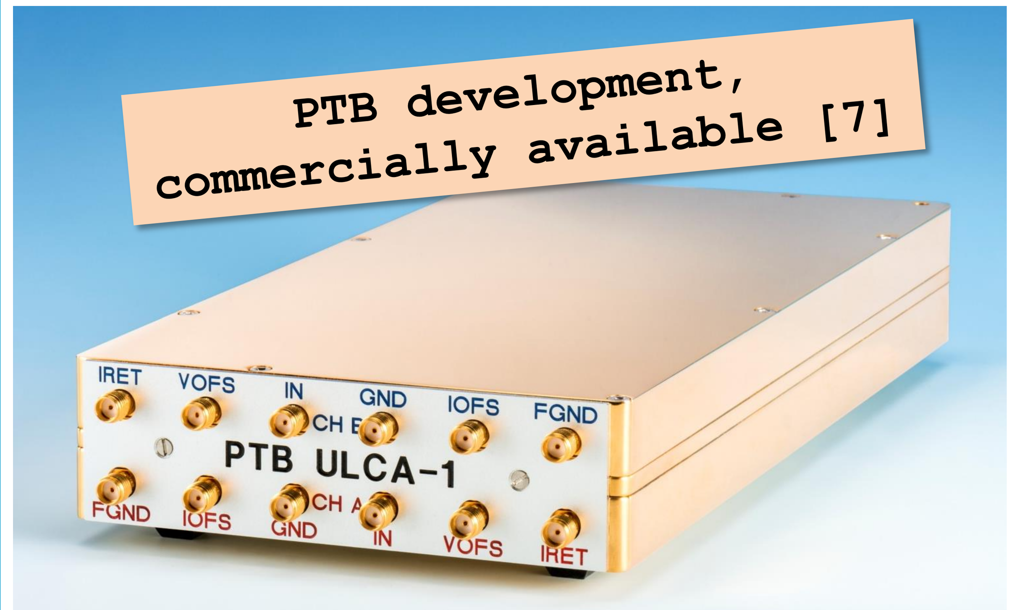
Abstract

We report on new calibration methods for picoammeters and low-current sources. The 'Ultrastable Low-noise Current Amplifier' (ULCA) was used for the calibration of commercial state-of-the-art ammeter and current source instruments for currents up to ±5 µA. The performance is compared with results obtained from two other calibration methods for small direct currents. It is shown that the ULCA as calibrator excels alternative techniques in terms of calibration accuracy, high flexibility and easiness of operation.

