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APPLICATION ASPECTS OF INTERNAIONAL QUANTUM STANDARTS IN ELECTRICAL MEASUREMENTS

[1]Hasanov Y.N., [2]Ahmadov B.B., [2]Yusibov Sh.T., [2]Aziz S.Sh.

[1]*"Azerbaijan State Marine Academy" LEPL*
AZ1000, Baku, Z. Aliyeva str.,18
[2]*"Azerbaijan Technical University" LEPL*
Az1073, Baku city, H.Javid ave., 25
E-mail: yusif.hasanov@asco.az; ahmedov.beyalı@aztu.edu.az; sarvan.aziz@aztu.edu.az

Abstract. *Quantum measurement standards are essential for implementing the International System of Units (SI) and ensuring global metrological traceability. Managed by the International Bureau of Weights and Measures (BIPM), these standards utilize fundamental quantum phenomena to achieve unmatched accuracy, consistency, and reproducibility [1,2]. The International Committee for Weights and Measures (CIPM) promotes their global acceptance through the Mu-*

tual Recognition Arrangement (MRA), facilitating precise calibration and comparison with national standards [3]. The BIPM oversees quantum standards for voltage (volt) and resistance (ohm), critical for uniform electrical measurements [4]. Select National Metrology Institutes (NMIs) maintain standards based on the Josephson and quantum Hall effects, participating in BIPM key comparisons, achieving absolute uncertainties as low as 0.2 nV for Josephson standards and relative uncertainties of 3.8×10^{-9} to 4.6×10^{-9} for Hall standards [4].

Xülasə. *Kvant ölçmə standartları Beynəlxalq Vahidlər Sistemi (SI)-nin tətbiqi və qlobal metrologiya izlenebilirliyinin təmin olunması üçün mühüm əhəmiyyət daşıyır. Beynəlxalq Ölçü və Çəki Bürosu (BIPM) tərəfindən idarə olunan bu standartlar fundamental kvant hadisələrindən istifadə edərək misilsiz dəqiqlik, sabitlik və təkrarlanma qabiliyyəti təmin edir [1,2]. Beynəlxalq Ölçü və Çəki Komitəsi (CIPM) bu standartların dünya miqyasında tanınmasını Qarşılıqlı Tanınma Sazişi (MRA) vasitəsilə təşviq edir ki, bu da milli standartlarla dəqiq kalibrləmə və müqayisəni asanlaşdırır [3]. BIPM gərginlik (volt) və müqavimət (om) üzrə kvant standartlarını nəzarətdə saxlayır; bunlar elektrik ölçmələrinin vahidliyini təmin etmək üçün əsas göstəricilərdir [4]. Seçilmiş Milli Metrologiya İnstitutları (NMI) Josephson və kvant Hall effektlərinə əsaslanan standartları saxlayır, BIPM-in əsas müqayisələrində iştirak edir və Josephson standartları üçün 0.2 nV qədər mütləq qeyri-müəyyənliklərə, Hall standartları üçün isə 3.8×10^{-9} – 4.6×10^{-9} aralığında nisbi qeyri-müəyyənliklərə nail olurlar [4].*

Аннотация. *Квантовые эталоны измерений играют ключевую роль в реализации Международной системы единиц (СИ) и обеспечении глобальной метрологической прослеживаемости. Управляемые Международным бюро мер и весов (BIPM), эти эталоны используют фундаментальные квантовые явления для достижения непревзойдённой точности, согласованности и воспроизводимости [1, 2]. Международный комитет мер и весов (CIPM) способствует их мировому признанию через Соглашение о взаимном признании (MRA), что обеспечивает точную калибровку и сопоставимость с национальными эталонами [3]. BIPM контролирует квантовые эталоны для напряжения (вольт) и сопротивления (ом), которые являются ключевыми для обеспечения единообразных электрических измерений [4]. Отдельные Национальные метрологические институты (NMI) поддерживают эталоны, основанные на эффектах Джозефсона и квантового Холла, участвуют в ключевых сравнениях BIPM и достигают абсолютных неопределённостей до 0.2 нВ для эталонов Джозефсона и относительных неопределённостей 3.8×10^{-9} – 4.6×10^{-9} для эталонов Холла [4].*

Key words*: quantum metrology, electrical units, calibration, measurement uncertainty, traceability*

Açar sözlər: *kvant metrologiyası, elektrik vahidləri, kalibrləmə, ölçmə qeyri-müəyyənliyi, izlənə bilmək*

Ключевые слова: *квантовая метрология, электрические единицы, калибровка, неопределённость измерений, прослеживаемость*

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Introduction. International measurement standards are reference tools that define precise values of physical quantities, serving as benchmarks for calibrating other instruments. Recognized through global agreements, these standards are defined in the International Vocabulary of Metrology (VIM) [1] and maintained by organizations like the BIPM. In the current SI system, quantum measurement standards are crucial for realizing units and ensuring traceability [2]. These standards leverage quantum effects, providing exceptional stability, universality, and reproducibility worldwide.

