10×10 GΩ Guarded Hamon Network for the Modified Wheatstone Bridge for High Value Resistors Calibration

Flavio Galliana, Pier Paolo Capra, and Enrico Gasparotto

***Abstract*—At the National Institute of Metrological Research (INRIM), a Hamon guarded 10 x 100 MΩ network was developed to improve the traceability levels of dc resistance at 1 GΩ level. Utilizing and revisiting this project, a Hamon 10 x 10 GΩ network is developed to extend the capabilities of the Hamon scaling technique up to 100 GΩ. The novelty of the 10 x 10 GΩ network is its improved guard system, and the improvement for INRIM is the extension of the range of the Hamon scaling method up to 100 GΩ A description of this technique at INRIM, accurate construction details of the network and of its particular suitability for the modified Wheatstone bridge for high resistors calibration measurement method are given. The 1:100 transfer reliability test of the network gave satisfactory results. An uncertainty budget from 10 kΩ to 100 GΩ is worked out. Some measurement results on the network, both in parallel and in series configuration, are shown.**

***Index Terms*—Guard system, Hamon resistors, high resistance measurements, measurement uncertainties, traceability.**

I. INTRODUCTION

AT THE NATIONAL Institute of Metrological Research (INRIM) in recent years, the resistance scale in the range 100 kΩ–100 TΩ has been revised, realizing a measurement method for high resistors calibration, based on a digital voltmeter and a dc voltage calibrator [1]. A Hamon scaling technique [2], involving commercially available Hamon boxes and a recently constructed guarded 10 × 100 MΩ Hamon network [3], is operated. Taking into account an appreciable work on Hamon networks, research has been performed at the National Institute of Standards and Technology (NIST) [4], a guarded 10×10 GΩ Hamon network [5] suitable for application with the Wheatstone bridge has also been constructed to extend the range of the Hamon scaling technique up to 100 GΩ at INRIM. Another accurate method based on a modified Wheatstone bridge for high resistors calibration [6]–[8] also operates at INRIM.

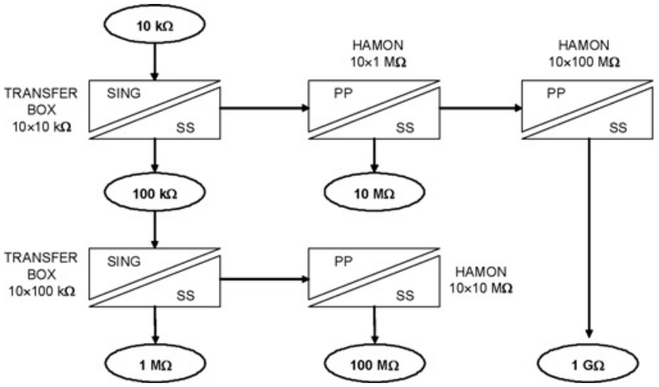

Fig. 1. Traceability of the Hamon method from 10 kΩ to 1 GΩ.

II. HAMON SCALING TECHNIQUE AT INRIM

The traceability chain of this technique operating actually at INRIM is shown in Fig. 1. The chain starts from a high performance 10-kΩ standard resistor with temperature coefficients $\alpha_{23} = -3.4 \times 10^{-8}/\text{C}$, $\beta = -2.9 \times 10^{-8}/\text{C}^2$ and drift on the order of 7.5×10^{-8}/year [9]. This resistor is calibrated at a 2σ relative uncertainty of 2.0×10^{-7} in terms of the INRIM 1 Ω primary group of standard resistors referred to the recommended value $R_{\text{K}-90}$. With two commercial 10 × 10 kΩ and 10 × 100 kΩ transfer boxes, both configured to measure their resistors singularly or in series,[1] two high stability 100 kΩ and 1 kΩ standard resistors are calibrated. With the same 10 × 10 kΩ and 10 × 100 kΩ transfer boxes also the parallel outputs of a 10×1 MΩ and of a 10×10 MΩ Hamon boxes are calibrated. The series outputs of these two boxes are compared, respectively, with two high performance 10 MΩ and 100 MΩ standard resistors. With the series output of a commercial 10 × 1 MΩ box, the parallel output of the 10 × 100 MΩ Hamon network [3] is also calibrated. The comparisons among each pair of resistors are made in a four-terminal configuration, in 1:1 ratio at 10 V, to a high accuracy digital multimeter (DMM). The series output of the 10 × 100 MΩ network is compared with a high performance 1 GΩ standard resistor at 100 V with the modified Wheatstone bridge method.

