# Annales Patroniensis


vol. I Nr. 3 22.XII.2023

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Vážení čitatelia,

V živote časopisov, rovnako ako v živote ľudí ako aj celej spoločnosti, sa nevyhnutne vyskytujú ťažké obdobia, ktoré sa niekedy označujú aj slovom „kríza“. V takomto období sa nechtiac ocitol aj náš časopis, keď sa nám nepodarilo do riadnej uzávierky získať ani jediný príspevok.

Keďže sme si však vedomí závažnosti poslania, ktoré pre slovenskú a svetovú vedu plníme, redakcia sa jednomyseľne rozhodla prijať jeden oneskorený článok, ktorý týmto tvorí jadro nášho posledného čísla v prvom ročníku.

Už pri svojom vzniku mali Patrónske Anály ambíciu neobmedzovať svoj dosah a rozlet len na geograficky obmedzené územie v okolí bratislavskej Patrónky. Ambícia bol globálny, dokonca celovesmírny dosah. Redakcia svoj plán plní a do tretieho čísla, ktoré práve čítate získala príspevok až z ďalekej Dúbravky. Vlak sa rozbieha...

Ďakujeme čitateľom za ich priazeň a spoločne sa tešíme na ďalšie vedecké príspevky v novom roku!

Redakcia

--- Novinky z akademického prostredia ---

Zo skúšky na fakulte elektrotechniky a informatiky:

*Skúšajúci:* Povedzte nám ktoré sú najdôležitejšie parametre operačných zosilňovačov?

*Študent:* ...nekonečné zosilnenie v otvorenej slučke. A hlavne sú nehlučné.

*Skúšajúci:* Nehlučné?

Študent: Áno nehlučné. To je veľmi dôležitá vlastnosť napríklad pre medicínsku techniku. V porovnaní napríklad s reléovými zosilňovačmi sú operačné zosilňovače nehlučné. To je dôležitá vlastnosť a výhoda.

*Skúšajúci:* .............

*Skúšajúci: snaží sa zachovať dekórum*

*Skúšajúci:* .............

*Skúšajúci: ...padá zo stoličky v kŕčoch od smiechu*

Príhoda ale inšpirovala vznik novej, vysoko perspektívnej technológie – elektromechanický operačný zosilňovač na báze motor-generátora s planetárnou prevodovkou. Tieto operačné zosilňovače sú odolné voči elektromagnetickému rušeniu, kozmickému žiareniu, radiácii, nukleárnemu elektromagnetickému pulzu, alebo výronu koronárnej hmoty. Drobná nevýhoda je, že v studenom počasí nemusia naštartovať, ale na to už bol vypísaný výskumný grant.

# Resistance transfer standard construction and measurements

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(peer reviewed version)

## 1. Introduction

In 1954, B. V. Hamon developed a very efficient method to transfer resistance value of a set of individual resistors to lower values by connecting them in parallel, and to higher values by connecting them in series. The so called "Resistance transfer standard" is a device, which has a number of resistors permanently connected in series, typically, 10 – 12 units as shown in Figure 1. All resistors have four terminal Kelvin connections accessible. The panel terminals are conveniently arranged such, that all, or a subset of resistors can be connected in parallel, using high conductivity, external shorting bars as shown in Figure 2.

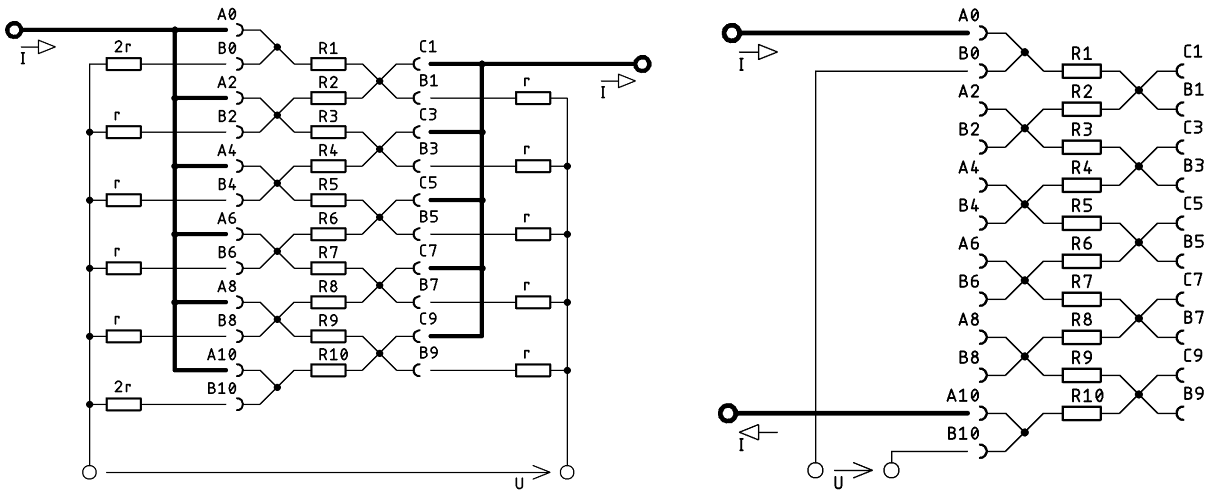


*Figure 1: left – parallel connection of 10 resistors formed by the shorting bars and a parallel compensation network. Right – series connection of 10 resistors.*

Hamon had proven that error on the ratio of the series and parallel combinations scales with square of the individual resistor tolerances. If, for example resistors with values known to 1 part in $10^4$ (0.01%) are used, the ratio error will be known in 1 part in $10^8$ without laboriously measuring exact values of each individual resistor [1].

## 2. Practical realization of Hamon network

Visit of the precision resistor factory in Japan triggered the authors to try out the concept. With good availability of high performance metal foil resistors five different Resistance transfer standard units with nominal values 10 Ω, 100 Ω, 1 kΩ, 10 kΩ, 100 kΩ were produced. Metrological characterisation commenced in December 2023.

