Final Report

EUROMET key comparison supplementing BIPM.EM-K10.a

"Comparison of Josephson array voltage standards by using a portable Josephson transfer standard"

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1. Introduction

In the Mutual Recognition Arrangement (MRA) it is stated, that the metrological equivalence of national measurement standards will be determined by a set of key comparisons chosen and organised by the Consultative Committees of the CIPM working closely together with the Regional Metrology Organisations (RMO's). In order to link more laboratories organised in EUROMET this RMO key comparison (EUROMET Project No. 723) supplementing BIPM.EM-K10.a was carried out. In addition, the comparison provides a link between institutes and BIPM via a portable Josephson voltage standard. The comparison was performed in a similar way as the bilateral Josephson voltage standard comparisons of the NMIs with the BIPM (see BIPM.EM-K10.a). As BIPM has also participated in this EUROMET comparison, we have an indirect link to BIPM (NMI - Transfer Standard - Transfer Standard - BIPM). In the KCDB the differences NMI - BIPM will be given together with the combined uncertainty of the two measurements. The KCRV will be the voltage supplied by the BIPM Josephson voltage standard, and therewith will be the same as for BIPM.EM-K10.a assumed that the output voltage of the BIPM standard will not change with time.

At the EUROMET Meeting of the Experts in Electrical DC and Quantum Metrology June 16 to 18, 2003, Bratislava, Slovakia a report of VNIIM and PTB was presented, showing that a suitable travelling standard was available. The comparison then started in October 2003, with PTB as the pilot laboratory, and finished in June 2004.

The mandatory value to be measured was 1 V with a 4 Ω output resistance of the portable Josephson voltage standard (PJVS) while an output resistance of 1.2 kΩ was requested as an option. Only the measurement of the mandatory value is considered in this report for the evaluation of the degrees of equivalence of the participants. These degrees of equivalence are reported in Appendix B. The uncertainty budgets are reported in Appendix C while the optional measurements are reported in Appendix D. The protocol of the comparison, reported in Appendix E, was prepared whilst paying attention to the requirements of the BIPM "Guidelines for CIPM Key Comparisons".

2. Participants and schedule

Twelve NMIs, plus BIPM, agreed to participate in the comparison. Table 1 lists all the participant laboratories in chronological order and the periods of their measurements. The dates of preliminary measurements are reported in Appendix A. The last column of the table reports the main events occurred during the comparison.

Instituto Nacional de Engenharia e Tecnologia Iundustrial (INETI/LME), Portugal, was listed in the preliminary schedule of the Technical Protocol, however the installation and verification of their new Josephson voltage standard took more time than planned. Therefore, the institute decided to withdraw from the comparison.

Table 1. List of participants and measurement dates.

Acronym	National Metrology Institute	Country	Loop	Standard at the laboratory	Comment
VNIIM	D. I. Mendeleyev Institute for Metrology	Russia	0	29-30 September 2003	
UME	Ulusal Metroloji Enstitusu	Turkey	1	13-17 October 2003	
PTB **Pilot**	Physikalisch-Technische Bundesanstalt	Germany	1	17-20 October 2003	
SP	Swedish National Testing and Research Institute	Sweden	1	20-23 October 2003	
NPL	National Physical Laboratory	U. K.	2	10-13 November 2003	
DFM	Danish Institute of Fundamental Metrology	Denmark	2	13-16 November 2003	Change of broken array in the PJVS
IEN	Istituto Elettrotecnico Nazionale Galileo Ferraris	Italy	2	16-20 November 2003	Change of broken array in the PJVS
EIM	Hellenic Institute of Metrology	Greece	3	9-14 February 2004	Change of array in the PJVS
BIPM	Bureau International des Poids et Mesures	International	3	21-24 March 2004	
MIKES	Centre for Metrology and Accreditation	Finland	3	24-27 March 2004	
GUM	Central Office of Measures	Poland	4	19-22 May 2004	
CMI	Czech Metrology Institute	Czech Republic	4	22-25 May 2004	
NMi-VSL	NMi Van Swinden Laboratorium	The Netherlands	4	25-28 May 2004	

Each participant had two or three days to carry out the measurements and was expected to ship the travelling standard to the next scheduled laboratory. A solid enclosure was provided so that the travelling standard could be shipped as hand luggage. After arrival the standard had to be maintained in a temperature controlled room for at least two hours before use. The standard was accompanied by an ATA carnet.

During the comparison the Josephson array was changed several times which resulted in a change of the PJVS output voltage. The changes of array were necessary because of damage which occurred during transportation. First this happened when the PJVS was transported from NPL to DFM in November 2003 and again when transporting the PJVS from DFM to IEN. After these bad experiences it was decided to remove the Josephson array from the PJVS before transportation.

During the time between loop 2 and loop 3 PTB supplied new arrays with larger current width of the voltage step and one of these was selected for the remainder of the comparison.

3. Transfer Standard and required measurements

The travelling standard was the VNIIM portable Josephson voltage standard (MN-1). It has a 1 V fixed output voltage and its value depends on the number of Josephson junctions in array. The PJVS has an output resistances of 4 Ω and optional 1.2 kΩ. The PJVS requires a time base of 5 MHz or 10 MHz. During all comparisons the PJVS was connected to the same time base as that used by the laboratory Josephson voltage standard (JVS).

Array	Name of array	Output Voltage / V	Institute	Remarks
1	JK-401/6	1.09	VNIIM	
1	JK-401/6	1.09	UME	
1	JK-401/6	1.09	PTB	
1	JK-401/6	1.09	SP	
2	JK-401/6	1.09	NPL	Array broken
3	AlD-112/6	1.11	DFM	Array broken
4	AlD-140/9	1.23	IEN	Replaced by an array with larger step width
4	BE-1/15	1.07	EIM	Modified number of junctions due to broken connection to pad
4	BE-1/15	1.03	BIPM	
4	BE-1/15	1.03	MIKES	
4	BE-1/15	1.03	GUM	
4	BE-1/15	1.03	CMI	
4	BE-1/15	1.03	NMi-VSL	

The required voltages to be measured by the JVSs were:

1.09 V VNIIM, UME, PTB, SP, NPL, array #1, JK-401/6, broken during transportation
1.11 V DFM, array #2, ALD-112/6, broken during transportation
1.23 V IEN, array #3, ALD-140/9, replaced by Be-1/15 with higher step width
1.07 V EIM, array #4, Be-1/15, modified number of junctions used due to broken some connection of junctions from pads
1.03 V BIPM, MIKES, GUM, CMI, NMi-VSL, array #4, Be-1/15

4. Behaviour of the transfer standard

The portable Josephson voltage standard is described in detail in two publications [1, 2], and has been tested by a bilateral direct comparison before starting this project [1]. The uncertainty of the PJVS output voltage does not depend on the number of Josephson junction in the array, and neither on transportation, temperature, humidity or pressure. Therefore, no further measurements or calibrations of the standard were necessary.

The preliminary comparison also showed that an additional uncertainty of the PJVS can be caused by electromagnetic interference (EMI) between the PJVS and the standard to which it is compared. The level of uncertainty depends on the amount of EMI and on the choice of measurement shield reference point. More information on this is given in Appendix E.

5. Measurement methods

The methods of the measurements used by the participants were all very similar. The PJVS and the laboratory JVS were connected in series opposition and the voltage difference was read with a null detector. Both systems were driven by the same 10 MHz frequency reference and polarity reversal of both standards ensured that all thermal electromotive forces (EMF) were cancelled.
The observed differences between laboratory measurements are a result of the different types of null detectors used and differences in the measurement routines. These details are important for the uncertainty calculation and are reported for each institute in appendix C.
Further information about the setting-up phase and a short description of equipment at the institutes can be found in appendix E.

6. Results of 1 V measurements with 4 Ω output resistance:

a) Participant results

Table 1 summarises the reported measurement results of each laboratory as a relative difference to the nominal value of the PJVS $d_{LAB} = (U_{\text{PJVS}} - U_{LAB}) / U_{LAB}$, the standard uncertainties of the measurement u_A (type A), the instrumental uncertainty u_B (type B), and the corresponding standard uncertainty u of the laboratory.

Table 1. Results of the laboratories

Lab	$d_{LAB} / 10^9$	$u_A / 10^9$	$u_B / 10^9$	$u_{LAB} / 10^9$
VNIIM	+0.05	0.09	0.08	0.12
UME	-0.06	0.26	0.25	0.36
PTB	+0.01	0.22	0.06	0.23
SP	+0.04	0.37	1.08	1.14
NPL	+1.3	0.55	0.20	0.59
DFM	-0.14	0.50	0.25	0.56
IEN	+0.10	0.29	0.11	0.31
EIM	+1.0	0.89	2.0	2.2
MIKES	-0.04	0.06	0.11	0.13
GUM	-1.2	1.1	2.9	3.1
CMI	+0.8	0.5	2.5	2.5
NMi-VSL	-1.6	5.9	1.0	6.0

After distributing the draft A report a few typing errors that slipped in or mistakes in the calculation of values have been corrected.
EIM and GUM have corrected their uncertainty budgets. For transparency both budgets from each laboratory are presented in the appendix. EIM has corrected their thermal emf estimation. GUM has modified their estimation for the null detector uncertainty. Now the calculation is based on daily internal calibrations of the detector and two calibrations against a well-known Zener, one directly before and the

other one directly after the comparison.

b) Link to the BIPM key comparison reference value

Table 2 reports the measurement result of BIPM as a difference to the nominal value of the PJVS $d_R = (U_{\mathrm{PJVS}} - U_{BIPM}) / U_{BIPM}$; the relative standard uncertainties (type A and type B) reported by the BIPM, the corresponding relative combined standard uncertainty u_{R} and the degree of freedom ν_{R}.

Lab	d_{R} / 10^{-9}	u_{A} / 10^{-9}	u_{B} / 10^{-9}	u_{R} / 10^{-9}	ν_{R}
BIPM	+0.07	0.12	0.05	0.13	80

Table 2. Results of BIPM

c) Degrees of equivalence with respect to the key comparison reference value (KCRV)

Following the Mutual Recognition Arrangement of the CIPM [3], the degree of equivalence of a laboratory with respect to the KCRV is given by two numbers: the difference of the laboratory's result with respect to the KCRV and the expanded uncertainty of this difference. This expanded uncertainty must be calculated at 95% level of confidence, which requires the knowledge of the degrees of freedom ν, associated with the standard uncertainty of the difference.

Table 3 reports the laboratory differences with respect to the KCRV $d_i = d_{LAB} - d_{\mathrm{R}}$, the standard uncertainty of the laboratory differences u_{LAB} and the corresponding number of degrees of freedom ν_{LAB}, the standard uncertainty $u(d_i) = (u_{LAB}(d_i)^2 + u_{\mathrm{F}}^2 + u_{\mathrm{R}}^2)^{1/2}$ of the difference d_i and the associated degrees of freedom ν_{eff}, the standard uncertainty of the time base u_{F}, the expansion factor k_{95} corresponding to a level of confidence of 95% from the Student's distribution and, in the last column, the expanded uncertainty $U(d_i) = k_{95}\, u(d_i)$.

Table 3. Degrees of equivalence

Lab	d_i /10^{-9}	$u_{LAB}(d_i)$ /10^{-9}	u_{F}* /10^{-9}	ν_{LAB}	u_{R} /10^{-9}	$\nu_{\mathrm{R},}$	$u(d_i)$ /10^{-9}	ν_{eff}	k_{95}	$U(d_i)$ /10^{-9}
VNIIM	-0.02	0.12	0.22	172	0.13	80	0.26	246	1.97	0.52
UME	-0.13	0.36	<0.01	116	0.13	80	0.38	145	1.98	0.76
PTB	-0.06	0.23	<0.01	91	0.13	80	0.26	142	1.98	0.52
SP	-0.03	1.14	<0.01	60	0.13	80	1.15	62	2.00	2.3
NPL	+1.23	0.59	<0.01	703	0.13	80	0.60	757	1.97	1.2
DFM	-0.21	0.56	<0.01	∞	0.13	80	0.57	∞	1.97	1.1
IEN	0.03	0.31	<0.01	12	0.13	80	0.33	17	2.11	0.71
EIM	0.93	2.2	<0.01	31	0.13	80	2.2	31	2.04	4.5
MIKES	-0.11	0.13	<0.01	69	0.13	80	0.18	148	1.98	0.36
GUM	-1.27	3.1	<0.01	64	0.13	80	3.1	64	2.00	6.2
CMI	0.73	2.5	<0.01	27	0.13	80	2.5	27	2.05	5.1
NMi-VSL	-1.67	6.0	<0.01	24	0.13	80	6.0	24	2.06	12.4

* The uncertainty for the time base frequency was not part of this comparison as always both systems have been connected to the same frequency reference. To give the degrees of equivalence between institutes for the unit of Volt this uncertainty component has to be taken into account. For most institutes this uncertainty component is negligible in relation to all other contributions.

d) Bilateral degrees of equivalence

Similarly to the degrees of equivalence with respect to the KCRV, the degrees of equivalence between two laboratories (bilateral degrees of equivalence) are given by the difference between the laboratory results and by the uncertainty of this difference, at 95% confidence level. Because the laboratory measurements are not correlated, the standard uncertainty of the laboratory difference is simply the quadratic summation of their standard uncertainties. The corresponding effective degrees of freedom can be calculated from those of the two laboratories using the Welch-Satterthwaite formula.

The bilateral degrees of equivalence are reported, together with the degrees of equivalence with respect to the KCRV, in Appendix B, in a format compliant with the requirements of the Key Comparison Data Base. As we assume the transfer standard to be stable and without significant uncertainty the data are not correlated.

7. Conclusion

In this comparison a new portable Josephson voltage standard (PJVS) has been used as a travelling standard accompanied and operated by a specialist. In contrast to most direct comparisons carried out by BIPM, the NMIs had to use their own null detector, polarity switch and measurement procedure to measure the output voltage of the PJVS. This method of comparison is more closely related to standard electronic voltage reference (e.g. Zener) measurements but without the limitation to their noise.

Even though the time for carrying out the measurements was limited at each institute, all deviations from the nominal value and uncertainties demonstrate a very high level of equivalence between the institutes. The observed differences in uncertainties are mostly caused by different measurement routines used which follow more or less electronic reference standard calibration routines usually performed.

The overall uncertainties presented by each institute cover each measured deviation to the nominal value of the travelling standard at the 95% confidence level ($k = 2$). Just the type A uncertainties ($k = 1$, 66 % confidence level) are sufficient to do so for 9 of 13 institutes (69 %). This might be due to two reasons. Firstly, type B uncertainties are not important or still overestimated sometimes, and secondly, the known value of the travelling quantum standard leads naturally to small deviations. An advantage of the prompt feedback is, however, that possible errors are obvious immediately and can be eliminated at once.

Finally, it has been demonstrated that the idea of using a portable quantum standard based on a programmable Josephson array as a travelling standard is a powerful tool to achieve equivalence between institutes fast and at a very good level of uncertainty. For the future a portable system with an unknown value might be preferable to demonstrate that the good equivalence is not just a result of the known value.

8. References

[1] A. Katkov, R. Behr, G. Telitchenko, and J. Niemeyer, "VNIIM-PTB comparison using a portable Josephson voltage standard," Metrologia 40, pp. 89-92, 2003.

[2] A. Katkov, V. Lovtsus, R. Behr, and J. Niemeyer, "Transportable Josephson voltage standard," CPEM'02 Conf. Dig., Conference on Precision Electromagnetic Measurements, Ottawa, Canada, 16-21 June 2002.

[3] Mutual Recognition of National Measurement Standards and of Calibration and Measurement Certificates Issued by National Metrology Institutes, endorsed by the International Committee on Weight and Measures, text available on the BIPM web site (www.bipm.fr).

APPENDIX A

Description of the portable Josephson standard

The portable Josephson voltage standard (PJVS) is described in detail in two publications [1, 2], and it has been tested by a bilateral direct comparison before starting this project.

No further measurements or calibrations of the standard were necessary as the travelling standard is a quantum standard immune to changes due to time or environmental conditions. Therefore, the protocols of the measurements at PTB and BIPM can be found in Appendix E together with all other protocols.

APPENDIX B

Degrees of equivalence for 1.018V

Key comparison EUROMET.EM.BIPM-K10.a

MEASURAND: DC Voltage

NOMINAL VALUE: 1.018 V

Pilot laboratory: PTB

TRAVELLING STANDARD: Portable Josephson Voltage Standard of VNIIM

d_i : results of measurements carried out by laboratory *i*, and related to the fractional difference $d_{0,i}$ from the nominal value, 1.018 V, by:

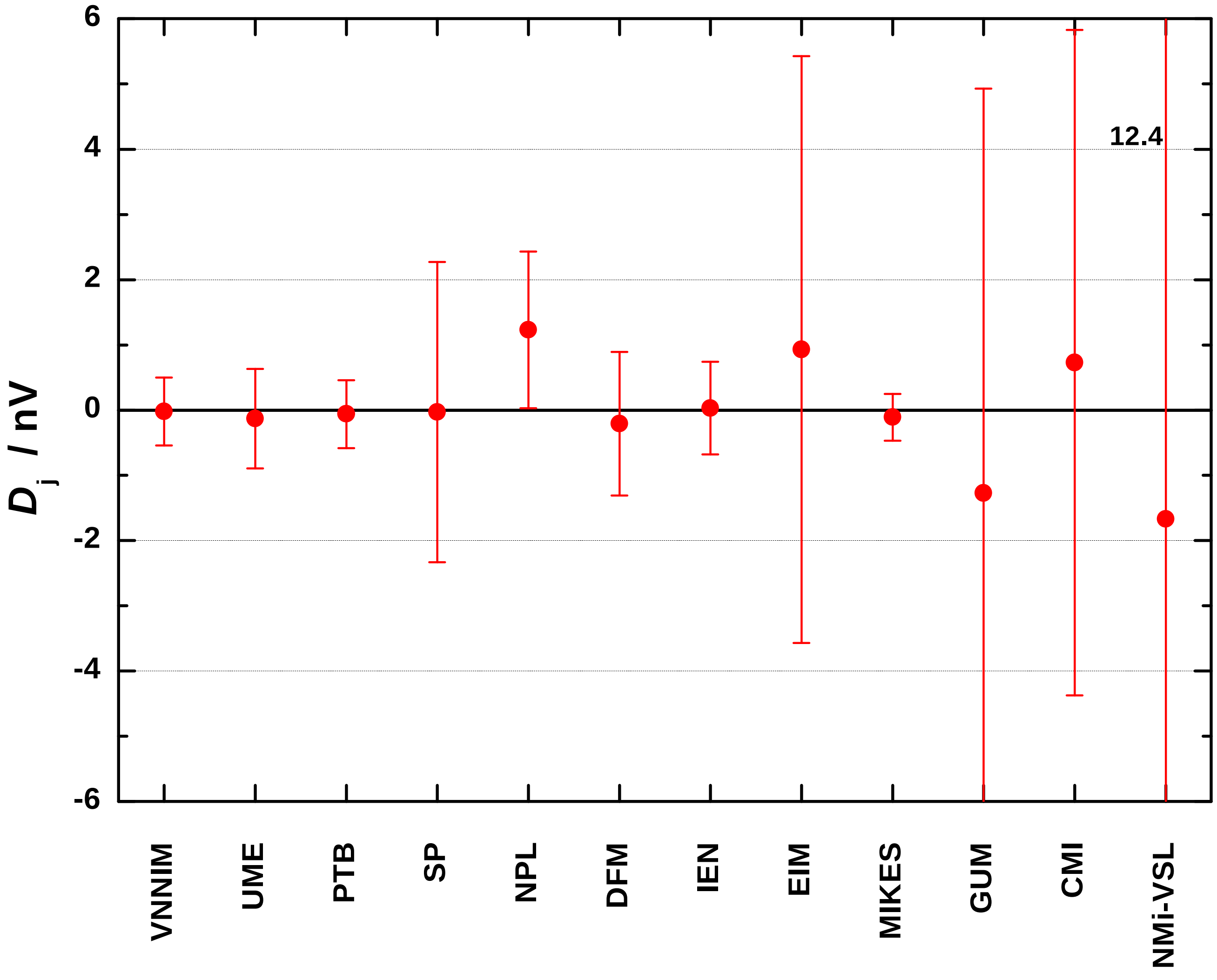
$x_{0,i}$ = 1.018 x (1+ $d_{0,i}$)

u_i : Relative expanded uncertainty of laboratory *i*

$\nu_{i,\mathrm{eff}}$: number of degrees of freedom of laboratory *i*

Lab *i*	$d_{0,i}/10^{-9}$	$u_i/10^{-9}$	$\nu_{i,eff}$	Date of measurement
VNIIM	-0.02	0.52	246	2003-09-29
UME	-0.13	0.76	145	2003-10-14
PTB	-0.06	0.52	142	2003-10-19
SP	-0.03	2.3	62	2003-10-22
NPL	+1.23	1.2	757	2003-11-12
DFM	-0.21	1.1	> 10^6	2003-11-15
IEN	+0.03	0.71	17	2003-11-19
EIM	+0.93	4.5	31	2004-02-12
MIKES	-0.11	0.36	148	2004-04-26
GUM	-1.27	6.2	64	2004-05-21
CMI	+0.73	5.1	27	2004-05-24
NMi-VSL	-1.67	12.4	24	2004-05-27

MEASURAND : DC voltage, Josephson standards
NOMINAL VALUE : 1.018 V
Degrees of equivalence D_i and expanded uncertainty U_i (k = 2)



APPENDIX B

Key comparison EUROMET.EM.BIPM-K10.a

MEASURAND: DC Voltage **NOMINAL VALUE: 1.018 V**

The key comparison reference value, Δ_R, of this comparison is the BIPM result of PJVS measurement. It gives the relative deviation of the nominal output voltage of PJVS. The standard uncertainty associated with Δ_R is the standard deviation of the result. It is found:

Δ_R = 0.07 10^{-9} with standard uncertainty of 0.13 10^{-9} and 80 degrees of freedom.

