RMO Supplementary Comparison EURAMET.EM-S47
Comparison of 2 GΩ high voltage resistance

FINAL REPORT

J. Hällström[1], A.-P. Elg[2], G. Rietveld[3], M. Hammarquist[2], J. Havunen[1], E. Houtzager[3],
A. Merev[4], Ö. Erkan[4]

[1] VTT Technical Research Centre of Finland
[2] RISE Research Institutes of Sweden
[3] VSL, Netherlands
[4] TUBITAK, Türkiye

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1. Introduction

Metrology area, branch	Electricity and Magnetism, High Voltage and Current
Description	Low voltage comparison of 2 GΩ high voltage resistance
Time of measurement	2022-03-07 – 2022-03-25
Measurand(s)	Resistance
Parameter(s)	Nominal resistance: 2.04 GΩ Voltage: up to 1 kV
Transfer device(s)	Star comparison, all references in one lab at the same time.
Comparison type	Supplementary comparison
Consultative Committee	CCEM (Consultative Committee for Electricity and Magnetism)
Related regional metrology organizations	EURAMET

2. Participants and organisation of the comparison

2.1 Co-ordinator and members of the support group

The pilot laboratory for the comparison was RISE (Sweden).

Co-ordinator: Alf-Peter Elg
+46 10 516 5734
alf.elg@ri.se

Support group: Jari Hällström
jari.hallstrom@vtt.fi

Gert Rietveld
grietveld@vsl.nl

2.2 List of participants

Acronym	Institute	Country	Status	Contact
RISE	Research Institutes of Sweden AB	Sweden	NMI	Dr. Alf-Peter Elg alf.elg@ri.se
VTT MIKES	Technical Research Centre of Finland Ltd	Finland	NMI	Dr. Jari Hällström jari.hallstrom@vtt.fi
TUBITAK	TÜBITAK Ulusal Metroloji Enstitüsü	Türkiye	NMI	Dr. Ahmet Merev ahmet.merev@tubitak.gov.tr
VSL	VSL National Metrology Institute (VSL)	Netherlands	NMI	Dr. Ernest Houtzager ehoutzager@vsl.nl

2.3 Organisation and comparison schedule

All participants sent their own dividers to pilot laboratory RISE for comparison. Participants defined the resistance of the high voltage arm of their divider using existing home laboratory procedures before sending the divider for comparison measurements at RISE. Each participant repeated their home calibration after the divider was returned from RISE. Comparison measurements at RISE were performed in February/March 2022 according to the schedule shown below.

Action	Start	Finish
Arrival of dividers to RISE	20.01.2022	22.02.2022
Temperature stabilization (7 days)	14.01.2022	01.03.2022
2 GΩ measurements	21.01.2022	01.03.2022
200 kV scale factor measurements (EURAMET.EM-S46)	07.03.2022	11.03.2022
Departure of dividers from RISE	21.03.2022	06.04.2022

2.4 Unexpected incidents

TUBITAK used a wrong connection when measuring the resistance, which caused them to become an outlier in the analysis. They became aware of this after Draft A was released, and they repeated the measurement using correct connection. The new result is in line with the CRV. For more details see Annex C and Annex D.

3. The standards and measurement instructions

3.1 Description of the standards

The standards listed in Table 1 were the high voltage arms of identical 200 kV divider high voltage modules [4] shown in Figure 1. The dividers were built in 2013 as part of EMRP project *Metrology for High Voltage Direct Current* (HVDC).

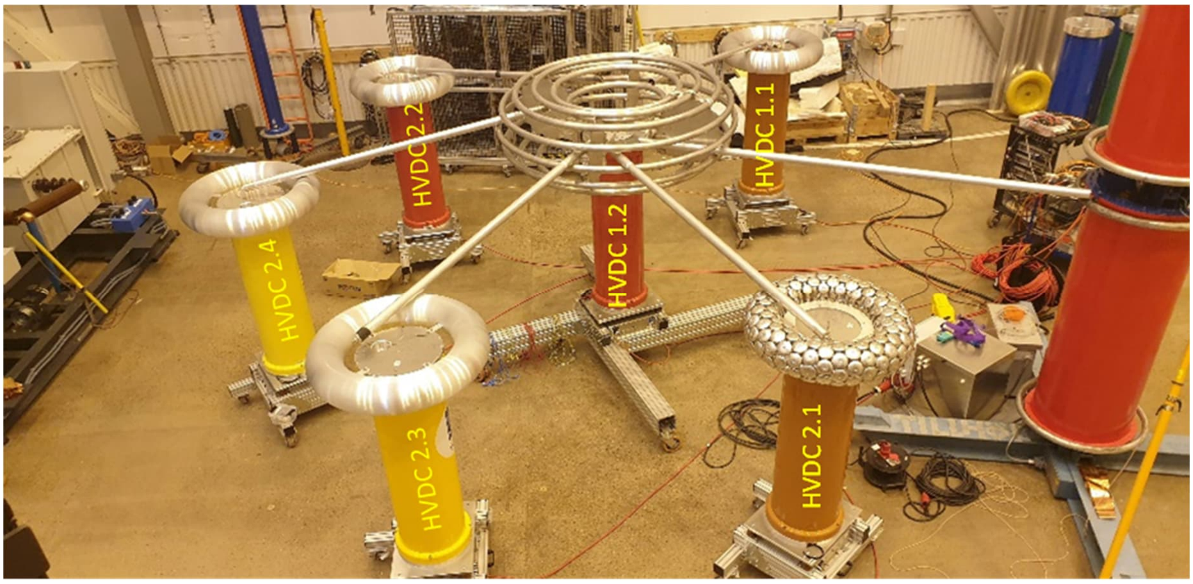
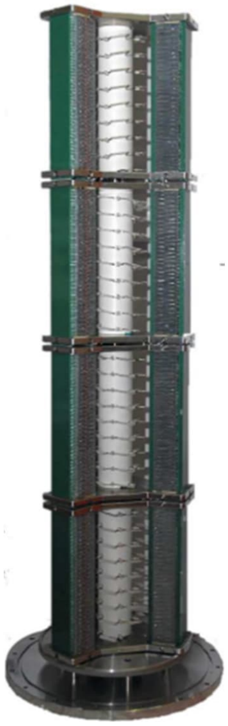


Figure 1 The five high voltage dividers around a sixth one used as transfer divider during EURAMET.EM-S46 DC ratio comparison. The setup was used in that DC ratio comparison, and it is not representative for this resistance comparison.

Table 1 Identifications of the divider modules

	RISE	PTB	TUBITAK	VSL	VTT	RISE
HV arm	HVDC1.1	HVDC2.1	HVDC2.2	HVDC2.3	HVDC2.4	HVDC 1.2

The outer diameter of a HV module is 480 mm, it is 1500 mm high, and it weighs 150 kg. A schematic of the internal structure of the HV module and the LV arm is shown in Figure 2. The components are enclosed in an SF_6 filled fiberglass tube. The top endplate houses a gas valve, pressure gauge and a feed-through for the reference divider signal. The bottom plate has a mating feed-through, so that the modules can be directly stacked and mounted on top of each other.



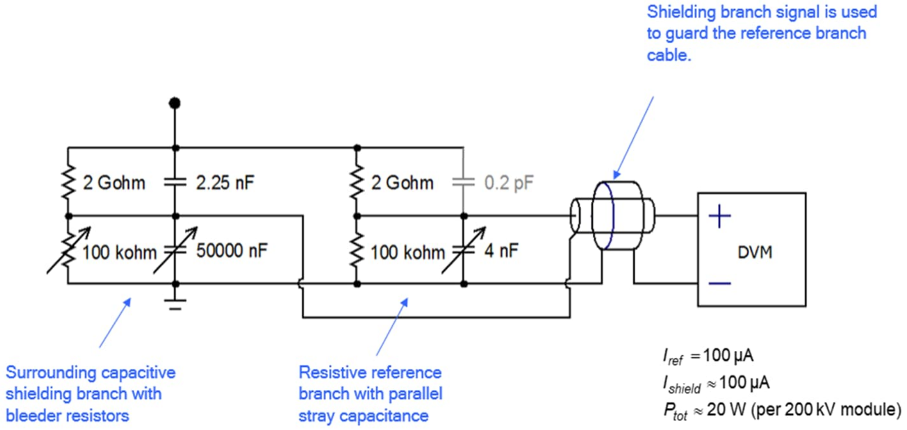


Figure 2 Left: Internal structure of the divider high voltage arm.
Resistive branch resistors on the white center support,
shielding branch capacitors inside the three green supports around it.
Right: The adjustments are used to optimise the AC behaviour, when needed.

3.2 Quantities to be measured and measurement conditions

The resistance of the reference branch of the high voltage divider modules, with nominal resistance of 2.04 GΩ.

Recommended ambient conditions are:

Temperature: (23 ± 0.5) °C

3.3 Measurement instructions

Measurement instructions are provided in the Technical Protocol (Annex B).

The standards were acclimatized for at least 7 days in the laboratory before commencement of measurements.

3.4 Deviations from the protocol

No adjustments of the protocol were necessary.

4. Method of measurement

Each participant calibrated the resistance of the high voltage arm of their divider using their own method before sending it to the coordinator, and again after it returned to the participant's laboratory. See Annex A for details of the methods used by each participant.

When the HV modules arrived at RISE, the reference branch resistances were measured in RISE primary lab for DC-LF metrology. The resistance calibration was performed using a guarded Wheatstone bridge as depicted in Figure 3. RISE resistance calibrations are traceable to graphene-based quantum Hall device.

The 2.04 GΩ resistance of the HVDC modules was calibrated against 10 MΩ reference resistor Mashpriborintorg P4020. The calibrator voltage *V*x (Datron 4708) was kept at 1000 V and the other voltage *V*s (Wavetek 4808) was adjusted to get a zero reading of the electrometer.

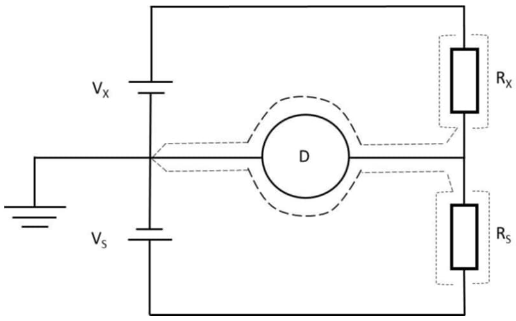


Figure 3 Wheatstone bridge with two calibrators as sources for V_s and V_x, a reference resistor R_s the unknown resistance R_x, and an electrometer D.

