FINAL REPORT
GULFMET.EM.BIPM-K11

Comparison on
10 V and 1.018 V DC Voltage

Standards and Calibration Laboratory (SCL)

13 July 2020

Contents

1. Introduction

GULFMET is the regional metrology organisation (RMO) for national metrology institutes (NMIs) of the Gulf region. The members and associate members within this RMO agreed to organize a key comparison (KC) on 1.018 V and 10 V DC voltages to link to the on-going comparisons BIPM.EM-K11.a & b. SCL, as an associate member of GULFMET and having participated in the previous APMP KC (APMP.EM.BIPM-K11.3), coordinated this KC and characterised the travelling standards. KRISS, as an associate member of GULFMET, having participated in the related BIPM KCs and coordinated the previous APMP KC (APMP.EM.BIPM-K11.3), participated in this comparison to support the link to the BIPM.EM-K11 comparison. BIPM also participated in this comparison to support the link to the BIPM.EM-K11 comparison and to characterise the travelling standards.

This comparison was approved by GULFMET Technical Committee TC EMTF (Electricity, Magnetism, Time and Frequency) and declared as GULFMET.EM.BIPM-K11. Two Zener standards, provided by SASO-NMCC and EMI were used as travelling standards. This KC covered comparison of both 1.018 V and 10 V which corresponds to KCs identified by BIPM.EM-K11.a and BIPM.EM-K11.b.

1.1 Support group members

This comparison received great support and valuable comments from the support group members: Dr Stephane Solve (BIPM), and Dr Kyu-tae Kim (KRISS).

2. Travelling Standards

The travelling standards, two Fluke 732B electronic DC reference standards, have identification as follows:

Unit ID #	Serial Number	Owner
GULF-1	2260038	EMI
GULF-2	1944005	SASO

Front view and rear view of a Fluke 732B is shown in Figure 1. The Fluke 732B electronic DC reference standard has two output voltages, nominally 1.018 V and 10 V. In this comparison, both the 10 V and the 1.018 V output was measured. A 9 pin D-Sub male connector was provided for the measurement of internal thermistor.

Figure 1 Photos showing front view and rear view of a Fluke 732B

3. Participants and organization for the comparison

3.1 List of Participants

Participants, in the alphabetical order of their Acronym, are listed in Table 3-1.

Table 3-1 List of participants

Name of Institute	**Acronym of Institute**	**Country / Economy**
Bureau international des poids et mesures	BIPM	BIPM
Institute of Metrology of Bosnia and Herzegovina	IMBIH	Bosnia and Herzegovina
Korea Research Institute of Standards and Science	KRISS	Republic of Korea
Abu Dhabi Quality and Conformity Council Emirates Metrology Institute	QCC EMI	United Arab Emirates
Saudi Standards, Metrology and Quality Organization	SASO-NMCC	Saudi Arabia
Standards and Calibration Laboratory	SCL	Hong Kong, China

3.2 Measurement Schedule

The measurement schedule of each participant is listed in Table 3-2.

Table 3-2: Measurement schedule

	Date of Measurements	Participant
1	9 March 2017 to 5 July 2017	SCL
2	24 July to 7 August 2017	KRISS
3	21 August to 8 September 2017	BIPM
4	15 to 21 September 2017	SCL
5	3 to 8 October 2017	QCC EMI
6	22 October 2017	SASO-NMCC
7	24 January to 23 February 2018	SCL
8	27 March to 12 April 2018	IMBIH
9	30 April to 5 May 2018	KRISS
10	4 to 7 June 2018	SCL
11	14 to 29 June 2018	BIPM
12	2 to 13 August 2018	SCL

3.3 Measurement Setup and Traceability

The measurement setup of each participant is listed in Annex A. The traceability of each participant is listed in table 3-3.

Table 3-3: Traceability of participant

Participant	Traceability
BIPM	Primary realization – Josephson standard
IMBIH	DMDM, Republic of Serbia
KRISS	Primary realization – Josephson standard
QCC EMI	NPL, United Kingdom
SASO-NMCC	UME, Republic of Turkey
SCL	Primary realization – Josephson standard

4. Characterisation of the Travelling Standards

The temperature sensitivity coefficients of the two travelling standards were characterized by BIPM in June 2018 and by SCL in November 2018. The temperature coefficient (αR) is expressed in terms of the thermistor resistance (R_o). The resistance of the temperature thermistor was used as an indicator for the temperature of the Zener standards. The αR was used to make corrections for temperature effects.

The pressure sensitivity coefficients of the two travelling standards were characterized by BIPM in September 2017 and by SCL in February 2017. The pressure coefficient (αP) is expressed in terms of the reference air pressure p_o which is equal to 1013.25 hPa. The αP was used to make corrections for pressure effects.

Both temperature and pressure coefficients of the travelling standards measured by BIPM were used and the parameters are shown in Table 4-1. Since the temperature coefficient of GULF-2 was found to show non-linear characteristics, it was decided not to correct the voltage for temperature for GULF-2, but to add a standard uncertainty, as shown in Table 4-2 to reflect this. The reported ambient temperature range of the participants, was between 20 - 25 °C and the standard uncertainty for the maximum difference from 23 °C of 3 °C was estimated from the manufacture specifications which were assumed to have a rectangular distribution.

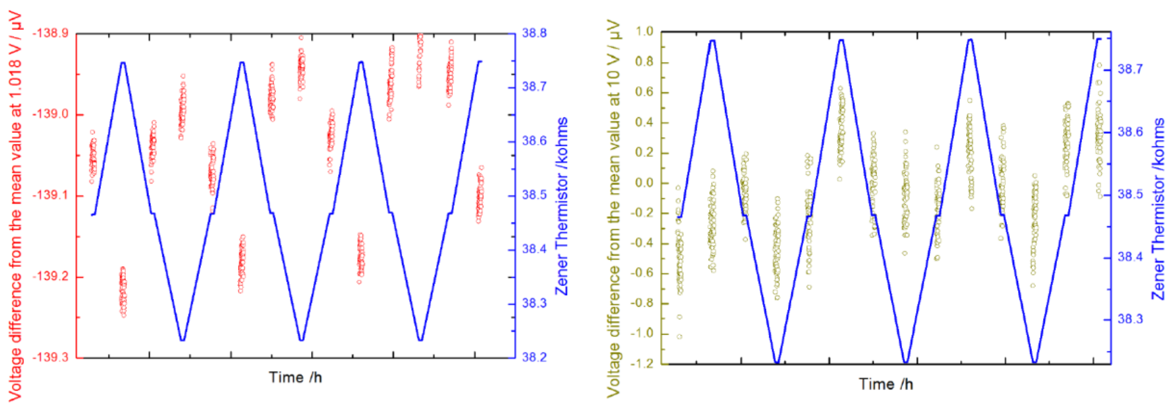
Table 4-1: Temperature and pressure coefficients of the travelling standards.

Unit ID #	Output Voltage (V)	Ref. Thermistor resistance (Ro) (kΩ)	Temperature coefficient (αR) (µV/kΩ)	Pressure coefficient (αP) (nV/hPa)
GULF-1 (s/n: 2260038)	1.018	38.50	-0.45 ± 0.06	1.11 ± 0.07
	10		0.84 ± 0.29	8.67 ± 0.70
GULF-2 (s/n: 1944005)	1.018	N/A	N/A	0.99 ± 0.06
	10		N/A	9.22 ± 0.36

Table 4-2: Additional uncertainty due to temperature effect of GULF-2

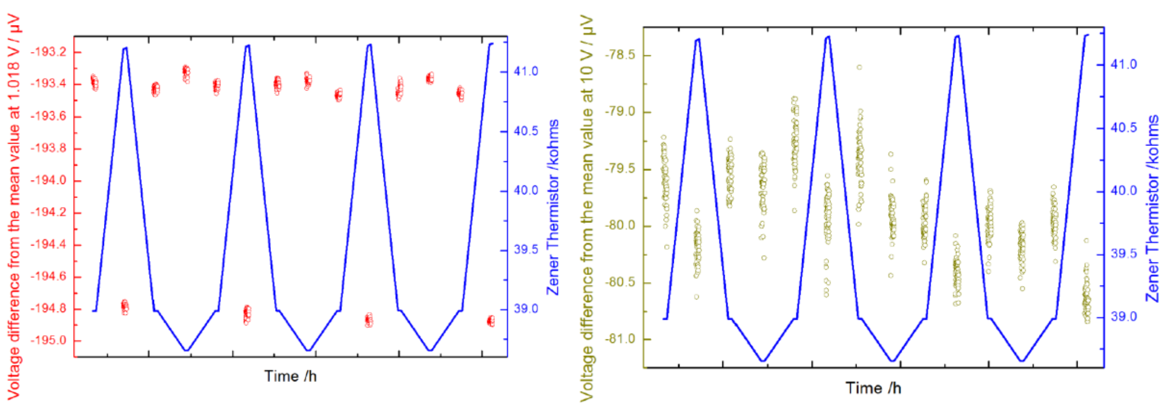
Unit ID #	Output Voltage (V)	Manufacturer specifications (ppm/°C)	Standard uncertainty (µV)
GULF-2 (s/n: 1944005)	1.018	0.1	0.17
	10	0.04	0.69

The output variation of GULF-1 and GULF-2 during temperature sensitive coefficients measurement at BIPM are shown in Fig 4-1 and Fig. 4-2 respectively.



(a) (b)

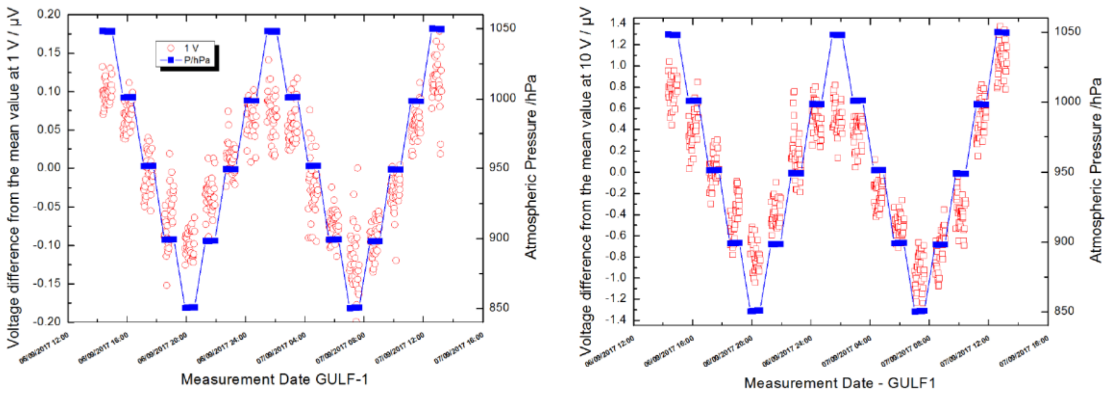
Fig. 4-1 (a) 1.018 V and (b) 10 V output variation of GULF-1 during temperature sensitive coefficients measurement at BIPM



(a) (b)

Fig. 4-2 (a) 1.018 V and (b) 10 V output variation of GULF-2 during temperature sensitive coefficients measurement at BIPM

The output variation of GULF-1 and GULF-2 during pressure sensitive coefficients measurement at BIPM are shown in Fig 4-3 and Fig. 4-4 respectively.



(a) (b)

Fig. 4-3 (a) 1.018 V and (b) 10 V output variation of GULF-1 during pressure sensitive coefficients measurement at BIPM

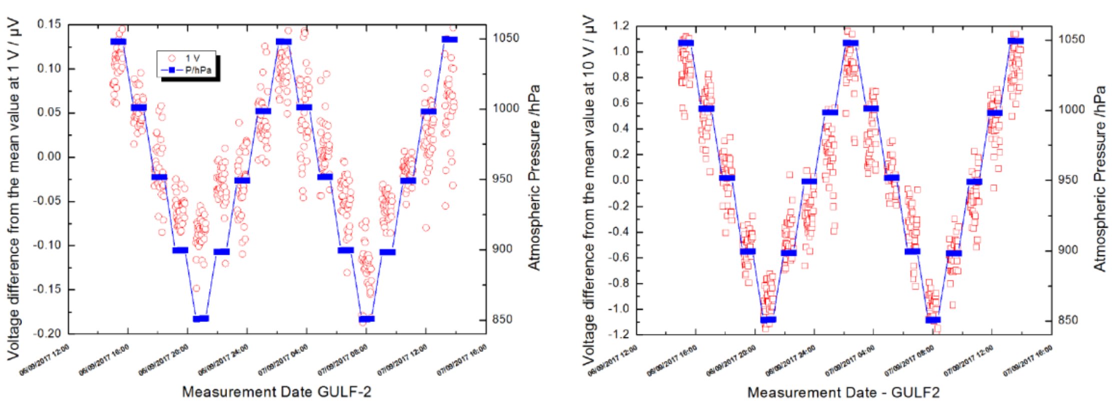


Fig. 4-4 (a) 1.018 V and (b) 10 V output variation of GULF-2 during pressure sensitive coefficients measurement at BIPM

5. Behaviour of the Travelling Standards

5.1 Stability of the travelling standards

Measurements made by SCL, KRISS and BIPM for each travelling standard at 1.018 V and 10 V are shown in Figure 2. All data are represented after the correction of the temperature (if applicable) and pressure effects. The drift rates of the artefacts were within the manufacturer's stated 30-day stability specifications. It was observed that the drift rate of 1.018 V is large in comparison with that of 10V.

