APMP.EM.BIPM-K11.5

APMP Key Comparison of DC Voltage at 10 V and 1.018 V

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Contents

Abstract

A key comparison of DC voltage at 10 V and 1.018 V has been conducted from 2013 to 2014 between NMIJ, CMS and KRISS. In this comparison, PJVS systems were compared via Zener travelling standards. All the results agree well to the key comparison reference values, which are provided by a conventional JVS system at KRISS, within 1 part in 10^7 for 10 V and 2 parts in 10^7 for 1.018 V, respectively.

1. Introduction

During the APMP TCEM meeting, held in Wellington, New Zealand on 23-24 November 2012, CMS (Chinese Taipei) had discussions with NMIJ (Japan) and proposed to organize a key comparison of DC voltage between their new programmable Josephson voltage standards (PJVS) to make a link to a relevant key comparison reference value (KCRV). After further discussions among CMS, NMIJ and KRISS (Republic of Korea), KRISS, who has participated in related BIPM KCs and coordinated the previous APMP KC (APMP.EM.BIPM-K11.3), kindly agreed to participate in the comparison as a coordinator and reference laboratory to support the link to the KCRV. This comparison was approved by the APMP TCEM on May 2013 and declared as APMP.EM.BIPM-K11.5. The same Zener standards as used for the previous K11.3 were provided by NMIJ to be used as travelling standards with additional batteries and known influence coefficients. This KC, APMP.EM.BIPM-K11.5, covers comparison of both 1.018 V and 10 V so the results can be linked to the KCs identified by BIPM.EM-K11.a and K11.b.

2. Participants and organization of the comparison

2.1 List of participants

The measurements of four Josephson systems of the three laboratories contributed to the comparison, as listed in Table 2-1. One of the systems was a conventional Josephson voltage standard (CJVS), which also provided a link to the KCRV, and the others were PJVS.

Table 2-1 List of participants

	Organization	Acronym	State or Economy	System
1	National Metrology Institute of Japan	NMIJ	Japan	PJVS
2	Center for Measurement Standards	CMS	Chinese Taipei	PJVS
3	Korea Research Institute of Standards and Science	KRISS	Republic of Korea	PJVS
4				CJVS

2.2 Comparison schedule

Table 2-2 Comparison schedule

Year	Date of Measurement	Laboratory	System	Country or Economy
2013	17 September – 7 October	KRISS	CJVS[2] System	Republic of Korea
	11 October – 11 November	NMIJ	PJVS[1] System	Japan
	15 November – 16 December	CMS	PJVS[1] System	Chinese Taipei
2014	14 January – 14 February	KRISS	CJVS[2] System	Republic of Korea
	19 June – 15 July	KRISS	PJVS[1] System	Republic of Korea

[1] PJVS : Programmable Josephson Voltage Standard

[2] CJVS : Conventional Josephson Voltage Standard

2.3 Organization of the comparison

The comparison schedule was initially organized with four measurement stages including KRISS (CJVS), NMIJ (PJVS), CMS (PJVS) and KRISS (CJVS). In the midst of the comparison, KRISS (PJVS) was added in the schedule.

A total of four weeks was scheduled for each participant. Generally, participants had at least two weeks and usually three weeks in which to make their measurements, depending on the time taken to receive the artifacts through the customs service in their country and to allow the artifacts to be stabilized with the environment in their laboratory.

The travelling standards, three Zener voltage references (provided by NMIJ) each of which was enclosed in a separate travel case, were transported in a larger wooden case by air cargo using an ATA or SCC carnet for customs where possible. A small thermo-hygro-barometer (provided by NMIJ) was also enclosed in the transport case to monitor the environmental change during the transport.

After the CMS (PJVS) measurement, the travelling standards were temporarily sent back to NMIJ for the refreshment of the carnet because the SCC carnet is only valid between Japan and Chinese Taipei while the ATA carnet is only valid between Japan and Republic of Korea in this circulation.

2.4 Unexpected incidents

2.4.1 Rearrangement of schedule

The comparison schedule of Table 2-2 is a result of several modifications from the original schedule. The PJVS measurement of KRISS was added after the CJVS measurement of KRISS. The circulation was completed in July 2014.

2.4.2 Deviation of the thermistor resistance of the travelling standards

In the middle of the comparison, it was pointed out by a participant (KRISS PJVS) that the thermistor resistance of one of the travelling standards (TZS-3) showed a large discrepancy of approximately 440 Ω to a reference value shown in Table 4-1 (Table I in the protocol), which was originally determined at an environmental temperature of 23 °C. This resulted in a large uncertainty due to the temperature correction of approximately 44 nV even though the measurement is carried out at a room temperature of 23 °C. The thermistor resistance of the standards corresponds to the internal temperature of a heater-controlled oven (~ 40 °C) in which a Zener-diode device is mounted. Therefore, we can speculate two possibilities related to the cause for this discrepancy of the thermistor resistance: one is that the internal temperature of the oven has changed, and the other is that the thermistor properties have changed. These changes might be caused by heat shock, etc., during the transportation of the travelling standards because the ambient temperature, humidity and air-pressure around the standards could be drastically changed during the flight and/or customs, as shown in Figure 2-1, Figure 2-2 and Figure 2-3.

In the former case, the change in the output voltage can be corrected by using the temperature coefficient as listed in Table I in the protocol though a large uncertainty is unavoidable. However, in the latter case, i.e., a change in the thermistor properties happened in the middle of the comparison, we can no longer make an appropriate correction by using the temperature coefficients as listed in Table I in the protocolTable 4-1. In order to verify the consistency of the thermistor properties, the environmental-temperature dependence of the thermistor resistance of the travelling standards has been investigated by a participant (KRISS PJVS), as shown in Figure 2-4. These plots show linear temperature dependences of the thermistor resistance at the time of this measurement. The solid lines denote linear least squares fits for the data, indicating a resistance value of 38.97 kΩ at an environmental-temperature of 23 °C for TZS-3. This value is different by 440 Ω from the reference value of 39.41 kΩ as shown in Table 4-1. In these plots, the thermistor resistance at the time of each participant's measurement that was reported by each participant is plotted against the room temperature of the participating laboratory. It seems that the reported thermistor resistances show no abnormal deviations from the measured dependences and maintain good consistency during the comparison. However, we cannot distinguish between a change of the oven temperature or the thermistor properties from these results. We then decided to directly check the actual values of the temperature coefficient of TZS-3.

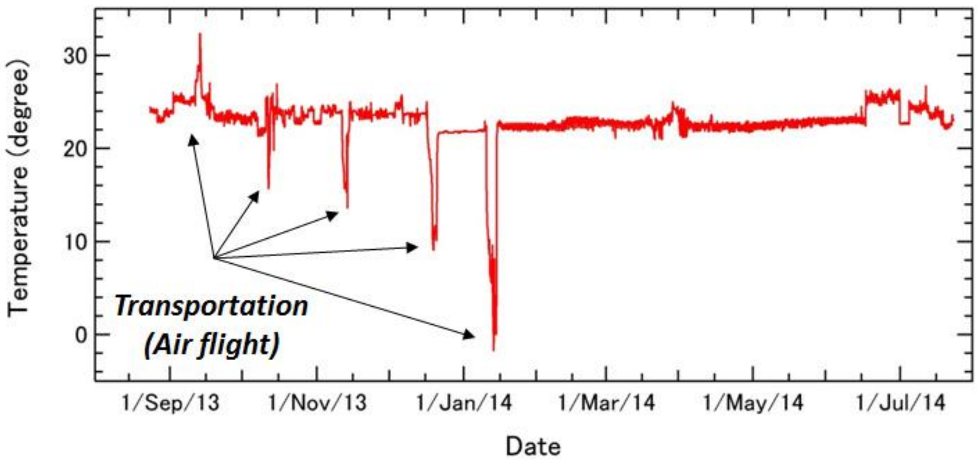


Figure 2-1 Temperature recorded during transportation.

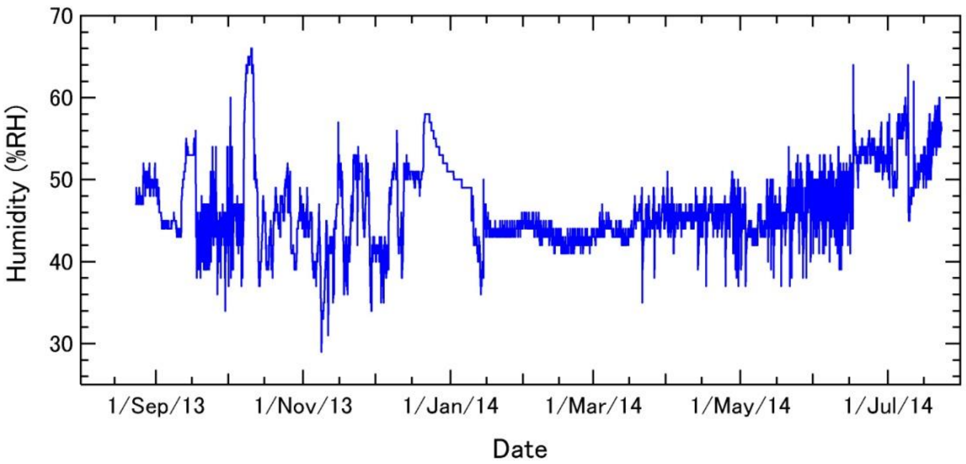


Figure 2-2 Humidity recorded during transportation.

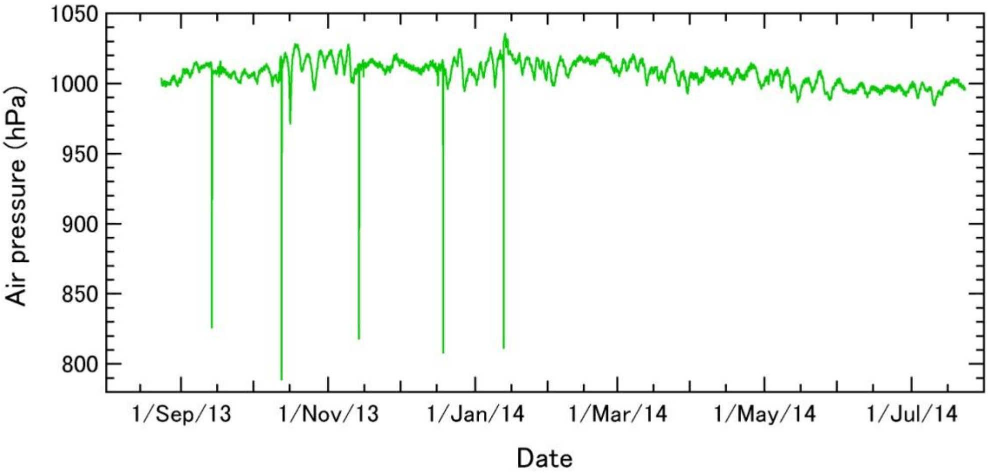


Figure 2-3 Air pressure recorded during transportation.

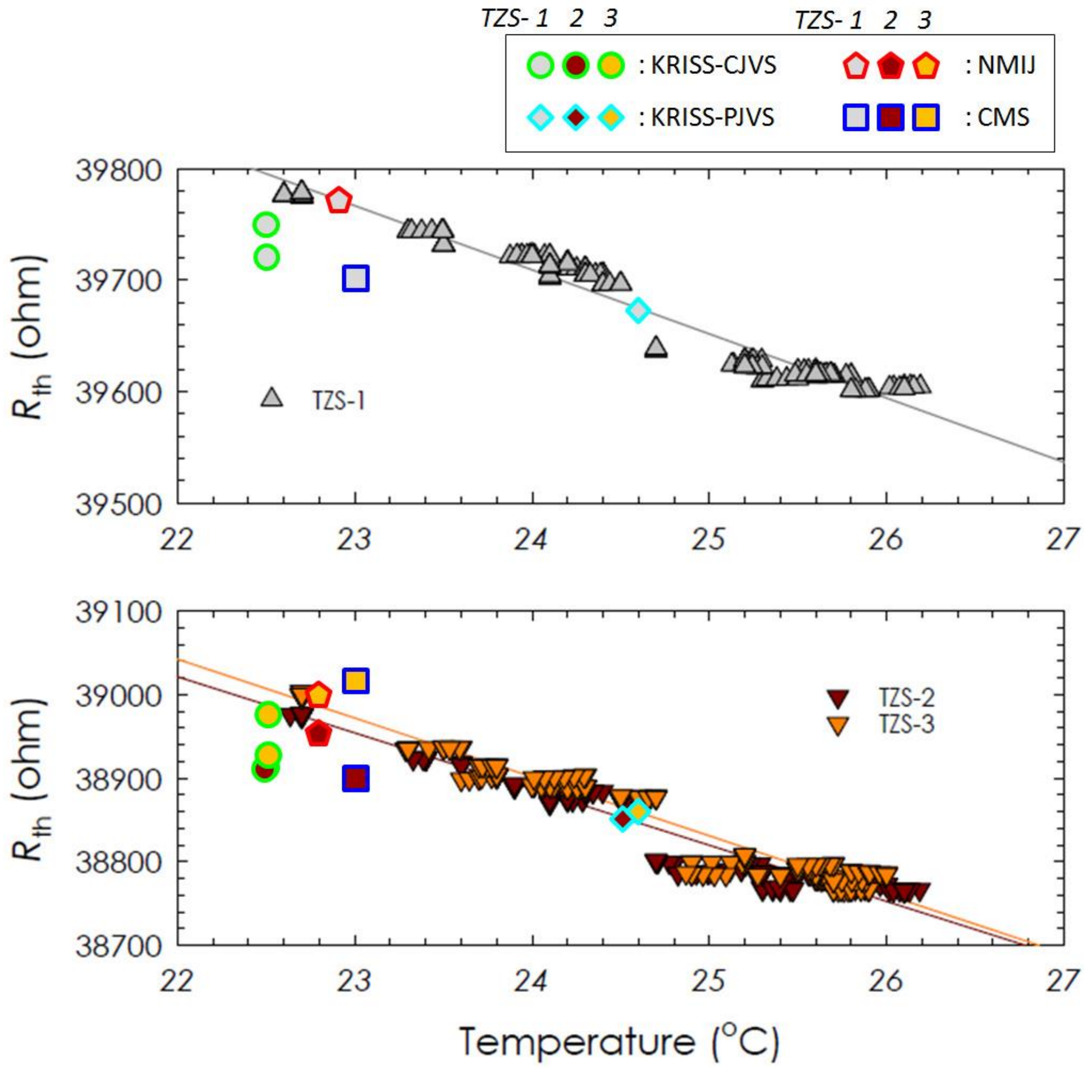


Figure 2-4 Temperature dependence of the thermistor resistance of the travelling standards. The straight lines represent the results of the least-square fitting for the measured data (triangles).

Figures 2-5 and 2-6 show the results of the re-estimation of the temperature dependences of the output voltage of TZS-3. The measurement was carried out in a constant temperature chamber at the pilot laboratory (NMIJ). The ambient temperature was changed as the sequence of 23 °C, 15 °C, 23 °C, 35 °C and 23 °C with keeping the Zener standard at each temperature for approximately 22 hours before each measurement. From Figure 2-6, the present values of the temperature coefficient of TZS-3 is now estimated to (2.0 ± 0.4) nV/Ω and (0.31 ± 0.03) nV/Ω for nominal 10 V and 1.018 V outputs, respectively, where the uncertainties are stated in terms of combined standard uncertainty, i.e., k = 1. These values show some differences from the original values of (1.3 ± 0.1) nV/Ω and (0.20 ± 0.05) nV/Ω for nominal 10 V and 1.018 V outputs, respectively, as listed in Table I in the protocol, suggesting approximately 50 % increases in the temperature coefficients. From these results, we concluded that the thermistor properties might be changed at some point after the former evaluation of the temperature coefficients. Accordingly, we decided to make corrections to the uncertainty values of the temperature coefficients for TZS-3. The revised values of the uncertainty was calculated to be 0.6 nV/Ω and 0.08 nV/Ω for nominal 10 V and 1.018 V outputs, respectively, as shown in Table 4-1, by carrying out the square sum of the uncertainties of the evaluations and the difference between the current and former values of the coefficient, where the difference was treated as a rectangular distribution.