The degree of equivalence of each laboratory with respect to the reference value is given by a pair of numbers: $D_i = (\Delta_i - \Delta_R)$, where Δ_i is the relative difference between laboratory and the PJVS, and the corresponding expanded uncertainty $U(D_i)$, assessed for a level of confidence of 95%.

The degree of equivalence between two laboratories is given by a pair of numbers: *Dij* = (*Di* - *Dj*) and the corresponding expanded uncertainty *Uij*, assessed for a level of confidence of 95%. The laboratory results are not correlated.

Table B1. Value 1.018 V

			VNIIM		UME		PTB		SP		NPL		DFM		IEN	
	D_i /10^{-9}	$U(D_i)$ /10^{-9}	D_{ij} /10^{-9}	U_{ij} /10^{-9}	D_{ij} /10^{-9}	U_{ij} /10^{-9}	D_{ij} /10^{-9}	U_{ij} /10^{-9}	D_{ij} /10^{-9}	U_{ij} /10^{-9}	D_{ij} /10^{-9}	U_{ij} /10^{-9}	D_{ij} /10^{-9}	U_{ij} /10^{-9}	D_{ij} /10^{-9}	U_{ij} /10^{-9}
VNIIM	-0.02	0.52	*	*	0.11	0.9	0.04	0.7	0.01	2.4	-1.25	1.3	0.19	1.2	-0.05	0.9
UME	-0.13	0.76	-0.11	0.9	*	*	-0.07	0.9	-0.1	2.4	-1.36	1.4	0.08	1.3	-0.16	1.0
PTB	-0.06	0.52	-0.04	0.7	0.07	0.9	*	*	-0.03	2.4	-1.29	1.3	0.15	1.2	-0.09	0.9
SP	-0.03	2.3	-0.01	2.4	0.1	2.4	0.03	2.4	*	*	-1.26	2.6	0.18	2.5	-0.06	2.4
NPL	1.23	1.2	1.25	1.3	1.36	1.4	1.29	1.3	1.26	2.6	*	*	1.44	1.6	1.2	1.4
DFM	-0.21	1.1	-0.19	1.2	-0.08	1.3	-0.15	1.2	-0.18	2.5	-1.44	1.6	*	*	-0.24	1.3
IEN	0.03	0.71	0.05	0.9	0.16	1.0	0.09	0.9	0.06	2.4	-1.2	1.4	0.24	1.3	*	*
EIM	0.93	4.5	0.95	4.5	1.06	4.6	0.99	4.5	0.96	5.1	-0.3	4.7	1.14	4.6	0.9	4.6
MIKES	-0.11	0.36	-0.09	0.6	0.02	0.8	-0.05	0.6	-0.08	2.3	-1.34	1.3	0.1	1.2	-0.14	0.8
GUM	-1.27	6.2	-1.25	6.2	-1.14	6.2	-1.21	6.2	-1.24	6.6	-2.5	6.3	-1.06	6.3	-1.3	6.2
CMI	0.73	5.1	0.75	5.1	0.86	5.2	0.79	5.1	0.76	5.6	-0.5	5.2	0.94	5.2	0.7	5.1
NMi-VSL	-1.67	12.4	-1.65	12.4	-1.54	12.4	-1.61	12.4	-1.64	12.6	-2.9	12.5	-1.46	12.4	-1.7	12.4

	EIM		MIKES		GUM		CMI		NMi-VSL							
	D_{ij} /10^{-9}	U_{ij} /10^{-9}	D_{ij} /10^{-9}	U_{ij} /10^{-9}	D_{ij} /10^{-9}	U_{ij} /10^{-9}	D_{ij} /10^{-9}	U_{ij} /10^{-9}	D_{ij} /10^{-9}	U_{ij} /10^{-9}						
VNIIM	-0.95	4.5	0.09	0.6	1.25	6.2	-0.75	5.1	1.65	12.4						
UME	-1.06	4.6	-0.02	0.8	1.14	6.2	-0.86	5.2	1.54	12.4						
PTB	-0.99	4.5	0.05	0.6	1.21	6.2	-0.79	5.1	1.61	12.4						
SP	-0.96	5.1	0.08	2.3	1.24	6.6	-0.76	5.6	1.64	12.6						
NPL	0.3	4.7	1.34	1.3	2.5	6.3	0.5	5.2	2.9	12.5						
DFM	-1.14	4.6	-0.1	1.2	1.06	6.3	-0.94	5.2	1.46	12.4						
IEN	-0.9	4.6	0.14	0.8	1.3	6.2	-0.7	5.1	1.7	12.4						
EIM	*	*	1.04	4.5	2.2	7.7	0.2	6.8	2.6	13.2						
MIKES	-1.04	4.5	*	*	1.16	6.2	-0.84	5.1	1.56	12.4						
GUM	-2.2	7.7	-1.16	6.2	*	*	-2	8.0	0.4	13.9						
CMI	-0.2	6.8	0.84	5.1	2	8.0	*	*	2.4	13.4						
NMi-VSL	-2.6	13.2	-1.56	12.4	-0.4	13.9	-2.4	13.4	*	*						

Appendix C
Participant uncertainty budget for value 1 V at 4 Ω

In the following the participant uncertainty budgets for 1 V are given. Because no common scheme to report the uncertainty had been established in the comparison protocol, these budgets were at the beginning difficult to compare. Towards the end of the comparison, the pilot laboratory asked all participants to rewrite their budgets in a common format. Fortunately all laboratories did comply with this request. Of course the new budgets had to report the same global uncertainty initially submitted.

The methods of the measurements used by the participants are all very similar. The portable Josephson voltage transfer standards (PJVS) and the laboratory JVS were connected in series opposition and the voltage difference was read by a null detector. Both systems are driven by the same 10 MHz frequency reference. By polarity reversal of both standards all thermal EMF are cancelled.
Differences between the laboratory measurements appear because of different types of null detectors and different routines changing polarity and periods of data measurements. These details are important for the uncertainty calculation and are reported for each institute.
Further information about the setting-up phase and a short description of equipment at all institutes can be found in appendix E.

Uncertainty budget of VNIIM, Russia

Output resistance of the PJVS: 4 Ω

$U_0 = N_{PJVS}\, f_{PJVS} / K_{J-90}$: **1.087 156 337 94 V.**

Quantity	Estimate	Uncertainty	Type	Probability distribution	Standard uncertainty	Sensitivity coefficient	Uncertainty Contribution	Degree of freedom
Measured mean voltage	1.087 156 337 89 V	0.1 nV	A	normal	0.16 nV	1	0.1 nV	6
Frequency*	74.882 GHz	8 Hz	B	rectangular	4.5 Hz	14.5 pV/Hz	0.07 nV	20
V_{leak}	0 nV **	0.07 nV	B	rectangular	0.04 nV	1	0.04 nV	5
V_{det}	1 µV***	0.05 nV	B	rectangular	0.03 nV	1	0.03 nV	∝
U_{LAB}	1.087 156 337 89 V						0.13 nV	ν_{eff} =16
Voltage difference U_0 - U_{LAB}	0.05 nV						0.13 nV	ν_{eff} =16

The final result of the comparison is:

$U_0 / U_{LAB} - 1 = 0.05 \times 10^{-9}$; $u_C / U_{LAB} = 0.12 \times 10^{-9}$ where u_C is the combined uncertainty (k = 1).

* The uncertainty contribution of the 5 MHz time base is 0.22 nV (0.20×10^{-9}) with degree of freedom = ∝.

** 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. Therefore, this voltage must not be added to the mean measured voltage to get U_{PJVS}. The gain error is compensated in the calculated mean voltage, and the uncertainty of the gain error incorporated in the uncertainty statement for V_{det}.

It is assumed that V_{off} = 0 due to polarity reversing by the two Josephson arrays without the use of a different switch positions. All stable thermal EMFs are cancelled and unstable thermal EMFs gives a type A contribution in the standard deviation.

Values of the laboratory

Frequency:	74.882 GHz
Series resistance of leads/filters:	30 Ω
Leakage resistance:	500 GΩ
Typical voltage at null detector	1 µV
Null detector and settings:	Keithley 2182, 10 mV range, 1 NPLC, analog filter - off, digital filter – on with counter = 14
Measurement sequence	+/–/–/+ sequence 560 readings of null detector in each sequence
Typical time for sequence	1 minute 20 s

Uncertainty budget of UME, Turkey

Output resistance of the PJVS: 4 Ω

$U_0 = N_{PJVS} f_{PJVS} / K_{J-90}$: **1.087 156 337 94 V.**

Quantity	Estimate	Uncertainty	Type	Probability distribution	Standard uncertainty	Sensitivity coefficient	Uncertainty Contribution	Degree of freedom
Measured mean voltage	1.087 156 338 01 V	0.28 nV	A	normal	0.28 nV	1	0.28 nV	34
Frequency	74.98887 GHz	15 Hz	B	rectangular	8.7 Hz	14.5 pV/Hz	0.13 nV	100
V_{leak}	0 nV *	0.38 nV	B	rectangular	0.22 nV	1	0.22 nV	∝
V_{det}	1 µV**	0.2 nV	B	rectangular	0.1 nV	1	0.1 nV	5
U_{LAB}	1.087 156 338 01 V						0.39 nV	ν_{eff} =116
Voltage difference $U_0 - U_{LAB}$	-0.07 nV						0.39 nV	ν_{eff} = 116

The final result of the comparison is:
$U_0 / U_{LAB} - 1 = -0.06 \times 10^{-9}$; $u_C / U_{LAB} = 0.36 \times 10^{-9}$ where u_C is the combined uncertainty (k = 1).

* 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. Therefore, this voltage must not be added to the mean measured voltage to get U_{PJVS}. The gain error is compensated in the calculated mean voltage, and the uncertainty of the gain error incorporated in the uncertainty statement for V_{det}.

It is assumed that V_{off} = 0 due to polarity reversing by the two Josephson arrays without the use of a different switch positions. All stable thermal EMFs are cancelled and unstable thermal EMFs gives a type A contribution in the standard deviation.

Values of the laboratory

Frequency:	74.98887 GHz
Series resistance of leads/filters:	3.5 Ω
Leakage resistance:	10 GΩ
Typical voltage at null detector	1 µV
Null detector and settings:	Keithley 182, 3 mV range, analog filter -off, digital filter - on (medium response)
Measurement sequence	+ / – sequence; 20 readings of null detector each in each polarity
Typical time for sequence	2 minutes

Uncertainty budget of PTB, Germany

Output resistance of the PJVS: 4 Ω

$\boldsymbol{U_0} = N_{\mathrm{PJVS}}\, f_{\mathrm{PJVS}} / K_{\mathrm{J\text{-}90}}$: **1.087 156 337 94 V.**

Quantity	Estimate	Uncertainty	Type	Probability distribution	Standard uncertainty	Sensitivity coefficient	Uncertainty Contribution	Degree of freedom
Measured mean voltage	1.087 156 337 93 V	0.24 nV	A	normal	0.24 nV	1	0.24 nV	80
Frequency	74.9353 GHz	4 Hz	B	normal	4 Hz	14.5 pV/Hz	0.06 nV	60
V_{leak}	0 nV *	0.01 nV	B	rectangular	0.006 nV	1	0.006 nV	∞
V_{det}	0.8 µV**	0.03 nV	B	rectangular	0.02 nV	1	0.02 nV	20
U_{LAB}	1.087 156 337 93V						0.25 nV	$\nu_{eff} = 91$
Voltage difference $U_0 - U_{LAB}$	0.01 nV						0.25 nV	$\nu_{eff} = 91$

The final result of the comparison is:
$U_0 / U_{LAB} - 1 = 0.01 \times 10^{-9}$; $u_C / U_{LAB} = 0.23 \times 10^{-9}$ where u_C is the combined uncertainty ($k = 1$).

* 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. Therefore, this voltage must not be added to the mean measured voltage to get U_{PJVS}. The gain error is compensated in the calculated mean voltage, and the uncertainty of the gain error incorporated in the uncertainty statement for V_{det}.

It is assumed that $V_{off} = 0$ due to polarity reversing by the two Josephson arrays without the use of a different switch positions. All stable thermal EMFs are cancelled and unstable thermal EMFs gives a type A contribution in the standard deviation.

Values of the laboratory

Frequency:	74.9353 GHz
Series resistance of leads/filters:	5 Ω
Leakage resistance:	>500 GΩ
Typical voltage at null detector	0.8 µV
Null detector and settings:	Keithley 2182, 10 mV range, 1 NPLC, no filters
Measurement sequence	+ / – sequence; 20 readings of null detector each in each polarity 100 readings of null detector each
Typical time for sequence	< 1 minute

Uncertainty budget of SP, Sweden

Output resistance of the PJVS: 4 Ω

$U_0 = N_{PJVS} f_{PJVS} / K_{J-90}$: **1.087 156 337 94 V.**

Quantity	Estimate	Uncertainty	Type	Probability distribution	Standard uncertainty	Sensitivity coefficient	Uncertainty Contribution	Degree of freedom
Measured mean voltage	1.087 156 337 90 V	0.40 nV	A	normal	0.40 nV	1	0.40 nV	9
Frequency	70,57 GHz	15 Hz	B	rectangular	8,70 Hz	14,2 pV/Hz	0.14 nV	5
V_{leak}	0 nV *	0.06 nV	B	rectangular	0.04 nV	1	0.04 nV	∞
V_{det}	0.1 µV**	2.00 nV	B	rectangular	1.16 nV	1	1.16 nV	50
U_{LAB}	1.087 156 337 90V						1.24 nV	$\nu_{eff} = 60$
Voltage difference $U_0 - U_{LAB}$	0.04 nV						1.24 nV	$\nu_{eff} = 60$

The final result of the comparison is:
$U_0 / U_{LAB} - 1 = 0.04 \times 10^{-9}$; $u_C / U_{LAB} = 1.14 \times 10^{-9}$ where u_C is the combined uncertainty ($k = 1$).

* 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. Therefore, this voltage must not be added to the mean measured voltage to get U_{PJVS}. The gain error is compensated in the calculated mean voltage, and the uncertainty of the gain error incorporated in the uncertainty statement for V_{det}.

It is assumed that $V_{off} = 0$ due to polarity reversing by the two Josephson arrays without the use of a different switch positions. All stable thermal EMFs are cancelled and unstable thermal EMFs gives a type A contribution in the standard deviation.

Values of the laboratory

Frequency:	70.57 GHz
Series resistance of leads/filters:	1.4 Ω
Leakage resistance:	100 GΩ
Typical voltage at null detector	less than 0.1 µV
Null detector and settings:	Keithley 182: 3 mV range, filter analog filter on, digital filter medium integration time 20 ms, four readings per second
Measurement sequence	+/–/+ sequence 800 readings of null detector in each sequence
Typical time for sequence	7-8 min

Uncertainty budget of NPL, United Kingdom

Output resistance of the PJVS: 4 Ω

$U_0 = N_{\mathrm{PJVS}} f_{\mathrm{PJVS}} / K_{J\text{-}90}$: **1.087 156 337 94 V.**

Quantity	Estimate	Uncertainty	Type	Probability distribution	Standard uncertainty	Sensitivity coefficient	Uncertainty Contribution	Degree of freedom
Measured mean voltage	1.087 156 336 5 V*	0.6 nV	A	normal	0.6 nV	1	0.6 nV	542
Frequency	76.903 GHz	26 Hz	B	rectangular	15 Hz	14 pV/Hz	0.2 nV	∞
V_{leak}	0 nV **	0.17 nV	B	rectangular	0.1 nV	1	0.1 nV	∞
V_{det}	1 mV	0.00 nV***						
U_{LAB}	1.087 156 336 5						0.65 nV	ν_{eff} = 703
Voltage difference $U_0 - U_{LAB}$	+1.4 nV						0.65 nV	ν_{eff} = 703

The final result of the comparison is:
$U_0 / U_{LAB} - 1 = +1.3 \times 10^{-9}$; $u_C / U_{LAB} = 0.59 \times 10^{-9}$ where u_C is the combined uncertainty (k = 1).

* Weighted mean.

** correction to the measured mean voltage is applied.

*** Detector gain and linearity uncertainty is included in the type A uncertainty.

It is assumed that V_{off} = 0 due to polarity reversing by the two Josephson arrays without the use of a different switch positions. All stable thermal EMFs are cancelled and unstable thermal EMFs gives a type A contribution in the standard deviation.

Values of the laboratory

Frequency:	76.903 GHz
Series resistance of leads/filters:	8 Ω
Leakage resistance:	50 GΩ
Typical voltage at null detector	1 mV
Null detector and settings:	HP34420A, 10 mV range, No filter, integration time (200ms), resolution 6.5 digit
Measurement sequence	+/- sequence, 12 times 8 readings of null detector each in each polarity
Typical time for sequence	8 minutes

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Uncertainty budget of DFM, Denmark

Output resistance of the PJVS: 4 Ω

$U_0 = N_{\text{PJVS}} f_{\text{PJVS}} / K_{J\text{-}90}$: **1.109 918 335 05 V.**

Quantity	Estimate	Uncertainty	Type	Probability distribution	Standard uncertainty	Sensitivity coefficient	Uncertainty Contribution	Degree of freedom
Measured mean voltage	1.109 918 335 20 V	0.55 nV	A	normal	0.55 nV	1	0.55 nV	∞
Frequency	75.9844 GHz	15 Hz	B	normal	8.7 Hz	14.6 pV/Hz	0.13 nV	∞
V_{leak}	0 nV *	0.01 nV	B	rectangular	0.006 nV	1	0.006 nV	∞
V_{det}	0.32 mV**	0.44 nV	B	rectangular	0.25 nV	1	0.26 nV	>100
U_{LAB}	1.109 918 335 20 V						0.62 nV	$\nu_{eff} = \infty$
Voltage difference U_0 - U_{LAB}	–0.15 nV						0.62 nV	$\nu_{eff} = \infty$

The final result of the comparison is:
$U_0 / U_{LAB} - 1 = -0.14 \times 10^{-9}$; $u_C / U_{LAB} = 0.56 \times 10^{-9}$ where u_C is the combined uncertainty ($k = 1$).

* 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. Therefore, this voltage must not be added to the mean measured voltage to get U_{PJVS}. The gain error is compensated in the calculated mean voltage, and the uncertainty of the gain error incorporated in the uncertainty statement for V_{det}.

It is assumed that $V_{off} = 0$ due to polarity reversing by the two Josephson arrays without the use of a different switch positions. All stable thermal EMFs are cancelled and unstable thermal EMFs gives a type A contribution in the standard deviation.

Values of the laboratory

Frequency:	75.9844 GHz
Series resistance of leads/filters:	1.0 Ω
Leakage resistance:	> 100 GΩ
Typical voltage at null detector	0.32 mV (average of absolute value of reading)
Null detector and settings:	Agilent 34420A, 1 mV range, analog filter on, digital filter off, NPLC 20.
Measurement sequence	+ / – / – / + sequence 10 - 25 readings of null detector each subsequence
Typical time for sequence	6 minutes

Remark The standard uncertainty of the simple average of the 26 measurements is 0.24 nV, but the noise-floor of the null detector (0.55 nV) is reached after 40 samples, and in all measurements 40 or more samples are used to calculate the value.

