In Situ Calibration of Heterogeneous Acquisition Systems: The Monitoring System of a Photovoltaic Plant

In-Situ Calibration of Heterogeneous Acquisition Systems: the Monitoring System of a Photovoltaic-Plant

Alessio Carullo, Simone Corbellini, Alessia Luoni, Alessandra Neri

Abstract—**This paper deals with the metrological management of an acquisition system that has been developed for monitoring an experimental PhotoVoltaic (PV) plant. The acquisition system has been conceived for comparing the performance of different PV technologies and for verifying the nominal specifications of the PV modules. For these reasons, the traceability of the monitoring system has to be ensured, and therefore it must be periodically calibrated. A remotely-exercised procedure is proposed for the calibration of the acquisition system, which is based on a calibrator specifically designed for this application. This calibrator has the capability to act as a reference for heterogeneous quantities, including electrical quantities, temperature, and solar irradiance. The architecture of this calibrator is described, and experimental results for the preliminary characterization of the prototype are described.**

Index Terms—**Calibration, measurement standards, AC generators, DC generators, electric variables measurement, photovoltaic cell measurements.**

I. Introduction

Multi-channel measuring systems are widely employed in different fields, such as in the monitoring of industrial processes, environmental pollution and energy-generation plants. A series of common characteristics can be highlighted for these systems, which are:

- heterogeneous nature, since different quantities have to be acquired;
- employment of complex measuring chains, which include several devices, such as sensors, signal-conditioning circuitry, optical links, and data acquisition boards;
- employment of software acquisition and processing algorithms, which have a large impact on the final measurements these systems provide.

While the mentioned characteristics make these systems very flexible and suitable for different scenarios, they may present problems with traceability and quality assurance. Common calibration procedures that require measuring devices to be moved to a calibration laboratory cannot be easily adopted, since these devices are usually deeply integrated into the monitored system. Furthermore, the calibration results might not always be representative of the behavior of the measuring chains in operating conditions and the effects of the software components are not taken into account.

These problems can be tackled by employing a conventional in-situ calibration procedure. However, this solution dramatically increases the overall calibration cost, since it requires transport of the reference standards and expert technicians to the operating site. In this paper, a different approach is proposed that employs a solution developed by the authors for other kinds of systems [1]-[3]. This approach is based on a remotely-exercised calibration procedure: a traveling standard is sent to the site where the system under calibration operates and the calibration procedure is remotely managed by interacting with the standard and the system under calibration through the network. For this purpose, a network-capable traveling standard must be available to acts as a reference for the quantities measured by the monitoring system. Besides the typical advantages of an in-situ calibration, the proposed procedure benefits by a significant reduction in cost and calibration time, since the remote monitoring capabilities remove the need for a skilled on-site technician.

In this work, the proposed approach is implemented for a specific case-study, the monitoring system of a Photo-Voltaic (PV) plant. The main characteristics of this system have been described in a previous work [4], therefore only a summary is presented in the next section. A specifically-designed calibrator has been also developed, whose architecture is described in this work. The section IV describes the results obtained during the preliminary metrological characterization of the calibrator prototype.

II. The monitoring system under calibration

The system requiring periodical calibration by means of a remotely-exercised procedure has been designed by the authors for monitoring the performance of an experimental PV plant, which is located in the Province of Cuneo (Piemonte), in the North-West of Italy. The plant, which is now under construction, includes nine arrays that employ PV modules based on different technologies, as specified in [4]. This experimental plant is designed to compare the performance of different PV technologies.

The performance indexes that can be employed to characterize a photovoltaic plant can be subdivided into two main categories: instantaneous and cumulative indexes. Among the instantaneous indexes, the ones of main concern are the PV module efficiency $\eta_{\rm PV}$ and the DC-AC efficiency of the power conditioning unit (PCU) $\eta_{\rm PCU}$:

$$\eta_{\rm PV} = \frac{P_{\rm DC}}{G \cdot S} \;\; ; \;\; \eta_{\rm PCU} = \frac{P_{\rm AC}}{P_{\rm DC}} \tag{1}$$

where $P_{\rm DC}$ and $P_{\rm AC}$ are DC (upstream of the PCU) and AC (downstream of the PCU) powers, G (W/m^2) is the solar irradiance and S (m^2) is the actual plant area. These

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definitions assume that the behavior of the MPPT (Maximum Power Point Tracker) algorithm of the PCU is ideal.