The expanded measurement uncertainty of the resistance measurement at RISE is 9 µΩ/Ω.

5. Behaviour of the standards

5.1 Temperature dependence

Temperature dependence of the resistors in the HV arm of the modules has been determined earlier to be (1.1 ± 0.2) µΩ/Ω/K [3]. This value has been used for this comparison.

5.2 Voltage coefficient

Voltage coefficient of the resistors in the HV arm of the modules has been determined earlier to be (10 ± 4) µΩ/Ω/kV [3]. More recent estimate is (10.4 ± 0.6) µΩ/Ω/kV, based on re-evaluation of results of publication [5]. For the complete high voltage arm with 204 resistors in series the voltage coefficient is 204 times lower, i.e. approximately 50 nΩ/Ω/kV.

6. Analysis of comparison data set

6.1 Uncertainty of measurement

All participants provided their results with the associated uncertainty budget. The uncertainties were reported using coverage factor k = 2, which for a normal distribution corresponds to a coverage probability of approximately 95 %. The uncertainty of the measurement was to be estimated according to the BIPM Guide to the expression of Uncertainty in Measurement [2].

Uncertainty budgets for each participant are provided in Annex A.

6.2 Resistance values reported by the participants

Each participant calibrated the resistance of the high voltage arm of their divider before sending it to RISE, and again after it returned to the participant. The resistance values, ambient temperatures and calibration voltage levels are shown in Table 2, together with respective uncertainties. The known temperature coefficient of the design, 1.1 µΩ/Ω/K (see clause 5) was used to normalize the results to 23 °C. All measurements were performed on 1 kV or less, and the respective voltage correction is ignored.

Table 2 Resistance results reported by the participants, with temperature correction to 23 °C .

	Lab	RISE	TUBITAK	VSL	VTT
	HV arm	HVDC1.1	HVDC2.2	HVDC2.3	HVDC2.4
Each lab before	Certificate	I10369-K08		3353083.02B	M-22E014
Results from certificates	Date	2022-01-25		2021-12-17	2022-01-20
	R [GΩ]	2.039423		2.039831	2.039950
	U[µΩ/Ω]	9		2.5	1.7
	Voltage [V]	1000		1000	8
	T [°C]	23		22.7	21
	U(*T*) [°C]	±1		±0.2	±2
	Temp corr. [µV/V] [1]	0.0		0.3	2.2
	@ 1 kV, 22.4 °C	2.039423		2.039832	2.039954
Each lab after	Certificate	I10723-K19	2022.02982	3353122.02B	M-23E175
Results from certificates	Date	2023-02-07	2023-01-05	2022-04-14	2023-03-23
	R [GΩ]	2.039426	2.039502	2.039831	2.039949
	Unc. [µΩ/Ω]	9	28	2.5	1.7
	Voltage [V]	1000	1000	1000	8
	T [°C]	23	23	22.8	21
	U(*T*) [°C]	±1	±1	±0.2	±2
	Temp corr. [µΩ/Ω] [1]	0.0	0.0	0.2	2.2
	@ 1 kV, 22.4 °C	2.039426	2.039502	2.039831	2.039953
	Unc.(corr.) [µV/V]	0.01	0.01	0.01	0.10

[1] (1.1 ± 0.2) µΩ/Ω/K [E. Houtzager et al., “Selection and characterization of resistors for a HVDC reference divider”, CPEM 2012]

6.3 Resistance measurements at RISE

The resistance comparison measurements at RISE were performed at 1 kV voltage using method as described in clause 4. The result of the comparison together with the analysis of the results is shown below. The quantity addressed in the comparison is the relative difference e_i of the resistance measurements between a given NMI and RISE. The uncertainty value quoted in this table for calibrations at RISE reflects the repeatability of resistance calibrations at RISE, not the overall uncertainty of the measured resistance value. The CRV and its uncertainty are calculated as described in clause 6.4.

Table 3 Comparison results.

Each lab, interpolation for 2022-02-15	*R* [GΩ]	2.039423	2.039502	2.039832	2.039954
	U(*R*) [μΩ/Ω]	9	28	2.5	1.7
Comparison at RISE	Certificate	I10369-K08	P105803-K02	P105803-K03	P105803-K04
	Date	2022-01-24	2022-02-17	2022-03-01	2022-02-23
Resistance	*R* [GΩ]	2.039423	2.039368	2.039829	2.039955
Repeatability (*k*=2)	*U*(*R*) [μΩ/Ω]	1.3	1.3	1.3	1.3
Deviation from RISE ref.	e_i [μΩ/Ω]	0.2	66	1.2	-0.3
Comparison uncertainty (*k*=2)	$U(e_i)$ [μΩ/Ω]	9.1	28	2.8	2.1

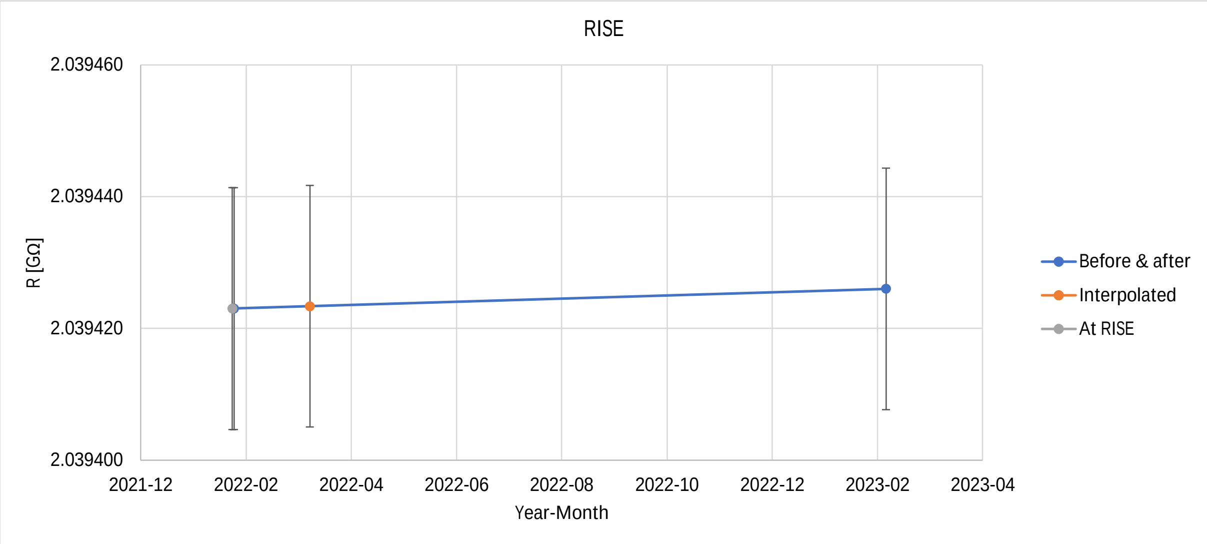


Figure 4 Timeline of RISE device calibrations (*k*=2)

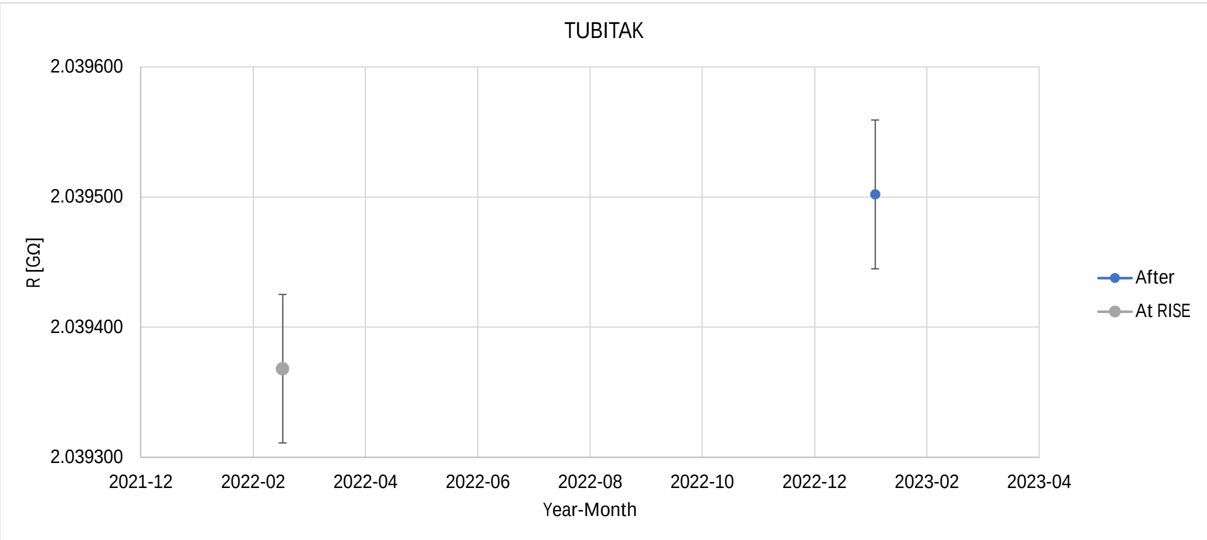


Figure 5 Timeline of TUBITAK device calibrations (*k*=2)

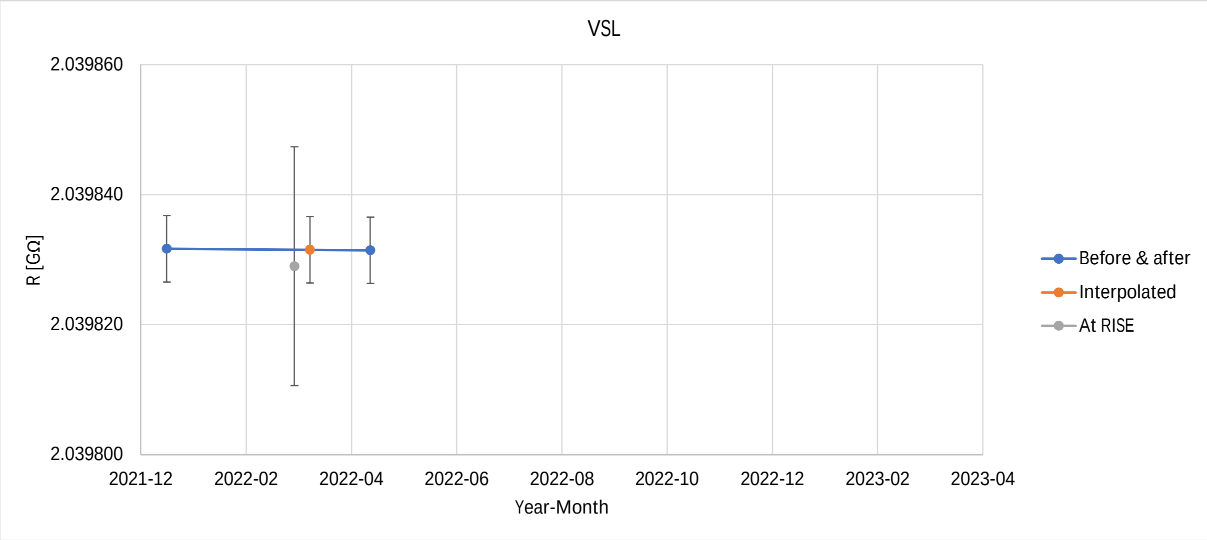


Figure 6 Timeline of VSL device calibrations (k=2)

