Experimental Determination of the Voltage Lead Error in an AC Josephson Voltage Standard

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***Abstract*—The National Research Council (NRC) of Canada has recently established an alternating-current Josephson voltage standard (ACJVS) system based on the National Institute of Standards and Technology pulse-driven Josephson junction arrays. This paper describes the efforts undertaken at the NRC and the experience that was gained. An experimental method of measuring corrections for the voltage probe lead errors is described, and first results are reported. By introducing the ACJVS, the NRC will be able to reduce the uncertainties of the thermal transfer standard calibration by threefold on the 200-mV range and five- to tenfold on the 20-mV range, in comparison with thermal-converter- and micropotentiometer-based calibrations.**

***Index Terms*—Digital–analog conversion, Josephson arrays, quantization, signal synthesis, standards, superconductor–normal–superconductor devices, voltage measurement.**

I. Introduction

THE MOST accurate measure of an alternating voltage (ac) source is obtained by comparing its output to a reference direct-current (dc) voltage using a multijunction thermal converter. An estimated ac–dc transfer difference uncertainty of the most accurate multijunction converters is in the range of one to two parts in 10^7. This ceiling was achieved over 20 years ago with a relatively low likelihood for significant improvement in the future. This is thus the practical limit of the most accurate ac voltage measurements, as the reference dc voltage can be generated in practice with the accuracy higher by one or two orders of magnitude, using quantum-effects-based Josephson junction arrays (JJAs).

Over the last several years, a significant effort led by the National Institute of Standards and Technology (NIST), USA, has attempted to eliminate the thermal converter as the link between ac and dc quantities, and to use the JJA to generate a standard ac voltage with quantum accuracy. Two main methods have been pursued. In the first method, a programmable JJA is used as a binary-weighted digital-to-analog converter to synthesize the sinusoidal waveform in a steplike fashion. In the second method, a quantum-accurate ac voltage is digitally synthesized with a pulse train. The NIST pulse-driven ac Josephson voltage standard (ACJVS) has been described in the literature [1] (see a detailed reference list in the review paper [2]). At the NIST, the ACJVS progressed from an experiment to a practical application [3]. Several other National Metrology Institutes, such as the Physikalisch-Technische Bundesanstalt, Germany [4]–[6]; the Dutch Metrology Institute (VSL), the Netherlands [7], [8]; and recently, Korea Research Institute of Standards and Science, Korea [9], have intensified efforts to adopt the ACJVS as a primary ac voltage standard.

An ACJVS system based on the NIST pulse-driven array has been also established at the National Research Council (NRC) of Canada in close cooperation with the NIST [10]. This paper describes a method of the experimental determination of the systematic error due to long leads between the pulse-driven Josephson array and an instrument under calibration. A procedure for determining the systematic error arising when connecting two arrays in series to double the output voltage is also proposed.

II. NRC Test System

A. System Description

The NRC system, as shown in Fig. 1, duplicates the configuration of the NIST system [11]. The source of the quantized ac voltage is a chip containing two independent arrays of 5120 junctions located inside a liquid helium Dewar. When appropriately energized and biased (“on margin”), each array can generate a maximum low-frequency (LF) root-mean-square (RMS) ac voltage of 110 mV. However, the typical maximum output voltage is 100 mV, matching the range of calibrated instruments. Two twisted-pair lines of copper magnet wire connect the arrays to the cryoprobe room-temperature output terminals. Outputs of the two arrays can be connected in series, doubling the RMS output voltage to 200 mV.

B. Challenges

In its present configuration, the proper operation of each array requires the synchronization of frequencies, levels, and phases of three different generators: a 10-GHz digital code generator (DCG), a 15-GHz continuous-wave (CW) generator, and an LF arbitrary waveform generator. Apart from the frequency of the common clock, i.e., 10 MHz, these signals require synchronization and relative phase stability. Amplitudes and phases of the CW and LF generators have to be independently tuned, in addition to three parameters of the DCG output pulses,

Manuscript received June 17, 2010; revised January 4, 2011; accepted January 19, 2011. Date of publication March 10, 2011; date of current version June 8, 2011. The Associate Editor coordinating the review process for this paper was Dr. George Jones.