5.2 Unexpected incident of the travelling standard

On 6 November 2017, SASO-NMCC reported that the "IN CAL" LED of the GULF-1 standard was turned off after their measurement. A new battery was installed by SASO-NMCC, and they reported a step change of -1.2 µV/V and -0.72 µV/V for the 1.018 V and 10 V output was observed respectively.

The artefact returned to SCL in January 2018, the repeated measurement showed that there was a step change of -3.9 µV/V and -0.78 µV/V from the predicted voltage values for the 1.018 V and 10 V output respectively on 22 Feb 2018. Refer to Figures 5a and 5b for details.

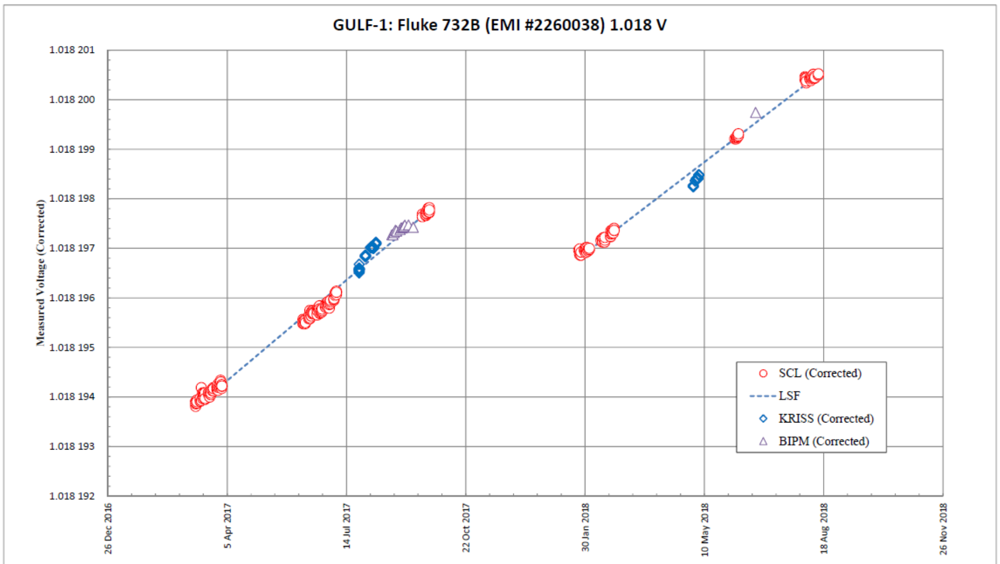


Figure 5a: GULF-1 1.018 V

(i) before Jan 2018 drift rate: +0.64 µV/30 days;

(ii) after Jan 2018 drift rate: +0.56 µV/30 days.

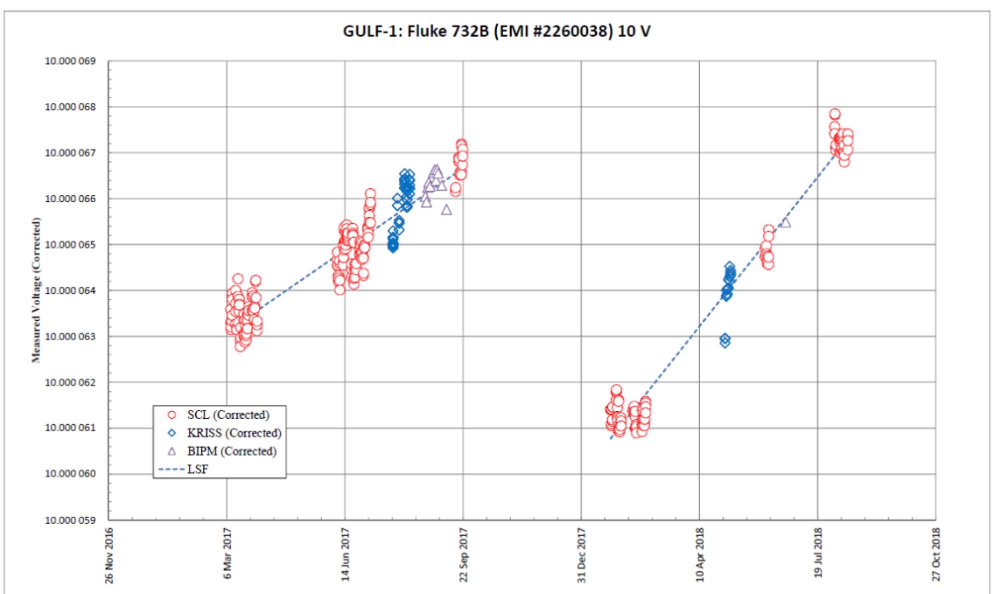


Figure 5b: GULF-1 10 V

(i) before Jan 2018 drift rate: +0.47 µV/30 days;

(ii) after Jan 2018 drift rate: +1.01 µV/30 days.

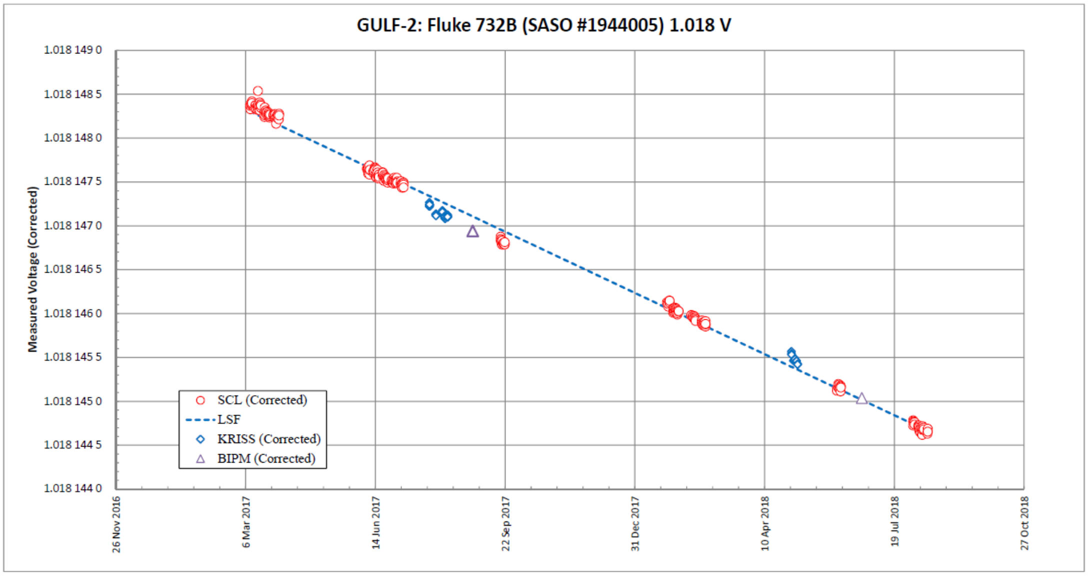


Figure 5c: GULF-2 1.018 V, Drift rate: -0.19 µV/30 days

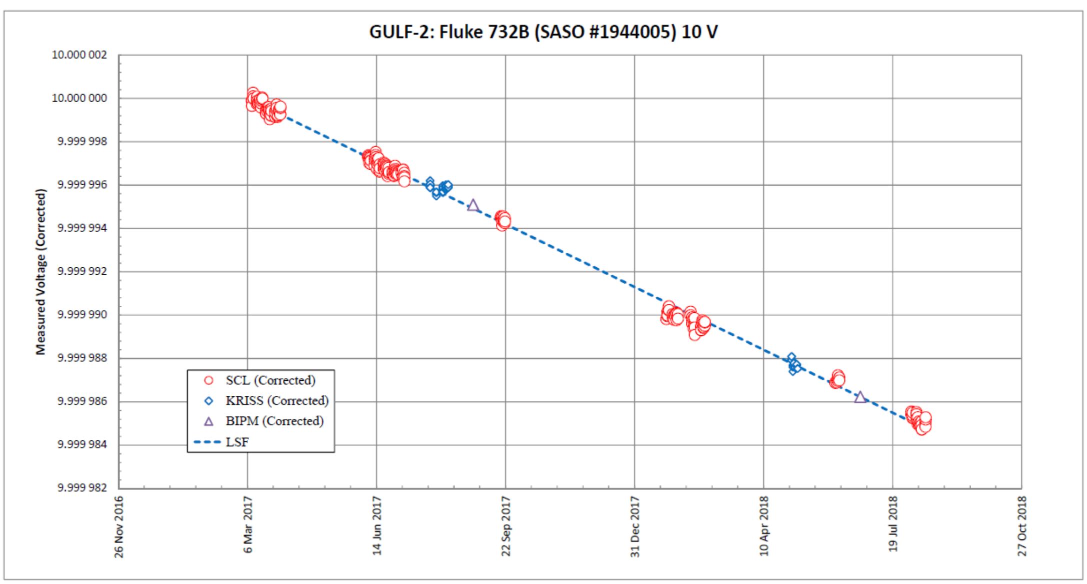


Figure 5d: GULF-2 10 V, Drift rate: -0.86 µV/30 days

6. Reference Values

6.1 Calculation of Reference Values

The SCL and KRISS measurement results, after correction for temperature (if applicable) and pressure effects, were used to estimate the reference value by a linear model based on least square fit method. The linear fit equation is given as in (1). For each Zener standard, the linear fit parameters are given in Table 6-1 below.

The fitted lines can be expressed as:

$$V_{ref} = \alpha + \beta t \tag{1}$$

where *t* represents the mean measurement date of each participant in Excel (with *t*=1 refers to 1 January 1900), and α and β are the fitting parameters. Once the fitting parameters are fixed, the standard uncertainty of the fitting, $u(V_{ref})$, is obtained as the deviation of the data points from the fitting line.

As there is an unexpected step change of the GULF-1 artefact, as described in section 5.2, separate linear fit equations were used to estimate the reference value of each section, before the step change (1a) and after the step change (1b).

Table 6-1. Linear fit parameters

Artefact	Nominal Voltage	*k*	Slope, β (nV/day)	Intercept, α (µV)	Standard error, $u(V_{ref})$ (µV)
GULF-1	10 V	1a	15.631	-605.368	0.276
		1b	33.826	-1398.284	0.127
	1.018 V	1a	21.478	-725.707	0.094
		1b	18.619	-606.212	0.151
GULF-2	10 V	2	-28.770	1231.477	0.176
	1.018 V		-6.446	424.439	0.071

6.2 Calculation of the reference values based on the least-square-fitting of participant results

The time-dependent reference values are calculated at the mean measurement date of each participant, based on the least-squares linear regression parameters listed in section 6.1 above. Since there was a step change in the reference value of GULF-1, an addition uncertainty of 5% of the step jump, estimated on 22 Feb 2018 and were assumed to have a rectangular distribution (i.e. 0.22 µV and 0.11 µV for 10 V and 1.018 V respectively), was added to the reference uncertainty.

The calculated reference values of each measurement are shown in Table 6-2 (a) and (b).

Table 6-2(a): Reference values for GULF-1

i	Participant	Mean Date	10 V		1.018 V	
			$V_{\text{ref }k,i}$ -10 V (µV)	$u(V_{\text{ref }k,i})$ (µV)	$V_{\text{ref }k,i}$ -1.018 V (µV)	$u(V_{\text{ref }k,i})$ (µV)
1	SCL	4-Jul-2017	65.513	0.355	196.114	0.146
2	KRISS	1-Aug-2017	66.013	0.355	196.801	0.146
3	BIPM	28-Aug-2017	66.373	0.355	197.295	0.146
4	SCL	20-Sep-2017	66.732	0.355	197.789	0.146
5	QCC EMI	5-Oct-2017	66.967	0.355	198.112	0.146
6	SASO-NMCC	22-Oct-2017	67.232	0.355	198.477	0.146
7	SCL	22-Feb-2018	61.389	0.258	197.263	0.187
8	IMBIH	2-Apr-2018	62.708	0.258	197.989	0.187
9	KRISS	4-May-2018	63.756	0.258	198.585	0.187
10	SCL	6-Jun-2018	64.906	0.258	199.200	0.187
11	BIPM	22-Jun-2018	65.448	0.258	199.498	0.187
12	SCL	11-Aug-2018	67.139	0.258	200.429	0.187

Table 6-2(b): Reference values for GULF-2

i	Participant	Mean Date	10 V		1.018 V	
			$V_{\text{ref k,i}}$ -10 V (μV)	$u(V_{\text{ref k,i}})$ (μV)	$V_{\text{ref k,i}}$ -1.018 V (μV)	$u(V_{\text{ref k,i}})$ (μV)
1	SCL	4-Jul-2017	-3.329	0.176	147.774	0.071
2	KRISS	5-Aug-2017	-4.135	0.176	147.594	0.071
3	BIPM	28-Aug-2017	-4.912	0.176	147.420	0.071
4	SCL	20-Sep-2017	-5.573	0.176	147.271	0.071
5	QCC EMI	5-Oct-2017	-6.005	0.176	147.175	0.071
6	SASO-NMCC	22-Oct-2017	-6.494	0.176	147.065	0.071
7	SCL	22-Feb-2018	-10.033	0.176	146.272	0.071
8	IMBIH	2-Apr-2018	-11.212	0.176	146.008	0.071
9	KRISS	3-May-2018	-12.047	0.176	145.821	0.071
10	SCL	6-Jun-2018	-13.025	0.176	145.602	0.071
11	BIPM	22-Jun-2018	-13.543	0.176	145.486	0.071
12	SCL	11-Aug-2018	-14.924	0.176	145.176	0.071

7. Measurement Results

7.1 Mathematical Model

The participants were requested to report both the original result and the corrected result during the result submission. Since the temperature coefficient and pressure coefficient were updated after the measurement. The uncorrected results (V_{meas}) from the participants were taken, and they were corrected (V_{corr}) by the updated coefficient values using equation (2).

$$V_{corr} = V_{meas} - \alpha_R(R - R_o) - \alpha_P(p - p_o) \qquad (2)$$

where α_R and α_p are the temperature and pressure coefficient as given in Table 4-1, p is the ambient air pressure, and p_o = 1013.25 hPa is the reference air pressure. The reference thermistor resistance Ro is only applied to GULF-1 and is given in Table 4-1.