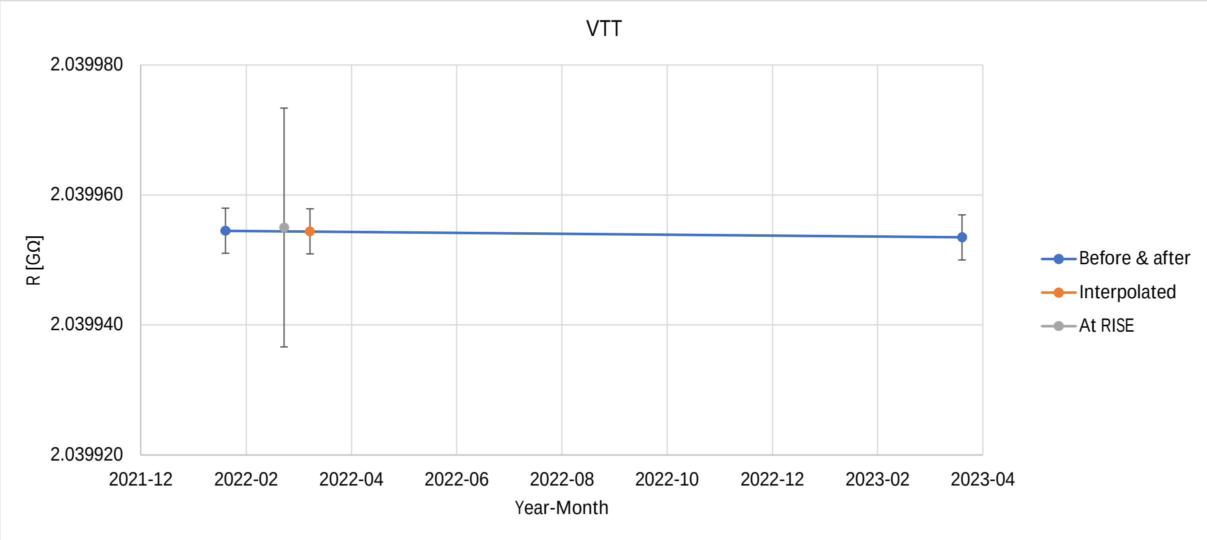


Figure 7 Timeline of VTT device calibrations (k=2)

6.4 Calculation of the comparison reference value

Analysis of comparison results is performed following the guidelines presented in [1].

The CRV is considered as an estimation of the measurand according to the measurements provided by the participating laboratories.

This estimation, y, is determined as a weighted mean of the provided results where the weights are the inverse values of the squares of the associated standard uncertainties. However, that cannot be applied in case where some of the measurements are not consistent with the others.

The procedure is implemented in four steps:

1) Determination of the comparison reference value CRV (y), using the inverse values of the squares of the uncertainties as the weights:

$$y = \frac{\sum_{i=1}^{N} x_i \, u^{-2}\left(e_i\right)}{\sum_{i=1}^{N} u^{-2}\left(e_i\right)} \; .$$

2) Calculation of standard uncertainty of CRV, *u(y)*:

$$u\left(y\right) \; = \; \frac{1}{\sqrt{\sum_{i=1}^{N} u^{-2}\left(e_i\right)}} \, .$$

3) Consistency of results

   A χ^2 test is applied to carry out an overall consistency check of the results obtained (i.e., if all results can be regarded as belonging to the same statistical ensemble). For each measured parameter, the observed chi-squared value χ^2_{obs} is determined as:

$$\chi^2_{\text{obs}} = \sum_{i=1}^{N} \frac{(e_i - y)^2}{u^2\left(e_i\right)} \; .$$

   The number of degrees of freedom is $\nu = N$ -1, for N results.

   The consistency check is considered failed if

$$\Pr\{\; \chi^2(\nu) > \chi^2_{obs} \;\} < 5\ \%,$$

   where Pr denotes “probability of”.

   If the χ^2 test fails, then the laboratory with the largest $|d_i|$ value (see below for definition) is excluded from the determination of the CRV and the consistency check repeated. The process is then repeated as needed.

4) Exclusion of incompatible results

   Compatibility index, d_i, is defined as the ratio between the difference from the reference value and the standard uncertainty:

$$d_i = \frac{\Delta e_i}{u\left(\Delta e_i\right)} = \frac{e_i - y}{\sqrt{u^2\left(e_i\right) - u^2(y)}} \; .$$

   The compatibility index $|d_i|$ describes the deviation from the CRV in relation to the calculated standard uncertainty of the deviation.

   The standard uncertainties of the differences corresponding to those laboratories whose results have not been considered in the reference value calculation are obtained applying the following expression:

$$u^2\left(\Delta e_i\right) = u^2(e_i) + u^2(y) \, ,$$

   since now the values are not correlated.

5) Compatibility of each laboratory with the estimate of CRV

   In each case, the degree of equivalence (DoE) of laboratory *i* with the CRV is determined as the pair of values for the deviation from the CRV and the uncertainty of this deviation [Δe_i, $U(\Delta e_i)$] according to the expressions:

$$E_n = \frac{\Delta e_i}{U(\Delta e_i)},$$

$$\Delta e_i = e_i - y \text{ and}$$

$$U(\Delta e_i) = 2 \cdot u(\Delta e_i),$$

where $u(\Delta e_i)$ is obtained applying the following expression:

$$u^2(\Delta e_i) = u^2(e_i) - u^2(y).$$

Note 1: The factor 2 in expression (1) above indicates a coverage factor of 95 % corresponding to a Gaussian distribution function.

Note 2: Expression (2) establishes a difference of two variances as consequence of the mutual dependence (or correlation) between x_i and *CRV*.

6.5 Analysis of the results

The results from 6.3 were analysed according to procedure described in 6.4. Probability Pr > 5 % was reached after excluding one outlier. The results (*k*=2) are shown in Table 4, Figure 8 and Figure 9.

Table 4 Resistance results reported by the participants, with temperature correction to 23 °C.

	RISE	TUBITAK	VSL	VTT
e_i [μΩ/Ω]	0.2	65.7	1.2	-0.3
$U(e_i)$ [μΩ/Ω]	9.1	28.0	2.8	2.1
$\Delta e_i = e_i - CRV$ [μΩ/Ω]	-0.1	65.5	1.0	-0.6
$U(\Delta e_i)$ [μΩ/Ω]	8.9	28.1	2.3	1.3
$\lvert E_n \rvert$	0.01	2.33	0.43	0.42
Exclude		1		