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Digital Object Identifier 10.1109/TIM.2011.2113830

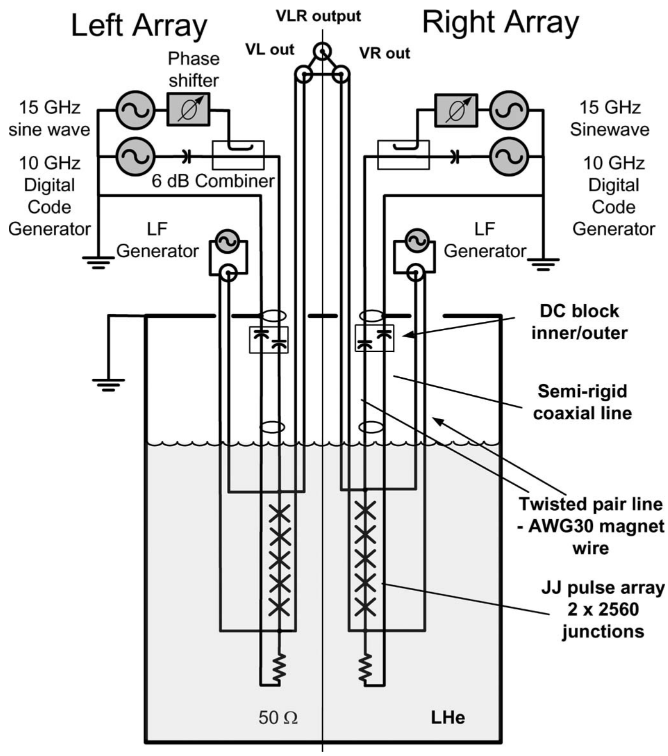

Fig. 1. Simplified diagram of an ACJVS.

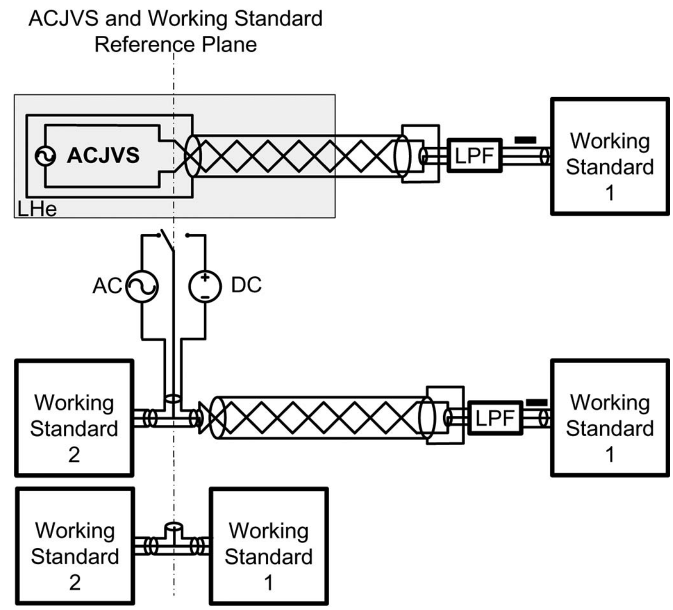

Fig. 2. Experimental determination of voltage lead corrections (LPF: low-pass filter).

for a total of seven parameters per array. The operation of the ACJVS is not yet fully automated and requires a manual intervention of a skilled operator. An initial setup of the system was significantly eased, however, by the fact that the approximate settings of the NIST system could be successfully used as the starting points for the NRC system.

We experienced difficulties with the semirigid coaxial cables located in the cryoprobe, which transmit the energizing 10-GHz DCG output pulses to the arrays. Due to repeated thermal cycling, its inner conductor shifted in the cable inner Teflon dielectric, and the connections between the JJA and the microwave/pulse generators mechanically broke. The problem was solved by replacing the semirigid cable by a flexible corrugated coaxial cable.

The LF ac-bias arbitrary waveform generators have to be synchronized with the pattern-generating DCG. The DCG generates a synchronizing pulse once at the beginning of each period. It was lengthened and shaped in a NIST-manufactured electronic circuit (not shown in Fig. 1) to synchronize the LF generators. At the beginning, we frequently experienced a loss in this synchronization due to a computer–IEEE-bus speed mismatch. This problem was solved through a software change.

