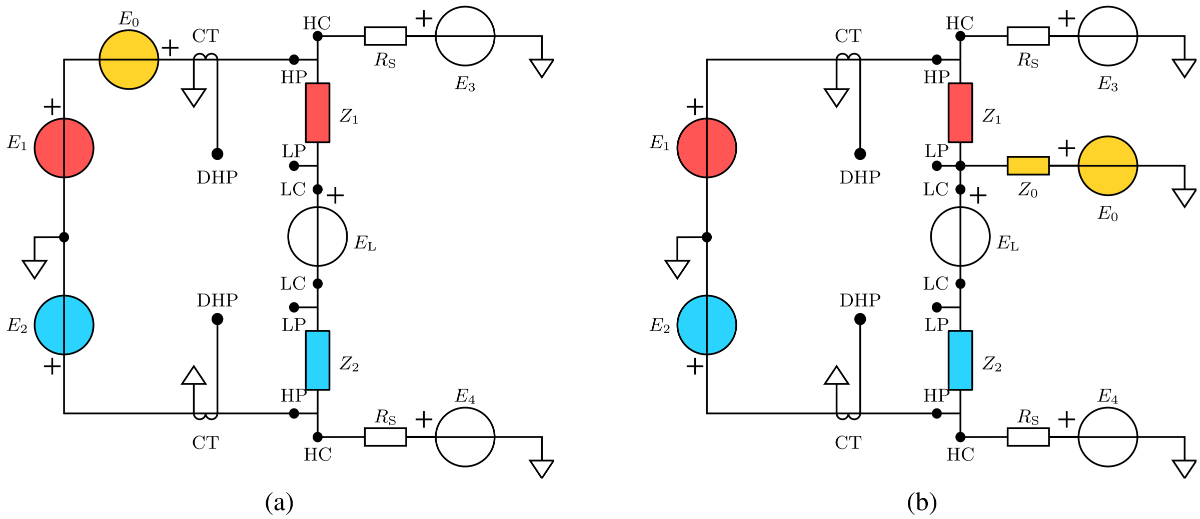

Fig. 1. Simplified principle schematics of the FDIBs and the DJIB used in the comparison. (a) CMI FDIB and METAS DJIB. (b) INRIM-POLITO FDIB. The measured impedances are Z_1 and Z_2 with terminal pairs labeled HC, HP, LP, and LC. The voltage sources E_1 and E_2 generate the reference voltage ratio E_1/E_2 to which the impedance ratio Z_1/Z_2 is compared. In the DJIB, E_1 and E_2 are the outputs of a dual Josephson arbitrary waveform synthesizer; in the FDIBs, E_1 and E_2 are two output channels of an electronic digital synthesizer. In both types of bridges, the auxiliary voltages E_0, E_3, E_4, and E_L are generated by an electronic synthesizer. In (a), E_0 and E_L are injected by means of a step-down transformer (100:1 turns ratio); in (b), E_L is injected by means of a step-down transformer (200:1 turns ratio), and Z_0 is a 1 or 10-pF capacitance standard. The bridge balances are checked at the terminal pairs LP and DHP. The transformer CT detects the currents through the HP terminal pairs.

(METAS), Switzerland, the Physikalisch-Technische Bundesanstalt (PTB), Germany, and the Politecnico di Torino (POLITO), Italy, started in 2020 the project EURAMET TC-EM 1501, *technical assessment of novel digital impedance bridges* [4]. The project is being coordinated by INRIM, and the Czech Metrology Institute (CMI), Czech Republic, joined it at the end of 2023. A first round of comparisons within this project took place from September to November 2021 when the INRIM-POLITO FDIB was moved to Braunschweig to be compared with the PTB DJIB. The results of this first round were published in [5]. A second round of comparisons took place in 2023 in Bern, where the INRIM-POLITO FDIB (from mid-October to December) and the CMI FDIB (one week in mid-October) were moved to and compared with the METAS DJIB. This work fully reports on these new results, a selection of which was first summarily reported in [6].

The plan is given as follows. Sections II and III briefly describe the impedance bridges and the standards involved in the comparison. Section IV presents the main results of the trilateral comparison and discusses some technical difficulties that arose during the comparison. The Appendix presents some additional results that were obtained during the subsequent period in which only the INRIM-POLITO FDIB remained at METAS.