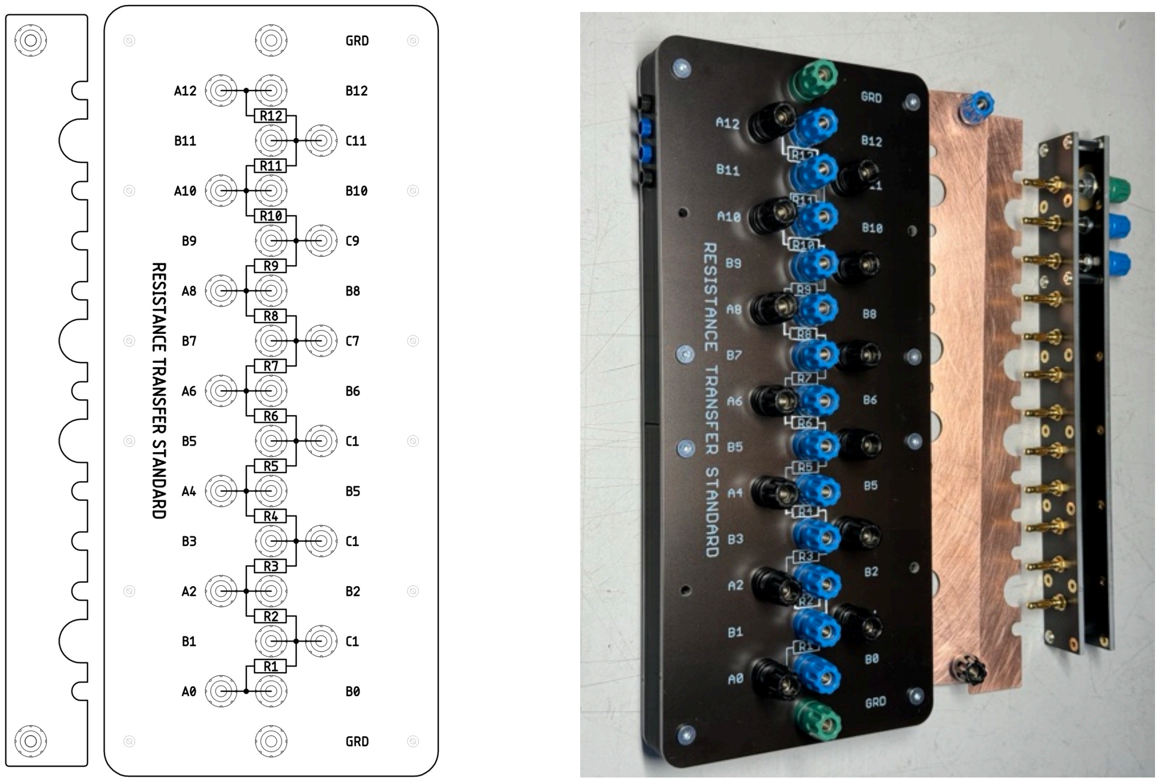



*Figure 2: Practical realization of a 12-resistor Hamon resistance transfer network.*

## 3. Selection of resistors

Resistors are SMT type, Ultra High-Precision Z1 Foil Technology FRSM Series High-Precision FRSM either wrap-around chip, flip chip models. The specifications of both are TCR of ±0.05 ppm/°C typical in the temperature range 0°C to +60°C and absolute value tolerance 0.01%.

Due to the technology limitations, lower value metal foil resistors are typically available only in less tight tolerance. Our 20 Ω chips used to build the 10 Ω nominal value standard are therefore 0.25%. The resulting ratio error if no selection is done should be known in 6.25 parts in $10^6$. Thanks to good availability, we could have purchased a larger batch and select values. Connecting two chips in parallel provides means to obtain value closer to the perfect one, circumventing the need for tighter tolerance, or trimming.

The 100 Ω resistors for the 100 Ω nominal value standard were not available in SMT version. A through hole version Z-foil VAR family was purchased what provided an interesting opportunity to also study sensitivity of the components (SMT/through hole) to the soldering process.

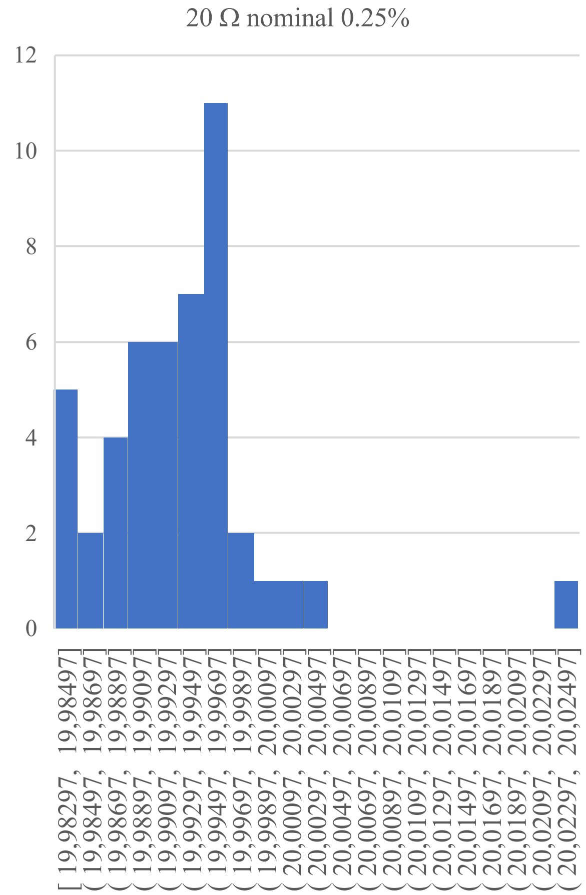
## 4. Selection of values

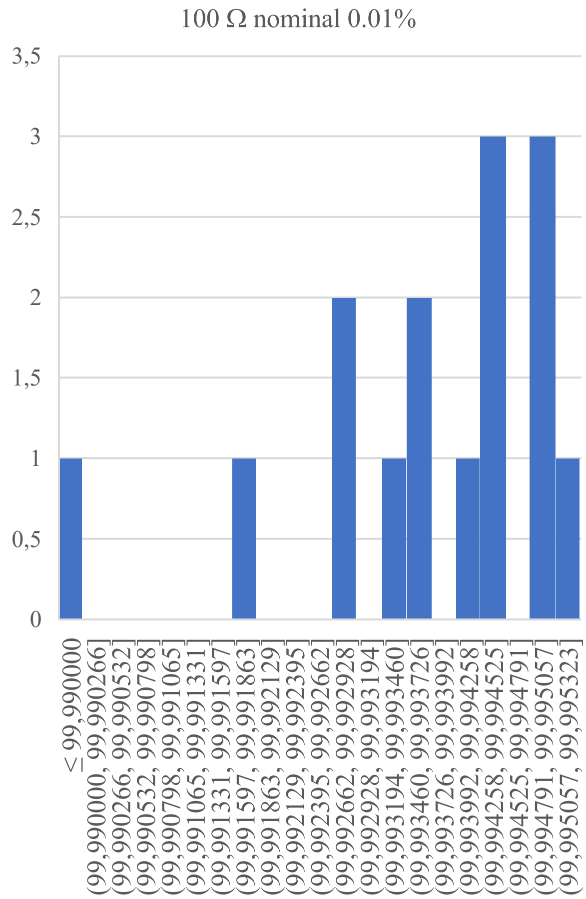
It is desirable for proper functioning of the resistance transfer standard to have the resistors equal. Not only in absolute value, but also drift. The standard can be used to provide resistances of different values by connecting different combinations in parallel, different combinations in series, or it can be used as a very accurate voltage divider. Therefore an extra effort was invested in selection of values of individual chips from the available batch. Value of each resistor from the incoming batch was measured and recorded, see Table 1.

