Use of the BVD for traceability of bipolar DC voltage scale from 1 mV up to 1200 V

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Abstract: This paper presents overview of new extension of use of the Binary Voltage Divider (BVD) based on Cutkosky principle for fully automated maintenance of voltage scale at positive and also negative voltages at range from 1 mV to 1200V. Existing Automated Potentiometer systems based on BVD principle are regularly used for maintenance of traceability for voltage scale usually at positive direction only. Nevertheless, with increasing demand on high accuracy calibration of DC voltage ranges of high end multifunction calibrators was raised request to provide ability of fully automated measurement of voltages at both polarities at the same uncertainty level and using practically the same equipments. We made the investigation of hardware possibilities and limitations of existing equipments and after it we designed necessary changes at hardware, firmware and also necessary extension of external software to make these fully automated measurements possible. In order to demonstrate proper function and necessary metrology characteristics of selected solution, all self-characterization procedures and standardization procedures were made at both polarities and results were compared. The extensive series of experiments and measurements were made together with the DC voltage laboratory of Czech Metrology Institute and their results showing good agreement with expected metrology characteristics are summarized at this paper.

Keywords: Cutkosky, Binary Voltage Divider, Positive and Negative Polarity, Associated Uncertainties

1. Introduction, Potentiometric voltage measurement method

The Potentiometric or Compensation method of voltage measurement was at past used namely for most demanding, most accurate and most sensitive measurement of voltage cells or voltage references. Main advantage of this method is measurement of the voltage with virtually no current taken from the voltage source being measured. For long time potentiometers were used mainly at the primary voltage labs and their applications were fairly limited to comparison of voltage references and building the positive voltage scale at range from mV up to about 1 kV (usually using also additional voltage divider together with the potentiometer). The automation of the potentiometer operation made the measurement easier, but still did not encouraged users to consider some other possible use of potentiometers for a long time.

1.1 New applications for potentiometers

It seemed that the long scale DVM's were much easier to be used for voltage measurement at calibration labs. Nevertheless the need to maintain the accuracy of the high level voltage calibrators required proper calibration of these long scales DVM's which turned the attention to the automated potentiometers, as they represent a way to achieve this required accuracy. This new application seems to suit well to the potentiometer systems, but quite soon brought up the issue of measurement of the voltages at both positive and negative polarities, as there are voltages of both polarities available at the output of calibrators. The same requirement represents also second new application of the potentiometers, which is the verification of the linearity of the long scale DVM's, where the exact voltage at the output of the voltage calibrator is determined by BVD potentiometer system and at the same time measured by the tested DVM. This was earlier achievable mainly for the laboratories, that are using JVS voltage standard, but the potentiometer system seems to offer accuracy required for this task too.

It is possible to find automated potentiometers at many laboratories. Usually it is model 8000A from Measurements International, designed according to the Cutkosky principle [1], [2] which offers suitable linearity and resolution needed for the above mentioned tasks. Unfortunately they were not set for the bipolar measurements, although it turned out that their hardware was designed for it.

2. Existing BVD system modifications

Requirements to make fully automated calibration of the DC voltage ranges of multifunction calibrators at the laboratory of Czech Metrology Institute and their experience with use of the 8000A and 8001A system for building the DC voltage scale were triggering points to the effort that resulted at fully automated bipolar voltage measurement capability being presented at this article. It is probably necessary to mention here that the 8000A Automated Potentiometer and the 8001A Extender are parts of the complete automated BVD Potentiometric measurement system. They cannot work in manual mode, but the measurement is fully controlled from external software, which makes necessary switching of both dividers and handles readings from the long scale DVM or nanovoltmeter, which is used as the null detector (see figure 1).

2.1 Hardware features and necessary modifications

First task on the way to automated bipolar measurements was analysis of hardware circuits of the BVD potentiometer in order to understand fully its operation and find out if the bipolar measurement would be achievable. It turned out that the 8000A has already built in the necessary relays allowing reversing the source voltage that is divided by the binary voltage divider, which is the simplest way of allowing the measurement of unknown voltages not only at positive polarity, but also at negative polarity. It is evident that the bipolar measurement was on mind of the designers at very beginning of the BVD potentiometer construction, but for some reasons it was never put to use. Some 8000A units may require adding the connections allowing proper control of these reversing relays. Principal schematic of the BVD modified for bipolar measurements is at figure 2.

