Republican Unitary Enterprise "Belarusian State Institute of Metrology" (BelGIM)

FINAL REPORT
COOMET.EM.BIPM-K10.b.1 (COOMET 903/BY-a/24)
"Key comparison of voltage unit standards based on the Josephson effect"

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Abstract

A key comparison of the national standard of the voltage unit - volt, of BelGIM, Republic of Belarus, and the State primary standard of electric voltage unit of VNIIM, Russia, was carried out. The measurements were carried out in October - November 2024 in accordance with option B of the technical protocol for BIPM.EM-K10.b.1. VNIIM provided a transportable comparison standard based on the Josephson effect to measure the output voltage of the BelGIM standard. The results obtained are in agreement with the reference value of BIPM.EM-K10.b - the voltage of the BIPM Josephson voltage standard: the relative voltage difference was $-2.5{\cdot}10^{-10}$ with a total relative standard uncertainty of $2.5{\cdot}10^{-10}$ for a nominal voltage of 10 V.

Introduction

The CIPM Mutual Recognition Agreement establishes that the metrological equivalence of national measurement standards is determined by a number of key comparisons selected and organized by the Consultative Committees of the International Committee on Weights and Measures working in cooperation with the Regional Metrology Organizations (RMOs). COOMET has carried out the key comparison COOMET.EM.BIPM-K10.b.1 (COOMET 903/BY-a/24). This comparison allows us to link the unit of the national voltage standard of BelGIM, Republic of Belarus, (hereinafter - BelGIM voltage standard) with the reference value of BIPM.EM-K10.b organized by the International Bureau of Weights and Measures (BIPM) through the completed key comparison with the State primary standard of electric voltage unit, VNIIM, Russia (hereinafter - VNIIM voltage standard). VNIIM participated in a comparison with the BIPM in 2010 using its transportable transfer standard (TS)

1. Participants and schedule of comparisons

BelGIM and VNIIM participated in the key comparison. Table 1 shows the schedule of the measurements performed.

Table 1.

National Metrology Institute	Country	Contact Person	Dates of measurements of the transfer standard
VNIIM	Russia	A.S. Katkov	08.10.2024
BelGIM	Republic of Belarus	V.V. Popko	12.11.-14.11.2024

To carry out the comparison, the transfer standard (hereinafter - TS) was delivered to BelGIM by train as a hand luggage. After completion of measurements in BelGIM, the TS was delivered to VNIIM by train.

2. Transfer standard and measurement requirements

As a transfer standard, we used a Josephson voltage standard, belonging to VNIIM, with an output voltage value of 10 V, which participated in key comparisons of VNIIM, BelGIM and BIPM voltage standards in 2010-2011 [1-3]. Measurements are carried out by connecting the TS and the participant's voltage standard in series-opposition and by measuring the small voltage difference. The TS is equipped with an array of Josephson junctions of SINIS type, providing 10 V [1]. The array is isolated from the case, with possibility of isolation from the case of the 10 MHz reference frequency source, and the possibility of switching the power supply of the microwave generator from mains to a battery. The microwave generator circuitry is isolated from the TS enclosure. Built-in filters allow the TS to operate both with and without grounding of the TS probe. After immersion in a Dewar vessel with liquid helium, the TS probe is kept for at least 4 hours before measurements.

During measurements, the polarity of the TS and the BelGIM voltage standard were reversed. Measurement conditions were monitored, including ambient temperature in the room, relative humidity and atmospheric pressure. Synchronization of the TS irradiation frequency is carried out from the 10 MHz reference of the BelGIM Josephson voltage standard.

3. Measurement methods

Measurements on the VNIIM voltage standard were carried out on October 8, 2024. After measurements in VNIIM the TS was delivered to BelGIM, where from November 12 to 14, 2024 measurements were carried out using the BelGIM voltage standard. The BelGIM and VNIIM voltage standards use arrays of SIS (Superconductor/Insulator/Superconductor) and SINIS (Superconductor/Insulator/ Normal Metal/Insulator/Superconductor) Josephson junctions, respectively, to produce the 10 V DC voltage.

During the comparisons, the voltage difference between the TS and the applied standard was measured using a digital nanovoltmeter. Measurements were carried out for both polarities in order to remove the linear evolution of the Thermal Electromotive Forces (EMFs) in the measurement setup, the results were averaged.