II. Participating Impedance Bridges

An impedance bridge determines the complex impedance ratio Z_1/Z_2 of two impedances Z_1 and Z_2. The simplified principle schematics of the DJIB and the two FDIBs participating in this work are represented in Fig. 1 in a comparative way. The two impedance standards are defined as four-terminal-pair (4TP) standards [7] with the terminal pairs labeled HC (high current), HP (high potential), LP (low potential), and LC (low current). The DJIB and the two FDIBs are *sourcing bridges* [8], in which the impedance ratio is determined from a reference voltage ratio generated by the channels E_1 and E_2 of a multiphase source. In the DJIB, the source is a dual Josephson arbitrary waveform synthesizer (JAWS); in the FDIBs, the source is an electronic digital synthesizer. The injection channel E_0 in Fig. 1(a) and the injection arm E_0-Z_0 in Fig. 1(b) are used to improve the resolution and the accuracy of the balance. The 4TP definition of the impedances is realized by the auxiliary channels E_3, E_4, and E_L, the resistors R_S, and the current detection transformer CT. A bridge is balanced when both the mean (main balance) and the difference (Kelvin balance) of the LP voltages are zero, and when the HP currents, as measured at the detection terminal pairs DHP are zero (current balances). To compensate for possible asymmetries in the bridge networks, the measurements are performed in two successive configurations, typically labeled *forward* and *reverse*, differing by the exchange of the impedances.

Fig. 2 shows a picture of the three bridges in the METAS laboratory.

The CMI FDIB, shown schematically in Fig. 1(a), is based on the reconfigurable bridge [11], where the reference ratio of the bridge is formed by the ultrastable two-channel source SWG [12]. The 4TP definition of the impedances under comparison is fulfilled by means of additional fully synchronized SWG sources and an injection circuit. In the 1:1 ratio mode, a two-step measurement is performed, where rebalancing in the second step is done with an additional injection circuit situated in one of the potential arms [E_0 in Fig. 1(a)]. The full automation of the bridge balancing with one lock-in amplifier and the reversing of source channels is performed with the second generation of coaxial switches based on [13]. The high stability of channel outputs and the low crosstalk between the two reference channels (both around 10 $\mathrm{nV\,V^{-1}}$) ensure the negligible influence of channel swapping and phase rotation of one channel on the output voltage of the second one.

TABLE I
LIST OF THE RESISTANCE (R) AND CAPACITANCE (C) STANDARDS EMPLOYED IN THE COMPARISON

Impedance label	Serial number	Nominal value	Description
R_1	G1_1132	$12\,906.4035\,\Omega$	NL Engineering UK Gibbings-type calculable quadrifilar resistance standard
R_2	G2_1137	$12\,906.4035\,\Omega$	NL Engineering UK Gibbings-type calculable quadrifilar resistance standard
R_{QHR}	G1511_41_96	$12\,906.4037\,\Omega$	PTB graphene AC QHR standard mounted on a METAS TO-8 holder [9]
C_1	10nF_SUT_METAS	$10\,\mathrm{nF}$	GUM-SUT construction with Murata GRM31 series C0G SMD capacitor [10]
C_2	INRIM_01-2021_8nF	$8\,\mathrm{nF}$	INRIM construction with GenRad 1409 capacitance standard ($1\,\mathrm{nF} + 2\,\mathrm{nF} + 5\,\mathrm{nF}$)

Fig. 2. METAS laboratory with some of the authors and the three installed bridges: from left to right, METAS DJIB, CMI FDIB, and INRIM-POLITO FDIB.

The INRIM-POLITO FDIB, shown schematically in Fig. 1(b), is optimized for 1:1 ratio magnitudes and is based on a polyphase digital source [14] with seven independently adjustable channels. Two channels provide E_1 and E_2, generating the main voltage ratio: one channel provides the auxiliary injection E_0, and the other channels are used to implement the 4TP definition of the impedances. The main, Kelvin, and current balances are detected by a lock-in amplifier, which is automatically switched across the various detection terminal pairs. A single complete measurement requires about 10 min to 15 min. The operating principle of the INRIM-POLITO FDIB, its balancing procedure, and its implementation without the full automation are described in detail in [15]. The bridge is now fully automated, and a number of improvements in the balancing procedure have been implemented.