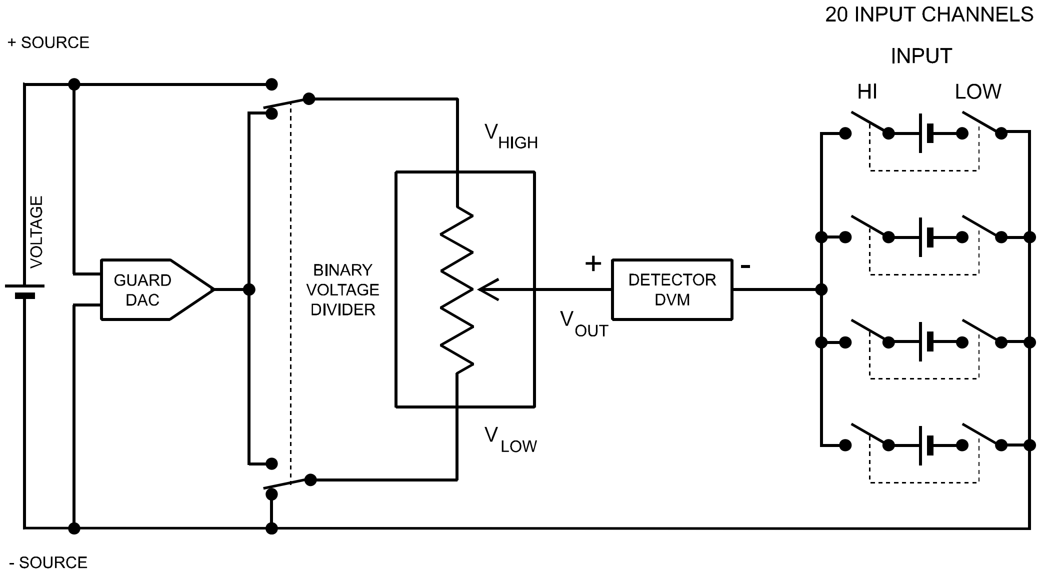


Figure 1. 8000A Functional Drawing.

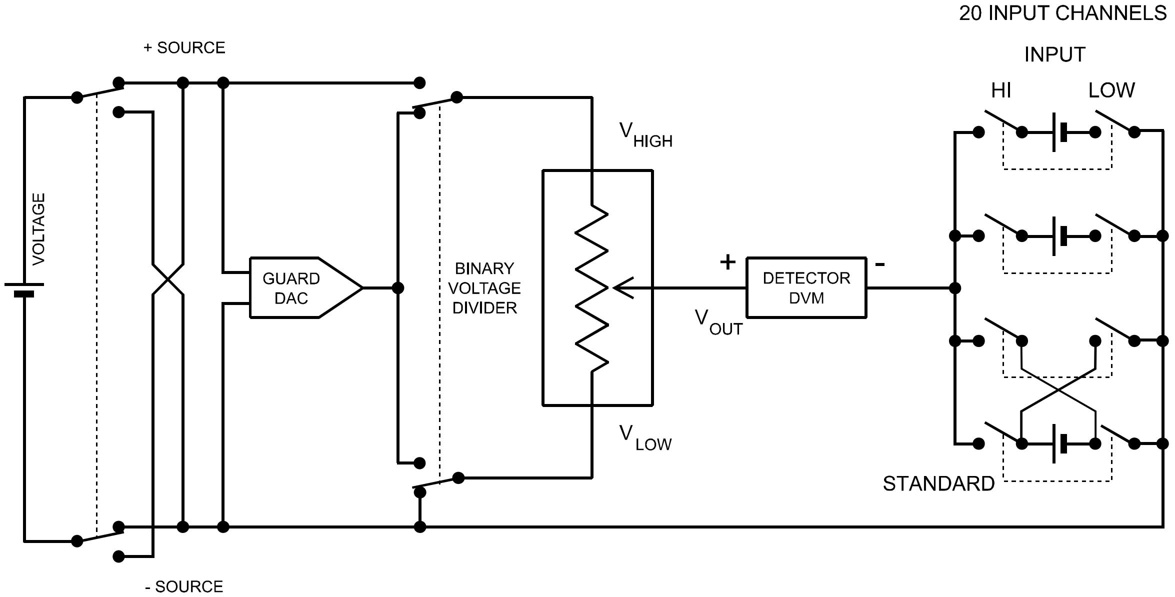


Figure 2. 8000A Functional Drawing with bipolar measurement enabled.

2.2 Firmware modifications

Next serious task was analysis of the firmware and its modification in order to make full use of the reversing relays and achieving their safe operation. The firmware was modified such a way that it allows to set positive polarity of the source, negative polarity of the source, to disconnect the source from the divider and to short the divider input, but it prevents to short the source even by mistake of sending the wrong series of the commands to the potentiometer.

2.3 Software modifications

Whenever the modifications of the 8000A hardware and firmware were finished, it was necessary to substantially modify also the 8000A software to make the bipolar measurements really work. These modifications of the software represented proper handling of the negative input voltages and proper setup of the reference source for negative measurement. Although theoretically the BVD shall be independent on the polarity of the source, real measuring system is burdened by cable offsets, leakage currents etc. Therefore the modification also represented adding calibration of the negative part of the BVD correction coefficients and the same for source standardization. Using of the crossed channels at the scanner for bipolar source standardization has been added for fully automated operation utilizing one reference standard only (see figure 2).

2.3.1 Software validation help

One of the important issues at the process of the accreditation of the laboratories and the method they use is validation of the software. Keeping this fact in mind, the special feature was built in the 8000A modified software. It allows running the SW at demonstration mode, but instead of use of the random numbers as the inputs for calculations of simulated results, it uses real data from files, that were captured at real measurements. These data can be then processed and evaluated externally and results compared with the results presented by software, which is one of the most efficient ways of evaluating and verifying its correct operation.