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[1] Each resistor of the box is compared in 1:1 ratio with the lower value standard, then the series is compared in the same ratio with the higher standard making the 1:10 unit transfer.

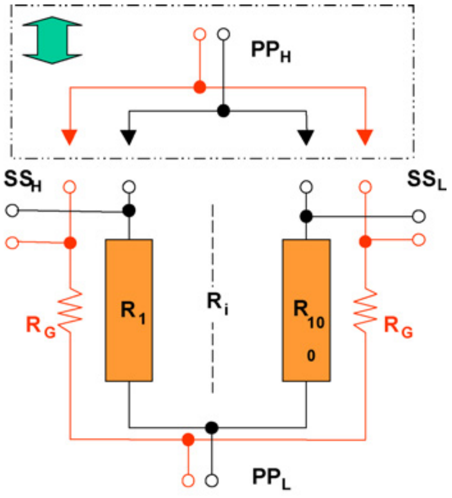

Fig. 2. Scheme of the 10×10 GΩ Hamon network. With R_i and with R_G, respectively, the main resistors, the guard resistors (≅20 MΩ) with SS_H, SS_L, PP_H e PP_L, respectively, the high and low outputs of the series and parallel configurations are indicated.

III. 10 × 10 GΩ HAMON NETWORK

The network, whose scheme is reported in Fig. 2, is made with a chain of ten 10 GΩ nominal value resistors to perform the traceability transfer from 1 GΩ to 100 GΩ. The resistors forming the network are film-type resistance elements. At NIST, a treatment technique on high value resistors also used for Hamon networks construction was realized with great advantage [10]. Ten resistance elements with the best possible match have been selected among several elements belonging to the same production lot, reaching a matching level on the order of 1.5×10^{-3}. The selected resistors were then modified to apply the guard circuit of the network; each resistor was put into a glass tube closed at the ends with two aluminum cylinders (Fig. 3) on which a resistors guard chain maintain a guard voltage.

Between the terminals of the 10 GΩ resistance elements and the aluminum cylinders, a PTFE bust was inserted to electrically isolate the measurement and guard circuits. The glass tube supports the guard chain with a suitable insulation, protects the resistors from environment variations and dust that can sensitively affect the measurement of high value resistors. The leakage resistances between the elements of the resistor were measured with a teraohmmeter (Fig. 3). The average insulation resistance between the Teflon and aluminum cylinders of the terminals of the encapsulated resistance element was about 10^{14}Ω, while the average insulation resistance between the alumininum cylinders of the terminals of the resistor was about 3×10^{13}Ω.

IV. DEVELOPMENT OF THE NETWORK

The ten main resistors are kept together with a cylindrical structure made with two perforated aluminum plates with a central plastic insulating spacer. The whole system is placed in an aluminum cylindrical case that acts both as electromagnetic shield and as mechanical support.

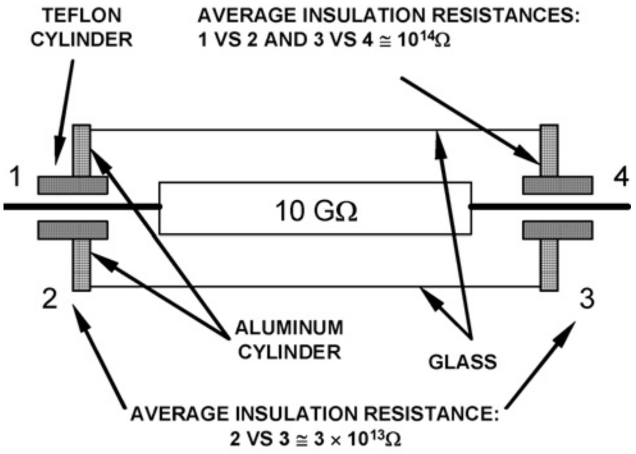

Fig. 3. Scheme of the resistor in the protection case. The case is a glass tube closed at the extremities with two aluminum cylinders electrically connected to the guard resistors. The insulation among the terminals of the 10 GΩ resistance element is obtained by two PFTE busts.

