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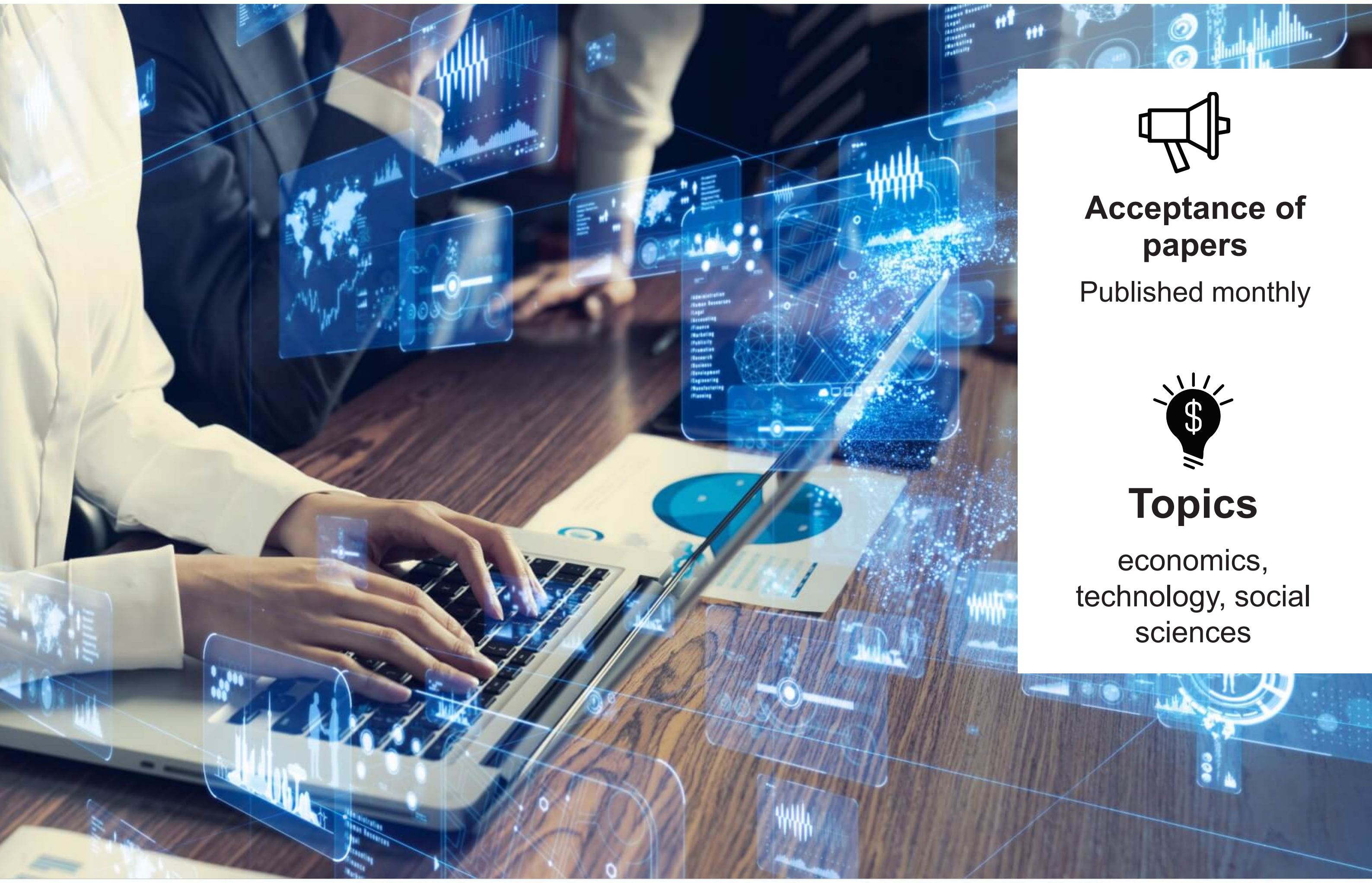