2.3.2 Measurement results and the uncertainty of measurements calculations

It is necessary to understand that in contrary to the simple, one box equipment, the potentiometer and its measurement principle represent actually fairly complex measurement system evaluating the measured unknown voltage on base of series of indirect measurement that all at the end contribute to the uncertainty of the result. The decision was made from very beginning that overall uncertainty evaluation of the measured voltage, which is presented by 8000A software shall be strictly following the GUM [3] rules. The only workable way turned to be use of the partial results of each related measurement including their degrees of freedom, or effective degrees of freedom (in case of complex partial results obtained as combinations of other partial measurement results). All these information are considered at the final voltage uncertainty result and its effective degrees of freedom determination, needed to obtain properly calculated expanded uncertainty of the measured voltage. Every calibration of the divider is accomplished by 660 readings of null detector, which represents 138 quantities. Typical measurement of a source under test is based on 210 readings of null detector, which represents 30 quantities. Thus the software calculates with about 200 of quantities to obtain one value of voltage and with almost 400 of individual uncertainties and degrees of freedom to obtain one value of expanded uncertainty.

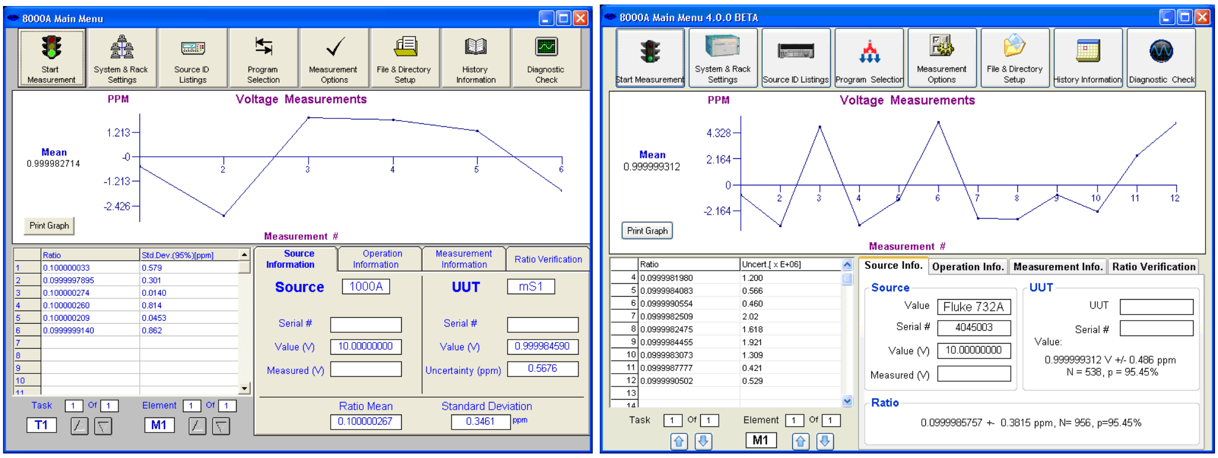
2.3.2.1 Old software

The old version of the 8000A software processes the calculations and the uncertainty of measurements determination a bit different way than the GUM methods suggest. The expanded uncertainty of each sub-process was determined (for calibration of each correction factor for the 13 stages of the divider; standardisation of the source; 8001A extender correction factors calibration; as well as the device under test (DUT) voltage measurements). These results were used at subsequent processes till the final expanded uncertainty of DUT voltage was obtained. Some of the calculations were based on the weighted averages, where the weights were set according the uncertainties of individual components being averaged.

2.3.2.2 New software

The new SW for bipolar measurements uses simple averaging, so the calculations needed to be changed accordingly and use the degrees of freedom or effective degrees of freedom, what shall result at proper and easier verifiable results of calculation of expanded uncertainty of measurements. Determination and in-depth uncertainty analysis was checked and verified using special software GUM Workbench Pro [4], allowing to make the decision of what sources of uncertainty are necessary to be used for calculation, and what may be considered negligible. It also helps to verify that the calculations programmed at the 8000A software are made correctly. Typical example of the results from the analysis for individual parts of the 8000A SW is presented below.

Screenshots of old and new software are shown in figures 3 and 4.



Mean 0.999982714

	Ratio	Std.Dev.(95%)[ppm]
1	0.100000033	0.579
2	0.0999997895	0.301
3	0.100000274	0.0140
4	0.100000260	0.814
5	0.100000209	0.0453
6	0.0999999140	0.862
7		
8		
9		
10		

Task 1 Of 1 Element 1 Of 1

Source 1000A
Serial #
Value (V) 10.00000000
Measured (V)

UUT mS1
Serial #
Value (V) 0.999984590
Uncertainty (ppm) 0.5676

Ratio Mean 0.100000267
Standard Deviation 0.3461 ppm

Mean 0.999999312

	Ratio	Uncert.[x E+06]
4	0.0999981980	1.200
5	0.0999984083	0.566
6	0.0999990554	0.460
7	0.0999982509	2.02
8	0.0999982475	1.618
9	0.0999984455	1.921
10	0.0999983073	1.309
11	0.0999987777	0.421
12	0.0999990502	0.529
13		