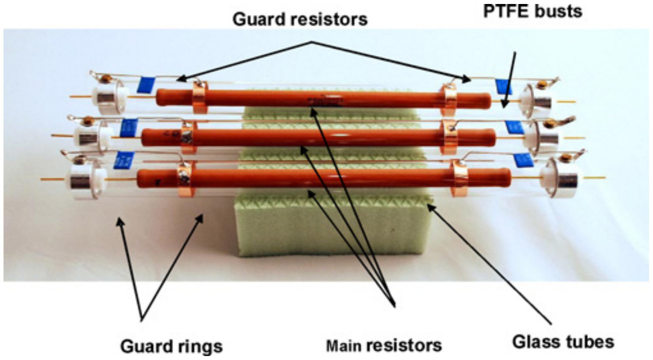

Fig. 4. View of the main components of the 10 × 10 GΩ Hamon network.

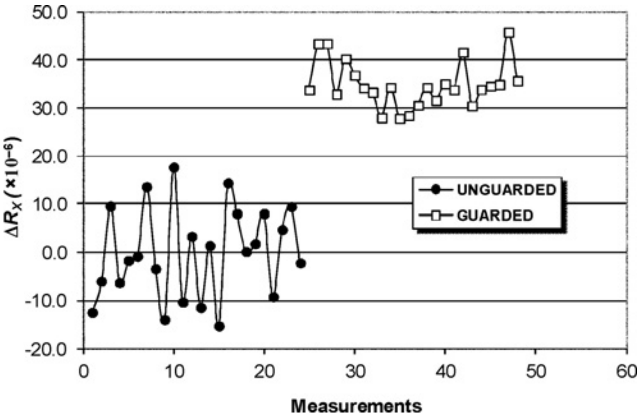

Fig. 5. Relative differences between guarded and unguarded measurements of the network in series configuration at 1000 V in ratio 100:1 with a high performance 1 GΩ standard resistor.

A platinum thermometer is inserted in the central part of the case near the resistors. the device for the parallel switching was put on one side of the case. The dc motor working as an actuator is put outside to avoid electromagnetic noises. The guarding system is composed of twenty 10 MΩ resistors mounted on the cylindrical body of the main resistors, as shown in Fig. 4. Each main resistor has two guard resistors

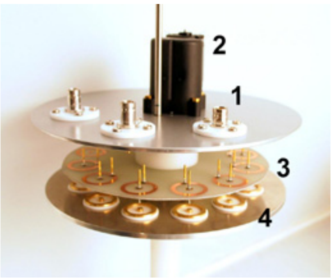

Fig. 6. View of construction details. 1. PTFE insulated connectors. 2. Motorized actuator. 3. Group of telescopic contacts for the parallel connection. 4. Shielded coaxial contacts.

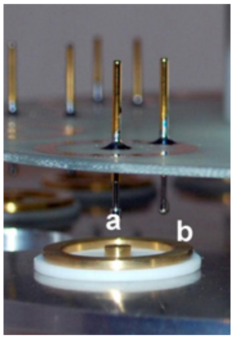

Fig. 7. View of other construction details. (a) Central contact of the parallel connection of the main resistors. (b) External contact connected to the guard voltage.

connected in series and placed at its terminals. All guard resistors were measured and opportunely selected and coupled to reach the best match among each main resistor and its two guard resistors. The project of the guard system, although deriving from the one developed for the $10 \times 100\,\mathrm{M}\Omega$ Hamon network [3], has been significantly modified as this guard system is a dynamic one acting both for parallel and series configurations of the network. The series-parallel switching system allows configuring in series or in parallel both main and guard resistors. The guard system of the network [3] is a static one consisting of a series of ten $10\,\mathrm{M}\Omega$ resistors connected permanently in series and acting only when the network is in series configuration. This improvement has been made to assure a comparable leakage errors suppression to both configurations of the network. To test the effectiveness of the guarding system, some measurements on the network in series configuration at 1000 V in ratio 100:1 with a high performance $1\,\mathrm{G}\Omega$ standard resistor connecting and disconnecting the guard chain of the network have been made. The unguarded measurements were lower than those guarded on the order of 3.5×10^{-5} and with higher instability (Fig. 5).

The ten main resistors are normally connected in series configuration. The parallel configuration is obtained by a micromotored axis acting on a printed board with a set of electrical telescopic contacts (Figs. 6 and 7). In Figs. 8–10, the internal and external views of the Hamon network are reported. The two external sides of the network for the series and parallel configurations are equipped, respectively, with N (Fig. 9) and BNC (Fig. 10) connectors for the Hi and Lo terminals. In the series side, there are also two four pins LEMO connectors for an auxiliary guard chain input and for the thermomether input. The parallel side of the $10 \times 10\,\mathrm{G}\Omega$ network is suitable for the 1:1 comparison with the series output of the $10 \times 100\,\mathrm{M}\Omega$ network, as shown in Fig. 10. The connector to connect the Hamon to the detector is a BNC one for both sides. In the parallel side, an input to connect the network case to ground potential is also available.