Two important cumulative indexes are the generation efficiency η_G and the actual equivalent hours h_e, which are defined respectively as:

$$\eta_G = \frac{E_{AC}}{T_M \cdot P_n} \; ; \; h_e = \frac{E_{AC}}{P_n} \tag{2}$$

where E_{AC} (Wh) is the energy produced in the operating time T_M (h), while P_n (W) is the nominal power.

The estimation of these indexes requires the measurement of voltage and current signals upstream (DC) and downstream (AC) of the PCU, of the solar irradiance G and of the module temperatures, thus allowing the estimated indexes to be referred to the Standard Test Conditions (STC): irradiance of 1000 W/m^2 and cell junction temperature of 25 °C. The wind speed is also measured because it affects the module temperature and, in turn, the efficiency, which depends on the cooling of the PV modules. Other measured quantities are temperature and humidity of the external environment and of the environment inside the site where the monitoring system is installed. Table I summarizes the quantities that are measured by the monitoring system, which has been developed in order to meet the requirements indicated in the same table in terms of range, sampling rate and maximum allowable uncertainty [5]. In Table I, the term global irradiance refers to the broadband (full spectrum) solar irradiance measured by means of a pyranometer, while the term module irradiance indicates the measurement provided by photovoltaic-based devices that exhibit the same spectral response as the corresponding PV modules.

TABLE I
Measurement requirements of the monitoring system under calibration.

Measured Quantities	**Range**	**Minimum sampling rate (kSa/s)**	**Maximum uncertainty**
DCV	$(100 \div 450)$ V	1	1 %
DCI	$(0.5 \div 6)$ A	1	1 %
ACV	230 V_{rms}	25	1 %
ACI	$(0.5 \div 8)$ A_{rms}	25	1 %
Global and module irradiance	$(0 \div 1500)$ W/m^2	1	5 %
Module temperature	$(-10 \div +80)$ °C	1	1 °C
External temperature and humidity	$(-20 \div +40)$ °C $(10 \div 90)$ %RH	1 1	1 °C 3 %RH
Internal temperature and humidity	$(18 \div 28)$ °C $(30 \div 70)$ %RH	1 1	0.5 °C 3 %RH
Wind speed	$(0.5 \div 50)$ m/s	1	5 %

In the developed monitoring system, the AC and DC voltages are conditioned through specifically designed circuits. These circuits essentially act as attenuators and ensure the galvanic insulation between the plant and the acquisition system, which employs three data acquisition boards installed inside a PXI chassis. The AC and DC currents are instead sensed by means of thru-hole Hall-effect sensors, which provide an output voltage proportional to the input current and ensure the galvanic insulation. The PXI chassis also embeds a PC-board with networking capabilities, which allows the acquisition system to be remotely managed through the LAN. Custom software, which has been developed in LabVIEW, acquires and processes the input signals of the three acquisition boards. The version of LabVIEW used in this system allows the development of a remote user interface. Front Panel Web Publishing [6] is used to embed the front panel of the monitoring system into a web page. One of the main advantages of this solution is the capability to access the front panel web page without requiring specific software, with the exception of the LabVIEW run-time engine and a web browser.

For calibration purposes, particular attention has been paid to designing the part of the monitoring system downstream of the PCU, as shown in the Figure 1. In this figure, the energy meter A measures the total energy produced by the photovoltaic plant (for feed-in tariff purpose), while the bidirectional energy meter B measures the net energy (deducted from the energy consumed by the local load Z_L) the plant provides to the mains. The dashed line in the figure highlights the part of the system the mains-manager makes inaccessible, in order to prevent any interference with the energy line that could alter the reading of the energy meters. To monitor the AC current and the calibration of the corresponding measuring chain, the thru-hole Hall-effect sensor is installed into the sealed part of the plant. The sensor allows a spare wire that crosses its hole to be employed as the current calibration input. Such an input, which does not interact with the plant in a significant way, remains open during the normal operation of the plant (switches SW1 and SW2 closed), while it is used to stimulate the sensor with a known current during the calibration of the monitoring system (switches SW1 and SW2 open). The voltage sensor is immune to this problem and can therefore be installed outside the sealed part of the plant, as shown in the figure 1.

Further details about the monitoring system can be found in [4].