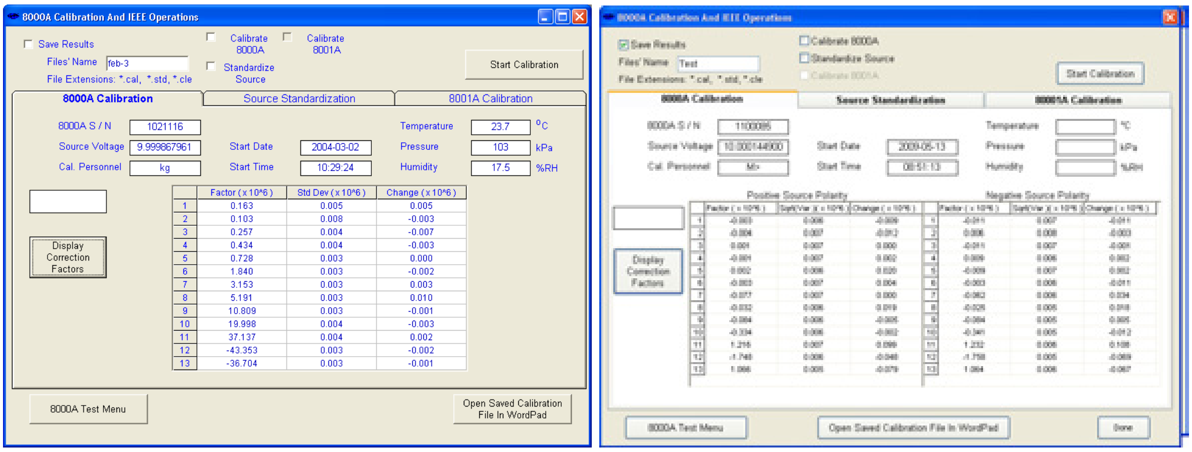
Task 1 Of 1 Element 1 Of 1

Source
Value Fluke 732A
Serial # 4045003
Value (V) 10.00000000
Measured (V)

UUT
UUT
Serial #
Value:
0.999999312 V +/- 0.486 ppm
N = 538, p = 95.45%

Ratio
0.0999985757 +- 0.3815 ppm, N= 956, p=95.45%

Figure 3. Screenshot from the old (left) and new (right) version of MI8000A software. Main measurement screen is shown. In new version, results are reported with expanded uncertainty and level of confidence. Also negative value was measured.



☐ Save Results

Files' Name: feb-3

File Extensions: *.cal, *.std, *.cle

☐ Calibrate 8000A ☐ Calibrate 8001A

☐ Standardize Source

8000A S / N: 1021116

Source Voltage: 9.999867961

Cal. Personnel: kg

Start Date: 2004-03-02

Start Time: 10:29:24

Temperature: 23.7 °C

Pressure: 103 kPa

Humidity: 17.5 %RH

	Factor (x 10^6)	Std Dev (x 10^6)	Change (x 10^6)
1	0.163	0.005	0.005
2	0.103	0.008	-0.003
3	0.257	0.004	-0.007
4	0.434	0.004	-0.003
5	0.728	0.003	0.000
6	1.840	0.003	-0.002
7	3.153	0.003	0.003
8	5.191	0.003	0.010
9	10.809	0.003	-0.001
10	19.998	0.004	-0.003
11	37.137	0.004	0.002
12	-43.353	0.003	-0.002
13	-36.704	0.003	-0.001

Figure 4. Screenshot from the old (left) and new (right) version of MI8000A software. Calibration of divider and its coefficients is shown. Every line of table contains calibration coefficient of one stage of the divider together with standard deviation (old version) or standard uncertainty (new version). Calibration of the divider at negative voltages is possible in new version.

3. Voltage measurements and sources of uncertainties

Basic equation is presented to demonstrate problems and complexity of calculations of measured voltage. During every measurement, nominal ratio of the divider P_i is automatically determined and set and a difference between measured voltage and divided source voltage V_d is measured. Whereon the divider is switched off and an offset voltage V_o of the null detector is measured. Therefore manual adjusting of the zero of the null detector is not necessary. The ratio is calculated, and the measured voltage is product of ratio and standardized voltage:

$$V = \overline{P_\mathrm{r}} \cdot V_\mathrm{std} = \overline{V_\mathrm{gnd}} + \frac{\sum_i \left(P_i \cdot V_\mathrm{std} - V_{\mathrm{res}\,i}\right)}{N}$$

$$u^2(V) = u^2\left(\overline{V_\mathrm{gnd}}\right) + \left(\frac{\sum_i P_i}{N}\right)^2 u^2(V_\mathrm{std}) + \left(\frac{V_\mathrm{std}}{N}\right)^2 \sum_i \left(u^2(P_i)\right) + \left(\frac{1}{N}\right)^2 \sum_i \left(u^2(V_{\mathrm{res}\,i})\right)$$

$$\begin{aligned}\nu_\mathrm{eff}(V) = u^4(V) \cdot \Bigg[& \frac{u^4\left(\overline{V_\mathrm{gnd}}\right)}{\nu_\mathrm{eff}\left(\overline{V_\mathrm{gnd}}\right)} + \left(\frac{\sum_i P_i}{N}\right)^4 \frac{u^4(V_\mathrm{std})}{\nu_\mathrm{eff}(V_\mathrm{std})} \\ & + \left(\frac{V_\mathrm{std}}{N}\right)^4 \left(\sum_i \frac{u^4(P_i)}{\nu_\mathrm{eff}(P_i)}\right) + \left(\frac{1}{N}\right)^4 \left(\sum_i \frac{u^4(V_{\mathrm{res}\,i})}{\nu_\mathrm{eff}(V_{\mathrm{res}\,i})}\right) \Bigg]^{-1}\end{aligned}$$

where $V_\mathrm{res} = V_\mathrm{d} - V_\mathrm{o}$, V_std is standardized voltage of the source, V_g is offset of the whole divider, N is the number of measurements, $u(X)$ is uncertainty of value X, $\nu_\mathrm{eff}(X)$ is effective degree of freedom of value X. The measurement and setting of the divider is repeated several times. Type A uncertainty of every measured voltage is calculated together with degree of freedom. Nominal ratio is determined by the binary state of the divider and a set of correction factors measured during calibration of the divider. Standardized voltage and zero offset of the divider are measured during calibration.