3.1 BelGIM voltage standard

The BelGIM voltage standard is based on the supraVOLTcontrol system [4, 5] (BelGIM voltage standard), serial number 004. The system is a 3-channel (channels A, B and C) voltage standard based on the Josephson effect (JVS) with microprocessor control and allows calibration of secondary voltage standards and external voltmeters. In most of the comparison's measurements, channel B was used. To maintain high accuracy of the nanovoltmeter from the BelGIM voltage standard, the system function "Calibration nanovoltmeter" was used at the beginning and at the end of each working day, after completion of which the corrected gain was stored in the system memory. The optimal irradiation frequency (close to 75 GHz) was selected using the system function "Search optimal frequency".

The BelGIM voltage standard uses different modes of operation preset in the software used. The operation mode of calibration (M1) was used to perform measurements with the transfer standard.

38 values of measurement results were obtained. In the M1 mode, for each point of voltage measurement of the TS, a change the polarity of the output voltages of the BelGIM standard and the TS is used.

To determine each of these values, 40 measurements (20 on each polarity) are taken for approximately 3 sec. During the measurement process the Josephson array is completely disconnected from "the ground" and from the circuits of the electronic block of the BelGIM voltage standard.

The resistance of the measuring leads of the BelGIM voltage standard is 3 ohm, the leakage resistance of the measuring leads (according to the results of the study) is 90 gigaohm.

During measurements, the housings of the TS Dewar vessels and the BelGIM voltage standard were grounded at one point connected to the grounding terminal of the BelGIM voltage standard room.

Measurements were carried out under different modes of operation of the measurement circuit including:

- disconnection of the TS galvanic coupling from the 10 MHz reference frequency source,

- use of microwave TS generator with mains and battery power supply.

3.2 Transfer standard

The TS provided by VNIIM [1] was built using a 10 V Josephson junction array manufactured in PTB, Germany, using SINIS technology [6]. The TS contains a cryoprobe with a Josephson array shielded from the Earth's magnetic field. The design of the cryoprobe allows changing its dimensions, which ensures compactness of the TS during transportation. The connectors of the Josephson array contain LC filters of low frequency, located at a temperature of 4 K. The microwave oscillator frequency of the TS is tunable from 68 to 72 GHz and has an output power of about 40 mW, which increases to 60 mW when a power amplifier is used. The microwave path has galvanic isolation from the measuring circuit, which allows to weaken the influence of interference sources on the output voltage and the equipment involved in comparisons. Output voltage control and control of TS parameters are realized from a small-size bias block based on accumulators. The resistance of the TS measuring leads is 10 ohm, the leakage resistance of the measuring leads is not less than 100 gigaohm.

3.3 VNIIM voltage standard

The TS voltage was measured on the VNIIM voltage standard [2, 3] using a nanovoltmeter included in the VNIIM voltage standard. The TS voltage is defined as the average voltage value measured at two polarities of the output voltage of the VNIIM voltage standard. In addition to changing the polarities of the TS and the VNIIM voltage standard, the automatic calibration of the nanovoltmeter using a Josephson array was carried out. The time of obtaining one single measurement reached 200 s, the time of obtaining the measurement result reached 100 min. The resistance of the measuring leads of the VNIIM voltage standard is 10 ohm, the leakage resistance of the measuring leads is not less than 100 gigaohm.

Measurements were carried out under different modes of operation of the measurement circuit, including:

- power supply of the microwave TS generator from the mains and from the battery.

No influence of changes in the measuring circuitry on the measurement results could be detected.

4. Results

4.1 Results of BelGIM measurements

In the period from 12.11.24 to 14.11.24 at BelGIM the comparison of the BelGIM voltage standard and the VNIIM voltage standard were carried out with the help of the transportable VNIIM Josephson standard (TS).

During the measurement process, research was performed on the measurement circuitry in order to achieve the highest accuracy of the results.

12.11.24. Preliminary measurements of the TS voltage (10 V) were carried out in order to identify and eliminate possible defects (caused by transportation) and to assess the compatibility of the systems. Optimal grounding points were selected, the systems operation possibilities were tested at galvanic isolation of the 10 MHz reference signal for the TS, the influence of switching the mains power supply of the TS microwave generator to the battery. The operation modes of the BelGIM voltage standard were tested.