The METAS DJIB, shown schematically in Fig. 1(a), relies on the reference voltages E_1 and E_2 generated by a dual JAWS system developed by the National Institute of Standards and Technology (NIST), Boulder, CO, USA. It consists of two JAWS chips mounted in separate probes, both cooled to 4.2 K within the same LHe dewar. Each JAWS chip comprises four arrays, totaling 51 240 Josephson junctions (JJs) [16]. While each JAWS chip can generate an rms voltage up to 1 V at a pulse repetition of 14.4 GHz, the system operates in a "zero-compensation" mode [17], limiting the maximum rms voltage to 0.3 V. The dual JAWS system provides reference voltages to a four-terminal-pair digitally assisted bridge developed by METAS [18]. This bridge allows accurate measurement of impedance ratios from 1:10 to 10:1 at frequencies ranging from less than 1 kHz to 80 kHz. The bridge is fully automated. The balancing and measurement procedure performed at a given frequency typically requires about 7 min. To compensate for the loading effect of the cables from the JAWS chip output inside the LHe dewar and the bridge in the laboratory, the balancing and measurement procedure must be repeated with the positions of the two impedance standards inverted. Therefore, the time required to perform a complete measurement cycle at a given frequency is about 14–16 min. For a comprehensive understanding of the DJIB, including its detailed working principle, balancing procedure, and performance metrics, refer to [19].

Before the international comparisons at PTB and METAS, the three bridges described in this section were also compared locally against the previous generation of transformer-ratio impedance bridges and reference standards operating at the respective institutions. The comparisons with the transformer-ratio bridges were described in [11], [15], [19], and [20].

III. COMPARED STANDARDS

The impedance bridges were compared with R:R and R:C standards at ratio magnitudes close to 1:1 (typically within few parts in 10^5). Table I and Fig. 3 list the standards employed in the comparison.

All room-temperature standards are temperature-controlled. A detailed description of the 10 nF capacitance standard 10nF_SUT_METAS is given in [10]; a description and a characterization of the graphene ac QHR standard are given in [9]. This device was operated in a liquid helium cryostat at a temperature of 4.2 K and at magnetic flux densities ranging from about 8 T to 10 T.

The standards R_1, R_2, C_1, and C_2 are defined as 4TP impedances. The ac QHR standard is defined as a 4TP impedance at two star points at the top of the cryostat, with triple connections [21] from the ac QHR standard to the star points. Four active current equalizers ensure the current equalization of the triple connections. The bridges were connected to the two standards under measurement with equal-length cables such that the cable effect is compensated by the ratio measurement [21]. The cable lengths were about 2 m and 4 m, depending on the position of the bridges in the laboratory with respect to the standards.

The matrix of Table II lists the impedance pairs that were measured during the comparison, with the measuring bridges and the measurement frequencies for each pair. For R:C measurements, the frequency f is such that $2\pi f RC \approx 1$. The

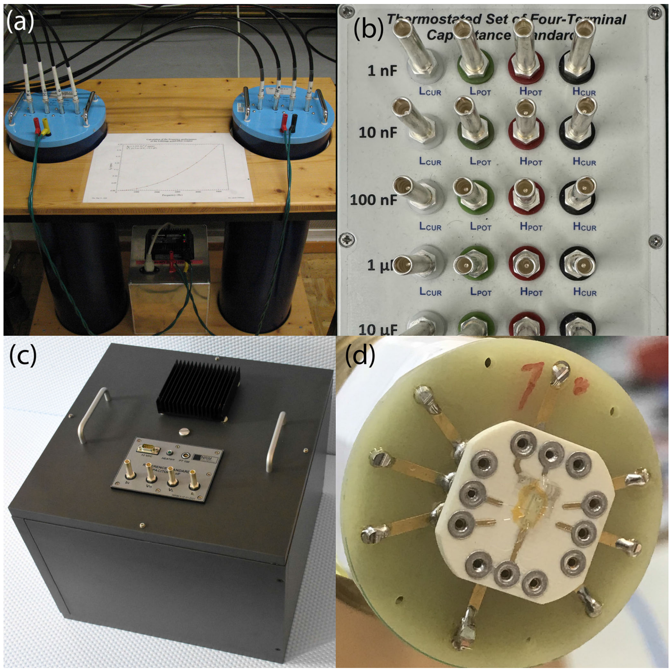

Fig. 3. Pictures of the impedance standards employed in the comparison. (a) R_1 and R_2. (b) C_1. (c) C_2. (d) R_{QHR}.

TABLE II

LIST OF THE IMPEDANCE STANDARDS PAIRS MEASURED DURING THE COMPARISON. FOR EACH PAIR, THE MEASURING BRIDGES AND THE MEASUREMENT FREQUENCIES ARE ALSO LISTED

	R_1	R_{QHR}
R_1		CMI INRIM-POLITO METAS 1233.147 Hz
R_2	CMI INRIM-POLITO METAS 1000 Hz, 1233.147 Hz, 5000 Hz	
C_1	CMI INRIM-POLITO METAS 1233.147 Hz	CMI INRIM-POLITO METAS 1233.147 Hz
C_2	INRIM-POLITO METAS 1541.434 Hz	

frequency 1233.147 Hz used for the measurements with C_1 is also of practical interest because it is close to one of those typically adopted for the representation of the farad and in international comparisons. The frequency 1541.434 Hz used for the measurements with C_2 is close to the one currently adopted at INRIM in the traceability chain of the farad [15]. During the measurements of the pair C_1:R_1, a General Radio 1422-CD variable air capacitor was connected in parallel to R_1, across the terminal pairs HC and LP to avoid increasing the cable correction, and set to a nominal value of 1.464 pF to adjust the phase angle to a value close to $-90°$.