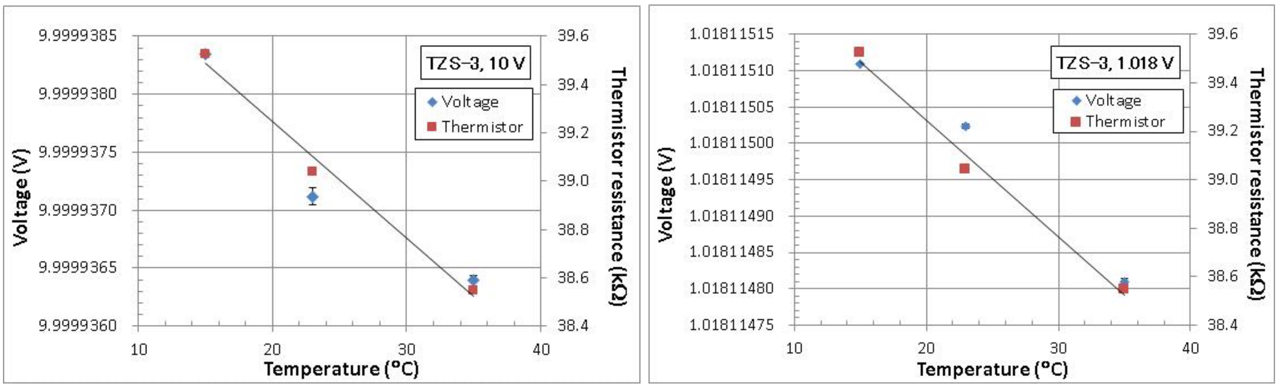


Figure 2-5 Temperature dependences of the output voltage and the thermistor resistance of the traveling standard, TZS-3, re-evaluated in a constant temperature chamber at the pilot laboratory. The error bars indicate standard uncertainty. Solid lines are the least-square-fitting for the data points. The values at 23 °C were obtained as the weighted mean of the two measurement data.

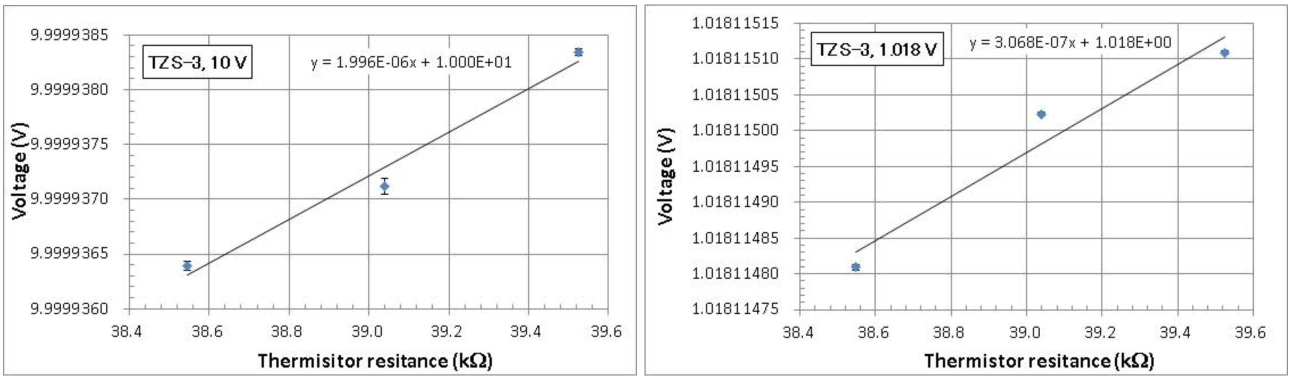


Figure 2-6 Thermistor-resistance dependence of the output voltage of the traveling standard, TZS-3, re-evaluated in a constant temperature chamber at the pilot laboratory. Note that the data are the same as those plotted in Figure 2-5. The error bars indicate standard uncertainty. Solid lines are the least-square-fitting for the data points. The values at 23 °C were obtained as the weighted mean of the two measurement data.

3. Withdrawals of results

Not applicable.

4. Travelling standard and measurement instructions

4.1 Description of the standards

The travelling standards, three Fluke 732B electronic DC reference standards, are identified as follows:

TZS-1	s/n 6950003
TZS-2	s/n 6950002
TZS-3	s/n 6950004

Figure 4-1 An upgrade-box for Fluke 732B with additional batteries inside.

The Fluke 732B electronic DC reference standard has two output voltages, nominally 10 V and 1.018 V, respectively. Within the comparison, both the 10 V and the 1.018 V output will be measured. Each Fluke 732B electronic DC reference standard is fixed in an upgrade-box (18.0 cm x 21.0 cm x 47.0 cm) (Figure 4-1). Two additional batteries are installed inside the upgrade-box. These batteries are used to increase the working time of the internal battery of the Fluke 732B. A BNC type female connector is provided for the measurement of internal thermistor resistance. The total weight of the upgrade box (with Fluke 732B and batteries) is around 14 kg. Each upgrade box is packed in a transportation case (27 cm x 27.5 cm x 55 cm). The two additional batteries are connected in parallel to the original internal battery through MONITOR/EXT BAT IN connectors on rear panel of the 732B. It is possible to recharge all three batteries at the same time by the automatic charging circuit of the Fluke 732B.

4.2 Quantities to be measured and conditions of measurements

For the key comparison, DC voltage outputs 10 V and 1.018 V of the three travelling standards were measured. Since different environmental conditions are used among participating laboratories, appropriate correction of measurement results against temperature, humidity and pressure is necessary. This makes it necessary for us to prepare a set of travelling standards with data on their environmental coefficients. Temperature, humidity and pressure coefficients of the 10 V and 1.018 V outputs and their standard uncertainties are provided by NMIJ who also provided the travelling Zener standards for this KC. The coefficient data are shown in Table 4-1. The measured voltages V_{measured} should be corrected for temperature and pressure effects. The temperature effect is taken into account through the thermistor resistance R. The following formula should be used to calculate the corrected voltages $V_{\mathrm{corrected}}$:

$$V_{\mathrm{corrected}} = V_{\mathrm{measured}} - \alpha_R \cdot (R - R_0) - \alpha_p \cdot (p - p_0) \qquad (1)$$

Here α_R and α_p are the temperature and pressure coefficients as given in Table 4-1, p is the ambient air pressure, and p_0 = 1013.25 hPa the reference atmospheric pressure. The reference thermistor resistances R_0 depend on the specific standard and are also given in the Table. The humidity effect of the Zener standards is known to have very slow time response [1]. In view of time schedule of comparison, the humidity effect will be treated as a drift effect when reference value is calculated by interpolation between reference measurements as in the earlier EUROMET KC [2]. The recommended measurement conditions are 23 °C and 55 % RH or below. Measurements should be carried out with the standard disconnected from the AC line power. To allow the standard to stabilize, measurements should not begin any sooner than 4 hours after disconnecting the standard from the AC line power. Connect the AC line after finishing the measurements to recharge the standards. Carrying out the voltage measurements with the Fluke 732B's disconnected from the AC line power, the CHASSIS (green terminal marked as "GROUND") of the upgrade box should be connected to the guard of the measuring system instead of the internal GUARD binding post of the Fluke 732B. At one point in the measurement system the guard should be connected to ground.

4.3 Measurement instructions

After arrival in the participant's laboratory, the standards should be allowed to stabilize in a temperature and, possibly, humidity controlled room for at least four days before the measurements can begin. The travelling standard should be handled carefully and be stored in a stabilized environment where relative humidity should be below 55 %. The internal thermistor resistance must be reported for each measurement result for each output voltage. The thermistor resistances of the standards have nominal values between 38 kΩ and 40 kΩ (see Table 4-1). To avoid heating of the thermistor, the test current should not exceed 10 μA. This implies that in most DMMs it may be necessary to use a much higher range than the 100 kΩ range, and the auto-range setting should be avoided. The small thermo-hygrometer (data logger) in the transit case, which records the environmental temperature and humidity during transport and stay at the participant's laboratory, should not be used to measure the environmental conditions during the measurement. Participating laboratories should use their own instrument for precise measurement of the environmental conditions. When not carrying out measurements, the standards must be connected continuously to the AC line power. Measurements can be carried out after full charge, i.e., after the charge indicator turns off.

Table 4-1 Temperature, humidity and pressure coefficients of 10 V and 1.018 V outputs

Voltage	Standard	Reference thermistor resistance at R_0 (kΩ)	Temperature coefficient α_R (nV Ω^{-1})	Humidity coefficient α_H (nV %RH^{-1})	Pressure coefficient α_p (nV hPa^{-1})
10 V	TZS-1	39.65	4.3 ± 1.3	<15	17.8 ± 0.7
	TZS-2	39.04	1.9 ± 0.2	<15	16.5 ± 0.5
	TZS-3	39.41	1.3 ± 0.6	<15	21.3 ± 1.1
1.018 V	TZS-1	39.65	0.25 ± 0.03	<1	2.04 ± 0.02
	TZS-2	39.04	0.24 ± 0.07	<1	1.43 ± 0.03
	TZS-3	39.41	0.20 ± 0.08	<1	2.14 ± 0.18

(The uncertainties are stated in terms of combined standard uncertainty, 1 sigma.)

(The uncertainties of the temperature coefficients for TZS-3 were changed (increased) from the values listed in Table I in the protocol, as described in Secs. 2.4.2 and 4.4.)

4.4 Deviations from the protocol

The revised values of the uncertainty of the temperature coefficients for TZS-3 as shown in Table 4-1 were employed in place of the original values as listed in Table I in the protocol for the reason as explained in Sec. 2.4.2.

5. Methods of measurement and traceability

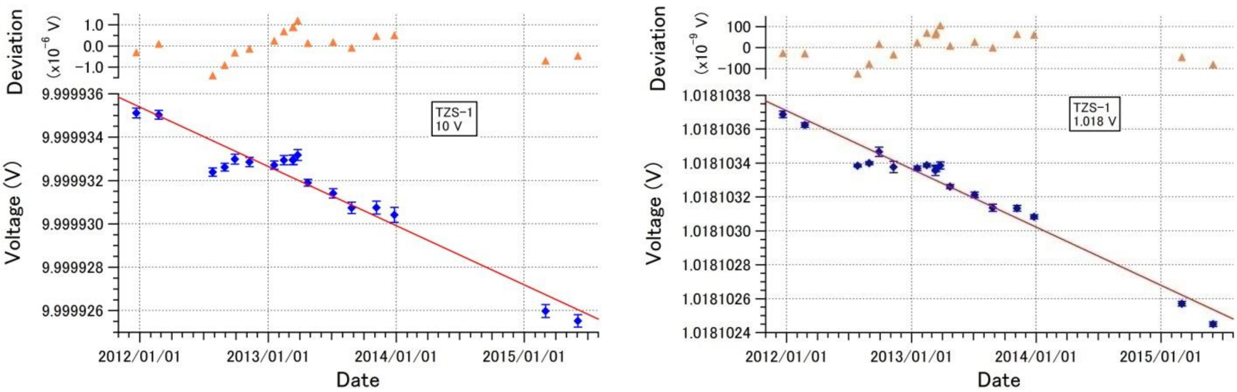
All the participants were using Josephson voltage standard for the measurements. Therefore each participant's measurement results are traceable to their own standard not to any other laboratory's. Further details of the measurement systems are given in *Appendix B*.

6. Measurements of the pilot laboratory

Measurements made by the pilot laboratory were used to estimate the short-term stability of the travelling standards, i.e., the day-by-day variation of the output voltage of each of the travelling standards. In order to assess only the instability with time, corrections for temperature and pressure effects were applied to all the measurement results. The estimated short-term stability was included in the uncertainty of the reference values.

6.1 Stability of the travelling standards

Measurements made by the pilot laboratory for each travelling standard at 10 V and 1.018 V are shown in Figure 6-1. The data were obtained from December 2011 to June 2015 (3.5 years) using a conventional CJVS system at NMIJ. All the data are represented after the correction of the local temperature and pressure effects. The least-square-fitting lines and the standard deviations of the data points from the fitting lines obtained from the figures are listed in Table 6-1. These results suggested that for 10 V outputs the travelling standards have decreasing drift characteristics with slopes about –8 nV/day or –0.4 nV/day and a day-by-day variation of about 400 nV to 700 nV. For 1.018 V outputs the drift characteristics are slopes of (–1, 0 or +1.5) nV/day and day-by-day variation of about 40 nV to 60 nV. The obtained day-by-day variations, i.e., the standard deviation of the data points from the fitting lines will be treated as the uncertainty contribution due to nonlinear deviation from the interpolated reference values, as represented as ΔV_Z in (2).



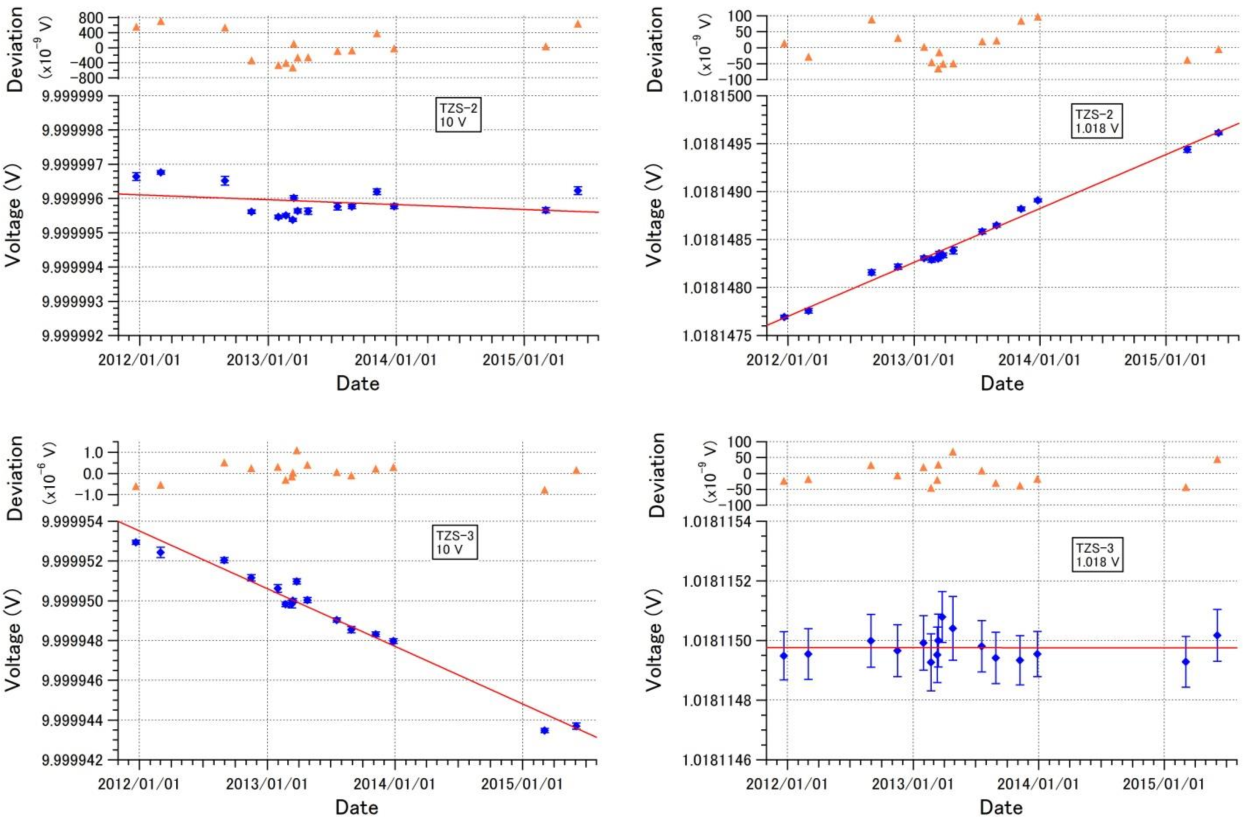


Figure 6-1 Repeated measurements by using a conventional CJVS of the pilot laboratory of 1.018 V and 10 V outputs from the three travelling standards. Error bars represent the expanded uncertainties of the measurements. Solid lines are the least-square-fitting for the data points. The upper insets show the deviation of the data points from the fitting lines.

Table 6-1 The least-square-fitting lines and the day-by-day variations obtained from Figure 6-1.

Voltage	Standard	Slope of fitting line (nV/day)	Intercept of fitting line (@Nov. 1, 2011) (V)	**Standard deviation from fitting line (nV)**	Degrees of freedom
10 V	TZS-1	–7.482	9.999 935 848	**673.5**	17
	TZS-2	–0.3911	9.999 996 135	**414.8**	15
	TZS-3	–7.941	9.999 953 994	**466.4**	15
1.018 V	TZS-1	–0.9408	1.018 103 767	**62.4**	17
	TZS-2	1.540	1.018 147 605	**51.6**	15
	TZS-3	–0.0004	1.018 114 976	**43.0**	15

7. Measurement results

7.1 Mathematical model

The participants were requested to report both the original result and the corrected result to allow the pilot to double-check the calculation. Participants' measurement for k-th Zener at the time of the i-th participant, after being corrected to account for the environmental conditions, $x_{k,i}$ is normalized by subtracting the reference value for the travelling standard, $q_{k,i}$, which is given by the interpolation as described in section 7.3 for the Zener,

$$d_{k,i} = V^{x}_{\mathrm{corrected},k,i} - \mathrm{V}^{\mathrm{ref}}_{\mathrm{corrected},k,i} + \Delta V_{\mathrm{Z}} = x_{k,i} - q_{k,i} + z_k \qquad (2)$$

Here we introduced the nonlinear deviation of the travelling standards as z_k ($= \Delta V_{\mathrm{Z}}$) for the purpose of uncertainty expression only, as the expectation value would be zero. All the $d_{k,i}$ are averaged over all Zeners by a weighted mean to obtain the averaged normalized result of the i-th participant, d_i,

$$d_i = \frac{\sum_{k=1}^{3} w_k d_{k,i}}{\sum_k w_k} \qquad (3)$$

For the weighting factor, we used w_k as given by;

$$w_k = 1/u^2(d_{k,i}) = 1/\{u^2(x_{k,i}) + u^2(q_{k,i}) + u^2(z_k)\}, \qquad (4)$$

where the standard uncertainty for the weighted mean, $u(d_{k,i})$ is expressed as the sum of squares of $u(x_{k,i})$, $u(q_{k,i})$ and $u(z_k)$. Then the uncertainty of d_i, is calculated by

$$u^2(d_i) = 1/\textstyle\sum_k w_k \qquad (5)$$

The uncertainty of the normalized value of the participant for the k-th Zener, $u(d_{k,i})$, which appears in (4), may be calculated with eliminating the uncertainties of the temperature and pressure corrections, which appear in (1), because the corrections are made for both the participant's results and the reference values. Thus when we calculate the difference between the participant's results and the reference values, the uncertainty component can be correlated because the coefficients are always the same for both results. However, it is difficult to eliminate the effect of the corrections from the reference values because these are obtained by fitting all the participant's data points that already include corrections. The sum of the uncertainties related to the terms in (2), which include the uncertainties of the temperature and pressure coefficients, is employed here for simplicity of the calculation. In (4), we added the additional contribution of the $u(z_k)$, the random instability of the travelling standard for which the uncertainties are given by Table 6-1. A summary of the participants' results calculated by (2)–(5) is described in the next section.