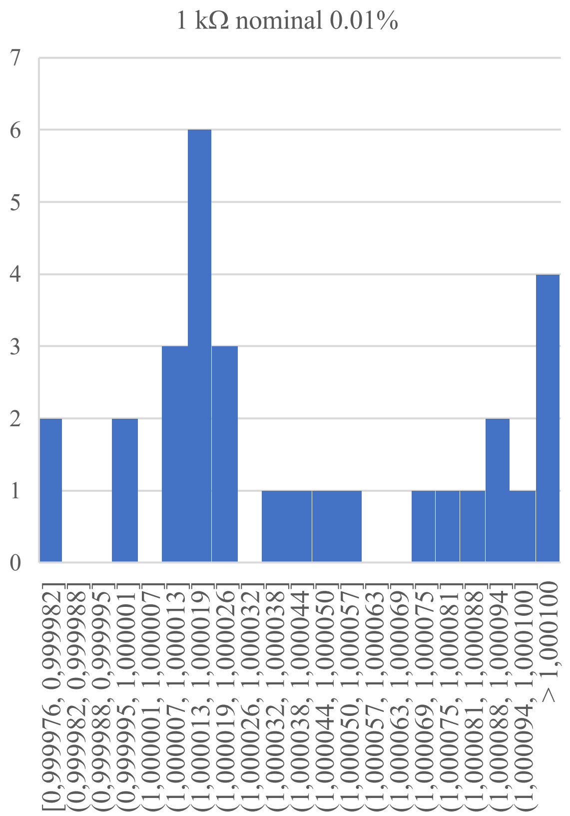
The optimization goal was set to obtain a voltage divider (full series combination) with the lowest possible linearity error (tap to tap). A simple algorithm based on intuition, rather than thorough mathematical analysis was tested. When compared with the best combination obtained by a brute force numeric optimization, the results were very close. 12 resistors should be selected from the available batch to have closest matching value. If there is a Gaussian-like distribution, the pick should be symmetric around the peak of the distribution. Starting from the one end of the distribution (e.g. the lowest value), populate every second resistor in the standard starting from R1 to R11. The next step is to take resistors from the other end of the distribution (starting with the highest value) and populate every second resistor starting from R2 to R12. Average of two neighbour values (R1+R2, R3+R4…) will then be very close, or equal to the mean distribution value.

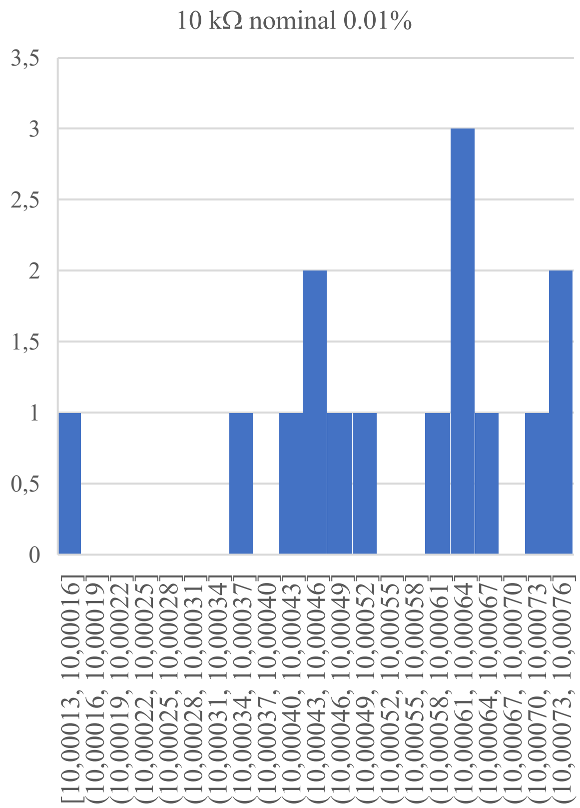
| **20 Ω nominal (Ω)** | | **100 Ω nominal (Ω)** | **1 kΩ nominal (kΩ)** | **10 kΩ nominal (kΩ)** | **100 kΩ nominal (kΩ)** |
|---|---|---|---|---|---|
| 19.98297 | | 99.989374 | 0.999976 | 10.000128 | 99.992839 |
| 19.98320 | | 99.991735 | 0.999977 | 10.000362 | 99.994640 |
| 19.98323 | | 99.992715 | 0.999995 | 10.000424 | 99.995020 |
| 19.98334 | | 99.992733 | 0.999995 | 10.000433 | 99.999910 |
| 19.98358 | | 99.993265 | 1,000008 | 10.000451 | 100.001244 |
| 19.98546 | | 99.993662 | 1,000010 | 10.000473 | 100.001350 |
| 19.98577 | | 99.993693 | 1,000011 | 10.000503 | 100.001830 |
| 19.98736 | | 99.994233 | 1,000015 | 10.000592 | 100.002006 |
| 19.98801 | | 99.994310 | 1,000015 | 10.000620 | 100.002023 |
| 19.98847 | | 99.994345 | 1,000015 | 10.000630 | 100.002049 |
| 19.98857 | | 99.994497 | 1,000016 | 10.000660 | 100.002430 |
| 19.98915 | | 99.994903 | 1,000017 | 10.000715 | 100.002680 |
| 19.98923 | | 99.994999 | 1,000019 | 10.000749 | 100.003300 |
| 19.98964 | | 99.995017 | 1,000020 | 10.000761 | 100.003646 |
| 19.99018 | | 99.995323 | 1,000020 | 10.000635 | 100.005980 |
| 19.99048 | 19.99525 | | 1,000021 | | |
| 19.99080 | 19.99529 | | 1,000036 | | |
| ~~19.99110~~ | 19.99545 | | 1,000040 | | |
| 19.99134 | 19.99557 | | 1,000048 | | |
| 19.99140 | 19.99571 | | 1,000052 | | |
| 19.99182 | 19.99572 | | 1,000070 | | |
| 19.99222 | 19.99573 | | 1,000081 | | |
| 19.99297 | 19.99629 | | 1,000083 | | |
| 19.99306 | 19.99649 | | 1,000088 | | |
| 19.99317 | 19.99677 | | 1,000088 | | |
| 19.99364 | 19.99713 | | 1,000096 | | |
| 19.99389 | 19.99765 | | 1,000103 | | |
| 19.99405 | 20.00027 | | 1,000111 | | |
| 19.99435 | 20.00297 | | 1,000118 | | |
| 19.99441 | 20.00474 | | 1,000125 | | |
| 19.99512 | 20.02393 | | | | |