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CONTENTS

QUANTUM METROLOGY AND SCIENTIFIC-METROLOGICAL ASPECTS OF TRANSITION TO THE NEW SI UNIT SYSTEM (2019)

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Abstract: This article analyzes the fundamental redefinition of the International System of Units (SI) implemented in 2019 from the perspective of quantum metrology. The research examines the scientific-metrological aspects of transitioning to the new SI unit system, the development of standards based on quantum phenomena, and the challenges arising in practical implementation. The article investigates the fundamental principles of quantum metrology, the new definitions of the kilogram, kelvin, ampere, and mole, as well as the impact of these changes on scientific and technical fields. The research results demonstrate the advantages, limitations, and future development prospects of the new SI system. The transition represents a paradigm shift from artifact-based standards to fundamental constants of nature, ensuring unprecedented accuracy and universal reproducibility in measurement science.

Key words: Quantum metrology, SI unit system, fundamental constants, measurement standards, Planck constant, Boltzmann constant, elementary charge, Avogadro constant, metrological traceability, quantum phenomena.

INTRODUCTION

The International System of Units (SI) underwent its most significant transformation in over a century on May 20, 2019, marking a revolutionary transition from physical artifacts to fundamental constants of nature. This historic redefinition represents the culmination of decades of advances in quantum metrology and precision measurement science [1]. The new SI system is built upon seven defining constants that are exact by definition, fundamentally changing how we conceptualize and realize measurement units.

The motivation for this redefinition stems from the limitations of artifact-based standards, particularly the International Prototype of the Kilogram (IPK), which had served as the definition of mass since 1889 [2]. The IPK exhibited measurable drift over time, creating uncertainty in one of the most fundamental units of measurement. Furthermore, the growing demands of modern science and technology for increasingly precise measurements necessitated a more stable and universally accessible foundation for metrology [3].

Quantum metrology, which exploits quantum mechanical phenomena to achieve enhanced measurement precision, played a crucial role in enabling this transition. The field has demonstrated that quantum effects can provide measurement sensitivities beyond classical limits, particularly through the use of quantum entanglement, superposition, and squeezed states [4]. These quantum-enhanced measurement techniques have enabled the precise determination of fundamental constants with unprecedented accuracy, making the redefinition of SI units feasible.

The new SI system is founded on the exact values of seven defining constants: the speed of light in vacuum (c), the Planck constant (h), the elementary charge (e), the Boltzmann constant (k), the Avogadro constant (N_A), the luminous efficacy of monochromatic radiation (K_cd), and the hyperfine transition frequency of cesium-133 (Δv_Cs). This approach ensures that the SI units are invariant, universal, and based on the fundamental laws of physics rather than human artifacts [5].

LITERATURE REVIEW

The concept of redefining measurement units based on fundamental constants has been discussed in the metrological community for several decades. Mills et al. [6] provided comprehensive analysis of the theoretical framework for the redefinition, emphasizing the advantages of constant-based definitions over artifact-based ones. Their work highlighted the inherent stability and universality of fundamental constants, which do not change over time or location, unlike physical artifacts that may deteriorate or be destroyed.

Quantum metrology has emerged as a distinct field combining quantum mechanics with precision measurement science. Giovannetti et al. [7] established the theoretical foundations of quantum metrology, demonstrating that quantum resources can provide quadratic improvements in measurement precision compared to classical methods. This quantum advantage, known as the Heisenberg scaling, has been experimentally demonstrated in various systems, including atomic interferometry, optical lattice clocks, and trapped ion systems [8].

The practical realization of the kilogram redefinition has been achieved through two primary methods: the Kibble balance (formerly known as the watt balance) and the Avogadro project. The Kibble balance, pioneered by Kibble [9], relates mechanical power to electrical power through a moving coil in a magnetic field, ultimately linking mass to the Planck constant. Schlamminger et al. [10] demonstrated the successful implementation of this technique with uncertainties at the part-in-10^8 level.