Uncertainty budget of IEN, Italy

Output resistance of the PJVS: 4 Ω

$U_0 = N_{\mathrm{PJVS}} f_{\mathrm{PJVS}} / K_{J\text{-}90}$: **1.227 444 565 00 V**

Quantity	Estimate	Uncertainty	Type	Probability distribution	Standard uncertainty	Sensitivity coefficient	Uncertainty Contribution	Degree of freedom
Measured mean voltage	1.227 444 564 88 V	0.35 nV	A	normal	0.35 nV	1	0.35 nV	12
Frequency	76,62187 GHz	15 Hz	B	rectangular	8.6 Hz	16 pV/Hz	0.13 nV	∞
V_{leak}	0 nV *	0.028 nV	B	rectangular	0.016 nV	1	0.016 nV	∞
V_{det}	-26.77 nV**	0.0 nV***						
U_{LAB}	1.227 444 564 88 V						0.37 nV	ν_{eff} = 12
Voltage difference U_0 - U_{LAB}	0.12 nV						0.37 nV	ν_{eff} = 12

The final result of the comparison is:

$U_0 / U_{LAB} - 1 = 0.10 \times 10^{-9}$; $u_C / U_{LAB} = 0.31 \times 10^{-9}$ where u_C is the combined uncertainty (k = 1).

* 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. Therefore, this voltage must not be added to the mean measured voltage to get U_{PJVS}. The gain error is compensated in the calculated mean voltage, and the uncertainty of the gain error incorporated in the uncertainty statement for V_{det}.

*** Detector gain and linearity uncertainty is included in the type A uncertainty.

It is assumed that V_{off} = 0 due to polarity reversing by the two Josephson arrays without the use of a different switch positions. All stable thermal EMFs are cancelled and unstable thermal EMFs gives a type A contribution in the standard deviation.

Values of the laboratory

Frequency:	76.62187 GHz
Series resistance of leads/filters:	3.6 Ω
Leakage resistance:	125 GΩ
Typical voltage at null detector	1.5 µV
Null detector and settings:	EM N11, 3 µV range, Filter 3
Measurement sequence	+/–/–/+ sequence from 14 up to 46 readings of null detector each
Typical time for sequence	8 minutes

Uncertainty budget (final) of EIM, Greece

Output resistance of the PJVS: 4 Ω

$U_0 = N_{\mathrm{PJVS}}\, f_{\mathrm{PJVS}} / K_{J\text{-}90}$: **1.068 884 802 85 V.**

Quantity	Estimate	Uncertainty	Type	Probability distribution	Standard uncertainty	Sensitivity coefficient	Uncertainty Contribution	Degree of freedom
Measured mean voltage	1.068 884 801 78 V	0.95 nV	A	normal	0.95 nV	1	0.95 nV	35
Frequency	75 GHz	15 Hz	B	rectangular	8.7 Hz	14 pV/Hz	0.12 nV	∞
V_{leak}	0 nV *	1.07 nV	B	rectangular	0.62 nV	1	0.62 nV	∞
V_{det}	2 mV**	2 nV	B	normal	2 nV	1	2 nV	18
U_{LAB}	1.068 884 801 78V						2.3 nV	ν_{eff} = 31
Voltage difference $U_0 - U_{LAB}$	+1.07 nV						2.3 nV	ν_{eff} = 31

The final result of the comparison is:
$U_0 / U_{LAB} - 1 = 1.0 \times 10^{-9}$; $u_C / U_{LAB} = 2.2 \times 10^{-9}$ where u_C is the combined uncertainty (k = 1).

* 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. Therefore, this voltage must not be added to the mean measured voltage to get U_{PJVS}. The gain error is compensated in the calculated mean voltage, and the uncertainty of the gain error incorporated in the uncertainty statement for V_{det}.

It is assumed that V_{off} = 0 due to polarity reversing by the two Josephson arrays without the use of a different switch positions. All stable thermal EMFs are cancelled and unstable thermal EMFs gives a type A contribution in the standard deviation.

Values of the laboratory

Frequency:	75 GHz
Series resistance of leads/filters:	20 Ω
Leakage resistance:	20 GΩ
Typical voltage at null detector	2 mV
Null detector and settings:	HP 34420A, 10 mV range, no filters
Measurement sequence	+/–/+/– sequence
	40 readings of null detector each
Typical time for sequence	6 minutes

Uncertainty budget (previous) of EIM, Greece

Output resistance of the PJVS: 4 Ω

$U_0 = N_{\mathrm{PJVS}} f_{\mathrm{PJVS}} / K_{J\text{-}90}$: **1.068 884 802 85 V.**

Quantity	Estimate	Uncertainty	Type	Probability distribution	Standard uncertainty	Sensitivity coefficient	Uncertainty Contribution	Degree of freedom
Measured mean voltage	1.068 884 801 78 V	0.95 nV	A	normal	0.97 nV	1	0.95 nV	35
Frequency	75 GHz	15 Hz	B	rectangular	8.7 Hz	14 pV/Hz	0.12 nV	∞
V_{leak}	0 nV *	1.07 nV	B	rectangular	0.62 nV	1	0.62 nV	∞
V_{det}	2 mV**	10 nV	B	rectangular	10 nV	1	10 nV	19
U_{LAB}	1.068 884 801 78V						10 nV	ν_{eff} =19
Voltage difference U_0 - U_{LAB}	+1.07 nV						10 nV	ν_{eff} = 19

The final result of the comparison is:
$U_0 / U_{LAB} -1 = 1.0 \times 10^{-9}$; $u_C / U_{LAB} = 9 \times 10^{-9}$ where u_C is the combined uncertainty (k = 1).

* 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. Therefore, this voltage must not be added to the mean measured voltage to get U_{PJVS}. The gain error is compensated in the calculated mean voltage, and the uncertainty of the gain error incorporated in the uncertainty statement for V_{det}.

It is assumed that V_{off} = 0 due to polarity reversing by the two Josephson arrays without the use of a different switch positions. All stable thermal EMFs are cancelled and unstable thermal EMFs gives a type A contribution in the standard deviation.

Values of the laboratory

Frequency:	75 GHz
Series resistance of leads/filters:	20 Ω
Leakage resistance:	20 GΩ
Typical voltage at null detector	2 mV
Null detector and settings:	HP 34420A, 10 mV range, no filters
Measurement sequence	+/–/+/– sequence 40 readings of null detector each
Typical time for sequence	6 minutes

Uncertainty budget of BIPM, International

Output resistance of the PJVS: 4 Ω

$U_0 = N_{\mathrm{PJVS}}\, f_{\mathrm{PJVS}} / K_{J\text{-}90}$: **1.029 244 862 31 V.**

Quantity	Estimate	Uncertainty	Type	Probability distribution	Standard uncertainty	Sensitivity coefficient	Uncertainty Contribution	Degree of freedom
Measured mean voltage	1.02924486224 V	0.12 nV	A	normal	0.12 nV	1	0.12 nV	37
Frequency	74.882 GHz	1.4 Hz	A	normal	1.4 Hz	13.7 pV/Hz	0.02 nV	60
V_{leak}	0 nV *	0.07 nV	B	rectangular	0.04 nV	1	0.04 nV	>5
V_{det}	0 nV **	0.06 nV***	B	rectangular	0.03 nV	1	0.03 nV	37
U_{LAB}	1.02924486224 V						0.13 nV	$\nu_{eff} = 80$
Voltage difference $U_0 - U_{LAB}$	+ 0.07 nV						0.13 nV	$\nu_{eff} = 80$

The final result of the comparison is:

$U_0 / U_{LAB} - 1 = 0.07 \times 10^{-9}$; $u_C / U_{LAB} = 0.13 \times 10^{-9}$ where u_C is the combined uncertainty ($k = 1$).

* no correction to the measured mean voltage is applied, as the path for the leakage is unknown.

** typical mean voltage at the null detector is 0, as both arrays where biased at exactly the same frequency, the residual being the difference in the thermal EMFs of the two systems.

*** uncertainty due to EMI, estimated from the difference between the results obtained for the different polarities of the detector. The difference is 0.06 nV with a type–A uncertainty of 0.10 nV. This difference is considered to be an estimate of the influence of the EMI on the detector, with a rectangular distribution.

Values of the laboratory

Frequency:	74.882 GHz
Series resistance of leads/filters:	3 Ω
Leakage resistance:	> 3×10^{10} Ω (mainly leakage % ground)
Typical voltage at null detector	< 0.1 µV
Null detector and settings:	EM N1a, 300 nV range, read via DVM, no filters Measurement sequence +R/+N/–R/–N/–R/–N/+R/+N (“R” for Reverse and “N” for Normal polarity of the detector), 300 readings of DVM each
Typical time for sequence	2 minutes

Uncertainty budget of MIKES, Finland

Output resistance of the PJVS: 4 Ω

$U_0 = N_{\mathrm{PJVS}}\, f_{\mathrm{PJVS}} / K_{J\text{-}90}$: **1.029 244 862 312 V.**

Quantity	Estimate	Uncertainty	Type	Probability distribution	Standard uncertainty	Sensitivity coefficient	Uncertainty Contribution	Degree of freedom
Measured mean voltage	1.029 244 862 351 V	0.065 nV	A	normal	0.065 nV	1	0.065 nV	4
Frequency	70.12407 GHz	10 Hz	B	rectangular	5.8 Hz	14.7 pV/Hz	0.085 nV	∞
V_{leak}	0 nV *	0.015 nV	B	rectangular	0.009 nV	1	0.009 nV	∞
V_{det}	10.667 nV**	0.081 nV	B	normal	0.081 nV	1	0.081 nV	200
U_{LAB}	1.029 244 862 351 V						0.134 nV	ν_{eff} =69
Voltage difference $U_0 - U_{LAB}$	-0.039 nV						0.134 nV	ν_{eff} =69

The final result of the comparison is:
$U_0 / U_{LAB} -1 = -0.038 \times 10^{-9}$; $u_C / U_{LAB} = 0.13 \times 10^{-9}$ where u_C is the combined uncertainty (k=1).

* 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. Therefore, this voltage must not be added to the mean measured voltage to get U_{PJVS}.

It is assumed that $V_{off} = 0$ due to polarity reversing by the two Josephson arrays without the use of a different switch positions. All stable thermal EMFs are cancelled and unstable thermal EMFs gives a type A contribution in the standard deviation.

Values of the laboratory

Frequency:	70.12407 GHz
Series resistance of leads/filters:	3 Ω
Leakage resistance:	200 GΩ
Typical voltage at null detector	10 nV
Null detector and settings:	EM N11, 30 nV range, filter 1
Measurement sequence	+/– sequence
	30 readings of null detector each in each polarity
Typical time for sequence	2.5-3 minutes

Uncertainty budget (final) of GUM, Poland

Output resistance of the PJVS: 4 Ω

$U_0 = N_{PJVS} f_{PJVS} / K_{J-90}$: **1.029 244 862 3 V.**

Quantity	Estimate	Uncertainty	Type	Probability distribution	Standard uncertainty	Sensitivity coefficient	Uncertainty Contribution	Degree of freedom
Measured mean voltage	1.029 244 863 5 V	1.1 nV	A	normal	1.1 nV	1	1.1 nV	24
Frequency	75 GHz	15 Hz	B	rectangular	8.7 Hz	13.7 pV/Hz	0.12 nV	5
V_{leak}	0 nV *	1 nV	B	rectangular	0.6 nV	1	0.6 nV	5
V_{det}	500µV**	5 nV	B	rectangular	2.9 nV	1	2.9 nV	48
U_{LAB}	1.029 244 863 5 V						3.16 nV	ν_{eff} = 64
Voltage difference U_0 - U_{LAB}	- 1.2 nV						3.16 nV	ν_{eff} = 64

The final result of the comparison is:
$U_0 / U_{LAB} - 1 = -1.2 \times 10^{-9}$; $u_C / U_{LAB} = 3.1 \times 10^{-9}$ where u_C is the combined uncertainty (k=1).

* 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. Therefore, this voltage must not be added to the mean measured voltage to get U_{PJVS}.

It is assumed that $V_{off} = 0$ due to polarity reversing by the two Josephson arrays without the use of a different switch positions. All stable thermal EMFs are cancelled and unstable thermal EMFs gives a type A contribution in the standard deviation.

Values of the laboratory

Frequency:	75 GHz
Series resistance of leads/filters:	10 Ω
Leakage resistance:	10 GΩ
Typical voltage at null detector	5 mV
Null detector and settings:	HP 3458A, 100 mV range, 1 NPLC, no filters
Measurement sequence	+/–/ – /+ sequence 40 readings of null detector each in each +/- measurement
Typical time for sequence	4 minutes 20 s

Uncertainty budget (previous) of GUM, Poland

Output resistance of the PJVS: 4 Ω

$U_0 = N_{\mathrm{PJVS}}\, f_{\mathrm{PJVS}} / K_{J\text{-}90}$: **1.029 244 862 3 V.**

Quantity	Estimate	Uncertainty	Type	Probability distribution	Standard uncertainty	Sensitivity coefficient	Uncertainty Contribution	Degree of freedom
Measured mean voltage	1.029 244 863 5 V	1.1 nV	A	normal	1.1 nV	1	1.1 nV	24
Frequency	75 GHz	15 Hz	B	rectangular	8.7 Hz	13.7 pV/Hz	0.12 nV	5
V_{leak}	0 nV *	1 nV	B	rectangular	0.6 nV	1	0.6 nV	5
V_{det}	500µV**	10 nV	B	rectangular	5.8 nV	1	5.8 nV	48
U_{LAB}	1.029 244 863 5 V						5.9 nV	ν_{eff} =52
Voltage difference $U_0 - U_{LAB}$	- 1.2 nV						5.9 nV	ν_{eff} = 52

The final result of the comparison is:
$U_0 / U_{LAB} - 1 = -1.2 \times 10^{-9}$; $u_C / U_{LAB} = 5.7 \times 10^{-9}$ where u_C is the combined uncertainty (k=1).

* 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. Therefore, this voltage must not be added to the mean measured voltage to get U_{PJVS}.

It is assumed that $V_{off} = 0$ due to polarity reversing by the two Josephson arrays without the use of a different switch positions. All stable thermal EMFs are cancelled and unstable thermal EMFs gives a type A contribution in the standard deviation.

Values of the laboratory

Frequency:	75 GHz
Series resistance of leads/filters:	10 Ω
Leakage resistance:	10 GΩ
Typical voltage at null detector	5 mV
Null detector and settings:	HP 3458A, 100 mV range, 1 NPLC, no filters
Measurement sequence	+/–/ – /+ sequence 40 readings of null detector each in each +/- measurement
Typical time for sequence	4 minutes 20 s

Uncertainty budget of CMI, Czech Republik

Output resistance of the PJVS: 4 Ω

$\boldsymbol{U_0} = N_{\mathrm{PJVS}}\, f_{\mathrm{PJVS}} / K_{J\text{-}90}$: **1.029 244 862 3 V.**

Quantity	Estimate	Uncertainty	Type	Probability distribution	Standard uncertainty	Sensitivity coefficient	Uncertainty Contribution	Degree of freedom
Measured mean voltage	1.029 244 861 5 V	0.50 nV	A	normal	0.50 nV	1	0.50 nV	24
Frequency	75.3 GHz	15 Hz	B	rectangular	8.7 Hz	13.8 pV/Hz	0.12 nV	∞
V_{leak}	0 nV *	0.88 nV	B	rectangular	0.51nV	1	0.51 nV	∞
V_{det}	60 µV**	2.5 nV	A	normal	2.5 nV	1	2.5 nV	23
U_{LAB}	1.029 244 861 5 V						2.6 nV	ν_{eff} =27
Voltage difference U_0 - U_{LAB}	0.8 nV						2.6 nV	ν_{eff} = 27

The final result of the comparison is:
$U_0 / U_{LAB} - 1 = 0.8 \times 10^{-9}$; $u_C / U_{LAB} = 2.5 \times 10^{-9}$ where u_C is the combined uncertainty (k=1).

* 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. Therefore, this voltage must not be added to the mean measured voltage to get U_{PJVS}.

It is assumed that V_{off} = 0 due to polarity reversing by the two Josephson arrays without the use of a different switch positions. All stable thermal EMFs are cancelled and unstable thermal EMFs gives a type A contribution in the standard deviation.

Values of the laboratory

Frequency:	75.3 GHz
Series resistance of leads/filters:	20 Ω
Leakage resistance:	23 GΩ
Typical voltage at null detector	1.5 mV
Null detector and settings:	Keithley 2182, 10 mV range, 5 NPLC, no filters
Measurement sequence	+/–/ + /– sequence 50 readings of null detector each in each +/- measurement
Typical time for sequence	6 minutes

Uncertainty budget of NMi-VSL, The Netherlands

Output resistance of the PJVS: 4 Ω

$U_0 = N_{\mathrm{PJVS}}\, f_{\mathrm{PJVS}} / K_{J\text{-}90}$: **1.029 244 862 3 V.**

Quantity	Estimate	Uncertainty	Type	Probability distribution	Standard uncertainty	Sensitivity coefficient	Uncertainty Contribution	Degree of freedom
Measured mean voltage	1.029 244 863 9 V	6 nV	A	normal	6 nV	1	6 nV	24
Frequency	76.3500 GHz	10 Hz	B	normal	10 Hz	13.5 pV/Hz	0.1 nV	∞
V_{leak}	0 nV *	0.44 nV	B	rectangular	0.3 nV	1	0.3 nV	∞
V_{det}	1 mV**	2 nV	B	rectangular	1 nV	1	1 nV	∞
U_{LAB}	1.029 244 863 9 V						6 nV	ν_{eff} = 24
Voltage difference $U_0 - U_{LAB}$	- 1.6 nV						6 nV	ν_{eff} = 24

The final result of the comparison is:
$U_0 / U_{LAB} - 1 = -1.6 \times 10^{-9}$; $u_C / U_{LAB} = 6 \times 10^{-9}$ where u_C is the combined uncertainty (k=1).

* 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. Therefore, this voltage must not be added to the mean measured voltage to get U_{PJVS}.

Zero contribution due to polarity reversing by the two Josephson arrays without the use of a different switch positions. All stable thermal EMFs are cancelled and unstable thermal EMFs give a type A contribution in the standard deviation. During typical calibration at NMi there is a piece of cable connecting a Zener diode and a scanner where the voltage polarity is not reversed and therefore thermal EMFs additionally contribute to the calibration uncertainty. For this reason NMi gives more conservative uncertainty budget for calibrations.

Values of the laboratory

Frequency:	76.33 GHz to 76.36 GHz
Series resistance of leads/filters:	2 Ω (for each current and each potential lead)
Leakage resistance:	27 GΩ: 140 GΩ (cryoprobe); 100 GΩ and 80 GΩ (voltage wires incl. the connector to cryoprobe, the cable, the scanner, the cable, connector to Keithley 182 and Keithley 182 itself)
Typical voltage at null detector	1000 µV
Null detector and settings:	Keithley 182, 3 mV range, no filters, the integration time is 0.1 s (over 5 power line cycles, or 5 NPLC).
Measurement sequence	+/–/–/+/ sequence 300 readings of null detector each
Typical time for sequence	27 minutes

Appendix D
Optional measurements

Uncertainty budget of VNIIM, Russia

Output resistance of the PJVS: 1.2 kΩ

$U_0 = N_{\text{PJVS}}\, f_{\text{PJVS}} / K_{J\text{-}90}$: **1.087 156 337 94 V.**

Quantity	Estimate	Uncertainty	Type	Probability distribution	Standard uncertainty	Sensitivity coefficient	Uncertainty Contribution	Degree of freedom
Measured mean voltage	1.087 156 337 98 V	0.185 nV	A	normal	0.185 nV	1	0.185 nV	6
Frequency	74.882 GHz	8 Hz	B	rectangular	4.5 Hz	14.5 pV/Hz	0.07 nV	20
V_{leak}	0 nV *	0.07 nV	B	rectangular	0.04 nV	1	0.04 nV	5
V_{det}	1 µV**	0.05 nV	B	rectangular	0.03 nV	1	0.03 nV	∝
U_{LAB}	1.087 156 337 98 V						0.20 nV	9
Voltage difference $U_0 - U_{LAB}$	-0.04 nV						0.20 nV	9

The final result of this comparison is:
$U_0 / U_{LAB} - 1 = -0.04 \times 10^{-9}$; $u_C / U_{LAB} = 0.18 \times 10^{-9}$ where u_C is the combined uncertainty (k=1).
The uncertainty contribution of the 5 MHz time base is 0.22 nV (0.20×10^{-9}) with degree of freedom = ∝.