*Table 1: Values of individual resistors used for realization of the Resistance Transfer Standard. Green colour shows which units were picked for each device. 10 W unit uses two chips in parallel. Orange colour indicates the second chip.*


20 Ω nominal 0.25%
0
2
4
6
8
10
12
[19,98297, 19,98497]
(19,98497, 19,98697]
(19,98697, 19,98897]
(19,98897, 19,99097]
(19,99097, 19,99297]
(19,99297, 19,99497]
(19,99497, 19,99697]
(19,99697, 19,99897]
(19,99897, 20,00097]
(20,00097, 20,00297]
(20,00297, 20,00497]
(20,00497, 20,00697]
(20,00697, 20,00897]
(20,00897, 20,01097]
(20,01097, 20,01297]
(20,01297, 20,01497]
(20,01497, 20,01697]
(20,01697, 20,01897]
(20,01897, 20,02097]
(20,02097, 20,02297]
(20,02297, 20,02497]


100 Ω nominal 0.01%
0
0,5
1
1,5
2
2,5
3
3,5
≤ 99,990000
(99,990000, 99,990266]
(99,990266, 99,990532]
(99,990532, 99,990798]
(99,990798, 99,991065]
(99,991065, 99,991331]
(99,991331, 99,991597]
(99,991597, 99,991863]
(99,991863, 99,992129]
(99,992129, 99,992395]
(99,992395, 99,992662]
(99,992662, 99,992928]
(99,992928, 99,993194]
(99,993194, 99,993460]
(99,993460, 99,993726]
(99,993726, 99,993992]
(99,993992, 99,994258]
(99,994258, 99,994525]
(99,994525, 99,994791]
(99,994791, 99,995057]
(99,995057, 99,995323]


1 kΩ nominal 0.01%
0
1
2
3
4
5
6
7
[0,999976, 0,999982]
(0,999982, 0,999988]
(0,999988, 0,999995]
(0,999995, 1,000001]
(1,000001, 1,000007]
(1,000007, 1,000013]
(1,000013, 1,000019]
(1,000019, 1,000026]
(1,000026, 1,000032]
(1,000032, 1,000038]
(1,000038, 1,000044]
(1,000044, 1,000050]
(1,000050, 1,000057]
(1,000057, 1,000063]
(1,000063, 1,000069]
(1,000069, 1,000075]
(1,000075, 1,000081]
(1,000081, 1,000088]
(1,000088, 1,000094]
(1,000094, 1,000100]
> 1,000100


10 kΩ nominal 0.01%
0
0,5
1
1,5
2
2,5
3
3,5
[10,00013, 10,00016]
(10,00016, 10,00019]
(10,00019, 10,00022]
(10,00022, 10,00025]
(10,00025, 10,00028]
(10,00028, 10,00031]
(10,00031, 10,00034]
(10,00034, 10,00037]
(10,00037, 10,00040]
(10,00040, 10,00043]
(10,00043, 10,00046]
(10,00046, 10,00049]
(10,00049, 10,00052]
(10,00052, 10,00055]
(10,00055, 10,00058]
(10,00058, 10,00061]
(10,00061, 10,00064]
(10,00064, 10,00067]
(10,00067, 10,00070]
(10,00070, 10,00073]
(10,00073, 10,00076]