To be exact, equations used to calculate P_i, V_{std} and V_{g} during calibration of the divider should be substituted into the above equation to calculate final uncertainty of voltage V. Otherwise, some uncertainties are multiply counted in, because e.g. P_i and V_{std} are functions of some common measured values. However, such equation would be extremely complex, and algebra computing system would be needed to determine correct uncertainty every time. Hence calculation was simplified. Nominal ratio, standardized voltage and zero offset enters the above equation as type B uncertainties.

Typical uncertainty budget of measurement of 1 V source is shown in table 1. The measurement together with setting of the divider was repeated 10 times, every voltage was measured 10 times. Total time of measurement was 10 minutes. Final voltage is the mean of all measurements.

4. Bipolar voltage measurements – verification of the operation

Whenever these changes were made and the system was able to do bipolar measurements, the testing started in order to prove the proper operation and also to get appropriate handling of the uncertainty of measurements.

4.1 Model testing using GUM Workbench

The proper operation of the system was tested at several measurements. First test was done by comparing of results with the software GUM Workbench. This software was validated by Danish Technological Institute. Measurement of source voltage of nominal voltage 1 V was chosen. The final result measured and calculated by new MI8000A software was $0.999999522 \pm 0.450 \bullet 10^{-6}$ at level of confidence 95.45% and degrees of freedom 60. Equations of the calibration, standardization and measurement were entered into the software together with values measured directly by the null detector and captured during measurement. Final values and uncertainties were calculated by GUM Workbench and compared to the MI8000A software. Due to the simplification of calculations, values of uncertainties in the MI8000A software were exaggerated by less than 10%.

Table 1. Typical uncertainty budget of measurement of stable 1 V source at 8000A divider. Uncertainty of the resulted voltage V is at level of confidence 95.45% of Student's t-distribution. ν_{eff} is effective degree of freedom.

Quantity	Value	Standard Uncertainty	ν_{eff}
V_{res_1}	$-230.677 \cdot 10^{-6}$	$60 \cdot 10^{-9}$	14
V_{res_2}	$-230.840 \cdot 10^{-6}$	$39 \cdot 10^{-9}$	17
V_{res_3}	$-230.727 \cdot 10^{-6}$	$487 \cdot 10^{-9}$	15
V_{res_4}	$-230.931 \cdot 10^{-6}$	$45 \cdot 10^{-9}$	13
V_{res_5}	$-230.935 \cdot 10^{-6}$	$67 \cdot 10^{-9}$	15
V_{res_6}	$-231.028 \cdot 10^{-6}$	$34 \cdot 10^{-9}$	16

V_{res_7}	$-230.850 \cdot 10^{-6}$	$64 \cdot 10^{-9}$	10
V_{res_8}	$-230.922 \cdot 10^{-6}$	$43 \cdot 10^{-9}$	17
V_{res_9}	$-230.874 \cdot 10^{-6}$	$47 \cdot 10^{-9}$	16
$V_{\mathrm{res}_{10}}$	$-230.842 \cdot 10^{-6}$	$48 \cdot 10^{-9}$	17
V_g	$3.6715 \cdot 10^{-6}$	$1.9 \cdot 10^{-9}$	64
V_{std}	10.0001339	$2.0 \cdot 10^{-6}$	50
P_1	0.0999752	$16 \cdot 10^{-9}$	180
P_2	0.0999752	$16 \cdot 10^{-9}$	180
P_3	0.0999752	$16 \cdot 10^{-9}$	180
P_4	0.0999752	$16 \cdot 10^{-9}$	180
P_5	0.0999752	$16 \cdot 10^{-9}$	180
P_6	0.0999752	$16 \cdot 10^{-9}$	180
P_7	0.0999752	$16 \cdot 10^{-9}$	180
P_8	0.0999752	$16 \cdot 10^{-9}$	180
P_9	0.0999752	$16 \cdot 10^{-9}$	180
P_{10}	0.0999752	$16 \cdot 10^{-9}$	180
V	0.999999522	$410 \cdot 10^{-9}$ (95.45%)	56

The distribution function of the final voltage for typical measurement was also calculated in GUM Workbench by means of Monte Carlo Method. The result is in the figure 5. The distribution function was very close to Student's t-distribution. Calculated mean value of the voltage and expanded uncertainty was the same as calculated by Bayesian method. Number of Monte Carlo Trials was 10^7.