7.2 Results of the participating institutes

The participants' final results are shown in the following tables. It should be noted that KRISS-CJVS has multiple participation data. For this laboratory, the first participation results were arbitrarily taken as its representative result. See the next section for the calculation of the reference values based on least-squares-fitting for all the participant's data.

7.2.1 10 V results

Table 7-1 Results of participating laboratories for the 10 V TZS1. See text for definition of symbols.

i	Participant	Date	Participant		Reference (See section 7.3.)		Stability	Difference	
			$x_{1,i}$ – 10 V	$u(x_{1,i})$	$q_{1,i}$ – 10 V	$u(q_{1,i})$	$u(z_1)$	$d_{1,i}$	$u(d_{1,i}) = w_1^{-1/2}$
		mm/dd/yy	μV	μV	μV	μV	μV	μV	μV
1	KRISS/CJVS	10/01/13	–69.594	0.168	–68.879	0.168	0.674	–0.715	0.714
2	NMIJ	10/24/13	–69.286	0.155	–69.167	0.168	0.674	–0.119	0.711
3	CMS	11/29/13	–69.214	0.124	–69.618	0.168	0.674	0.404	0.705
4	KRISS/CJVS	02/12/14	–70.181	0.145	–70.558	0.168	0.674	0.377	0.709
5	KRISS/PJVS	07/02/14	–72.370	0.064	–72.313	0.168	0.674	–0.057	0.697

Table 7-2 Results of participating laboratories for the 10 V TZS2. See text for definition of symbols.

i	Participant	Date	Participant		Reference (See section 7.3.)		Stability	Difference	
			$x_{2,i}$ – 10 V	$u(x_{2,i})$	$q_{2,i}$ – 10 V	$u(q_{2,i})$	$u(z_2)$	$d_{2,i}$	$u(d_{2,i}) = w_2^{-1/2}$
		mm/dd/yy	μV	μV	μV	μV	μV	μV	μV
1	KRISS/CJVS	10/01/13	–3.707	0.051	–3.563	0.072	0.415	–0.144	0.424
2	NMIJ	10/24/13	–3.554	0.030	–3.645	0.072	0.415	0.091	0.422
3	CMS	11/29/13	–4.043	0.091	–3.774	0.072	0.415	–0.269	0.431
4	KRISS/CJVS	02/12/14	–4.213	0.087	–4.042	0.072	0.415	–0.171	0.430
5	KRISS/PJVS	07/02/14	–4.500	0.068	–4.544	0.072	0.415	0.044	0.426

Table 7-3 Results of participating laboratories for the 10 V TZS3. See text for definition of symbols.

i	Participant	Date	Participant		Reference (See section 7.3.)		Stability	Difference	
			$x_{3,i}$ – 10 V	$u(x_{3,i})$	$q_{3,i}$ – 10 V	$u(q_{3,i})$	$u(z_3)$	$d_{3,i}$	$u(d_{1,i}) = w_3^{-1/2}$
		mm/dd/yy	μV	μV	μV	μV	μV	μV	μV
1	KRISS/CJVS	10/01/13	–51.639	0.261	–51.509	0.076	0.466	–0.130	0.540

2	NMIJ	10/24/13	−51.500	0.246	−51.689	0.076	0.466	0.189	0.533
3	CMS	11/29/13	−52.120	0.330	−51.973	0.076	0.466	−0.148	0.576
4	KRISS/CJVS	02/12/14	−52.547	0.300	−52.562	0.076	0.466	−0.015	0.560
5	KRISS/PJVS	07/02/14	−53.670	0.340	−53.663	0.076	0.466	−0.007	0.582

7.2.2 1.018 V results

Table 7-4 Results of participating laboratories for the 1.018 V TZS1. See text for definition of symbols.

i	Participant	Date	Participant		Reference (See section 7.3.)		Stability	Difference	
			$x_{1,i}-$ 1.018 V	$u(x_{1,i})$	$q_{1,i}-$ 1.018 V	$u(q_{1,i})$	$u(z_1)$	$d_{1,i}$	$u(d_{1,i}) = w_1^{-1/2}$
		mm/dd/yy	μV	μV	μV	μV	μV	μV	μV
1	KRISS/CJVS	09/29/13	103.108	0.013	103.151	0.010	0.062	−0.043	0.064
2	NMIJ	10/24/13	103.119	0.006	103.119	0.010	0.062	0.000	0.063
3	CMS	11/29/13	103.149	0.027	103.074	0.010	0.062	0.075	0.069
4	KRISS/CJVS	02/12/14	102.994	0.006	102.978	0.010	0.062	0.016	0.063
5	KRISS/PJVS	07/02/14	102.794	0.006	102.800	0.010	0.062	−0.006	0.063

Table 7-5 Results of participating laboratories for the 1.018 V TZS2. See text for definition of symbols.

i	Participant	Date	Participant		Reference (See section 7.3.)		Stability	Difference	
			$x_{2,i}-$ 1.018 V	$u(x_{2,i})$	$q_{2,i}-$ 1.018 V	$u(q_{2,i})$	$u(z_2)$	$d_{2,i}$	$u(d_{2,i}) = w_2^{-1/2}$
		mm/dd/yy	μV	μV	μV	μV	μV	μV	μV
1	KRISS/CJVS	09/29/13	148.822	0.018	148.806	0.017	0.052	0.016	0.057
2	NMIJ	10/24/13	148.839	0.009	148.834	0.017	0.052	0.005	0.055
3	CMS	11/29/13	148.893	0.032	148.874	0.017	0.052	0.019	0.063
4	KRISS/CJVS	02/12/14	148.904	0.015	148.959	0.017	0.052	−0.055	0.056
5	KRISS/PJVS	07/02/14	149.161	0.021	149.117	0.017	0.052	0.044	0.058

Table 7-6 Results of participating laboratories for the 1.018 V TZS3. See text for definition of symbols.

i	Participant	Date	Participant		Reference (See section 7.3.)		Stability	Difference	
			$x_{3,i}$ – 1.018 V	$u(x_{3,i})$	$q_{3,i}$ – 1.018 V	$u(q_{3,i})$	$u(z_3)$	$d_{3,i}$	$u(d_{3,i}) = w_3^{-1/2}$
		mm/dd/yy	μV	μV	μV	μV	μV	μV	μV
1	KRISS/CJVS	09/29/13	114.988	0.048	114.958	0.011	0.043	0.030	0.065
2	NMIJ	10/24/13	114.945	0.042	114.962	0.011	0.043	–0.017	0.061
3	CMS	11/29/13	114.947	0.058	114.968	0.011	0.043	–0.021	0.073
4	KRISS/CJVS	02/12/14	114.981	0.049	114.980	0.011	0.043	0.001	0.066
5	KRISS/PJVS	07/02/14	115.008	0.056	115.003	0.011	0.043	0.005	0.071

7.2.3 Summary of 10 V and 1.018 V results

The weighted mean of the normalized results over the three Zeners and the uncertainty for 10 V and 1.018 V as described in (3), (4) and (5) are summarized in Table 7-7.

Table 7-7 Averaged results of participating laboratories for the three TZS's. See text for definition of symbols.

i	Participant	Date	10 V		1.018 V	
			d_i	$u(d_i)$	d_i	$u(d_i)$
		mm/dd/yy	μV	μV	μV	μV
1	KRISS/CJVS	09/30/13	–0.242	0.302	0.002	0.036
2	NMIJ	10/24/13	0.085	0.300	–0.003	0.034
3	CMS	11/29/13	–0.104	0.310	0.026	0.039
4	KRISS/CJVS	02/12/14	–0.012	0.307	–0.016	0.036
5	KRISS/PJVS	07/02/14	0.010	0.308	0.017	0.037

7.3 Calculation of the reference value based on least-squares fitting

The reference values are calculated by interpolation of the linear fits that are obtained by weighted least-squares-fitting for the participant's data, with the assumption of the linear drift of the output voltage of the travelling standards, as shown in Figure 7-1.

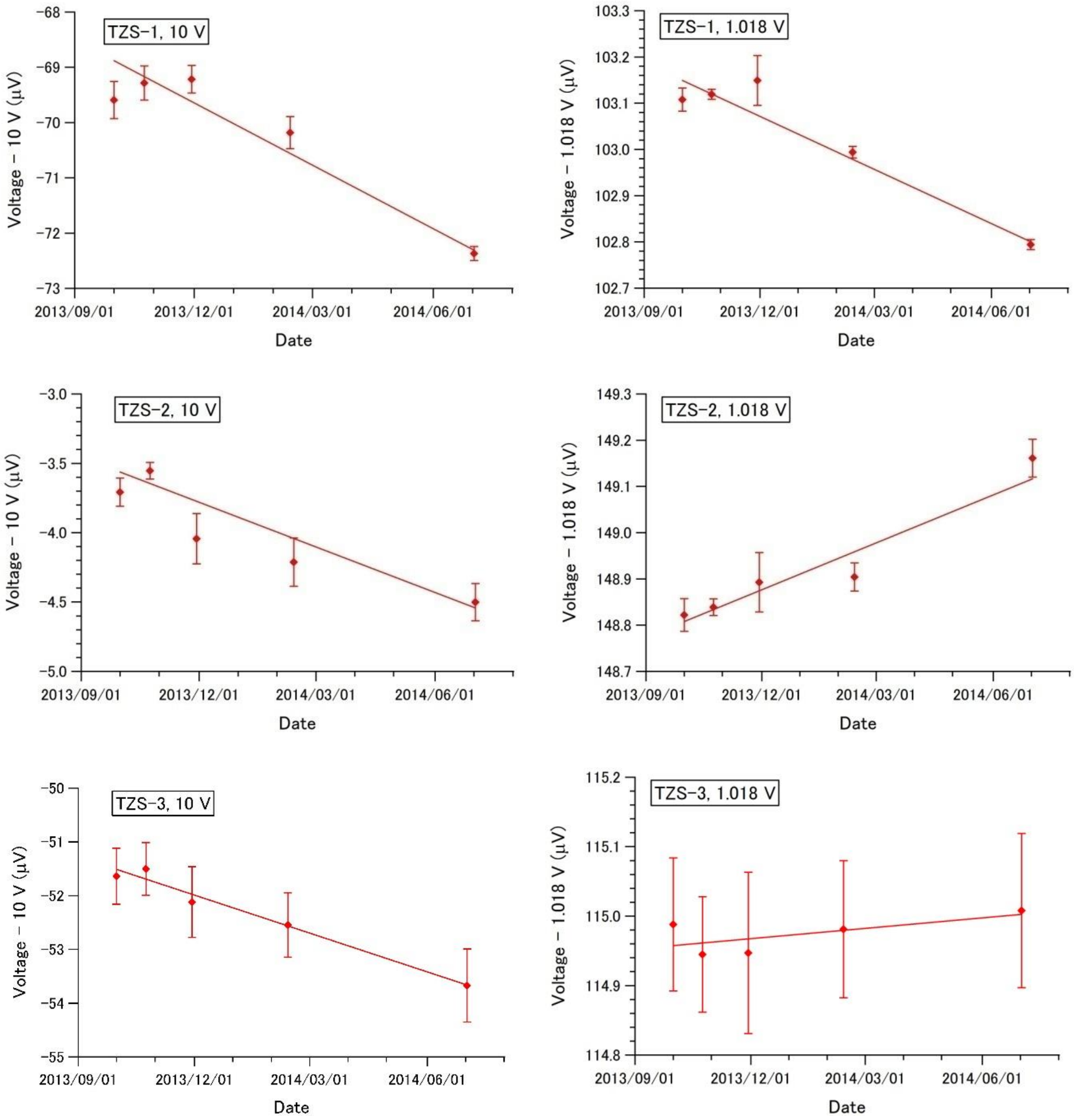


Figure 7-1 Calculation of the reference values based on the least-square-fitting for the participant's data. Error bars represent the expanded uncertainty of the participant's data.

The fitting lines are expressed as

$$V^{\mathrm{ref}} = a\, t + b, \tag{6}$$

where t represents time, and a and b are the fitting parameters. The standard uncertainty of each participant's data point, $u(x_{k,i})$, is used for the weighting factor as $1/u^2(x_{k,i})$. Once the fitting parameters are fixed, the standard uncertainty of the fitting, $u(q_{k,i})$, is obtained as the deviation of the data points from the fitting line as

$$u^2(q_{k,i}) = \sum_{i=1}^{5} \left\{ \frac{x_{k,i} - [a\, t(i) + b]}{u(x_{k,i})} \right\}^2 / \left[(5-2) \sum_{i=1}^{5} u^{-2}(x_{k,i}) \right]. \tag{7}$$

The obtained fitting parameters are summarized in Table 7-8

Table 7-8 Results of the weighted least-square fitting for the participant's data.

k	Standard	10 V				1.018 V			
		Slope a	Intercept b (@Jan. 1, 1990)	$u(q_{k,i})$	Degrees of freedom	Slope a	Intercept b (@Jan. 1, 1990)	$u(q_{k,i})$	Degrees of freedom
		nV/day	μV	μV		nV/day	μV	μV	
1	TZS1	–12.531	433.457	**0.168**	3	–1.2720	154.14	**0.010**	3
2	TZS2	–3.5791	139.908	**0.072**	3	1.1276	103.607	**0.017**	3
3	TZS3	–7.8629	263.684	**0.076**	3	0.16310	108.420	**0.011**	3

7.4 Calculation of the APMP comparison reference value and its uncertainty

The APMP comparison reference values (CRVs) and their uncertainties which are calculated by the weighted mean over all the participants' results should be checked before accepting them with respect to their consistency. We followed a statistical validation process suggested by [3]. The summary of the validation process is shown in Table 7-9.

Table 7-9 Grand average over all participants' results for CRV calculation.

Parameter	Description	10 V		1.018 V	
		Value	Standard uncertainty	Value	Standard uncertainty
		μV	μV	μV	μV
$<d>$, $u(<d>)$	Weighted mean	–0.052	0.137	0.004	0.016
Parameter	Description	Value	Remark	Value	Remark
χ^2_{obs}	$\sum_{i=1}^{5}\left(\frac{d_i-<d>}{u_i}\right)^2$	0.69	-	0.82	-
ν	$N-1$	4	DOF	4	DOF
$P(\chi^2 > \chi^2_{\text{obs}})$	χ^2 probability	95.3 %	> 5 %, Consistency not failed	93.6 %	> 5 %, Consistency not failed

As we see in the table, both for 10 V and 1.018 V, the weighted mean did not fail the consistency check, and may be accepted as the CRV. The finally accepted CRV's denoted by d_{ref} are summarized in Table 7-10.

Table 7-10 APMP comparison reference value (CRV) calculation result.

10 V		1.018 V	
d_{ref}	$u\ (d_{ref})$	d_{ref}	$u\ (d_{ref})$
μV	μV	μV	μV
–0.052	0.137	0.004	0.016
Remark		Remark	
Weighted mean		Weighted mean	

7.5 Degrees of equivalence

7.5.1 Degrees of equivalence of participants to comparison reference values

The regional metrology organization (RMO) degrees of equivalence (DOE) of the i-th participant with respect to the comparison reference value (CRV), D_i^{R} is calculated as

$$D_i^{\mathrm{R}} = d_i - d_{\mathrm{ref}}. \tag{8}$$

The expanded uncertainty associated with this result, $U(D_i^{\mathrm{R}})$, is then $U(D_i^{\mathrm{R}}) = 2 \cdot u(D_i^{\mathrm{R}})$, where the coverage factor 2 is chosen to give approximately 95 % confidence level. The standard uncertainty of the DOE is given by (9) taking the correlation between $u(d_i)$ and $u(d_{\mathrm{ref}})$ into account.

$$u\left(D_i^{\mathrm{R}}\right) = \sqrt{u^2(d_i) - u^2(d_{\mathrm{ref}})} \tag{9}$$

The degrees of equivalence of the participating institutes relative to the comparison reference values are tabulated in Table 7-11 and represented graphically in Figure 7-2 and Figure 7-3.

