Progress of the BIPM Pilot Studies on Differential Measurements of an ac Source with Programmable Josephson Voltage Standards

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***Abstract* — BIPM performed two pilot studies in 2023 to support the uncertainty budget for the programmable Josephson voltage standard (PJVS). The studies involved differential sampling with an ac source, as proposed in the new BIPM on-site comparison protocol. Sinewave signals of 1 V rms at different frequencies (62.5 Hz, 125 Hz, 250 Hz, 625 Hz, 1250 Hz) were investigated with PTB and KRISS. The results exhibited excellent repeatability and reproducibility when comparing measurements with two identical PJVS systems based on the KRISS voltage standard. Conversely, the comparison of two different PJVS systems (BIPM and PTB PJVS systems) led to divergent results. The suspected cause of the discrepancy is likely the presence of larger leakage-current-induced errors on the BIPM PJVS setup. Further pilot studies will be performed in 2024 to resolve this problem.**

***Index Terms* — Josephson junctions, Metrology, Sampling methods, Standards, Superconducting integrated circuits, Voltage measurement.**

I. Introduction

Ever since the extension of the JVS protocol for alternating (ac) voltage on-site comparisons was released in June 2022 [1], BIPM has been focusing on reducing measurement uncertainties with the most demanding option of the protocol using its transportable PJVS.

In this option, the transfer standard to be measured is a solid-state ac source provided by the BIPM [2]. This ac source is measured alternately by the BIPM and the participant (Fig. 1), as well as constantly measured by a full sampling meter (Agilent 3458A). This source is battery-powered, temperature-regulated, optically isolated, includes a 10 V external reference, and offers state-of-the-art stability both in voltage amplitude and phase.

Two new pilot studies were carried out in 2023 when PTB (Germany) visited BIPM in March 2023 and BIPM visited KRISS (Rep. of South Korea) in August 2023. The objective of the first exercise was to repeat the results obtained in the PTB laboratories in August 2022 using the PTB PJVS, BIPM transportable PJVS, and the BIPM ac source as voltage transfer standard. Despite many efforts in the search for the best grounding and shielding configuration, the March 2023 comparison measurement results were divergent by several hundreds of nanovolts and, even worse, were not even repeatable from one measurement set to the next.

The issues were identified to be coming from the BIPM PJVS as the simple addition of the full sampling meter in parallel to the ac source would introduce a systematic error in the rms value measured by BIPM (Fig.1). Since a significant leakage current was found to be responsible for this effect, it was decided that another comparison using two identical PJVS systems should be organized.

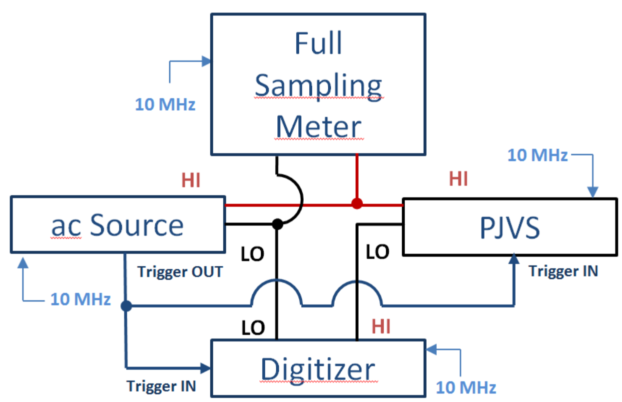

Fig. 1. Schematic of the measurement and synchronization circuit; the ac source output is constantly measured by a full-sampling meter for monitoring purposes. The PJVS and digitizer blocks were identical during the KRISS-BIPM pilot study, making possible the complete exchange of the probes between the two setups.