IV. RESULTS AND DISCUSSION

In this section, we present the results of the comparison. We have chosen to display the results in the form of plots to better cover extended periods of time and highlight potential drifts. In all plots, the uncertainty bars represent standard uncertainties with coverage factor $k = 1$.

The symbols R_1, R_2, R_{QHR}, C_1, and C_2 denote both the standards (the objects) and their primary parameters, resistance, or capacitance. The symbols $Z(R_1)$, $Z(R_2)$, $Z(R_{\mathrm{QHR}})$, $Z(C_1)$, and $Z(C_2)$ denote the associated complex impedances. Where convenient, the impedances are represented with a parallel equivalent model, such that $Z(R_n) = R_n/(1-\mathrm{j}2\pi f \tau_n)$, with τ_n being the resistor time constant and $n = 1, 2$, and $Z(C_n) = 1/(G_n + \mathrm{j}2\pi f C_n)$, with G_n being the capacitor parallel conductance.

The plots in Fig. 4 show the results for the C_1:R_1 ratio measurements at 1233.147 Hz with all three bridges. It can be observed from Fig. 4(a) that the results for the magnitude ratio $|Z(C_1)/Z(R_1)|$ are generally compatible, for most measurements within the standard uncertainties, and for all measurements within the expanded uncertainties with coverage factor $k = 2$. However, Fig. 4(b) shows incompatibility between the measurements of the phase, $\arg Z(C_1)/Z(R_1) = \arg Z(C_1) - \arg Z(R_1)$. The discrepancies between the results of the INRIM-POLITO FDIB from those of the METAS DJIB decrease after October 29, date marked by the vertical dashed line. Before this date, the impedances in the INRIM-POLITO FDIB were exchanged from the forward to the reverse configurations only at the terminal pairs HP and HC, leaving the terminal pairs LP and LC unexchanged; as a result, the asymmetry of the Kelvin arm containing E_{L} was not compensated, and this caused a significant phase deviation. It was then decided to exchange the impedances at all terminal pairs, and the phase deviation has been reduced from October 29. There remains, however, a residual incompatibility between the phase measurements, which is likely due to an uncompensated asymmetry in the INRIM-POLITO FDIB between the forward and reverse configurations. This uncompensated asymmetry may be caused by either the source crosstalk (see [8]: this is accounted for in the uncertainty budget, but it might have been underestimated) or the potentially limited efficiency of the passive current equalizers employed in the network of the INRIM-POLITO FDIB. In fact, about the latter cause of asymmetry, common-mode current measurements in the INRIM-POLITO FDIB yielded excessively high values in some branches of the bridge network for certain arrangements of the bridge equipment in the laboratory, with values changing from the forward to the reverse configurations, and this suggests that there were measuring conditions in which the current equalizers were not enough effective. Similar behavior was observed with the CMI FDIB on later measurements [see Fig. 5(b) and (d)], where the phase deviation of the measurement was significantly lowered when all terminal pairs of C_1 and R_1 where swapped or even when only the reference voltage sources E_1 and E_2 were swapped. Additional measurements of crosstalk between sources E_1 and E_2 in the CMI FDIB demonstrated negligible crosstalk effects (on the level of 10^{-9}) [22]; thus, the current equalization in the