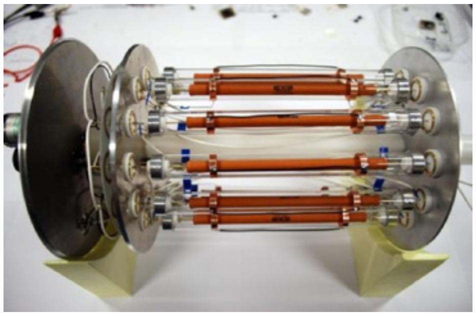

Fig. 8. Internal view of the Hamon network.

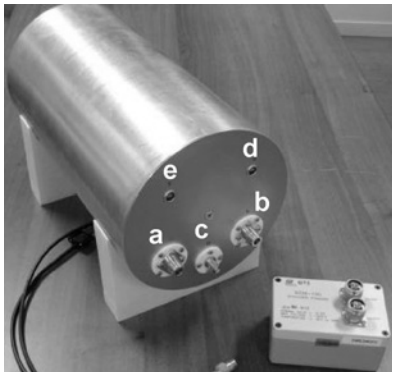

Fig. 9. External view of the Hamon network. Series side. (a) Hi N connector. (b) Lo N connector. (c) BNC connector to the detector of the modified Wheatstone bridge. (d) Thermometer input. (e) Auxiliary input of the guard chain.

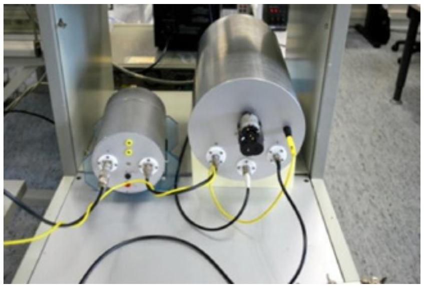

Fig. 10. External view of the Hamon network (right case): parallel side with BNC connectors. In the photo, an input for the ground connection of the network case and the dc motor for parallel to series switch are also visible.

V. HAMON DIRECT CONNECTION SUITABLE FOR THE WHEATSTONE BRIDGE CIRCUIT

The modified Wheatstone bridge method for high resistances is a well-known and reliable measurement method [6]–[8]. This method was also implemented at INRIM. For this reason, the project of the $10 \times 10\,\mathrm{G}\Omega$ network was oriented

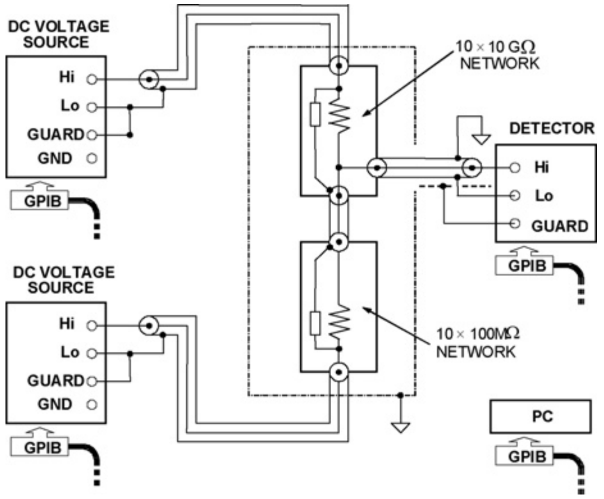

Fig. 11. Scheme of the Wheatstone bridge method comparing the INRIM $10 \times 100\,\mathrm{M\Omega}$ and $10 \times 10\,\mathrm{G\Omega}$ Hamon networks.