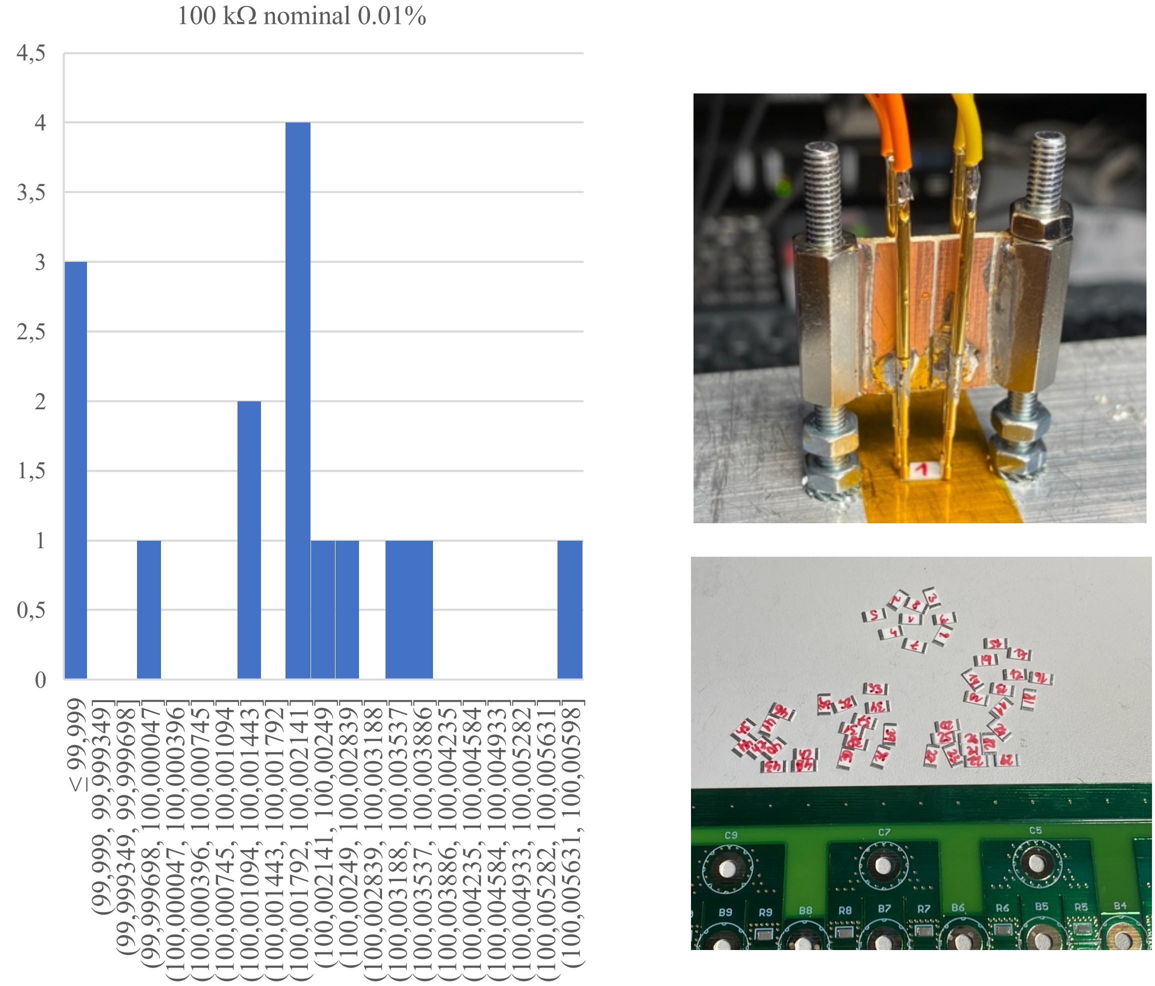



*Figure 3: Value distributions of the used resistor batches. Full scale represents the manufacturer's tolerance (e.g. ±0.01%, or 0.25%). Photo on the right hand side shows the test rig for 4-wire resitance value measurement before soldering..*

## 5. PCB resistance and resistor value change due to soldering

SMT resistors are mounted on a 4-layer printed board, each copper layer is 70 µm thick. The layout is made such to provide a Kelvin style connection to each chip, as shown in Figure 4.

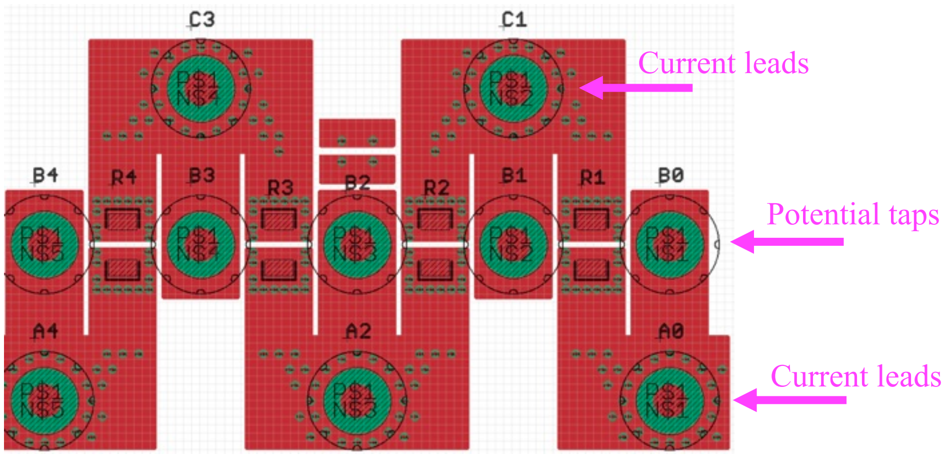



*Figure 4: PCB layout showing the 4-wire connection to the resistors. The grid is 1 mm.*

The islands on the printed board are designed to minimize current flow through potential taps. The estimated contribution of printed board including solder joint to the resistance is on order of 5 mΩ.

After soldering, before installation into the final enclosure all resistors on the printed board have been re-measured to assess the value change due to thermal cycle. It can be seen that manual soldering has a large detrimental effect to the value stability, the value can shift by few hundreds ppm. Soldering in an oven is better, a vapour-phase oven is recommended.

Figure 5 shows change in value for all resistors on all produced Resistance transfer standards. As expected, SMT resistors are not the best in terms of sensitivity to a heat cycle. Blue trace shows the through hole VAR family Z-foil resistors, where the value change is much lower and mainly represented by additional lead length plus PCB resistance. Resistor number 12 was soldered with extremely short leads, what possed a stress to the resistor body. After measurement, it was decided to leave about 10 mm leads on these resistors. The value seen from outside slightly shifted due to additional resistance of the leads, however the resistor itself did not suffer much thermal stress.


*Figure 5: Resistor value change after soldering*

## 6. Preliminary measurements using the fabricated Resistance Transfer Standards

### Fluke 8588A multimeter calibration and drift verification at 10 Ω range

Instruments used (Figure 6):

- Standard resistor CERN No. 274127 installed in an oil bath, kept at constant temperature. Nominal value 10 Ω, calibrated at METAS in November 2022. Absolute value known within ±0.3 ppm.
- 6010B Automatic resistance bridge
- 4220A/30 Low thermal matrix scanner
- Portable standard resistor Fluke 742A-10. nominal value 10 Ω
- Reference multimeter Fluke 8588A, to be calibrated
- Resistance Transfer Standard RTS-100. nominal value 100 Ω