The ULCA as small-current calibrator



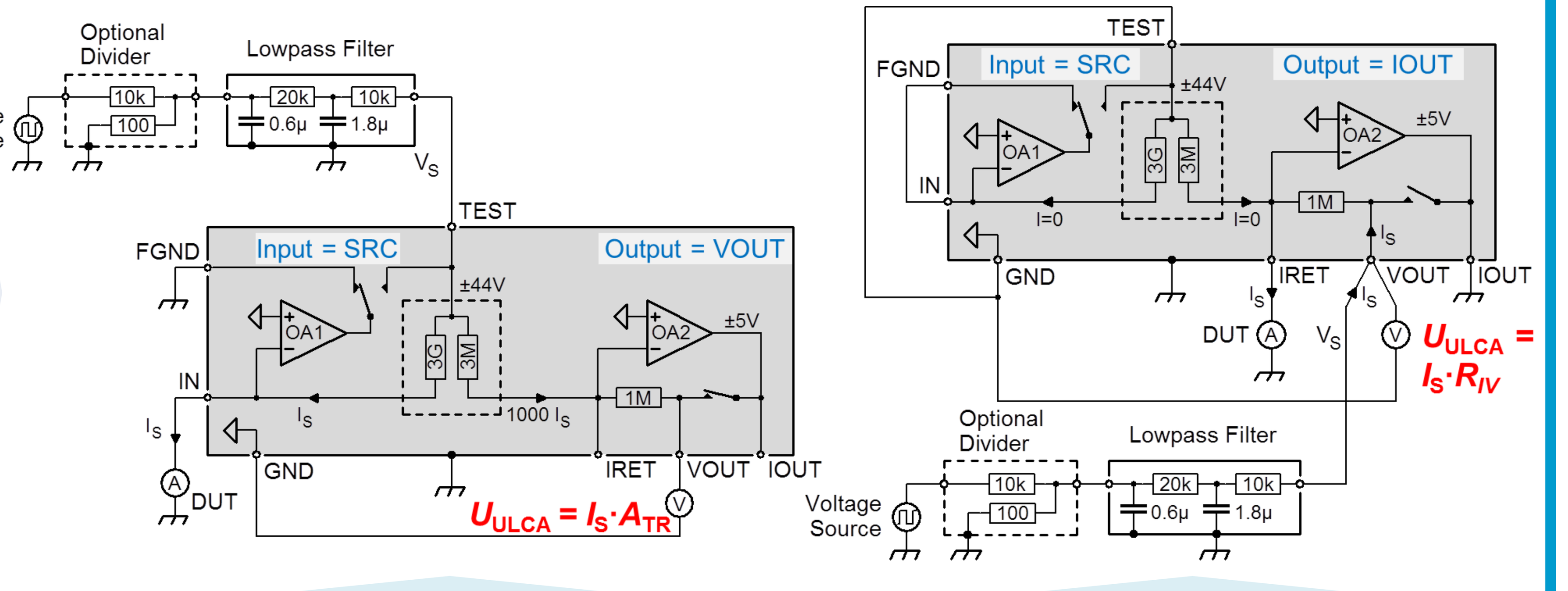
ULCA ('standard' version) key specifications	
Effective transresistance A_{TR}	1 GΩ (1000 × 1 MΩ)
Temperature coefficient of A_{TR}	0.2 ppm/K typical
Long-term stability of A_{TR}	drift < 5 ppm/year
Fluctuations of A_{TR} in 1 week	0.1 ppm typical
Input current range	±5 nA
Input impedance	< 1 Ω
Effective input noise	2.4 fA/√Hz (f < 1 Hz)
$1/f$-noise corner	< 1 mHz

The 'standard' version of the ULCA is a transresistance amplifier with a 3 GΩ/3 MΩ thin-film resistor network (1st amplifier stage) providing 1000-fold current amplification, and a metal foil resistor (2nd stage) with R_{IV} = 1 MΩ for current-to-voltage conversion [1]. The ULCA temperature is monitored by an internal sensor to enable corrections of temperature effects for applications requiring ultimate accuracy. Calibrations of A_{TR} and R_{IV} are performed with PTB's 14-bit cryogenic current comparator with uncertainties < 0.05 µΩ/Ω [2]. The ULCA has proven to be a powerful tool for the highly accurate traceable measurement and generation of small electrical currents [1]–[4].

Calibration setups & ULCA configurations

ULCA calibrating pico-ammeters

Combined with a voltage source the ULCA is used as calibrator current source.