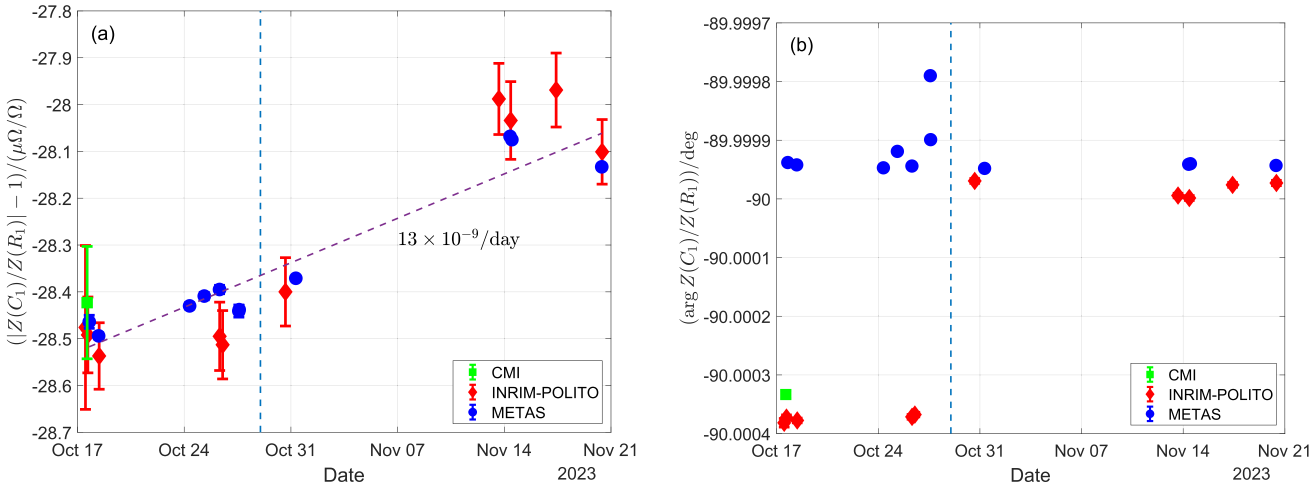

Fig. 4. Measurement results for the C_1:R_1 ratio at 1233.147 Hz. (a) Deviation from the unit of the impedance magnitude ratio, $|Z(C_1)/Z(R_1)|$. (b) Angle of the impedance ratio, $\arg Z(C_1)/Z(R_1)$. The uncertainty bars represent the standard uncertainties with coverage factor $k = 1$. The vertical dashed line in plots (a) and (b) marks October 29, when, afterward, the impedances in the INRIM-POLITO FDIB were fully exchanged between the forward and reverse configurations. The oblique dashed line in plot (a) represents the least-square fit of the METAS DJIB measurements, indicating a relative drift coefficient of C_1 of about 13×10^{-9} d^{-1}.