CRV [μΩ/Ω]	0.3
U(CRV) [μΩ/Ω]	1.7
Pr	68 %

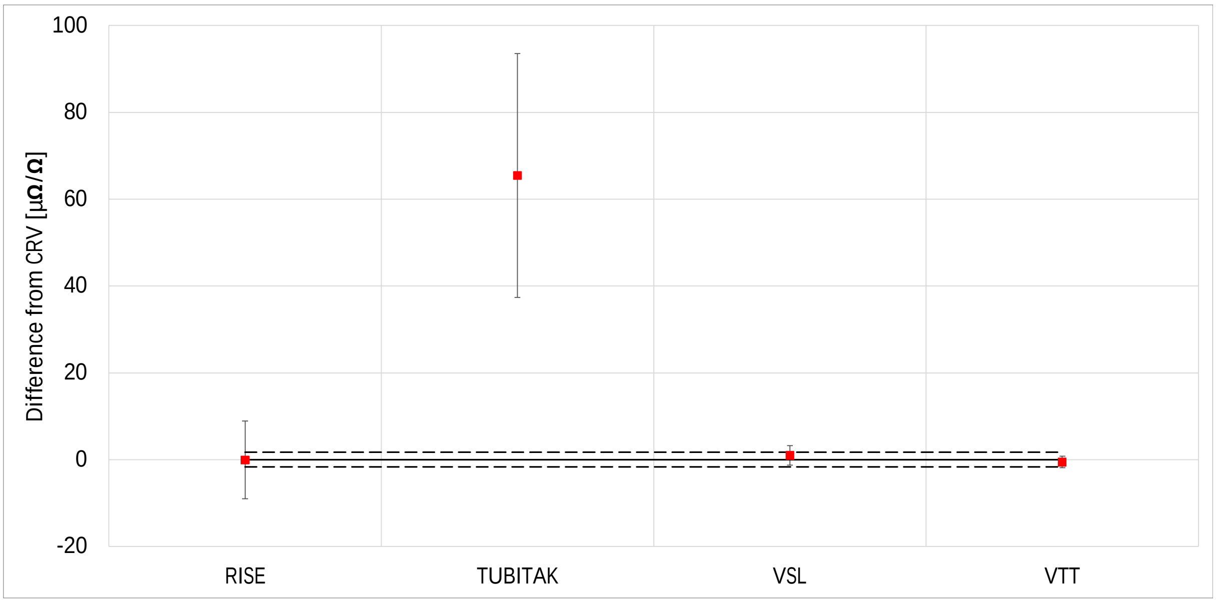


Figure 8 Deviations from the CRV

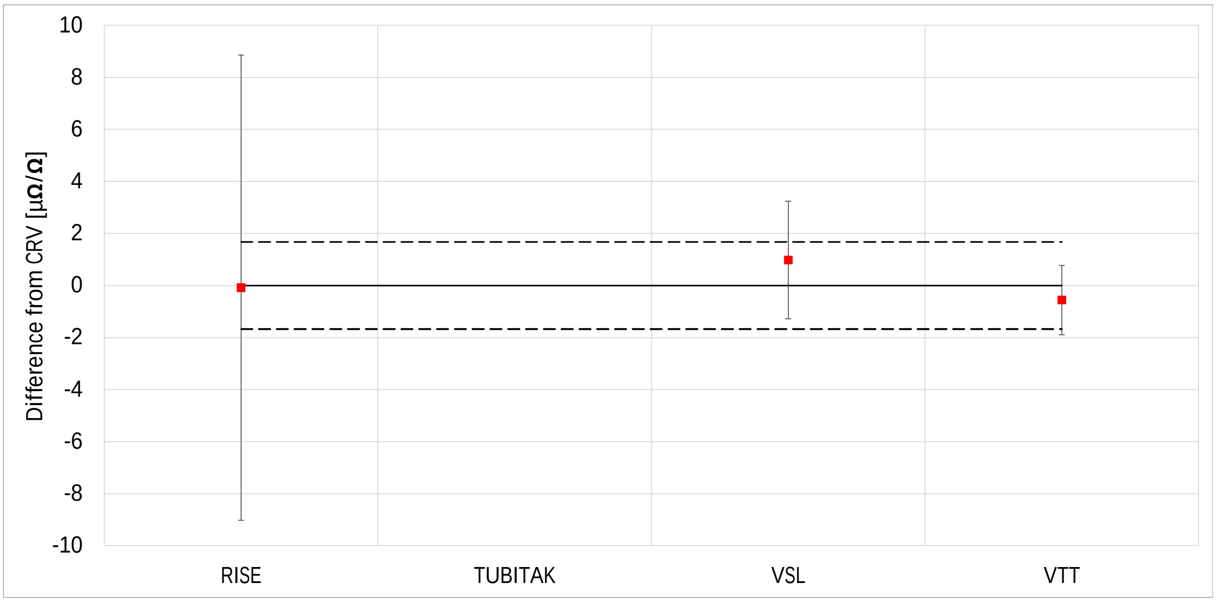


Figure 9 Deviations from the CRV, closeup

7. Conclusions

Good results were achieved in the 2 GΩ high voltage resistance comparison, that aims to support DC high voltage calibrations. The proper connection of the reference resistors' shield was found critical. When the internal shield of the resistor was properly connected, the spread of the value of 2.04 GΩ resistance was 2.2 μΩ/Ω, and after removal of one outlier the expanded uncertainty (k=2) of the comparison reference value was 1.7 μΩ/Ω. The reference resistor design has been found very stable. Most measurements were performed within 16 months from the start, one repeated measurement after 30 months from the start. Three labs used resistance bridges at 1 kV; one lab used voltage-current method at 8 V, with Ultra-stable Low-noise Current Amplifier (ULCA) for current measurement.

8. References

[1] Cox M. G.: The Evaluation of Key Comparison Data. Metrologia 39, pp. 589-595, 2002, https://iopscience.iop.org/article/10.1088/0026-1394/39/6/10

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[3] E. Houtzager, G. Rietveld, J. Hällström, A. -P. Elg and J. H. N. van der Beek, "Selection and characterization of resistors for a HVDC reference divider," *2012 Conference on Precision electromagnetic Measurements*, Washington, DC, USA, 2012, pp. 197-198, doi: 10.1109/CPEM.2012.6250869.

[4] J. Hällström *et al.*, "Performance of a Wideband 200-kV HVDC Reference Divider Module," in *IEEE Transactions on Instrumentation and Measurement*, vol. 63, no. 9, pp. 2264-2270, Sept. 2014, doi: 10.1109/TIM.2014.2304857.

[5] A.-P. Elg, A. Bergman, J. Hällström, M. Kharezy and T. Nieminen, "Traceability and characterization of a 1000 kV HVDC reference divider," *29th Conference on Precision Electromagnetic Measurements (CPEM 2014)*, Rio de Janeiro, Brazil, 2014, pp. 780-781, doi: 10.1109/CPEM.2014.6898618.

Annex A Description of calibration method and traceability

A.1 RISE

The traceability is established by calibration of the resistance of six HV modules and two LV arms of the 200 kV divider in the primary lab for DC-LF metrology. The scale factor of HVDC 1.1 with either LV arm is also calibrated. The traceability is established at RISE for all quantities; the voltage by the Josephson reference; the realization of time with atomic clocks; and the resistance by quantum Hall (now using graphene). The resistance calibration is performed in the primary lab using a guarded Wheatstone bridge as depicted in Figure A.1.

Calibrating the high ohmic resistance of the HVDC modules, having a resistance of 2.04 GΩ a reference resistor 10 MΩ Mashpriborintorg P4020 is used. The calibrator Vx (Datron 4708) is kept at 1000 V and the other Vs (Wavetek 4808) is adjusted to get a zero reading of the electrometer.

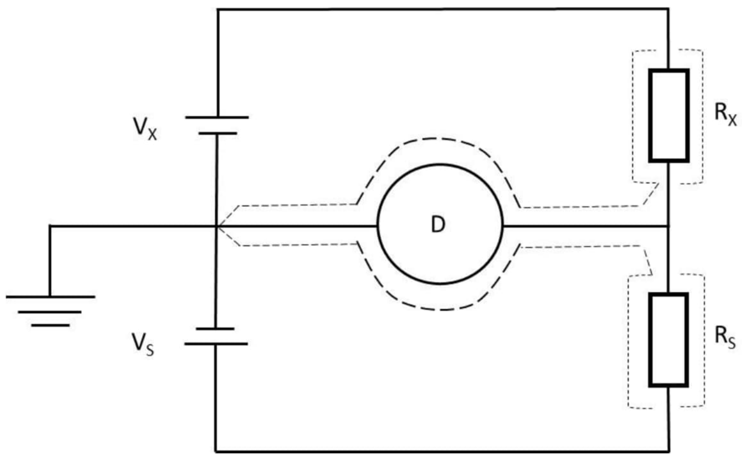

Figure A.1 Wheatstone bridge with two calibrators as sources for Vs and Vx, a reference resistor Rs the unknown resistance Rx, and an electrometer D.

The scale factor values of any HV divider configuration can now be calculated and is also compared with a calibrated scale factor of the 200 kV HVDC 1.1 and with LV arm 5 or LV arm 6 measurement system. The scale factors of different configuration, with the expanded measurement uncertainty of the LV arm resistance with an expanded measurement uncertainty of < 1.0 µΩ/Ω, and a HV arm resistance expanded measurement uncertainty of 9 µΩ/Ω. The scale factor calibration of HVDC 1.1 and with LV arm 5 or LV arm 6 has an expanded uncertainty contribution of < 6 µV/V.

The value of the unknown resistance is obtained from:

$$R_x = R_s \cdot r \cdot (1+\delta r) \cdot (1+\delta_{res}) \cdot (1+\delta_{bal}) \cdot (1+\delta R_{xbal}),$$

where:

- R_x - value of the unknown resistor
- R_s - value of the reference resistor
- r - measured voltage ratio
- δr - correction for error in voltage ratio due to calibration and stability of voltage ratio
- δ_{res} - correction for error due to detector resolution
- δ_{bal} - correction for error in bridge balance due to leakage and uncompensated offset effects in detector
- δR_{xbal} - correction for error due to voltage change over unknown resistor during the bridge balancing process caused by potential voltage dependence of unknown resistor

Based on the model equation above, the relative standard uncertainty for the measured resistor $u(R_x)/R_x$ can be determined as:

$$\left(\frac{u(R_x)}{R_x}\right)^2 = \left(\frac{u(R_s)}{R_s}\right)^2 + \left(\frac{u(r)}{r}\right)^2 + u^2(\delta r) + u^2(\delta_{res}) + u^2(\delta_{bal}) + u^2(\delta R_{xbal})$$

where:

- $u(R_s)$ - uncertainty in reference resistor value due to step up procedure from QHR, stability, temperature and voltage dependence
- $u(r)$ - mean value standard deviation of measured voltage ratio
- $u(\delta r)$ - voltage ratio uncertainty due to calibration and stability of voltage ratio
- $u(\delta_{res})$ - uncertainty due to detector resolution
- $u(\delta_{bal})$ - bridge balance uncertainty due to leakage and uncompensated offset effects of detector
- $u(\delta R_{xbal})$ - uncertainty due to voltage change over unknown resistor during bridge balancing process, caused by potential voltage dependence of unknown resistor

Quantity X_i	Estimation x_i	Relative standard uncertainty(10^{-6}) $u(x_i)$	Probability distribution / evaluation (A, B)	Sensitivity factor c_i	Relative uncertainty contribution, (10^{-6}) $u(R_i)$	Number of degrees of freedom ν_i
R_s	10 MΩ	1,7	rectangular / B	1	1,7	∞
r	200	0,1	normal / A	1	0,1	9
δr	0	2,9	rectangular / B	1	2,9	∞
δ_{res}	0	0,0	rectangular / B	1	0,0	∞
δ_{bal}	0	2,3	rectangular / B	1	2,3	∞
δR_{xbal}	0	0,0	rectangular / B	1	0,0	∞
R_x	2 GΩ					
		Combined standard uncertainty:			4,1 μΩ/Ω	
		Effective number of degrees of freedom:			2644	
		Expanded measurement uncertainty (95% coverage factor):			8,3 μΩ/Ω	

A.2 TUBITAK

Calibration method

The calibration of the high voltage arm of the divider 2 GΩ resistor was performed by comparing with 1 GΩ reference resistors using the active guarded Wheatstone Bridge as shown in Figure A.2.1. The resistance value of the high voltage arm resistor was calculated from the ratio of the bridge. Measurement was performed at 1000 V DC voltage. Reference resistors are traceable to Quantum Hall resistor.