Table 7-11 Degrees of equivalence of the participating institutes relative to the comparison reference values.

i	Participant	RMO DOE at 10 V		RMO DOE at 1.018 V	
		D_i^{R}	$u(D_i^{\mathrm{R}})$	D_i^{R}	$u(D_i^{\mathrm{R}})$
		μV	μV	μV	μV
1	KRISS/CJVS	–0.190	0.270	–0.002	0.032
2	NMIJ	0.137	0.267	–0.007	0.030
3	CMS	–0.051	0.278	0.022	0.036
5	KRISS/PJVS	0.062	0.277	0.013	0.033

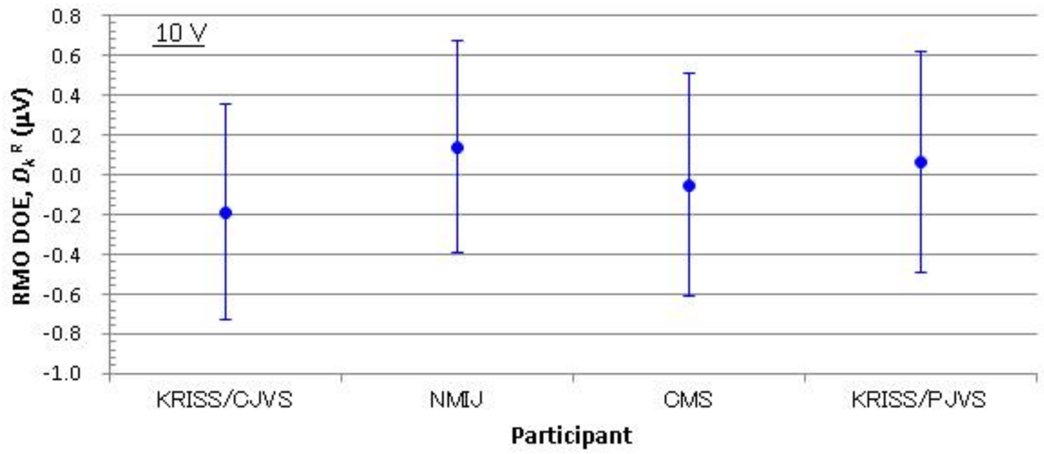


Figure 7-2 Degrees of equivalence D_i^R of the participating institutes (listed in participation order) at 10 V with respect to the comparison reference value. Error bars represent the expanded uncertainty $U(D_i^R)$.

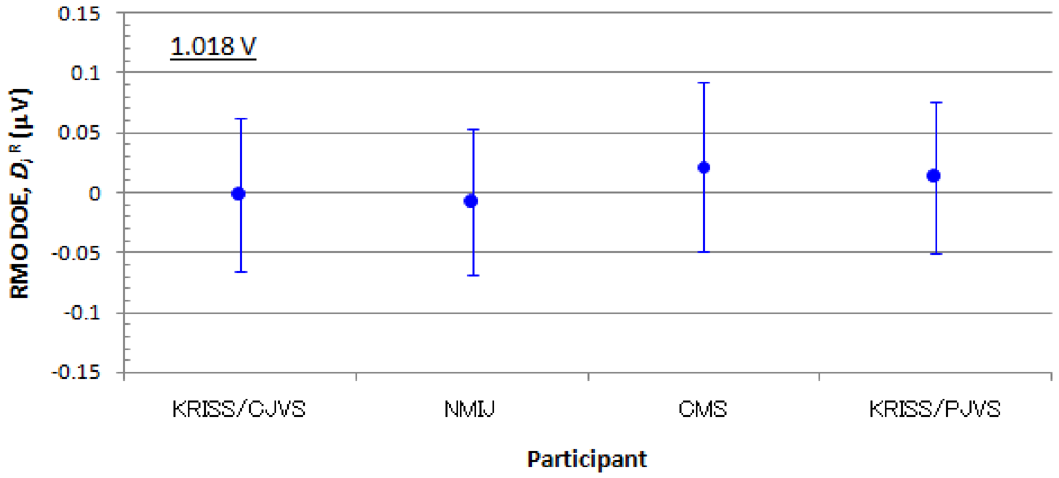


Figure 7-3 Degrees of equivalence D_i^R of the participating institutes (listed in participation order) at 1.018 V with respect to the comparison reference value. Error bars represent the expanded uncertainty $U(D_i^R)$.

7.5.2 Pair-wise degrees of equivalence

Pair-wise degrees of equivalence of the participating institutes are calculated as

$$D_{i,j} = d_i - d_j = x_i - q_i - (x_j - q_j). \qquad (10)$$

In calculating the uncertainty associated with this result, correlations between d_i and d_j are negligible, thus the standard uncertainty $u(D_{i,j})$ is as follows.

$$u(D_{i,j}) = \sqrt{u^2(d_i) + u^2(d_j)} \qquad (11)$$

The expanded uncertainty is calculated as $U(D_{i,j}) = 2 \cdot u(D_{i,j})$. For further details of the calculation of the pair-wise degrees of equivalence, refer to *Appendix A*.

8. Proposal for linking to BIPM.EM-K11 key comparison and degrees of equivalence

The results of APMP.EM.BIPM-K11.5 can be linked to BIPM.EM-K11.a and K11.b using a method similar to that used to link EUROMET.EM.BIPM-K11.b to BIPM.EM-K11.b (see D. Reymann [4]). The link is computed using the results of the KRISS CJVS measurements. The links to the BIPM.EM-K11.a and K11.b are for 1.018 V and 10 V, respectively. It should be noted that, in this comparison, KRISS-CJVS is regarded as not only the linking laboratory but also one of the participants. For this laboratory, the first participation results were arbitrarily taken as its representative result, as mentioned in section 7-2. The reason why KRISS inserted two entries of different primary standards (CJVS and PJVS) is that it is a transition period from CJVS to PJVS and we consider that it is meaningful to equally compare them in this circulation.

8.1 Calculation of linking correction for CRV with respect to KCRV

Let CRV be denoted for the reference vale of this RMO comparison and KCRV for the reference value of the BIPM.EM-K11, and Δ be the difference, CRV – KCRV. The difference Δ is calculated on the basis of the results of the linking laboratory as follows.

D_{i_L}, $d_{i\_\mathrm{L}}{}^{0}$: Results of BIPM.EM-K11 for a linking laboratory

$D_{i\_\mathrm{L}}{}^{\mathrm{R}}$, d_{i_L} : Results of this RMO comparison for a linking laboratory

D_i : DOE of i-th participant with respect to the BIPM.EM-K11 KCRV

Δ_{i_L} : Difference defined by (12),

$$\Delta_{i\_\mathrm{L}} = D_{i\_\mathrm{L}} - D_{i\_\mathrm{L}}{}^{\mathrm{R}} = (d_{i\_\mathrm{L}}{}^{0} - \mathrm{KCRV}) - (d_{i\_\mathrm{L}} - \mathrm{CRV}). \qquad (12)$$

Measurements from the linking laboratory provide the estimates of Δ_{i_L} for the linking correction Δ, which are equivalent to CRV – KCRV. The correction Δ is then calculated as the weighted mean of the estimates of the linking laboratory, that is:

$$\Delta = \frac{\sum_{i\_\mathrm{L}=1}^{2} w_{i\_\mathrm{L}} \Delta_{i\_\mathrm{L}}}{\sum_{i\_\mathrm{L}=1}^{2} w_{i\_\mathrm{L}}}, \qquad (13)$$

where

$$w_{i\_\mathrm{L}} = \frac{1}{u^2(\Delta_{i\_\mathrm{L}})} \quad \text{and} \quad u^2(\Delta) = \frac{1}{\sum_{i\_\mathrm{L}=1}^{2} u^2(w_{i\_\mathrm{L}})}. \qquad (14)$$

The uncertainty, $u(\Delta_{i\_\mathrm{L}})$ associated with $D_{i\_\mathrm{L}} - D_{i\_\mathrm{L}}{}^{\mathrm{R}}$ is calculated by (15),

$$u^2(\Delta_{i\_\mathrm{L}}) = u^2(D_{i\_\mathrm{L}}^{\mathrm{R}}) + u^2(D_{i\_\mathrm{L}}). \qquad (15)$$

The calculation results for Δ is summarized in Table 8-1 and Table 8-2.

Table 8-1 Summary of calculation results for the linking correction Δ for 10 V. All quantities are in μV unit, and the uncertainties are standard estimates (1 sigma).

i	Linking Lab.	Date	10 V					
			D_{i_L}	$u(D_{i\_\mathrm{L}})$	$D_{i\_\mathrm{L}}{}^{\mathrm{R}}$	$u(D_{i\_\mathrm{L}}{}^{\mathrm{R}})$	Δ_{i_L}	$u(\Delta_{i\_\mathrm{L}})$

1	KRISS	10/01/13	–0.030	0.100	–0.190	0.270	0.160	0.287
2	KRISS	02/12/14			0.041	0.275	–0.071	0.293
Weighted mean, Δ							**0.047**	
Standard uncertainty, u (Δ)							**0.205**	

Table 8-2 Summary of calculation results for the linking correction Δ for 1.018 V. All quantities are in μV unit, and the uncertainties are standard estimates (1 sigma).

i	Linking Lab.	Date	1.018 V					
			D_{i_L}	$u\,(D_{i\_L})$	$D_{i\_L}^{R}$	$u\,(D_{i\_L}^{R})$	Δ_{i_L}	$u\,(\Delta_{i\_L})$
1	KRISS	09/29/13	0.070	0.050	–0.002	0.032	0.072	0.059
2	KRISS	02/12/14			–0.020	0.032	0.090	0.059
Weighted mean, Δ							**0.081**	
Standard uncertainty, u (Δ)							**0.042**	

8.2 Degrees of equivalence with respect to BIPM.EM-K11 reference value

The degrees of equivalence with respect to the KCRV of BIPM.EM.K11 for each participant of this comparison are then calculated by (16).

$$D_i = D_i^{R} + \Delta, \tag{16}$$

where the D_i^{R} values are given in Table 7-11. The uncertainty for $u(D_i)$ is calculated by (17).

$$u^2(D_i) = u^2\left(D_i^{R}\right) + u^2(\Delta) \tag{17}$$

The degrees of equivalence for each participant with respect to BIPM.EM.K11 KCRV are summarized in Table 8-3, Figure 8-1 and Figure 8-2.

Table 8-3 Degrees of equivalence of the participating institutes relative to the BIPM.EM-K11 KCRV.

i	Participant	KCRV DOE at 10 V		KCRV DOE at 1.018 V	
		D_i	$u(D_i)$	D_i	$u(D_i)$
		μV	μV	μV	μV
1	KRISS/CJVS	–0.143	0.339	0.079	0.053
2	NMIJ	0.184	0.337	0.074	0.052
3	CMS	–0.005	0.346	0.103	0.055
5	KRISS/PJVS	0.109	0.344	0.094	0.053

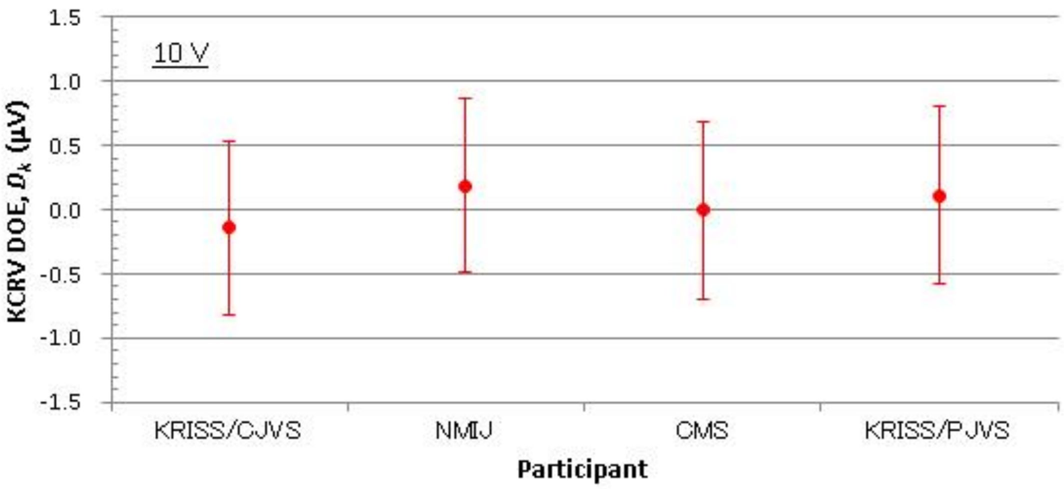


Figure 8-1 Degrees of equivalence D_i of the participating institutes (listed in participation order) at 10 V with respect to the BIPM.EM-K11.b KCRV. Error bars represent the expanded uncertainty $U(D_i)$.

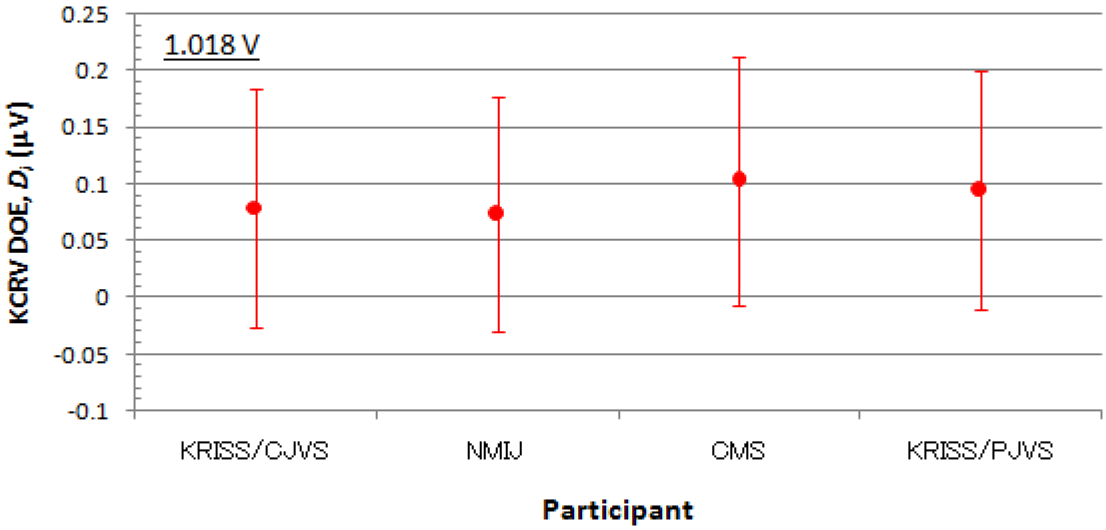


Figure 8-2 Degrees of equivalence D_i of the participating institutes (listed in participation order) at 1.018 V with respect to the BIPM.EM-K11.a KCRV. Error bars represent the expanded uncertainty $U(D_i)$.

8.3 Pair-wise degrees of equivalence

The pair-wise DOE, $D_{i,j}$, does not depend on the reference values because it is a difference between laboratories i and j. Thus existing degrees of equivalence of *Appendix A* will commonly stand for both DOEs of RMO CRV and BIPM KCRV.

9. Summary and conclusions

9.1 Summary

The key comparisons of DC voltage at 10 V and 1.018 V have been conducted between participating APMP member laboratories. In general, there is good agreement between participating laboratories in the region for both quantities. The consistency test with χ^2 probability does not fail either for 10 V or 1.018 V. The measurement results are tabulated in Table 7-7, with which the RMO comparison reference value (CRV) was calculated as Table 7-10. The degrees of equivalence with respect to CRV were tabulated in Table 7-11, and represented graphically in Figure 7-2 and Figure 7-3.

9.2 Link to the BIPM KC

The linking correction, the difference between CRV and BIPM.EM-K11 reference value (KCRV), was calculated on the basis of a linking laboratory as described in section 8.1. The degrees of equivalence with respect to the KCRV were tabulated in Table 8-3, and represented graphically in Figure 8-1 and Figure 8-2. It is expected that this comparison will be able to provide support for participants' entries in the MRA Appendix C.

9.3 Impact of the comparison on the calibration and measurements capabilities of the participating laboratories

The DOE and CMC in the BIPM KCDB for the participating institutes are compared in Table 9-1. The DOE does not support CMC for any participants, who claim very low uncertainties in calibration of Zeners. But it should be noted that any validation of the consistency between DOE and CMC would not be possible with this comparison because the uncertainty of this comparison is much larger than their CMC's.

Table 9-1 DOE and CMC of the participating institutes.