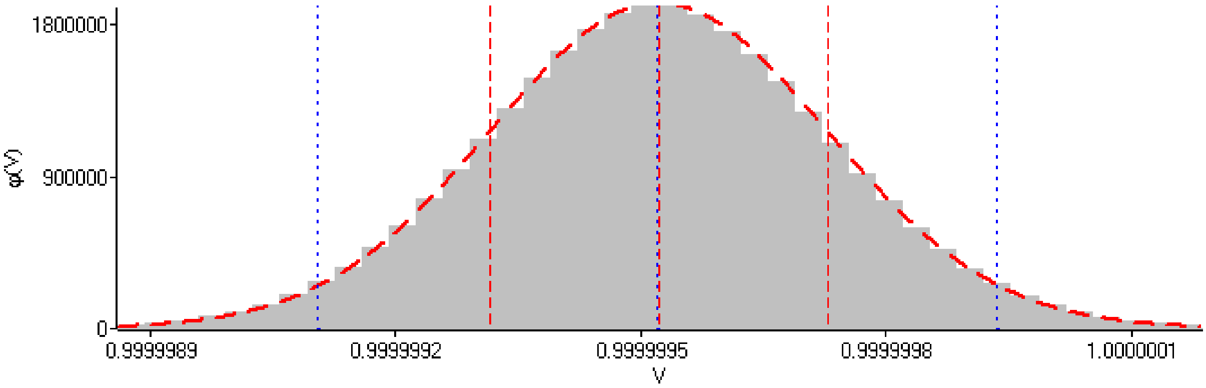


Figure 5. Distribution function of final voltage calculated by GUM Workbench. Grey area presents histogram of distribution function of parameters: mean value: 0.999999522; expanded uncertainty interval at level of confidence p=0.95: $\pm 4.1 \cdot 10^{-7}$; number of Monte Carlo trials: 10^7.

Red dash line presents corresponding Student's t-distribution function for the same mean value as histogram and for 56 degrees of freedom.

4.2 Ratio verification factor

Second test was measurement of so called Ratio verification factor (see figure 6). The voltage of the source was divided by two stable resistors R_1 and R_2, and the ratio P_A between the source voltage and divided voltage was measured. Afterwards, resistors were swapped and ratio P_B was measured. Because of the swapping of resistors and by definition sum of ratios must be equal to 1:

$$P_A + P_B = 1$$

Ratios are not ideal thus the ratio verification factor e is defined as the average error of two ratios:

$$(P_A + e) + (P_B + e) = 1$$

$$e = -\frac{P_A + P_B - 1}{2}$$

Ideally, the verification factor e should be zero.

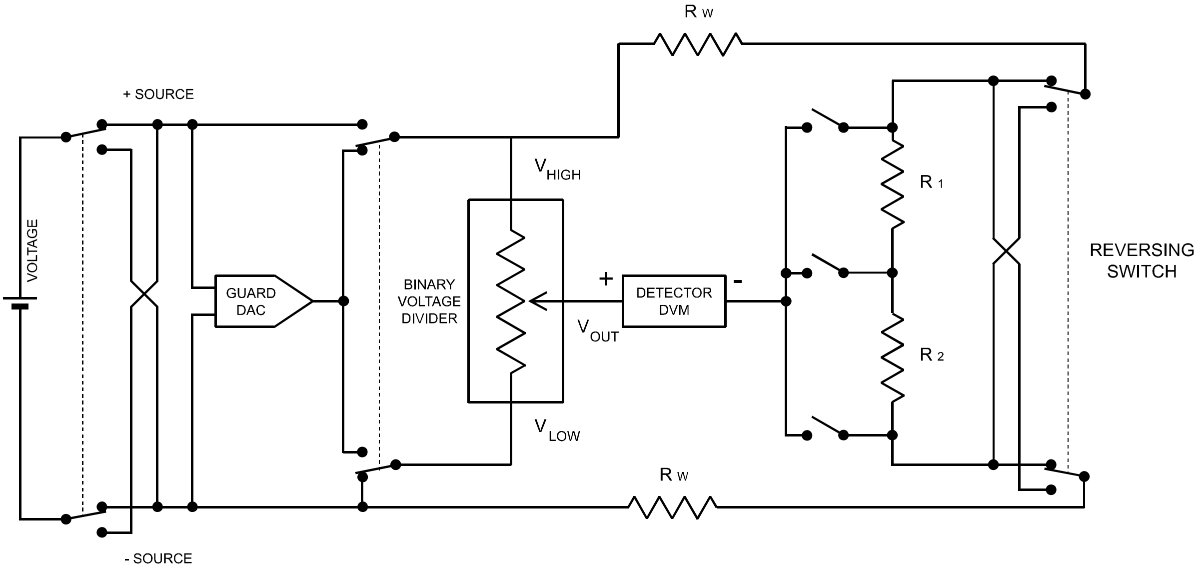


Figure 6. Functional drawing of the verification factor measurement.

Series of resistors was used to verify different ratios of the divider. All resistors were of high quality and long term stability and were made by fy Tinsley. To determine the influence of connecting wires R_w, voltages and corresponding ratios were measured at three points at resistors. Ratios P_A or P_B is calculated as difference of measured ratios.

Results of verification factors for both positive and negative polarities of the voltage source are listed in table 2. Verification factors are for both polarities and for all ratios one order less than uncertainty.

Table 2: Nominal ratios P_A and P_B, nominal values R_v of resistors and measured ratio verification factors e. Reported uncertainties u(e) are at level of confidence 95.45% of Student's t-distribution with effective degrees of freedom ν_{eff}.