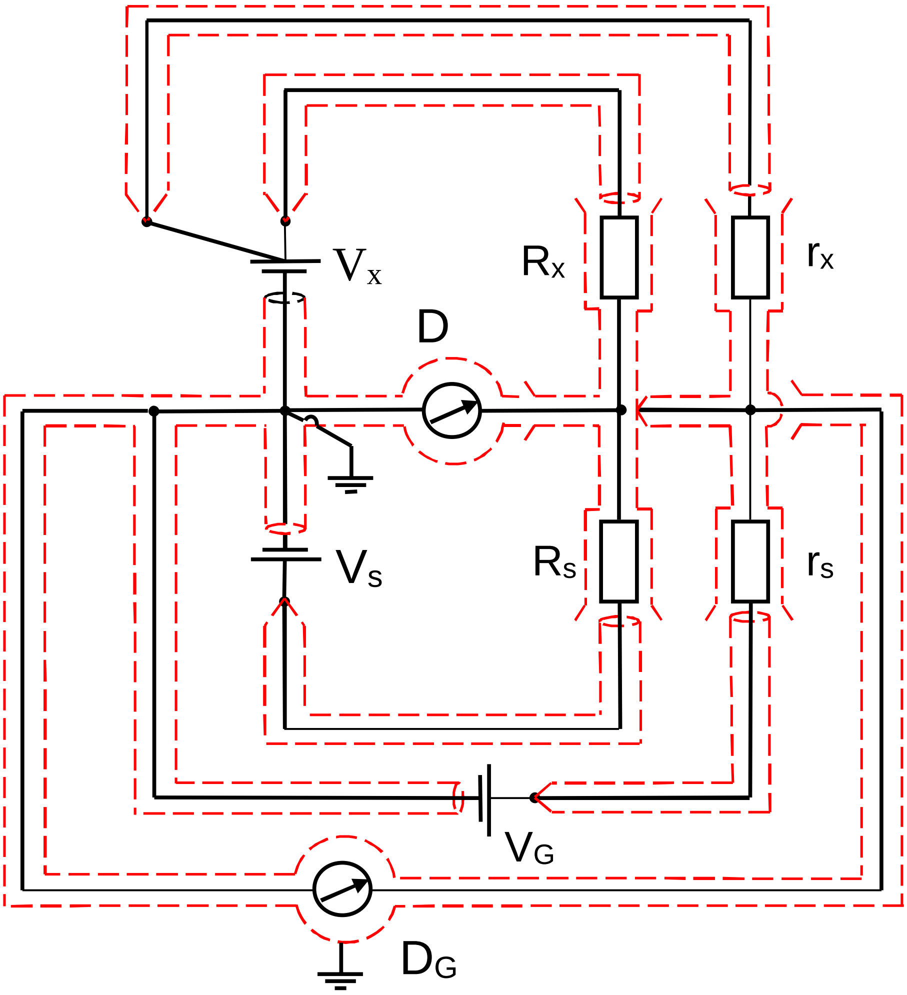

Figure A.2.1 Wheatstone Bridge Electrical Connection Diagram

The resistor connection was made to the BNC connectors named as “High” and “Low” as shown in blue arrows in Figure A.2.2.

Figure A.2.2 2 GΩ resistor connection of HVDC divider (the model of HVDC 2.2-LV2)

Ambient Conditions

Temperature : (23 ± 1) °C
Relative Humidity : (45 ± 15) %rh

Measurement Results

Measurement result is given in Table A.2.1.

Table A.2.1 Comparison Results of HVDC2.2 Divider Resistor

Average Measurement Date	Resistance (GΩ)	Uncertainty (GΩ)
05.01.2023	2,039502	0,000057

Measurement uncertainty

Measurement uncertainty is stated as the standard uncertainty of the measurement multiplied by the coverage factor k=2, which for a normal distribution corresponds to a coverage probability of approximately 95%. The standard uncertainties of the measurements have been determined in accordance with GUM (Evaluation of measurement data-Guide to the expression of uncertainty in measurement, JCGM 100:2008) and EA-4/02 documents.

Model function is given below. Measurement uncertainty budget is given below in Table A.2.2.

$$R_x = \frac{1}{2} \cdot \left(R_S + \delta R_{Sdrf} + \delta R_{Spow} + \delta R_{Stemp}\right) \cdot \left(\frac{V_X^- + \delta V_{Xdrf}^- + \delta V_{Xres}^-}{V_S^+ + \delta V_{Sdrf}^+ + \delta V_{Sres}^+} + \frac{V_X^+ + \delta V_{Xdrf}^+ + \delta V_{Xres}^+}{V_S^- + \delta V_{Sdrf}^- + \delta V_{Sres}^-}\right) - \delta R_{Xtemp}$$

Table A.2.2 Uncertainty budget of HVDC2.2 Resistor Measurement

Symbol	Estimated Value	Standard Uncertainty	Distribution Function	Sensitivity Coefficient	Uncertainty Contribution
R_S	1,0E+9 Ω	1,5E+4 Ω	Normal, k=2	-2	-1,50E+4 Ω
δR_{Sdrf}	0	1,0E+4 Ω	Rectangular	-2	-1,15E+4 Ω
δR_{Spow}	0	0,0E+0 Ω	Rectangular	-2	0,00E+0 Ω
δR_{Stemp}	0	2,5E+3 Ω	Rectangular	-2	-2,89E+3 Ω
V^+_X	1000 V	2,0E-3 V	Normal, k=2	-1,0E+6 Ω/V	-1,00E+3 Ω
δV^+_{Xdrf}	0	1,0E-2 V	Rectangular	-1,0E+6 Ω/V	-5,84E+3 Ω
δV^+_{Xres}	0	5,0E-6 V	Rectangular	-1,0E+6 Ω/V	-2,89E+0 Ω
V^-_X	-1000 V	2,0E-3 V	Normal, k=2	1,0E+6 Ω/V	1,00E+3 Ω
δV^-_{Xdrf}	0	1,0E-2 V	Rectangular	1,0E+6 Ω/V	5,84E+3 Ω
δV^-_{Xres}	0	5,0E-6 V	Rectangular	1,0E+6 Ω/V	2,89E+0 Ω
V^+_S	500 V	1,0E-3 V	Normal, k=2	2,0E+6 Ω/V	1,00E+3 Ω
δV^+_{Sdrf}	0	5,1E-3 V	Rectangular	2,0E+6 Ω/V	5,89E+3 Ω
δV^+_{Sres}	0	5,0E-6 V	Rectangular	2,0E+6 Ω/V	5,77E+0 Ω
V^-_S	-500 V	1,0E-3 V	Normal, k=2	-2,0E+6 Ω/V	-1,00E+3 Ω
δV^-_{Sdrf}	0	5,1E-3 V	Rectangular	-2,0E+6 Ω/V	-5,89E+3 Ω
δV^-_{Sres}	0	5,0E-6 V	Rectangular	-2,0E+6 Ω/V	-5,77E+0 Ω
δR_{Xtemp}	0	1,0E+4 Ω	Rectangular	-1	-5,77E+3 Ω
Rx_{std}	0	1,5E+4 Ω	Normal, k=1	1	1,49E+4 Ω
			Standard Uncertainty		2,76E+4 Ω
Rx	2,04E+9 Ω		Expanded Uncertainty		27,6 µΩ/Ω
			Declared Uncertainty		**28 µΩ/Ω**

A.3 VSL

Calibration method

To determine the scale factor, the resistance of both arms is measured with specialized resistance bridges. Afterwards the scaling factor is corrected for the voltage, temperature, and power dependence.

The resistance of both the high-voltage arm and the low-voltage arm were determined just before and directly after transportation to RISE.

Uncertainty resistance:

List of Quantities

Quantity	Unit	Definition
R_{DUT}	Ω	Resistance value of the DUT
R_{ref}	Ω	Resistance value of reference resistor, determined at certain T and V
dR_{refpwr}	Ω/Ω/W	Power and/or voltage effect of reference resistor: calibration and use not always at the same voltage (1:10 step up method)
dR_{refT}	Ω/Ω/W	Temperature effect of reference resistor: calibration and use not always at same temperature. Includes non-equilibrium temperature of resistor and temperature sensor.
r	-	Measured ratio with adapted Wheatstone bridge (value at average date)
dr_{Vcal}	V/V	Combined uncertainty of voltage calibration with HP 3458A DVM
dr_{Vdrift}	V/V	Drift in Fluke / Krohn-Hite voltage sources since last voltage calibration
dr_{Vlin}	V/V	Effect of non-linearity of the HP 3458A in the determination of the 1:10 voltage ratio
dV_{lin}	V/V	Linearity of Rs voltage source around setpoint
dr_{null}	V/V	Gain error of null-detector. For resistance measurements <= 1G and >= 100G, voltage and current null-detector is used respectively. Between 1G and 100G either method can be used. Effect: (balance - average$_{zero}$a) * gain$_{error}$.
$dr_{bridgesens}$	Ω/Ω	Effect of bridge sensitivity. For resistance values above 10 GOhm this can be significantly different from the theoretical bridge sensitivity. Therefore, the actual bridge sensitivity is measured in a first 'trial' series of measurements.
dr_{posneg}	Ω/Ω	Effect of differences in Rx(+V) and Rx(-V) values; 25 % of measured difference is taken as uncertainty contribution
dr_{decay}	Ω/Ω	Effect of insufficient wait times (25 % of the measured difference between initial and final "circuit zero" readings).
$dr_{closure}$	Ω/Ω	Measured closure: 10M - 100M - 1G with SIQ Hamon; 1G - 10G - 100G - 1G and 10G - 100G - 1T - 10G
dr_{leak}	Ω/Ω	Effect of leakage in the bridge, cables, reference resistor and DUT

Uncertainty budget for 2 GΩ at 1 kV

Quantity	Value	Standard Uncertainty	Distribution	Sensitivity Coefficient	Uncertainty Contribution
R_{ref}	$100.0081600\cdot10^{6}$	60.0	normal	20	1200
δR_{refpwr}	0.0	$115\cdot10^{-9}$	rectangular	$2.0\cdot10^{9}$	240
δR_{refT}	0.0	$28.9\cdot10^{-9}$	rectangular	$2.0\cdot10^{9}$	59
r	20.396655350	$250\cdot10^{-9}$	normal	$100\cdot10^{6}$	25
δr_{Vcal}	0.0	$820\cdot10^{-9}$	normal	$2.0\cdot10^{9}$	1700
δr_{Vdrift}	0.0	$231\cdot10^{-9}$	rectangular	$2.0\cdot10^{9}$	470
δr_{Vlin}	0.0	$115\cdot10^{-9}$	rectangular	$2.0\cdot10^{9}$	240
δV_{lin}	0.0	$20.4\cdot10^{-9}$	triangular	$2.0\cdot10^{9}$	42
δr_{null}	0.0	$28.9\cdot10^{-9}$	rectangular	$2.0\cdot10^{9}$	59
$\delta r_{bridgesens}$	0.0	$28.9\cdot10^{-9}$	rectangular	$2.0\cdot10^{9}$	59
δr_{posneg}	0.0	$86.6\cdot10^{-9}$	rectangular	$2.0\cdot10^{9}$	180
δr_{decay}	0.0	$28.9\cdot10^{-9}$	rectangular	$2.0\cdot10^{9}$	59
$\delta r_{closure}$	0.0	$173\cdot10^{-9}$	rectangular	$2.0\cdot10^{9}$	350
δr_{leak}	0.0	$115\cdot10^{-9}$	rectangular	$2.0\cdot10^{9}$	240
R_{DUT}	$2.03983197\cdot10^{9}$	2200			

Quantity	Value	Expanded Uncertainty	Coverage factor	Coverage
R_{DUT}	$2.0398320\cdot10^{9}$ *	$2.2\cdot10^{-6}$ **(relative)	2.00	95% (normal)

*) for indication only. The uncertainty budget is only used to calculate the uncertainty.
**) The traveling uncertainty of less than 1 ppm is not included in the uncertainty budget.