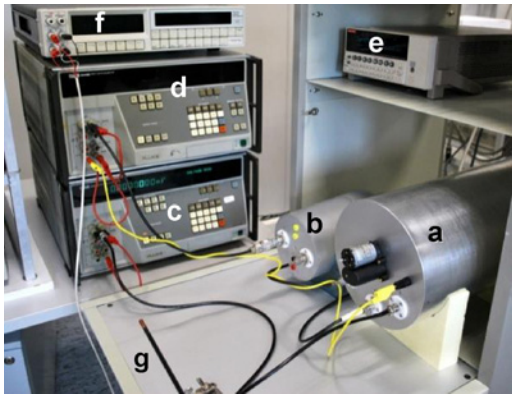

Fig. 12. View of the measurement setup of Fig. 11. (a) $10{\times}10$ GΩ Hamon network. (b) $10{\times}100$ MΩ Hamon network. (c) dc voltage calibrator. (d) dc voltage calibrator. (e) Detector (high performance electrometer). (f) DMM to measure the temperature inside the network. (g) Thermometer.

for the utilization with this technique. To simplify the circuit and to avoid many connections, the network has a direct low-impedance connection to the detector both for the parallel and series configurations (Fig. 11). This connection minimizes the triboelectric currents due to the friction between the insulator and the conductor of the cable to the detector. This assures a simplification of the circuit and an improved measurements repeatability. This connection is also used for the distribution of the ground potential through the detector. The circuit has been developed with shielded cables and coaxial technical solutions typical of ac current measurements to minimize electromagnetic noises. The photo of the setup is shown in Fig. 12.

VI. METROLOGICAL COMPATIBILITY TESTS ON THE NETWORK

To evaluate the performance of the Hamon network as the 1:100 transfer standard, two compatibility checks with two other measurement techniques were made. First, the Hamon network was calibrated in free air both in parallel and in series, respectively, at 100 V and 1000 V with the Wheatstone bridge method using as reference a high performance $1\,\mathrm{G\Omega}$ standard resistor (Fig. 13). The measurements have been performed in a shielded laboratory at a temperature of (23 ± 0.5) °C. The two obtained values showed a relative difference of 8.1×10^{-6} at $100\,\mathrm{G\Omega}$. The procedure depicted in Fig. 14 has been applied successively. In the first step, the Hamon network $10{\times}100\,\mathrm{M\Omega}$ [3] was calibrated in parallel configuration at 10 V using as a reference resistor a high-performance $10\,\mathrm{M\Omega}$ standard resistor placed in a thermo-regulated air bath used to maintain the resistance scale at $10\,\mathrm{M\Omega}$ level. The measurement was performed in a four-terminal configuration by substitution with a high precision DMM, following the instructions of the user manual of the DMM for the guard connection. In a second step, the series output of the same network was compared at 100 V with the parallel input of the $10 \times 10\,\mathrm{G\Omega}$ Hamon network with the Wheastone bridge method in ratio 1:1. Then, a first series value of the $10 \times 10\,\mathrm{G\Omega}$ Hamon network was obtained with Hamon transfer. In the third step, the series output of the $10 \times 10\,\mathrm{G\Omega}$ network was calibrated at 1000 V always with the Wheastone bridge versus the series output of the $10{\times}100\,\mathrm{M\Omega}$ network in ratio 1:100 (right side of Fig. 14), obtaining a second series value of the $10 \times 10\,\mathrm{G\Omega}$ Hamon network. The two obtained $100\,\mathrm{G\Omega}$ values of the network showed a relative difference of 1.4×10^{-5} that is within the

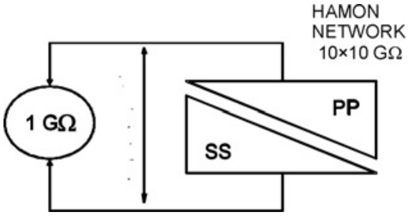

Fig. 13. Scheme of the first compatibility check on the Hamon network.

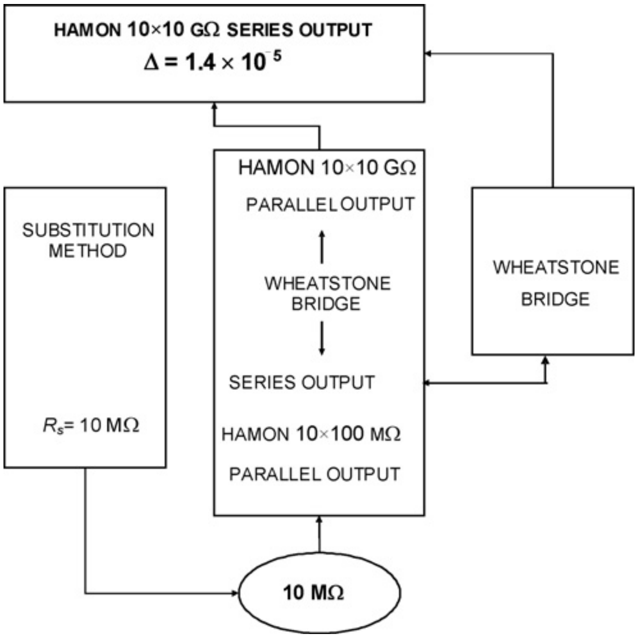

Fig. 14. Scheme of the second compatibility check on the Hamon network.