III. Voltage Lead Error Corrections

One of the factors limiting the *accuracy* of the ACJVS is an error due to the presence of long voltage leads between the reference plane of the quantum-accurate voltage at the array output and the input of the working standard under test. This frequency-dependent voltage lead error is relatively large and requires correction. The correction can be estimated from the measured parameters of the twisted-pair line and the coaxial cable (cf. [11] and [12]). It can be also experimentally determined, as described below.

In the NRC setup, the voltage leads of each array consist of a twisted-pair line of copper magnet wire 1.3 m in length, connecting the arrays to the cryoprobe room-temperature output terminals, and a coaxial cable 0.9 to 1.5 m, wound on a magnetic core as a coaxer (equalizer, balun). The twisted-pair lines of both arrays can be appropriately joined at the cryoprobe head, connecting the outputs of the arrays in series. The calibrated instrument is a commercial amplifier-aided ac–dc thermal transfer standard. Its input is connected to the output of the cryoprobe either directly or through the coaxer. Usually, an additional first-order RC low-pass filter was directly added at the cryoprobe output (see Fig. 2).

A. Single-Array Lead Error

The method of the experimental determination of the voltage lead correction is illustrated in Fig. 2. The reference plane of the generated quantum-accurate ac and dc voltages is directly at the output of the superconducting JJA. The voltage rise/drop between the array reference plane and the input of working standard 1 was measured using an auxiliary working standard 2. The JJA is substituted by working standard 2, with its input placed at the voltage reference plane. A type-N connector connecting the probe to a tee of an ac–dc transfer comparator was soldered in place of the array. It was assumed that the added capacitance of the type-N connection (a few picofarads), shunted by a low source impedance of the comparator (see below), does not modify the frequency characteristic of the leads significantly.

The ac–dc transfer differences of working standards 1 and 2 were measured twice, i.e., with and without the voltage lead in between. The difference between these two measurements, conducted at room temperature on the actual probe, is used as the voltage lead correction. The application of this correction can

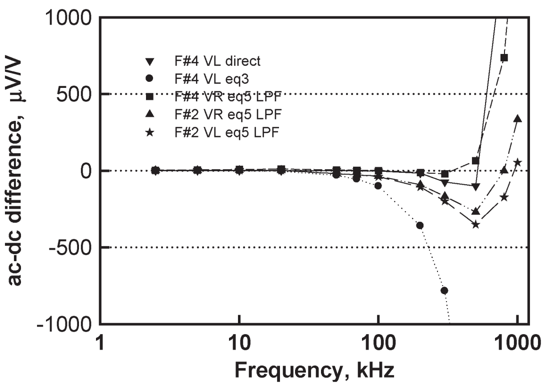

Fig. 3. AC–DC difference of different voltage lead configurations measured at room temperature. Loading: transfer standard F#2 or F#4; coaxers: eq3 and eq5; low-pass filter: LPF first order, 6 MHz.

be considered equivalent to the shifting of working-standard-1 input reference plane from its input to the JJA output.

The magnitudes of voltage errors for different lead configurations are shown in Fig. 3. The errors are expressed as a difference of ac–dc transfer differences of working standard 2, connected to one arm of the tee, and working standard 1, with and without the leads connected to the other arm. Three different transfer standards designated F#2, F#4, and F#5 were used in the position of the calibrated working standard 1. All tests were conducted at 100 mV using the same auxiliary working standard 2. The trace marked *F#4 VL direct* shows an error introduced by the twisted-pair line only; the F#4 input was directly connected to the cryoprobe head. The ac–dc transfer difference is negative in this configuration up to 500 kHz, indicating a slight resonance. When an additional coaxer is connected between the cryoprobe head and working standard 1, the lead ac–dc difference is negative even beyond the 1-MHz test band, i.e., *F#4 VL eq3*, indicating a sharp resonant rise. By adding a simple RC filter between the cryoprobe head and the coaxer, we have shaped the voltage lead error to be maximally flat up to 100 kHz to minimize the magnitude of error to be corrected. The corner frequency of this filter was approximately 6 MHz.