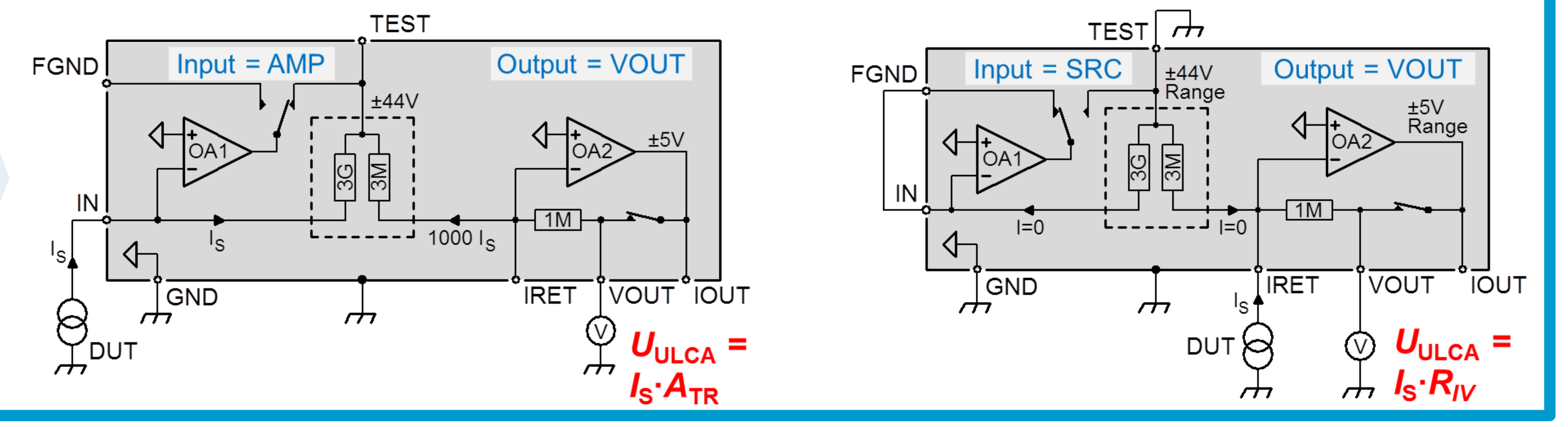


I ≤ 5 nA
ULCA in 'normal mode' using A_{TR} = 1 GΩ

5 nA ≤ I ≤ 5 µA
ULCA in 'extended mode' using R_{IV} = 1 MΩ

ULCA calibrating small-current sources

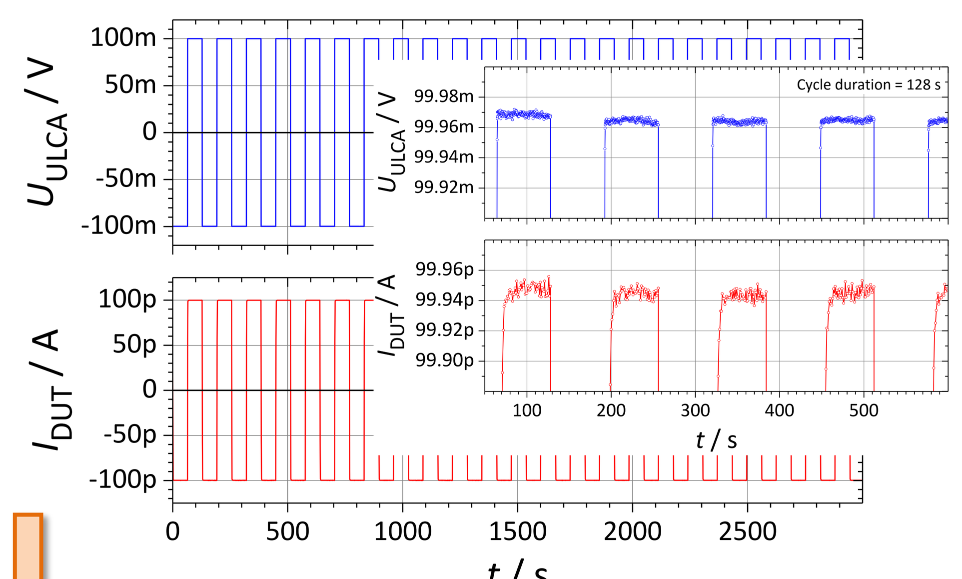
The ULCA is used as calibrator electrometer.



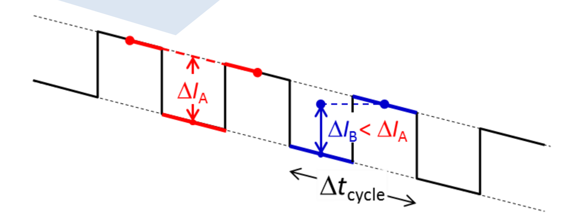
Calibration of a picoammeter (example)

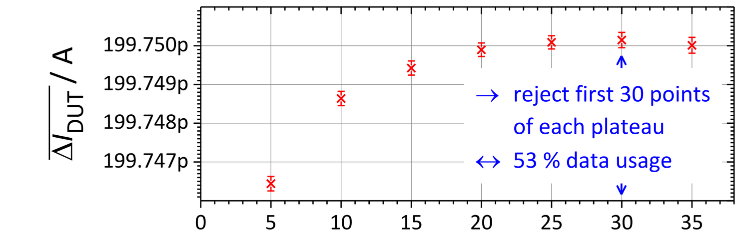
Device under test (DUT): Picoammeter type K6430

Raw data time traces:



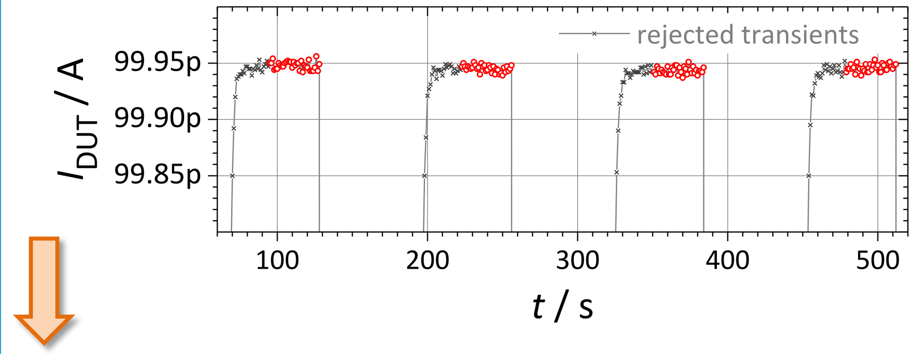
Triple-wise analysis of mean plateaux differences eliminates 'slow' drift and fluctuation effects



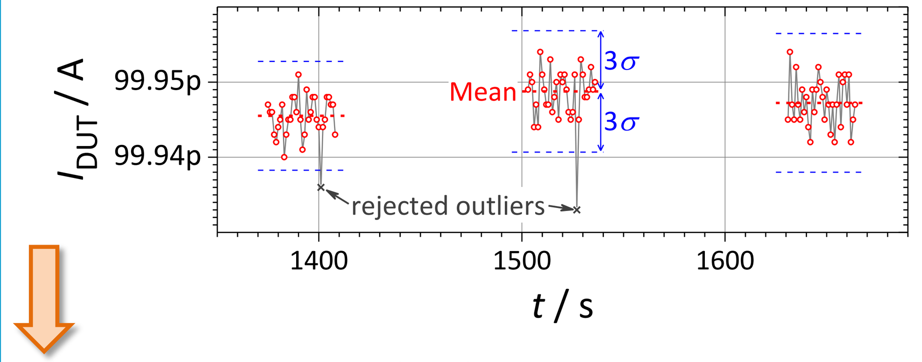


Determine # of transient points to be rejected (here: 30)

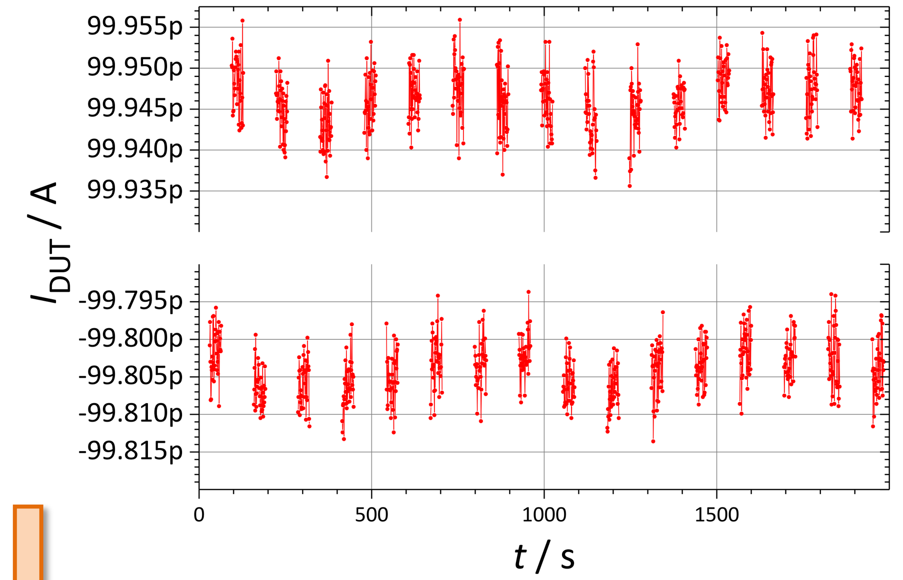
Remove transient points:



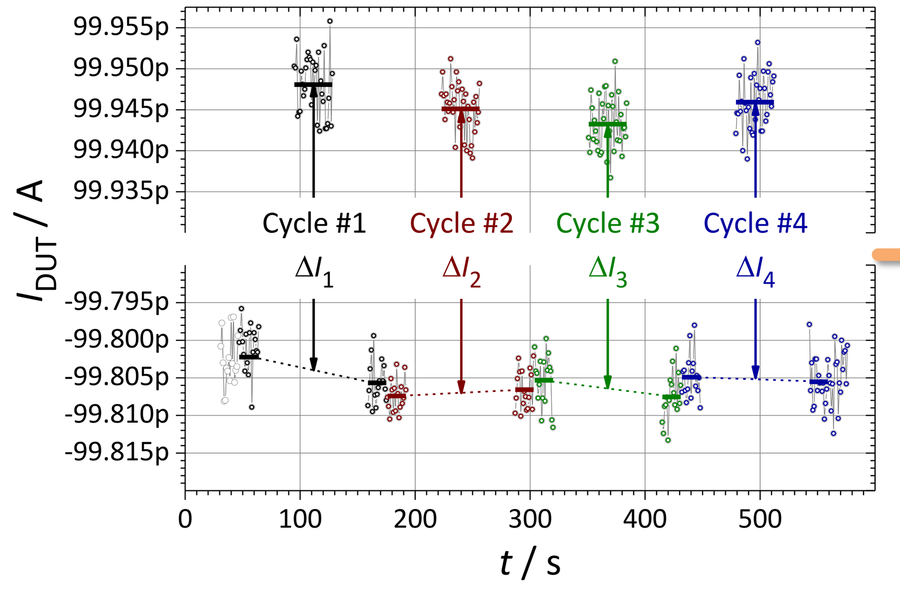
Remove outlier points:

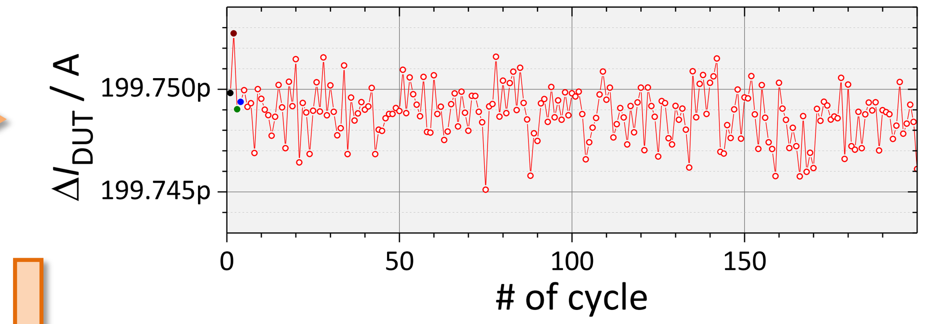


I_{DUT} plateaus data for further evaluation:

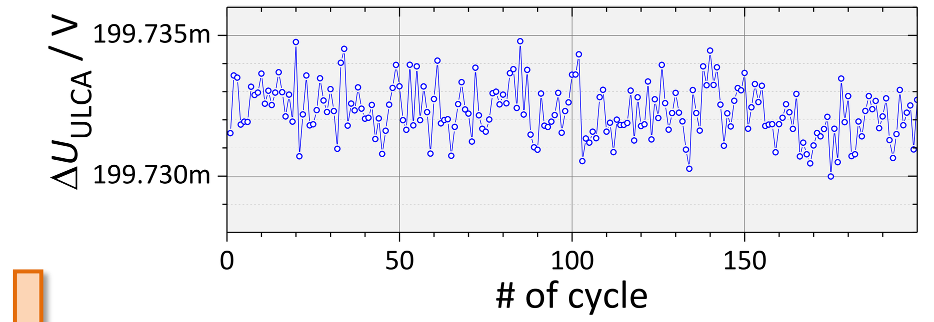


"Triple-wise" calculation of plateaux differences:

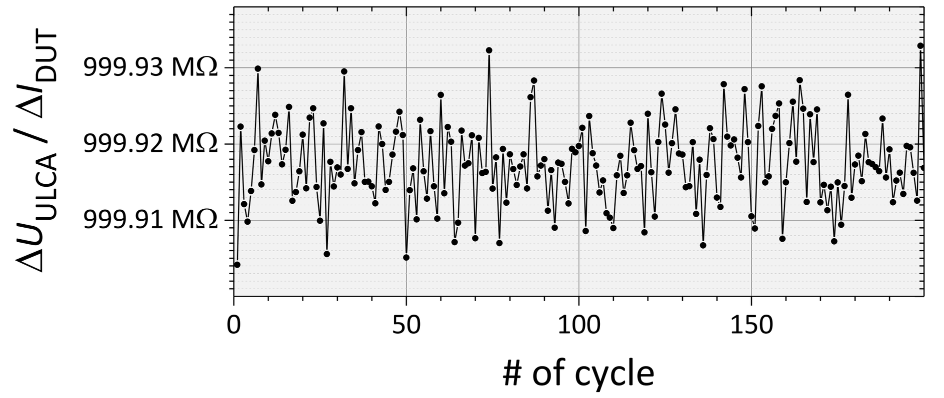




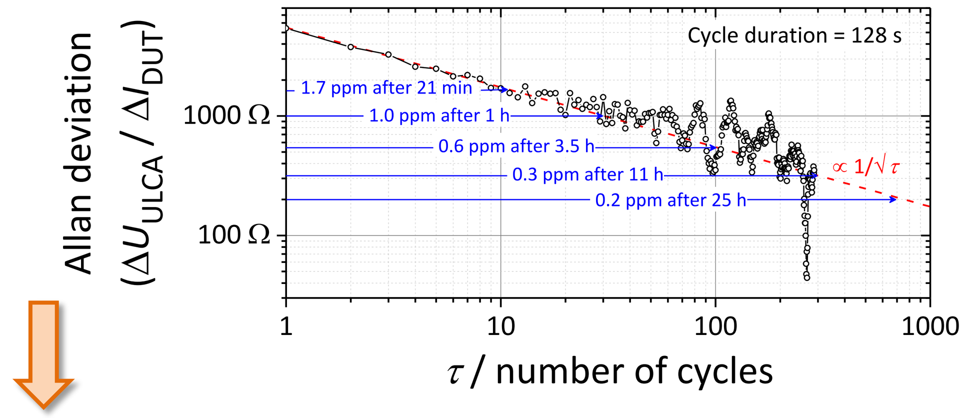
... and perform same analysis for U_{ULCA}:



Calculate $\Delta U_{ULCA}/\Delta I_{DUT}$ (point-wise):



... and its Allan deviation:



The ratio of A_{TR} and $\Delta U_{ULCA}/\Delta I_{DUT}$ yields the calibration factor $Q := I_{read}/I_{cal}$