* 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. Therefore, this voltage must not be added to the mean measured voltage to get U_{PJVS}.

It is assumed that Voff = 0 due to polarity reversing by the two Josephson arrays without the use of a different switch positions. All stable thermal EMFs are cancelled and unstable thermal EMFs gives a type A contribution in the standard deviation.

Uncertainty budget of MIKES, Finland

Output resistance of the PJVS: 1.2 kΩ

$U_0 = N_{PJVS}\, f_{PJVS} / K_{J-90}$: **1.029 244 862 312 V**

Quantity	Estimate	Uncertainty	Type	Probability distribution	Standard uncertainty	Sensitivity coefficient	Uncertainty Contribution	Degree of freedom
Measured mean voltage	1.029 244 861 968 V	0.195 nV	A	normal	0.195 nV	1	0.195 nV	14
Frequency	70.12407 GHz	10 Hz	B	rectangular	5.8 Hz	14.7 pV/Hz	0.085 nV	∞
V_{leak}	0 nV *	0.015 nV	B	rectangular	0.009 nV	1	0.009 nV	∞
V_{det}	10.285 nV**	0.078 nV	B	normal	0.078 nV	1	0.078 nV	200
U_{LAB}	1.029 244 861 968 V						0.227 nV	ν_{eff} =25
Voltage difference U_0 - U_{LAB}	0.344 nV						0.227 nV	ν_{eff} =25

The final result of this comparison is:
$U_0 / U_{LAB} - 1 = 0.33 \times 10^{-9}$; $u_C / U_{LAB} = 0.22 \times 10^{-9}$ where u_C is the combined uncertainty (k=1).

* 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. Therefore, this voltage must not be added to the mean measured voltage to get U_{PJVS}.

It is assumed that V_{off} = 0 due to polarity reversing by the two Josephson arrays without the use of a different switch positions. All stable thermal EMFs are cancelled and unstable thermal EMFs gives a type A contribution in the standard deviation.

Uncertainty budget of SP, Sweden

Output resistance of the PJVS: 1.2 kΩ

$U_0 = N_{PJVS} f_{PJVS} / K_{J-90}$: **1.087 156 337 9 V.**

Quantity	Estimate	Uncertainty	Type	Probability distribution	Standard uncertainty	Sensitivity coefficient	Uncertainty Contribution	Degree of freedom
Measured mean voltage	1.087 156 337 2 V	0.36 nV	A	normal	0.36 nV	1	0.36 nV	9
Frequency	70,57 GHz	15 Hz	B	rectangular	8,70 Hz	14,2 pV/Hz	0.14 nV	5
V_{leak}	0 nV *	0.06 nV	B	rectangular	0.04 nV	1	0.04 nV	∞
V_{det}	0.1 μV**	2.00 nV	B	rectangular	1.16 nV	1	1.2 nV	50
U_{LAB}	1.087 156 337 2V						1.2 nV	$\nu_{eff} = 60$
Voltage difference $U_0 - U_{LAB}$	0.7 nV						1.2 nV	$\nu_{eff} = 60$

The final result of this comparison is:
$U_0 / U_{LAB} -1 = 0.7 \times 10^{-9}$; $u_C / U_{LAB} = 1.2 \times 10^{-9}$ where u_C is the combined uncertainty (k=1).

* 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. Therefore, this voltage must not be added to the mean measured voltage to get U_{PJVS}.

It is assumed that $V_{off} = 0$ due to polarity reversing by the two Josephson arrays without the use of a different switch positions. All stable thermal EMFs are cancelled and unstable thermal EMFs gives a type A contribution in the standard deviation.

Uncertainty budget of NPL, United Kingdom

Output resistance of the PJVS: 1.2 kΩ

$U_0 = N_{\text{PJVS}} f_{\text{PJVS}} / K_{J\text{-}90}$: **1.087 156 338 V.**

Quantity	Estimate	Uncertainty	Type	Probability distribution	Standard uncertainty	Sensitivity coefficient	Uncertainty Contribution	Degree of freedom
Measured mean voltage	1.087 156 332 9 V*	0.6 nV	A	normal	0.6 nV	1	4.3 nV	190
Frequency	76.903 GHz	26 Hz	B	rectangular	15 Hz	14 pV/Hz	0.2 nV	∞
V_{leak}	0 nV *	17 nV	B	rectangular	10 nV	1	10 nV	∞
V_{ldet}	1 mV ***	0.0 nV						
U_{LAB}	1.087 156 329 V						10.9 nV	ν_{eff} = 7400
Voltage difference U_0 - U_{LAB}	+ 9 nV						10.9 nV	ν_{eff} = 7400

The final result of theis comparison is:
$U_0 / U_{LAB} - 1 = +9 \times 10^{-9}$; $u_C / U_{LAB} = 10 \times 10^{-9}$ where u_C is the combined uncertainty (k=1).

* Weighted mean.

** correction to the measured mean voltage is applied.

*** Detector gain and linearity uncertainty is included in the type A uncertainty.

It is assumed that $V_{off} = 0$ due to polarity reversing by the two Josephson arrays without the use of a different switch positions. All stable thermal EMFs are cancelled and unstable thermal EMFs gives a type A contribution in the standard deviation.

APPENDIX E

Technical protocol and comparison reports of the institutes

In the following the participant reports are given. Because no common scheme was given the protocols are very different. As e.g. the PJVS is common to all comparisons and further parts are already described in detail elsewhere within this report, e.g. the uncertainty budgets in Appendix C and Appendix D, these parts of the reports have been omitted here.

E1) Technical Protocol

E2) Comparison Reports of the institutes

E1) Technical Protocol

EUROMET key comparison supplementing BIPM.EM-K10.a

"Comparison of Josephson array voltage standards by using a portable Josephson transfer standard"

Technical protocol
(last correction of 2003-10-07)

Content

1. Introduction
2. Travelling standard and uncertainty requirement
3. Organisation
  3.1 Participants
  3.2 Time schedule
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  3.5 Failure with a travelling standard
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4. Conditions and methods of measurement
5. Measurement uncertainty
6. Measurement report
7. Report of the comparison

Annex
A1. List of participants
A2. Circulation time schedule
A3. Uncertainty budget
A4. Summary of results form

1. Introduction

In the Mutual Recognition Arrangement (MRA) it is stated, that the metrological equivalence of national measurement standards will be determined by a set of key comparisons chosen and organised by the Consultative Committees of the CIPM working closely together with the Regional Metrology Organisations (RMO's). In order to link more laboratories organised in EUROMET this RMO key comparison (EUROMET Project No. 723) supplementing BIPM.EM-K10.a will be carried out. In addition, the comparison provides a link between institutes and BIPM via a portable Josephson voltage standard. The comparison will be performed in a similar way as the bilateral Josephson voltage standard comparisons of the NMIs with the BIPM (see BIPM.EM-K10.a). As BIPM will also participate in this EUROMET comparison, we will have an indirect link to BIPM (NMI - Transfer Standard - Transfer Standard - BIPM). In the KCDB the differences NMI - BIPM will be given together with the combined uncertainty of the two measurements. The KCRV will be the voltage supplied by the BIPM Josephson voltage standard, and therewith will be the same as for BIPM.EM-K10.a assumed that the output voltage of the BIPM standard will not change with time.

The procedures outlined in this document are intended to allow for a clear and unequivocal comparison of the measurement results and to demonstrate the equivalence of measuring results obtained with–various quantized Josephson voltage standards in different national institutes. This technical protocol was prepared following the EUROMET Guidelines on Conducting Comparisons.

The members of EUROMET are agreed that projects and comparisons shall be carried out within a spirit of partnership and on the basis of mutual confidence for the benefit of both parties. All expenses incurred in EUROMET comparisons will usually be borne by the respective partners. In this case, however, due to the configuration of the comparison, the necessity of accompanied transportation and personal participation in the measurements, very high expenses will be incurred which cannot be imposed on the *VNIIM* as the executing institute.**Therefore, the costs of travelling and living expenses' of a VNIIM specialist must be born by the participating institute as well as the costs for visa and ATA carnet (proportionately).**

2. Traveling standard and uncertainty requirement

As travelling standard the VNIIM portable Josephson voltage standard will be used, owned by VNIIM and described in detail in A. Katkov et al., Metrologia 40, pp. 89-92, (2003).
The voltage to be measured is 1.09 V with an output resistance of 4 Ω and optionally with output resistance of 1.2 kΩ.
The goal of the comparison is to use the expected high level of agreement between the participating laboratories (relative standard uncertainty (combined type A and type B) of 1×10^{-9} or less at a $k = 1$ coverage factor or less) to draw specific conclusions about the present state-of-the-art for maintaining international equivalence of measurement services for DC voltage.

3. Organisation

The PTB (Germany) has agreed to act as the pilot laboratory for this comparison and Ralf Behr will be the co-ordinator. The VNIIM (Russia) will give support by providing their portable Josephson voltage standard

(PJVS) to be used as a travelling standard and by participating in preliminary measurements and in organising comparison loops.
The TC chairman of EUROMET EM will be regularly informed about the progress of this comparison.

3.1 Participants

The address of the co-ordinator of the pilot laboratory is:

Ralf Behr — *phone:* +49 531 592 2242
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Germany

Following the Guidelines for EUROMET key comparisons two institutes from the provisional list of participants were nominated to help the pilot laboratory with the organisation. These are VNIIM (A. Katkov) and BIPM (D. Reymann).

A detailed list of all participating institutes and contact persons with their addresses is enclosed in Annex A1.

3.2 Time schedule

The time schedule for the key comparison is given in the Annex 2. The PTB and VNIIM have completed an evaluation of the travelling standard. Following this and the establishment of the schedule the comparison will start. This will be no later than October 2003. The comparison should be completed in about one year.

The circulation of the travelling standard will be organised in loops. Each laboratory will have at least one day to carry out the measurements. The circulation of the PJVS will be accompanied by a VNIIM specialist. The PJVS will normally be accompanied by an ATA carnet. Laboratories in countries that do not recognise the ATA carnet should provide an acceptable way to pass the standard through customs.
In agreeing with the proposed circulation time schedule, each participating laboratory confirms that it is capable to perform the measurements in the limited time period allocated in the time schedule. If, for some reasons, the measurement facility is not ready the laboratory is requested to contact immediately the co-ordinator in the pilot laboratory.

3.3 Transportation

The PJVS will be transported as hand luggage by the specialist of VNIIM.

3.4 Unpacking, handling, packing

After arrival the system will be unpacked and installed by the specialist of VNIIM.

3.5 Failure with a travelling standard

Should the travelling standard be damaged during the comparison the pilot laboratory must be informed immediately.

3.6 Financial aspects, insurance

Each participating laboratory covers the costs of the measurement and eventual customs formalities as well as for any damage that may have been caused by the participant. In addition, each participating institute agrees to cover the costs of travelling and living expenses' of a VNIIM specialist as well as the costs for visa and ATA carnet (proportionately) by signing a declaration of intent with VNIIM.

The overall costs for the organisation of the comparison are covered by the organising pilot laboratory. The pilot laboratory has no insurance for any loss or damage of the standards during transportation.

4 Conditions and methods of measurement

After arrival in a laboratory the PJVS should be allowed to stabilise at least one hour before use.

The dewar with liquid helium to cover more than 200 mm length of PJVS sampler holder (1 m) should be supplied. The VNIIM cryoprobe has a standard NW 50 flange.

Pressure in the dewar must be defended from jumping in gaseous helium collection system or it can be open-air system. The PJVS is ready to do measurements two hours after cooling down.

The reference frequency (for example rubidium standard of JVS or internal time base of the EIP counter) with 10 MHz or 5 MHz output frequency with amplitude (0.3-2) V must be supplied.

To control PJVS parameters (output voltage and width of current step) a 6.5 digit voltmeter with an uncertainty in the order of 5 to 10 ppm must be supplied.

The PJVS must be measured at the nominal output voltage 1.09 V. The voltage is provided at copper clamps. Changing polarity is made manually at the PJVS which takes about 5-10 seconds. When using automated Josephson systems, please make sure that it is possible to reverse polarity when the automated systems changes polarity.

The ambient conditions for measurements are (20 - 24) °C ± 0.5 °C and relative humidity no greater than 70%.

Typically a time of two hours should be sufficient to receive data of PJVS comparison. Any method can be used for calibrating the output voltage of PJVS. The calibration method must be reported together with the results.

5. Measurement uncertainty

Since this comparison is a Euromet key comparison all participants must provide their results with the associated uncertainty of measurement and a complete uncertainty budget including the degrees of freedom (see Annex A3). The uncertainty must be evaluated at a level of one standard uncertainty. The uncertainty of measurement of the measuring results must be estimated according to the *ISO Guide to the Expression of Uncertainty in Measurement* (GUM). A list of the principal components of the uncertainty budget to be evaluated by each participant is included in this technical protocol (Annex A3).

A list of type B uncertainty components is given in Annex A3. There is space for additional items and comments: laboratories are encouraged to add additional items to help in preparing a new uncertainty list, which will be sent to the laboratories with the final protocol.

6. Measurement report

The individual results with date and the standard uncertainty should be reported to the pilot laboratory (please use the attached summary of results sheet, Annex A4). The report of the comparison must include all measurements which have been performed in the setting-up phase of the PJVS to ensure proper operation. After the setting-up phase all data of the comparison phase are going to the result sheet of Annex A4. Preliminary results can be sent by e-mail as soon as possible but not later than six weeks after the measurements are completed. In any case, a printed and signed report of the results must be sent by mail. In case of any differences, the paper forms are considered to be the valid version.

It is recommended to include in the report the following items:
+ type of array (SIS, SINIS, ..., "1V" or "10V") and origin
+ detector used, scale
+ measurements made with or without reversing the detector polarity
+ bias source (NIST, commercial, home made...)
+ array floating (or not) ; disconnected from the bias (or not)
+ software used (NISTVOLT N° ?? or modified or home made or ...)
+ frequency source stabiliser (EIP + control device, or ....)
+ order of magnitude of the frequency stability (few Hz or more)
+ order of magnitude of the thermal EMFs
+ impedance in the measurement leads
+ are the measurements made in a shielded room (or not).
The laboratories shall write a brief presentation of their equipment that would be added in an appendix of the final report.

In case of large deviations or failure of an apparatus the comparison can be repeated after the above programme is completed.

7. Report of the comparison

Within 3 months after completion of the last loop, the pilot laboratory will prepare a first draft report and send it to the participants for comments. In this report an overview about the different measuring systems will be included. Subsequently, the procedure outlined in the Euromet Guidelines will be followed.

List of participants **Annex A1**

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Circulation Time Schedule **Annex A2**

Loop 1

Institution	Country	Start date	Time for measurement and transportation (days planned)
VNIIM(initial meas.)	Russia	October 2003	
UME	Turkey	October 2003	2 - 4 days (12-17 October)
PTB (pilot)	Germany	October 2003	2 - 4 days (17-20 October)
SP	Sweden	October- 2003	2 - 4 days (20-23 October)

Loop 2

Institution	Country	Start date	Time for measurement and transportation (days planned)
NPL	United Kingdom	November 2003	2 - 4 days (10-13 November)
DFM	Denmark	November 2003	2 - 4 days (13-16 November)
IEN	Italy	November 2003	2 - 4 days (16-20 November)

Loop 3

Institution	Country	Start date	Time for measurement and transportation
NMi-VSL	The Netherlands	February 2004	2 - 4 days
BIPM	International	February 2004	2 - 4 days
INETI	Portugal	February 2004	2 - 4 days
EIM	Greece	February 2004	2 - 4 days
MIKES	Finland	March 2004	2 - 4 days

Loop 4

Institution	Country	Start date	Time for measurement and transportation
GUM	Poland	May 2004	2 - 4 days
CMI	Czech Republic	May 2004	2 - 4 days

Uncertainty budget **Annex A3**

Institute:	
Known sources of instrumental uncertainty (please add and/or comment)	
Comparison. with PJVS	*Comment*
Null detector	
Leakage resistance	
Frequency offset	
Different time bases	
Comments (mark the pertinent row and explain here; this space may also be used for other comments):	

Proposed scheme for an uncertainty budget for V_X

Quantity X_i	Estimate x_i	Relative standard uncertainty $u(x_i)$	Probability distribution / method of evaluation(A,B)	Sensitivity coefficient c_i	Relative uncertainty contribution $u_i(R_x)$	Degree of freedom ν_i
V_X						ν_{eff}

Summary of results form **Annex A4**

Measurement Set no.	Date of measurement	Output resistance of PJVS	Number of data points	Measurement result	Standard uncertainty of measurement

E2) Comparison Reports of the institutes

VNIIM, Russia

Date of meassurements: **29-30 September 2003**

Brief presentation of VNIIM JAVS

As shown in Fig. 1 the system has four parts: 1) a microwave source, rubidium frequency standard, synthesizer, phase-lock controller, isolator, mixer and attenuator; 2) cryoprobe with array and LF filters that is immersed in Dewar with liquid helium; 3) bias circuit with oscilloscope; and 4) PC with comparator that consist digital nanovoltmeter (DVM), scanner and reversing polarity switch.

The system was designed to use several types of Josephson array produced at PTB: 1V and 10 V SIS junction array and 1 V SINIS junction array produced at PTB. The SIS arrays generate constant voltage step near 1 volt and 10 V. The peak-to-peak current width of the steps at 1 V SIS arrays that used at the comparison is typically 40 μA. The array is enclosed with a cryoperm magnetic shield.

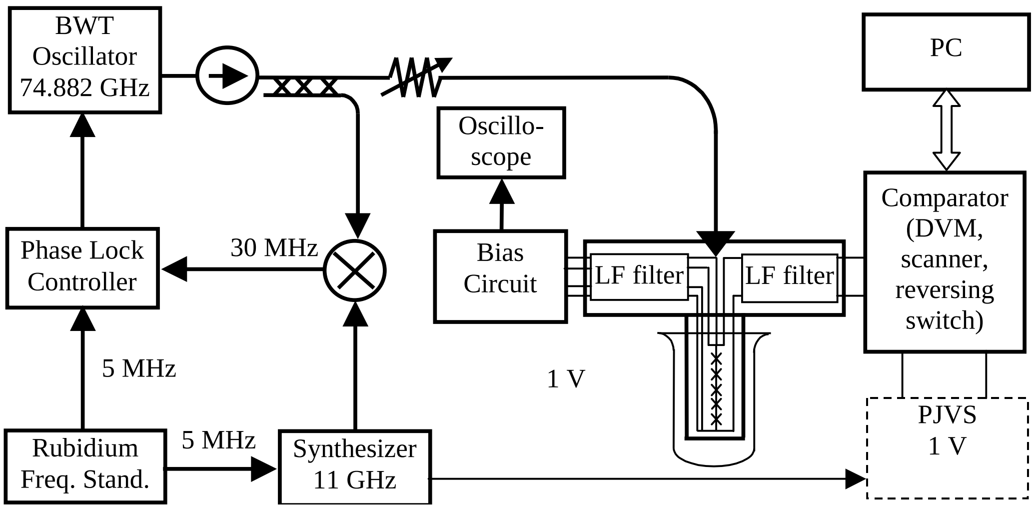


Fig. 1. Schematic diagram of the VNIIM JAVS

The cryoprobe is constructed with 20 mm stainless steel tube through which the waveguide and three pairs of electrical leads pass. One pair is for the current supply and the others is for voltage measurement. These leads are connected to the measuring circuit via an LF filter box attached to the top of the cryoprobe. The output voltage leads have 30 Ω series resistance. The 14 mm laboratory-made oversized circular waveguides are used in cryoprobes to irradiate millimeter waves from oscillator to a array in liquid helium. The length of the waveguides components to the array is 1.4 m and the insertion loss is in the range of 1.5 dB. The order of magnitude of the thermal EMFs is usually less than 250 nV.