The voltage drop/rise on the leads depends on several different parameters, such as impedances on both ends of the leads and parasitic impedances to the enclosure, changing with the changing spatial position of the twisted-pair lines. As a result, they change with the ac–dc comparator source impedance (in our measurements, it was set to 2 Ω, approximating the resistance of the line), the impedance of working standard 1, and the grounding of both working standards. *F#2/F#4 VL/VR eq5/eq3 LPF* lines were measured using leads of left or right array, VL or VR, respectively, with two different working standards, a coaxer (equalizer 5 or 3), and a 6-MHz first-order low-pass filter. It can be noted that the RC filter, which was adjusted to flatten the frequency characteristic of the leads in one configuration (*F#4 VR*), was no longer optimal when used with a different transfer standard or in a different configuration of leads.

The magnitude of the measured lead corrections is in the range of 1.5–6 μV/V at 2.5 kHz and increases with increasing frequency.

TABLE I
MEASURED AC–DC TRANSFER DIFFERENCE. WORKING STANDARD F#2 AT 6, 12, 50, 100, AND 200 mV ON THE 22- AND 220-mV RANGES. NO CORRECTIONS APPLIED

ac-dc transfer difference μV/V

		Frequency kHz				
Voltage	Array	2.5	5	10	20	50
12 mV	VL	74.3	92.8	61.7	49.2	27
12 mV	VR	72.0	88.7	68.4	54.3	30.2
2x6 mV	Both	72.4	89.1	53.7	-6.4	-152.9
Loop error		-0.8	-1.7	-11.4	-58.2	-181.5
100 mV	VL	-5.7	-7.4	-11.2	-9.0	-5.4
100 mV	VR	-6.0	-7.9	-11.3	-9.0	-9.0
2x50 mV	Both	-6.2	-11.3	-28.0	-68.9	-180.0
Loop error		-0.3	-3.6	-16.8	-59.9	-172.8
2x100 mV	Both	-8.5	-14.8	-30.5	-72.7	-180.8

It is assumed that the change in the twisted-pair line resistance between the air-temperature bench tests and the actual working conditions (partially immersed in the liquid helium) does not change the voltage lead error significantly when used with the high-input resistance transfer standard (input resistance above 1.5 MΩ at frequencies of 100 kHz and below). This was confirmed by simulations such as that described in [11]. However, more experimental work is necessary to establish if such an assumption is justified for higher frequencies. The accuracy of this correction method depends on the value and the frequency characteristic of an input impedance of the calibrated instrument.

B. Two Arrays Connected in Series

When the two arrays are connected in series to double the output voltage, the connections between the arrays at the ac are more complex than at the dc [11]. At the ac, capacitances to ground of the dc blocks of the microwave connections create an unwanted closed loop between the arrays, significantly increasing the lead errors. Additionally, the internal capacitances of the transfer standard, that is, the small input capacitance (approximately 40 pF), and large capacitances (a few nanofarads) from the input low to the guard and the guard to ground load the ACJVS output asymmetrically. The magnitude of the closed-loop error was estimated in [11] theoretically from parameters of the equivalent circuit. However, in a limited frequency range, this error can be also experimentally determined by measuring the transfer standard ac–dc transfer difference at the same point twice using a single array energized at voltage V and two arrays connected in series, each energized at $V/2$.

Table I shows results of such tests conducted on two different ranges of a transfer standard at 12 (22-mV range), 100, and 200 mV (220-mV range). The rows *12-mV VL* and *12-mV VR* show the ac–dc difference measured using left (VL) and right (VR) arrays separately. These results are degraded by a single-array lead error, which was experimentally determined, as described in Section III-A. The third row, i.e., 2×6 mV *Both*, shows results of calibration using both arrays in series. The difference between the two-array measurement and the average of single-array measurements named in Table I as "loop error" is a direct measure of the additional lead error arising from

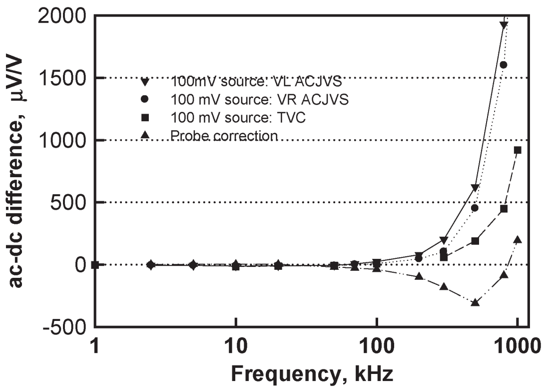

Fig. 4. Characterizations of transfer standard F#2 using left (VL) and right (VR) arrays of the ACJVS and a thermal converter.