III. Metrological management of the monitoring system

A. Calibrator architecture

The device that allows the described monitoring system to be remotely calibrated has to act as a reference for the measured quantities and has to exhibit networking capabilities, in order to be controlled by a remote calibration laboratory. Another important requirement this device has

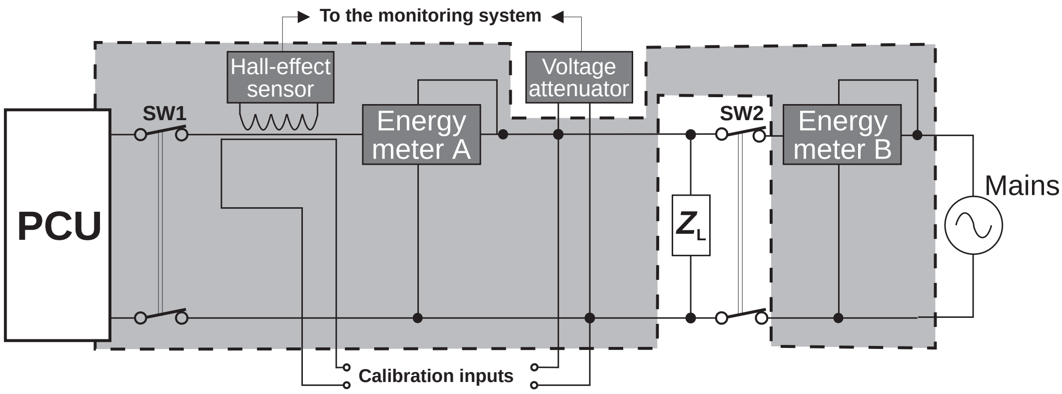

Fig. 1. Plant and sensors of voltage and current downstream of Power Conditioning Unit.

to meet is related to the uncertainties of the quantities it provides, which have to be lower than the uncertainties of the system under calibration (see Table I). During the design phase, the device has been essentially conceived as a programmable source of DC and AC voltage and current signals; furthermore, it has been equipped with standard sensors for temperature and irradiance.

Figure 2 shows the block diagram of the calibrator, where three main sections can be highlighted: a control board, an output board and a sensing board.

The control board, which is based on a microcontroller (μC: Microchip PIC18F2525), embeds a double-channel voltage generator. Each channel of this generator includes a DDS chip (Analog Devices AD9833), which provides a sinusoidal signal with variable frequency and phase; this signal is amplified and then employed as the reference voltage of a multiplying Digital-to-Analog Converter (DAC: Texas Instruments DAC8811). The μC, which communicates with the other devices through SPI interfaces, sets frequency (from DC to 2.5 kHz) and phase of the generated signals by sending a control word to the DDS generators and sets the amplitude of the output signals (from 0 V to 10 V_{pp}) by sending the input code to the multiplying DACs. The calibrator is networked to a personal computer via an RS-232 serial interface. A first prototype of calibrator was equipped with an embedded PC, thus obtaining a full autonomous device. The version that is now under development instead employs the PC-board embedded in the PXI-chassis of the monitoring system under calibration. One should note that this solution, which allows a rugged system to be arranged, can be adopted in almost all the situations where a data acquisition system has to be calibrated, since these systems are usually hosted by a PC.

The output board (see Figure 3) is essentially a phantom-power generator, which provides the high voltage and current signals applied to the inputs of the system under calibration. The AC high-voltage generator includes an audio power-amplifier (ST Microelectronics TDA 2052), which is fed by one of the output signals of the control board. The output of this amplifier drives a step-up transformer with a nominal turns ratio of 40, which provides the AC output voltage in the frequency range of 50 Hz to 2.5 kHz. The DC output voltage is obtained by rectifying the transformer output, thus obtaining a continuous voltage up to 500 V. The current generator is based on a high output-current operational amplifier (Burr-Brown OPA501) that is configured as a transconductance amplifier. The voltage drop across the shunt resistor R_S (0.5 Ω; 50 W) is used as a reference for the feedback signal of the amplifier. This circuitry allows currents to be generated from DC to 2.5 kHz with amplitude up to 18 A_{pp}.