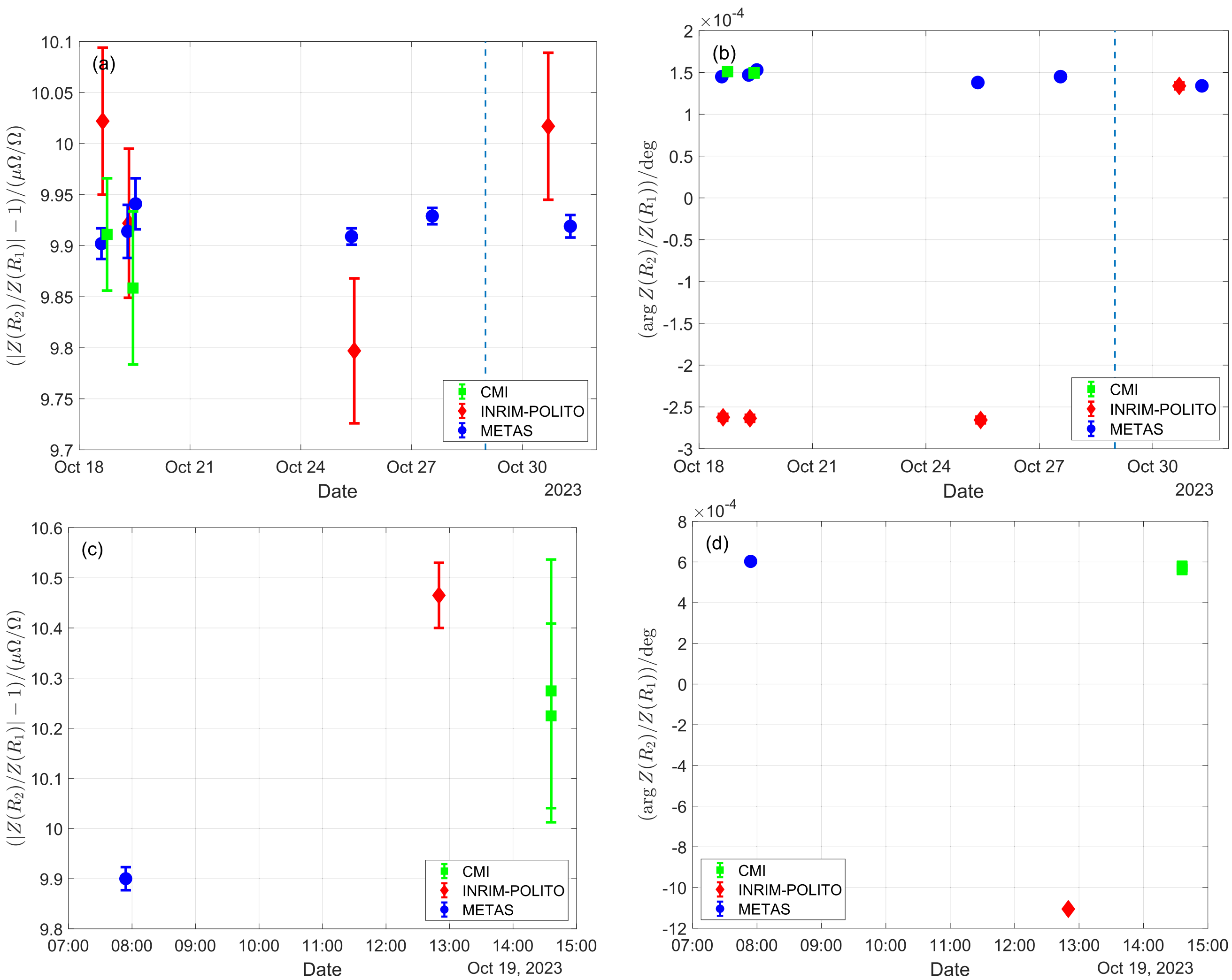

Fig. 5. Measurement results for the R_2:R_1 ratio. (a) and (c) Deviation from the unit of the impedance magnitude ratio, $|Z(R_2)/Z(R_1)|$. (b) and (d) Angle of the impedance ratio, $\arg Z(R_2)/Z(R_1)$/ (a) and (b) Measurements at 1233.147 Hz. (c) and (d) Measurements at 5000 Hz. The uncertainty bars represent the standard uncertainties with coverage factor $k = 1$. The vertical dashed line in plots (a) and (b) marks October 29, as in Fig. 4.

network is supposed to be the source of asymmetry. Further investigations on these effects will be performed in the future.

Fig. 4(a) reports also the relative drift of $|Z(C_1)/Z(R_1)|$, which virtually coincides with the drift of C_1. The oblique

TABLE III

INRIM-POLITO FDIB MEASUREMENT RESULTS FOR THE R_2:R_1 RATIO (SEE TEXT FOR DETAILS)

Date	f	$(R_2 - R_2^{\mathrm{REF}})/R_2^{\mathrm{REF}}$ nΩ/Ω	$\tau_2 - \tau_2^{\mathrm{REF}}$ ps	Repetitions	Measurement time
22 Nov 2023	1000.000	35(75)	13(11)	6	48 min
22 Nov 2023	5000.000	57(140)	13(5)	8	95 min
23 Nov 2023	1008.704	61(72)	5(11)	8	65 min
23 Nov 2023	4983.000	−120(110)	20(6)	2	19 min
23 Nov 2023	4983.000	−116(110)	12(5)	8	94 min

TABLE IV

INRIM-POLITO FDIB MEASUREMENT RESULTS FOR THE C_2:R_1 RATIO AT 1541.434 Hz COMPARED WITH THE METAS DJIB RESULTS

Date	$(C_2^{\mathrm{INRIM}} - C_2^{\mathrm{METAS}})/C^{\mathrm{nom}}$ nF/F	$G_2^{\mathrm{INRIM}} - G_2^{\mathrm{METAS}}$ nS	Repetitions	Measurement time
09 Nov 2023	−2(78)	−0.958(31)	2	30 min
09 Nov 2023	−304(78)	−0.956(31)	6	77 min
04 Dec 2023	−27(81)	−0.562(80)	8	74 min