The system uses a back-wave-tube (BWT) oscillator (Model G4-142) as millimetre wave source. Its output power is 30 mW and its frequency is tuneable over the range from 54 to 79 GHz. During comparison it was used frequency 74.882 GHz that was equal to frequency used in PJVS. The BWT oscillator is phase-locked to an X-band reference signal through a wide-bandwidth control loop made by VNIIM. The X-band reference signal is generated by a microwave synthesiser (Model RCh-03) which in turn is locked to a 5 MHz reference signal generated by a rubidium frequency standard.. The microwave source has electrical isolation from cryoprobe. The PJVS system used the same 5 MHz reference signal.

A bias circuit with variable internal resistance (from 1000 to 30 Ω was built to provide up to 1.2 V or 10 V continuously to the array for step selection, and to bias up to 14 V instantaneously for the reset of all junctions in SIS array to the same polarity. The bias circuit is laboratory-made and manually-controlled the step selection sequence. An oscilloscope is connected to bias circuit to monitor the *I-V* characteristic of array. The bias circuit has one point connection to ground and do not disconnect from array during measurement.

The detector is a Keithley 2182 nanovoltmeter, and the reversing switch and scanner are custom-made switches with low thermal EMF. During comparison with PJVS 10 mV range of nanovoltmeter was used. Measurements were made without reversing the detector polarity. To control and calculate of measurements data the home made software is used.

Measurements were made without reversing the detector polarity. The voltage difference readings are symmetrically arranged in time to compensate linear drift effect. Time period to receive one data point is about 80 s. To control and calculate of measurements data the laboratory-made software is used. The VNIIM JAVS is used in screening room. The PJVS system used the same 5 MHz reference signal.
A liquid helium container with a capacity of 40 L is used for the cryostat. The amount of liquid helium is enough to keep cryogenic temperatures during about the five weeks when the array- is immersed. The VNIIM JAVS is used in screening room.

UME, Turkey

Date of meassurements: 13-16 October 2003

UME JOSEPHSON VOLTAGE STANDARD (JAVS)

UME Josephson Voltage Standard has been described in detail in Selçik S., Akyel B., Gutmann P. CPEM'98 Conference Digest, 556-557 (1998).

The UME standard is based on 10V SIS arrays produced by Physikalisch-Technische Bundesanstalt-PTB, PREMA and Hypress.

The array chip is mounted at one end of a circular waveguide and connected to the millimeter source, Farran Technology Gunn diode type GN12H, via 30dB coupler. The Gunn diode that provides 85 mW at 75 GHz is phase-locked by an EIP 578B counter or Pronova PLO control module, PLO-12-100-75E.

The bias control unit, which provides stable current to array in order to force the junctions to the desired operating point, is the PTB version. The control unit is connected to the system during the measurements.

Keithley 182 or 2182 Voltmeters are used to measure voltage difference between Josephson voltage and the unit under test. A special low thermal emf switch connects the array, voltmeter and the unit under test.

The standard operates in normal laboratory conditions, not in an electromagnetically shielded room.

UME JAVS During the Measurements

10V PREMA array (SIS) and PREMA probe were used in UME system. The battery supplied bias source, made by PTB, was connected to the system, during the measurements. The UME array connected to the ground through the input amplifier of the oscilloscope.

The microwave source of UME JAVS was a Gunn diode stabilised in frequencies by an EIP 578B counter. During the measurements, HP 5071A Primary Frequency Standard was used as common frequency reference.

Keithley 182 and 2182 nanovoltmeters were used as a detector.

The filters on the output voltage leads have 3.5 Ω of series resistance and a leakage resistance of about 10 GΩ.

Comparison Procedure

PJVS and JAVS of UME were connected in series opposition and the voltage differences were measured by using digital nanovoltmeter, Keithley 182, using on the lowest ranges; 3 mV. Since the polarities of the array voltages were reversed, the polarity of the nanovoltmeter was not reversed. The mean values of 20 measurements for each polarity were used for the determination of the value of the unit under test.

The comparison measurements at UME were performed manually in normal laboratory conditions, not in an electromagnetically shielded room.

During the measurements, frequency variations were within 5 Hz of the central frequency.

Description of the Measurements

After arrival in UME laboratory on October 13, the PJVS was allowed to stabilise at least one hour before the measurements and the measurements were started after two hours than PJVS and JAVS of UME cooled down.

The first measurements were carried out in the afternoon. The first set indicated not a bad discrepancy but a larger dispersion than expected.

On the next day morning, the measurements were repeated with the same configuration. But, the results indicated a larger discrepancy and dispersion than the day before. The detector changed with another Keithley 182 and 2182 nanovoltmeter and no better results could be achieved, until 03:00 pm. While using the same detector with that was used the day before, the results carried out after 03:00 pm showed a good discrepancy and dispersion.

When we repeated measurements in the next morning (on October 15), we recognised a bad results again. Several measurements were carried out with different configurations as described below:

- The internal time base of EIP counter was used.
- The microwave part (Gunn diode, directional coupler, harmonic mixer, attenuator) was changed with another.

- EIP counter was replaced, and measurements were carried out while the gunn diode was fully phase-controlled by Pronova PLO control unit. (The gunn oscillator is locked to the 15th harmonic of the microwave reference minus the fundamental reference frequency and gives the fixed output frequency of 74.99 GHz.)
- Detector connection was changed.
- PREMA probe and array was changed with PTB probe and array.

Unfortunately, we couldn’t achieve a result with a low uncertainty, again until 03:00 pm.

On October 16, direct comparison was carried out with computer controlled, using the software developed at UME for the calibrations of DC reference standards by using JAVS. Unfortunately, the results were much larger than expected. We did not work on computer-controlled measurements much more. The last measurements of the comparison were carried out manually in the afternoon.

We assume that, the reason of achieving good results late in the afternoon is most probably due to the interference of unknown origin.

RESULTS OF MEASUREMENTS AT UME

DATE & TIME	f (GHz)	V_+ (µV)	V_- (µV)	V_{mean} (µV)	V_{DVM} (V)	n	V_{JUME} (V)	V_{PJVS} (V)
14.10.03 15:03	74,98887	1,342	-0,503	0,923	1,08715726	7011	1,08715725931	1,08715633681
14.10.03 15:05	74,98887	1,344	-0,499	0,922	1,08715726	7011	1,08715725931	1,08715633781
14.10.03 15:07	74,98887	1,347	-0,503	0,925	1,08715726	7011	1,08715725931	1,08715633431
14.10.03 15:09	74,98887	1,353	-0,485	0,919	1,08715726	7011	1,08715725931	1,08715634031
14.10.03 15:11	74,98887	1,352	-0,487	0,920	1,08715726	7011	1,08715725931	1,08715633981
14.10.03 15:13	74,98887	1,353	-0,486	0,920	1,08715726	7011	1,08715725931	1,08715633981
14.10.03 15:15	74,98887	1,355	-0,481	0,918	1,08715726	7011	1,08715725931	1,08715634131
14.10.03 15:17	74,98887	1,359	-0,483	0,921	1,08715726	7011	1,08715725931	1,08715633831
14.10.03 15:19	74,98887	1,357	-0,488	0,923	1,08715726	7011	1,08715725931	1,08715633681
14.10.03 15:21	74,98887	1,356	-0,488	0,922	1,08715726	7011	1,08715725931	1,08715633731
14.10.03 15:23	74,98887	1,360	-0,488	0,924	1,08715726	7011	1,08715725931	1,08715633531
14.10.03 15:25	74,98887	1,352	-0,490	0,921	1,08715726	7011	1,08715725931	1,08715633831
14.10.03 15:27	74,98887	1,357	-0,489	0,923	1,08715726	7011	1,08715725931	1,08715633631
14.10.03 15:29	74,98887	1,360	-0,482	0,921	1,08715726	7011	1,08715725931	1,08715633831
14.10.03 15:31	74,98887	1,361	-0,484	0,923	1,08715726	7011	1,08715725931	1,08715633681
14.10.03 15:33	74,98887	1,356	-0,484	0,920	1,08715726	7011	1,08715725931	1,08715633931
14.10.03 15:35	74,98887	1,361	-0,480	0,921	1,08715726	7011	1,08715725931	1,08715633881
14.10.03 15:37	74,98887	1,356	-0,485	0,921	1,08715726	7011	1,08715725931	1,08715633881
14.10.03 15:39	74,98887	1,357	-0,488	0,923	1,08715726	7011	1,08715725931	1,08715633681
14.10.03 15:41	74,98887	1,362	-0,486	0,924	1,08715726	7011	1,08715725931	1,08715633531
14.10.03 15:42	74,98887	1,355	-0,487	0,921	1,08715726	7011	1,08715725931	1,08715633831
14.10.03 15:43	74,98887	1,354	-0,485	0,920	1,08715726	7011	1,08715725931	1,08715633981
14.10.03 15:44	74,98887	1,354	-0,486	0,920	1,08715726	7011	1,08715725931	1,08715633931
14.10.03 15:45	74,98887	1,360	-0,486	0,923	1,08715726	7011	1,08715725931	1,08715633631
14.10.03 15:46	74,98887	1,360	-0,485	0,923	1,08715726	7011	1,08715725931	1,08715633681
14.10.03 15:48	74,98887	1,358	-0,483	0,921	1,08715726	7011	1,08715725931	1,08715633881
14.10.03 15:50	74,98887	1,357	-0,482	0,920	1,08715726	7011	1,08715725931	1,08715633981
14.10.03 15:51	74,98887	1,360	-0,486	0,923	1,08715726	7011	1,08715725931	1,08715633631
14.10.03 15:53	74,98887	1,358	-0,481	0,920	1,08715726	7011	1,08715725931	1,08715633981
14.10.03 15:56	74,98887	1,364	-0,482	0,923	1,08715726	7011	1,08715725931	1,08715633631
14.10.03 15:57	74,98887	1,358	-0,487	0,923	1,08715726	7011	1,08715725931	1,08715633681
14.10.03 15:58	74,98887	1,360	-0,480	0,920	1,08715726	7011	1,08715725931	1,08715633931
14.10.03 15:59	74,98887	1,361	-0,479	0,920	1,08715726	7011	1,08715725931	1,08715633931
14.10.03 16:00	74,98887	1,359	-0,484	0,922	1,08715726	7011	1,08715725931	1,08715633781
14.10.03 16:02	74,98887	1,357	-0,484	0,921	1,08715726	7011	1,08715725931	1,08715633881
							AVG	**1,08715633801**

PTB, Germany

Date of meassurements: 19-20 October 2003

Method of comparison:

Direct comparison due to series connection between the Portable Josephson Voltage Standard (PJVS) of VNIIM and the Josephson Voltage Standard of PTB. The PTB equipment has been used in other comparisons before [1, 2]. It operates a 10 V SIS array fabricated at the PTB's clean room facility. The array is mounted in a cryoprobe with dielectric waveguide of 2.5 dB attenuation. Selected copper wires reduce thermal voltages of the cryoprobe to usually smaller than 300 nV in a freely evaporating He transport dewar. The highly isolated measurement leads have a resistance of 3 Ω and are lowpass filtered at cut-off frequency of about 100 kHz.

For calibrating Zener references at the 1 V level a Keithley 182 nanovoltmeter is routinely used as null detector (without filter and 200 ms integration time). The bias source is grounded and keeps connected to the array during the measurement. A home made LabView program is used to set/control the EIP counter/stabiliser to a frequency that keeps the maximum voltage difference of the Josephson voltage and the device under test (DUT) at the null-detector below 1.0 µV. Furthermore it calculates the voltage of the device under test.

On 7 October 2003 the 10 V SIS Josephson standard was tested in a direct comparison (two PTB systems) with a SINIS Josephson array standard at the 1 V level. Especially, for preparing the comparison with the PJVS a new set-up with an EM N11 as a preamplifier using an optical link to the Keithley 182 was tested. Within 45 minutes 25 ±-measurements have been taken recording each 40 readings within 40 s at one polarity. The measured voltage difference was:
$U_{SIS} - U_{SINIS}$ = -0.07 nV,
with a type A uncertainty of 0.15 nV (1 σ).

Results during the installation: Output voltage of PJVS

19 October 2003

Meas. set no.	Date of measurement	Output resistance of PJVS	Number of ±-measurements	Null detector	U_{PJVS} - U_{nom}, nV	Standard uncertainty of measurement, nV
1	19.10.03	4 Ω	5	EM N11	+1.17	0.44
2	19.10.03	4 Ω	20	Keithley 2182	+0.61	0.31
3	19.10.03	4 Ω	26	Keithley 182	+0.64	0.38
4	19.10.03	4 Ω	16	Keithley 182	+0.43	0.59
5	19.10.03	4 Ω	16	Keithley 182	+1.20	0.30
6	19.10.03	4 Ω	8	Keithley 182	+0.56	0.57

1) The measurement were very noisy i.e. due to large EMI. This became apparent in much reduced step width of the SIS array. Therefore, this measurement set was stopped and a fault analysis was started.
2) The EMI was smaller than with the EM N11, but obviously still a deviation from the expected value was visible.
3) This set-up has been used in a previous comparison [2] getting very good agreement between both standards. The deviation indicated that something is wrong.
4) Measurement with changed ground connections of the PJVS has changed nothing. Searching for an error was continued.
5) Changed frequency at the PTB system to see influence of the voltage at the null detector had no effect to the deviation.
Searching for an error was continued with a check of the PJVS frequency. The deviation between expected and measured frequency of the PJVS is just +2 Hz. Therefore, searching for an error was continued.
6) A changed of the bias current on the PJVS and using zero current steps with the PTB JVS did not gave better results.

Continue of the measurements on **20 October 2003**.
A check of leakage resistances of the both systems was made. The rotary switch at the PTB system has a leakage resistance of 2 GΩ! Of course, this can easily make an error of 10^{-9}.
This rotary switch was taken out. Both arrays were connected directly together and switching of both arrays was made synchronously. The calibration of the PJVS was performed from taking 80 ±-measurements in the time from 10:10 to 11:20 a.m using a Keithley 2182 as null detector.

Measurement system (final system):
Type of array: 10V SIS, Me-168/4, PTB
Detector: Keithley 2182, 10 mV range, no filter, NPLC = 1
Bias source: PTB made
Measurements made without opening the measurement circuit
Software used: PTB produced calibration LabView program
Frequency Counter Stabiliser: EIP 578B using the external locking, stability 1 Hz
Thermal emf approximately 600 nV
Impedance of the measuring leads 5 Ω

[1] D. Reymann, T. Witt, G. Eklund, H. Pajander, H. Nilsson, R. Behr, T. Funck und F. Müller
A three way, on-site comparison of the 10-V Josepshon voltage standards of the PTB, the SP and the BIPM
IEEE Trans. Instrum. Meas. **48**, pp. 257-261, 1999.

[2] A. Katkov, R. Behr, G. Telitchenko, und J. Niemeyer
VNIIM-PTB comparison using a portable Josephson voltage standard
Metrologia **40**, 89-92, 2003.

SP, Sweden

Date of meassurements: **21 October 2003**

Description of the measuring method

The travelling standard was used with a 60 litre dewar supplied by SP and the same 10 MHz reference frequency source was used for the travelling Josephson standard and the SP Josephson standard.

The measurements were performed by measuring the fixed Josephson voltage of approximately 1.087 V generated by the travelling standard with the SP Josephson voltage standard. The SP Josephson standard was used in the same way as ordinary measurements of Zener references or Weston cells with the exception that the reversing switch was used in one fixed position. The necessary polarity reversing was performed by the reversing of the two Josephson voltages of the travelling standard and the SP Josephson standard. Due to this all stable thermal voltages were eliminated and the uncertainty is therefore lower than in ordinary measurements with the SP Josephson standard.

Description of the SP voltage standard

The SP Josephson voltage standard is based on 1 V and 10 V SIS Josephson arrays developed and manufactured by the Physikalisch-Technische Bundesanstalt (PTB) and the National Institute of Standards and Technology (NIST). The microwave source is a Farran Technology Gunn diode operating at 69 GHz - 74 GHz stabilized by an EIP 578 frequency counter-stabilizer via a phase-lock loop driver. A calibrated 10 MHz reference signal is connected to the EIP 578 counter and PJVS. The cryoprobe is based on a design developed at the DFM. The array bias source is a RMC JBS-200A connected to the array via filters. The filters on the output voltage leads have a total series resistance of 1.4 Ω and a leakage resistance grater than 10^{11}Ω. The detector to measure the voltage between the Josephson array voltage and the voltage to be measured is a Keithley 182 nanovoltmeter and the reversing switch is a Guildline 9145A. Software developed by the NIST is used with a computer to read the EIP counter and the nanovoltmeter and calculate the measurement result. In the measurement process the microwave frequency is adjusted to minimize the reading of the nanovoltmeter. Effects of the thermal electromotive forces (EMFs) between the array and the reversing switch as well as those of any voltage generated by the bias current from the nanovoltmeter are eliminated by the reversing switch. The residual thermal EMF, a few nanovolts, between the reversing switch and the voltage standard being calibrated is not automatically eliminated. It is measured separately and a correction is applied to the results if considered necessary.

The SP Josephson voltage standard is routinely used to measure SP's primary Weston cells with a combined type A and type B standard uncertainty of less than 3 nV/V.

Conditions of the SP Josephson voltage standard for the comparison

- The Josephson array used was the PTB SIS array Me-178/6.
- The Keithley 182 nanovoltmeter was used with 1 nV resolution on the 3 mV range. Maximum reading was 100 nV. The Keithley 182 was not separately reversed.
- The used software was NISTVOLT 2.5 rev SP 971216.
- Effects of thermal electromotive forces (approximately 0.5 µV) between the array and the reversing switch as well as those of any voltage generated by the bias current from the nanovoltmeter are eliminated by the reversing of the Josephson voltages of the SP Josephson voltage standard and the travelling standard.
- The Josephson bias source was connected to the array during the precision measurements and floating with battery operation and approximately 10 MΩ leakage to ground.
- The microwave frequency stability was within ± 100 Hz or better.
- The measurements at SP were carried out during one day and were performed in a shielded room. One measurement series were performed for each of the two possible output resistance settings of the travelling Josephson standard.
- Each measurement of the measurement series consist of 10 calculated values from totally 800 readings of the null detector and the microwave frequency counter in a 200-400-200 (positive-negative-positive polarity) reading sequence with a measurement time of typically 7-8 minutes. The final value is from a series of 10 measurements with a duration of less than 3 hours.

NPL, United Kingdom

Date of meassurements: **10-13 November 2003**

The NPL voltage calibration system is designed to run fully automated without the need for operator adjustments. All customer standards are directly measured against the primary standard thereby significantly reducing the traceability chain. The main compromise made is that the Gunn frequency is not adjusted to minimise the null detector reading. The array is biased with an NPL designed and built bias source which features an optically isolated interface link with the measurement computer and high performance isolated power supplies which allow the bias source to be permanently powered from the mains. Also the GPIB interface and 10MHz are optically isolated. The bias source is fully automated and controlled via a LabVIEW executable which contains features for observing IV-curves, step selection, relay switching etc. The bias source and array are floating from the measurement shield which means that we can choose our measurement shield reference point arbitrarily. In the NPL system the customer standards are powered from the mains and the standards' guard and measurement ground are connected to the low voltage side of the standard. This means that the standard always has the same potential relative to mains ground independent of a forward or reverse measurement.

- Type of array: 10V SIS, PTB produced s/n ME37-9.
- Detector: HP34420A, scale used 10mV.
- Measurements made without reversing the detector polarity i.e. by reversing array bias.
- Bias source: IPBS-JJ-02, NPL produced bias source.
- Array disconnected from bias source during measurements.
- Software used: Measurements made with MacroLIP Version 7.0.6, NPL produced measurement program based on LabVIEW. Analysis made with AGJD Version 4.0.2, NPL Josephson analysis program based on LabVIEW.
- Frequency source stabiliser: EIP 578B using internal locking, stability a few Hz.
- Thermal emf approximately 400nV.
- Impedance of measurement leads approximately 8 Ω.

Measurements are made in screened room (although we always have the door open).The dominant uncertainty contribution is the uncertainty of the linearity of the null detector. In the NPL system we don't adjust the frequency and therefore the detector reads on average 1 mV. The CMRR of the null detector is also important which appears as a leakage resistance of approximately 50 GΩ to ground at the unknown side of the detector (Lo terminal). The measurements for 1.2 kΩ output have been corrected for this leakage. Also this leakage is responsible for the different sensitivity coefficients for 4 Ω and 1.2 kΩ source resistances.