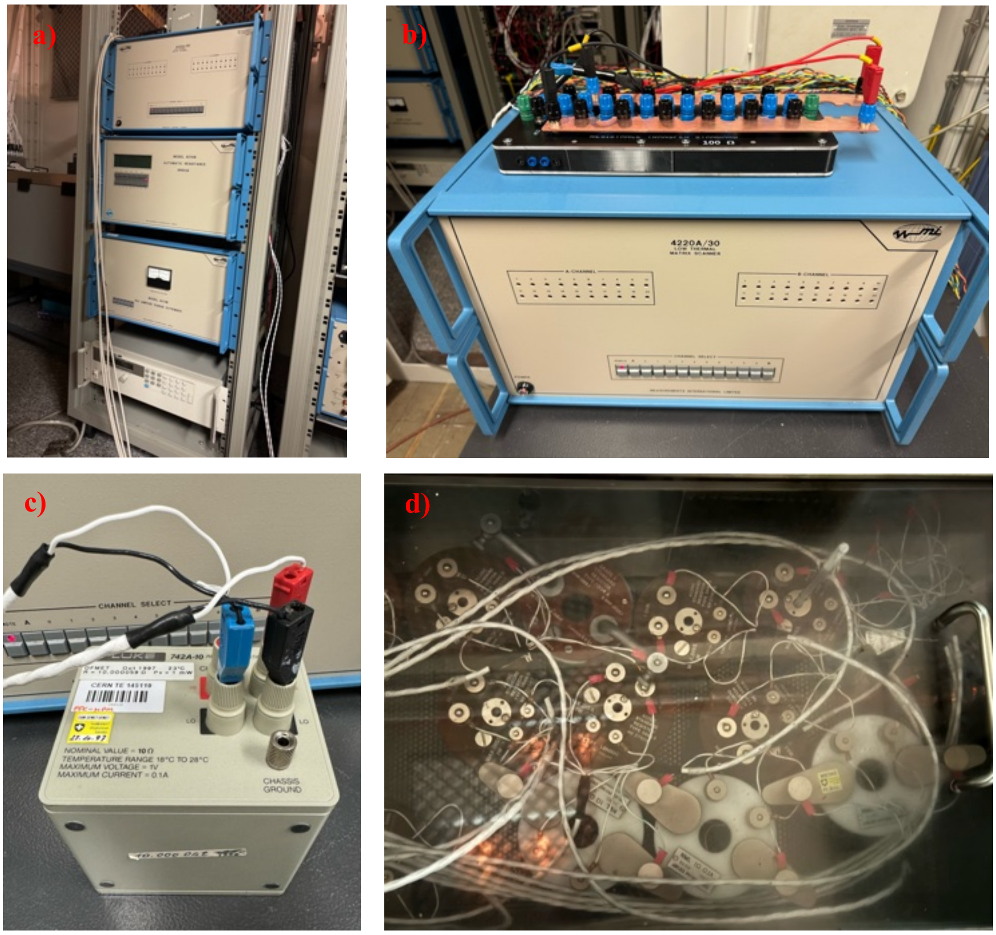



*Figure 6: Measurement setup. a) automatic resistance bridge and low thermal EMF scanner, b) second scanner and measured transfer standard, c) portable standard resistor Fluke d) CERN reference resistors in oil bath*

Using the bridge and the known standard resistor No. 274127, absolute value of the portable standard resistor Fluke 742A-10 was found (using 16 measurements) as:

$$R_{REF10\Omega} = 10.000\,712\,25 \pm 0.000\,003\,0\,\Omega$$

Transfer uncertainty calculated by the automated measurement system was ±0.02 ppm.

Following, the portable standard resistor Fluke 742A-10 was measured by the Fluke 8588A to be calibrated. The value found is:

$$R_{8588\,REF10\Omega} = 10.000\,715\,4 \pm 0.000\,003\,3\,\Omega$$

Measurement current of 8588A was 10 mA, integration time 500 NPLC (10 s).

Reference multimeter Fluke 8588A being calibrated, has a “gain” error at 10 Ω range:

$$\Delta_{8588@10\Omega} = \frac{R_{8588\,REF10\Omega}}{R_{REF10\Omega}} = \frac{10.000\,715\,4 \pm 0.000\,003\,3\,\Omega}{10.000\,712\,25 \pm 0.000\,003\,0\,\Omega} =$$

$$\Delta_{8588@10\Omega} = 1.000\,000\,315 \pm 0.000\,000\,446$$

The 8588A was last calibrated more than 2 years ago. The datasheet specification for absolute accuracy over 365 days, $T_{cal}$ ±1°C is 7.7 μΩ/Ω of reading + 1.4 μΩ/Ω of range (95% confidence). The multimeter stability seems to be much better than the datasheet specification.

## Various measurements using the Resistance Transfer Standard RTS-100

### *Parallel connection*

First measurement of the home made, 100 Ω nominal value Resistance Transfer Standard is parallel combination of the R1-R10 resistors, using the shorting bar. The parallel compensation network was not used for this measurement. The value measured by the multimeter is later calibrated and uncertainty calculated in an attempt to obtain a real absolute value of the resistance.

First, the reference resistance value of the RTS-100 is obtained using the bridge is (from 16 measurements)

$$R_{BRIDGE} = 9.999\,870\,1 \pm 0.000\,002\,9\,\Omega$$

Following, the very same resistor was measured using Fluke 8588A (376 measurements, 10 second integration time)

$$R_{FLUKE\ RAW} = 9.999\,872\,5 \pm 0.000\,003\,1\,\Omega$$

Using the calibration factor obtained earlier, we can correct the raw value measured by the 8588A to obtain true resistance value:

$$R_{FLUKE\ CORR} = \frac{R_{FLUKE}}{\Delta_{8588@10\Omega}} = \frac{9.999\,872\,5 \pm 0.000\,003\,1\,\Omega}{1.000\,000\,315 \pm 0.000\,000\,446} =$$

$$R_{FLUKE\ CORR} = 9.999\,869\,4 \pm 0.000\,003\,1\,\Omega$$

Both values obtained by the bridge (reference) and corrected/calibrated multimeter show good agreement:

$$R_{BRIDGE} = 9.999\,870\,1 \pm 0.000\,002\,9\,\Omega$$

$$R_{FLUKE\ CORR} = 9.999\,869\,4 \pm 0.000\,003\,1\,\Omega$$

### *Voltage calibration of the Fluke 8588A multimeter for 10 V range and use of the multimeter transfer mode*

Apart of resistances, the standards laboratory at CERN possess also a very accurate 10 mA current source, called PBC and a set of voltage standards Fluke 732A and 732B. Both are regularly calibrated at METAS and their values are traceable to the Swiss national standards. An alternative way to measure the RTS-100 resistance value would be using voltages and currents and profiting from a short time transfer accuracy of Fluke 8588A.

The reference current of PBC is specified to have an absolute value with an uncertainty lower than 0.5 ppm, i.e. $I_{PBC}$ = 10.000 000 ± 0.000 005 mA. Compliance voltage of the current source is ~11 V, so a series combination up to 1 kΩ can be excited. Unit number HCRCAAB001-14 is used for the following measurements. The noise of the generated current is negligible with respect to the value uncertainty (type B uncertainty is dominant).

First, we calibrate the Fluke 8588A multimeter on the 10 V range using a known voltage $V_{PBCREF}$ from calibrated PBC's voltage output. This value is known as 10 V/-7.9 ppm (calibrated in November 2022, traceable to METAS), and type B uncertainty of 0.5 ppm.

The reference $V_{PBCREF}$ value can be therefore calculated as

$$V_{PBCREF} = 10V - 7.9ppm = 9.999\,921\,0 \pm 0.000\,005\,0\,V$$

Fluke 8588A multimeter measured

$$V_{8588ARAW} = 9.999\,925\,1 \pm 0.000\,000\,6\,V$$

Now we can again calculate the 10 V range gain error/calibration factor as

$$\Delta_{8588@10V} = \frac{V_{8588RAW}}{V_{VPBCREF}} = \frac{9.999\,925\,1 \pm 0.000\,000\,6\,V}{9.999\,921\,0 \pm 0.000\,005\,0\,V} =$$

$$\Delta_{8588@10V} = 1.000\,000\,41 \pm 0.000\,000\,50$$

The multimeter is now calibrated and ready for voltage drop measurement generated by the 10 mA current source, as shown in Figure 7.