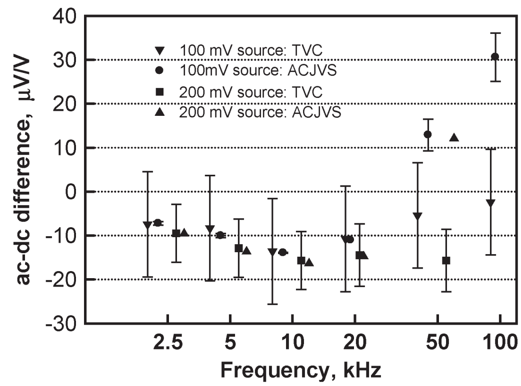

Fig. 5. Calibration of a transfer standard F#2 at 100 and 200 mV using the ACJVS and a thermal converter (TVC). The differences between calibrations using left and right arrays are shown as 100-mV ACJVS error bars.

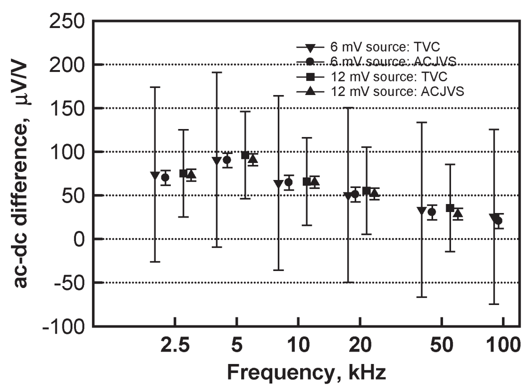

Fig. 6. Calibration of a transfer standard F#2 at 6 and 12 mV using the ACJVS and a micropotentiometer (TVC). The differences between calibrations using left and right arrays are shown as ACJVS error bars.

the parasitic closed loop. Table I shows that this error does not significantly change with the transfer standard range; the results obtained at 100 and 12 mV are very close. Experimentally determined at one level on a given range, it can be then used to correct the measurements at a different level at the same range.

The last row of Table I shows results of calibration at 200 mV. It can be inferred from results at frequencies 20 and 50 kHz that the measured ac–dc difference is to a large degree due to the loop error.

IV. Test Results

The NRC ACJVS test system has been fully operational since September 2008. We have conducted numerous tests to characterize three transfer standards between 2 and 200 mV and frequencies from 2.5 kHz to 1 MHz. We have also participated in the first international comparison of quantum ac voltage standards between the NRC and the NIST [13].

Fig. 4 shows, as an example, results of characterizing the transfer standard F#2 at 100 mV in the frequency band from 2.5 kHz to 1 MHz. The F#2 ac–dc transfer difference was measured using each array separately, i.e., VL and VR, and a thermal voltage converter (TVC). For comparison, the measured frequency characteristic of the voltage lead correction is also shown in Fig. 4. The characterizations using left and right arrays diverge above approximately 100 kHz. This divergence is due to differences in reactances of twisted-pair lines, dc blocks, as well as parasitic reactances associated with each output lead channel. The magnitude of the voltage lead error is significantly lower than the difference between the ACJVS and thermal converter characterizations. This indicates the presence of yet another systematic error not originating in the impedance of the voltage leads. Here, a source of this error is discussed at the end.

The absolute values of the ac–dc transfer difference of F#2 are shown in greater detail in Fig. 5. At 100 mV, F#2 was calibrated using left and right arrays separately, with the results averaged and a voltage lead correction applied. At 200 mV, both arrays were connected in series, and a correction for a closed-loop error, calculated as described in Section III-B, was applied. The ACJVS data were averaged over several runs; the type-A pooled standard deviation was approximately 0.3 μV/V. The error bars on thermal converter calibration curves are expanded uncertainties of the NRC calibration of F#2.

Between 2.5 and 20 kHz, the difference between the characterization of the transfer standard obtained using the ACJVS and a thermal converter is less than 1 μV/V in most points. This difference is two to three times smaller than the currently assigned NRC uncertainty. It appears from our experience that, given the transfer standard interaction with the operating ACJVS and its short−term stability, at these voltage levels, we are very close to the achievable transfer standard calibration uncertainty limit. To further decrease the calibration uncertainty while transferring the ACJVS value, we are experimenting with an electronically buffered thermal converter. Results of these experiments will be presented in a future paper.