$$= \Delta I_{DUT}/\Delta I_{ULCA} = \Delta I_{DUT}/(\Delta U_{ULCA}/A_{TR})$$

$$= A_{TR}/(\Delta U_{ULCA}/\Delta I_{DUT})$$

Uncertainty analysis

for DUT picoammeter type K6430 and voltmeter type 3458A

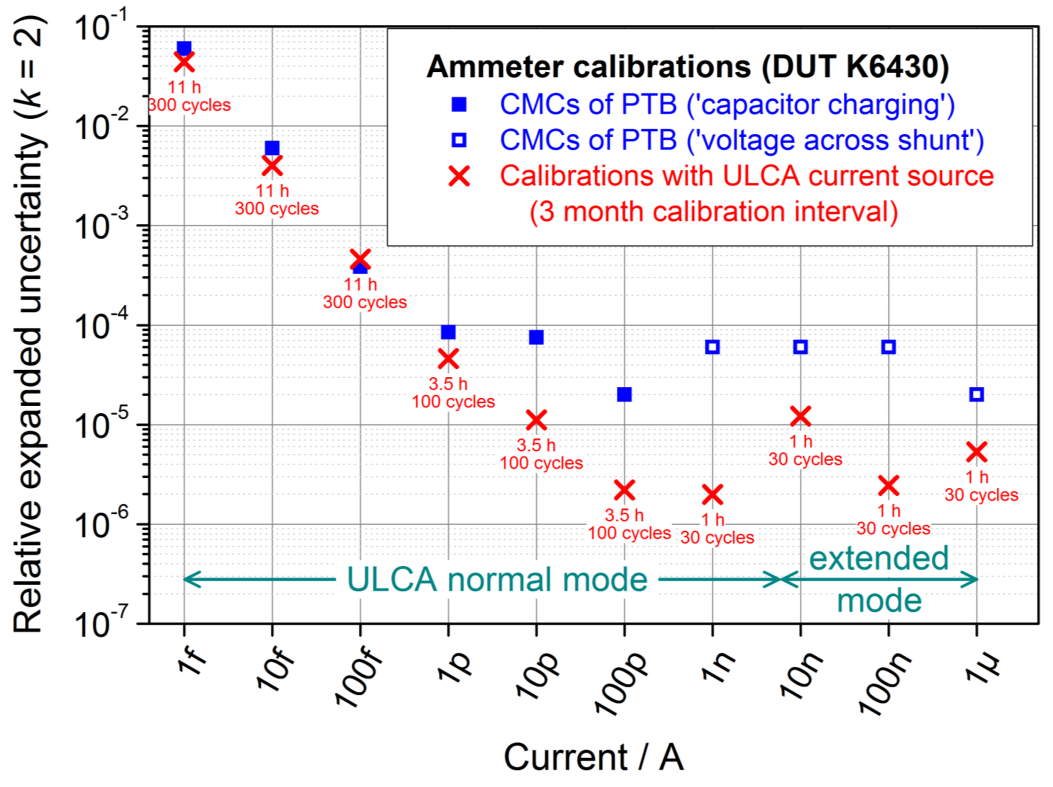
Type-A (k = 1)

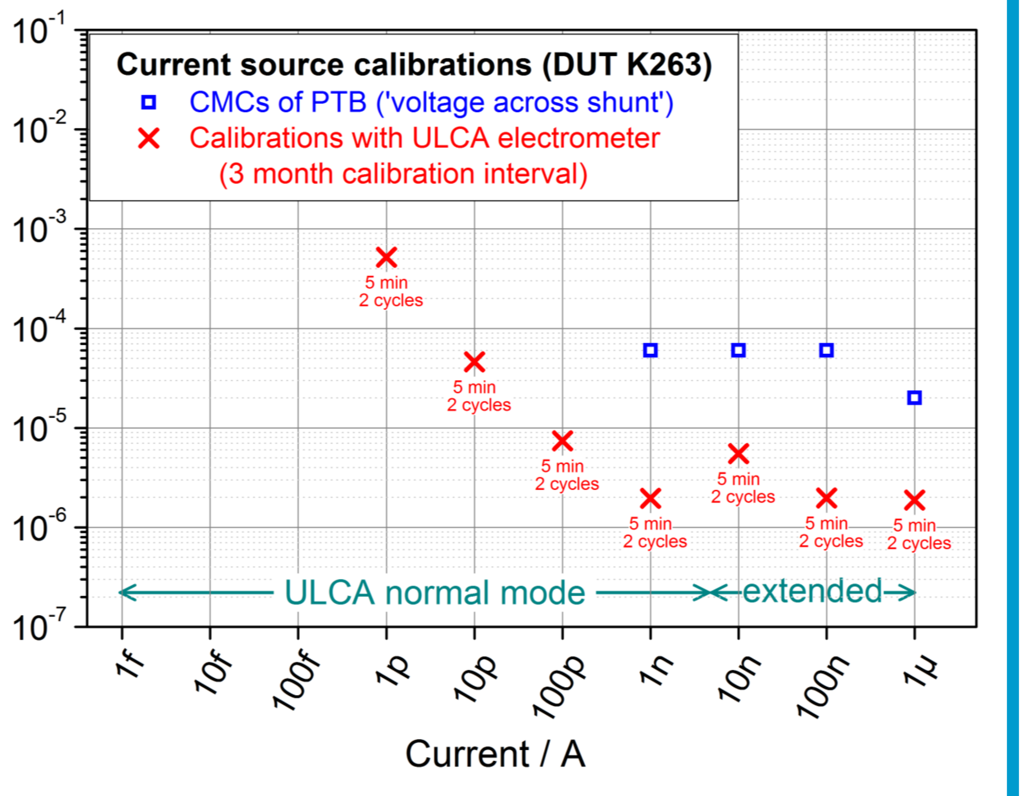
Calibration current	Picoammeter DUT range	ULCA mode	Type-A uncertainty vs. total measurement duration (number of cycles, each 128 s)		
Nominal value	Type K6430	Calibrator source	1 h (30 cycles)	3.5 h (100 cycles)	11 h (300 cycles)
± 1 fA	1 pA	normal	67 mA/A	37 mA/A	22 mA/A
± 10 fA	1 pA	normal	6.3 mA/A	3.5 mA/A	2.0 mA/A
± 100 fA	1 pA	normal	0.71 mA/A	0.40 mA/A	0.23 mA/A
± 1 pA	1 pA	normal	70 µA/A	40 µA/A	23 µA/A
± 10 pA	10 pA	normal	10 µA/A	5.5 µA/A	3.0 µA/A
± 100 pA	100 pA	normal	1.0 µA/A	0.6 µA/A	0.3 µA/A
± 1 nA	1 nA	normal	0.35 µA/A		
± 10 nA	10 nA	extended	6.0 µA/A	3.5 µA/A	2.0 µA/A
± 100 nA	100 nA	extended	0.8 µA/A	0.4 µA/A	0.25 µA/A
± 1 µA	1 µA	extended	2.5 µA/A	1.4 µA/A	0.8 µA/A