The sensing board embeds two standard sensors and the corresponding conditioning circuitry. The reference temperature measurement is carried out by a class-A platinum resistance thermometer (Pt100); the reference value of the global irradiance is obtained by employing a pyranometer (Kipp & Zonen CMP22). A bridge circuit is used to convert the resistance change of the thermal detector into a voltage signal, while a low-noise amplifier is connected to the output of the pyranometer. The output voltage-signals of temperature (V_θ) and irradiance (V_G) measuring chains are sent to the inputs of the 10-bit resolution Analog-to-Digital Converter (ADC) of the μC on the control board. By taking into account the contributions related to the sensors and to the conditioning circuitry, the expected measurement uncertainty is 0.3 °C for the temperature and 2% for the solar irradiance.

B. Remote calibration procedure

The proposed calibration procedure can be summarized in the following steps.

1. The traveling standard is calibrated at the remote laboratory and then it is sent to the site where the system requiring periodical calibration is installed.
2. The on-site operator who receives the traveling standard is responsible for:
   - supplying the traveling standard and connecting it to the PC-board of the PXI system by means of an RS-232C interface;
   - disconnecting the monitoring system from the PV plant and from the mains by opening the switches SW1 and SW2;
   - connecting the traveling-standard outputs to the in-

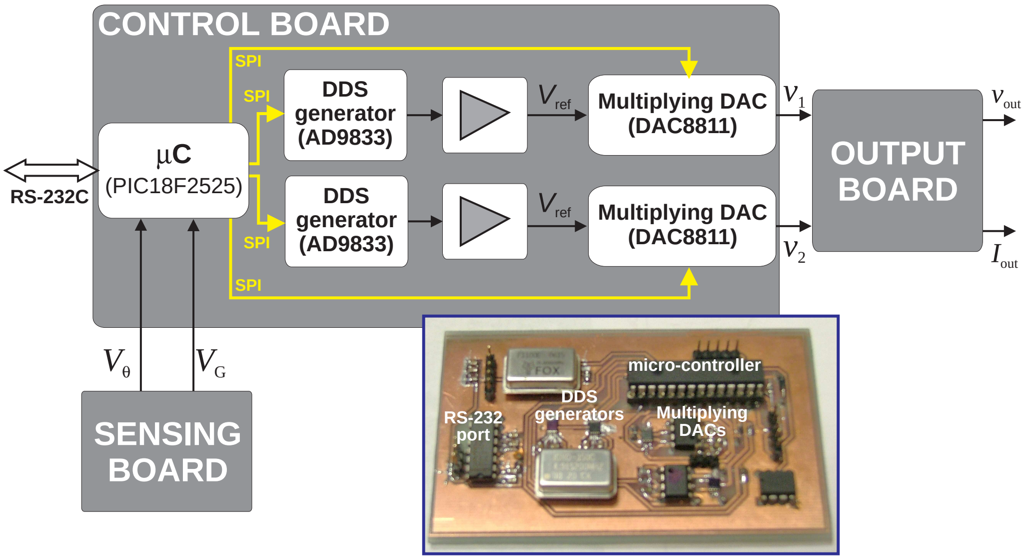

Fig. 2. Block diagram of the developed calibrator.

puts of the monitoring system (calibration inputs in the figure 1).

3. The calibration procedure starts when the PC in the remote laboratory contacts the calibrator through the PXI PC-board. This communication is based on a remote master-slave application over the Internet: the slave runs on the PC-board embedded in the PXI-chassis of the system under calibration, while the master runs on a PC in the remote laboratory. The communication is performed by means of the TCP/IP protocol and text-based commands. At the beginning of the connection, an authentication routine assures that only authorized clients can access the system.
4. The LabVIEW program suspends the normal activities to execute the commands requested by the remote PC.
5. Temperature and relative humidity of the environment where the calibration takes place are acquired.
6. The master application sets the calibrator to generate the reference electrical signals, which are applied to the input channels of the system under calibration. The master application also acquires the measurements the monitoring system makes, so that the deviation between the reference and the measured values can be estimated. The voltage and current channels of the monitoring system are verified for different amplitude and, for the AC quantities, also for different frequency values.
7. Temperature and irradiance sensors of the monitoring system are verified by comparing their measurements to the reference values provided by the standard sensors embedded into the calibrator. In order to make this procedure effective, the temperature standard sensor has to be mounted as close as possible to the sensors under calibration and in the same thermal conditions, especially for the sensors that measure the PV-module temperatures. Particular attention has to be paid to the calibration of the irradiance sensors, since the standard sensor (a pyranometer) provides an estimation of the broadband solar irradiance, while the different photovoltaic-based devices weight the solar irradiance by means of their corresponding spectral responses, which have to be taken into account in order to correctly perform the comparison.