Summary of results form

Measurement Set no.	Date of measurement	Output resistance of PJVS	Number of data points	Measurement result	Type A Standard uncertainty of measurement
1	11/11/2003	4 Ω	88	1.087 156 336 V	1.16 nV
2	11/11/2003	4 Ω	96	1.087 156 337 V	1.38 nV
3	11/11/2003	4 Ω	96	1.087 156 337 V	1.55 nV
4	12/11/2003	4 Ω	96	1.087 156 335 V	1.60 nV
5	12/11/2003	4 Ω	96	1.087 156 337 V	0.74 nV
6	12/11/2003	4 Ω	76	1.087 156 335 V	1.85 nV
7	12/11/2003	1.2 kΩ	96	1.087 156 333 V	4.27 nV
8	12/11/2003	1.2 kΩ	96	1.087 156 325 V	4.29 nV

DFM, Denmark

Date of measurements: **15 November 2003**

1 The DFM Set-up

DFM has operated a Josephson voltage standard since 1987, originally with a VTT developed single junction array, and with a 1 V array based Josephson standard since 1989. In 1991 the system was upgraded with a 10 V chip, originally supplied by NIST, later replaced by a chip produces by Hypres. The array system is not operated in a shielded room.

1.1 Instrumentation

The array used is a Hypres SIS 10 V array, serial 2484H-1. The array is biased using a JBS 500 Josephson Bias source (produced by Astro Endyne, Boulder). The array is connected to the bias circuit during measurements. The bias source provides a virtual ground and the reference ground for the measurement circuit is the ground connection in the bias source.

The array is mounted on a microwave carrier by Hypress with a WG12 flange and solder points as the external interface. The carrier is mounted at the end of a sample holder made by DFM on a CuBe WG12 waveguide. A 15 cm section of the WG12 waveguide has been machined to a smaller wall thickness to reduce the thermal leak to room temperature. Three teflon isolated, silver-clad Cu wires connect each side of the array to the room temperature connectors. At the head of the sample holder, each wire passes through a double-ladder LC filter. The series resistance in the voltage sense leads is about 1 Ω. The leakage resistance from each lead to any other lead and to ground is larger than 100 GΩ.

The detector is an Agilent 34420A Nanovoltmeter. The array is biased so that the 1 mV scale is used. Prior to measurements, the scale linearity is determined by applying various array voltages to the detector and from the readings of the nanovoltmeter versus the quantized voltages the scale error is inferred. The detector is used with analog filter on, digital filter off, and NPLC 20. To circumvent the "pump-out" current problem of this detector, a 220 nF polypropylene capacitor is connected across the input. The detector is not reversed during measurements.

The microwave system comprises a Millitech GDM-12-2018 IN Gunn oscillator biased from a Farran FDB-F8 modulated voltage bias source. The microwave signal is supplied to the array through a standard WG12 CuBe waveguide via a 20 dB coupler and an attenuator. The microwave frequency is read by an EIP 578B counter referenced to the 10 MHz output of a Stanford Research Systems PRS10 Rb oscillator. The PRS10 output is compared continuously with the DCF77 signal monitored by PTB (The PTB bulletin provides the traceability of the long-term frequency stability of the PRS10). The EIP counter provides the feedback voltage to the Farran bias source. The frequency display of the EIP shows during lock and normal operation a variation of at most ±5 Hz.

The array and the nanovoltmeter are connected to the object under calibration via a Guildline 9145 Low Thermal switchbox, and are so connected that the polarity of the calibration object may be reversed at the switchbox. The total voltage offset in the circuit, which is compensated by polarity reversals, is usually of the order 300 nV.

1.2 Measurement method and derivation of individual results

The DFM Josephson system is run in semi-automatic mode. Biasing, data acquisition and calculation of the calibrated value is done by computer, while polarity reversal is performed manually. Polarity reversal was in this case not done on the Guildline 9145 switch box, which was left in one position during each measurement, but on the bias polarity switch of the PJVS bias supply.

The measurement method follows that of Hamilton *et al.* with determination of the nanovoltmeter gain error (usually performed once a day), a measurement of a short circuit for the estimation of un-compensated voltage offsets, and finally measurement of the voltage difference between the biased array and the calibration object with two polarity reversals in a A-B-B-A sequence. Usually 10 or 25 readings are performed at each polarity. The array is connected to its bias circuitry during measurement. From the voltage difference readings a least squares estimate of three parameters is done: The voltage of the calibration object, the voltage offset from thermal emfs etc., and a first order drift during the measurement.

2 Comparison measurements and final result

The PJVS was arrived on 13 November 2003, and on 14 November, the PJVS was assembled. However, it was realized that the PJVS chip was destroyed. Dr. Behr of PTB was contacted and during the day it was arranged to have two cursory tested replacement PJVS chips shipped from PTB to DFM. The chips arrived by courier on the morning of 15 November. During the day, the two chips were tested in the PJVS setup, and one was found to work satisfactory. The two Josephson systems were connected together, and a source of interference was observed preventing stable operation. The source was identified and eliminated, and the two setups were ready for the comparison measurements.

The measurements were performed on 15 November 2003 from 17:45 till 20:20.

The PJVS was biased permanently at Josephson step number 7168 and its fixed frequency source generated at microwave signal at 74.882 GHz referenced to the DFM PRS10 source. Hence the nominal voltage of the PJVS was U_{nom} = 1,109 918 335 05 V.

The raw results obtained in this single measurement set by DFM are listed in the table below.

Time of measurement	U_{PJVS} / V	u_A(UPJVS)/nV	n	Δ / nV
2003-11-15 17:45:53	1,109 918 333 3	0,3	50	-1,75
2003-11-15 17:55:15	1,109 918 336 3	0,3	50	1,25
2003-11-15 18:03:53	1,109 918 335 8	0,3	50	0,75
2003-11-15 18:37:42	1,109 918 337 6	0,3	50	2,55
2003-11-15 18:45:50	1,109 918 336 9	0,3	50	1,85
2003-11-15 18:53:16	1,109 918 334 0	0,3	50	-1,05
2003-11-15 19:00:14	1,109 918 333 9	0,3	50	-1,15
2003-11-15 19:07:42	1,109 918 333 4	0,3	25	-1,65
2003-11-15 19:11:28	1,109 918 334 0	0,3	25	-1,05
2003-11-15 19:15:13	1,109 918 335 5	0,4	25	0,45
2003-11-15 19:19:24	1,109 918 335 4	0,4	25	0,35
2003-11-15 19:30:57	1,109 918 334 6	0,6	25	-0,45
2003-11-15 19:34:28	1,109 918 334 2	0,6	25	-0,85
2003-11-15 19:37:38	1,109 918 336 9	0,5	25	1,85
2003-11-15 19:40:25	1,109 918 337 2	0,5	25	2,15
2003-11-15 19:43:36	1,109 918 334 5	0,5	25	-0,55
2003-11-15 19:46:46	1,109 918 335 8	0,5	25	0,75
2003-11-15 19:49:51	1,109 918 336 9	0,5	25	1,85
2003-11-15 19:52:51	1,109 918 335 1	0,5	25	0,05
2003-11-15 19:55:36	1,109 918 335 6	0,5	25	0,55
2003-11-15 19:59:20	1,109 918 334 1	0,5	25	-0,95
2003-11-15 20:02:37	1,109 918 335 9	0,5	25	0,85
2003-11-15 20:05:54	1,109 918 335 2	0,5	25	0,15
2003-11-15 20:08:59	1,109 918 335 4	0,5	25	0,35
2003-11-15 20:12:55	1,109 918 336 1	0,5	25	1,05
2003-11-15 20:18:25	1,109 918 335 6	0,5	25	0,55

Given are the time of measurement, type-A standard uncertainty of the value determined from the least squares fit, the number of readings per polarity and the calculated difference between the DFM result and the nominal PJVS value.

We find no significant differences in the result when the DFM array is biased on the “best” step, minimizing the voltage difference, or when any other step in the 1 mV voltage difference range is used. We also did not observe any significant difference whether the bias source was on or bias was disconnected during measurement. Also we find no significant difference whether the output impedance of the PJVS is 4 Ω or 1.2 kΩ. Results in these configurations are also included above.

The type-A standard uncertainty of the average of the results above is 0,23 nV, but is below the minimum Allan standard deviation of the DFM Agilent 34420A in the its white noise regime, s(~50 samples). The type-A standard uncertainty of our result is hence limited by the 1/f noise characteristic to 0,55 nV.

When calibrating other voltage sources (Zeners), uncompensated voltage offsets are also considered. However, in the case with the PJVS, the voltage reversal is performed by the PJVS biasing itself, presenting no uncompensated voltage.

IEN, Italy

Date of meassurements: **18 November 2003**

Conditions and methods of measurement

SYSTEM SETUP

a) The microwave generation/control system, is realized with a 70 mW, 76 GHz gunn oscillator and is synchronized with the IEN frequency standard (10 MHz signal) by means of a commercial counter/phase lock.
b) The cryogenic devices w/ stainless steel, circular waveguide,
c) The DC measurement instrumentation consisting in:
- a DC bias source realized with a modified commercial instrument
- an oscilloscope for IV array characteristic visualization
- custom made low-thermal scanner for reversals
- a high sensitivity (EM N11) nanovoltmeter, whose isolated output is read trough a DVM by a computer for automated data acquisition and storage. After the proper step is selected the bias source is disconnected, and the measurement circuit is completely floating because the detector is battery supplied.

e) The array chip was made by Hypres and has critical current ~ 150 µV and 10 V step width ~ 30 µV.

MEASUREMENT PROCEDURE

After arrival in a laboratory the PJVS was allowed to stabilise several hours hour before measurements. Measurements made in a shielded room. The ambient conditions for measurements were 23 °C ± 0.5 °C and relative humidity than 50% ± 0.5 %.
The helium dewars of PJVS and JAVS was a vented, open-air system.
The reference frequency was a 10 MHz signal from IEN frequency standard.
After the proper step was selected the bias source was disconnected, leaving the measurement circuit completely floating.
Changing polarity of the JAVS was made manually to match the PJVS polarity. The measurement time for every polarity was between 50 and 200 seconds. 4 reversals were performed in each measurement (JAVS and nanovoltmeter).
The thermal emf were about 1.5 µV during all measurements and the nanovoltmeter was operated on the 3 µV range.

Summary of results form

Measurement Set no.	Date of measurement	Output resistance of PJVS / Ohm	Number of data points	Measurement result	Standard uncertainty of measurement
1	18 nov 03 - 13:16	4	39	V_X + 0,90 nV	0,8 nV / V
2	18 nov 03 - 15:11	4	22	V_X + 1,77 nV	0,8 nV / V
3	18 nov 03 - 15:39	4	37	V_X + 1,02 nV	0,8 nV / V
4	18 nov 03 - 16:36	4	33	V_X - 2,58 nV	0,8 nV / V
5	18 nov 03 - 16:46	4	14	V_X - 0,58 nV	0,8 nV / V
6	18 nov 03 - 17:00	4	33	V_X - 0,08 nV	0,8 nV / V
7	18 nov 03 - 17:58	4	35	V_X + 0,36 nV	0,8 nV / V
8	18 nov 03 - 18:13	4	41	V_X - 0,72 nV	0,8 nV / V
9	18 nov 03 - 18:26	4	46	V_X - 0,64 nV	0,8 nV / V
10	18 nov 03 - 18:41	4	44	V_X - 0,82 nV	0,8 nV / V
11	18 nov 03 - 18:59	4	43	V_X + 0,01 nV	0,8 nV / V

EIM, Greece

The measurements were carried out on February 11 and 12, 2004.

System setup and Measuring Procedure
The Portable Josephson Voltage standard (hereafter mentioned as "PJVS") was measured by comparison with the Josephson voltage standard of EIM (hereafter, mentioned as "array"), which is a 1V SIS type (Niobium/Aluminum-Oxide/Niobium) junction supplied by HYPRES provided by HYPRES (USA) and designed with NIST cooperation. The circuit used is shown in Fig. 1, where the PJVS and the array were connected in series opposition across a null meter:

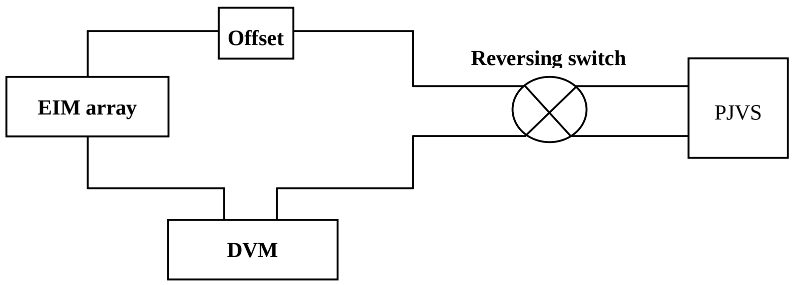


Fig. 1 Circuit diagram

The difference voltage between PJVS and EIM's array was measured on a reversing switch by a Hewlett Packard HP3442A 7.5 digits nanoVolt/Micro-Ohm Meter. A 75.7GHz microwave signal was applied to the array using a Millitech Gun Diode RF Source and its value was measured and locked with an EIP 578B locking microwave counter. A 10 MHz frequency reference was used, which was directly traceable to UTC via GPS and the frequency stability was ±1Hz. The Josephson array, bias voltage, frequency locking and voltmeter were controlled by a JBS501B Controller, which links all system parts and is drived by a computer, working with NISTVOLT standard control program designed with NIST cooperation. The equipment used in the measurement setup is

EQUIPMENT
1. Array: 1V Josephson array provided by HYPRES
2. Bias source: Model JVS1000
3. Software: NISTVolt for DOS
4. RF Source: Millitech 75GHz Gunn diode, attenuator, mixer
5. Frequency counter: EIP module 578B Locking microwave counter
6. Frequency reference: 10MHz reference frequency from Cs clock steered to UTC via GPS
7. DVM: HP34420A 7.5 digits nanoVolt/Micro-Ohm Meter

The measurements were performed within two days and resulted in 37 measurement results in total. The output resistance of the PJVS was 4Ω. Each measurement result is equal to the mean of the absolute values of two intermediate results, one with positive current through PJVS and the other with negative. In this way, any offsets on the PJVS side of the reversing switch are eliminated. To eliminate other offsets that are involved in the measurement (thermal EMF on the array side of the reversing switch, voltmeter's offset and gain), the following procedure is used, from which each of the above-mentioned intermediate results (of opposite PJVS current polarities) is derived:
First, an initial estimate V_e of the PJVS voltage is made. Then, the SIS array is locked to a proper step matching V_e, the bias leads are disconnected and the system starts acquiring measurements of the difference V(DVM)=V_{array}-V_{PJVS}. 10 first data points are taken. Next, the connections to PJVS are reversed by means of the reversing switch, the SIS array is again locked to a negative step and ten more data points are acquired and stored. Two more reversals generate third and fourth 10 data sets. All data (40 in total) can be represented by

$$V_{DVM} = Nf\frac{h}{2e} + V_{OFFSET} - PV_{PJVS}$$, where

$N = Round\left\{\frac{(V_{DVM} + V_e)}{fh/2e}\right\}$ is the Josephson quantum step number (it is computed anew with each acquisition of V_{DVM}, where V_e is the initial estimate of the PJVS voltage taken at the beginning of each one of the 4 data sets and *Round* means rounded to the nearest integer),
f is the microwave frequency (its value is 75.7GHz),

P is the polarity of the reversing switch, which is 1, -1, 1 and -1 for the data sets 1,2,3 and 4 respectively,
V_{PJVS} is the PJVS voltage and
V_{OFFSET} is a combination of the thermal EMFs on the array side of the reversing switch and the DVM offset (see Fig. 1), including also a first order drift.
A linear squares fit is performed on these data and the best estimates for V_{PJVS} and V_{OFFSET} are derived, giving the one intermediate result for V_{PJVS}. V_{OFFSET} values were of the order of 70nV.

When the first intermediate result is derived, the PJVS current is reversed and the above procedure is repeated for the derivation of the second intermediate result – of opposite sine. Then, the mean of the absolute values of the two gives one of the 37 measurement results, which are presented in Table 1 below. The thermal EMFs occurring in the wiring between the reversing switch and the PJVS device can be computed from the (algebraic) mean of the two intermediate results and it is of the order of 90nV.

Measurements mean
To compute the overall measurements mean of the 37 results taken in two days time, we first check their consistency. Indeed, the two sets, performed under the same circumstances are found to be consistent according to the F test and their overall mean is:

Measurements Mean: $\overline{V} = \dfrac{n_1\overline{V_1} + n_2\overline{V_2}}{n_1 + n_2}$, where

$\overline{V_1} = \sum_{i=1}^{n_1} \dfrac{V_{1,i}}{n_1}$, $\overline{V_2} = \sum_{i=1}^{n_2} \dfrac{V_{2,i}}{n_2}$ are the individual mean values in the two days and
n_1 and n_2 are the corresponding number of measurements (n_1, n_2 were 30, 7 respectively and it turned out that $\overline{V_1} = \overline{V_2} = 1.068\,884\,802$ V, equal to the 1nV digit). The number of degrees of freedom assigned to it is n_1 - n_2 -2 = 35.

Uncertainty evaluation
Uncertainty evaluation is based on "The Guide to the Expression of Uncertainty in Measurement" published by ISO. The terms contributing to the uncertainty are the following:

1. Frequency uncertainty (type B)

This comprises of three terms:

b) The frequency stability, which is ±1Hz. This gives a contribution to uncertainty of ±1Hz/75.7GHz=$\pm 1\cdot 10^{-11}$.

c) The accuracy of the EIP counter, which is ±15Hz, which gives a contribution of ±15Hz/75.7GHz=$\pm 2\cdot 10^{-10}$.

d) The accuracy of the 10MHz reference, which is $\pm 1\cdot 10^{-14}$.

The total of all the above terms is $\pm 2\cdot 10^{-10}$ and a rectangular distribution is assumed.

2. Leakage uncertainty (type B)

This is the uncertainty due to leakage current between the array voltage leads or from these leads to ground. The worst case is when this current flows 100% through the cryoprobe filters. In this case the error is computed to be $1\cdot 10^{-9}$ and the same value is used for the uncertainty. The error correction is applied to the measurement results and the uncertainty is assumed to obey a rectangular distribution, since it is evaluated as a worst-case value. The corrected measurement results are presented in Table 1.

3. Repeatability of measurements (type A)

This is the type A uncertainty of measurements, which, as the data were found to be consistent, is taken as the standard deviation of the mean of all 37 measurements:

$s^2(\overline{V}) = \sum_{i=1}^{n_1+n_2} \dfrac{\left(V_i - \overline{V}\right)^2}{\left(n_1 + n_2\right)\left(n_1 + n_2 - 1\right)}$, where

n_1+n_2=37 is the total number of measurements and $\overline{V}$ is the overall measurements mean defined already.
The resulting uncertainty value is 0.95nV.

4. Zero offset uncertainty (type A)

This term comprises all uncertainties except frequency, leakage and noise from the device under test. These are DVM's gain and linearity error uncertainty (all stable thermal emfs are cancelled and unstable EMFs give a Type A contribution on the standard deviation). Since it does not depend on the magnitude of the voltage measured, it can be evaluated from short circuit measurements. This was done by shorting the terminals normally connected to the PJVS and making a set of N measurements of V_{zero} using the same algorithm and the same setup as in the 1V measurements (similar microwave frequency/ power, remaining wiring, environment). Then the zero offset uncertainty is taken as:

$$\sqrt{\sum_i \frac{{V_{zero,i}}^2}{N}}$$

and the result for N=19 was 2 nV.

Results

In Table 1 the results of the measurements are presented. More specifically, the date and time of measurement, the output resistance of PJVS, the number of data points that were used to extract each measurement result, the measurement result and the standard uncertainty of the measurement result are shown. The standard uncertainty comprises of the standard deviation of the 40 data points and the (10nV, as measured) zero offset uncertainty of the array side of the circuit.

Table 1.