The standard uncertainty associated with each measurement data is based on the uncertainty reported by the participant.

The corrected participant results and uncertainties are listed in Table 7-2 (a) to (b).

7.2 Results of the Participating Institutes

The participant's reported results are corrected by temperature (if applicable) and pressure coefficient using equation (2) and the parameters listed in section 4. Their corrected results and its associate standard measurement uncertainties, *u*, are given in Tables 7-2(a) to (b). Detailed uncertainty budgets from all participants are given in Annex B.

Table 7-2(a): Corrected participant values for GULF-1

i	Participant	Mean Date	10 V		1.018 V	
			$V_{corr\ k,i}$ -10 V (µV)	$u(V_{corr\ k,i})$ (µV)	$V_{corr\ k,i}$ -1.018 V (µV)	$u(V_{corr\ k,i})$ (µV)
1	SCL	4-Jul-2017	65.645	0.107	196.069	0.0269
2	KRISS	5-Aug-2017	65.789	0.099	196.878	0.0320
3	BIPM	28-Aug-2017	66.337	0.103	197.379	0.0210
4	SCL	20-Sep-2017	66.824	0.093	197.758	0.0242
5	QCC EMI	5-Oct-2017	71.526	3.66	198.166	1.27
6	SASO-NMCC	22-Oct-2017	67.271	1.752	198.430	0.3756
7	SCL	22-Feb-2018	61.336	0.076	197.348	0.0257
8	IMBIH	2-Apr-2018	62.637	2.454	197.507	0.477
9	KRISS	3,4-May-2018	63.938	0.077	198.384	0.0170
10	SCL	6-Jun-2018	64.820	0.080	199.258	0.0263
11	BIPM	22-Jun-2018	65.342	0.103	199.627	0.0230
12	SCL	11-Aug-2018	67.130	0.079	200.468	0.0254

Table 7-2(b): Corrected participant values for GULF-2

i	Participant	Mean Date	10 V		1.018 V	
			$V_{corr\ k,i}$ -10 V	$u(V_{corr\ k,i})$	$V_{corr\ k,i}$ -1.018 V	$u(V_{corr\ k,i})$
			(µV)	(µV)	(µV)	(µV)
1	SCL	4-Jul-2017	-3.383	0.061	147.866	0.0219
2	KRISS	1-Aug-2017	-4.055	0.030	147.517	0.0110
3	BIPM	28-Aug-2017	-4.782	0.110	147.315	0.0120
4	SCL	20-Sep-2017	-5.468	0.044	147.213	0.0204
5	QCC EMI	5-Oct-2017	-2.246	3.66	147.306	1.27
6	SASO-NMCC	22-Oct-2017	-7.641	1.752	146.800	0.3756
7	SCL	22-Feb-2018	-10.301	0.048	146.296	0.0213
8	IMBIH	4-Apr-2018	-12.206	2.452	145.444	0.475
9	KRISS	3,4-May-2018	-12.160	0.039	145.880	0.0090
10	SCL	6-Jun-2018	-12.806	0.049	145.604	0.0217
11	BIPM	24-Jun-2018	-13.638	0.104	145.423	0.0110
12	SCL	11-Aug-2018	-14.892	0.064	145.128	0.0213

7.3 Difference from Reference Value

The reference value for each measurement is calculated based on the method specified in section 6. The calculated reference values of each participant were shown in Table 6-2 (a) and (b). In this section, the difference (D) of corrected participant results and reference value are calculated using equation (3). The standard uncertainty of each difference from the reference value of GULF-1 is calculated by the root sum square value of the standard uncertainty of the corrected voltage and the standard uncertainty of the reference voltage, as shown in equation (4a). For GULF-2, the standard uncertainty of each difference from the reference value is calculated by equation (4b), it included an additional temperature uncertainty component with estimated values listed in Table 4-2.

$$D_{k,i} = V_{corr\ k,i} - V_{ref\ k,i} \quad (3)$$

GULF-1: $$u^2(D_{k,i}) = u^2(V_{corr\ k,i}) + u^2(V_{ref\ k,i}) \quad (4a)$$

GULF-2: $$u^2(D_{k,i}) = u^2(V_{corr\ k,i}) + u^2(V_{ref\ k,i}) + u^2(V_{tc\ k,i}) \quad (4b)$$

Table 7-3(a): Difference from reference value for GULF-1

i	Participant	Mean Date	10 V		1.018 V	
			$D_{k,i}$ (µV)	$u(D_{k,i})$ (µV)	$D_{k,i}$ (µV)	$u(D_{k,i})$ (µV)
1	SCL	4-Jul-2017	0.132	0.371	-0.045	0.148
2	KRISS	1-Aug-2017	-0.224	0.369	0.077	0.149
3	BIPM	28-Aug-2017	-0.036	0.370	0.084	0.147
4	SCL	20-Sep-2017	0.092	0.367	-0.031	0.148
5	QCC EMI	5-Oct-2017	4.559	3.677	0.054	1.278
6	SASO-NMCC	22-Oct-2017	0.039	1.788	-0.047	0.403
7	SCL	22-Feb-2018	-0.053	0.269	0.085	0.189
8	IMBIH	2-Apr-2018	-0.071	2.467	-0.482	0.513
9	KRISS	4-May-2018	0.182	0.269	-0.201	0.188
10	SCL	6-Jun-2018	-0.086	0.270	0.058	0.189
11	BIPM	22-Jun-2018	-0.106	0.277	0.129	0.189
12	SCL	11-Aug-2018	-0.009	0.269	0.039	0.189

Table 7-3(b): Difference from reference value for GULF-2

i	Participant	Mean Date	10 V		1.018 V	
			$D_{k,i}$ (µV)	$u(D_{k,i})$ (µV)	$D_{k,i}$ (µV)	$u(D_{k,i})$ (µV)
1	SCL	4-Jul-2017	-0.054	0.717	0.092	0.191
2	KRISS	5-Aug-2017	0.080	0.715	-0.077	0.190
3	BIPM	28-Aug-2017	0.130	0.723	-0.105	0.190
4	SCL	20-Sep-2017	0.105	0.716	-0.058	0.191
5	QCC EMI	5-Oct-2017	3.759	3.729	0.131	1.284
6	SASO-NMCC	22-Oct-2017	-1.147	1.892	-0.265	0.421
7	SCL	22-Feb-2018	-0.268	0.716	0.024	0.191
8	IMBIH	2-Apr-2018	-0.994	2.554	-0.564	0.512
9	KRISS	3-May-2018	-0.113	0.716	0.059	0.190
10	SCL	6-Jun-2018	0.219	0.716	0.002	0.191
11	BIPM	22-Jun-2018	-0.095	0.722	-0.063	0.190
12	SCL	11-Aug-2018	0.032	0.718	-0.048	0.191

7.4 Analysis and Linking to BIPM.EM-K11.a and BIPM.EM-K11.b

The comparison results were analyzed and linked to the BIPM key comparisons (BIPM.EM-K11.a and BIPM.EM-K11.b) using the Generalized Least-Squares Method [9]. This method can directly estimate the degree of equivalence for each laboratory, with all the measured data considered, to the BIPM KCRV (key comparison reference value). Two participants, BIPM and KRISS can provide the link to the BIPM.EM-K11 comparison. Their linking parameters are listed in Table 7-4 (a).

The analysis can be modelled by equation (5).

$$\boldsymbol{y} = \boldsymbol{X}\,\boldsymbol{\beta} + \boldsymbol{e} \tag{5}$$

Where $\boldsymbol{y}$ is a vector of the measurement results, $\boldsymbol{X}$ is a design matrix, $\boldsymbol{\beta}$ is a vector of unknowns and $\boldsymbol{e}$ is a vector of random errors or disturbances. Each measurement result is in the corresponding row of vector $\boldsymbol{y}$.

The solutions ($\boldsymbol{\beta}$) of equation (5) can be calculated by equation (6), with an uncertainty matrix $\boldsymbol{C}$ as given by equation (7). $\boldsymbol{\phi}$ is the input covariance matrix for the measurement results $\boldsymbol{y}$.

$$\boldsymbol{\beta} = \boldsymbol{C}\boldsymbol{X}^{\mathrm{T}}\boldsymbol{\Phi}^{-1}\boldsymbol{y} \tag{6}$$

$$\boldsymbol{C} = (\boldsymbol{X}^{\mathrm{T}}\boldsymbol{\Phi}^{-1}\boldsymbol{X})^{-1} \tag{7}$$

For the analysis of each output voltage, there are 8 unknowns (6 laboratories and 2 travelling standards) plus one constraint parameter, and 27 values for y (24 measurement results, 2 linking labs KCRV results and 1 constraint value). The degree of freedom ν equals to 18. The design matrix ($\boldsymbol{X}$), as shown as equation (8), has 27 rows and 9 columns. Row 1 to 12 and 13 to 24 are for the measurements of GULF-1 and GULF-2 respectively. Row 25 and 26 are for the linking KCRV parameter, and row 27 is for the constraint.

Table 7-4 (a): Degrees of equivalence of the two linking laboratories from the BIPM.EM-K11.a and BIPM.EM-K11.b key comparisons

Linking Lab.	10 V		1.018 V	
	D_i^{link} (µV)	$u(D_i^{link})$ (µV)	D_i^{link} (µV)	$u(D_i^{link})$ (µV)
KRISS	-0.03	0.1	0.07	0.05
BIPM	0	0.1	0	0.01

Equation (8). Design matrix ***X*** of both 10 V and 1.018 V for linking to the BIPM key comparisons.

X =

SCL	KRISS	BIPM	EMI	SASO	IMBIH	GULF1	GULF2	K-mc	
1	0	0	0	0	0	-1	0	0	SCL
0	1	0	0	0	0	-1	0	0	KRISS
0	0	1	0	0	0	-1	0	0	BIPM
1	0	0	0	0	0	-1	0	0	SCL
0	0	0	1	0	0	-1	0	0	EMI
0	0	0	0	1	0	-1	0	0	SASO
1	0	0	0	0	0	-1	0	0	SCL
0	0	0	0	0	1	-1	0	0	IMBIH
0	1	0	0	0	0	-1	0	0	KRISS
1	0	0	0	0	0	-1	0	0	SCL
0	0	1	0	0	0	-1	0	0	BIPM
1	0	0	0	0	0	-1	0	0	SCL
1	0	0	0	0	0	0	-1	0	SCL
0	1	0	0	0	0	0	-1	0	KRISS
0	0	1	0	0	0	0	-1	0	BIPM
1	0	0	0	0	0	0	-1	0	SCL
0	0	0	1	0	0	0	-1	0	EMI
0	0	0	0	1	0	0	-1	0	SASO
1	0	0	0	0	0	0	-1	0	SCL
0	0	0	0	0	1	0	-1	0	IMBIH
0	1	0	0	0	0	0	-1	0	KRISS
1	0	0	0	0	0	0	-1	0	SCL
0	0	1	0	0	0	0	-1	0	BIPM
1	0	0	0	0	0	0	-1	0	SCL
0	1	0	0	0	0	0	0	-1	KRISS
0	0	1	0	0	0	0	0	-1	BIPM
0	0	0	0	0	0	0	0	1	Constraint

Matrix $\boldsymbol{\phi}$ is a 27 x 27 input covariance matrix. The diagonal terms of this matrix are the variance (square of standard uncertainty) associated with each measurement result as presented in Table 7-3 (a) and (b). Off-diagonal entries are the covariance (correlation) between measurements. The type B uncertainty of the measurement system of each laboratory (as listed in Table 7-4(b)) for correlation between multiple measurement of the same participant and the standard error of least-squares linear regression of reference value (as listed in Table 6-2 (a) and (b)) for the calculation of participant's difference from reference value were included as correlations between measurement results. The traceability of the participants (as listed in Table 3-3) was either realized by the participant's primary Josephson standard or traceable to different external NMIs that maintains their primary Josephson standard. Therefore, no correlation component between participants due to traceability was added to the covariance matrix.