A.4 VTT

Calibration method

Calibration was performed using voltage/current method. Voltage was fed from a calibrator /1/ to the high voltage terminal of the resistor under calibration. The current flowing from the low voltage terminal to ground was sensed by a transimpedance amplifier /2/. The voltage across the resistor under calibration and the output of the transimpedance amplifier were measured using two multimeters /3,4/. Readings were taken simultaneously by the two multimeters with c. 0.7 s interval for c. 30 min. The applied voltage was reversed every 60 s.

Gain difference of the two multimeters was compensated by connecting them in parallel to the calibrator output and observing the difference of the readings.

The high voltage divider and the transimpedance amplifier were located behind the grounded fence in the high voltage laboratory. The voltage was applied also to the shield branch of the resistor; the low voltage terminal of the shield branch was grounded.

Measurement standards used in calibration

/1/ Fluke 5520 calibrator, MIKES000116, M-21E005
/2/ ULCA, Ultrastable Low-noise Current Amplifier, MIKES011321, M-21E280
/3,4/ Hewlett Packard 3458A digital voltmeters

Metrological traceability of calibration results

Calibration results are traceable to the International System of Units (SI) via Finnish national measurement standards.

ULCA was calibrated using the CCCDrive of Magnicon GmbH (serial number CCC2015-02) with a 12-bit Cryogenic Current Comparator (CCC), and the traceability of voltage-to-current ratio is based on a 12.9 kΩ standard resistor ESI SR51215 (MIKES000001) which is traceable to the primary quantum Hall resistance standard of MIKES.

Measurement uncertainty

While calculating the uncertainties of the calibrations, the following contributions were considered:

- standard deviation of the readings;
- uncertainty of ULCA calibration;
- internal temperature of ULCA;
- ULCA drift; and
- different gains of the digital voltmeters.

The long-term stability effects of the device under calibration are not included.

Measurement uncertainty is estimated and stated according to GUM (Evaluation of measurement data – Guide to the expression of uncertainty in measurement, JCGM 100:2008) using the coverage factor $k = 2$, which for a normal distribution corresponds to a probability of approximately 95 %.

Annex B Comparison protocol

Supplementary Comparison EURAMET.EM-S46 and EURAMET.EM-S47
High voltage comparison of DC ratio and high resistance

TECHNICAL PROTOCOL

version 1.0, Oct 07, 2022

A.-P. Elg[1], J. Hällström[2], G. Rietveld[3]

[1] RISE Research Institutes of Sweden, Brinellgatan 4, 50115 Borås, Sweden
[2] VTT Technical Research Centre of Finland, National Metrology Institute VTT MIKES, Tekniikantie 1, 02150 Espoo, Finland
[3] VSL National Metrology Institute, Thijsseweg 11, Delft 2629JA, The Netherlands

1. Introduction

Metrology area, branch	Electricity and Magnetism, High Voltage and Current
Description	High DC voltage ratio up to 200 kV
Time of measurement	2022-03-07 – 2022-03-25
Measurand(s)	DC voltage ratio DC resistance
Parameter(s)	Nominal ratio: 20000 Nominal resistance: 2 GΩ Voltage: up to 200 kV
Transfer device(s)	Star comparison, all references in one lab at the same time.
Comparison type	Supplementary comparison
Consultative Committee	CCEM (Consultative Committee for Electricity and Magnetism)
Related regional metrology organizations	EURAMET

The 200 kV reference dividers were built in 2014 for RISE, VTT, PTB, VSL and TUBITAK as part of EMRP project HVDC. These dividers will be transported to RISE in February/March 2022 to compare their ratios and high voltage arm resistances.

2. Standards

The standards to be compared are identical 200 kV divider modules shown in Figure 1.

Figure 1 The five high voltage dividers to be compared (coloured).

The outer diameter of a module is 480 mm, it is 1500 mm high, and it weighs about 150 kg. The internal structure of the module is shown in Figure 2. The components are enclosed in an SF6 filled fiberglass tube. The top endplate houses a gas valve, pressure gauge and a feed-through for the reference divider signal. The bottom plate has a mating feed-through, so that the modules can be directly stacked and mounted on top of each other.

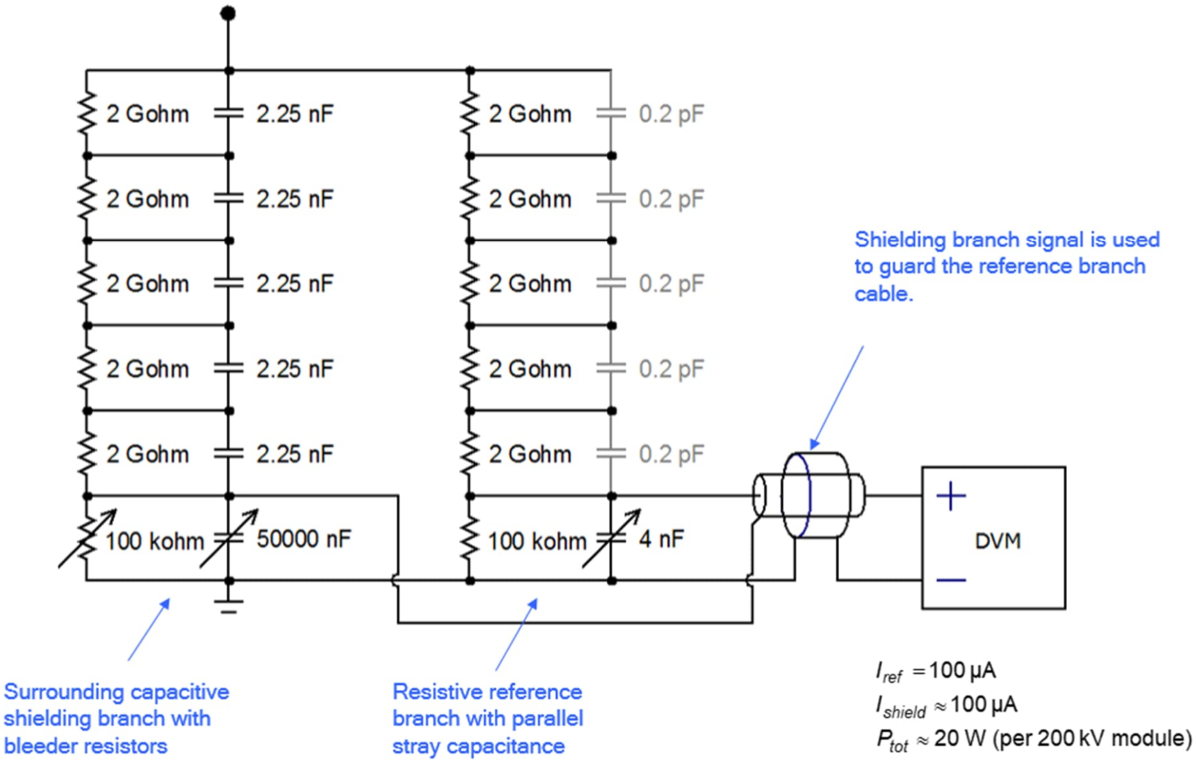

Figure 2 Internal structure of the dividers. The adjustments are used to optimise the AC behaviour, when needed.

3. Measurement methods

3.1 General

Participants shall define the scale factor (ratio) and the resistance of the reference branch high voltage resistor of their divider using existing home laboratory procedures before sending the divider for comparison measurements at RISE. Each participant shall repeat their home calibration after the divider has returned after comparison.

4. Quantities to be measured

1. The DC ratio of the divider, with nominal value of 20000; and
2. The resistance of the high voltage reference branch resistor, with nominal value of 2 GΩ.

4.1 Ambient conditions

Ambient conditions shall be reported for each home calibration (before and after measurements at RISE), and for measurements at RISE. Recorded temperature values will be used for correcting the final report results to reflect performance at e.g. 22.0 °C. Humidity does not have to be controlled, but shall be reported.

The dividers must be acclimatized for a suitable duration (not less than 7 days) in the laboratory before the measurements in order to reach stable temperature.

4.2 HVDC ratio

The scale factor (ratio) of the dividers will be compared at RISE on the voltage levels shown in Table 1.

Table 1 Voltages for ratio comparison

Nominal voltage [kV]
1
10
100
200
-200

The comparison at RISE will be performed by connecting two or several dividers in parallel to measure the high voltage. The output of each divider will be measured using calibrated 3458A multimeter(s).

4.3 High voltage arm resistance

The high voltage arm resistance of each divider will be separately measured at RISE at 1 kV using voltage bridge method.

5. Measurement reporting

5.1 Before RISE comparison measurements

Each participant shall calibrate their divider before the comparison session. The calibration certificate shall be signed before the start of the RISE session and, at minimum, it shall contain the following:

- description of the measuring set-up(s) including the electrical circuit configuration;
- traceability scheme; if the traceability to the SI is provided by another NMI, the name of the NMI has to be stated (needed to identify possible sources of correlation);
- value and uncertainty of the scale factor, and respective voltage level(s);
- value and uncertainty of the reference branch high voltage resistor, and respective voltage level(s);
- description of the measurement procedure(s);
- the ambient conditions of the measurement: the temperature and humidity with limits of variation.

5.2 RISE comparison measurements

The pilot (RISE) prepares a report summarising the results of the measurements described in chapters 4.2 and 4.3. RISE will not disclose this report to other participants until all calibration certificates described in clauses 5.1 and 5.2 are submitted.