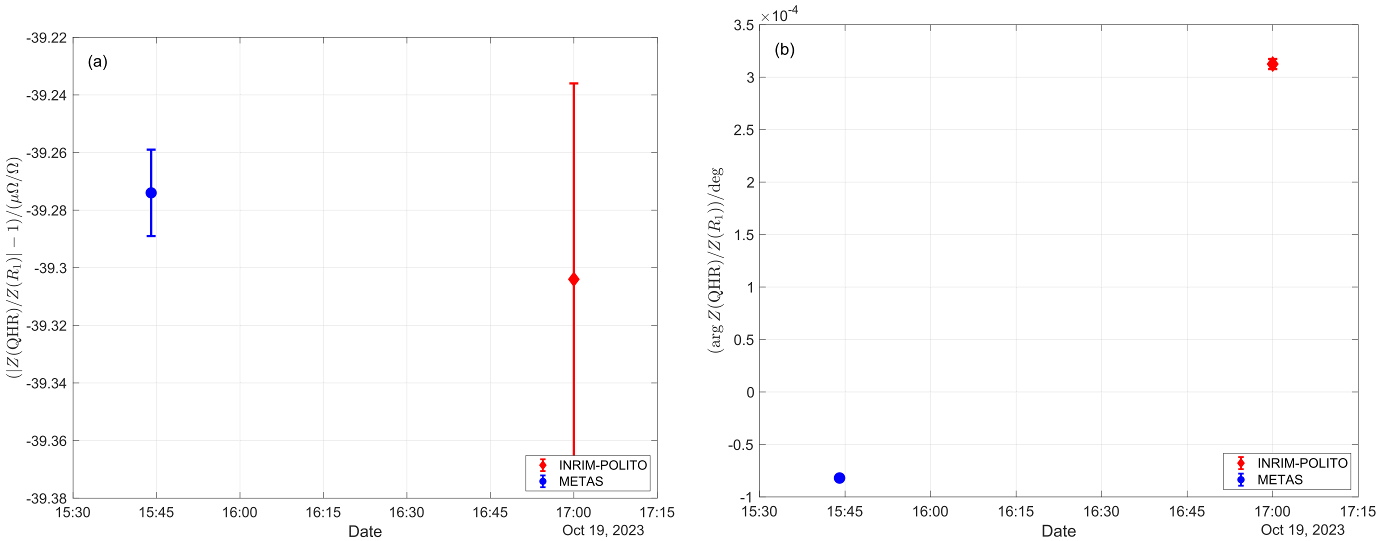

Fig. 6. Measurement results for the R_{QHR}:R_1 ratio at 1233.147 Hz. (a) Deviation from the unit of the impedance magnitude ratio, $|Z(R_{\mathrm{QHR}})/Z(R_1)|$. (b) Angle of the impedance ratio, $\arg Z(R_{\mathrm{QHR}})/Z(R_1)$. The uncertainty bars represent the standard uncertainties with coverage factor $k = 1$.

dashed line in plot (a) represents the least-squares fit of the METAS DJIB measurements, indicating a relative drift coefficient $(\mathrm{d}C_1/\mathrm{d}t)/C_1 \approx 13 \times 10^{-9}$ d^{-1}. Since C_1 is of recent construction, this result yielded a preliminary characterization of its stability. The drift of R_1 was measured in dc during the same period being $(\mathrm{d}R_1/\mathrm{d}t)/R_1 \approx 2 \times 10^{-9}$ d^{-1}.

The plots in Fig. 5(a) and (b) show the results for the R_2:R_1 ratio measurements at 1233.147 Hz. As in the previous case, the magnitude ratio results are compatible with the expanded uncertainties with coverage factor $k = 2$, and the phase measurements for the INRIM-POLITO FDIB deviate significantly from the other measurements before October 29. After this date, there is full compatibility also on the phase measurements. Indeed, the bridge network set for R:R ratio measurement is intrinsically more symmetric under impedance reversal with respect to the case of R:C ratio measurements, and the problem of uncompensated asymmetries is here less significant. The plots in Fig. 5(c) and (d) show the results for the R_2:R_1 ratio measurements at 5000 Hz. These measurements were performed before October 29, and the reported INRIM-POLITO FDIB result at 5000 Hz is incompatible with the other two results. Both the magnitude and phase discrepancies were removed after October 29 by the full exchange of the impedances (see the results in the Appendix).

V. CONCLUSION

Onsite comparisons have always been an invaluable tool to validate and improve measuring systems at the highest level of accuracy because, with rare exceptions (see [23]), traveling standards do not typically have enough stability. Moreover, onsite comparisons allow NMIs to access a wide range of standards in the same place at the same time. The results herewith presented confirm the significance of onsite comparisons and the diagnostic power that these have in highlighting issues that could go undetected otherwise.

This comparison and the previous one reported in [5] both performed within the framework of the project EURAMET TC-EM 1501, *technical assessment of novel digital impedance bridges*, have demonstrated that dual Josephson impedance bridges and electronic fully digital impedance bridges perform with state-of-the-art accuracy in the kilohertz frequency range, and these kind of bridges allow NMIs to realize the unit of capacitance directly from a calculable resistance standard or, with some more technical care, from the quantum Hall effect.

It should be finally noted that impedance comparisons are typically limited to the primary parameters of the compared impedances (resistance, capacitance, or inductance), and the secondary parameters (time constant, dissipation factor, or series resistance), which are related to the impedance phase angle, are not considered quantities of interest. This comparison has instead shown that phase angle measurements need to be considered for complete characterization and perfection of impedance measuring systems (see also [3]).