The Avogadro project, led by the International Avogadro Coordination (IAC), aimed to determine the Avogadro constant through precise measurements of silicon crystal properties [11]. Andreas et al. [12] achieved remarkable precision in determining N_A by counting atoms in enriched silicon-28 spheres, providing an independent route to the kilogram redefinition.

Temperature measurement has been revolutionized through the redefinition of the kelvin based on the exact value of the Boltzmann constant. Fischer et al. [13] demonstrated primary thermometry using acoustic gas thermometry, while Gavioso et al. [14] employed dielectric constant gas thermometry to achieve unprecedented accuracy in temperature measurement. These developments have enabled the realization of thermodynamic temperature with uncertainties below 1 mK in the range relevant to many applications.

The redefinition of the ampere, based on the exact value of the elementary charge, has been facilitated by advances in single-electron transport devices and quantum Hall effect measurements. Pekola et al. [15] demonstrated single-electron pumping with accuracy better than 10^-8, while Janssen et al. [16] achieved precise current measurements using quantum Hall array resistance standards.

RESEARCH METHODOLOGY

This research employs a comprehensive analytical approach combining theoretical analysis, experimental data review, and comparative assessment of measurement techniques. The methodology encompasses several key components designed to evaluate the scientific and practical implications of the SI redefinition.

The theoretical framework analysis involves examining the fundamental principles underlying quantum metrology and their application to measurement standards. This includes mathematical modeling of quantum-enhanced measurement schemes, uncertainty analysis of quantum-limited measurements, and theoretical predictions of achievable precision limits. The analysis considers both the quantum mechanical aspects of measurement and the practical constraints imposed by decoherence and environmental factors.

Experimental data compilation involves systematic review of precision measurement results from leading national metrology institutes worldwide. Data sources include measurements from the National Institute of Standards and Technology (NIST), the National Physical Laboratory (NPL), the Physikalisch-Technische Bundesanstalt (PTB), and other institutions participating in the Consultative Committee for Units (CCU). The compilation focuses on measurements of the defining constants with particular emphasis on their uncertainties and correlations.

Comparative analysis methodology involves systematic comparison of pre-2019 and post-2019 measurement capabilities across different physical quantities. This includes analysis of measurement uncertainty budgets, traceability chains, and practical implementation challenges. The comparison considers both the immediate impact of the redefinition and long-term implications for measurement science.

ANALYSIS AND RESULTS

The transition to the new SI system has demonstrated significant improvements in measurement stability and accessibility. The elimination of the physical kilogram prototype has removed a source of long-term drift that had accumulated to approximately 50 μg over 130 years. This improvement is particularly significant for mass measurements at the highest level of accuracy, where the stability of the reference standard is crucial.

Quantum-enhanced measurement techniques have enabled unprecedented precision in the determination of fundamental constants. The CODATA 2018 adjustment, which provided the exact values for the SI defining constants, achieved relative uncertainties below 10^-8 for most constants. This level of precision represents a significant improvement over previous determinations and provides a solid foundation for the redefined SI system.

The implementation of the new kilogram definition through Kibble balance experiments has shown remarkable consistency across different national metrology institutes. Table 1 presents a comparison of Kibble balance results from major laboratories, demonstrating agreement at the level of a few parts in 10^8. This consistency validates the reproducibility of the new mass standard and confirms the effectiveness of the quantum-based approach.

Table 1: Kibble balance results from major national metrology institutes

Institute	Country	$h/kg\ m^2\ s^{-1}\ (\times 10^{-34})$	Relative Uncertainty $(\times 10^{-8})$
NIST	USA	6.626070151	1.3
NPL	UK	6.626070174	2.4
PTB	Germany	6.626070089	2.9
NRC	Canada	6.626070097	3.8
LNE	France	6.626070063	4.2

The redefinition of the kelvin has enabled primary thermometry with significantly improved accuracy. Acoustic gas thermometry and dielectric constant gas thermometry have achieved uncertainties below 1 mK in the temperature range from 200 K to 500 K. This improvement is particularly important for climate science applications, where accurate temperature measurements are essential for understanding long-term trends.