Participating Lab.	10 V			1.018 V		
	D_i	$U(D_i)$	CMC (k = 2)	D_i	$U(D_i)$	CMC (k = 2)
	μV	μV	μV	μV	μV	μV
KRISS/CJVS	–0.143	0.677	0.055	0.079	0.105	0.02
NMIJ	0.184	0.673	0.045	0.074	0.103	0.008
CMS	–0.005	0.691	0.098	0.103	0.110	0.05
KRISS/PJVS	0.109	0.689	0.055	0.094	0.106	0.02

Appendices

Appendix A: Pair-wise degrees of equivalence

Degrees of equivalence for participants of APMP.EM-K11.5 with respect to BIPM.EM-K11 are given in Table A-1 for 10 V and Table A-2 for 1.018 V.

Table A-1 Degrees of equivalence of the participating institutes relative to the BIPM.EM-K11.b KCRV (10 V).

	Lab. j →		KRISS/CJVS		NMIJ		CMS		KRIS/PJVS	
Lab. i ↓	D_i	$U(D_i)$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$
	μV	μV	μV	μV	μV	μV	μV	μV	μV	μV
KRISS/CJVS	–0.143	0.339			–0.327	0.478	–0.138	0.484	–0.252	0.483
NMIJ	0.188	0.337	0.327	0.478			0.189	0.482	0.075	0.482
CMS	–0.005	0.346	0.138	0.484	–0.189	0.482			–0.113	0.488
KRISS/PJVS	0.109	0.344	0.252	0.483	–0.075	0.482	0.113	0.488		

Table A-2 Degrees of equivalence of the participating institutes relative to the BIPM.EM-K11.a KCRV (1.018 V).

	Lab. j →		KRISS/CJVS		NMIJ		CMS		KRIS/PJVS	
Lab. i ↓	D_i	$U(D_i)$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$	$D_{i,j}$	$U(D_{i,j})$
	μV	μV	μV	μV	μV	μV	μV	μV	μV	μV
KRISS/CJVS	0.079	0.053			0.006	0.074	–0.024	0.076	–0.015	0.075
NMIJ	0.074	0.052	–0.006	0.074			–0.029	0.075	–0.020	0.074
CMS	0.103	0.055	0.024	0.076	0.029	0.075			0.009	0.077
KRISS/PJVS	0.094	0.053	0.015	0.075	0.020	0.074	–0.009	0.077		

Appendix B: Methods of measurement

Details of the method of measurement and traceability to the SI, as reported by participants, are given below.

B.1 KRISS (CJVS), Republic of 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 synthetiser 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.

KRISS JVS participated in BIPM.EM-K10.a in 1995, and BIPM.EM-K10.b, BIPM.EM-K11(.a & .b) in 2008.

B.2 NMIJ, Japan

The travelling standards have been measured by a programmable Josephson voltage standard system with a $NbN/TiN_x/NbN$ overdamped array, which is cooled with a Gifford McMahon refrigerator. The microwave with a frequency of approximately 15.75 GHz, which is generated with a commercial signal generator and amplified with an amplifier, is applied to the array. The variable range of the frequency is ±50 MHz. The detector used for measuring a null voltage between the array and the travelling standards is a nanovoltmeter, Agilent 34420A, with a 100 mV range. The maximum null voltage is less than 0.5 μV. The thermal EMF between the array and the detector is canceled out by reversing polarity using negative bias currents for the array and a low-thermal EMF rotary switch for the travelling standards.

B.3 CMS, Chinese Taipei

The travelling standards are calibrated by using the back-to-back method based on the programmable Josephson voltage standard (PJVS) system. The thermal offset voltage is eliminated by automatic polarity switching, and we use the floating circuit such that there is no guarding or connection to the earth. The Josephson step number is tuned by JVS650 automatically such that the difference between the Josephson voltage and measured voltage is below 1 μV. Four sets of 10 points in a sequence of polarity of "+", "–", "–", and "+" were taken, with each point being the mean of 3 digital voltmeter readings. It takes about 5 minutes for a single point measurement.

B.4 KRISS (PJVS), Republic of Korea

The KRISS PJVS system was developed by employing a NIST 10-V PJVS array, which consists of 265,116 superconductor-normal metal-superconductor junctions divided into 23 subarrays. The PJVS system is fully controlled by the *KRISS PJVS Suite* software written in Visual Studio 2008. The 24-channel bias electronics developed in KRISS for the PJVS system is battery operated and is remotely controlled through the optically isolated RS-232C interface. The Keithley 2182A nanovoltmeter was used as a detector at 10-mV range, without adopting any filter. The daily measurement procedure was started at least 5 hours after disconnecting AC-power lines from the travelling Zener standards (hereafter called TZS). Single measurement is completed with obtaining four sets of data taken in two different configurations: in positive polarity of the PJVS and the TZS outputs for the first and the third sets and in negative polarity of the PJVS and the TZS outputs for the second and the fourth sets. The polarity change of the TZS outputs was made with the low-thermal scanner (Dataproof 160). Each data set consists of 20 readings with 10 NPLC at 10-mV range of the detector. All the data with time stamps are stored in the control PC, and the TZS output value is deduced by a linear least-squares fit for the data, which is aimed to reduce a measurement error due to the voltage drift. For a day, 10 measurements per each of the TZS output were performed. Before measurements for an output, a preliminary measurement was carried out to get a rough estimation of the output, where the PJVS output was set to the nominal value of the output, i.e., 1.018 V or 10 V. At the first measurement, the PJVS output is set to the estimated value, which gives rise to minimize the voltage difference between the TZS and the PJVS outputs, and thus to minimize the gain error of nanovoltmeter. For the 1.018-V outputs, typical voltage difference is less than 100 nV, while the difference is far below 1 μV for the 10-V outputs. For three travelling standards, total 60 measurements a day were carried out, which were repeated for 26 days.

Appendix C: Uncertainty statements

Details of the uncertainty statements of the measurements, as reported by participants, are given below.

C.1 KRISS (CJVS), Republic of Korea

Uncertainty Budget: 10 V Zener

No.	Component	Distribution	c_i	$u(x_i)$ nV	$\|c_i.u(x_i)\|$ nV	ν_i
1	Microwave freq. (1 Hz/75 GHz)		1	0.13	0.13	500
2	Probe leakage (DWG), (0.3 Ω/10 GΩ @ 0.5 min)		1	0.3	0.30	50
3	Circuit leakage (1 k Ω/1 T Ω for 1.018 V Zener, 40 Ω/1 T Ω for 10 V Zener)		1	0.4	0.40	50
4	Thermals (incl. Reverse sw. Repeatability, Circuits)	appr. norma	1	1.93	1.93	32
5	Digital nanovoltmeter (0.5 mV reading w/Keithley 2182)	appr normal	1	2.02	2.02	50
	RSS Type B, u_B				2.84	84.93

Uncertainty Budget: 1.018 V KRISS Zener

No.	Component	Distribution	c_i	$u(x_i)$ nV	$\|c_i.u(x_i)\|$ nV	ν_i
1	Microwave freq. (1 Hz/75 GHz)		1	0.013	0.01	500
2	Probe leakage (DWG), (0.3 Ω/10 GΩ @ 0.5 min)		1	0.03	0.03	50
3	Circuit leakage (1 k Ω/1 T Ω for 1.018 V Zener, 40 Ω/1 T Ω for 10 V Zener)		1	1	1.00	50
4	Thermals (incl. Reverse sw. Repeatability, Circuits)	appr. norma	1	1.93	1.93	32
5	Digital nanovoltmeter (0.5 mV reading w/Keithley 2182)	appr normal	1	2.02	2.02	50
	RSS Type B, u_B				2.97	98.59

C.2 NMIJ, Japan

Uncertainty budget (**10 V / TZS-1** / NMIJ / K11.5.b / Oct. 24, 2013)

Quantity	Estimate	Uncertainty	Type	Probability distribution	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Measured mean voltage	9.999 931 261 0 V	22.3 nV	A	normal	22.3 nV	1	22.3 nV	15
Frequency	15.75 GHz	0.8 Hz	B	rectangular	0.46 Hz	0.64 nV/Hz	0.3 nV	∞
Leakage voltage	0 nV*	0.1 nV	B	rectangular	0.06 nV	1	0.1 nV	∞
Voltage at null detector	200 nV**	0.05 nV	B	rectangular	0.03 nV	1	0.03 nV	∞
Step flatness evaluation	0 nV***	5 nV	B	rectangular	2.9 nV	1	2.9 nV	∞
Thermal emf of rotary switch	0 nV****	1.5 nV	B	normal	1.5 nV	1	1.5 nV	∞
Correction for temperature effect	-507.4 nV	153.4 nV	B	normal	153.4 nV	1	153.4 nV	∞
Correction for pressure effect	-39.7 nV	1.6 nV	B	normal	1.6 nV	1	1.6 nV	∞
Corrected voltage at R0 and p0	9.999 930 713 9 V	-	-	-	-	-	155.0 nV	35370

* no correction to the measured mean voltage is applied, as the path for the leakage is unknown.
** typical voltage at the null detector, that is already part of the mean measured voltage.
*** no correction to the measured mean voltage is applied, as the effect of the step flatness is unknown.
The threshold value for the flatness check is incorporated in the uncertainty statement.
**** no correction to the measured mean voltage is applied, as the emf voltage could drift within its uncertainty.

Series resistance of leads/filters:	10 Ω
Leakage resistance:	>10^{12} Ω
Null detector and settings:	HP 34420A, 1 mV range, no filters, NPLC 100, analog lowpass filter with f_c = 1 kHz
Measurement sequence:	+/-/-/+ sequence using mechanical switch; 1 reading of null detector in each polarity, null voltage <=200 nV
Typical time for sequence:	2 min
Thermistor resistance:	R = 39.768 kΩ, R0 = 39.65 kΩ, α = 4.3 ± 1.3 nV/Ω
Ambient pressure:	p = 1015.48 hPa, p0 = 1013.25 hPa, α = 17.8 ± 0.7 nV/hPa

Uncertainty budget (**10 V / TZS-2** / NMIJ / K11.5.b / Oct. 24, 2013)

Quantity	Estimate	Uncertainty	Type	Probability distribution	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Measured mean voltage	9.999 996 324 0 V	24.3 nV	A	normal	24.3 nV	1	24.3 nV	15
Frequency	15.75 GHz	0.8 Hz	B	rectangular	0.46 Hz	0.64 nV/Hz	0.3 nV	∞
Leakage voltage	0 nV*	0.1 nV	B	rectangular	0.06 nV	1	0.1 nV	∞
Voltage at null detector	200 nV**	0.05 nV	B	rectangular	0.03 nV	1	0.03 nV	∞
Step flatness evaluation	0 nV***	5 nV	B	rectangular	2.9 nV	1	2.9 nV	∞
Thermal emf of rotary switch	0 nV****	1.5 nV	B	normal	1.5 nV	1	1.5 nV	∞
Correction for temperature effect	+161.5 nV	17.0 nV	B	normal	17.0 nV	1	17.0 nV	∞
Correction for pressure effect	-39.8 nV	1.2 nV	B	normal	1.2 nV	1	1.2 nV	∞
Corrected voltage at R0 and p0	9.999 996 445 7 V	-	-	-	-	-	29.8 nV	34

* no correction to the measured mean voltage is applied, as the path for the leakage is unknown.
** typical voltage at the null detector, that is already part of the mean measured voltage.
*** no correction to the measured mean voltage is applied, as the effect of the step flatness is unknown.
The threshold value for the flatness check is incorporated in the uncertainty statement.
**** no correction to the measured mean voltage is applied, as the emf voltage could drift within its uncertainty.

Series resistance of leads/filters:	10 Ω
Leakage resistance:	>10^{12} Ω
Null detector and settings:	HP 34420A, 1 mV range, no filters, NPLC 100, analog lowpass filter with f_c = 1 kHz
Measurement sequence:	+/-/-/+ sequence using mechanical switch; 1 reading of null detector in each polarity, null voltage <=200 nV
Typical time for sequence:	2 min
Thermistor resistance:	R = 38.955 kΩ, R0 = 39.04 kΩ, α = 1.9 ± 0.2 nV/Ω
Ambient pressure:	p = 1015.66 hPa, p0 = 1013.25 hPa, α = 16.5 ± 0.5 nV/hPa

Uncertainty budget (**10 V / TZS-3** / NMIJ / K11.5.b / Oct. 24, 2013)

Quantity	Estimate	Uncertainty	Type	Probability distribution	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Measured mean voltage	9.999 948 092 0 V	30.3 nV	A	normal	30.3 nV	1	30.3 nV	15
Frequency	15.75 GHz	0.8 Hz	B	rectangular	0.46 Hz	0.64 nV/Hz	0.3 nV	∞
Leakage voltage	0 nV*	0.1 nV	B	rectangular	0.06 nV	1	0.1 nV	∞
Voltage at null detector	200 nV**	0.05 nV	B	rectangular	0.03 nV	1	0.03 nV	∞
Step flatness evaluation	0 nV***	5 nV	B	rectangular	2.9 nV	1	2.9 nV	∞
Thermal emf of rotary switch	0 nV****	1.5 nV	B	normal	1.5 nV	1	1.5 nV	∞
Correction for temperature effect	+527.8 nV	243.6 nV	B	normal	243.6 nV	1	243.6 nV	∞
Correction for pressure effect	-119.7 nV	6.2 nV	B	normal	6.2 nV	1	6.2 nV	∞
Corrected voltage at R0 and p0	9.999 948 500 1 V	-	-	-	-	-	245.6 nV	65147

* no correction to the measured mean voltage is applied, as the path for the leakage is unknown.
** typical voltage at the null detector, that is already part of the mean measured voltage.
*** no correction to the measured mean voltage is applied, as the effect of the step flatness is unknown.
The threshold value for the flatness check is incorporated in the uncertainty statement.
**** no correction to the measured mean voltage is applied, as the emf voltage could drift within its uncertainty.

Series resistance of leads/filters:	10 Ω
Leakage resistance:	>10^{12} Ω
Null detector and settings:	HP 34420A, 1 mV range, no filters, NPLC 100, analog lowpass filter with f_c = 1 kHz
Measurement sequence:	+/-/-/+ sequence using mechanical switch; 1 reading of null detector in each polarity, null voltage <=200 nV
Typical time for sequence:	2 min
Thermistor resistance:	R = 39.004 kΩ, R0 = 39.41 kΩ, α = 1.3 ± 0.6 nV/Ω
Ambient pressure:	p = 1018.87 hPa, p0 = 1013.25 hPa, α = 21.3 ± 1.1 nV/hPa

Uncertainty budget (**1.018 V** / **TZS-1** / NMIJ / K11.5.a / Oct. 24, 2013)

Quantity	Estimate	Uncertainty	Type	Probability distribution	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Measured mean voltage	1.018 103 157 0 V	4.3 nV	A	normal	4.3 nV	1	4.3 nV	15
Frequency	15.75 GHz	0.8 Hz	B	rectangular	0.46 Hz	0.064 nV/Hz	0.03 nV	∞
Leakage voltage	0 nV*	0.01 nV	B	rectangular	0.006 nV	1	0.01 nV	∞
Voltage at null detector	200 nV**	0.05 nV	B	rectangular	0.03 nV	1	0.03 nV	∞
Step flatness evaluation	0 nV***	5 nV	B	rectangular	2.9 nV	1	2.9 nV	∞
Thermal emf of rotary switch	0 nV****	1.5 nV	B	normal	1.5 nV	1	1.5 nV	∞
Correction for temperature effect	-33.3 nV	0.0 nV	B	normal	0.0 nV	1	0.0 nV	∞
Correction for pressure effect	-4.4 nV	0.0 nV	B	normal	0.0 nV	1	0.0 nV	∞
Corrected voltage at R0 and p0	1.018 103 119 3 V	-	-	-	-	-	5.4 nV	38

* no correction to the measured mean voltage is applied, as the path for the leakage is unknown.
** typical voltage at the null detector, that is already part of the mean measured voltage.
*** no correction to the measured mean voltage is applied, as the effect of the step flatness is unknown.
The threshold value for the flatness evaluation is incorporated in the uncertainty statement.
**** no correction to the measured mean voltage is applied, as the emf voltage could drift within its uncertainty.

Series resistance of leads/filters:	10 Ω
Leakage resistance:	$>10^{12}$ Ω
Null detector and settings:	HP 34420A, 1 mV range, no filters, NPLC 100, analog lowpass filter with f_c = 1 kHz
Measurement sequence:	+/-/-/+ sequence using mechanical switch; 1 reading of null detector in each polarity, null voltage <=200 nV
Typical time for sequence:	2 min
Thermistor resistance:	R = 39.761 kΩ, R0 = 39.65 kΩ, α = 0.3 ± 0.0 nV/Ω
Ambient pressure:	p = 1015.43 hPa, p0 = 1013.25 hPa, α = 2.0 ± 0.0 nV/hPa

!33

Uncertainty budget (**1.018 V** / **TZS-2** / NMIJ / K11.5.a / Oct. 24, 2013)

Quantity	Estimate	Uncertainty	Type	Probability distribution	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Measured mean voltage	1.018 148 827 0 V	2.5 nV	A	normal	2.5 nV	1	2.5 nV	15
Frequency	15.75 GHz	0.8 Hz	B	rectangular	0.46 Hz	0.064 nV/Hz	0.03 nV	∞
Leakage voltage	0 nV*	0.01 nV	B	rectangular	0.006 nV	1	0.01 nV	∞
Voltage at null detector	200 nV**	0.05 nV	B	rectangular	0.03 nV	1	0.03 nV	∞
Step flatness evaluation	0 nV***	5 nV	B	rectangular	2.9 nV	1	2.9 nV	∞
Thermal emf of rotary switch	0 nV****	1.5 nV	B	normal	1.5 nV	1	1.5 nV	∞
Correction for temperature effect	+16.2 nV	8.1 nV	B	normal	8.1 nV	1	8.1 nV	∞
Correction for pressure effect	-4.0 nV	0.0 nV	B	normal	0.0 nV	1	0.0 nV	∞
Corrected voltage at R0 and p0	1.018 148 839 2 V	-	-	-	-	-	9.1 nV	2609

* no correction to the measured mean voltage is applied, as the path for the leakage is unknown.
** typical voltage at the null detector, that is already part of the mean measured voltage.
*** no correction to the measured mean voltage is applied, as the effect of the step flatness is unknown.
The threshold value for the flatness check is incorporated in the uncertainty statement.
**** no correction to the measured mean voltage is applied, as the emf voltage could drift within its uncertainty.