Appendix
Further Results

This section reports measurements from the INRIM-POLITO and METAS bridges only, and we have chosen to display the results mostly in the form of tables because each impedance pair was measured for at most a day or two.

Table III reports the results for the $R_2{:}R_1$ ratio measurements at around 1 and 5 kHz with the INRIM-POLITO FDIB only. For this measurement, the two calculable resistance standards R_1 and R_2 were calibrated against the dc QHR standard by means of a cryogenic current comparator (CCC), and then, the ac/dc transfer coefficients were used to calculate the reference resistance values R_1^{REF} and R_2^{REF}, and the reference time constant values τ_1^{REF} and τ_2^{REF} at the frequencies of interest. The ratio $Z(R_2)/Z(R_1)$ was measured with the INRIM-POLITO FDIB, and values R_2 and τ_2 were determined from R_1^{REF} and τ_1^{REF}. Table III reports the deviations of the measured values R_2 and τ_2 from the reference values R_2^{REF} and τ_2^{REF}. The reported uncertainties are only those due to the INRIM-POLITO FDIB, not considering the uncertainties of R_1^{REF}, R_2^{REF}, τ_1^{REF}, and τ_2^{REF}. Taking into account that the uncertainty of τ_2^{REF} is about 100 ps, all measurements are compatible in both magnitude and phase. At 1 kHz, the measurement time for one repetition is about 8 min, whereas, at 5 kHz, the measurement time for one repetition increases at about 12 min. This is due to the fact that the waveforms at 5 kHz are synthesized with fewer samples, thus reducing the adjustment resolution.

Table IV reports the results for the $C_2{:}R_1$ ratio measurements at 1541.434 Hz performed with both the INRIM-POLITO FDIB and the METAS DJIB. The number of repetitions and the measurement time are those of the INRIM-POLITO FDIB. For this measurement, the calculable resistance standard R_1 was calibrated against the dc QHR standard by means of the CCC, and then, the ac/dc transfer coefficients were used to calculate the reference resistance value R_1^{REF} and the reference time constant value τ_1^{REF} at the frequency of interest. The ratio $Z(C_2)/Z(R_1)$ was measured with both the INRIM-POLITO FDIB and the METAS DJIB, and values C_2^{INRIM}, G_2^{INRIM}, C_2^{METAS}, and G_2^{METAS} were determined from R_1^{REF} and τ_1^{REF}.

The November 9 measurement with the INRIM-POLITO FDIB consisted of eight successive repetitions, which have been split into two parts in Table IV. For the first two repetitions, the results for C_2 are well compatible, but, for the next six repetitions, the results are clearly no longer compatible. This phenomenon was likely due to the fact that C_2 was first connected to the METAS DJIB with the shorter cables (about 2 m long) and then to the INRIM-POLITO FDIB with the longer cables (about 4 m long), and this caused a thermal transient in the capacitance standard due to the change in the thermal load toward the ambient. This thermal transient then caused a change in the capacitance during the measurement. This problem was solved during the December 4 measurement, in which the 4-m-long cables were used with both bridges and the capacitance value remained stable.

Table IV also shows that the measurement results for G_2 are not compatible. This is again due to the incompatibility of phase measurements discussed in Section IV.

Finally, the plots in Fig. 6 show the results for the $R_{\mathrm{QHR}}{:}R_1$ ratio measurements performed at 1233.147 Hz with both the INRIM-POLITO FDIB and the METAS DJIB. It should be noted that these measurements were taken on October 19, before the full exchange of the impedances in the INRIM-POLITO FDIB, and the results are similar to those of Fig. 5 on the same date at the same frequency: the magnitude ratio results are compatible, whereas the phase results are incompatible. The phase deviation between the INRIM-POLITO FDIB and the METAS DJIB measurements is the same in Figs. 5 and 6 (there is a fictitious change of sign, which is just due to the connection order of the impedances). Later measurements with the QHR standard revealed a malfunction of the INRIM-POLITO FDIB when connected to the QHR network due to an interaction with the active current equalizers employed at METAS. This interaction was likely caused by an unwanted ground loop current that shifted the balance of the bridge, which unfortunately could not be eliminated during the time of the comparison. For this reason, the result with the INRIM-POLITO FDIB from Fig. 6 should be considered with caution.

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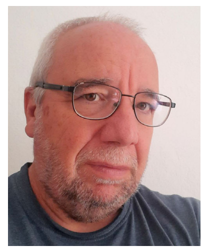

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