TABLE I

UNCERTAINTIES BUDGET FROM 10 kΩ TO 100 GΩ

Step	Uncertainty Source	Type	$1\sigma(\times 10^{-6})$
	Uncertainty, drift 10 kΩ	B	0.1
10 kΩ	Therm. voltages instab.	B	0.1
	DMM non lin. instab.	B	0.2
	10 kΩ–10 kΩ RSS stdv	A	0.2
Transfer	1:10 transfer error	B	0.5
Box	Temp. instability, drift	B	0.3
10 × 10 kΩ	Therm. voltages instab.	B	0.1
	DMM non lin. instab.	B	0.3
	Repeatability	A	1.0
	Temp. instability, drift	B	0.2
	Therm. voltages instab.	B	0.1
Hamon	1:100 transfer error	B	1.0
10 × 1 MΩ	DMM non linear. input imp. bias curr. instab.	B	1.0
	Repeatability	A	1.0
	Temp., hum. instab, drift	B	1.3
	Therm. voltages instab.	B	negl.
Hamon	Leakages	B	1.0
10 × 100 MΩ	Connections	B	1.0
	1:100 transfer error	B	1.2
	Wheat. bridge	B	5.5
	Repeatability	A	1.2
	Temp., hum. instab, drift	B	5
	Therm. voltages instab.	B	negl.
	Leakages	B	5.0
Hamon	Connections	B	1.0
10 × 10 GΩ	1:100 transfer error	B	7.0
	Wheat. bridge	B	24
	Repeatability	A	10
100 GΩ standard		Total RSS	28.6

uncertainties of the two measurement ways. The result of these compatibility checks allows the addition of the network in the traceability chain of the INRIM Hamon scaling technique.

VII. CALIBRATION AND USE OF THE HAMON NETWORK

The traceability chain in which the network is now involved is shown in Fig. 15. The chain starts from the previously cited high precision 10 kΩ standard resistor [9]. Passing through a high stability 10 × 10 kΩ transfer box, the parallel output of a Hamon 10 × 1 MΩ commercial box is calibrated. The parallel output of the 10 × 100 MΩ Hamon network [3] is compared with the series output of the Hamon 10 × 1 MΩ. All these comparisons are performed in 1:1 ratio with a DMM. The comparison of the series output of the 10 × 100 MΩ Hamon network with the parallel output of the 10 × 10 GΩ and the comparisons of the series output of the 10 × 10 GΩ network with a high performance 100 GΩ used to maintain the unit at this level are made with the modified Wheatstone bridge.

VIII. UNCERTAINTIES BUDGET

In Table I, the steps of the Hamon scaling method from 10 kΩ to 100 GΩ at INRIM according to the traceability chain of Fig. 15, along with their standard (1σ) uncertainty components, are listed. The uncertainty values reported in the last steps of the table have to be successively confirmed with further measurements. Although humidity is an environmental parameter that affects high resistance measurements and high value resistors as reported in [11] and [12] in our budget, a specific component was not added, as considered negligible or widely included in the drift component. This because normally Hamon networks don't act as long-time standards, but as short-time transfer standards (typically from some hours to a few days), period in which humidity can be maintained within tolerance values during the traceability transfer.

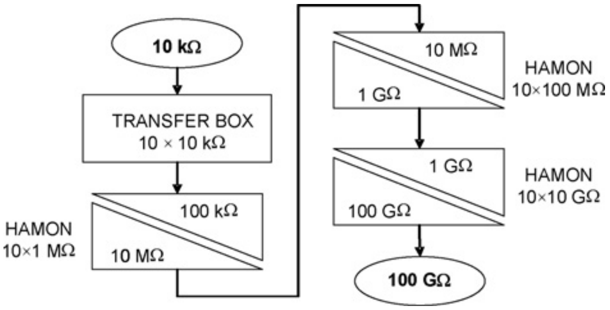

Fig. 15. Traceability chain from 10 kΩ to 100 GΩ.