Series resistance of leads/filters:	10 Ω
Leakage resistance:	>10^{12} Ω
Null detector and settings:	HP 34420A, 1 mV range, no filters, NPLC 100, analog lowpass filter with f_c = 1 kHz
Measurement sequence:	+/-/-/+ sequence using mechanical switch; 1 reading of null detector in each polarity, null voltage <=200 nV
Typical time for sequence:	2 min
Thermistor resistance:	R = 38.959 kΩ, R0 = 39.04 kΩ, α = 0.2 ± 0.1 nV/Ω
Ambient pressure:	p = 1016.08 hPa, p0 = 1013.25 hPa, α = 1.4 ± 0.0 nV/hPa

Uncertainty budget (**1.018 V** / **TZS-3** / NMIJ / K11.5.a / Oct. 24, 2013)

Quantity	Estimate	Uncertainty	Type	Probability distribution	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degree of freedom
Measured mean voltage	1.018 114 873 0 V	3.3 nV	A	normal	3.3 nV	1	3.3 nV	15
Frequency	15.75 GHz	0.8 Hz	B	rectangular	0.46 Hz	0.064 nV/Hz	0.03 nV	∞
Leakage voltage	0 nV*	0.01 nV	B	rectangular	0.006 nV	1	0.01 nV	∞
Voltage at null detector	200 nV**	0.05 nV	B	rectangular	0.03 nV	1	0.03 nV	∞
Step flatness evaluation	0 nV***	5 nV	B	rectangular	2.9 nV	1	2.9 nV	∞
Thermal emf of rotary switch	0 nV****	1.5 nV	B	normal	1.5 nV	1	1.5 nV	∞
Correction for temperature effect	+82.2 nV	41.1 nV	B	normal	41.1 nV	1	41.1 nV	∞
Correction for pressure effect	-10.5 nV	1.0 nV	B	normal	1.0 nV	1	1.0 nV	∞
Corrected voltage at R0 and p0	1.018 114 944 7 V	-	-	-	-	-	41.4 nV	393758

* no correction to the measured mean voltage is applied, as the path for the leakage is unknown.
** typical voltage at the null detector, that is already part of the mean measured voltage.
*** no correction to the measured mean voltage is applied, as the effect of the step flatness is unknown.
The threshold value for the flatness check is incorporated in the uncertainty statement.
**** no correction to the measured mean voltage is applied, as the emf voltage could drift within its uncertainty.

Series resistance of leads/filters:	10 Ω
Leakage resistance:	$>10^{12}$ Ω
Null detector and settings:	HP 34420A, 1 mV range, no filters, NPLC 100, analog lowpass filter with f_c = 1 kHz
Measurement sequence:	+/-/-/+ sequence using mechanical switch; 1 reading of null detector in each polarity, null voltage <=200 nV
Typical time for sequence:	2 min
Thermistor resistance:	R = 38.999 kΩ, R0 = 39.41 kΩ, α = 0.2 ± 0.1 nV/Ω
Ambient pressure:	p = 1018.25 hPa, p0 = 1013.25 hPa, α = 2.1 ± 0.2 nV/hPa

C.3 CMS, Chinese Taipei

	the uncertainty due to the thermistor (nV)		the uncertainty due to the pressure (nV)		type B uncertainty of the system (nV)	type B (nV)	type A (nV)	combined (nV)	effective degree of freedom	coverage factor	Expanded (nV)
TZS1 10 V	65	25	5	10	49	86	85	121	28	2.05	248
TZS2 10 V	30	11	3	10	49	60	64	88	25	2.06	182
TZS3 10 V	294	8	7	12	49	299	94	314	871	2.00	628
TZS1 1.018 V	0	2	0	1	25	26	7	27	1549	2.00	54
TZS2 1.018 V	15	1	0	1	25	30	11	32	501	2.00	64
TZS3 1.018 V	49	1	1	1	25	56	15	58	1564	2.00	116

	$\lvert(R_{avg}-R_0)\rvert$	α_R	$\triangle\alpha_p$	α_p
TZS1 10 V	0.05	4300	0.7	17.8
TZS2 10 V	0.15	1900	0.5	16.5
TZS3 10 V	0.49	1300	1.1	21.3
TZS1 1.018 V	0.05	300	0	2
TZS2 1.018 V	0.15	200	0	1.4
TZS3 1.018 V	0.49	200	0.2	2.1

C.4 KRISS (PJVS), Republic of Korea

Zener: TZS1, 10 V								
Component	Distribution	Type	Sensitivity Coefficient	Uncertainty	Uncertainty Contribution	DOF	[ci*u(x)]^2	[ci*u(x)]^4/DOF
Repeatability	t	A	1	51.66	51.66 nV	24	2668.76	296760.69
Microwave frequency	Rectangular	B	1	0.29	0.29 nV	50	0.08	0.00
DVM gain (±1 μV reading span)	Rectangular	B	1	0.58	0.58 nV	50	0.33	0.00
Leakage	Rectangular	B	1	0.50	0.50 nV	50	0.25	0.00
Reversing error of scanner	Normal	A	1	3.15	3.15 nV	28	9.92	3.52
Temperature correction: Coefficient	Normal	B	-27.15 Ω	1.30 nV/Ω	35.30 nV	50	1245.92	31046.44
Temperature correction: Resistance measurement	Rectangular	B	-4.30 nV/Ω	0.58 Ω	2.49 nV	50	6.22	0.77
Pressure correction: Coefficient	Normal	B	18.59 hPa	0.70 nV/hPa	13.01 nV	50	169.28	573.12
Pressure correction: Pressure measurement	Rectangular	B	-17.80 nV/hPa	0.12 hPa	2.14 nV	50	4.56	0.42
uc					64.07 nV	51		
k					2.00			
U					128.15 nV			

Zener: TZS2, 10 V								
Component	Distribution	Type	Sensitivity Coefficient	Uncertainty	Uncertainty Contribution	DOF	[ci*u(x)]^2	[ci*u(x)]^4/DOF
Repeatability	t	A	1	55.20	55.20 nV	24	3047.04	386852.20
Microwave frequency	Rectangular	B	1	0.29	0.29 nV	50	0.08	0.00
DVM gain (±1 μV reading span)	Rectangular	B	1	0.58	0.58 nV	50	0.33	0.00
Leakage	Rectangular	B	1	0.50	0.50 nV	50	0.25	0.00
Reversing error of scanner	Normal	A	1	3.32	3.32 nV	28	11.02	4.34
Temperature correction: Coefficient	Normal	B	188.71 Ω	0.20 nV/Ω	37.74 nV	50	1424.43	40580.07
Temperature correction: Resistance measurement	Rectangular	B	-1.90 nV/Ω	0.58 Ω	1.10 nV	50	1.21	0.03
Pressure correction: Coefficient	Normal	B	18.39 hPa	0.50 nV/hPa	9.19 nV	50	84.54	142.95
Pressure correction: Pressure measurement	Rectangular	B	-16.50 nV/hPa	0.12 hPa	1.98 nV	50	3.92	0.31
uc					67.62 nV	49		
k					2.00			
U					135.25 nV			

Zener: TZS3, 10 V								
Component	Distribution	Type	Sensitivity Coefficient	Uncertainty	Uncertainty Contribution	DOF	[ci*u(x)]^2	[ci*u(x)]^4/DOF
Repeatability	t	A	1	78.60	78.60 nV	25	6177.96	1526687.59
Microwave frequency	Rectangular	B	1	0.29	0.29 nV	50	0.08	0.00
DVM gain (±1 μV reading span)	Rectangular	B	1	0.58	0.58 nV	50	0.33	0.00
Leakage	Rectangular	B	1	0.50	0.50 nV	50	0.25	0.00
Reversing error of scanner	Normal	A	1	2.82	2.82 nV	29	7.95	2.18
Temperature correction: Coefficient	Normal	B	549.99 Ω	0.60 nV/Ω	329.99 nV	50	108894.89	237161961.86
Temperature correction: Resistance measurement	Rectangular	B	-1.30 nV/Ω	0.58 Ω	0.75 nV	50	0.57	0.01
Pressure correction: Coefficient	Normal	B	18.27 hPa	1.10 nV/hPa	20.10 nV	50	403.99	3264.15
Pressure correction: Pressure measurement	Rectangular	B	-21.30 nV/hPa	0.12 hPa	2.56 nV	50	6.53	0.85
uc					339.84 nV	56		
k					2.00			
U					679.68 nV			

Zener: TZS1, 1.018 V								
Component	Distribution	Type	Sensitivity Coefficient	Uncertainty	Uncertainty Contribution	DOF	[ci*u(x)]^2	[ci*u(x)]^4/DOF
Repeatability	t	A	1	4.60 nV	4.60 nV	24	21.16	18.66
Microwave frequency	Rectangular	B	1	0.03 nV	0.03 nV	50	0.00	0.00
DVM gain (±200 nV reading span)	Rectangular	B	1	0.06 nV	0.06 nV	50	0.00	0.00
Leakage	Rectangular	B	1	0.05 nV	0.05 nV	50	0.00	0.00
Reversing error of scanner	Normal	A	1	3.11 nV	3.11 nV	28	9.67	3.34
Temperature correction: Coefficient	Normal	B	-27.08 Ω	0.00 nV/Ω	0.00 nV	50	0.00	0.00
Temperature correction: Resistance measurement	Rectangular	B	-0.30 nV/Ω	0.58 Ω	0.17 nV	50	0.03	0.00
Pressure correction: Coefficient	Normal	B	18.53 hPa	0.00 nV/hPa	0.00 nV	50	0.00	0.00
Pressure correction: Pressure measurement	Rectangular	B	-2.00 nV/hPa	0.12 hPa	0.24 nV	50	0.06	0.00
uc					5.56 nV	43		
k					2.00			
U					11.12 nV			

Zener: TZS2, 1.018 V								
Component	Distribution	Type	Sensitivity Coefficient	Uncertainty	Uncertainty Contribution	DOF	[ci*u(x)]^2	[ci*u(x)]^4/DOF
Repeatability	t	A	1	6.62	6.62 nV	24	43.82	80.02
Microwave frequency	Rectangular	B	1	0.03	0.03 nV	50	0.00	0.00
DVM gain (±200 nV reading span)	Rectangular	B	1	0.06	0.06 nV	50	0.00	0.00
Leakage	Rectangular	B	1	0.05	0.05 nV	50	0.00	0.00
Reversing error of scanner	Normal	A	1	2.83	2.83 nV	28	8.01	2.29
Temperature correction: Coefficient	Normal	B	189.64 Ω	0.10 nV/Ω	18.96 nV	50	359.65	2586.99
Temperature correction: Resistance measurement	Rectangular	B	-0.20 nV/Ω	0.58 Ω	0.12 nV	50	0.01	0.00
Pressure correction: Coefficient	Normal	B	18.25 hPa	0.00 nV/hPa	0.00 nV	50	0.00	0.00
Pressure correction: Pressure measurement	Rectangular	B	-1.40 nV/hPa	0.12 hPa	0.17 nV	50	0.03	0.00
uc					20.29 nV	63		
k					2.00			
U					40.57 nV			

Zener: TZS3, 1.018 V								
Component	Distribution	Type	Sensitivity Coefficient	Uncertainty	Uncertainty Contribution	DOF	[ci*u(x)]^2	[ci*u(x)]^4/DOF
Repeatability	t	A	1	6.75	6.75 nV	24	45.56	86.50
Microwave frequency	Rectangular	B	1	0.03	0.03 nV	50	0.00	0.00
DVM gain (±200 nV reading span)	Rectangular	B	1	0.06	0.06 nV	50	0.00	0.00
Leakage	Rectangular	B	1	0.05	0.05 nV	50	0.00	0.00
Reversing error of scanner	Normal	A	1	2.76	2.76 nV	28	7.62	2.07
Temperature correction: Coefficient	Normal	B	550.22 Ω	0.10 nV/Ω	55.02 nV	50	3027.44	183307.54
Temperature correction: Resistance measurement	Rectangular	B	-0.20 nV/Ω	0.58 Ω	0.12 nV	50	0.01	0.00
Pressure correction: Coefficient	Normal	B	18.10 hPa	0.20 nV/hPa	3.62 nV	50	13.10	3.43
Pressure correction: Pressure measurement	Rectangular	B	-2.10 nV/hPa	0.12 hPa	0.25 nV	50	0.06	0.00
uc					55.62 nV	52		
k					2.00			
U					111.24 nV			

Appendix D: Summary of participants' measurements

D.1 KRISS (CJVS), Republic of Korea

KRISS measurement result (1): 24 Sep 2013 ~ 2 Oct 2013

1.018 V

	Mean Date	Raw Data (V)	Corrected Value (V)	u_c (nV)	ν	k (95 %)	U (nV)	Meas Started	Meas Finished	T (°C)	Humidity (%)	Pressure (hPa)	Thermistor (kohm)	No of meas	Type A (nV	Type B_correct (nV	Type B_JVS (nV)
TZS1	2013-9-29 12:08 AM	1.018 103 117	1.018 103 108	12.1	21.8	2.08	25.1	2013-9-24 9:05 PM	2013-10-2 5:26 PM	22.5	49.7	1003.3	39.744	16	11	4	3
TZS2	2013-9-29 6:52 PM	1.018 148 784	1.018 148 822	18.0	2837.7	1.96	35.2	2013-9-25 9:58 PM	2013-10-2 7:00 PM	22.5	46.3	1004.6	38.913	18	5	17	3
TZS3	2013-9-30 2:58 AM	1.018 114 883	1.018 114 988	48.9	3790.4	1.96	95.8	2013-9-25 10:39 PM	2013-10-2 7:34 PM	22.5	48.3	1005.0	38.974	20	13	47	3

10 V

	Mean Date	Raw Data (V)	Corrected Value (V)	u_c (nV)	ν	k (95 %)	U (nV)	Meas Started	Meas Finished	T (°C)	Humidity (%)	Pressure (hPa)	Thermistor (kohm)	No of meas	Type A (nV	Type B_correct (nV	Type B_JVS (nV)
TZS1	2013-10-1 12:43 AM	9.999 930 773	9.999 930 406	171.6	8674.1	1.96	336.4	2013-9-26 7:51 PM	2013-10-4 7:08 PM	22.4	47.0	1007.4	39.757	16	35	168	3
TZS2	2013-10-1 7:56 AM	9.999 995 962	9.999 996 293	51.3	99.2	1.98	101.8	2013-9-27 3:06 PM	2013-10-4 4:26 PM	22.4	45.3	1007.0	38.919	16	32	40	3
TZS3	2013-10-1 9:44 AM	9.999 947 664	9.999 948 361	262.4	16506.0	2.00	522.1	2013-9-27 3:51 PM	2013-10-4 3:46 PM	22.6	46.3	1006.8	38.980	18	47	258	3

KRISS measurement result (2): 10 Feb 2014 ~ 14 Feb 2014

1.018 V

	Mean Date	Raw Data (V)	Corrected Value (V)	u_c (nV)	ν	k (95 %)	U (nV)	Meas Started	Meas Finished	T (°C)	Humidity (%)	Pressure (hPa)	Thermistor (kohm)	No of meas	Type A (nV	Type B_correct (nV	Type B_JVS (nV)
TZS1	2014-2-12 3:06 PM	1.018 103 024	1.018 102 994	6.4	164.2	1.97	12.6	2014-2-10 5:18 PM	2014-2-14 5:59 PM	22.5	42.6	1015.9	39.735	26	4	4	3
TZS2	2014-2-12 4:54 PM	1.018 148 883	1.018 148 904	15.6	16767.0	1.96	30.6	2014-2-10 4:42 PM	2014-2-14 5:29 PM	22.4	42.4	1015.8	38.918	24	3	15	3
TZS3	2014-2-12 4:32 PM	1.018 114 890	1.018 114 981	50.4	114947.2	1.96	98.9	2014-2-10 4:12 PM	2014-2-14 4:59 PM	22.6	42.0	1015.5	38.928	24	6	50	3