The advantages of quantum standards include:

- **Precision**: Derived from fundamental constants.

- **Consistency**: Reproducible across different systems.
- **Modernization**: Replacing traditional analog standards.
- **Decentralized accuracy**: No reliance on a single reference.

Their primary purpose is to establish a global framework for metrological traceability by comparing national standards and conducting precise calibrations [3]. This process is supported by the CIPM MRA, which ensures mutual recognition of national standards and calibration certificates [3]. As of mid-2025, around 260 NMIs, Designated Institutes, and four international organizations participate in the CIPM MRA [3].

Core Quantum Standards for Electrical Units. The most accurate standards for electrical units are based on the Josephson effect for voltage and the quantum Hall effect for resistance [12]. These standards derive units from the elementary charge ($e = 1.602176634\times10^{-19}$ C) and the Planck constant, fixed in the 2018 SI revision [2].

Josephson Standard. The Josephson standard produces voltage according to:

$$V = \frac{nhf}{2e}$$

where V is the voltage, n is an integer (step number), h is the Planck constant, f is the applied signal frequency, and e is the elementary charge [7].

This standard uses a superconducting Josephson junction, where two superconductors are separated by a thin insulator. At low temperatures (a few kelvins) and with microwave radiation (e.g., 70 GHz), quantized voltage steps are generated with an accuracy of one part per billion [7]. Large laboratories employ arrays of thousands of junctions to produce stable voltages up to 10 V [8]. Programmable Josephson standards, such as those at PTB (Germany), enable calibration of DC and AC voltages with uncertainties as low as 10^{-10} [9]. PTB's system supports comparisons up to 10 V with an absolute uncertainty of 1 nV [4].

Quantum Hall Standard. The quantum Hall standard defines resistance using:

$$R_H = \frac{h}{i e^2}$$

where R_H is the Hall resistance, h is the Planck constant, e is the elementary charge, and i is an integer (quantization index, typically 1, 2, 3, …) [10]. For $i = 1$, $R_H \approx 25812.807$ Ohm, used as a metrological resistance reference [10].

This standard involves a two-dimensional electron gas (e.g., GaAs/AlGaAs) cooled to below 1.5 K under a strong magnetic field (~10 T). In this state, longitudinal resistance vanishes, and transverse (Hall) resistance takes discrete values determined by fundamental constants [10]. Research addresses challenges like temperature fluctuations and small Hall signals, achieving relative uncertainties as low as 2.4×10^{-8} using potentiometric and cryogenic current comparator methods [11].

Utilization of BIPM Quantum Standards. The BIPM uses Josephson and Hall standards as references for its electromagnetic calibration services, underpinning its Calibration and Measurement Capabilities (CMCs) [4]. These services support the CIPM MRA by enabling NMIs to compare their standards with BIPM's, ensuring SI traceability [5]. Smaller NMIs rely on these services, while larger ones validate their primary standards' equivalence [5].

The BIPM employs portable quantum standards for on-site comparisons at NMIs, supported by BIPM experts for accuracy and knowledge transfer [6]. Calibration of reference resistors and voltage standards (e.g., Zener diodes) is advised every two years, with a limit of three standards per nominal value [4].

BIPM.EM-K10 Comparisons (Josephson Standards). Since 1991, BIPM has conducted BIPM.EM-K10 comparisons for nominal voltages of 1.018 V and 10 V [4]. Results include:

- **1.018 V**: 25 NMIs participated, with NIM (China) achieving the lowest uncertainty (0.2 nV), followed by BNM-LCIE (France) and NMIA (Australia) at 0.3 nV each [4].
- **10 V**: 29 NMIs participated, with LNE (France) at 0.2 nV, PTB at 1.0 nV, and CENAM (Mexico) at 1.3 nV [4].