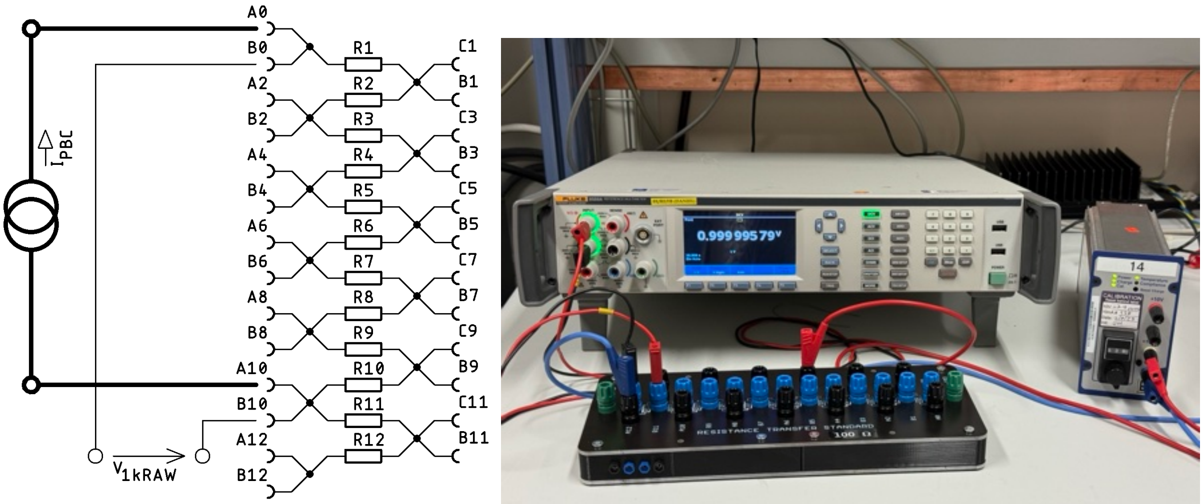



*Figure 7: Measurement using the PBC 10 mA constant current source and a voltage drop.*

RTS-100 is now configured for series combination providing a nominal value of 1 kΩ. Voltage drop across the series combination was measured:

$$V_{1kRAW} = 9.999\,767\,6 \pm 0.000\,000\,8\,V$$

Voltage drop corrected for the 8588A gain error

$$V_{1kCORR} = \frac{V_{1kRAW}}{\Delta_{8588@10V}} = \frac{9.999\,767\,6 \pm 0.000\,000\,8\,V}{1.000\,000\,41 \pm 0.000\,000\,50} =$$

$$V_{1kCORR} = 9.999\,763\,5 \pm 0.000\,005\,1\,V$$

Series combination resistance of RTS-100 can now be calculated using the Ohm’s law as

$$R_{1k\,PBC} = \frac{V_{1kCORR}}{I_{PBC}} = \frac{9.999\,763\,5 \pm 0.000\,005\,1\,V}{10.000\,000 \pm 0.000\,005\,mA} =$$

$$R_{1k\,PBC} = 999.976\,35 \pm 0.000\,71\,\Omega$$

### RTS-100 series connection measurement using standard resistor and resistance bridge

Obtained value of the series combination (1 kΩ) from the previous exercise was independently verified using the resistance bridge referencing it to the standard resistor CERN No. 274308, nominal value 100 Ω, calibrated by METAS in November 2022. Absolute value of the standard resistor No. 274308 is known to within ±0.3 ppm. Transfer uncertainty calculated by the automated measurement system was ±0.02 ppm.

$$R_{1k\,BRIDGE} = 999.977\,193 \pm 0.000\,299\,\Omega$$

We can compare this result to the one obtained by volt-ampere method:

$$R_{1k\ PBC} = 999.976\ 35 \pm 0.000\ 71\ \Omega$$

Both values show good agreement.

### *Fluke 8588A multimeter calibration and drift verification at 1000 Ω range*

The series combination from RTS-100 was subsequently measured by Fluke 8588A in resistance mode, using the 1k range:

And subsequently by the 8588A multimeter

$$R_{1k\ FLUKE} = 999.980\ 61 \pm 0.000\ 12\ \Omega$$

Using the two measured values from the transfer standard measured by 8588A multimeter and resistance bridge, we can now calculate the Fluke 8588A gain error at 1 kΩ range:

$$\Delta_{8588@1k\Omega} = \frac{R_{1k\ FLUKE}}{R_{1k\ BRIDGE}} = \frac{999.977\ 19 \pm 0.000\ 30\ \Omega}{999.980\ 61 \pm 0.000\ 12\ \Omega} =$$

$$\Delta_{8588@1k\Omega} = 0.999\ 996\ 58 \pm 0.000\ 000\ 32$$

The datasheet specification for absolute accuracy over 365 days, $T_{cal}$ ±1°C is 7.1 μΩ/Ω of reading + 0.5 μΩ/Ω of range (95% confidence). The multimeter stability seems to be much better than the datasheet specification.

### *Voltage calibration of the Fluke 8588A multimeter for 1 V range and use of the multimeter transfer mode*

Now we will use the volt-ampere method to measure absolute values of all individual 100 Ω resistors on RTS-100. We need to do a similar voltage calibration exercise as for 10V, this time using 1.018 V output of Fluke 732B Ref. CERN TE 145112 calibrated in November 2022 and traceable to METAS (Figure 8). The reference value is

$$V_{732B\ REF} = 1.018\ 038\ 50 \pm 0.000\ 000\ 31\ V$$

Fluke 8588A measures (10 s integration)

$$V_{8588A+} = 1.018\ 040\ 41 \pm 0.000\ 000\ 04\ V$$

After swapping the polarity

$$V_{8588A-} = -1.018\ 038\ 36 \pm 0.000\ 000\ 04\ V$$


*Figure 8: Voltage standard Fluke 732B used for 1V calibration*

We can consider

$$V_{8588A} = \frac{1.018\ 040\ 41 \pm 0.000\ 000\ 04 - -1.018\ 038\ 36 \pm 0.000\ 000\ 04}{2} =$$

$$V_{8588A} = 1.018\ 039\ 39 \pm 0.000\ 000\ 06\ \mathrm{V}$$

The multimeter gain error at 1 V range

$$\Delta_{8588@1V} = \frac{V_{8588A}}{V_{732B\ REF}} = \frac{1.018\,039\,39 \pm 0.000\,000\,06\,V}{1.018\,038\,50 \pm 0.000\,000\,31\,V}$$