No. of measurement	Date	Time	Output resistance of PJVS	No. of data points	Measurement result (V)	STD (nV)
.1	2/11/04	10:02	4Ω	80	1.068 884 806	< 3.2
2	2/11/04	10:21	4Ω	80	1.068 884 791	< 3.2
3	2/11/04	10:33	4Ω	80	1.068 884 805	< 3.2
4	2/11/04	10:46	4Ω	80	1.068 884 818	< 3.2
5	2/11/04	11:00	4Ω	80	1.068 884 799	< 3.2
6	2/11/04	11:13	4Ω	80	1.068 884 805	< 3.2
7	2/11/04	12:03	4Ω	80	1.068 884 787	< 3.2
8	2/11/04	12:15	4Ω	80	1.068 884 805	< 3.2
9	2/11/04	12:29	4Ω	80	1.068 884 801	< 3.2
10	2/11/04	12:42	4Ω	80	1.068 884 800	< 3.2
11	2/11/04	12:54	4Ω	80	1.068 884 802	< 3.2
12	2/11/04	14:03	4Ω	80	1.068 884 802	< 3.2
13	2/11/04	14:16	4Ω	80	1.068 884 799	< 3.2
14	2/11/04	14:28	4Ω	80	1.068 884 798	< 3.2
15	2/11/04	14:40	4Ω	80	1.068 884 803	< 3.2
16	2/11/04	14:53	4Ω	80	1.068 884 801	< 3.2
17	2/11/04	15:05	4Ω	80	1.068 884 797	< 3.2
18	2/11/04	15:20	4Ω	80	1.068 884 796	< 3.2
19	2/11/04	15:32	4Ω	80	1.068 884 801	< 3.2
20	2/11/04	16:04	4Ω	80	1.068 884 810	< 3.2
21	2/11/04	16:23	4Ω	80	1.068 884 804	< 3.2
22	2/11/04	17:26	4Ω	80	1.068 884 807	< 3.2
23	2/11/04	17:40	4Ω	80	1.068 884 801	< 3.2
24	2/11/04	17:53	4Ω	80	1.068 884 812	< 3.2
25	2/11/04	18:06	4Ω	80	1.068 884 800	< 3.2
26	2/11/04	18:17	4Ω	80	1.068 884 801	< 3.2
27	2/11/04	18:28	4Ω	80	1.068 884 805	< 3.2
28	2/11/04	18:39	4Ω	80	1.068 884 806	< 3.2
29	2/11/04	18:51	4Ω	80	1.068 884 798	< 3.2
30	2/11/04	19:03	4Ω	80	1.068 884 797	< 3.2
31	2/12/04	10:57	4Ω	80	1.068 884 795	< 3.2
32	2/12/04	11:08	4Ω	80	1.068 884 800	< 3.2
33	2/12/04	11:19	4Ω	80	1.068 884 803	< 3.2
34	2/12/04	11:29	4Ω	80	1.068 884 809	< 3.2
35	2/12/04	11:42	4Ω	80	1.068 884 812	< 3.2
36	2/12/04	11:54	4Ω	80	1.068 884 798	< 3.2
37	2/12/04	12:08	4Ω	80	1.068 884 802	< 3.2

BIPM, International

The measurements were carried out on March 22 and 23, 2004.

For the reasons explained below, only some of the measurements were taken into account to provide the final result.

The BIPM measurement device.
The array is a 10 V Hypress SIS array, operating at about 75 GHz. The probe holder is BIPM made and includes an efficient set of filters on both bias and measurement leads. The bias supply is a modified NIST unit that can be operated at a floating potential or grounded. During the measurements, the array is disconnected from the bias supply. The detector is a analogic nanovoltmeter (EM N1a) used on the +/– 0.3 µV scale, whose output is connected via an isolation unity gain amplifier to a pen recorder and a DVM for data acquisition. The measurement schedule includes both reversing the polarity of the array and of the detector. The result of each measurement is computed separately for both polarities of the detector, the difference between those values being used to estimate the possible influence of the EMI on the detector. The software was written in the BIPM. The frequency source is controlled by an EIP counter and a ETL/Advantest stabiliser. The stability of the frequency is a few Hz around the programmed value. The two arrays were biased at the same frequency. The uncertainty for the BIPM frequency is derived from measurements published in *Metrologia*, 1996, **33**, 475-478. The thermal EMFs in the BIPM device are below 0.1 µV. The impedance of the measurement leads is about 3 Ω. The room where the measurements were carried out cannot be considered as shielded. All this equipment is used for routine measurements at the BIPM and has been used for international comparisons (apart from the array itself). Comparisons between this equipment and a similar arrangement using a SINIS (PTB) array have shown no difference to within a few parts in 10^{10}.
Measurement progress.
The two arrays were connected in series opposition and the voltage difference was measured with the nanovoltmeter. To summarise the different measurements, the differences observed in the first sets of measurement were thought to be due to possible leakage resistance. It appeared then that they were due to the non verticality of the SINIS steps. Different actions were undertaken to fix the problem or, at least, to reduce it. Finally, it appeared that the most efficient action was to connect the "common" of the two arrays to ground. Several measurements were used to determine the values of the current bias of the SINIS where the voltage could be considered as constant. Only the 38 measurements carried out at the "centre" of the steps (bias current between 1.30 mA and 1.35 mA) were used to compute the final result. Taking into account all 48 measurements where the bias current was between 1.25 mA and 1.40 mA would have given exactly the same value. Although some measurements were made with the "High impedance output", none of them were made in the "good step conditions". A weighted mean of the (only) three series of measurements would have given a difference of the order of 1 nV, with a type A uncertainty 5 times larger. This result should not be taken in consideration for the final report.
Leakage resistance
In fact there are two different sources of uncertainty for leakage resistance: one (A) is due to the leakage between the two measurement leads (> 10^{11} Ω for the BIPM system) and the other (B) is between these leads and ground (> 3 10^{10} Ω for the BIPM system). The series resistance of each measurement leads is about 1.5 Ω. In both cases, we cannot identify the path for the leakage current and we can only estimate the "worst" case for which we assume a rectangular distribution.
(A) Typical value of the resistances : $r_1 = r_2 = 0.7$ Ω (winded inductance), $R_1 = R_2 > 10^{12}$ Ω, $R_L > 10^{11}$ Ω. In this case, the leakage is through the feed-through capacitors (via the ground) and through the (teflon) filter capacitors. The series resistance is contained mainly in the inductance of the filters. The order of magnitude of this effect, to first approximation, is equal to $2\times r_1/2\times R_L$, i.e. : 0.7 10^{-11}. (see Fig. 1)
(B) Typical value of the resistances : $r_{BI} = 1.5$ Ω, $r_{ref} = 2$ Ω, $R_{BI} = R_{ref} > 3\times10^{10}$ Ω, In this case, the two leakage paths compensate. The order of magnitude of this effect, to first approximation, would be $(r_{BI}/R_{BI}) - (r_{ref}/R_{ref})$, i.e. in the worst case: 0.7 10^{-10}. (see Fig. 2)
Taking into account those two effects, the relative uncertainty due to leakage resistance is 4 parts in 10^{11}.

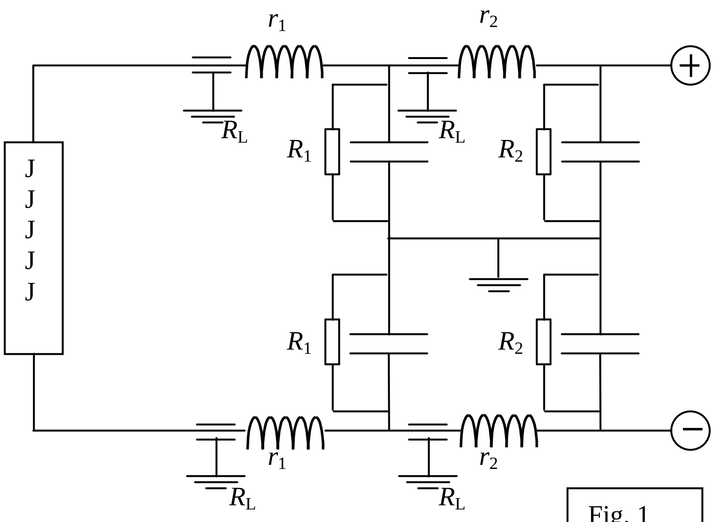

r1
r2
RL
RL
R1
R2
J
J
J
J
J
R1
R2
r1
r2
RL
RL

Fig. 1

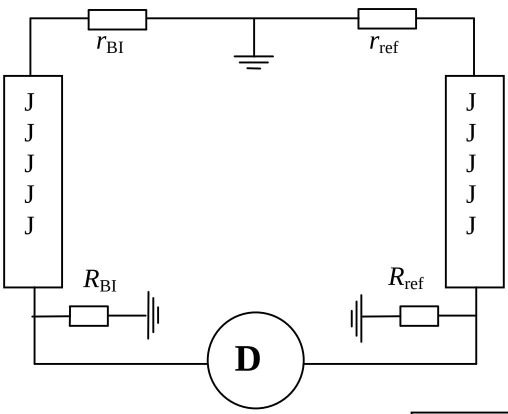

rBI
rref
J
J
J
J
J
J
J
J
J
J
RBI
Rref
D

Fig. 2

Monday 22 March 2004

The BIPM SIS array was already in place. The SINIS array was connected on the probe holder and cooled. The measurements began at 9:10. The microwave frequency for the SIS was 74.97976 GHz. Two series of 3 and 8 measurements were made to calibrate the SINIS as if it were a Zener. (The only modification to the current BIPM program was an increase of the number of displayed digits in the result sheet.). The value obtained by the BIPM was about 3 nV higher than the expected (theoretical) value. Another series of 3 measurements was made with the "high impedance" output of the SINIS and the measured value was about 7.5 nV too high.

The current bias of the SINIS was then readjusted and two series of 8 measurements were made; the second one after turning off the air conditioning (remained so for all subsequent measurements). The measured values were 0.6 nV and 0.2 nV too high. In order to reduce the difference between the two arrays (and hence to reduce possible uncertainty coming from the calibration of the detector), the SIS microwave frequency was changed to 74.882 GHz which appeared to be exactly that of the SINIS array. This frequency remained the same for all subsequent measurements. A series of 9 measurements was made and the measured value was about 1.6 nV too high. After lunch, the bias current of the SINIS was verified and a new series of 4 measurements was made: the measured value was still 2 nV too high. Thinking of a possible problem of leakage resistance in the BIPM device, a capacitor connected in parallel with the bias of the SIS was removed, without changing the results of the difference obtained in the next series of 2 measurements: 2.4 nV. A second series of 2 measurements was made with the "high impedance" output of the SINIS and the measured value was about 6 nV too high. In the BIPM measurement system a time lag of 3 or 4 seconds is introduced after each change in the detector polarity to eliminate possible transient effects. For the next series of 3 "low impedance" measurements, the time lag was increased to 10 seconds, but the result remained the same, a measured value 2 nV too high.

After this, all leakage resistances were measured: in the BIPM circuit the leakage resistance to ground was 30 GΩ, which was reduced by a factor 2 when connecting the SINIS. The resistance in the measurement circuit being 3 Ω for the SIS and 4 Ω for the SINIS, the leakage resistance would have resulted in worst case in a change of 1 part in 10^{10}. In the research process for explaining the observed differences, a balance was made at 0 volt on both arrays. A rather large difference appeared between the "thermal EMF" values measured on the SINIS with the microwave signal on or off, that could be due to the rectification of the RF signal by one point of the SINIS. After this, the SINIS array was warmed up and the leads were connected to another portion of the array. After cooling, it appeared that the voltage measured on the "measurement leads" and the "bias voltage leads" was different, the bias leads being connected at a wrong point. The rectification effect had disappeared, but the series of 2 measurements made showed an even larger difference, about 13 nV. Changing the bias current by about 40 µA resulted in a change of the measured voltage by 20 nV, corresponding to a slope of 0.5 mΩ. Without the microwave, a change of the bias current near the critical current (between 0.91 mA and 1.1 mA) resulted in a voltage change equivalent to 0.2 mΩ. Two attempts to obtain better results with two other arrays were undertaken without success; the first one because the array was disconnected from its support, and the second because of a very large noise on the measurement leads. It was then decided to try again next day to make measurements with the first array (correctly connected) and to make a precise analysis of the bias current dependence.

Tuesday 23 March 2004

The connection of the SINIS array corresponds to 6647 junctions. Five series of measurements were made at different bias currents between 1.3 mA and 1.55 mA. No flat region was observed on the steps, the slope near 1.35 mA being about 0.2 mΩ. (series 1 in Fig. 1). In order to prevent a possible ground loop via the 10 MHz reference signal, a DC block was made on the connecting cable using a ceramic capacitor on the external shield. This seems to ameliorate the flatness of the steps and the results of the next two series of measurements (probably made with a bias current of 1.38 mA) were only 0.2 nV and 0.5 nV too high. A third series of 2 measurements made with the "high impedance" output of the SINIS gave a measured value about 9 nV too low. Five new series of measurements were made at different bias currents between 1.3 mA and 1.48 mA. Now a quite flat region can be observed at 1.35 mA with an apparent slope equivalent to 16 µΩ. (series 2 in Fig. 1). Two series of measurement were then made at different currents (1.33 mA and 1.48 mA) using different 10 MHz signals for the SIS and the SINIS, but the apparent slope was even larger than before. The results obtained in the next series using the same 10 MHz reference signal without DC block were rather better! Then three series of measurements were made with a 0.01 µF teflon capacitor as a shunt across the output measurement connections of the SINIS. The results obtained when changing the bias current between 1.3 mA and 1.4 mA were within 1 nV, the apparent slope being less than 10 µΩ (series 3 in Fig. 1). Repeating the measurement with a bias current of 1.4 mA without the shunt capacitor resulted in a change of about 4 nV, demonstrating that the roundness of the steps was directly connected to the noise entering in the SINIS via the measurement leads.

It was then decided to connect directly the "low" (–) output connection of the SINIS to ground. Twelve series of measurements were made in those conditions with bias currents between 1.25 mA and 1.55 mA (Fig. 2). The results of these measurements showed that between 1.28 mA and 1.40 mA, the steps could be considered as "flat". Nevertheless, only the results of the 38 measurements made with bias currents between 1.30 mA and 1.35 mA were taken into account for the final result.

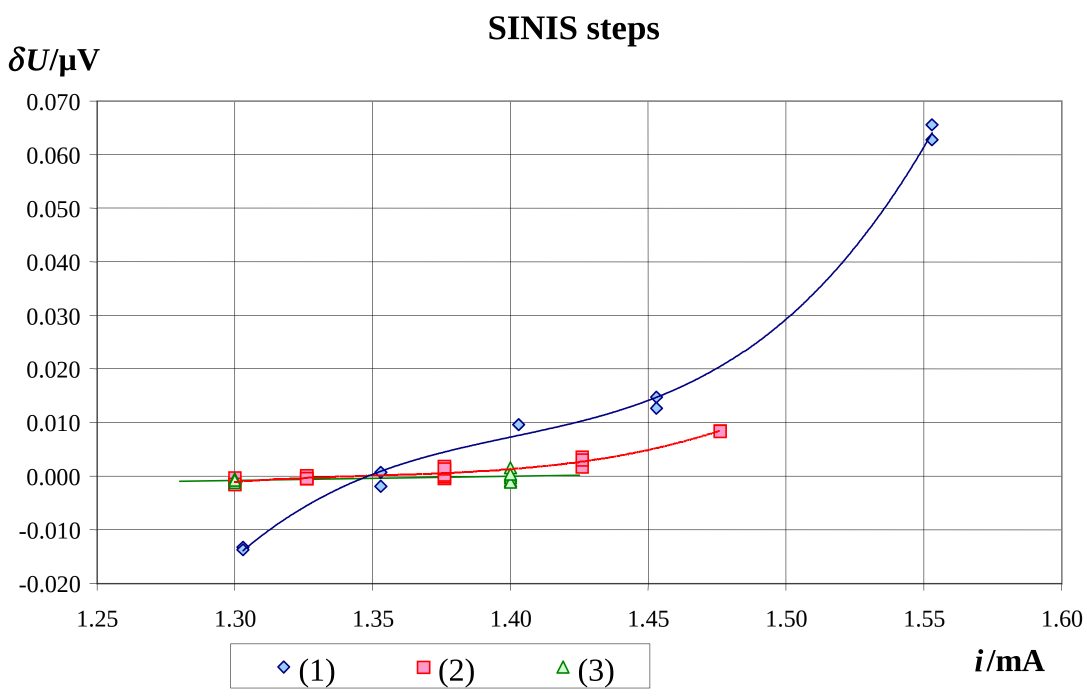


Fig. 1. Estimation of the SINIS step flatness in different conditions :
(1) adjustment at the origin
(2) with decoupled 10MHz reference
(3) with shunt capacitor across SINIS measurement outputs

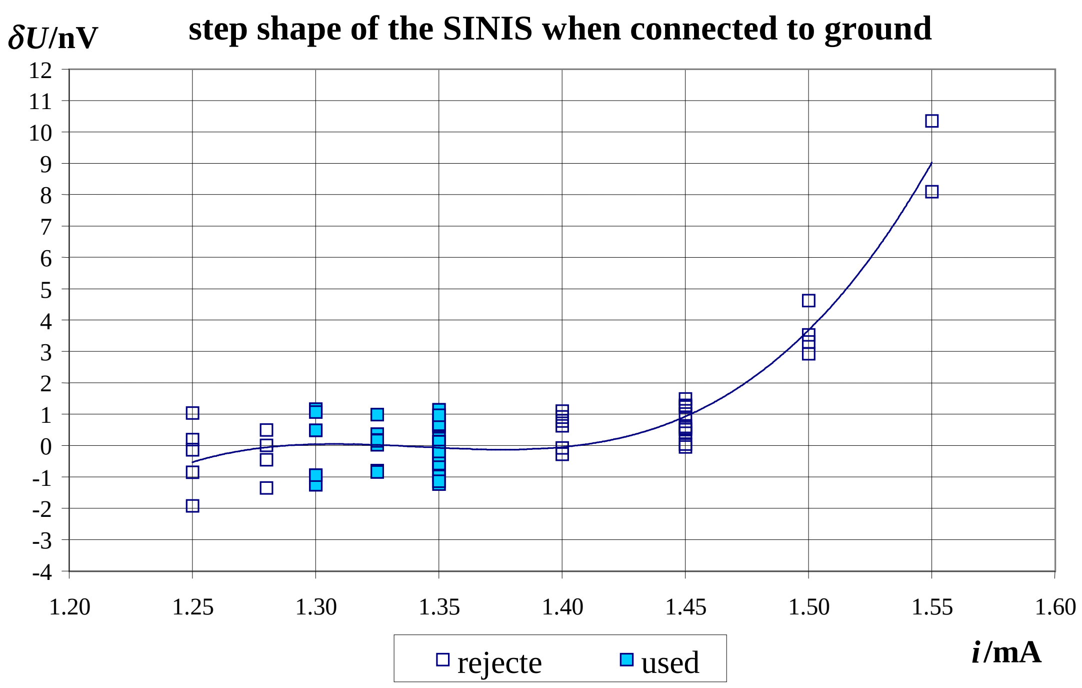


Fig. 2. Step flatness when then (–) measurement lead of the SINIS is connected to ground.
The dark square are the results used for the comparison result.

MIKES, Finland

The measurements were carried out on 25. - 26.03.2004.

1. Calibration method
The Portable Josephson standard (PJVS) was measured against the 10 V Josephson array voltage standard (JAVS) of MIKES. The SIS type array of the MIKES JAVS has been manufactured by PTB. The MIKES JAVS was set at a quantized voltage of 1.029244851684 V (step number 7098). The voltage difference between the standards set at series opposition was then measured with a calibrated EM N11 nanovoltmeter. The dc-bias source of MIKES JAVS is a modified model JBS-501 with battery operation. The bias source connects the array to the earth potential (also when the bias is off). For 70.12407 GHz irradiation a Gunn oscillator (Farran GN-12) was used. It was powered from the Gunn diode modulator unit of JBS-501 with a separate floating dc-supply. The mm-wave frequency was stabilized with a source-locking frequency counter EIP 578B. The frequency readings of the EIP 578B counter were stable within ± 1 Hz. Possible unknown frequency offset of this counter is expected to be smaller than ± 10 Hz.
The mm-wave frequencies of both Josephson standards were derived from a common time base of 10 MHz which is traceable to the national time and frequency laboratory. For compensation of offset voltages in the measurement circuit, measurements were performed alternately with normal (+) and reversed (-) polarities of both Josephson standards. Polarities were reversed by changing the directions of the bias currents. A low thermal emf manual switch was used to disconnect the standards from the input of the nanovoltmeter during polarity reversals. Polarity of the nanovoltmeter was not reversed. The main fraction of a thermal emf of 50 - 60 nV was cancelled out using the nanovoltmeter's offset voltage control. In all measurements the 30 nV range and filter setting 1 (250 ms time constant) of EM N11 were used. The direct output of battery-operated EM N11 was connected to HP 3458A DMM. A simple LabView-based program was used to store the readings of the DMM and the microwave counter on a laptop computer. Each series of measurements consists of 8 to 16 pairs of measurements at different polarities. During most of the measurements the MIKES array was connected to the bias source and adjusted for zero current condition. For each polarity, nanovoltmeter voltages were recorded for 40 to 50 seconds with a one-second integration time. The time spent for the reversal was typically 1 min.