Type-B (k = 1)

	Component	Distribution	Comment	Type-B uncertainty 1 month (3 months) after cal.
Calibration of ULCA with PTB's 14-bit CCC	Noise	Normal	Sampling time $\tau \approx$ 1 h A_{TR}	0.01 µA/A
	SQUID nonlinearity	Rectangular	$\lvert\Delta\Phi\rvert < 0.5\ \mu\Phi_0$	0.008 µA/A
	CCC	Rectangular	Comparator incl. electronics	0.002 µA/A
Application of ULCA as calibrator	Settling	Rectangular	5 s wait after current reversal	0.008 µA/A
	Temperature	Rectangular	Temp. uncertainty < 0.1 K	0.002 µA/A
	Resistor nonlinearity	Rectangular	From PCR or VCR	0.01 µA/A
	Amplifier nonlinearity	Rectangular	Open-loop gain > 10^9	0.001 µA/A
	A_{TR} stability (long-term)	Rectangular	Upper limit 5 ppm/year	0.24 µA/A (0.72 µA/A)
	A_{TR} fluctuations (short-t.)	Rectangular	Within 1 week	0.06 µA/A
Other	Voltmeter gain calibration	Rectangular	3458A calibrated with Zener	0.06 µA/A
	Voltmeter gain stability	Rectangular	3458A w. 'high stability' opt.	0.19 µA/A (0.58 µA/A)
Total				**0.32 µA/A (0.93 µA/A)**

Results, conclusions & outlook





In summary, the ULCA provides several significant advantages compared with other calibration methods for electrometers and low-current sources:

i. calibration uncertainties can be reduced at moderate measurement times,
ii. only one calibrator instrument can replace at least two different setups for calibrations over nine decades of current, and
iii. calibration procedures are simplified by the ease in operation and handling offered by the ULCA.

Outlook: Besides the 'standard' version, further ULCA variants for special application purposes are currently under development [5, 6], for instance an instrument with further reduced input current noise level of only 1.2 fA/√Hz.

References

[1] D. Drung, C. Krause, U. Becker, H. Scherer, and F. J. Ahlers, *Rev. Sci. Instrum.* **86**, 024703 (2015)
[2] D. Drung, M. Götz, E. Pesel, and H. Scherer, *IEEE Trans. Instrum. Meas.* **64**, 3021-3030 (2015)
[3] D. Drung *et al.*, *Metrologia* **52**, 756-763 (2015)
[4] F. Stein *et al.*, *Appl. Phys. Lett.* **107**, 103501 (2015)
[5] D. Drung and C. Krause, CPEM 2016 Conference Digest (2016), oral session Mo-6 Current I
[6] C. Krause, H. Scherer, and D. Drung, CPEM 2016 Conference Digest (2016), poster session Tu-PS4 Current
[7] Magnicon GmbH, Barkhausenweg 11, 22339 Hamburg, Germany. http://www.magnicon.com/metrology/