IX. EXPERIMENTAL RESULTS

In Figs. 16 and 17, the behaviors of the Hamon network, respectively, in parallel and in series both compared with the

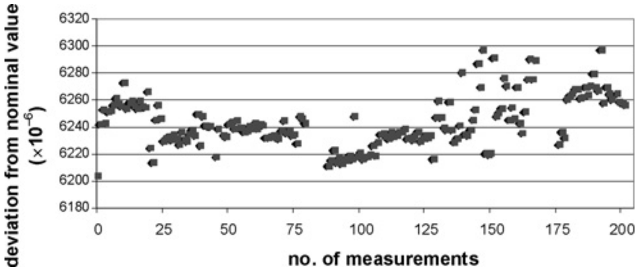

Fig. 16. Measurements trend of the $10 \times 10\,\mathrm{G\Omega}$ Hamon network in parallel configuration versus the series output of the $10 \times 100\,\mathrm{M\Omega}$ Hamon network in a 14-h measurement period. The gaps between measurements groups are due to the different measurement polarities.

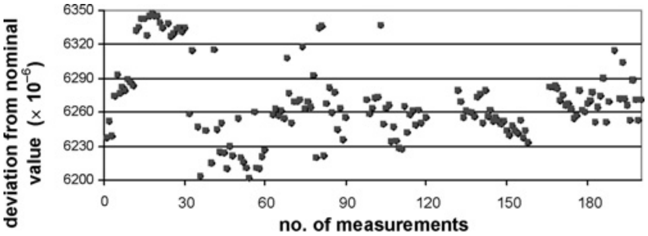

Fig. 17. Measurements trend of the $10 \times 10\,\mathrm{G\Omega}$ Hamon network in series configuration versus the series output of the $10 \times 100\,\mathrm{M\Omega}$ Hamon network network in a 14-h measurement period. The gaps between measurements groups are due to the different measurement polarities.

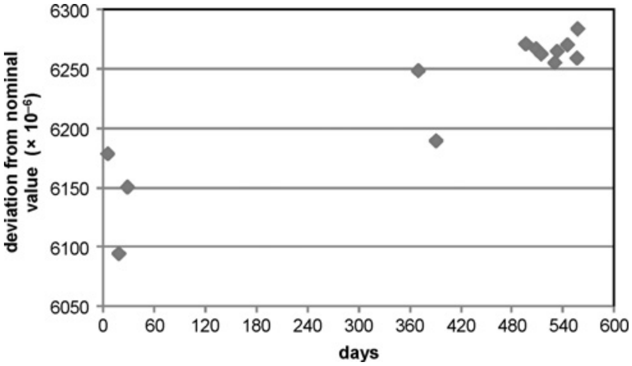

Fig. 18. Long-term drift of the $10{\times}10$ GΩ Hamon network in parallel configuration in a 20-months period.

series output of the $10 \times 100\,\mathrm{M\Omega}$ Hamon network are shown. Both measurements required about 14 h.

In Fig. 18, some measurements of the parallel output of the network obtained with the modified Wheatstone bridge in a time period of about 20 months since its construction are shown.

During the first 14 months measurement period some internal connection changes in the network have been applied to achieve a better resistance stability. Their effect can be observed in the last plotted measurements that confirm also the long-term drift of the network. From other measurements on the network in parallel configuration made with the DMM-dc voltage calibrator [1], [8], the network showed a satisfactory mid-term (typically five days) stability on the order of 2–$3{\times}10^{-6}$/day, so the Hamon network could be used in a series configuration as a transfer standard for a period of about a week without recalibration. Anyway, a long-term humidity dependence of the network has been detected. This fact suggests further investigations on the effectiveness of the guard system. For humidity control also the solution presented in [13] could be taken into account.

X. CONCLUSION

With the development of the $10 \times 10\,\mathrm{G\Omega}$ Hamon network INRIM can extend the range of the Hamon measurement method up to $100\,\mathrm{G\Omega}$. In the past, measurements at this level were made at INRIM only with the methods described in [8]. Future goals of this paper will be a further test on the effectiveness of the guarding circuit, the permanent placement of the system involving the Hamon networks and high value resistors in a rigorously temperature and humidity controlled laboratory, or the development or acquisition of thermo-regulated air baths. With this new Hamon network, it will also be possible to extend the capabilities of the calibration system for pico-ammeters at dc current already developed at INRIM [14].

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