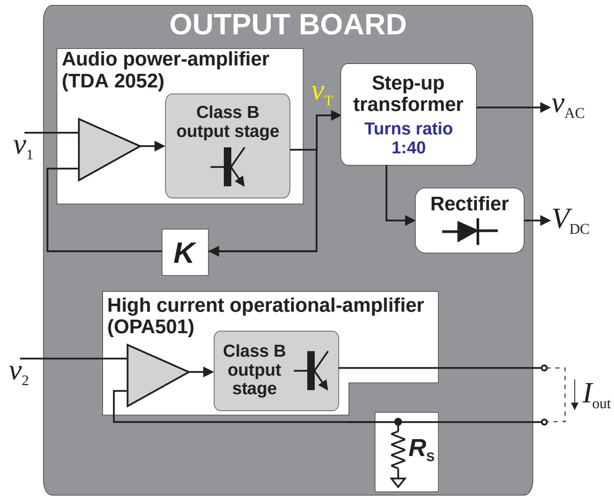

Fig. 3. Block scheme of the output board.

8. The traveling standard is eventually sent to the remote laboratory, where the possible transport effects on its metrological characteristics are estimated. If these effects are negligible, the calibration certificate of the monitoring system is issued.

TABLE II
EXAMPLE OF REPEATABILITY RESULTS.

Quantity	Average value (V)	Standard deviation (mV)
DC voltage	124.918	10
	246.350	15
	368.886	25
AC voltage ($f = 50$ Hz)	229.596	10

IV. Experimental results

The experimental results refer to functional tests of the calibrator and to its preliminary metrological characterization.

The calibrator capabilities and the effectiveness of the proposed solution have been verified. The master-slave application over the network has been employed to set the calibrator, which is able to generate DC voltages up to 480 V and AC voltages of 230 V_{rms} in the frequency range of 50 Hz to 2.5 kHz. The current channel provides DC current up to 8 A and AC current up to 6 A_{rms} for frequencies in the range of 50 Hz to 2.5 kHz.

A series of experimental tests have been performed in order to estimate the metrological specifications of the calibrator, such as thermal drift, repeatability, short-term and medium-term time drift, harmonic distortion of the AC output signals, and ripple of the DC voltage output.

The thermal drift has been estimated by placing the calibrator inside a climatic chamber and measuring output voltage and current in the temperature range of 18 °C to 28 °C. Results are shown in figure 4, where the output voltages of: control board (v_1), audio-amplifier (v_T) and transformer (v_{AC}) are drawn with respect to the temperature when the calibrator is set to generate an AC voltage of 230 V_{rms} at 50 Hz. In this case, the thermal drift was less than 0.02 %/°C as expected; similar results were also obtained for the DC voltage output and for the current output.

The repeatability of the calibrator outputs has been estimated by acquiring a series of multiple readings in a time interval of about one hour in steady conditions for the main influence quantities (temperature and power supply). Table II summarizes the results for DC and AC voltage outputs: the standard deviations show that the noise-related uncertainty contribution is negligible, since its effect is lower than 0.01 % of the output. During the observation period, the acquired readings did not show any significant drift. Another example is reported in Figure 5, which shows 2000 readings of the AC current output: in this case, a periodic fluctuation of the readings due to temperature fluctuation of about 3 °C is responsible for a relative standard deviation of about 0.015 %, which is larger than the ones obtained in the other tests.

The calibrator outputs have been monitored for a period of one month in order to estimate the time drift. During this period, the AC and DC voltage and current outputs have been recorded daily with the calibrator always powered and placed in an environment at controlled temperature and relative humidity ((23 ± 2) °C, (50 ± 15) %RH). The maximum drift has been obtained for the DC current output, with a change of about 3 mA for the 5 A current, which corresponds to an average drift of about 0.002 %/day.