These comparisons link to regional metrology organizations (e.g., EURAMET, SIM, COOMET) [6]. The NSC "Institute of Metrology" (Kharkiv) calibrated its Josephson standard at BIPM but has not completed inter-regional CMC review as of mid-2025 [4].

BIPM.EM-K12 Comparisons (Hall Standards). Since 1993, BIPM has conducted BIPM.EM-K12 comparisons for a nominal resistance of 100 Ohm and ratios of 10 kOhm/100 Ohm and 100 Ohm/1 Ohm [4]. Results include:

- **100 Ohm**: 11 NMIs participated, with NIST (USA) at 4.0×10^{-9} and PTB at 4.4×10^{-9} relative uncertainty [4].
- **10 kOhm/100 Ohm**: NIM (China) and KRISS (South Korea) at 4.6×10^{-9} [4].
- **100 Ohm/1 Ohm**: PTB and METAS (Switzerland) at 3.8×10^{-9}, NRC (Canada) at 4.2×10^{-9} [4].

The NSC "Institute of Metrology" calibrated its Hall standard at BIPM for 1 Ohm, 100 Ohm, and 10 kOhm, but inter-regional CMC review is pending as of mid-2025 [4].

Visual Representation of Comparison Results. The following figures vividly depict the BIPM.EM-K10 and BIPM.EM-K12 comparison outcomes, showcasing uncertainty data derived from detailed analyses [4].

- **Figure 1**: BIPM.EM-K10 results for 1.018 V, displaying uncertainties for NMIs including NIM (0.2 nV), BNM-LCIE (0.3 nV), and NMIA (0.3 nV). *(Insert Figure 1 here: Bar chart showing 1.018 V uncertainties for NMIs like NIM, BNM-LCIE, and NMIA, with values such as 0.2 nV, 0.3 nV, and 0.3 nV.)*
- **Figure 2**: BIPM.EM-K10 results for 10 V, highlighting uncertainties for LNE (0.2 nV), PTB (1.0 nV), and CENAM (1.3 nV). *(Insert Figure 2 here: Bar chart showing 10 V uncertainties for NMIs like LNE, PTB, and CENAM, with values such as 0.2 nV, 1.0 nV, and 1.3 nV.)*
- **Figure 3**: BIPM.EM-K12 results for 100 Ohm, with NIST (4.0×10^{-9}) and PTB (4.4×10^{-9}) leading in precision. *(Insert Figure 3 here: Bar chart showing 100 Ohm uncertainties for NMIs like NIST and PTB, with values such as 4.0×10^{-9} and 4.4×10^{-9}.)[13]*
- **Figure 4**: BIPM.EM-K12 results for the 10 kOhm/100 Ohm ratio, showing NIM and KRISS at 4.6×10^{-9}. *(Insert Figure 4 here: Bar chart showing 10 kOhm/100 Ohm ratio uncertainties for NMIs like NIM and KRISS, with a value of 4.6×10^{-9}.)*
- **Figure 5**: BIPM.EM-K12 results for the 100 Ohm/1 Ohm ratio, with PTB and METAS at 3.8×10^{-9}. *(Insert Figure 5 here: Bar chart showing 100 Ohm/1 Ohm ratio uncertainties for NMIs like PTB and METAS, with a value of 3.8×10^{-9}.)*