10 V

	Mean Date	Raw Data (V)	Corrected Value (V)	u_c (nV)	ν	k (95 %)	U (nV)	Meas Started	Meas Finished	T (°C)	Humidity (%)	Pressure (hPa)	Thermistor (kohm)	No of meas	Type A (nV	Type B_correct (nV	Type B_JVS (nV)
TZS1	2014-2-12 5:52 PM	9.999 930 087	9.999 929 819	147.8	4225.4	1.96	289.8	2014-2-10 11:22 AM	2014-2-14 3:05 PM	22.4	42.2	1016.0	39.704	26	41	142	3
TZS2	2014-2-12 3:38 PM	9.999 995 572	9.999 995 787	86.0	39.8	2.02	174.0	2014-2-10 2:48 PM	2014-2-14 2:52 PM	22.4	42.3	1015.6	38.907	24	75	42	3
TZS3	2014-2-12 4:03 PM	9.999 946 868	9.999 947 453	299.7	4574.0	2.00	599.4	2014-2-10 3:28 PM	2014-2-14 3:37 PM	22.5	42.0	1015.4	38.926	24	74	290	3

D.2 NMIJ, Japan

K11.5.a (1.018 V)

Identification of standard	TZS1	TZS2	TZS3
Method of measurement	**Josephson/ Zero method**	**Josephson/ Zero method**	**Josephson/ Zero method**
Date and time of measurement (from to)	**Oct. 24, 2013 15:54-16:26**	**Oct. 24, 2013 13:17-13:50**	**Oct. 24, 2013 11:20-11:52**
Measured voltage (V)	**1.018 103 157**	**1.018 148 827**	**1.018 114 873**
Thermistor resistance (ohm)/ Ambient temperature (°C)	**39 761 / 22.8**	**38 959 / 22.7**	**38 999 / 22.8**
Humidity (% R.H.)/ Pressure (hPa)	**48.9 / 1015.43**	**49.3 / 1016.08**	**48.4 / 1018.25**
Corrected voltage at R_0 and p_0 (V)	**1.018 103 119**	**1.018 148 839**	**1.018 114 945**
Number of measurements	**16**	**16**	**16**
Type A standard uncertainty (nV)	**4.3**	**2.5**	**3.3**
Type B standard uncertainty (nV)	**3.3**	**8.7**	**41.2**
Combined standard uncertainty (nV)	**5.4**	**9.1**	**41.4**
Expanded uncertainty (nV)	**11**	**18**	**83**
Coverage factor k	**2.0**	**2.0**	**2.0**
Effective degrees of freedom	**38**	**2609**	**393758**

K11.5.b (10 V)

Identification of standard	TZS1	TZS2	TZS3
Method of measurement	**Josephson/ Zero method**	**Josephson/ Zero method**	**Josephson/ Zero method**
Date and time of measurement (from to)	**Oct. 24, 2013 15:07-15:41**	**Oct. 24, 2013 14:06-14:39**	**Oct. 24, 2013 10:30-11:03**
Measured voltage (V)	**9.999 931 261**	**9.999 996 324**	**9.999 948 092**
Thermistor resistance (ohm)/ Ambient temperature (°C)	**39 768 / 22.9**	**38 955 / 22.8**	**39 004 / 22.8**
Humidity (% R.H.)/ Pressure (hPa)	**49.0 / 1015.48**	**48.8 / 1015.66**	**48.1 / 1018.87**
Corrected voltage at R_0 and p_0 (V)	**9.999 930 714**	**9.999 996 446**	**9.999 948 500**
Number of measurements	**16**	**16**	**16**
Type A standard uncertainty (nV)	**22.3**	**24.3**	**30.3**
Type B standard uncertainty (nV)	**153.4**	**17.4**	**243.7**
Combined standard uncertainty (nV)	**155.0**	**29.8**	**245.6**
Expanded uncertainty (nV)	**310**	**60**	**491**
Coverage factor k	**2.0**	**2.0**	**2**
Effective degrees of freedom	**35370**	**34**	**65147**

D.3 CMS, Chinese Taipei

K11.5.a (1.018 V)

Identification of standard	TZS1	TZS2	TZS3
Method of measurement	The traveling standards are calibrated by using the back-to-back method. The thermal offset voltage is eliminated by automatic polarity switching, and we use the floating circuit such that there is no guarding or connection to the earth. The Josephson step number is tuned by JVS650 automatically such that the difference between the Josephson voltage and measured voltage is below 1 μV. Four sets of 10 points in a sequence of polarity of "+", "–", "–", and "+" were taken, with each point being the mean of 3 digital voltmeter readings. It takes about 5 minutes for a single point measurement.		
Date and time of measurement (from to)	From Nov. 27 to Nov. 30, 2013	From Nov. 27 to Nov. 30, 2013	From Nov. 27 to Nov. 30, 2013
Measured voltage (V)	1.018 103 168 V	1.018 148 866 V	1.018 114 854 V
Thermistor resistance (ohm)/ Ambient temperature (°C)	39.70 kΩ/ (23±1.5) °C	38.89 kΩ/ (23±1.5) °C	38.92 kΩ/ (23±1.5) °C
Humidity (% R.H.)/ Pressure (hPa)	(45±10) % / 1015.46 hPa	(45±10) % / 1015.46 hPa	(45±10) % / 1015.46 hPa
Corrected voltage at R_0 and p_0 (V)	1.018 103 149 V	1.018 148 893 V	1.018 114 947 V
Number of measurements	8	8	8
Type A standard uncertainty (nV)	7 nV	11 nV	15 nV
Type B standard uncertainty (nV)	26 nV	30 nV	56 nV
Combined standard uncertainty (nV)	27 nV	32 nV	58 nV
Expanded uncertainty (nV)	54 nV	64 nV	116 nV
Coverage factor k	2.00	2.00	2.00
Effective degrees of freedom	1549	501	1564

K11.5.b (10 V)

Identification of standard	TZS1	TZS2	TZS3
Method of measurement	The traveling standards are calibrated by using the back-to-back method. The thermal offset voltage is eliminated by automatic polarity switching, and we use the floating circuit such that there is no guarding or connection to the earth. The measurements are under bias-off, and the Josephson step number is tuned by JVS650 automatically such that the difference between the Josephson voltage and measured voltage is below 10 μV. Four sets of 10 points in a sequence of polarity of "+", "−", "−", and "+" were taken, with each point being the mean of 3 digital voltmeter readings. It takes about 5 minutes for a single point measurement.		
Date and time of measurement (from to)	From Nov. 27 to Nov. 30, 2013	From Nov. 27 to Nov. 30, 2013	From Nov. 27 to Nov. 30, 2013
Measured voltage (V)	9.999 931 040 V	9.999 995 708 V	9.999 947 290 V
Thermistor resistance (ohm)/ Ambient temperature (°C)	39.70 kΩ/ (23±1.5) °C	38.89 kΩ/ (23±1.5) °C	38.92 kΩ/ (23±1.5) °C
Humidity (% R.H.)/ Pressure (hPa)	(45±10) % / 1015.46 hPa	(45±10) % / 1015.46 hPa	(45±10) % / 1015.46 hPa
Corrected voltage at R_0 and p_0 (V)	9.999 930 786 V	9.999 995 957 V	9.999 947 880 V
Number of measurements	8	8	8
Type A standard uncertainty (nV)	85 nV	64 nV	94 nV
Type B standard uncertainty (nV)	86 nV	60 nV	299 nV
Combined standard uncertainty (nV)	121 nV	88 nV	314 nV
Expanded uncertainty (nV)	248 nV	182 nV	628 nV
Coverage factor k	2.05	2.06	2.00
Effective degrees of freedom	28	25	871

Appendix：Budget of type B Uncertainty

	TZS-1 10 V	TZS-2 10 V	TZS-3 10 V	TZS-1 1.018 V	TZS-2 1.018 V	TZS-3 1.018 V
Uncertainty component due to the temperature correction	70 nV	32 nV	294 nV	2 nV	16 nV	50 nV
Uncertainty component due to the pressure correction	12 nV	11 nV	15 nV	2 nV	1 nV	2 nV
Type B uncertainty of system	49 nV	49 nV	49 nV	25 nV	25 nV	25 nV
Remark	● To evaluate the uncertainty for the temperature correction, we take into account the coefficient uncertainty, the uncertainty of the DMM, and the uncertainty during the measurements. ● To evaluate the uncertainty for the pressure correction, we take into account the coefficient uncertainty, the uncertainty of pressure meter, and the uncertainty during the measurements. ● The type B uncertainty of system includes uncertainty of the frequency stability of the RF source, leakage correction of the cryoprobe, DVM gain error, and offset voltage. The leakage is obtained by evaluating the leakage current of the cryoprobe at the room temperature, and the DVM gain error is obtained by using the Josephson voltage to calibrate the DVM. The zero-point offset voltage is obtained by the zero-point measurement and the uncorrected thermal offset voltage is estimated based on NIST's experience.					

D.4 KRISS (PJVS), Republic of Korea

K11.5.a (1.018 V)

Identification of standard	TZS1	TZS2	TZS3
Method of measurement	Difference Measurement		
Date and time of measurement	from Jun. 19, 2014 to Jul. 15, 2014 AC-power line was disconnected from traveling standards at 05:30 am. Measurements were started 5 hours after the disconnection at least.		
Measured voltage (V)	1.018 102 765	1.018 149 098	1.018 114 860
Thermistor resistance (ohm)/ Ambient temperature (°C)	39,677.1/24.6	38,850.4/24.5	38,859.8/24.6
Humidity (% R.H.)/ Pressure (hPa)	51.9/994.7	51.9/995.0	51.9/995.2
Corrected voltage at R_0 and p_0 (V)	1.018 102 794	1.018 149 161	1.018 115 008
Number of measurements	26	26	26
Type A standard uncertainty (nV)	4.6	6.6	6.7
Type B standard uncertainty (nV)	3.1	19.2	55.2
Combined standard uncertainty (nV)	5.6	20.3	55.6
Expanded uncertainty (nV)	11	41	111
Coverage factor k	2	2	2
Effective degrees of freedom	45	64	52

K11.5.a (10 V)

Identification of standard	TZS1	TZS2	TZS3
Method of measurement	Difference Measurement		
Date and time of measurement	from Jun. 19, 2014 to Jul. 15, 2014 AC-power line was disconnected from traveling standards at 05:30 am. Measurements were started 5 hours after the disconnection at least.		
Measured voltage (V)	9.999 927 42	9.999 994 84	9.999 945 22
Thermistor resistance (ohm)/ Ambient temperature (°C)	39,677.2/24.6	38,851.3/24.5	38,860.0/24.5
Humidity (% R.H.)/ Pressure (hPa)	51.8/994.7	51.9/994.9	52.2/995.0
Corrected voltage at R_0 and p_0 (V)	9.999 927 63	9.999 995 50	9.999 946 33
Number of measurements	26	26	26
Type A standard uncertainty (nV)	52	55	79
Type B standard uncertainty (nV)	38	39	331
Combined standard uncertainty (nV)	64	68	340
Expanded uncertainty (nV)	128	135	680
Coverage factor k	2	2	2
Effective degrees of freedom	53	51	8570

Appendix E: References

[1] L.X. Liu et al, “APMP Comparison of DC voltage,” Report APMP-IC-6-95, 2001.

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

[3] M. G. Cox, “The evaluation of key comparison data,” Metrologia, 39, 589-595 (2002).

[4] D. Reymann, “Link between the comparison EUROMET.EM.BIPM-K11.b and the ongoing comparison BIPM.EM-K11.b,” on-line available from BIPM KCDB.

Appendix F: Comparison protocol

The comparison protocol is given below.

Technical Protocol

Key comparison APMP.EM.BIPM-K11.5: 10 V and 1.018 V DC VOLTAGE

Ver.1.2 (April 11, 2013)

CONTENTS

1. INTRODUCTION

NMIJ (Japan), CMS (Chinese Taipei) and KRISS (Republic of Korea) have recently agreed to organize a key comparison DC voltage between their new programmable Josephson voltage standards (PJVS) to make a link to the key comparison reference value (KCRV). KRISS, who has participated in the related BIPM KCs and coordinated the previous APMP KC (APMP.EM.BIPM-K11.3) decided to participate in their comparison to support their link to the KCRV. This comparison was approved by APMP TCEM and declared as **APMP.EM.BIPM-K11.5**. The same Zener standards as the previous K11.3 will be provided by NMIJ to be used as traveling standards. This KC APMP.EM.BIPM-K11.5 covers comparison of both 1.018 V and 10 V which corresponds to KCs identified by BIPM.EM-K11.a and BIPM.EM-K11.b.

2. TRAVELING STANDARDS

2.1 General requirements

The traveling standard should have good stability of its output voltages during transportation. To reduce the consequences of any unexpected behavior of the traveling standards, several Zener standards are usually used [1]. The three Zener standards, the same as the previous K11.3 will be used as traveling standards for which the temperature and pressure coefficients are already known. Humidity effect of the Zener standards is known to have very slow time response [2]. In view of time schedule of comparison, the humidity effect will be treated as a drift effect when reference value is calculated by interpolation between two reference measurements as in the earlier EUROMET KC [3].

Characteristics of the standards

In Table 1, the temperature and pressure coefficients of the output voltages of the traveling standards are given as determined by NMIJ. The temperature effect is expressed in terms of the oven thermistor resistance (α_R). The coefficient α_R will be used to make corrections for temperature effects (see measurement procedure) because the resistance of the oven temperature thermistor will be used as an indicator for the temperature of the Zener standards.

Table 1: Temperature, humidity and pressure coefficients of 10 V and 1.018 V outputs.
(The uncertainties are stated in terms of combined standard uncertainty, 1 sigma)

Standard	Output	Reference thermistor resistance at R_0 (kΩ)	Temperature coefficient α_R (nV Ω^{-1})	Humidity coefficient α_H(nV %RH^{-1})	Pressure coefficient α_p (nV hPa^{-1})
TZS-1	10 V	39.65	4.3 ± 1.3	<15	17.8 ± 0.7
TZS-2	10 V	39.04	1.9 ± 0.2	<15	16.5 ± 0.5
TZS-3	10 V	39.41	1.3 ± 0.1	<15	21.3 ± 1.1
TZS-1	1.018 V	39.65	0.3 ± 0.0	<1	2.0 ± 0.0
TZS-2	1.018 V	39.04	0.2 ± 0.1	<1	1.4 ± 0.0
TZS-3	1.018 V	39.41	0.2 ± 0.1	<1	2.1 ± 0.2

2.2 Description of standards

The traveling standards, three Fluke 732B electronic DC reference standards, have identification as follows:

TZS-1	s/n 6950003
TZS-2	s/n 6950002
TZS-3	s/n 6950004

The Fluke 732 B electronic DC reference standard has two output voltages, nominally 1.018 V and 10 V, respectively. Each Fluke 732B electronic DC reference standard is fixed in an upgrade-box (18.0 cm x 21.0 cm x 47.0 cm) (Fig. 1). Two additional batteries are installed inside the upgrade-box to extend the battery working time. A BNC type female connector is provided for the measurement of internal thermistor resistance (**see <u>'Measuring the internal thermistor resistance'</u> in Clause 4.2**). The total weight of the upgrade box (with Fluke 732B and batteries) is around 14 kg. Each upgrade box is packed in a transportation case (27 x 27.5 x 55) cm. Note that all three batteries including the original battery inside of the 732B are charged at the same time by the internal charging circuit of the Fluke 732B when AC power is supplied at the rear connector.

Fig. 1: An upgrade-box with Fluke 732B and additional batteries (inside).

2.3 Quantities to be measured

DC voltage outputs 1.018 V and 10 V for the three traveling standards.

2.4 Method of computation of the KCRV

Time drift of the traveling standards will be characterized using results of the Pilot Laboratory. The difference between participant's result and the interpolated time drift will be calculated. Robust evaluation [4] using median of the difference can be used for computation of the KCRV for this comparison.

3. ORGANIZATION

3.1 Coordinator and members of the support group

<u>Coordinator:</u>

The KRISS will coordinate the comparison and act as reference laboratory.

<u>Address for correspondence</u>	<u>Address for dispatching the standards</u>
Dr. Kyu-Tae Kim	Dr. Kyu-Tae Kim
KRISS	Div. Physical Metrology

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Support group:

Support group including the pilot consists of following members;

National Metrology Institute of Japan (NMIJ), Michitaka Maruyama
Center for Measurement Standards (CMS), Ray-Rong Lao
Korea Research Institute of Standards and Science (KRISS), Kyu-Tae Kim

3.2 Participants

National Metrology Institute of Japan (NMIJ), Pilot
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3.3 Time schedule

The comparison will be organized as Table 2.