Table 7-4(b): Type B uncertainty of the measurement system of participant as part of the off-diagonal entries of Matrix $\boldsymbol{\phi}$

Participant	System Type B uncertainty	
	10 V (μV)	1.018 V (μV)
SCL	0.033	0.019
KRISS	0.020	0.007
BIPM	0.00087	0.0034
EMI	3.66	1.245
SASO	1.75	0.375
IMBIH	2.33	0.476

The consistency between the model and the measurement results were check by the chi-squared test using equation (9). Both 10 V and 1.018 V results meet the consistency check. A summary of the validation result is presented in Table 7-4(c).

$$\chi^2_{obs} = (\boldsymbol{Y} - \boldsymbol{X\beta})^T \boldsymbol{\Phi}^{-1} (\boldsymbol{Y} - \boldsymbol{X\beta}) \tag{9}$$

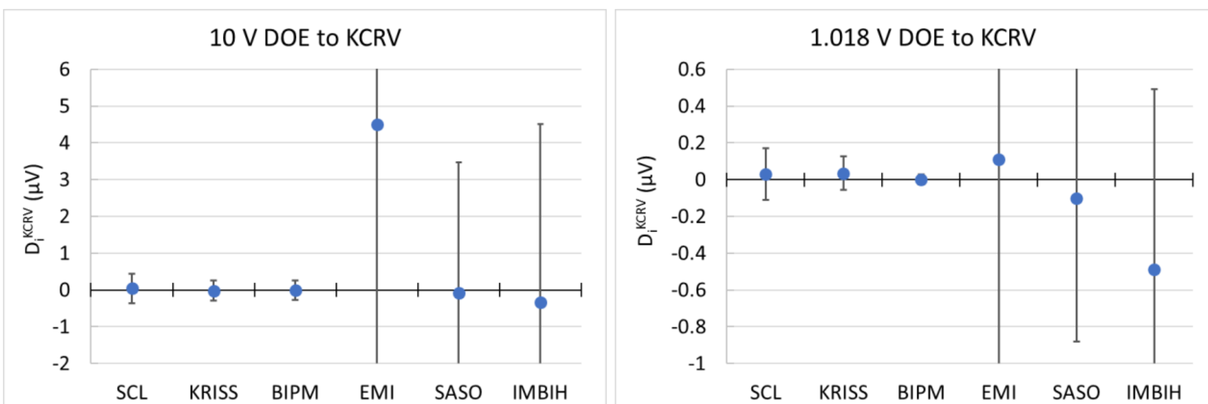
Table 7-4(c): Validation of calculated results

	10 V	1.018 V
χ^2_{obs}	6.02	9.6
ν	18	18
P($\chi^2 > \chi^2_{obs}$)	99.6%	94.4%
Remark	>5%, consistency criteria met	>5%, consistency criteria met

Result vector $\boldsymbol{\beta}$ and the matrix ***C*** give the expected deviation of each laboratory's result from the KCRV and the variance associated with this deviation. The results are summarized in Table 7-4 (d) and graphically presented in Figure 7.4. The expanded uncertainty can be calculated from the corresponding diagonal element of ***C*** as $2\sqrt{\boldsymbol{C_{ii}}}$, where the coverage factor *k* is equal to 2.

Table 7-4 (d): DOE from the KCRV and their associated expanded measurement uncertainty (*k*=2) for each participating laboratory.

Participant	10 V		1.018 V	
	D_j^{KCRV} (µV)	$U(D_j^{KCRV})$ (µV)	D_j^{KCRV} (µV)	$U(D_j^{KCRV})$ (µV)
SCL	0.04	0.40	0.03	0.14
KRISS	-0.02	0.27	0.034	0.091
BIPM	-0.01	0.27	0.001	0.028
QCC EMI	4.49	7.34	0.11	2.53
SASO-NMCC	-0.09	3.55	-0.10	0.78
IMBIH	-0.33	4.84	-0.49	0.98



(a) (b)

Figure 7-4 (a) 1.018 V and (b) 10 V. Degree of equivalence of the participating institutes with respect to the key comparison reference value. Uncertainty bars represent the expanded measurement uncertainty.

8. Summary

The key comparison of DC voltage at 10 V and 1.018 V has been conducted for GULFMET member laboratories, with the support from BIPM and GULFMET associate members, KRISS and SCL, from the APMP.

The linking difference with BIPM.EM-K11 KCRV was calculated and presented in section 7.4. The DOE with respect to KCRV were tabulated in Table 7-4 (d) and illustrated graphically in Figure 7-4 (a) and (b). The agreement between participating laboratories is good. The KCRV DOE and their CMC of non-linking laboratories are tabulated in Table 8-1.

It is expected that this comparison could provide support for EMI and SASO in submitting new measurement capability entries and for IMBIH to submit new measurement capability at 1.018 V and improve its 10 V measurement capability in the CIPM MRA appendix C.

Table 8-1: KCRV DOE and CMC of the participating institutes.

Participant	10 V			1.018 V		
	D_j^{KCRV} (μV)	$U(D_j^{KCRV})$ (μV)	CMC(k=2) (μV)	D_j^{KCRV} (μV)	$U(D_j^{KCRV})$ (μV)	CMC(k=2) (μV)
SCL	0.04	0.40	0.60	0.03	0.14	0.12
QCC EMI	4.49	7.34	N. A.	0.11	2.53	N. A.
SASO-NMCC	-0.09	3.55	N. A.	-0.10	0.78	N. A.
IMBIH	-0.33	4.84	10	-0.49	0.98	N. A.

*N. A. stands for not available.

Annex A: Methods of Measurement

Details of measurement method and metrological traceability to SI units by individual participants are given below:

A.1 SCL, Hong Kong, China

<u>System Descriptions</u>

1.1 The Josephson Array Voltage Standard (JAVS) of SCL consists of:
   (a) Prema 10 V Array Josephson junctions;
   (b) Millitech Gunn-Diode with integral isolator, operating near 75 GHz;
   (c) RMC WR12 dielectric waveguide;
   (d) EIP 578B Source Locking Microwave Counter;
   (e) Astro Endyne JBS500 Josephson Bias Source;
   (f) HP 3458A digital multimeter;
   (g) Guildline 9145A5 Low Thermal selector switch; and
   (h) Tektronix 2225 Oscilloscope.
   (i) Control Software: NISTVolt version 5.2.

1.2 HP 5061B Cesium Beam Frequency Standard.

1.3 Mensor 2103 Precision Barometric Pressure Indicator.

1.4 Vaisala HM 70 Temperature/Humidity Indicator.

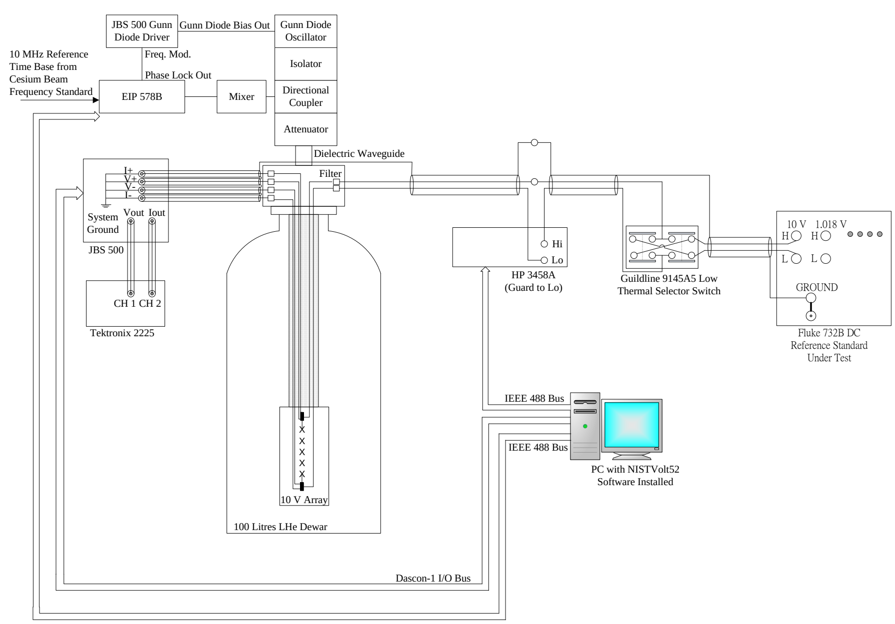


Figure 1: System Hook-up

Measurement Methodology

2.1 The two travelling standards (Zeners) were allowed to stabilize in the SCL environment for more than two days before making measurements.

2.2 The Zeners were powered by an AC line power of 230 V and 50 Hz before the measurements. They were disconnected from the AC mains and powered from their internal batteries at least four hours prior to and during the measurement.

2.3 Measurements were made at ambient temperature of (23±1) °C, (45±8) %RH and 100 kPa (nominal) barometric pressure.

2.4 For each measurement, the Zener's output voltage was recorded together with other data including the time and date of measurement, the environmental temperature, relative humidity, barometric pressure and the internal thermistor resistance of the Fluke 732B.

2.5 During the measurement, the Fluke 732B's output terminals were floating from the system ground. The unit's GROUND terminal was connected to system ground, via the connection shield. Detailed connection is shown in Figure 1.

2.6 The outputs Zeners were measured by differential method against the quantized output voltages of the Laboratory's JAVS. An HP 3458A DMM was used as a null detector for measuring the voltage difference. The microwave source of the JAVS was a Gunn diode oscillator operating at 75 GHz. The JAVS operating frequency was stabilized and monitored by an EIP 578B counter. The 10 MHz time base frequency of the counter was supplied from an HP 5061B Cesium Beam Frequency Standard. The measurement process was under computer control using the NISTVolt 5.2 software (software).

2.7 The Josephson step number was adjusted by the software. The step number was selected so that the voltage difference between the array output and the Zeners output was less than ±10 mV. After selected the correct step, the bias voltage was cut-off and the null voltages were recorded by the software.

2.8 A measured value consisted of 40 measured voltage differences. A measured voltage difference was the mean of 2 DVM readings. Measurement polarities were in the pattern of "normal", "reverse", "normal", "reverse"; for elimination of the effect of the offset voltage in the system. The output voltage of the Zeners and the offset voltage of the JAVS system were calculated based on the 40 measured values by software using least square method.

2.9 The output voltage of Zeners was reversed using a manual operated Guildline 9145A5 low thermal switch. The array voltage was reversed by changing the polarity of the array bias voltage through the control program. The offset voltage error due to the Guildline 9145A5 switch was not corrected but treated as measurement uncertainty and included in the uncertainty budget.

2.10 The resistance of the internal thermistor was measured by an Agilent 34420A Nano volt/Micro ohm meter. Prior to the measurement, correction to meter reading(s) was determined by comparison against SCL's 10 kΩ and 100 kΩ reference standard resistors. The meter was configured to operate at 100 kΩ range and Low Power Mode, which the test current applied to the thermistor has been verified to be 5 µA.

A.2 KRISS, Republic of South Korea

The travelling standards have been measured by KRISS calibration procedure C13-1-002-2012. The JVS of KRISS has following features. The KRISS JAVS was connected to two different current sources: the scope was powered through an isolated line (isolation transformer) while the RF equipment was referred to the standard power distribution of the shielded room.

- Type of array: 10 V SIS, manufactured by IPHT (s/n 1469-2);
- Detector: Keithley 2182, used on the 10 mV range (without any filter);
- Bias source: Homemade source based on a PTB design;
- Oscilloscope: A Tektronix 7603 oscilloscope is used to visualise the steps and to adjust the RF power level at the beginning of a series of measurements;
- Software: Homemade under Visual Basic environment;
- Frequency source stabilizer: Counter EIP 578B with locking of the frequency to the external 10 MHz reference and a stability better than ±1 Hz during the period of the comparison. The KRISS array is irradiated at a frequency around 75 GHz;
- The 10 MHz reference signal for the counter is provided by a synthesiser HP3325A which is itself referred to the 10 MHz signal coming from the reference clock.
- Thermal EMF (including array connections): approximately 500 nV-600 nV, varies with liquid He level in reservoir;
- Total impedance of the two array measurement leads: 40 Ω or 80 Ω; this resistance includes the series resistance of a filter inserted in the two measurement leads (possible choice between two different filters).
- Leakage resistance of measurement leads: 1×10^{12} Ω.

A.3 BIPM

The output voltage of the Zener standard to be measured is connected to the BIPM Josephson Voltage Standard (in series opposition with the BIPM array) through a low thermal EMF switch. The binding post "CHASSIS" of the Zener standard is connected to a single point which is the grounding reference point of the measurement setup.

The measurements start after at least two hours after the mains plug at the rear of the Zeners has been disconnected.

The BIPM detector consists of an EM model N1a analog nanovoltmeter whose output is connected, via an optically-coupled isolation amplifier, to a pen recorder and a digital voltmeter (DVM) which is connected to a computer.

This computer is used to monitor measurements, acquire data and calculate results. Low thermal electromotive force switches are used for critical switching, such as polarity reversal of the detector input.

After the BIPM array biasing frequency has been adjusted to a value where the voltage difference between the primary and the secondary voltage standards is below 0.8 µV, the nanovoltmeter is set to its 3 µV or 10 µV range to perform measurements at 1.018 V and 10 V respectively. The measurement sequence can then be carried out. Three consecutive measurement points are acquired according to the following procedure (Cf. Figure below: Note that the polarity of the Zener follows the polarity of the array.

1- Positive array polarity and reverse position of the detector;

2- Data acquisition;

3- Positive array polarity and normal position of the detector;

4- Data acquisition;

5- Negative array polarity and reverse position of the detector;

6- Data acquisition;

7- Negative array polarity and normal position of the detector;

8- Data acquisition;

9- Negative array polarity and reverse position of the detector;

10- Data acquisition;

11- Negative array polarity and normal position of the detector;

12- Data acquisition;

13- Positive array polarity and reverse position of the detector;

14- Data acquisition;

15- Positive array polarity and normal position of the detector;

16- Data acquisition.