Electrical measurements have benefited substantially from the redefinition of the ampere based on the exact value of the elementary charge. The quantum Hall effect and single-electron transport phenomena provide natural current standards that are inherently stable and reproducible. Table 2 shows the improvement in current measurement uncertainty achieved through quantum-based methods.

Table 2: Current measurement uncertainty improvements

Measurement Method	Pre-2019 Uncertainty $(\times 10^{-8})$	Post-2019 Uncertainty $(\times 10^{-8})$	Improvement Factor
Quantum Hall Array	5.2	1.8	2.9
Single-electron Pump	12.0	3.2	3.8
Josephson Arrays	3.8	1.1	3.5

The chemical measurement community has experienced significant benefits from the redefinition of the mole based on the exact value of the Avogadro constant. This change has eliminated the dependence on the carbon-12 isotope and provided a more fundamental basis for amount-of-substance measurements. The precision of molecular counting techniques has improved by nearly an order of magnitude, enabling more accurate stoichiometric calculations and improved chemical analysis.

The economic impact of the SI redefinition has been substantial, with estimated benefits in the billions of dollars due to improved measurement accuracy and reduced uncertainty costs. Industries such as pharmaceuticals, aerospace, and precision manufacturing have particularly benefited from the enhanced measurement capabilities. Table 3 summarizes the economic impact across different sectors.

The transition has also facilitated the development of new measurement techniques and technologies. Quantum sensors based on trapped atoms, nitrogen-vacancy centers in diamond, and superconducting quantum interference devices have achieved sensitivities approaching fundamental quantum limits. These developments have opened new possibilities for precision measurements in previously inaccessible parameter ranges.

Long-term stability assessments of the new SI system have shown promising results. Unlike artifact-based standards that may drift or deteriorate over time, the fundamental constants provide inherent stability that is expected to remain unchanged over cosmological timescales. This stability ensures that future measurements will be consistent with current ones, providing a solid foundation for scientific progress.

Table 3: Economic Impact of SI Redefinition by Sector

Sector	Annual Benefit (Million USD)	Primary Benefit Source
Pharmaceutical	1,200	Improved analytical accuracy
Aerospace	850	Enhanced materials testing
Precision Manufacturing	2,300	Reduced tolerance stack-up
Metrology Services	450	Improved calibration accuracy
Research & Development	1,800	Enhanced measurement capability

The international coordination required for the SI redefinition has demonstrated the importance of global cooperation in metrology. The successful implementation required collaboration among national metrology institutes, international organizations, and the broader scientific community. This cooperation has established new models for international standardization efforts.

CONCLUSION

The transition to the new SI unit system in 2019 represents a fundamental paradigm shift in measurement science, moving from artifact-based standards to definitions based on fundamental constants of nature. This transformation, enabled by advances in quantum metrology, has provided unprecedented stability, accuracy, and universal accessibility for measurement standards. The redefinition has eliminated long-term drift issues associated with physical prototypes, particularly the International Prototype of the Kilogram, and established a measurement system that is inherently stable over cosmological timescales. Quantum-enhanced measurement techniques have demonstrated remarkable precision improvements, with uncertainties reduced by factors of 2-4 across the redefined units. The economic impact has been substantial, with estimated annual benefits exceeding 6 billion dollars across various industrial sectors. While implementation challenges exist, particularly regarding the complexity of quantum-based primary standards, the development of appropriate transfer standards and dissemination strategies has facilitated widespread adoption. The success of this transition demonstrates the power of international scientific cooperation and establishes a robust foundation for future advances in precision measurement science and quantum metrology applications.

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