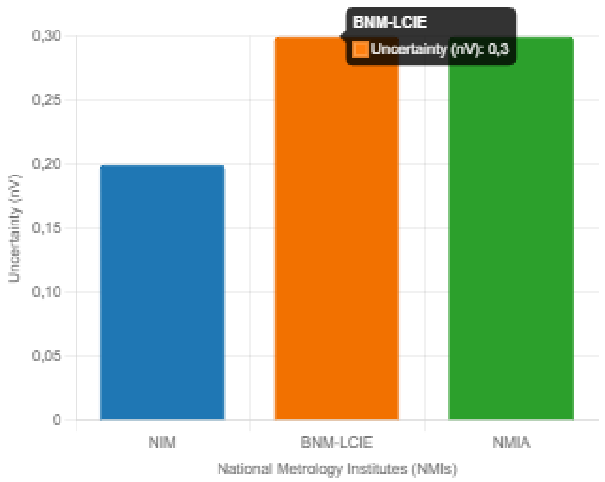

Figure 1. *BIPM.EM-K10 for 1.018 V*

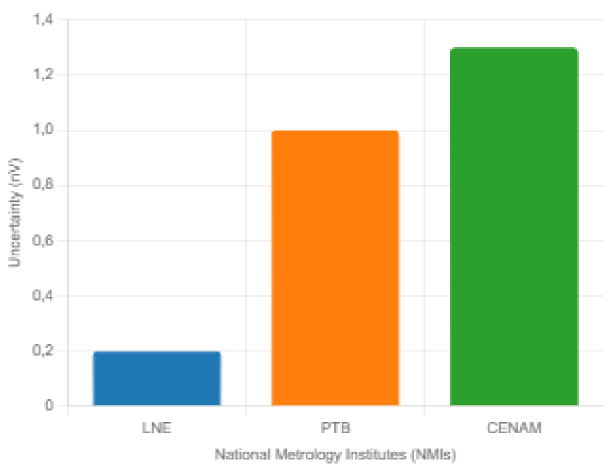

Figure 2. *BIPM.EM-K10 for 10 V*

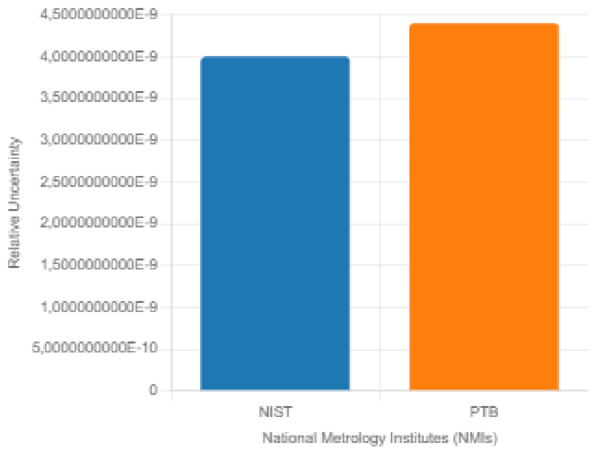

Figure 3. *BIPM.EM-K12 for 100 Ohm*

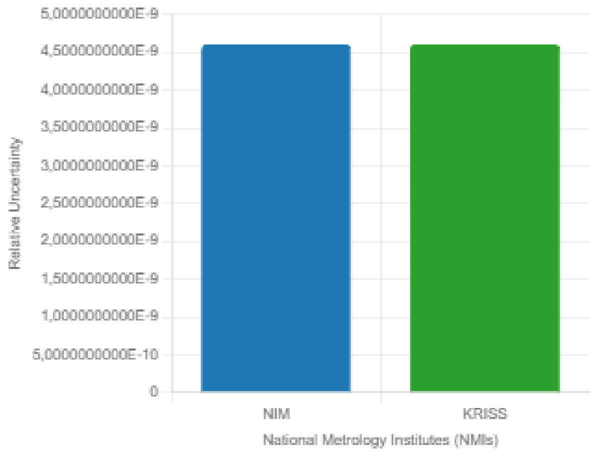

Figure 4. *BIPM.EM-K12 for 10 kOhm/100 Ohm Ratio*

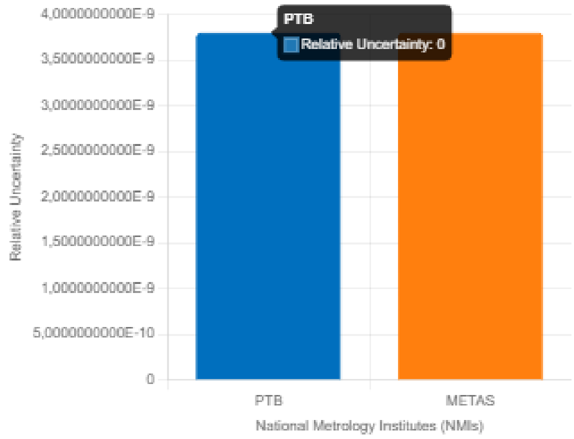

Figure 5. *BIPM.EM-K12 for 100 Ohm/1 Ohm Ratio*

Conclusion. The BIPM's quantum standards for voltage and resistance are vital for implementing SI electrical units and ensuring global traceability [2, 3]. Based on the Josephson and Hall effects, these standards enable precise comparisons under the CIPM MRA [3, 6]. Only select NMIs maintain these standards, participating in BIPM's key comparisons [4]. Josephson standards achieve uncertainties as low as 0.2 nV for 1.018 V and 10 V, while Hall standards reach relative uncertainties of 3.8×10^{-9} to 4.6×10^{-9} for resistance measurements [4]. These advancements ensure the reliability of global electrical metrology.

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