R_{nom}	R_v	Verification Factor e					
		Positive Polarity			Negative Polarity		
		e	u(e)	ν_{eff}	e	u(e)	ν_{eff}
0.9/0.1	10kΩ/1kΩ	$-0.26\cdot10^{-8}$	$2.51\cdot10^{-8}$	371	$0.06\cdot10^{-8}$	$2.64\cdot10^{-8}$	347
0.1/0.9	1kΩ/10kΩ	$0.35\cdot10^{-8}$	$2.51\cdot10^{-8}$	372	$-0.33\cdot10^{-8}$	$2.67\cdot10^{-8}$	353
0.09/0.01	100kΩ/1kΩ	$-0.13\cdot10^{-8}$	$2.48\cdot10^{-8}$	362	$0.03\cdot10^{-8}$	$2.62\cdot10^{-8}$	341
0.009/0.001	1MΩ/1kΩ	$0.15\cdot10^{-8}$	$2.21\cdot10^{-8}$	274	$-0.99\cdot10^{-8}$	$2.32\cdot10^{-8}$	260
0.0009/0.001	10MΩ/1kΩ	$0.15\cdot10^{-8}$	$2.36\cdot10^{-8}$	323	$0.33\cdot10^{-8}$	$2.49\cdot10^{-8}$	307

Unfortunately such measurement reveals many sources of errors with the exception of offset errors and errors of the source standardization, because difference of ratios is calculated. Thus any possible offset was subtracted and other verification methods were needed.

4.3 Comparison of old and new software

The results of old and new software was compared directly by measuring Zener reference standard, model Fluke 732A at nominal voltage 1.018 V, see figure 7. Differences of results are below uncertainties, although uncertainty correctly calculated by the new software is slightly bigger than calculated by old software.

4.4 Bipolar voltage measurement test

Another test was measurement of the same voltage source, but with reversed input, in order to check that both positive and negative measurement paths and software processing will give the same result. Zener reference standard, model Fluke 732A was used as a voltage source. This reference is periodically measured against CMI national standard. First, the reference source of nominal voltage 10V was measured. Thus the divider's ratio was 1 (none divider's stage was used) and only connecting cables, voltage offsets and standardized source values were checked. Every measurement is averaged from 10 sub-measurements and every reading of the null detector was repeated 10 times. The results have shown that no significant error was neglected; all measured values are within limits of the expanded uncertainty value (level of confidence 95.45%) of the standard (see Figure 8).

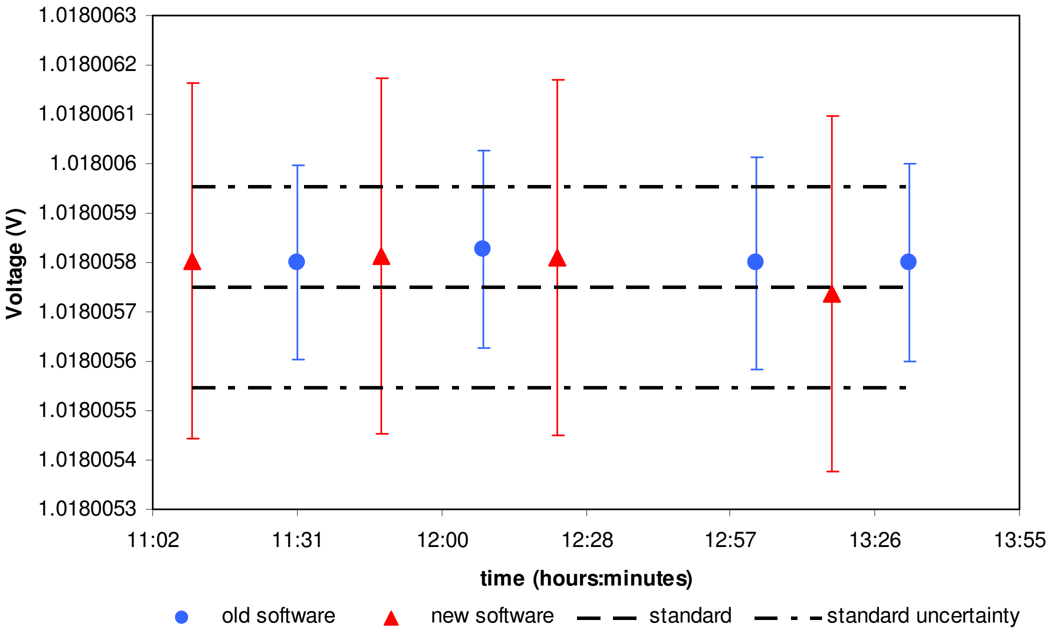


Figure 7. Measurement of reference nominal voltage 1.018 V. Absolute values of results of old and new software are presented. Uncertainties of the new software are at level of confidence 95.45% of Student's t-distribution.

Next was measured source voltage of nominal voltage 1.018V. Again results are in agreement with voltage value of standard, although offset for negative values is observed. This offset is about 0.2 µV and was lower than 0.37 µV uncertainty. Because of correct measurement of 10 and -10 V, this offset is expected to be attributed to negative ratio correction factors, although source of this offset is currently unknown. (See figure 9.) Further work will hopefully reveal source of this offset.

5. Summary

Hardware and firmware of automated BVD potentiometer system was modified to make possible bipolar measurement. Calculations of uncertainties in the new controlling software were modified according GUM. Results of several tests made in order to verify the proper system operation were presented. Equations and software was checked by GUM Workbench software. Results were checked by ratio verification method an against Zener reference standards. Small offset error of 0.2 µV is still present at negative polarity, although is smaller than uncertainty of the measurement. The offset is negligible when common calibrators are measured. The additional work on determination of the reason for offset on the lower negative voltage results needs to be done.