The reversal of the detector polarity is done to cancel out any detector offset error and internal linear component of the variations of the thermo-electromotive forces.

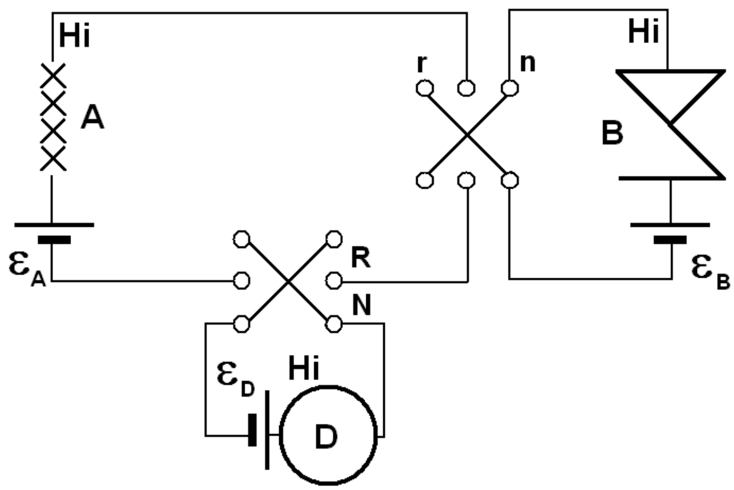


Figure: Schematic of the measurement setup where the polarity reversing switches and the thermal electromotive generators (εi) are represented.

Note that no potential reference is represented as both standards are floating from the ground during the acquisition sequence.

Each “Data Acquisition” step consists of 30 preliminary points followed by 500 measurement points. Each of these should not differ from the mean of the preliminary points by more than twice their standard deviation. The “Data Acquisition” sequence lasts 25 seconds and is basically the time period during which the array is to stay on the selected step. The total measurement time (including polarity reversals and data acquisition) is approximately 5 minutes.

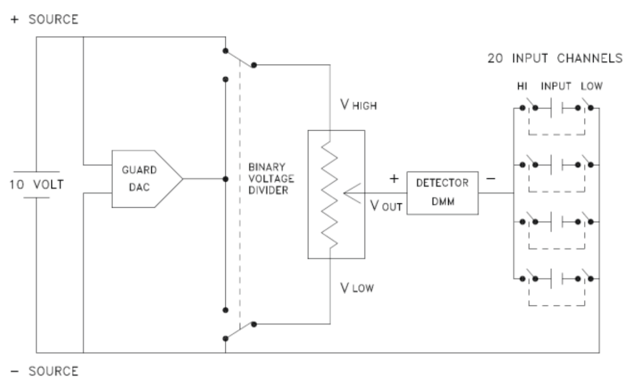
This procedure is repeated three times and the mean value corresponds to one point on the graph.

A.4 QCC EMI, United Arab Emirates

Measurements were made using a Measurements International 8000A Automatic Potentiometer, with “8000A version 4.2.7” software in accordance with EMI Procedure CP-E-03 between 3 October 2017 and 8 October 2017.

Description

The 8000A Automatic Potentiometer is a computer controlled binary resistive voltage divider, based on the design by R.D Custosky.



MI 8000A Block Diagram

During each measurement of V_{IN} the ratio of the divider R_{NOM} is adjusted such that the divided source voltage V_{OUT} is set to be within 1.2 mV of the measured voltage V_{IN}. The difference V_{DIF} between the input voltage and divided source voltage is measured using the DMM. The divider is then switched off and the offset voltage V_{OFFSET} of the DMM is measured.

$$V_{IN} = V_{OUT} + (V_{DIF} - V_{OFFSET})$$

$$V_{OUT} = V_{SOURCE} \times R_{NOM}$$

Therefore

$$V_{IN} = (V_{SOURCE} \times R_{NOM}) + (V_{DIF} - V_{OFFSET})$$

The measured value of V_{IN} and the measured ratio $\frac{V_{IN}}{V_{SOURCE}}$ are available in the data file produced by the 8000A. The values of R_{NOM}, V_{DIF} and V_{OFFSET} are internal to the 8000A software and are not available to the user.

The MI 8000A System

Self-Calibration

The first step in the measurement process is to perform a self-calibration of the 8000A. This process measures and corrects for the errors in the 13 stages of the Binary Voltage Divider.

Source Standardization

The second step in the measurement process is source standardization. The calibrated Standard Reference Fluke 732, is connected to Input “1” and connected with reversed polarity to input “2” to allow measurements of negative voltage. The source is used to measure the value of the calibrated Reference V_{REF}, and the voltage of the source V_{SOURCE} is calculated based on this measurement.

Stability of 8000A and Source

The two preceding steps need to be performed every 24 hours in order to minimize the uncertainty of the subsequent measurements due to changes in the 8000A and the source.

Measurement of Units Under Test

The next step in the measurement process is measurement of the units under test (UUTs). The UUTs are connected to the 8000A Inputs. The source is used to measure the value of the UUT V_{UUT}

Zero Offset

Measurements using the 8000A indicate that there is a zero offset V_{ZERO}. The value of this offset changes each time the bridge is calibrated and standardized, but it appears to be stable between these processes. Measurements performed indicate that V_{ZERO} is less than 2 μV.

A.5 SASO-NMCC, Saudi Arabia

SASO-NMCC used Favored Cell Design, in this method all units in the test are compared against one favored unit, which usually is the most stable standard available. The small difference between the favored cell and each of the test units is first measured with the favored cell on the right side and then again with the favored cell on the left side. Equipment used: Fluke 734B DC Standard, DataProof 160B Low thermal scanner and Keithley 2182A Nanovoltmeter.

A.6 IMBIH, Bosnia and Herzegovina

IMBIH laboratory consider a two Zener voltage standards (GULF 1-UUT and GULF 2-UUT) that are calibrated against a stable IMBIH's Zener voltage reference on the voltage levels 10 V and 1,018V over a two-week period (*measurements for GULF-1 seven (7) days und for GULF-2 six (6) days*). On each of *J* days (in our case *J*=7 or *J*=6 days) during the period, K=10 independent repeated observations of the voltage differences VN between GULF x-UUT and IMBIH's reference standard are made. The measurement of voltage differences VN between travelling standards (GULF x-UUT) and IMBIH's reference standard (Zener cell Fluke 732B) are performed with digital nano-voltmeter Keithley 2182A. Both of travelling standards are calibrated against Fluke 732B (s/n 2231035) which is traceable to the Josephson Voltage standard of DMDM (Republic of Serbia). Results of estimated daily mean values of voltage differences are given in Table 1 and 2.

In order to eliminate EMF contributions of cables, measurement of voltage differences with nano-voltmeter are performed with cable connection at both polarities. In these cases, the nano-voltmeter measures the small difference between two units several (ten) times, reverses the connection and measures the difference several (ten) times again, then mean value of recorded measurements is calculated.

Further, the same process is repeated 10 times to get one measurement point per day. All mentioned above sequence is repeated 10 times in order to get total of 10 measurements within one day which are further used for calculation daily mean values of voltage differences.

Annex B: Uncertainty Statements

B.1 SCL, Hong Kong, China

(a) Jun-2017 (GULF-1*1.018 V)

(i) Type A uncertainty evaluation:

Source of Uncertainty	Type	u_i		Dist.	c		cu_i	ν_{eff}
		Value			Value		(nV)	
Standard deviation of the mean value	A	16.9	nV	N	1		16.9	11
Random effects and noise	A	0.00890	µV/V	N	1.018	V	9.06	39
Combined standard meas. uncertainty, u_c				N			19.2	17

(ii) Type B uncertainty evaluation:

Source of Uncertainty	Type	u_i		Dist.	c		cu_i	ν_{eff}
		Value			Value		(nV)	
DVM gain error uncertainty	B	1	µV/V	R	0.01	V	5.77	∞
Uncompensated offset voltage on switch	B	30	nV	R	1		17.3	∞
Leakage-error uncertainty	B	0.5	nV	R	1		0.289	∞
Frequency uncertainty	B	5.13	Hz	N	1.36E-11	V/Hz	0.070	200
Uncertainty in measuring ambient pressure [1]	B	2	hPa	N	1.11	nV/hPa	2.22	200
Uncertainty in pressure coefficient	B	0.07	nV/hPa	N	20.89	hPa	1.5	∞
Uncertainty in measuring thermistor resistance [2]	B	3.8	ohm	R	0.45	nV/ohm	0.987	∞
Uncertainty in thermistor coefficient	B	0.06	nV/ohm	N	56.0	ohm	3	∞
Combined standard meas. uncertainty, u_c				N			18.8	1024580

(iii) Measurement uncertainty::

Source of Uncertainty	Type	u_i		Dist.	c		cu_i	ν_{eff}
		Value			Value		(nV)	
Type A	B	19.2		N	1		19.2	17
Type B	B	18.8		N	1		18.8	1024580
Combined standard meas. uncertainty, u_c				N			26.9	65
Coverage factor, k							2.0	
Expandded measurement uncertainty, U							53.7	

(b) Jun-2017 (GULF-1*10 V)

(i) Type A uncertainty evaluation:

Source of Uncertainty	Type	u_i Value		Dist.	c Value		cu_i (nV)	v_{eff}
Standard deviation of the mean value	A	100.2	nV	N	1		100.2	11
Random effects and noise	A	0.00180	µV/V	N	10	V	18.0	39
Combined standard meas. uncertainty, u_c				N			101.8	11

(ii) Type B uncertainty evaluation:

Source of Uncertainty	Type	u_i Value		Dist.	c Value		cu_i (nV)	v_{eff}
DVM gain error uncertainty	B	1	µV/V	R	0.01	V	5.77	∞
Uncompensated offset voltage on switch	B	30	nV	R	1		17.3	∞
Leakage-error uncertainty	B	0.5	nV	R	1		0.289	∞
Frequency uncertainty	B	5.13	Hz	N	1.36E-11	V/Hz	0.070	200
Uncertainty in measuring ambient pressure [1]	B	2	hPa	N	8.67	nV/hPa	17.34	200
Uncertainty in pressure coefficient	B	0.7	nV/hPa	N	20.98	hPa	14.7	∞
Uncertainty in measuring thermistor resistance [2]	B	3.8	ohm	R	0.84	nV/ohm	1.843	∞
Uncertainty in thermistor coefficient	B	0.29	nV/ohm	N	55.6	ohm	16	∞
Combined standard meas. uncertainty, u_c				N			33	2742

(iii) Measurement uncertainty::

Source of Uncertainty	Type	u_i Value		Dist.	c Value		cu_i (nV)	v_{eff}
Type A	B	101.8		N	1		101.8	11
Type B	B	33.4		N	1		33.4	2742
Combined standard meas. uncertainty, u_c				N			107	13
Coverage factor, k							2.2	
Expandded measurement uncertainty, U							236	

(c) Jun-2017 (GULF-2*1.018 V)

(i) Type A uncertainty evaluation:

Source of Uncertainty	Type	u_i		Dist.	c		cu_i	v_{eff}
		Value			Value		(nV)	
Standard deviation of the mean value	A	6.4	nV	N	1		6.4	11
Random effects and noise	A	0.00980	μV/V	N	1.018	V	10.0	39
Combined standard meas. uncertainty, u_c				N			11.9	48

(ii) Type B uncertainty evaluation:

Source of Uncertainty	Type	u_i		Dist.	c		cu_i	v_{eff}
		Value			Value		(nV)	
DVM gain error uncertainty	B	1	μV/V	R	0.01	V	5.77	∞
Uncompensated offset voltage on switch	B	30	nV	R	1		17.3	∞
Leakage-error uncertainty	B	0.5	nV	R	1		0.289	∞
Frequency uncertainty	B	5.13	Hz	N	1.36E-11	V/Hz	0.070	200
Uncertainty in measuring ambient pressure [1]	B	2	hPa	N	0.99	nV/hPa	1.98	200
Uncertainty in pressure coefficient	B	0.06	nV/hPa	N	20.81	hPa	1.2	∞
Uncertainty in measuring thermistor resistance [2]	B	3.8	ohm	R	0	nV/ohm	0.000	∞
Uncertainty in thermistor coefficient	B	0	nV/ohm	N	636.3	ohm	0	∞
Combined standard meas. uncertainty, u_c				N			18.4	1494557

(iii) Measurement uncertainty::

Source of Uncertainty	Type	u_i		Dist.	c		cu_i	v_{eff}
		Value			Value		(nV)	
Type A	B	11.9		N	1		11.9	48
Type B	B	18.4		N	1		18.4	1494557
Combined standard meas. uncertainty, u_c				N			21.9	558
Coverage factor, k							2.0	
Expandded measurement uncertainty, U							43.8	

(d) Jun-2017 (GULF-2*10 V)

(i) Type A uncertainty evaluation:

Source of Uncertainty	Type	u_i Value		Dist.	c Value		cu_i (nV)	v_{eff}
Standard deviation of the mean value	A	53.5	nV	N	1		53.5	11
Random effects and noise	A	0.00120	µV/V	N	10	V	12.0	39
Combined standard meas. uncertainty, u_c				N			54.9	12

(ii) Type B uncertainty evaluation:

Source of Uncertainty	Type	u_i Value		Dist.	c Value		cu_i (nV)	v_{eff}
DVM gain error uncertainty	B	1	µV/V	R	0.01	V	5.77	∞
Uncompensated offset voltage on switch	B	30	nV	R	1		17.3	∞
Leakage-error uncertainty	B	0.5	nV	R	1		0.289	∞
Frequency uncertainty	B	5.13	Hz	N	1.36E-11	V/Hz	0.070	200
Uncertainty in measuring ambient pressure [1]	B	2	hPa	N	9.22	nV/hPa	18.44	200
Uncertainty in pressure coefficient	B	0.36	nV/hPa	N	20.96	hPa	7.5	∞
Uncertainty in measuring thermistor resistance [2]	B	3.8	ohm	R	0	nV/ohm	0.000	∞
Uncertainty in thermistor coefficient	B	0	nV/ohm	N	633.2	ohm	0	∞
Combined standard meas. uncertainty, u_c				N			27	922

(iii) Measurement uncertainty::

Source of Uncertainty	Type	u_i Value		Dist.	c Value		cu_i (nV)	v_{eff}
Type A	B	54.9		N	1		54.9	12
Type B	B	27		N	1		27.0	922
Combined standard meas. uncertainty, u_c				N			61	18
Coverage factor, k							2.1	
Expandded measurement uncertainty, U							128	

B.2 KRISS, Republic of South Korea

The type B uncertainty of KRISS measurement system, excluding the temperature and pressure correction uncertainty, are 7 nV and 20 nV for 1.018 V and 10 V respectively.