$$= 1.000\,000\,874 \pm 0.000\,000\,32$$

*Fluke 8588A multimeter calibration and drift verification at 100 Ω range*

A parallel combination from RTS-1000 was used for Fluke 8588A calibration in resistance mode, using the 100 Ω range:

$$R_{100\Omega\ FLUKE} = 100.002\,836 \pm 0.000\,020\,\Omega$$

The same resistor measured by bridge with transfer error ±0.02 ppm calculated by the automated measurement software

$$R_{100\Omega\ BRIDGE} = 100.002\,722\,6 \pm 0.000\,030\,\Omega$$

Using the two measured values from the transfer standard measured by 8588A multimeter and resistance bridge, we can now calculate the Fluke 8588A gain error at 1 kΩ range:

$$\Delta_{8588@100\Omega} = \frac{R_{100\Omega\ FLUKE}}{R_{100\Omega\ BRIDGE}} = \frac{100.002\,836 \pm 0.000\,020\,\Omega}{100.002\,722\,6 \pm 0.000\,030\,\Omega} =$$

$$\Delta_{8588@100\Omega} = 1.000\,001\,1 \pm 0.000\,000\,36$$

The datasheet specification for absolute accuracy over 365 days, $T_{cal}$ ±1°C is 7.2 μΩ/Ω of reading + 0.5 μΩ/Ω of range (95% confidence). The multimeter stability seems to be much better than the datasheet specification.

*Individual 100 Ω resistor measurements using two methods*

Final test was measurement of each individual 100 Ω resistor using the V-A method with calibrated multimeter on 100 Ω range. The measurement was done next day, in a different laboratory with less tight temperature control. Therefore additional type-B uncertainty was added to reflect we are not in the transfer mode anymore. Table 2 shows the detailed results.

| | $V_{8588}$ corrected (V) | $R_{V\text{-}A}$ method (Ω) | Uncern-tainty | $R_{8588direct}$ corrected (Ω) | Uncern-tainty | Delta (μΩ/Ω) |
|---|---|---|---|---|---|---|
| R1 | 0.999 951 52 | 99.995 152 6 | 0.000 059 | 99.995 290 | 0.000 036 | -1.4 |
| R2 | 0.999 994 19 | 99.999 419 6 | 0.000 059 | 99.998 998 | 0.000 036 | 4.2 |
| R3 | 0.999 962 42 | 99.996 242 6 | 0.000 059 | 99.996 255 | 0.000 036 | -0.1 |
| R4 | 0.999 974 46 | 99.997 446 6 | 0.000 059 | 99.996 851 | 0.000 036 | 6.0 |
| R5 | 0.999 97416 | 99.997 416 6 | 0.000 059 | 99.997 209 | 0.000 036 | 2.1 |
| R6 | 0.999 988 16 | 99.998 816 6 | 0.000 059 | 99.998 815 | 0.000 036 | 0.0 |
| R7 | 0.999 969 97 | 99.996 997 6 | 0.000 059 | 99.996 710 | 0.000 036 | 2.9 |
| R8 | 0.999 990 47 | 99.999 047 6 | 0.000 059 | 99.998 986 | 0.000 036 | 0.6 |
| R9 | 0.999 973 23 | 99.997 323 6 | 0.000 059 | 99.997 100 | 0.000 036 | 2.2 |
| R10 | 0.999 981 61 | 99.998 161 6 | 0.000 059 | 99.998 021 | 0.000 036 | 1.4 |
| R11 | 0.999 976 76 | 99.997 676 6 | 0.000 059 | 99.997 407 | 0.000 036 | 2.7 |
| R12 | 0.999 995 05 | 99.999 505 6 | 0.000 059 | 99.999 007 | 0.000 036 | 5.0 |
| | | Sum V-A method 999.976 025 ±0.000 187 Ω | | Sum direct measurement 999.974 235 ±0.000 114 Ω (type A) ±0.001 199 Ω (type B) | | |

*Table 2: Measured values of individual 100 Ω resistors in RTS-100*

Now we can compare four independent measurements of the same resistance value:

By reference resistance bridge:

$$R_{1k\ BRIDGE} = 999.977\ 193 \pm 0.000\ 299\ \Omega$$

By volt-ampere method:

$$R_{1k\ PBC} = 999.976\ 35 \pm 0.000\ 71\ \Omega$$

By volt-ampere method, measuring each individual resistor:

$$R_{VA\ 10x100\Omega} = 999.976\ 025 \pm 0.000\ 187\ \Omega$$

And by measuring each individual resistor using calibrated multimeter

$$R_{MULT\ 10x100\Omega} = 999.974\ 025 \pm 0.001\ 314\ \Omega$$

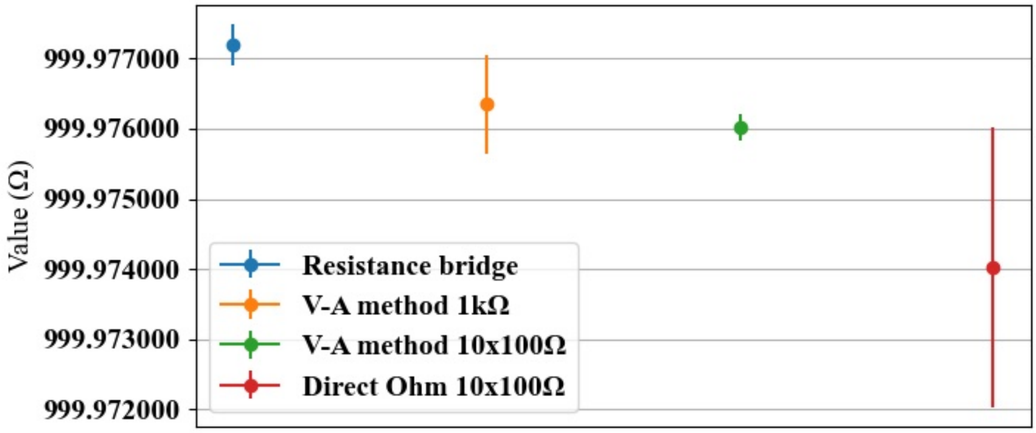



*Figure 9: Graphical comparison of four different measurements*

## 7. Future work

Due to lack of time and absence of the parallel compensation network the transfer of ratios was not yet measured. We are looking forward to complete this step in a very near future.

## 8. Acknowledgements

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## 9. References

[1] B.V. Hamon: A 1-100 Ω build-up resistor for the calibration of standard resistors. J. Sci. Instrum. 31 450