

Calibration of Current-to-voltage Converters for Radiometric Applications at Picoampere Level

P. Sipilä¹, R. Rajala², P. Kärhä¹, A. Manninen², E. Ikonen^{1,2}

¹ Metrology Research Institute, Helsinki University of Technology (TKK), P.O.Box 3000, FI-02015 TKK, Finland

² Centre for Metrology and Accreditation (MIKES), P.O.B. 239, FI-00181 Helsinki, Finland

Abstract. A constant-voltage method for accurate calibration of current-to-voltage converters has been studied and implemented down to 1-pA level with expanded uncertainty ($k=2$) of 3800 ppm. The same method is implemented for the characterisation of standard resistors, which is crucial for the calibration itself. The goal of this work is to achieve accurate and traceable measurements for radiometric and photometric applications producing photocurrents at picoampere level.

Introduction

Filter radiometers are increasing their popularity in modern photometry and radiometry. At the Helsinki University of Technology (TKK) they have been successfully used in spectral irradiance, illuminance and radiation temperature measurements. One major limitation of extending the use of filter radiometers is the measurement of the photocurrent. Measuring spectral irradiance in the ultraviolet region or measuring relatively low temperatures results in photocurrents that are in the picoampere range. Current-to-voltage converters needed for the measurements rarely have a traceable calibration for currents smaller than 10 nA.

To reduce the uncertainties of ultraviolet and temperature measurements, TKK and MIKES (Centre for Metrology and Accreditation) have developed a calibration method for the picoampere range. At present we report progress on 0.1 fA resolution that allows us to measure photocurrents down to 1 pA with an uncertainty of 3800 ppm ($k=2$).

Constant-voltage method for current calibration

In the constant-voltage method for current calibrations a precise voltage, U , is applied over a precise resistor, R , and the current, I , determined by the classical Ohm's law, is measured. The schematic of the setup is presented in Figure 1. The accuracy of the method is determined in practice by the accuracy of the resistor and the stability of the current-to-voltage converter as accurate voltage generators are easy to obtain.

Active guarding is not needed, because the leakage current from the high voltage source is conducted to the ground lead and thus not measured by the current meter. In most cases, the input impedance of the current-to-voltage converter, the internal resistance of the voltage source and the lead resistances can be assumed to be small enough not to have a measurable effect on the results. On the other hand, the offset voltage of the current-to-voltage converter can be assumed to be small enough and the insulation resistance of

the high quality cables large enough that no leakage current occurs from the low potential of the resistor.

The main advantage of this method is its simplicity. However, with this method a trade-off for the accuracy has to be made as compared to methods based on capacitive components [1,2]. Also, there are difficulties with the use of resistive components, such as their long term stability and voltage dependence.

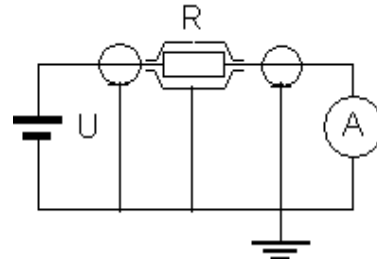


Figure 1. Schematic diagram of the current calibration setup based on the constant-voltage method. The applied voltage U over the resistor R generates a current which is measured with the current-to-voltage converter, A .

Characterisation of standard resistors

The importance of the characterisation of the standard resistor rises from the fact that the accuracy of these resistors dominates the uncertainty of the current calibration (if noise is not considered). The poor long term stability of the high ohmic resistors forces a frequent characterisation of the standard resistors to be part of the current calibration process itself.

The voltage dependence characterisation of the standard resistors was done with the same constant-voltage method as the current calibration itself. The current was measured with Keithley 6157 electrometer, the supply voltage source was Fluke 5440B/AF (max. output 1000 V) and the standard resistors were hermetically sealed five-part 9331S-series resistors from Measurement International Ltd. (from 10 G Ω to 100 T Ω). With this setup one could achieve precise currents between 1 pA and 100 nA.