On 13.11.24 and 14.11.24 measurements of the TS voltage were continued in the operating mode (M1) of the BelGIM voltage standard (p. 3.1). The power supply of the TS microwave generator was changed, the parameters of the BelGIM voltage standard were adjusted, including the choice of the optimal microwave frequency and the nanovoltmeter gain. The results of these measurements are presented in Figure 1.

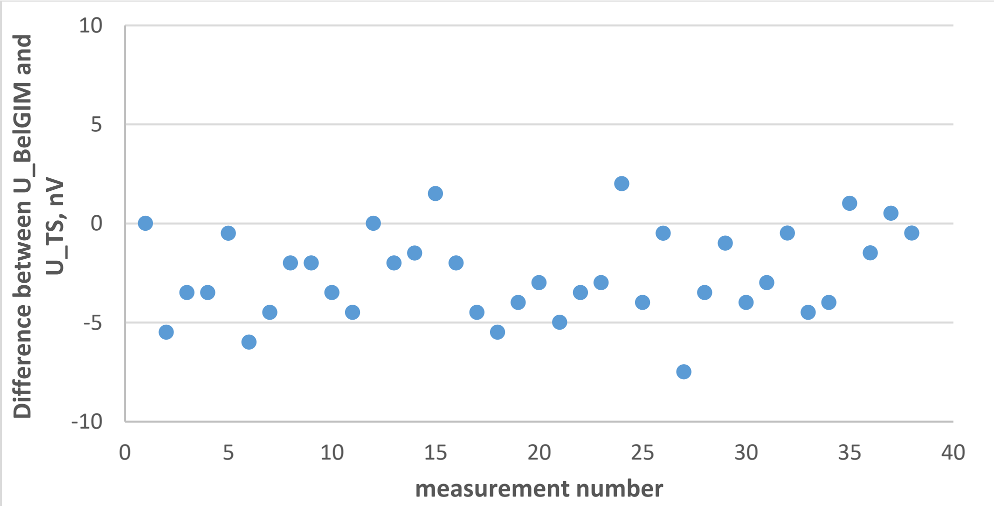

Figure 1: Measurement results of voltage difference between the BelGIM voltage standard and the TS.

TS measurements were carried out at the microwave generator frequency of 69.4575 GHz; galvanic coupling isolation of the reference frequency was used; battery power supply of the microwave generator was applied at points 1-11, 18-32, mains power supply at other points. The measurement mode M1, channel B was used in the BelGIM voltage standard.

Experimental data obtained under different measurement regimes suggest that the measurements were largely independent.

Results of comparisons of the BelGIM voltage standard and TS:

- voltage difference - degree of equivalence of the BelGIM $D_{TS\text{-}BelGIM}$ voltage standard:

$$D_{TS-BelGIM} = U_{TS} - U_{BelGIM} = \frac{1}{38}\sum_{i=1}^{38} \Delta U_{BelGIM_i} = -2.60 \text{ nV},$$

$$\Delta U_{BelGIM_i} = U_{BelGIM} - U_{TS_i}$$

U_{BelGIM} – average voltage value of the BelGIM voltage standard, V;

U_{TS_i} - *i-th* voltage value of the TS, V;

U_{TS} –average value of TS voltage, V;

- Type A standard uncertainty

$$u_A(BelGIM - TS) = \sqrt{\frac{1}{38}\sum_{i=1}^{38}\frac{\left(\Delta U_{BelGIM_i} - D_{BelGIM-TS}\right)^2}{37}} = 0.36\ \text{nV}$$

- Type B standard uncertainty

$$u_B(BelGIM - TS) = \sqrt{u_B^2(BelGIM) + u_B^2(TS)} = 1.17\ \text{nV}$$

- total standard uncertainty

$$u_c(BelGIM - TS) = \sqrt{u_\text{A}^2(BelGIM - TS) + u_B^2(BelGIM - TS)} = 1.22\ \text{nV}$$

The Type B uncertainty estimate for the result of the comparison of the TS and the BelGIM voltage standard is calculated according to the uncertainty budget given in Table 2.