5.3 After RISE comparison measurements

Each participant shall repeat the calibration described in chapter 5.1 within 2 months after return of the divider to their laboratory and send both calibration certificates to the coordinator.

6. Final report of the comparison

Within 3 months after completion of all measurements, the VTT will prepare the first draft report and send it to the participants for comments.

This final report will summarise the results from the calibration certificates and comparison report described in chapter 5.

7. Organization

7.1 Coordinator

Dr. Alf-Peter Elg

RISE Research Institutes of Sweden
Measurement Science and Technology
Brinellgatan 4, P.O. Box 857
SE-501 15. Boras
SWEDEN
alf.elg@ri.se

7.2 Support group

Dr. Jari Hällström

National Metrology Institute VTT MIKES
Tekniikantie 1
FIN 02150 Espoo
FINLAND
jari.hallstrom@mikes.fi

Prof. Dr. Ir. Gert Rietveld

VSL National Metrology Institute
Thijsseweg 11
Delft 2629JA
The Netherlands
grietveld@vsl.nl

7.3 Participants

Acro-nym	Institute	Country	Sta-tus	Contact
RISE	Research Institutes of Sweden AB	Sweden	NMI	Dr. Alf-Peter Elg alf.elg@ri.se
VTT MI-KES	Technical Research Centre of Finland Ltd	Finland	NMI	Dr. Jari Hällström jari.hallstrom@vtt.fi
PTB	Physikalisch-Technische Bundesanstalt	Germany	NMI	Dr. Johann Meisner johann.meisner@ptb.de
TUBITAK	TÜBITAK Ulusal Metroloji Enstitüsü	Turkey	NMI	Dr. Ahmet Merev ahmet.merev@tubitak.gov.tr
VSL	VSL National Metrology Institute (VSL)	Nether-lands	NMI	Dr. Ernest Houtzager ehoutzager@vsl.nl

7.4 Time schedule

Comparison measurement will be performed in February/March 2022 at RISE according to the schedule shown below.

Timetable

Action	Start	Finish
Arrival of dividers to RISE	20.01.2022	22.02.2022
Temperature stabilization (7 days)	14.01.2022	01.03.2022
2 GΩ measurements	21.01.2022	01.03.2022
200 kV scale factor measurements	7.03.2022	11.03.2022
Divider departure from RISE	21.03.2022	06.04.2022

7.5 Transportation

Participants will be responsible for arranging transportation for their own divider to and from RISE.

7.6 Financial aspects, insurance

Each participating laboratory covers the costs of its own labor and transportation cost, as well as of any possible damage to their own equipment.

Annex C TUBITAK UME corrective action

An analysis of the preliminary results of the comparison shows that TUBITAK UME measurements deviates from the RV (Reference Value).

Extensive investigation has been performed about the measurements we performed in the comparison. During the discussion with the colleagues in the High Voltage Laboratory of TUBITAK UME about the internal structure of the High Voltage Divider, it was realized that the screen at the high voltage side of the divider resistor was not connected to any point and it was floating during the measurements. Due to the large size of the High Voltage Divider, it creates leakage currents, and these leakage currents were dependent on the location of the device in the laboratory. This effect explains the large deviation observed between the measurement results of TUBITAK UME and RISE.

Therefore, the divider used in the intercomparison was requested from the High Voltage Laboratory of TUBITAK UME and the measurements were repeated. Unlike the first measurements, the screen of the divider in the high voltage side (2 GΩ part) was connected to a separate guard (1000 V DC) as shown by the blue line in Figure C.1. The red dotted lines are the screens of the low noise cables. The connections are also shown in Figure C.2 and C.3.

Two different 1 GΩ reference resistors were used as R_s in the measurements.

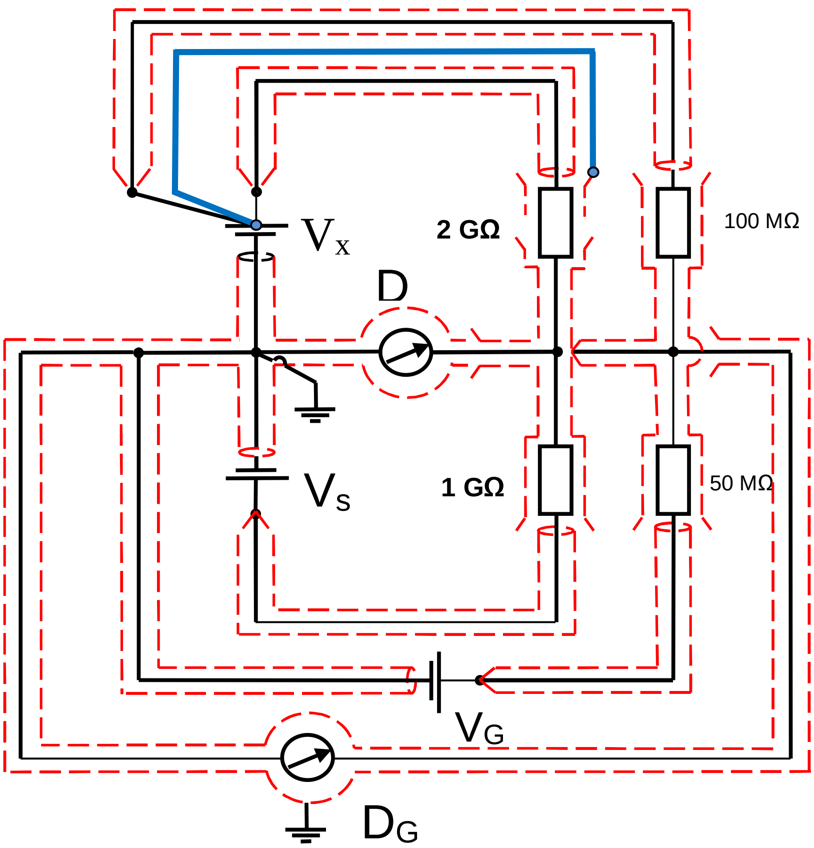

Figure C.1. Wheatstone Bridge Electrical Connection Diagram for HVDC2.2

Figure C.2. High Voltage Divider HVDC2.2 2 GΩ Resistor High Voltage Side Connections

Figure C.3. High Voltage Divider HVDC2.2 2 GΩ Resistor High Voltage Side Connections

We have performed the measurements with this configuration several times. The measurement results are given below in Table C.1 and Figure C.4 as a graphic.

Table C.1. Measurement Results of HVDC2.2 Divider Resistor

Measurement Date	Resistance (GΩ)	Uncertainty (GΩ)
23.05.2024	2,039365	0,000037
24.05.2024	2,039373	0,000037
27.05.2024	2,039372	0,000037
28.05.2024	2,039366	0,000037
01.06.2024	2,039380	0,000037
03.06.2024	2,039372	0,000038
04.06.2024	2,039379	0,000037
07.06.2024	2,039367	0,000038
26.06.2024	2,039361	0,000038
27.06.2024	2,039369	0,000037

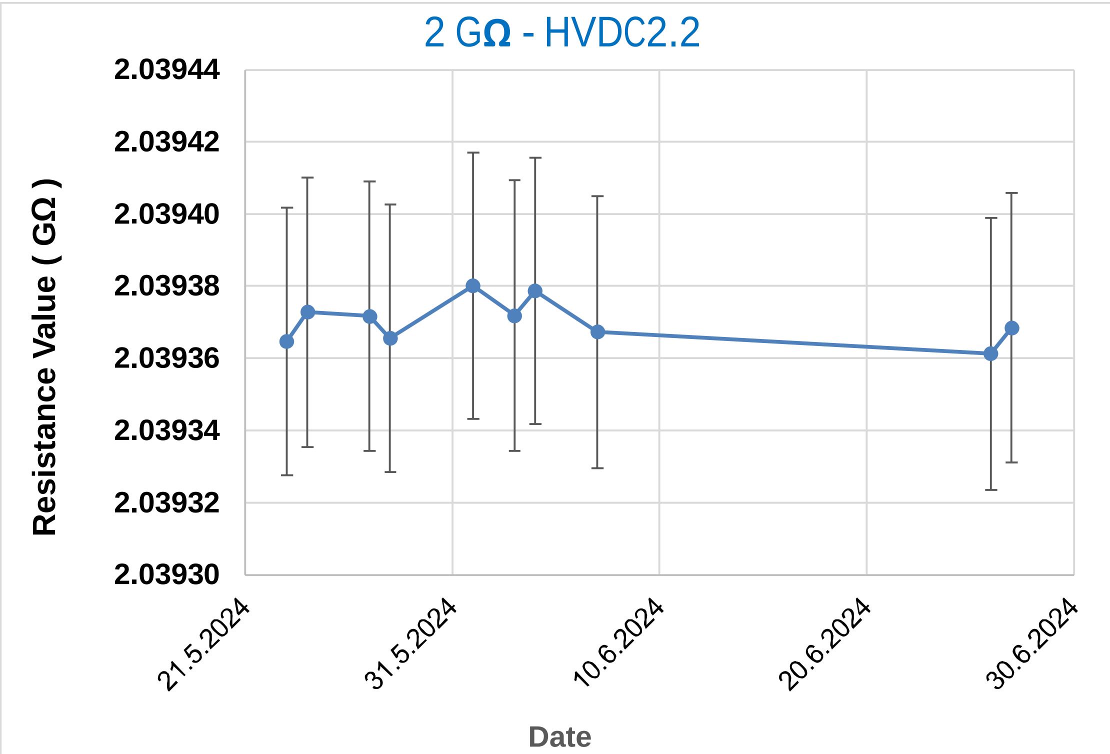

Figure C.4. High Voltage Divider HVDC2.2, 2 GΩ Resistor Measurement Results

Final comparison value and previous measurements with their associated uncertainties are given below in Table C.2.