The characterisation procedure for resistors from 10 G Ω to 100 T Ω was done in a ladder type sequence. In the characterisation process, first the electrometer's range used for characterising the 10 G Ω standard resistor was calibrated with a known calibrated standard resistor of 1 G Ω . The precise value of the 1 G Ω resistor was traceable to the reference value from the quantum Hall-effect. The main principle is that the current measured with the electrometer should be the same when 100 V over a 1 G Ω resistor and 1000 V over a 10 G Ω resistor is applied. Thus, the

correction factor for the current value, obtained from the known 1 G Ω resistor, is transferred to measurements of 10 G Ω resistor. Only one value for the correction factor of the current meter is rarely sufficient, because the current meter suffers from non-linearity and other non-idealities, and the correction factor for the current value does not remain the same throughout the range. Thus the correction factor is measured in multiple points from 20 V to 100 V with 1 G Ω resistor, which is transferred to measurements with 10 G Ω (corresponding to currents generated with voltages from 200 V to 1000 V, respectively). Both polarities should be measured and the results averaged to eliminate the effect of offsets. Without this a systematic error of 500 fA is measured in the worst case.

The biggest difficulty in the calibration is to distinguish which part of the deviation is due to the resistor and which is due to the current meter. This was solved so that first a model for the correction factor of the electrometer was extended down to the currents corresponding to 20 V applied voltage. Then respective currents were measured. A model for the voltage dependence of the resistor was formed from the measured values between 20 V to 1000 V with the correction factor. The modelling was based on the observation that the resistance was linearly dependent on the applied voltage. It is crucial that the electrometer's range-setting does not change during this procedure. One should repeat the resistance measurements from voltages 20 V to 100 V with range setting a decade lower and form a correction factor for this range (the range for characterising the next resistor). The procedure is then repeated with resistors up to 100 T Ω .

With the lowest calibrated current values the 1/f-noise becomes the limiting factor for the accuracy of the characterisation. The temperature drift component of 1/f-noise is minimised by using a temperature stabilised environment (23 °C \pm 0.025 °C) for the resistor and the meter. A 1/f noise value of 2 fA has been measured at current levels of 1 pA and 10 pA.

Calibration of current-to-voltage converters

For TKK's radiometric applications the two highest sensitivity ranges of Vinculum SP042-series current-to-voltage converter were calibrated with the constant-voltage method. The calibrated current range was from 1 pA to 100 pA. The largest possible voltage values were used to minimise the effect of the offset voltage. A method for eliminating the offset voltage by applying both voltage polarities and then averaging the results is not applicable as it also eliminates the offset current, which should exist in the calibration. The error effects of the input resistance of the current-to-voltage converter were neglected as the lowest standard resistor value used was 1 T Ω . The output of the current-to-voltage converter and its offset were measured with HP3458A multimeter with time span long enough for the current to settle and to minimise noise (except the 1/f-noise).

The reported 3800 ppm uncertainty of the current calibration at 1 pA consists in practice of the 1/f noise and

the resistor value (Table 1). The resistor uncertainty at the two lowest current levels also consists mostly of the 1/f noise. The source of the 1/f-noise is in practice the current-to-voltage converter and, thus, its quality determines the noise level and the accuracy of the calibration. The reported 1300 ppm 1/f-noise was measured with the Keithley 6517 electrometer, but with the Vinculum SP042 the value was a decade higher leading to expanded uncertainty ($k=2$) of 1.5 %.

Other uncertainty components are close to insignificant as compared to these. One should also note the poor long term stability of the high-value resistor elements. A maximum of 1 % variation for the resistor element within 3000 hours in unstable temperature and non-hermetic conditions (5 - 35 °C and 45 - 85 % relative humidity) have been reported by the manufacturer (Japan Hydrazine Inc.). Thus the current calibration itself must be made within a month of the characterisation measurements of the resistors.

Table 1. Uncertainty budget of the current-to-voltage converter calibrations for the 100 pA, 10 pA and 1 pA -levels.

Uncertainty component	1 pA [ppm]	10 pA [ppm]	100 pA [ppm]
Voltage measurement	50	10	10
Resistor value	1350	190	70
1/f-noise	1300	130	13
Source voltage	10	10	10
Combined standard uncertainty	1900	230	75
Expanded uncertainty ($k=2$)	3800	460	150

Conclusions

A traceable calibration setup for currents was implemented based on the constant-voltage method. With this method one can achieve expanded uncertainty ($k=2$) of 3800 ppm at 1 pA-level, 480 ppm at 10 pA-level and 150 ppm at 100 pA-level (if high-quality current meter is used). Alternative methods should be sought if smaller currents than 1 pA need to be calibrated. The 1/f-noise and the uncertainty of the resistor value used in the calibration are the limiting factors for the accuracy. Due to the instability of the standard resistors, the characterisation of these is an inseparable part of the current calibration process itself.

References

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