Table 2: Time schedule

Year	Date of Measurement	Laboratory	System	Country or Economy
2013	September	KRISS	CJVS[2] System	Republic of Korea
	October	NMIJ	PJVS[1] System	Japan
	November	CMS	PJVS[1] System	Chinese Taipei
2014	April	KRISS	CJVS[2] System	Republic of Korea
	June	KRISS	PJVS[1] System	Republic of Korea

[1] PJVS：Programmable Josephson Voltage Standard
[2] CJVS：Conventional Josephson Voltage Standard

If unforeseen circumstances prevent a laboratory from carrying out the measurements within the time allocated, it should send the standards as originally scheduled without delay to the next laboratory in the schedule. Afterwards, the laboratory may be allowed to carry out the measurements before the end of the KC.

3.4 Transportation

The standards will normally be accompanied by an ATA carnet. Each participant is expected to ship using express door-to-door delivery service or to hand-carry the standard to deliver it to the next scheduled laboratory.

Because the standards should always be in the “IN CAL” state, both during transit and measurement, quick and safe transport is essential. Prompt communication with pilot laboratory should be ensured by the participating laboratory regarding the transport information and status of the standards via both email and FAX.

Every arrival and departure of the standards must be communicated to the pilot laboratory and the next scheduled laboratory using the forms that are attached in the Appendix C of this protocol.

Two or three weeks will be allowed for each participant to keep the standards in his (her) laboratory. This period includes recharging of the operation batteries, stabilization to the laboratory environment, and the measurements. **The standards must be sent to the next laboratory according to the schedule (Table 2), even if the laboratory could not finish all measurements.** If the receiver could pick up the standards from the customs earlier than the schedule, the laboratory will be able to have more measurement days. **One week is allocated as the maximum period for the door-to-door transportation of the standards to the <u>next</u> participant**. Both the receiver laboratory and the sender laboratory should report promptly to the pilot laboratory about the transportation. If any delay is expected, the sender and the receiver should promptly contact the pilot laboratory that will give specific instructions.

Please be sure to fully recharge the standards before sending them.

If any participants want to hand-carry the standards by themselves, they may arrange the transportation taking responsibility of the traveling cost. In this case, the transportation information of the standards should be reported to the pilot laboratory.

3.5 Unpacking, handling, packing

The traveling standards should be handled carefully. Extreme temperature, humidity or pressure changes as well as violent mechanical shocks must be avoided. Each participating laboratory is assumed to accept the following duties

- Prompt communication with pilot lab regarding the transport information, status of the standards and measurement report via both email and FAX.
- The transport standard should be handled carefully and be stored in a stabilized environment where relative humidity should be below 55 % R.H.
- Participating lab should fully recharge the transit battery and built-in operation battery (see ‘Powering the standard’ in Clause 3.5) before starting measurement.
- The sending lab is responsible for choosing an express delivery agent that provides a tracking number, with a facility for a real time web-check for the transportation status on the way to the next destination.

- The sending lab should arrange and pay the charge (incl. insurance) for the door-to-door transportation of the standard to the next scheduled lab.

Package

The package contains the following items:

- Fluke 732B electronic DC reference standard s/n 6950003 AIST ref. 00AB6279
- Fluke 732B electronic DC reference standard s/n 6950002 AIST ref. 00AB6278
- Fluke 732B electronic DC reference standard s/n 6950004 AIST ref. 00AB6280
- SUNJEM 9600A upgrade boxes (incl. batteries) (3x)
- Transit cases (3x) AIST ref. 00AF7410 AIST ref. 00AF7411 AIST ref. 00AF7412
- Reusable wooden box which can contain the three transit cases
- Fluke 732B instruction manual
- AC line power cord (3x)
- TR-73U data-logger for temperature, humidity and pressure s/n F806049E
- ATA carnet (732B:JY950,000.-, Carry box: JY100,000.-, TR-72U JY30,000.-, 9600A JY800,000,- cord :JY1,200.- , each)

When the package arrives at your laboratory, fill the "Receiving-the-standard form" in Appendix C and send it to pilot by both email and FAX.

When you are preparing the package for sending, fill the "Shipping-the-standard checklist form" in the Appendix C and put it in the envelope for the next lab in line.

Powering of the standard

As soon as the standards arrive at the laboratory, each Fluke 732B must be supplied from the AC power line so that the attached batteries are fully charged with the self-contained automatic charger. **Be sure to check each AC line voltage selector at the rear of the Fluke 732B before connecting the AC power cable. Be careful not to supply higher than rated voltage to the Fluke 732B! The full recharge will take about half of the transit time.** If any problems are encountered in charging the transit batteries, this must be immediately reported to the pilot laboratory, which will give specific instructions.

After measurements on each working day, the standards must continuously receive uninterrupted voltage from the AC line power overnight or on weekend to fully recharge the standards for next day measurements. At least half of total battery operation time is required to recharge the Fluke 732B. The front panel **AC PWR** indicator lights when the standard is connected to the AC line power.

During measurements, the Fluke 732B should be disconnected from the AC line power. If the internal battery voltage drops low, the front panel **LOW BAT** indicator will start blinking. Then the standard must be plugged into the AC line power immediately to allow the battery to be recharged. The **IN CAL** indicator must be lit "on" during the whole comparison. In any case that the indicator is found to be "off", the laboratory should report immediately to the pilot laboratory, which will give specific instructions.
In order to simplify the charging process, all the additional batteries in the 'Upgrade box' are permanently connected in parallel to the internal battery of the Fluke 732B, so that no other

charging devices are required. By connecting the power cable to the 'Upgrade Box' the self-contained automatic charger of the Fluke 732B will do work of charging.

<u>Front panel indicators</u>

- **AC PWR**
  The AC PWR indicator lights whenever the standard is connected to AC line power (e.g. 220 V, 60 Hz). **<u>Be sure to adjust each AC line voltage selector at the rear of the Fluke 732B before connecting the AC power cable. Be careful not to supply higher than rated voltage to the Fluke 732B!</u>**

- **IN CAL**
  The IN CAL indicator goes out after excessive drops in battery operating voltage or gross changes in oven temperature.
  If the IN CAL indicator doesn't light, you must immediately contact the pilot laboratory, which will give specific instructions how to proceed.

- **CHARGE**
  The CHARGE indicator lights on when the standard is connected to the AC line power and the internal battery is in the charging mode. When the battery is near full charge, the CHARGE indicator goes off.

- **LOW BAT**
  The LOW BAT indicator blinks when approximately 5 hours of battery operation time remains. The standard can keep its internal oven at normal temperature for at least 7 days with the help of permanently attached three batteries.
  When LOW BAT blinks, plug the Fluke 732B into the AC line power immediately to avoid extinguishing the IN CAL indicator. The battery is recharged in about half of the used time with the self-contained automatic battery charger.

3.6 Failure of the traveling standard

In case of any damage or malfunctioning of the standards, the participating laboratory must report immediately to the pilot laboratory. If the standards happen to be cooled because of a delay in customs clearance at receiving laboratory's country, additional uncertainty for the thermal hysteresis will be imposed to the uncertainty of the standards.

3.7 Financial aspects, insurance

The sending laboratory is responsible for choosing an express delivery agent, who is capable of providing a tracking number, which will enable a real time web-check of the transportation status on the way to the next destination (door-to-door).
The sending laboratory should pay the charge for the transportation (incl. insurance: 430,000￥ per each Fluke 732B) of the standard to the next laboratory.
In case the prepared ATA carnet is not accepted in the participant's economy, the customs duty, if applicable, on his/her border should be paid by the participating laboratory.

4. MEASUREMENT INSTRUCTIONS

4.1 Tests before measurements

Precautions

- Do not short the outputs.
- Make sure not to disconnect the standard from the AC line power for too long.
- Avoid extreme temperature, humidity or pressure changes as well as violent impacts.

Stabilization of the standards

After arrival in the participant's laboratory, the standards should be allowed to stabilize in a temperature and, possibly, humidity controlled room for at least four days before the measurements can begin.
The traveling standard should be handled carefully and be stored in a stabilized environment where relative humidity should be below 55 %.

Powering of the standard during the measurements

When not carrying out measurements, the standards must be connected continuously to the AC line power. Measurement can be carried out after full charge, i.e., after charge indicator turns off.
Measurements should be carried out with the standard disconnected from the AC line power. To allow the standard to stabilize, measurements should not begin any sooner than 4 hours after disconnecting the standard from the AC line power. Connect the AC line after finishing the measurements to recharge the standards. (See **'LOW BAT' in Clause 3.5)**

In addition to the battery-operated measurements, measurements can be made (and submitted to the pilot laboratory) with the standards connected to the AC line power. Notice that connection to the AC line power during measurement will probably have consequences for the connection of guard and/or ground.

4.2 Measurement Performance

Guarding

Assuming that you carry out the voltage measurements with the Fluke 732B's disconnected from the AC line power, instead of the internal GUARD binding post of the Fluke 732B, the CHASSIS (green terminal marked as "GROUND") of the upgrade box should be connected to the guard of your measuring system. At one point in your system the guard should be connected to ground.

Measuring the internal thermistor resistance

The internal thermistor resistance must be reported for each measurement result of output voltage. The thermistor resistances of the standards have nominal values between 38 kΩ and 40 kΩ (see Table 1). To avoid heating of the thermistor, the test current should **not exceed 10 µA**. This implies that most DMMs can not be used in their 100 kΩ range or auto-range setting.

Environmental conditions

The ambient temperature, humidity and pressure must be measured. Corrections must be made for temperature and pressure effects (see next section). Recommended measurement conditions are 23 °C and below 55 %RH.

During transport and stay at the participant's laboratory, the environmental temperature and humidity will be recorded by the data-logger in transit case to check any extreme change in environment. However, please use your own measurement instruments to report more precisely the temperature, relative humidity, and atmospheric pressure during your measurement.

4.3 Method of measurement

Making corrections for temperature and pressure effects

The measured voltages U_{measured} should be corrected for temperature and pressure effects. The temperature effect is taken into account through the thermistor resistance R. The following formula should be used to calculate the corrected voltages $U_{\text{corrected}}$:

$$U_{\text{corrected}} = U_{\text{measured}} - \alpha_{\text{R}} \cdot (R - R_0) - \alpha_{\text{p}} \cdot (p - p_0),$$

where α_{R} and α_{p} are the temperature and pressure coefficients as given in Table 1, p is the ambient air pressure, and p_0 = 1013.25 hPa the reference air pressure. The reference thermistor resistances R_0 depend on the specific standard and are given in Table 1.

Obviously, the uncertainties of both the thermistor resistance measurement and the air pressure measurement contribute to the total uncertainty of measurement.

5. UNCERTAINTY OF MEASUREMENT

5.1 Main uncertainty components, including sources and typical values

The uncertainty calculations must comply with the requirements of the 'Guide to the Expression of Uncertainty in Measurement' (issued by the International Organization for Standardization, first edition 1993, ISBN 92-67-10188-9). Foreseen sources of uncertainty:

- Type A
- DVM or null-detector gain-error uncertainty
- Uncertainty due to irreversibility of scanner or switch
- Leakage-error uncertainty
- Uncertainty due to uncompensated offset voltages
- Microwave-frequency uncertainty
- Uncertainty due to EMI
- Calibration uncertainty of measurement equipment (e.g., for measuring the thermistor resistance, pressure, etc.)

This is not a complete list and should be extended with uncertainty contributions that are specific for the participant's measurement system.

5.2 Scheme to report the uncertainty budget

See Appendix B and Chapter 6

6. MEASUREMENT REPORT

Software

The participant's report must be sent to the pilot laboratory within <u>two months</u> from the completion of his measurements. Reports should be submitted electronically, using the following software:

- Word 2003 or later version for the report including the participant's results
- Excel 2003 or later version for the raw data and detailed uncertainty budget

Contents of report

The report must contain:

- **<u>The results of the measurement</u>**
  For each reported value the following information must be provided using the form attached in Appendix:
  - identification of standard
  - method of measurement
  - date and time of measurement
  - waiting time before starting measurement after disconnect AC line from the Fluke 732B
  - measured voltage
  - thermistor resistance
  - ambient temperature, humidity, and pressure
  - values of correction for temperature and pressure effects
  - measured voltage corrected for temperature and pressure effects
  - the Type A standard uncertainty
  - the Type B standard uncertainty
  - combined standard uncertainty
  - the expanded uncertainty of measurement (confidence level of appr. 95 %)
  - effective degrees of freedom

- **<u>Uncertainty budget and calculation</u>**
  The uncertainty analysis should include a list of all sources of Type B uncertainty, together with the associated standard uncertainties as well as their evaluation method. For clarity, it is recommended to present the uncertainty budget in the form of a table (see, e.g., chapter 4 of the EA-4/02 document 'Expression of the Uncertainty of Measurement in Calibration').
  For each reported value, the expanded uncertainty of measurement and the coverage factor *k* must be given for confidence level of approximate 95 %.

- **<u>Description of the method of measurement</u>**
  This includes information on:
  - the method applied for correction of offset voltages
    (manual or automatic switching, reversal of null-detector or not, etc.)
  - the method applied for guarding and shielding, and connection to earth
  - method applied for biasing the Josephson array
    (bias on or off during measurement)

- method for Josephson step number adjustment and maximum value of null voltage
- ‘bandwidth’ of the voltage measurement (null-detector analog or digital filtering, number of samples, averaging, etc.)

7. REPORT OF THE COMPARISON

The draft version of the final report will be issued within four months after completion of the comparison. The draft report will be sent to the participants and will be discussed. The whole procedure will be based on the CCEM Guidelines document WGLF/2007-12.

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

[5] EA-4/02 “Expression of the Uncertainty of Measurement in Calibration”.

APPENDIX A: List of participants

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APPENDIX B: Forms for Summary Report

K11.5.a (1.018 V)

Identification of standard	TZS1	TZS2	TZS3
Method of measurement			
Date and time of measurement (from to)			
Measured voltage (V)			
Thermistor resistance (ohm)/ Ambient temperature (^{o}C)			
Humidity (% R.H.)/ Pressure (hPa)			
Corrected voltage at R_0 and p_0 (V)			
Number of measurements			
Type A standard uncertainty (nV)			
Type B standard uncertainty (nV)			
Combined standard uncertainty (nV)			
Expanded uncertainty (nV)			
Coverage factor k			
Effective degrees of freedom			

K11.5.b (10 V)

Identification of standard	TZS1	TZS2	TZS3
Method of measurement			
Date and time of measurement (from to)			
Measured voltage (V)			
Thermistor resistance (ohm)/ Ambient temperature (^{o}C)			
Humidity (% R.H.)/ Pressure (hPa)			
Corrected voltage at R_0 and p_0 (V)			
Number of measurements			
Type A standard uncertainty (nV)			
Type B standard uncertainty (nV)			
Combined standard uncertainty (nV)			
Expanded uncertainty (nV)			
Coverage factor k			
Effective degrees of freedom			

APPENDIX C: Forms for Transportation Report

(See next pages)

APMP.EM.BIPM-K11.5 COMPARISON

Shipping-the-standard form No 1
(Send this form to the pilot as soon as you have shipped the standard)

Date …………….. **Pages**……………..**(**including this one)

TO	
FROM	

Comments on the behavior of the standard:

The standard has been shipped to the address:

Shipped on: ***Date***…………… ***Time*** …………….

Means of transport: ***Airplane*** ☐ ***Other*** …………..

Carrier:

Comments on shipment (include tracking number):

APMP.EM.BIPM-K11.5 COMPARISON

Shipping-the-standard form No 2

(Send this form to both the pilot and the lab next in line, as soon as you have shipped the standard)

Date …………….. **Pages**……………..**(**including this one)

TO	
FROM	

Comments on the behavior of the standard:

The standard has been shipped to the address:

Shipped on: ***Date***…………… ***Time*** …………….

Means of transport: ***Airplane*** ☐ ***Other*** …………..

Carrier:

Comments on shipment (include tracking number):

APMP.EM.BIPM-K11.5 COMPARISON fax

Receiving-the-standard form

(Send this form to the pilot laboratory as soon as you receive the standard)

Date …………….. **Pages**……………..(including this one)

TO	
FROM	

Arrival at the lab: *Date* **………** *Time***……………**

IN CAL lamp ***ON*** □ ***Off*** □

LOW BAT lamp ***Blinks*** □ ***Off*** □

Was the TR-73U data-logger for temperature, humidity and pressure working well? ***Yes*** □ ***No*** □

Was the package damaged? **Yes** □ **No** □

Comments:

Was the standards damaged? **Yes** □ **No** □

Comments:

Was all the material available, following the receiving checklist? **Yes** □ **No** □

Comments:

APMP.EM.BIPM-K11.5 COMPARISON

Shipping-the-standard checklist form.
(While you are making the package ready, check that all material is included)

Are these items in the package?

	YES ☐	NO ☐
Three Fluke 732B's with upgrade box	YES ☐	NO ☐
Data-logger for temperature, humidity and pressure	YES ☐	NO ☐
Fluke732B instruction manual	YES ☐	NO ☐
ATA Carnet	YES ☐	NO ☐
Sealed envelopes for laboratories next in line in your circulation loop	YES ☐	NO ☐

Recharge of the batteries:

Did you fully recharge the operation batteries?	YES ☐	NO ☐

Please, when the package is ready, seal it in the most convenient way for you in order to prevent unauthorised access to the instrument. Refer to the pilot laboratory co-ordinator if you need further information.

Checked by ____

Date ____