Table C.2. Comparison Results of HVDC2.2 Divider Resistor

	2 GΩ High Side Screen	Average Measurement Date	Resistance (GΩ)	Uncertainty (GΩ)
Previous Value	Floating	05.01.2023	2,039502	0,000057
Final Comparison Value	Connected to guard (1000 V DC)	04.06.2024	2,039370	0,000041

Model function of the measurement is given below. Uncertainty parameters are explained in Table C.3.

$$R_x = \frac{1}{2} \cdot \left(R_S + \delta R_{Sdrf} + \delta R_{Spow} + \delta R_{Stemp}\right) \cdot \left(\frac{V_X^- + \delta V_{Xdrf}^- + \delta V_{Xres}^-}{V_S^+ + \delta V_{Sdrf}^+ + \delta V_{Sres}^+} + \frac{V_X^+ + \delta V_{Xdrf}^+ + \delta V_{Xres}^+}{V_S^- + \delta V_{Sdrf}^- + \delta V_{Sres}^-}\right) - \delta R_{Xtemp}$$

Table C.3. Uncertainty Parameters

$u(R_S)$	Calibration uncertainty of the reference resistor, normal distribution.
$u(\delta R_{Sdrf})$	Uncertainty due to drift of the reference resistor, rectangular distribution.
$u(\delta R_{STemp})$	Uncertainty due to temperature variation of the reference resistor, rectangular distribution.
$u(\delta R_{SPow})$	Uncertainty due to the power coefficient of the reference resistor.
$u(V_x^+)$, $U(V_s^+)$	Calibration uncertainty of the DMM, normal distribution.
$u(V_x^-)$, $U(V_s^-)$	Calibration uncertainty of the DMM, normal distribution.
$u(\delta V_{xdrf}^+)$, $U(\delta V_{sdrf}^+)$	Uncertainty due to drift of the DMM, rectangular distribution.
$u(\delta V_{xdrf}^-)$, $U(\delta V_{sdrf}^-)$	Uncertainty due to drift of the DMM, rectangular distribution.
$u(\delta V_{Xres}^+)$, $U(\delta V_{Sres}^+)$	Uncertainty due to finite resolution of the DMM, rectangular distribution.
$u(\delta V_{Xres}^-)$, $U(\delta V_{Sres}^-)$	Uncertainty due to finite resolution of the DMM, rectangular distribution.
$u(\delta R_{XTemp})$	Uncertainty due to temperature variation of the reference resistor, rectangular distribution.

Detailed uncertainty budget is presented in Table C.4.

Table C.4. Uncertainty budget of HVDC2.2 Resistor Measurement

Symbol	Estimated Value	Standard Uncertainty	Distribution Function	Sensitivity Coefficient	Uncertainty Contribution
R_S	1,0E+9 Ω	1,2E+4 Ω	Normal, k=2	-2	-1,20E+4 Ω
δR_{Sdrf}	0	0,0E+0 Ω	Rectangular	-2	0,00E+0 Ω
δR_{Spow}	0	0,0E+0 Ω	Rectangular	-2	0,00E+0 Ω
δR_{Stemp}	0	2,5E+3 Ω	Rectangular	-2	-2,89E+3 Ω
V^+_X	1000 V	2,0E-3 V	Normal, k=2	-1,0E+6 Ω/V	-1,00E+3 Ω
δV^+_{Xdrf}	0	1,0E-2 V	Rectangular	-1,0E+6 Ω/V	-5,84E+3 Ω
δV^+_{Xres}	0	5,0E-6 V	Rectangular	-1,0E+6 Ω/V	-2,89E+0 Ω
V^-_X	-1000 V	2,0E-3 V	Normal, k=2	1,0E+6 Ω/V	1,00E+3 Ω
δV^-_{Xdrf}	0	1,0E-2 V	Rectangular	1,0E+6 Ω/V	5,84E+3 Ω
δV^-_{Xres}	0	5,0E-6 V	Rectangular	1,0E+6 Ω/V	2,89E+0 Ω
V^+_S	500 V	1,0E-3 V	Normal, k=2	2,0E+6 Ω/V	1,00E+3 Ω
δV^+_{Sdrf}	0	5,1E-3 V	Rectangular	2,0E+6 Ω/V	5,89E+3 Ω
δV^+_{Sres}	0	5,0E-6 V	Rectangular	2,0E+6 Ω/V	5,77E+0 Ω
V^-_S	-500 V	1,0E-3 V	Normal, k=2	-2,0E+6 Ω/V	-1,00E+3 Ω
δV^-_{Sdrf}	0	5,1E-3 V	Rectangular	-2,0E+6 Ω/V	-5,89E+3 Ω
δV^-_{Sres}	0	5,0E-6 V	Rectangular	-2,0E+6 Ω/V	-5,77E+0 Ω
δR_{Xtemp}	0	1,0E+4 Ω	Rectangular	-1	-5,77E+3 Ω
Rx_{std}	0	6,2E+3 Ω	Normal, k=1	1	6,17E+3 Ω
			Standard Uncertainty		1,91E+4 Ω
Rx	2,04E+9 Ω		Expanded Uncertainty		19,1 µΩ/Ω
			Declared Uncertainty		**20 µΩ/Ω**

Annex D Recalculation of results after TUBITAK UME corrective action

There is no longer need to exclude TUBITAK value from evaluation of CRV. The recalculation with new TUBITAK values is shown below in Table D.1, Figure D.1 and Figure D.3.

With the new analysis the CRV changes from (0.25 ± 1.68) μΩ/Ω to (0.26 ± 1.67) μΩ/Ω (*k*=2).

Table D.1 Resistance results reported by the participants, with temperature correction to 23 °C (*k*=2).

	RISE	TU-BITAK	VSL	VTT
e_i [μΩ/Ω]	0.2	1.0	1.2	-0.3
$U(e_i)$ [μΩ/Ω]	9.1	20.0	2.8	2.1
$\Delta e_i = e_i - CRV$ [μΩ/Ω]	-0.1	0.7	1.0	-0.6
$U(\Delta e_i)$ [μΩ/Ω]	8.9	20.0	2.3	1.3
$\lvert E_n \rvert$	0.01	0.04	0.43	0.42
Exclude				

CRV [μΩ/Ω]	0.3
U(CRV) [μΩ/Ω]	1.7
Pr	86 %

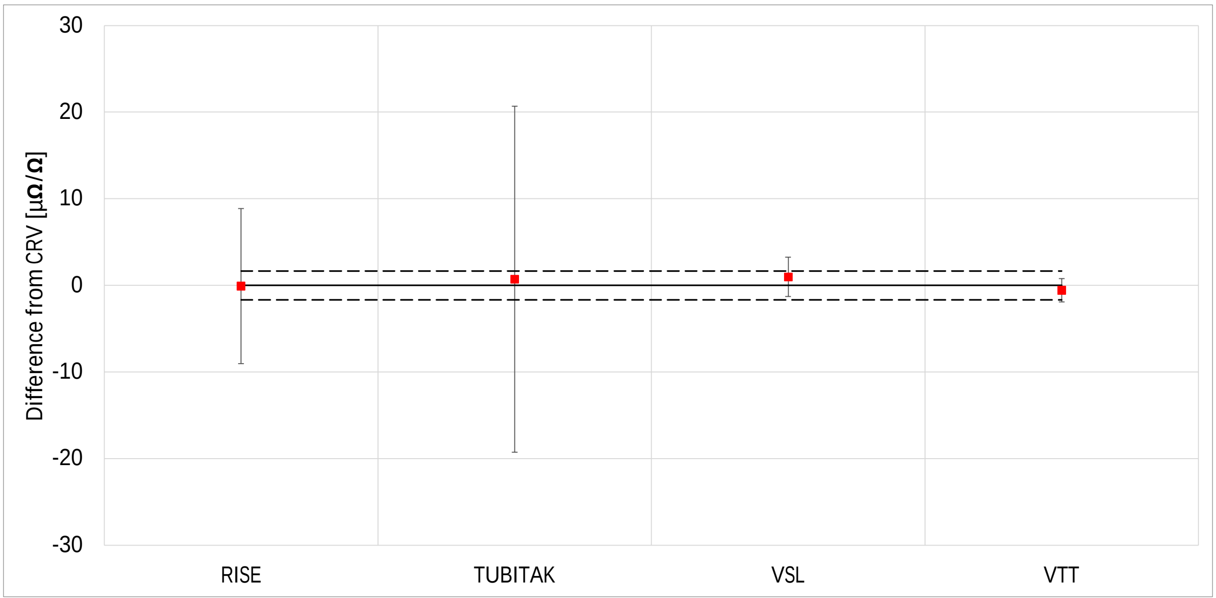

Figure D.1 Deviations from the CRV (*k*=2)

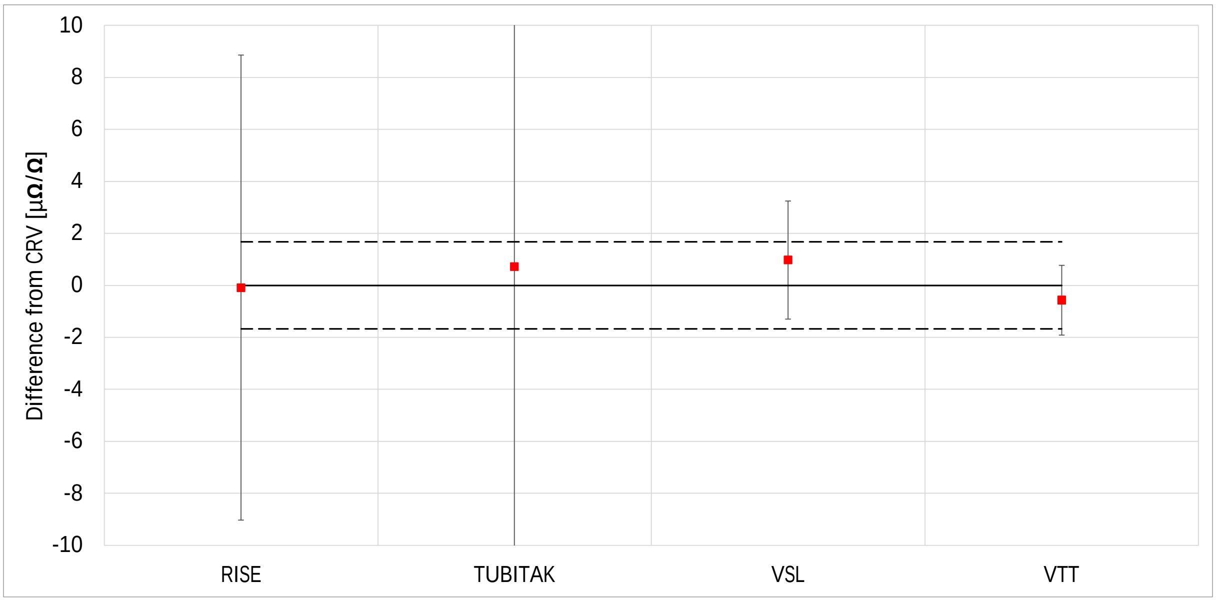

Figure D.2 Deviations from the CRV (*k*=2), closeup