II. Setup

The BIPM and the KRISS PJVS systems consist of nominally identical equipment (electronics, software, cable, probe, PJVS circuit). They were compared in the KRISS laboratory using two KRISS PJVS [3] bias modules and associated KRISS software and two commercial cryoprobes associated with a NIST 10 V programmable array [4]. The two differential sampling measurement setups were fully identical from a technical point of view so that unidentified interference errors would lead to the same error signals. The aim was to circumvent any possible systematic errors due to the apparatus

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or the software: only the differences in the leakage currents (bias source to Earth potential) could cause a systematic error. Five different frequencies from 62.5 Hz to 1250 Hz for an rms voltage of 1 V were investigated. The best grounding configuration was with the dewars, the PJVS equipment chassis, and the guard of the digitizer, all connected to the voltage ground reference point with a star configuration. The differential voltage between the source and the PJVS was measured alternately by a commercial digitizer: Fluke 8588A[1] or NI-5922. The digitizer was placed between the low-potential terminals of the source and PJVS to minimize common-mode and leakage effects. All instruments shared a common 10 MHz reference and were synchronized with an optical trigger signal from the source at the waveform frequency.

III. Results

The number of samples per period was adjusted as a function of the frequency of the measured signal (Table 1). The number of periods over which the voltage difference was acquired and the number of measurement repetitions were selected so that the elapsed time for the complete measurement was the same for each frequency. The gains of the digitizers were regularly measured comparing the full sampling rms value of a triangle signal to the theoretical one. The latest gain correction measured was always applied to the readings during the exercise. Even if the gain correction is of several tens of ppm, it was stable with time.

The results obtained are presented in Table 1. The measured voltage difference increases with frequency, suggesting a capacitive effect, acting differently on each system, and introducing a systematic error in the results.

Table 1. Comparison results obtained at KRISS at 1 V. For each frequency we list the number (*N*) of voltage steps per period in the PJVS approximated sinewave, the measured voltage difference between BIPM and KRISS signals, and the typical Type A uncertainty.

Freq./Hz	*N*	Difference/nV	Typ. Type A unc./nV
62.5	64	5	30
125	64	7	20
250	32	44	20
625	32	100	20
1250	16	200	30

Figure 2 presents a chronological example of results obtained at 1250 Hz using the two different digitizers. A relative difference of 2×10^{-7} is visible between the two digitizers on the KRISS system while not so obvious on the BIPM system. This could be linked to the fact that the NI-5922 digitizer is not equipped with a guard potential point. The drift of the voltage output of the source is also visible over the 2 h duration of the comparison measurement.

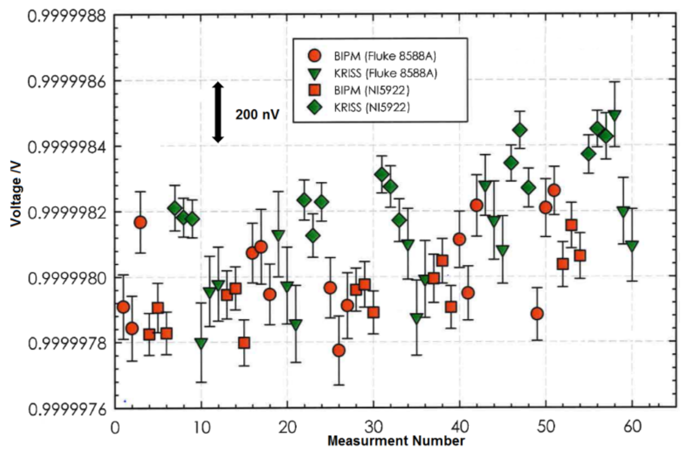

Fig. 2. Example of results of the KRISS-BIPM comparison at 1250 Hz: Transfer Standard output voltage measured by the two differential sampling setups and two different samplers (Fluke 8588A and NI-5922). KRISS measurements are shown in green, and BIPM measurements in red/orange.

IV. Conclusion and Perspective

The pilot study comparison of two equivalent PJVS systems at KRISS demonstrated repeatable and reproducible results within the Type A uncertainty: from 5 nV difference at 62.5 Hz to 200 nV at 1250 Hz. The next challenge is to perform a new pilot study with PTB in 2024, focusing on understanding the leakage effects observed in 2023 on the BIPM transportable PJVS using different bias sources. The results will be presented at the conference.

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[1] Certain commercial instruments are identified in this paper to facilitate understanding. Such identification does not imply recommendation or endorsement by BIPM, KRISS, PTB, NMIA and NIST, nor does it imply that the materials or equipment that are identified are necessarily the best available for the purpose.