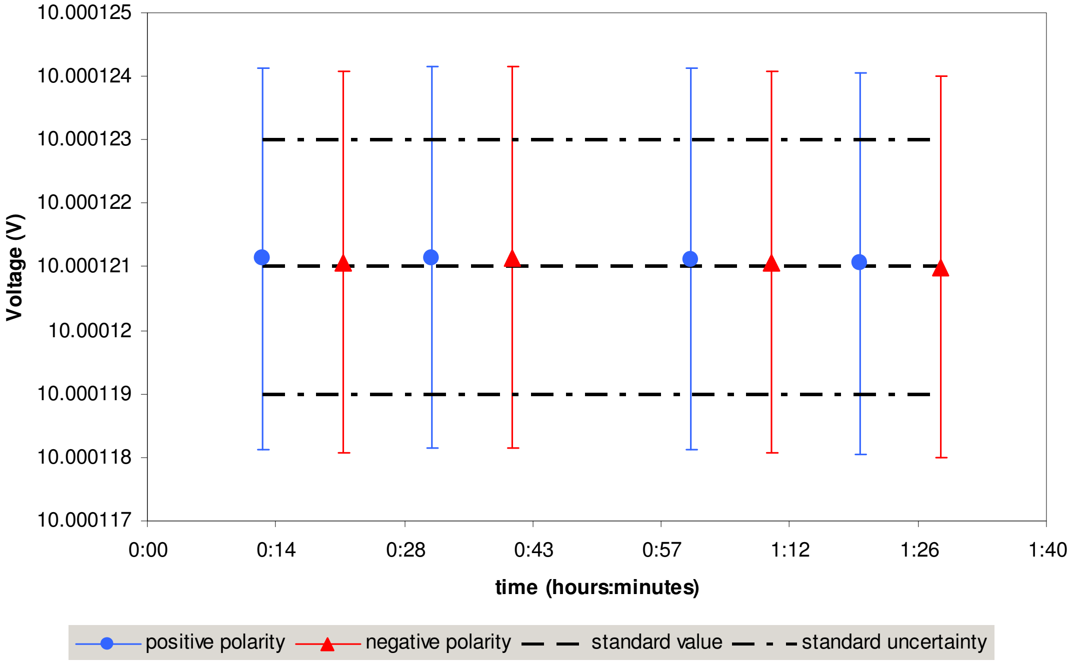


Figure 8. Measurement of reference nominal voltage 10 and -10 V. Absolute values are shown. Uncertainties are at level of confidence 95.45% of Student's t-distribution.

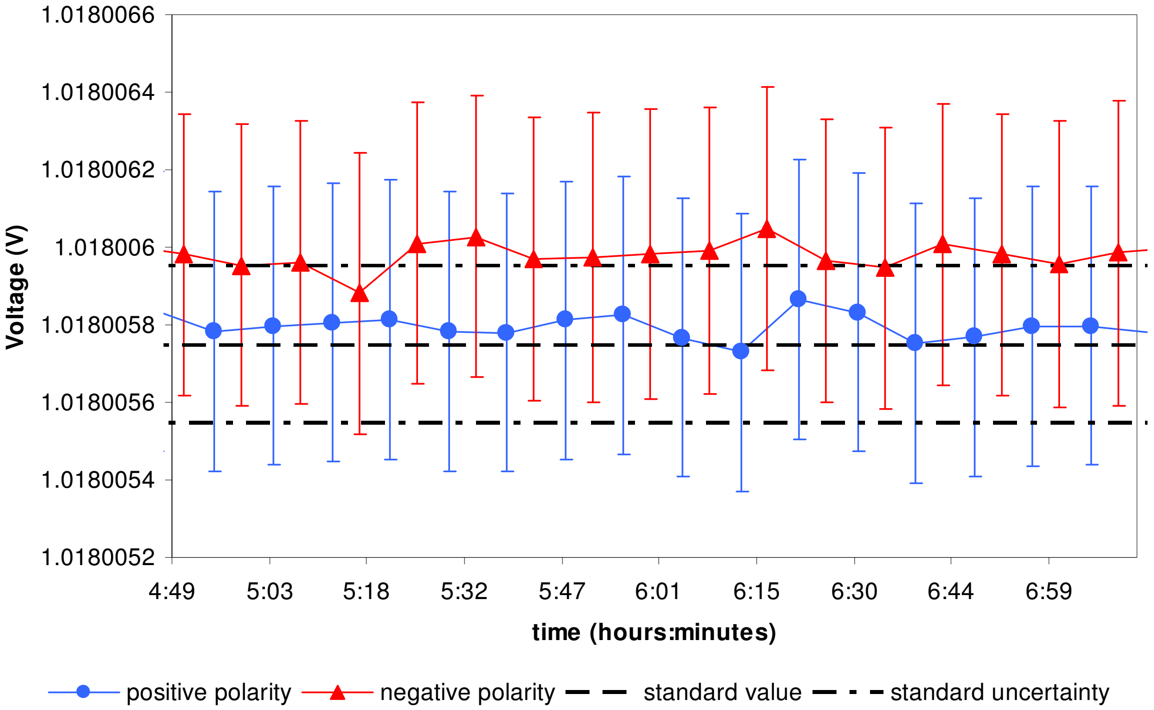


Figure 9. Long time measurement of reference nominal voltage 1.018 and -1.018 V. Absolute values are shown. Uncertainties are at level of confidence 95.45% of Student's t-distribution.

6. References

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