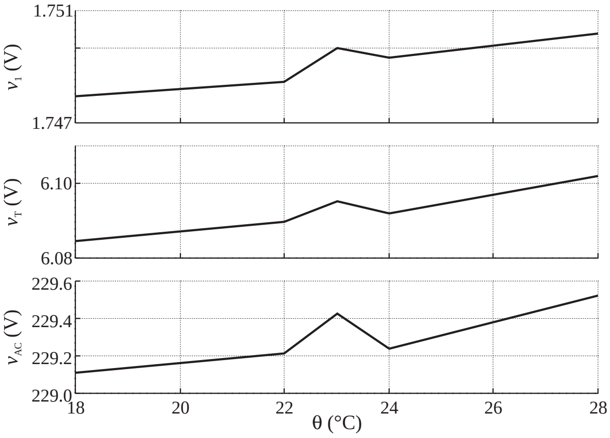

Fig. 4. Thermal drift of the AC voltage output in the temperature range of 18 °C to 28 °C. The figure shows the voltage outputs of: control board (v_1), audio amplifier (v_T) and output board (v_{AC}).

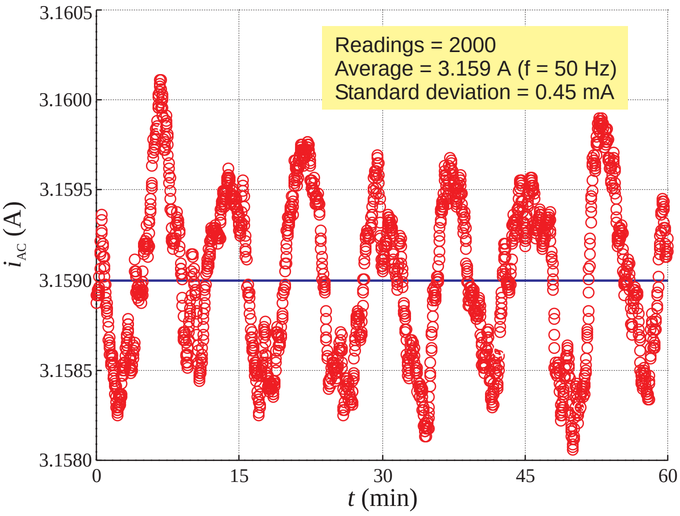

Fig. 5. Example of repeatability results: 2000 readings acquired at the AC current output of the calibrator.

These results allow a preliminary analysis of the calibrator behavior to be performed, providing useful information about the suitability of the calibrator as a standard for the system under calibration. The maximum uncertainty of the calibrator outputs is fixed to 0.25 % of the generated quantities, in order to obtain a Test Uncertainty Ratio of 4 with respect to the maximum uncertainty of the system under calibration (see Table I). In this situation, assuming a nominal calibration temperature of 23 °C, which corresponds to a temperature effect of ±0.1 % in the range of

18 °C to 28 °C, and taking into account the uncertainty contributions related to noise and time drift, the required uncertainty is ensured within a time interval of 2 months from the calibration.

Results are also available for the distortion of the AC voltage and current outputs and the ripple of the DC voltage output. For the distortion of the AC voltage output, the worst result corresponds to a fundamental frequency of 50 Hz, where a Total Harmonic Distortion (THD) of 1 % has been obtained in a bandwidth of 3.125 kHz, while a THD of 0.3 % for the fundamental frequency of 2.5 kHz in a bandwidth of 25 kHz has been obtained. The THD of the current output is always lower than 0.2 %. The ripple of the DC voltage output was about 0.2 % for an output voltage of 480 V.

V. Conclusions

In this paper, an in-situ calibration procedure is described for the metrological management of the monitoring system of a photovoltaic plant. The application of such a procedure has required the development of a multifunction calibrator, which is essentially a programmable generator of electrical signals and embeds standard sensors of temperature and irradiance. In addition, a remote master-slave application over the network has been developed that allows the calibration procedure to be automatically managed by a remote laboratory, thus minimizing both technician intervention and calibration time.

A prototype of the calibrator has been developed, which is based on a simple and low-cost architecture, and experimental tests have been performed in order to characterize its behavior from a metrological point of view. The results demonstrate that the device is suitable as a standard for the system under calibration, ensuring a TUR greater than four, over a calibration interval of two months. Authors are now working on a new prototype of calibrator with the aim of improving the time stability, so that a greater calibration interval can be used. Further experimental tests will be also planned to estimate the transport effects on the calibrator uncertainty, since this device has to be employed as a traveling standard.

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