2. Calibration results
The voltage difference between the PJVS and the MIKES JAVS was determined from successive pairs of + and – polarity results. Six measurement sets were carried out during two days. The measurement conditions of each set are given in table 1 and measurement results (output voltage *U*PJVS) in table 2. Since the measurement conditions (bias currents and output resistance) do not significantly influence the result, a weighted mean of the results of sets 1-6 was also calculated.
The standard uncertainties of measurements (coverage factor k=1) shown in table 2 have been determined in accordance with the *ISO Guide to the Expression of Uncertainty in Measurement* (GUM). The dominant uncertainty stems from the fluctuation of thermal emf in the measurement loop. Uncertainties related to the gain of the nanovoltmeter, voltage drops in the measurement leads due to finite isolations resistance and possible mm-wave frequency offset were also evaluated and taken into account. Detailed uncertainty budgets are given in Appendix 1.

Table 1. Conditions of the measurement sets.

Measurement Set no.	Date of measurement	Bias current of PJVS [mA]	Bias source of MIKES JAVS on/off	Output resistance of PJVS [Ω]
1	25.3.2004	1.40	on	4
2	25.3.2004	1.35	on	4
3	25.3.2004	1.45	on	4
4	26.3.2004	1.40	on	4
5	26.3.2004	1.40	on	1200
6	26.3.2004	1.40	off	4

Table 2. Calibration results.

Measurement Set no.	Number of +/- pairs	Measurement result *U*PJVS [V]	Standard uncertainty of measurement [nV]	Degrees of freedom
1	10	1.029244862223	0.199	21
2	8	1.029244862586	0.225	13
3	7	1.029244862128	0.226	11
4	12	1.029244862307	0.159	52
5	15	1.029244861968	0.227	25
6	16	1.029244862588	0.179	46

3. Ambient conditions

The measurements were carried out in a shielded and air-conditioned laboratory. During the measurements the ambient temperature was 23.0 °C ± 0.4 °C and the relative humidity 46 % ± 5 %. The atmospheric pressure in the laboratory was 1007 hPa ± 3 hPa.

4. Equipment used in the calibration

- MIKES primary Josephson voltage standard, output impedance 3 W Josephson array, PTB 10 V, Mü10-9/1
- Cryoprobe and chip carrier, IPHT kryoelektronik, 22 mm cryoprobe designed for PTB chips 1998
- Gunn oscillator, FarranTechnology Ltd. GN-12, s.n. FTL 2910
- Source-locking frequency counter, EIP Microwave, Inc. EIP 578B, s.n. 2019 00640
- Bias current source, Astro Endyne Co., Inc. JBS-501, s.n. 031
- Nanovoltmeter, EM Electronics DC Nanovoltmeter model N11, s.n. 2836
- Digital multimeter, Hewlett-Packard HP 3458A, s.n. 2823A 26673
- Frequency reference source, modified Jutel TV-sync FC40, s.n. 168
- Low thermal emf switch box, modified Guildline switch
- Laptop computer, HP omnibook 6000, s.n. TW 1320 1792

GUM, Poland

Period of measurement: from 20th May to 21st May 2004.

Method of measurement: Opposite series connection between JVS GUM and VNIIM's PJVS through scanner Data Proof and HP 3458A

The describe of system:

- The type of array is SIS, 10V.
- The detector used HP 3458A - 100 mV scale.
- The measurements made with reversing the detector polarity.
- The bias source is of NIST.
- The array is floating; disconnected from the bias.
- The software used NISTVolt N° 5.6.
- The frequency source stabilizer is EIP.
- The order of magnitude of the frequency stability is 13 Hz.
- The measurements made in a shielded room.

<u>Results</u>:*Output voltage of PJVS*

Measurement Set no.	Date of measurement	Output resistance of PJVS	Number of data points	Measurement result, 1 029 244 800 + nV	Standard uncertainty of measurement, nV
1	20.05.04	4 Ω	2	61,0	
2	20.05.04	4 Ω	2	57,5	
3	20.05.04	4 Ω	2	58,0	
4	20.05.04	4 Ω	2	55,5	
5	20.05.04	4 Ω	2	68,5	
6	20.05.04	4 Ω	2	58,0	
7	20.05.04	4 Ω	2	61,5	
8	20.05.04	4 Ω	2	63,5	
9	20.05.04	4 Ω	2	57,5	
10	20.05.04	4 Ω	2	73,5	
11	20.05.04	4 Ω	2	53,5	
12	20.05.04	4 Ω	2	69,5	
13	20.05.04	4 Ω	2	65,0	
14	20.05.04	4 Ω	2	73,5	
15	20.05.04	4 Ω	2	70,5	
16	20.05.04	4 Ω	2	67,5	
17	20.05.04	4 Ω	2	58,5	
18	20.05.04	4 Ω	2	65,0	
19	20.05.04	4 Ω	2	61,5	
20	20.05.04	4 Ω	2	63,5	
21	21.05.04	4 Ω	2	69,0	
22	21.05.04	4 Ω	2	67,0	
23	21.05.04	4 Ω	2	62,0	
24	21.05.04	4 Ω	2	65,5	
25	21.05.04	4 Ω	2	61,5	1,14

Note: standard uncertainty is calculated using the equation: $u_A(\overline{q}) = \sqrt{\frac{\sum_{k=1}^{n}(q_k - \overline{q})^2}{n(n-1)}}$

Each single point measurement is calculated from 40 points.
Time period to receive one data point is about 260 s and consists of 130 s of + and --measurements and about 130 s to change polarity of 1 V SIS array in GUM's JVS.
The current I = 1,40 mA and added capacitance 0.069 µF.

During measurements problems occurred with noise between VNIIM and GUM systems. In order to eliminate this noise additional capacitor with the capacities of 0.069 µF was installed.

CMI, Czech Republic

Date of measurement: May 24 – 25, 2004

System description:
The CMI is operating the *Closed-cycle Refrigerator (CCR) Primary Voltage Standard System* from HYPRES. The Hypres‘ SIS 10 V Josephson Junction Array Chip is used in the system with operating frequency 75.3 GHz. The Gun diode from Millitech and the Gunn bias source GS 1002 from VMETRIX together with Source Locking Microwave Frequency Counters EIP 578B is used as a microwave source. The 10 MHz reference frequency for EIP 578B comes from rubidium oscillator which is locked to GPS. The bias source for array is JVS 1000 from VMETRIX. The nanovoltmeter Keithley 2182 is used as a null detector and system voltmeter. The whole system is controlled by computer with software NISTVOLT version 9.2. (This software was modified for using the Keithley 2182 as a null detector).

Masurement procedure:
The JVS_CMI and PJVS_VNIIM are connected in opposite series through nanovoltmeter Keithley 2182. The 50 single point measurements are made during the comparison. After each two measurements the polarity of output voltage of PJVS_VNIIM is reversed.
The single point measurement is made by using the NISTVOLT procedure for measurement Zener references. This algorithm accumulates difference voltage measurements using a + - + - reversal sequence. Ten measurements are taken for each sequence. Each of these measurements is calculated as average from five readings of nanovoltmeter.
The final values of output voltage of PJVS_VNIIM are calculated as the means of the set of 25 pair averages.
During the measurements the array was floating, disconnecting from the bias source. The stability of frequency was ± 2 Hz.
Both systems were connected to the same 10 MHz reference frequency.
The measurements are made in non shielded room.

NMi-VSL, The Netherlands

Date of measurement: May 26 – 27, 2004

Summary
In this report the Euromet key comparison of Josephson array voltage standard by using a portable Josephson transfer standard at NMi Van Swinden Laboratorium performed on 26-27 May 2004 in Delft, the Netherlands is described.

Definition of the measurand
A measurand in this case is a DC voltage of about 1 Volt generated by PJVS when it was connected to the pair of terminals of complete voltage standard of NMi (JVS- including the Josephson array, the cryoprobe, the null detector, the bias source, the frequency stabiliser, the software and wiring) where a zener diode is usually connected during routine calibrations. NMi setup In brief, NMi JVS consists of 10 V Josephson array surrounded by magnetic shield and placed in helium Dewar, a cryoprobe with RFI filters, attenuator, mixer, EIP578 counter, 75 GHz Gunn diode, JBS500 automation controller, oscilloscope, Data Proof scanner, null detector, computer and wiring.

Further details of the arrangement of NMi JVS are as follows:
Josephson array: type of array SIS, 10 V; origin: Hypres, not floating and connected to the bias.
Null detector: Keithley 182 sensitive digital voltmeter (serial nr. 515015), range ± 3 mV.
Bias source: JBS500 from NIST.
Frequency source stabiliser: (EIP counter + control device); frequency stable values in the range from 76.330000 GHz to 76.360000 GHz were used, the variation: few Hz.
Software used: NISTVOLT, version N° 4.7 dated January 1995, modified by NMi and called NMIVOLT, version 1.5.

Method of measurement
The voltage generated by PJVS was measured by comparing it to the voltage generated by the JVS of NMi. To perform this measurement, both voltage generators (PJVS and JVS) were in fact connected in series opposition and the voltage difference was measured with the null detector. The established at NMi measurement procedure was followed during the measurement as close as possible and as if the PJVS was a standard to be calibrated.

Measurement protocol
The following protocol was followed during the measurement. Check if each of the standards:
PJVS, JVS works separately. Connect both standards in series opposition. For selected directions of DC currents in PJVS and JVS: wait for thermal emf to stabilize. Perform the measurement at one polarity of the voltage. Reverse the polarity of the voltage using Data Proof scanner. Wait for thermal emf to stabilize. Perform the measurement, etc. In the measurement at one polarity of the voltage a number of samples per each printed point was equal to 10, a number of measurements per cycle at the same polarity was 10, then the polarity was reversed and the cycle was repeated, after completion of the cycle the polarity was reversed again and the cycle was repeated again, so that finally for each reported value of the measured (reference) voltage there are 300 sample points taken in 3 measurement cycles completed with two polarities of the voltage, see Annex 1.
After completion, repeat the measurement at the same selected directions of DC currents in PJVS and JVS or: reverse selected direction of DC current in PJVS and repeat the measurement as described in the previous section. This measurement gives next reported value of the measured (reference) voltage with the same or opposite to previous measurement polarity of the voltage as shown in Annex 2.

Measurement conditions
During the measurement ambient temperature was 21.6±0.5 ºC, air pressure was 1023±10 hPa and humidity was 44±5%.

NMivolt 1.5
NMi Van Swinden Laboratorium
Delft, The Netherlands

Reference Standard Measurement: ID # key1 --- 05-26-2004 18:53

Comment:

NMIVOLT Version 1.5 (4.7)
System Digital Voltmeter: K-182
Air pressure = 1022.27 hPa
System Temperature = 21.6 degrees C
Scanner Channel: 3

Chip Serial No. 2546H-9
Microwave Frequency = 76.3500000 GHz
Samples Per Printed Point: 10
Bias Mode: OpenCir

AVERAGED NULL VOLTAGE MEASUREMENT DATA

*** (+) Polarity ***		*** (-) Polarity ***		*** (+) Polarity ***	
Time m	V(Array)-V(DVM)	Time m	V(Array)-V(DVM)	Time m	V(Array)-V(DVM)
0.65	+1.029245348	2.47	-1.029245215	5.23	+1.029245382
0.75	+1.029245347	2.60	-1.029245215	5.30	+1.029245382
0.90	+1.029245355	2.77	-1.029245211	5.37	+1.029245380
0.98	+1.029245361	2.97	-1.029245214	5.43	+1.029245389
1.08	+1.029245356	3.10	-1.029245220	5.52	+1.029245392
1.22	+1.029245358	3.35	-1.029245212	5.60	+1.029245380
1.30	+1.029245357	3.48	-1.029245211	5.67	+1.029245385
1.38	+1.029245360	3.82	-1.029245212	5.73	+1.029245382
1.45	+1.029245360	3.95	-1.029245215	5.83	+1.029245385
1.55	+1.029245357	4.30	-1.029245211	5.90	+1.029245380
*** AVERAGES ***		*** AVERAGES ***		*** AVERAGES ***	
1.13	+1.029245356	3.28	-1.029245214	5.56	+1.029245384

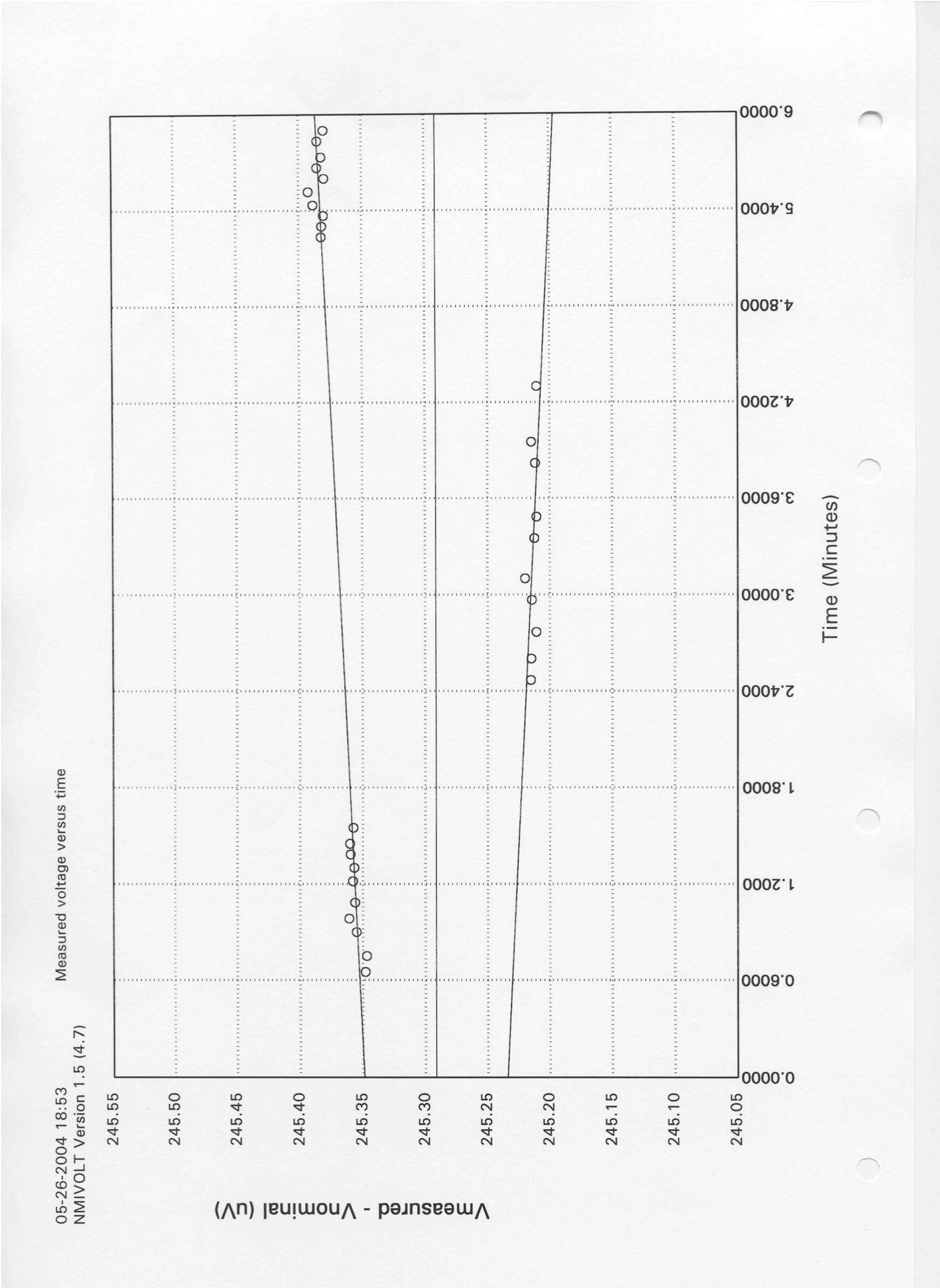
Reference Standard Voltage = +1.029245291 V

Total Offset Voltage = -0.057 uV
Total Offset Drift = -0.033 uV
Spontaneous Step Transitions = 97
Residual System DVM Error = 2.92 ppm

Type A (Random) Uncertainty = +0.001 ppm
Frequency Type B Uncertainty = +0.001 ppm
Null Voltage Type B Uncertainty = +0.005 ppm
Wiring Leakage Correction = +0.000 ppm
Leakage Type B Uncertainty = +0.020 ppm
Offset Type B Uncertainty = +0.039 ppm

```
*****************************************************
**                                                 **
**   Reference   ID #  key1        Tap Number  1   **
**   Reference Voltage         =  +1.029245291 V   **
**   Deviation From Nominal    =  +245.291 uV      **
**   Combined Std. Uncertainty =     0.044 ppm     **
**                                                 **
*****************************************************
```

Annex A1 Typical internal measurement report of NMi (raw data)



Annex A2 Summary of results of the measurements performed at NMi

Table T2. Summary of results of the measurements at NMi Annex A1 (A4)

Measurement set nr.	Date of measurement	Output resistance of PJVS, Ω	Number of data points	Measurement results *V*m, V	Standard uncertainty of measurement, nV/V
18:09	26/05/2004	4	400	1.0292452	44
18:26	26/05/2004	4	400	-1.0292445	44
18:34	26/05/2004	4	400	-1.0292445	44
18:43	26/05/2004	4	400	1.0292453	44
18:53	26/05/2004	4	400	1.0292453	44
19:05	26/05/2004	4	400	-1.0292444	44
19:14	26/05/2004	4	400	-1.0292444	44
19:23	26/05/2004	4	400	1.0292453	44
19:32	26/05/2004	4	400	1.0292454	44
19:49	26/05/2004	4	400	-1.0292444	44
09:14	27/05/2004	4	400	1.0292455	44
09:22	27/05/2004	4	400	-1.0292442	44
09:30	27/05/2004	4	400	-1.0292442	44
09:41	27/05/2004	4	400	1.0292455	44
09:49	27/05/2004	4	400	1.0292455	44
09:57	27/05/2004	4	400	-1.0292442	44
10:08	27/05/2004	4	400	-1.0292442	44
10:16	27/05/2004	4	400	1.0292455	44
10:25	27/05/2004	4	400	1.0292455	44
10:42	27/05/2004	4	400	-1.0292442	44
10:53	27/05/2004	4	400	-1.0292442	44
11:00	27/05/2004	4	400	-1.0292442	44
11:16	27/05/2004	4	400	-1.0292442	44
11:24	27/05/2004	4	400	1.0292455	44
11:41	27/05/2004	4	400	1.0292455	44
11:53	27/05/2004	4	400	-1.0292442	44
12:03	27/05/2004	4	400	-1.0292443	44
12:11	27/05/2004	4	400	1.0292455	44
12:18	27/05/2004	4	400	1.0292455	44
12:25	27/05/2004	4	400	-1.0292443	44
12:33	27/05/2004	4	400	-1.0292443	44
12:41	27/05/2004	4	400	1.0292455	44
12:49	27/05/2004	4	400	1.0292455	44
12:56	27/05/2004	4	400	-1.0292442	44
13:04	27/05/2004	4	400	-1.0292442	44
13:18	27/05/2004	4	400	1.0292455	44
13:25	27/05/2004	4	400	1.0292455	44
13:33	27/05/2004	4	400	-1.0292442	44
13:41	27/05/2004	4	400	-1.0292442	44
13:49	27/05/2004	4	400	1.0292455	44
13:56	27/05/2004	4	400	1.0292455	44
14:03	27/05/2004	4	400	-1.0292442	44
14:16	27/05/2004	4	400	1.0292455	44
14:23	27/05/2004	4	400	-1.0292442	44
14:30	27/05/2004	4	400	-1.0292442	44
14:38	27/05/2004	4	400	1.0292455	44
14:45	27/05/2004	4	400	1.0292455	44
14:53	27/05/2004	4	400	-1.0292442	44
15:01	27/05/2004	4	400	-1.0292442	44
15:14	27/05/2004	4	400	1.0292455	44
15:22	27/05/2004	4	400	1.0292455	44
15:41	27/05/2004	4	400	-1.0292442	44

Note: *V*m is the reported value of the measured voltage.