		Measurement Uncertainty			
Artefact	Mean Date	Type A	Type B	u_c	U
		(nV)	(nV)	(nV)	(nV)
GULF_1*1.018 V	1/Aug/2017	30	10	32	64
	3/May/2018	14	10	17	34
GULF_1*10 V	1/Aug/2017	93	33	99	198
	4/May/2018	72	28	77	155
GULF_2*1.018 V	5/Aug/2017	9	7	11	22
	3/May/2018	6	7	9	18
GULF_2*10 V	5/Aug/2017	22	20	30	60
	3/May/2018	34	20	39	79

B.3 BIPM

B.3.1 (August 2017)

Table 2. Results of the BIPM in the first measurement session of GULFMET.EM.BIPM-K11.a of 1.018 V standards using two Zener traveling standards: reference date 28 August 2017. Uncertainties are 1 σ estimates.

		GULF-1	GULF-2
1	BIPM (U_Z – 1.018 V)/µV	197.38	147.25
2	Type A uncertainty/µV	0.020	0.010
3	correlated unc./µV	0.001	
4	pressure and temperature	0.006	0.007
5	uncorrelated uncertainty/µV	0.021	0.012
6	Total combined uncertainty/µV	0.021	0.012

Table 3. Estimated standard uncertainties of the BIPM JVS and measurement chain for Zener calibrations with the BIPM equipment at the level of 1.018 V without the contribution of the Zener noise and the contribution of the pressure and temperature corrections.

JVS & detector uncertainty components	Type	Uncertainty/nV
Measurement loop noise	A	3.4
Nanovoltmeter accuracy	A	0.11
Accuracy of the JVS RF frequency	B	0.03
Leakage resistance	B	0.03
Pressure and temperature correction	B	included in the Zener unc. budget
Zener noise	A	included in the Zener unc. budget
Total		3.4

Table 5. Results of the BIPM in the first measurement session of GULFMET.EM.BIPM-K11.b of 10 V standards using two Zener traveling standards: reference date 28 August 2017. Uncertainties are 1 σ estimates.

		GULF-1	GULF-2
1	BIPM (UZ – 10 V)/µV	66.31	-4.92
2	Type A uncertainty/µV	0.100	0.100
3	correlated unc./µV	0.001	
4	pressure and temperature	0. 026	0.047
5	uncorrelated uncertainty/µV	0.103	0.110
6	Total combined uncertainty/µV	0.103	0.110

Table 6. Estimated standard uncertainties for Zener calibrations with the BIPM equipment at the level of 10 V without the contribution of the Zener noise and the contribution of the pressure and temperature corrections.

JVS & detector uncertainty components	Type	Uncertainty/nV
Measurement loop noise	A	0.86
Nanovoltmeter accuracy	A	0.11
Accuracy of the JVS RF frequency	B	0.03
Leakage resistance	B	0.03
Pressure and temperature correction	B	included in the Zener unc. budget
Zener noise	A	included in the Zener unc. budget
Total		0.87

B.3.2 (June 2018)

Table 2. Results of the BIPM in the second measurement session of GULFMET.EM.BIPM-K11.a of 1.018 V standards using two Zener traveling standards: reference date 22 June 2018 for GULF-1 and 24 June for GULF-2. Uncertainties are 1 σ estimates.

		GULF-1	GULF-2
1	BIPM (U_Z – 1.018 V)/µV	199.744	145.383
2	Type A uncertainty/µV	0.023	0.010
3	correlated unc./µV	0.001	
4	pressure and temperature	0.004	0.005
5	uncorrelated uncertainty/µV	0.023	0.011
6	Total combined uncertainty/µV	0.023	0.011

Table 3. Estimated standard uncertainties of the BIPM JVS and measurement chain for Zener calibrations with the BIPM equipment at the level of 1.018 V without the contribution of the Zener noise and the contribution of the pressure and temperature corrections.

JVS & detector uncertainty components	Type	Uncertainty/nV
Measurement loop noise	A	3.4
Nanovoltmeter accuracy	A	0.11
Accuracy of the JVS RF frequency	B	0.03
Leakage resistance	B	0.03
Pressure and temperature correction	B	included in the Zener unc. budget
Zener noise	A	included in the Zener unc. budget
Total		3.4

Table 5. Results of the BIPM in the first measurement session of GULFMET.EM.BIPM-K11.b of 10 V standards using two Zener traveling standards: reference date 22 June 2018 for GULF-1 and 24 June for GULF-2. Uncertainties are 1 σ estimates.

		GULF-1	**GULF-2**
1	BIPM (UZ – 10 V)/µV	65.49	-13.71
2	Type A uncertainty/µV	0.100	0.100
3	correlated unc./µV	0.001	
4	pressure and temperature	0. 025	0.028
5	uncorrelated uncertainty/µV	0.103	0.104
6	Total combined uncertainty/µV	0.103	0.104

Table 6. Estimated standard uncertainties for Zener calibrations with the BIPM equipment at the level of 10 V without the contribution of the Zener noise and the contribution of the pressure and temperature corrections.

JVS & detector uncertainty components	Type	Uncertainty/nV
Measurement loop noise	A	0.86
Nanovoltmeter accuracy	A	0.11
Accuracy of the JVS RF frequency	B	0.03
Leakage resistance	B	0.03
Pressure and temperature correction	B	included in the Zener unc. budget
Zener noise	A	included in the Zener unc. budget
Total		0.87

B.4 QCC EMI, United Arab Emirates

Uncertainty Data for:	2260038 10 V output						
Type A Uncertainty							
Uncertainty Description	Uncertainty / ppm	Reference	Distribution	Divisor	Standard Uncertainty	Variance	Veff
Repeatability	0.009	Data worksheet	Normal k=1	1.000	8.543E-03	7.299E-05	11
Combined Type A Uncertainty					8.543E-03	7.299E-05	11
Type B Uncertainty							
Uncertainty Description	Uncertainty / ppm	Reference	Distribution	Divisor	Standard Uncertainty	Variance	Veff
732B Standard Calibration	0.020	NPL Certificate	Normal k=2	2.0000	1.000E-02	1.000E-04	inf
732B Transportation Uncertainty	0.300	Offset of EMI measurements before & after calibration from prediction	Rectangular	1.7321	1.732E-01	3.000E-02	inf
732B Drift Uncertainty	0.500	Difference between last calibration and prediction from history	Rectangular	1.7321	2.887E-01	8.333E-02	inf
732B Temperature uncertainty	0.120	Specification	Rectangular	1.7321	6.928E-02	4.800E-03	inf
732B Noise	0.060	Specification	Rectangular	1.7321	3.464E-02	1.200E-03	inf
Thermoelectric Voltage	0.030	Estimate	Rectangular	1.7321	1.732E-02	3.000E-04	inf
8000A Zero offset	0.200	Estimate	Rectangular	1.7321	1.155E-01	1.333E-02	inf
8000A Resolution	0.010	Specification	Rectangular	1.7321	5.774E-03	3.333E-05	inf
8000A Ratio Uncertainty	0.044	Ratio Verification	Rectangular	1.7321	2.540E-02	6.453E-04	inf
Temperature correction uncertainty	0.007	Estimate	Rectangular	1.7321	4.321E-03	1.867E-05	inf
Pressure correction uncertainty	0.003	Estimate	Rectangular	1.7321	1.792E-03	3.212E-06	inf
Combined Type B Uncertainty					3.657E-01	1.338E-01	inf
Combined Uncertainty Results / ppm		Combined Uncertainty Results /nV	Distribution	Divisor			
TYPE A Standard Uncertainty	0.009	8.54E+01	Rectangular	1.7321			
TYPE A Variance	0.000		Triangular	2.4495			
TYPE B Standard Uncertainty	0.366	3.66E+03	U - Shaped	1.4142			
TYPE B Variance	0.134		Normal k=1	1.0000			
Combined Standard Uncertainty	0.366	3.66E+03	Normal k=2	2.0000			
Combined Variance	0.134						
Veff	36985768						
Coverage Factor (k)	2.000						
Uncertainty	**0.732**	**7.32E+03**					

Uncertainty Data for: 1944005 10 V output							
Type A Uncertainty							
Uncertainty Description	Uncertainty / ppm	Reference	Distribution	Divisor	Standard Uncertainty	Variance	Veff
Repeatability	0.009	Data worksheet	Normal k=1	1.000	9.469E-03	8.967E-05	11
Combined Type A Uncertainty					9.469E-03	8.967E-05	11
Type B Uncertainty							
Uncertainty Description	Uncertainty / ppm	Reference	Distribution	Divisor	Standard Uncertainty	Variance	Veff
732B Standard Calibration	0.020	NPL Certificate	Normal k=2	2.0000	1.000E-02	1.000E-04	inf
732B Transportation Uncertainty	0.300	Offset of EMI measurements before & after calibration from prediction	Rectangular	1.7321	1.732E-01	3.000E-02	inf
732B Drift Uncertainty	0.500	Difference between last calibration and prediction from history	Rectangular	1.7321	2.887E-01	8.333E-02	inf
732B Temperature uncertainty	0.120	Specification	Rectangular	1.7321	6.928E-02	4.800E-03	inf
732B Noise	0.060	Specification	Rectangular	1.7321	3.464E-02	1.200E-03	inf
Thermoelectric Voltage	0.030	Estimate	Rectangular	1.7321	1.732E-02	3.000E-04	inf
8000A Zero offset	0.200	Estimate	Rectangular	1.7321	1.155E-01	1.333E-02	inf
8000A Resolution	0.010	Specification	Rectangular	1.7321	5.774E-03	3.333E-05	inf
8000A Ratio Uncertainty	0.044	Ratio Verification	Rectangular	1.7321	2.540E-02	6.453E-04	inf
Temperature correction uncertainty	0.003	Estimate	Rectangular	1.7321	1.526E-03	2.328E-06	inf
Pressure correction uncertainty	0.003	Estimate	Rectangular	1.7321	1.725E-03	2.976E-06	inf
Combined Type B Uncertainty					3.657E-01	1.338E-01	inf

Combined Uncertainty Results / ppm		Combined Uncertainty Results /nV	Distribution	Divisor
TYPE A Standard Uncertainty	0.009	9.47E+01	Rectangular	1.7321
TYPE A Variance	0.000		Triangular	2.4495
TYPE B Standard Uncertainty	0.366	3.66E+03	U - Shaped	1.4142
TYPE B Variance	0.134		Normal k=1	1.0000
Combined Standard Uncertainty	0.366	3.66E+03	Normal k=2	2.0000
Combined Variance	0.134			
Veff	24507168			
Coverage Factor (k)	2.000			
Uncertainty	**0.732**	**7.32E+03**		

Uncertainty Data for:	2260038 1.018 V output						
Type A Uncertainty							
Uncertainty Description	Uncertainty / ppm	Reference	Distribution	Divisor	Standard Uncertainty	Variance	Veff
Repeatability	0.034	Data worksheet	Normal k=1	1.000	3.397E-02	1.154E-03	11
Combined Type A Uncertainty					3.397E-02	1.154E-03	11
Type B Uncertainty							
Uncertainty Description	Uncertainty / ppm	Reference	Distribution	Divisor	Standard Uncertainty	Variance	Veff
732B Standard Calibration	0.020	NPL Certificate	Normal k=2	2.0000	1.000E-02	1.000E-04	inf
732B Transportation Uncertainty	0.300	Offset of EMI measurements before & after calibration from prediction	Rectangular	1.7321	1.732E-01	3.000E-02	inf
732B Drift Uncertainty	0.500	Difference between last calibration and prediction from history	Rectangular	1.7321	2.887E-01	8.333E-02	inf
732B Temperature uncertainty	0.120	Specification	Rectangular	1.7321	6.928E-02	4.800E-03	inf
732B Noise	0.060	Specification	Rectangular	1.7321	3.464E-02	1.200E-03	inf
Thermoelectric Voltage	0.300	Estimate	Rectangular	1.7321	1.732E-01	3.000E-02	inf
8000A Zero offset	2.000	Measurement	Rectangular	1.7321	1.155E+00	1.333E+00	inf
8000A Resolution	0.100	Specification	Rectangular	1.7321	5.774E-02	3.333E-03	inf
8000A Ratio Uncertainty	0.440	Ratio Verification	Rectangular	1.7321	2.540E-01	6.453E-02	inf
Temperature correction uncertainty	0.011	Estimate	Rectangular	1.7321	6.185E-03	3.826E-05	inf
Pressure correction uncertainty	0.004	Estimate	Rectangular	1.7321	2.414E-03	5.827E-06	inf
Combined Type B Uncertainty					1.245E+00	1.551E+00	inf