Table 2. Uncertainty budget for type B when comparing the TS with the BelGIM voltage standard

Influencing factors	Standard uncertainty for type B, nV	
	BelGIM voltage standard	TS [2]
Frequency offset	0.01	0.5
Insulation leaks	0.33	1
Nanovoltmeter	0.5	-
Total standard uncertainty	0.6	1.1

4.2 VNIIM measurement results

Before the trip to BelGIM, in VNIIM on 08.10.24, comparisons of the TS with the VNIIM voltage standard were carried out.

The TS voltage measurements were carried out under different modes of TS operation. This included operating the TS operated without a power amplifier, changing the reference source connection and the method of power supply of the TS microwave generator (mains supply or battery). The irradiation frequency of the TS was chosen equal to 69.4575 GHz, the irradiation frequency of the VNIIM voltage standard was chosen equal to 72.0680 GHz. The total voltage of the measured difference contained the thermal EMF of the two standards and the nanovoltmeter voltage offset (less than 1.5 μV). The results of these measurements with eliminated thermal EMF and offset by polarity reversals are presented in Figure 2.

The use of a battery to power the microwave generator of the TS was used in points 21-30, mains power was used in the remaining points.

Experimental data obtained under different measurement regimes suggest that the measurements were largely independent.

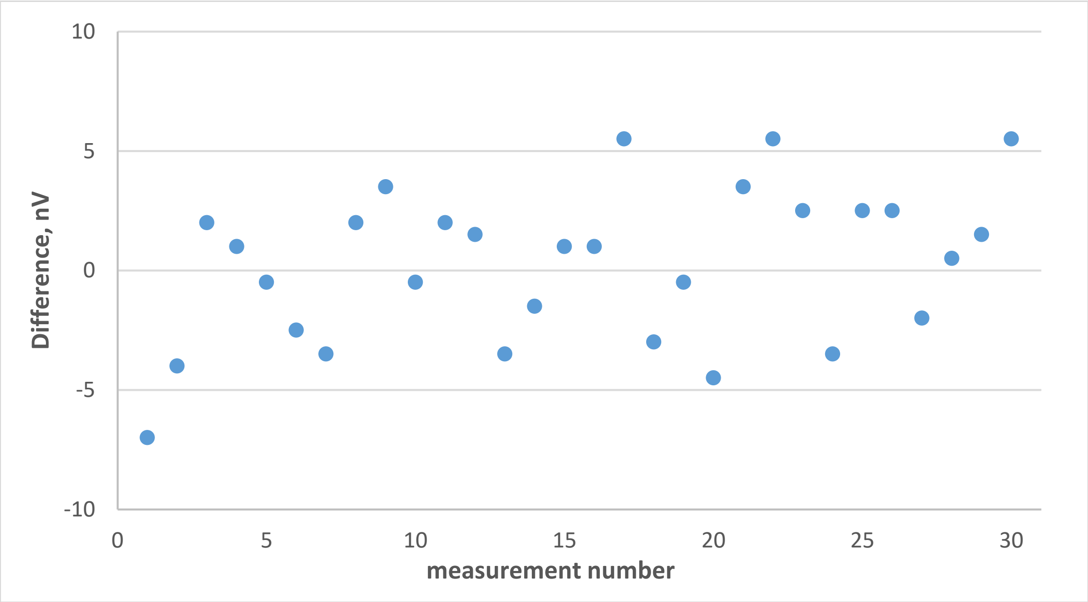

Figure 2: Measurement results of voltage difference between TS and VNIIM voltage standard.

Results of comparisons of TS and VNIIM voltage standard:

voltage difference - degree of equivalence of the VNIIM voltage standard $D_{TS\text{-}VNIIM}$:

$$D_{TS-VNIIM} = U_{TS} - U_{VNIIM} = \frac{1}{30}\sum_{i=1}^{30} \Delta U_{VNIIM_i} = 0.24 \text{ nV}$$

$$\Delta U_{VNIIM_i} = U_{TS_i} - U_{VNIIM}$$

U_{VNIIM} – value of the VNIIM voltage standard, V;

U_{TS_i} – *i-th* voltage value of the TS, V;

U_{TS} – average value of TS voltage, V;