Similar calibrations were performed at different voltage levels. Fig. 6 shows results obtained at 6 and 12 mV using each array separately and averaging the results. For comparison, the transfer standard was also calibrated at these two levels using micropotentiometers ("micropots") [14]. Shown as error bars, expanded uncertainties of the micropot calibrations are in the range of 50–100 μV/V. The micropot was characterized in a step-down procedure, with uncertainty increasing at every step. Twelve steps are required to reach the 6-mV level. The ACJVS calibration bypasses this step-down process.

Two important conclusions can be drawn from Fig. 6. The difference between the ACJVS and micropot calibrations of the transfer standard is one fifth to one tenth of the uncertainty assigned to the micropot calibration. This means that the NRC calibration uncertainty can be significantly reduced at these points (proportionally less at higher millivolt voltage values). It should be also noted that, unlike at 100 and 200 mV, the ACJVS calibrations do not diverge from the micropot calibrations even at 100 kHz. This can be explained as follows.

For proper operation, an array has to be properly biased at an LF to "reinsert" the LF component, which was filtered out of the energizing 10-GHz pulse bias by the capacitance of the dc blocks. However, at low voltage levels such as 12 mV and below, the array can operate without the compensation bias, albeit within a much smaller operating margin. The calibrations shown in Fig. 6 were performed without this compensation. The compensation bias current, which is in phase with the JJA-generated voltage, creates a voltage drop on the internal inductance of an array (approximately 6.9 nH). In an ideal situation, this voltage drop is orthogonal to the JJA voltage and does not significantly modify the ACJVS output. An error arises, however, when it has an in-phase component. We assume that the presence of such an in-phase component is the origin of the divergence between the ACJVS calibration (corrected for the voltage lead error) and the thermal converter calibration, as shown in Fig. 5. Several techniques were already employed in reducing and measuring this error source, as described in [15] and [16]. We are working on the better characterization of this error induced by the compensation current, with a goal of correcting its influence for frequencies of operation above 20 kHz.

V. Conclusion

An ACJVS system based on the pulse-driven JJA has been established at the NRC. Three thermal transfer standards have been calibrated using the ACJVS at voltages ranging from 6 to 200 mV and frequencies from 2.5 to 100 kHz (and up to 1 MHz with reduced accuracy). Methods for the experimental determination of the voltage lead correction and the parasitic closed-loop correction have been developed. For frequencies between 2.5 and 20 kHz and voltages of 100 and 200 mV, the transfer standard calibrations using traditional methods, i.e., a thermal converter, agree with the ACJVS (with voltage lead corrections applied) to better than ± 1 μV/V in most points (better than ± 1.6 μV/V everywhere). At low voltages, i.e., 6 and 12 mV, the excellent agreement between the traditional and ACJVS calibration methods extends to 100 kHz. After the full evaluation of the ACJVS error budget, we expect to be able to lower the NRC calibration uncertainties in these ranges by a factor of 1/2 to 1/10.

The establishment of ac voltage measurements with the ACJVS system is a first step in a paradigm change in ac metrology, i.e., a shift from artifact-based ac primary standards to quantum-effect-based standards. The quantum-effect-based standards bring new and unique challenges to the field. Their operation is drastically different from the operation of the traditional ac–dc voltage transfer systems. The accuracy of this measurement/calibration technique relies on conditions that are different from that of traditional RMS-based calibration techniques with thermal transfer standards. They may also require new intermediate standards to transfer their values to the working standards with a minimal loss of accuracy. At present, our efforts concentrate on understanding better the ACJVS error sources, establishing accurate corrections, and constructing a full error budget. Hardware changes will include upgrading voltage lead connections in the cryoprobe and building electronics to allow for direct comparison of the ACJVS to a multijunction thermal converter at 100 and 200 mV.

Our short-term objective is the incorporation of the ACJVS into the NRC-standard chain for the ac–dc transfer difference and, ultimately, as a primary ac voltage standard. The presented results have shown that the short-term objective is already closely within reach.

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