Combined Uncertainty Results / ppm		Combined Uncertainty Results /nV	Distribution	Divisor
TYPE A Standard Uncertainty	0.034	3.46E+01	Rectangular	1.7321
TYPE A Variance	0.001		Triangular	2.4495
TYPE B Standard Uncertainty	1.245	1.27E+03	U - Shaped	1.4142
TYPE B Variance	1.551		Normal k=1	1.0000
Combined Standard Uncertainty	1.246	1.27E+03	Normal k=2	2.0000
Combined Variance	1.552			
Veff	19894120			
Coverage Factor (k)	2.000			
Uncertainty	**2.491**	**2.54E+03**		

Uncertainty Data for: 1944005 1.018 V output							
Type A Uncertainty							
Uncertainty Description	Uncertainty / ppm	Reference	Distribution	Divisor	Standard Uncertainty	Variance	Veff
Repeatability	0.022	Data worksheet	Normal k=1	1.000	2.239E-02	5.014E-04	11
Combined Type A Uncertainty					2.239E-02	5.014E-04	11
Type B Uncertainty							
Uncertainty Description	Uncertainty / ppm	Reference	Distribution	Divisor	Standard Uncertainty	Variance	Veff
732B Standard Calibration	0.020	NPL Certificate	Normal k=2	2.0000	1.000E-02	1.000E-04	inf
732B Transportation Uncertainty	0.300	Offset of EMI measurements before & after calibration from prediction	Rectangular	1.7321	1.732E-01	3.000E-02	inf
732B Drift Uncertainty	0.500	Difference between last calibration and prediction from history	Rectangular	1.7321	2.887E-01	8.333E-02	inf
732B Temperature uncertainty	0.120	Specification	Rectangular	1.7321	6.928E-02	4.800E-03	inf
732B Noise	0.060	Specification	Rectangular	1.7321	3.464E-02	1.200E-03	inf
Thermoelectric Voltage	0.300	Estimate	Rectangular	1.7321	1.732E-01	3.000E-02	inf
8000A Zero offset	2.000	Measurement	Rectangular	1.7321	1.155E+00	1.333E+00	inf
8000A Resolution	0.100	Specification	Rectangular	1.7321	5.774E-02	3.333E-03	inf
8000A Ratio Uncertainty	0.440	Ratio Verification	Rectangular	1.7321	2.540E-01	6.453E-02	inf
Temperature correction uncertainty	0.011	Estimate	Rectangular	1.7321	6.232E-03	3.884E-05	inf
Pressure correction uncertainty	0.004	Estimate	Rectangular	1.7321	2.073E-03	4.296E-06	inf
Combined Type B Uncertainty					1.245E+00	1.551E+00	inf

Combined Uncertainty Results / ppm		Combined Uncertainty Results /nV	Distribution	Divisor
TYPE A Standard Uncertainty	0.022	2.28E+01	Rectangular	1.7321
TYPE A Variance	0.001		Triangular	2.4495
TYPE B Standard Uncertainty	1.245	1.27E+03	U - Shaped	1.4142
TYPE B Variance	1.551		Normal k=1	1.0000
Combined Standard Uncertainty	1.245	1.27E+03	Normal k=2	2.0000
Combined Variance	1.551			
Veff	105261302			
Coverage Factor (k)	2.000			
Uncertainty	**2.491**	**2.54E+03**		

B.5 SASO-NMCC, Saudi Arabia

$$V_x = V_{STD} - V_{DVM} + \alpha_t(t - t_0) - \delta V_{DVM} + \delta V_{scanner} + \delta V_{emf} - \alpha_R(R - R_0) - \alpha_p(p - p_0)$$

1.018 V
Gulf-1 SN:2260038

Description	Symbol	Estimated Value		Uncertainty		Probability Distribution	Factor	Standard Unvertainty		Sensitivity Coefficients		Uncertainty Contribution		υ_i
Measured voltage difference (Standard deviation)	$V_{\Delta DVM}$	-13765	nV	10	nV	normal	1.0	10	nV	-1		10.1	nV	19
Voltage of Reference DC Voltage Standard	V_{STD}	1.01818350	V	150	nV	normal	0.5	75	nV	1		75.0	nV	55
Drift of Ref. DC Voltage standard	δV_{STD}	1121.2	nV	600	nV	rectangular	0.577	346	nV	1		346.4	nV	21
Nanovoltmeter	δV_{DVM}	0	nV	50	nV	rectangular	0.577	29	nV	-1		28.9	nV	1000
Scanner	$\delta V_{scanner}$	0	nV	50	nV	rectangular	0.577	29	nV	1		28.9	nV	1000
Residual EMF	δV_{emf}	0	nV	100	nV	rectangular	0.577	58	nV	1		57.7	nV	1000
Reference pressure	p_0	1013.25	hPa	0	hPa	normal	1.0	0		-2	nV/hPa	0.0	nV	20
Reference thermistor resistance	R_0	39.65	kΩ	0	kΩ	normal	1.0	0		-0.3	nV/kΩ	0.0	nV	20
Measured pressure	p	952.6	hPa	1.4	hPa	rectangular	0.577	0.82	hPa	-2	nV/hPa	1.6	nV	19
Measured thermistor resistance	R	38.440	kΩ	0.003	kΩ	rectangular	0.577	0.0017	kΩ	-0.3	nV/kΩ	0.0005	nV	19
Pressure coefficient	α_p	2	nV/hPa	2.9	nV/hPa	rectangular	0.577	1.67	nV/hPa	60.65	hPa	101.5	nV	20
Thermistor coefficient	α_R	0.3	nV/kΩ	2.9	nV/kΩ	rectangular	0.577	1.67	nV/kΩ	1.21	kΩ	2.0	nV	20
Corrected Measured Voltage	V_x	1.01819887	V						Type B Uncertainty			375.4	nV	
Time of Comparison measurement	t	10/27/2017							Combined Uncertainty			375.6	nV	
Calibration time of Reference DC Voltage Std.	t_0	1/26/2017							Coverage Factor, k			2.05	v_{eff}	28.8
									Expanded uncertainty			770	nV	
									Declared Expanded Uncertainty			500	nV	0.49 µV/V
									Declared Expanded Uncertainty			0.50 µV/V		

$$V_x = V_{STD} - V_{DVM} + \alpha_t(t - t_0) - \delta V_{DVM} + \delta V_{scanner} + \delta V_{emf} - \alpha_R(R - R_0) - \alpha_p(p - p_0)$$

1.018 V
Gulf-2 SN:1944005

Description	Symbol	Estimated Value		Uncertainty		Probability Distribution	Factor	Standard Unvertainty		Sensitivity Coefficients		Uncertainty Contribution		υ_i
Measured voltage difference (Standard deviation)	$V_{\Delta DVM}$	37879	nV	13	nV	normal	1.0	13	nV	-1		13.1	nV	19
Voltage of Reference DC Voltage Standard	V_{STD}	1.01818350	V	150	nV	normal	0.5	75	nV	1		75.0	nV	55
Drift of Ref. DC Voltage standard	δV_{STD}	1121.2	nV	600	nV	rectangular	0.577	346	nV	1		346.4	nV	21
Nanovoltmeter	δV_{DVM}	0	nV	50	nV	rectangular	0.577	29	nV	-1		28.9	nV	1000
Scanner	$\delta V_{scanner}$	0	nV	50	nV	rectangular	0.577	29	nV	1		28.9	nV	1000
Residual EMF	δV_{emf}	0	nV	100	nV	rectangular	0.577	58	nV	1		57.7	nV	1000
Reference pressure	p_0	1013.25	hPa	0	hPa	normal	1.0	0		-1.4	nV/hPa	0.0	nV	20
Reference thermistor resistance	R_0	38.65	kΩ	0	kΩ	normal	1.0	0		-0.2	nV/kΩ	0.0	nV	20
Measured pressure	p	952.6	hPa	1.4	hPa	rectangular	0.577	0.82	hPa	-1.4	nV/hPa	1.2	nV	19
Measured thermistor resistance	R	38.932	kΩ	0.003	kΩ	rectangular	0.577	0.0017	kΩ	-0.2	nV/kΩ	0.0003	nV	19
Pressure coefficient	α_p	1.4	nV/hPa	2.9	nV/hPa	rectangular	0.577	1.67431578	nV/hPa	60.65	hPa	101.5	nV	20
Thermistor coefficient	α_R	0.2	nV/kΩ	2.9	nV/kΩ	rectangular	0.577	1.67431578	nV/kΩ	-0.28	kΩ	0.5	nV	20
Corrected Measured Voltage	V_x	1.01814677	V						Type B Uncertainty			375.4	nV	
Time of Comparison measurement	t	10/27/2017							Combined Uncertainty			375.6	nV	
Calibration time of Reference DC Voltage Std.	t_0	1/26/2017							Coverage Factor, k			2.05	v_{eff}	28.8
									Expanded uncertainty			770	nV	
									Declared Expanded Uncertainty			500	nV	0.49 µV/V
									Declared Expanded Uncertainty			0.50 µV/V		

GULFMET
التجمع الخليجي للمترولوجيا

$$V_x = V_{STD} - V_{iDVM} + \alpha_t(t-t_0) - \delta V_{DVM} + \delta V_{scanner} + \delta V_{emf} - \alpha_R(R-R_0) - \alpha_p(p-p_0)$$

10 V
Gulf-1 SN:2260038

Description	Symbol	Estimated Value		Uncertainty		Probability Distribution	Factor	Standard Uncertainty		Sensitivity Coefficients		Uncertainty Contribution		υ_i
Measured voltage difference (Standard deviation)	V_{iDVM}	-29920	nV	97	nV	normal	1.0	97	nV	-1		97.3	nV	19
Voltage of Reference DC Voltage Standard	V_{STD}	10.00004325	V	400	nV	normal	0.5	200	nV	1		200.0	nV	55
Drift of Ref. DC Voltage standard	δV_{STD}	-6513.3	nV	3000	nV	rectangular	0.577	1732	nV	1		1732.1	nV	21
Nanovoltmeter	δV_{DVM}	0	nV	50	nV	rectangular	0.577	29	nV	-1		28.9	nV	1000
Scanner	$\delta V_{scanner}$	0	nV	50	nV	rectangular	0.577	29	nV	1		28.9	nV	1000
Residual EMF	δV_{emf}	0	nV	100	nV	rectangular	0.577	58	nV	1		57.7	nV	1000
Reference pressure	p_0	1013.25	hPa	0	hPa	normal	1.0	0	hPa	-17.8	nV/hPa	0.0	nV	20
Reference thermistor resistance	R_0	39.65	kΩ	0	kΩ	normal	1.0	0	kΩ	-4.3	nV/kΩ	0.0	nV	20
Measured pressure	p	952.6	hPa	1.4	hPa	rectangular	0.577	0.82	hPa	-17.8	nV/hPa	14.7	nV	19
Measured thermistor resistance	R	38.447	kΩ	0.003	kΩ	rectangular	0.577	0.0017	kΩ	-4.3	nV/kΩ	0.0074	nV	19
Pressure coefficient	α_p	17.8	nV/hPa	3.6	nV/hPa	rectangular	0.577	2.08	nV/hPa	60.65	hPa	126.1	nV	20
Thermistor coefficient	α_R	4.3	nV/kΩ	2.9	nV/kΩ	rectangular	0.577	1.67	nV/kΩ	1.20	kΩ	2.0	nV	20
Corrected Measured Voltage	V_x	10.00007291	V						Type B Uncartainty			1749.6	nV	
Time of Comparison measurement	t	10/27/2017							Combined Uncertainty			1752.3	nV	
Calibration time of Reference DC Voltage Std.	t_0	1/26/2017							Coverage Factor, k			2.11	v_{eff}	22.0
									Expanded uncertainty			**3697**	**nV**	
									Declared Expanded Uncertainty			**2500**	**nV**	**0.25 µV/V**
									Declared Expanded Uncertainty			**0.25 µV/V**		

$$V_x = V_{STD} - V_{iDVM} + \alpha_t(t-t_0) - \delta V_{DVM} + \delta V_{scanner} + \delta V_{emf} - \alpha_R(R-R_0) - \alpha_p(p-p_0)$$