- Type A standard uncertainty

$$u_A(TS - VNIIM) = \sqrt{\frac{1}{30}\sum_{i=1}^{30}\frac{\left(\Delta U_{VNIIM_i} - D_{TS-VNIIM}\right)^2}{29}} = 0.58 \text{ nV}$$

- Type B standard uncertainty

$$u_B(TS - VNIIM) = \sqrt{u_B^2(VNIIM) + u_B^2(TS)} = 1.2 \text{ nV}$$

- total standard uncertainty

$$u_c(TS - VNIIM) = \sqrt{u_\mathrm{A}^2(TS - VNIIM) + u_B^2(TS - VNIIM)} = 1.33 \text{ nV}$$

The Type B uncertainty estimate for the result of TS and VNIIM voltage standard comparisons is calculated according to the uncertainty budget given in Table 3.

Table 3: Type B uncertainty budget for comparison of TS with the VNIIM voltage standard

Influencing factors	Standard uncertainty for type B, nV	
	VNIIM voltage standard	TS [2]
Frequency offset	0.5	0.5
Insulation leaks	0.12	1
Nanovoltmeter	0.01	-
Total standard uncertainty	0.51	1.1

4.3 Reference value

As a reference value the voltage value of the BIPM voltage standard is used, which is assumed to be constant in time. The value of the reference voltage from BIPM is transferred by means of the participation of VNIIM in a comparison with the BIPM in 2010, and assuming that the VNIIM voltage standard has been stable over time.

4.4 Degree of equivalence with respect to the reference value

The degree of equivalence of the BelGIM voltage standard - $D_{BelGIM-BIPM}$ between the BelGIM and BIPM voltage standards is calculated on the basis of comparisons between BIPM and VNIIM in 2010, and VNIIM and BelGIM using TS:

$$D_{BelGIM-BIPM} = D_{VNIIM-BIPM} + (D_{BelGIM-TS} + D_{TS-VNIIM})$$

with total standard uncertainty:

$$u_c(BelGIM - BIPM) = \sqrt{u_c^2(VNIIM - BIPM) + u_c^2(BelGIM - TS) + u_c^2(TS - VNIIM)}$$

The results of the comparisons of the BIPM, VNIIM and BelGIM voltage standards using TS are presented in Table 4.

Table 4: Results of voltage standard comparisons using TS.

Voltage standards to be compared	Degree of equivalence D, nV	Total standard uncertainty, u_c, nV
VNIIM - BIPM	-0.105	2.04
BelGIM - TS	-2.60	0.6*
TS-VNIIM	0.24	1.33
BelGIM - BIPM	-2.47	2.51

*The value does not contain TS Type B uncertainty because it is included in TS-VNIIM measurements.

The degree of equivalence of the BelGIM voltage standard at 10 V is -2.5 nV with a total standard uncertainty of 2.5 nV.

Conclusion.

The comparisons confirmed the metrological characteristics of the BelGIM voltage standard and the reliability of the equipment.

References

1. A.S. Katkov, V.E. Lovtsyus, Compact Comparison Standard on Josephson Effect with 10 V Output Voltage, Izmeritel'naya tekhnika, 2011, №7, c. 41-45. (In Russ.)

2. A. S. Katkov, V. E. Lovtsyus, A compact comparison standard based on the Josephson effect with an output voltage of 10 V, Measurement Techniques vol. 54, issue 7, 2011. p. 801-807.

3 S. Solve et al 2011, Metrologia 48 01007, Comparison of the Josephson voltage standards of the VNIIM and the BIPM (part of the ongoing BIPM key comparison BIPM.EM-K10.b), DOI 10.1088/0026-1394/48/1A/01007.

4. A. S. Katkov and P. A. Chernyaev, 2015 *Metrologia* 52 01024, Final Report Key Comparison COOMET.EM.BIPM-K10.b. Comparison of the 10 V Josephson Voltage Standards COOMET 542/RU/11, DOI 10.1088/0026-1394/52/1A/01024.

5. Supracon, Josephson Voltage Standard supraVOLTcontrol, MANUAL. 2007.

6. F. Müller et al., “Improved 10 V SINIS series arrays for applications in AC voltage metrology,” IEEE Trans. Appl. Supercond., 17, 649–652 (2007).