10 V
Gulf-2 SN:1944005

Description	Symbol	Estimated Value		Uncertainty		Probability Distribution	Factor	Standard Uncertainty		Sensitivity Coefficients		Uncertainty Contribution		υ_i
Measured voltage difference (Standard deviation)	V_{iDVM}	44985	nV	103	nV	normal	1.0	103	nV	-1		103.5	nV	19
Voltage of Reference DC Voltage Standard	V_{STD}	10.00004325	V	400	nV	normal	0.5	200	nV	1		200.0	nV	55
Drift of Ref. DC Voltage standard	δV_{STD}	-6513.3	nV	3000	nV	rectangular	0.577	1732	nV	1		1732.1	nV	21
Nanovoltmeter	δV_{DVM}	0	nV	50	nV	rectangular	0.577	29	nV	-1		28.9	nV	1000
Scanner	$\delta V_{scanner}$	0	nV	50	nV	rectangular	0.577	29	nV	1		28.9	nV	1000
Residual EMF	δV_{emf}	0	nV	100	nV	rectangular	0.577	58	nV	1		57.7	nV	1000
Reference pressure	p_0	1013.25	hPa	0	hPa	normal	1.0	0	hPa	-16.5	nV/hPa	0.0	nV	20
Reference thermistor resistance	R_0	38.65	kΩ	0	kΩ	normal	1.0	0	kΩ	-1.9	nV/kΩ	0.0	nV	20
Measured pressure	p	952.6	hPa	1.4	hPa	rectangular	0.577	0.82	hPa	-16.5	nV/hPa	13.6	nV	19
Measured thermistor resistance	R	38.941	kΩ	0.003	kΩ	rectangular	0.577	0.0017	kΩ	-1.9	nV/kΩ	0.0033	nV	19
Pressure coefficient	α_p	16.5	nV/hPa	3.5	nV/hPa	rectangular	0.577	2.0207259	nV/hPa	60.65	hPa	122.6	nV	20
Thermistor coefficient	α_R	1.9	nV/kΩ	2.9	nV/kΩ	rectangular	0.577	1.6743158	nV/kΩ	-0.29	kΩ	0.5	nV	20
Corrected Measured Voltage	V_x	9.99999220	V						Type B Uncartainty			1749.3	nV	
Time of Comparison measurement	t	10/27/2017							Combined Uncertainty			1752.4	nV	
Calibration time of Reference DC Voltage Std.	t_0	1/26/2017							Coverage Factor, k			2.11	v_{eff}	22.0
									Expanded uncertainty			**3698**	**nV**	
									Declared Expanded Uncertainty			**2500**	**nV**	**0.25 µV/V**
									Declared Expanded Uncertainty			**0.25 µV/V**		

B.6 IMBIH, Bosnia and Herzegovina

10 V GULF-1

Table 3. Uncertainty budget for 10 V DC voltage of GULF-1 Zener cell Fluke 732B

Input quantities		Estimated value		Uncertainty sources U (xi)		Divider	Standard uncertainty $u(x_i)$ (k=1)		Probability distribution	Sensitivity coeficients c_i		Uncertainty contribution $u_i(V_{UUT})$		Degrees of freedom
Mean value of voltage difference	V_N	0,007 99	mV	-	-	-	-	-	-	-	-	-	-	-
Corretion due to accuracy of nanovoltmeter	$\delta V_{N,spec}$	0		4,04E-02	µV	1,73	2,33E-02	µV	rectangular	1	µV/µV	2,33E-02	µV	∞
Corretion due to resolution of nanovoltmeter	$\delta V_{N,res}$	0		1,00E-02	µV	3,46	2,89E-03	µV	rectangular	1	µV/µV	2,89E-03	µV	∞
Correction due to scattering measurement results (type A)	$\delta V_{N,a}$	0		1,77E-01	µV	1	1,77E-01	µV	normal	1	µV/µV	1,77E-01	µV	6
DC voltage value of reference standard	V_Z	10,000 054	V	-	-	-	-	-	-	-	-	-	-	-
Correction due to environment temperature effect on reference standard	$\delta V_{Z,T}$	0		4,00E-01	µV	1,73	2,31E-01	µV	rectangular	1	V/V	2,31E-01	µV	∞
Correction due to calibration uncertainty of reference standard	$\delta V_{Z,cal}$	0		4,00E-01	µV	2	2,00E-01	µV	normal	1	V/V	2,00E-01	µV	∞
Correction due to noise of reference standard	$\delta V_{Z,noise}$	0		1,30E+00	µV	1,73	7,51E-01	µV	rectangular	1	V/V	7,51E-01	µV	∞
Correction due to drift of reference standard value from its last calibration	$\delta V_{Z,drift}$	0		4,00E+00	µV	1,73	2,31E+00	µV	rectangular	1	V/V	2,31E+00	µV	∞
Estimated value and uncertainty of UUT	V_{UUT} =	10,000 062	±	0,000 005 V			Combined standard uncertainty					2,45	µV	
							Expanded uncertainty (95%)					4,91	µV	
							Relative expanded uncertainty (95%)					0,49	µV/V	
							Effective degrees of freedom, v_{eff}					223540,04		
							Coverage factor, k					2,00		

1.018 V GULF-1

Table 4. Uncertainty budget for 1.018 V DC voltage of GULF-1 Zener cell Fluke 732B

Input quantities		Estimated value		Uncertainty sources U (xi)		Divider	Standard uncertainty $u(x_i)$ (k=1)		Probability distribution	Sensitivity coeficients c_i		Uncertainty contribution $u_i(V_{UUT})$		Degrees of freedom
Mean value of voltage difference	V_N	0,131 33	mV	-	-	-	-	-	-	-	-	-	-	-
Corretion due to accuracy of nanovoltmeter	$\delta V_{N,spec}$	0		4,66E-02	µV	1,73	2,69E-02	µV	rectangular	1	µV/µV	2,69E-02	µV	∞
Corretion due to resolution of nanovoltmeter	$\delta V_{N,res}$	0		1,00E-02	µV	3,46	2,89E-03	µV	rectangular	1	µV/µV	2,89E-03	µV	∞
Correction due to scattering measurement results (type A)	$\delta V_{N,a}$	0		2,48E-02	µV	1	2,48E-02	µV	normal	1	µV/µV	2,48E-02	µV	6
DC voltage value of reference standard	V_Z	1,018 066	V	-	-	-	-	-	-	-	-	-	-	-
Correction due to environment temperature effect on reference standard	$\delta V_{Z,T}$	0		1,00E-01	µV	1,73	5,77E-02	µV	rectangular	1	V/V	5,77E-02	µV	∞
Correction due to calibration uncertainty of reference standard	$\delta V_{Z,cal}$	0		1,50E-01	µV	2	7,50E-02	µV	normal	1	V/V	7,50E-02	µV	∞
Correction due to noise of reference standard	$\delta V_{Z,noise}$	0		4,00E-01	µV	1,73	2,31E-01	µV	rectangular	1	V/V	2,31E-01	µV	∞
Correction due to drift of reference standard value from its last calibration	$\delta V_{Z,drift}$	0		7,00E-01	µV	1,73	4,04E-01	µV	rectangular	1	V/V	4,04E-01	µV	∞
Estimated value and uncertainty of UUT	V_{UUT} =	1,018 197	±	0,000 001 V			Combined standard uncertainty					0,48	µV	
							Expanded uncertainty (95%)					0,95	µV	
							Relative expanded uncertainty (95%)					0,94	µV/V	
							Effective degrees of freedom, v_{eff}					818892,52		
							Coverage factor, k					2,00		

GULFMET

التجمع الخليجي للمترولوجيا

10 V GULF-2

Table 5. Uncertainty budget for 10 V DC voltage of GULF-2 Zener cell Fluke 732B

Input quantities		Estimated value		Uncertainty sources U (xi)		Divider	Standard uncertainty u(xᵢ) (k=1)		Probability distribution	Sensitivity coeficients cᵢ		Uncertainty contribution uᵢ(V_{UUT})		Degrees of freedom
Mean value of voltage difference	V_N	-0,066 36	mV	-	-	-	-	-	-	-	-	-	-	-
Corretion due to accuracy of nanovotmeter	$\delta V_{N,spec}$	0		3,67E-02	µV	1,73	2,12E-02	µV	rectangular	1	µV/µV	2,12E-02	µV	∞
Corretion due to resolution of nanovoltmeter	$\delta V_{N,res}$	0		1,00E-02	µV	3,46	2,89E-03	µV	rectangular	1	µV/µV	2,89E-03	µV	∞
Correction due to scattering measurement results (type A)	$\delta V_{N,s}$	0		1,51E-01	µV	1	1,51E-01	µV	normal	1	µV/µV	1,51E-01	µV	5
DC voltage value of reference standard	V_Z	10,000 054	V	-	-	-	-	-	-	-	-	-	-	-
Correction due to environment temperature effect on reference standard	$\delta V_{Z,T}$	0		4,00E-01	µV	1,73	2,31E-01	µV	rectangular	1	V/V	2,31E-01	µV	∞
Correction due to calibration uncertainty of reference standard	$\delta V_{Z,cal}$	0		4,00E-01	µV	2	2,00E-01	µV	normal	1	V/V	2,00E-01	µV	∞
Correction due to noise of reference standard	$\delta V_{Z,noise}$	0		1,30E+00	µV	1,73	7,51E-01	µV	rectangular	1	V/V	7,51E-01	µV	∞
Correction due to drift of reference standard value from its last calibration	$\delta V_{Z,drift}$	0		4,00E+00	µV	1,73	2,31E+00	µV	rectangular	1	V/V	2,31E+00	µV	∞
Estimated value and uncertainty of UUT	V_{UUT}=	9,999 987	±	0,000 005 V			Combined standard uncertainty					2,452	µV	
							Expanded uncertainty (95%)					4,905	µV	
							Relative expanded uncertainty (95%)					0,490	µV/V	
							Effective degrees of freedom, ν_{eff}					352209,88		
							Coverage factor, k					2,00		

1.018 V GULF-2

Table 6. Uncertainty budget for 1.018 V DC voltage of GULF-2 Zener cell Fluke 732B

Input quantities		Estimated value		Uncertainty sources U (xi)		Divider	Standard uncertainty u(xᵢ) (k=1)		Probability distribution	Sensitivity coeficients cᵢ		Uncertainty contribution uᵢ(V_{UUT})		Degrees of freedom
Mean value of voltage difference	V_N	0,079 38	mV	-	-	-	-	-	-	-	-	-	-	-
Corretion due to accuracy of nanovotmeter	$\delta V_{N,spec}$	0		4,40E-02	µV	1,73	2,54E-02	µV	rectangular	1	µV/µV	2,54E-02	µV	∞
Corretion due to resolution of nanovoltmeter	$\delta V_{N,res}$	0		1,00E-02	µV	3,46	2,89E-03	µV	rectangular	1	µV/µV	2,89E-03	µV	∞
Correction due to scattering measurement results (type A)	$\delta V_{N,s}$	0		2,28E-02	µV	1	2,28E-02	µV	normal	1	µV/µV	2,28E-02	µV	5
DC voltage value of reference standard	V_Z	1,018 066	V	-	-	-	-	-	-	-	-	-	-	-
Correction due to environment temperature effect on reference standard	$\delta V_{Z,T}$	0		1,00E-01	µV	1,73	5,77E-02	µV	rectangular	1	V/V	5,77E-02	µV	∞
Correction due to calibration uncertainty of reference standard	$\delta V_{Z,cal}$	0		1,25E-01	µV	2	6,25E-02	µV	normal	1	V/V	6,25E-02	µV	∞
Correction due to noise of reference standard	$\delta V_{Z,noise}$	0		4,00E-01	µV	1,73	2,31E-01	µV	rectangular	1	V/V	2,31E-01	µV	∞
Correction due to drift of reference standard value from its last calibration	$\delta V_{Z,drift}$	0		7,00E-01	µV	1,73	4,04E-01	µV	rectangular	1	V/V	4,04E-01	µV	∞
Estimated value and uncertainty of UUT	V_{UUT}=	1,018 145	±	0,000 001 V			Combined standard uncertainty					0,47	µV	
							Expanded uncertainty (95%)					0,95	µV	
							Relative expanded uncertainty (95%)					0,93	µV/V	
							Effective degrees of freedom, ν_{eff}					945718,59		
							Coverage factor, k					2,00		

Annex C: Reference

[1] CCEM Guidelines for Planning, Organizing, Conducting and Reporting Key, Supplementary and Pilot Comparisons, 2007 (available on the BIPM website: http://www.bipm.org/utils/common/pdf/CC/CCEM/ccem_guidelines.pdf)

[2] Thomas J. Witt, "Key Comparisons in Electricity: Case Studies from the BIPM," APMP TCEM MEETING, 5 September 2005.

[3] K. T. Kim, et al, "APMP Key Comparison of DC voltage at 1.018 V and 10 V," Final Report APMP.EM.BIPM-K11.3, 2017.

[4] M. Maruyama, et al, "APMP Key Comparison of DC voltage at 1.018 V and 10 V," Final Report APMP.EM.BIPM-K11.5, 2016.

[5] F. Liefrink et al, "Comparison of 10 V Electronic Voltage Standards," Final Report: EUROMET project no. 429, September 2002.

[6] J.W. Mueller, "Possible Advantages of a Robust Evaluation of Comparisons," J. Res. Natl. Inst. Stand. Technol. **105**, 551, 2000.

[7] CIPM MRA-D-05 version 1.6, "Measurement comparisons in the CIPM MRA".

[8] Evaluation of measurement data - Guide to the Expression of Uncertainty in Measurement (GUM), JCGM 100, First edition, September 2008 (available on the BIPM website: http://www.bipm.org/utils/common/documents/jcgm/JCGM_100_2008_E.pdf)

[9] C. M. Sutton, "Analysis and linking of international measurement comparison" 2004 Metrologia 41 272