# Stability of Some DC Reference Standards

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***Abstract*— Some 15 years ago, after 80 years of utilization of the Weston cell as voltage standard, commercial designs of sources with Zener diodes, the so-called "dc reference standards" appeared on the market. They have much more favorable properties compared to Weston Standard Cells. The stability of one commercial dc reference standard Fluke 732A at the 10 V output was analyzed in relation to the calibration data obtained in the Fluke, NIST, and PTB laboratories during a period of seven years. Two approaches to accessible data for regression line calculation were compared. In the first approach all the data were taken into consideration, whereas in the second approach only the mean values of particular calibration expressed for the mean date were taken into account and were calculated with weights. Both approaches show a very good agreement. The voltage of the analyzed source at the 10 V output changes for about 0.1 × $10^{-6}$/year, which is several times less than the value given in the manufacturer's specifications.**

***Index Terms*—DC reference standards, dc voltage standards, maintenance, voltage measurement, Zener diode standards.**

## I. Introduction

During the past 20 years, in numerous national metrology institutes as well as in larger calibration laboratories, the standards based on the Josephson effect, the so-called Josephson Standards or Josephson array voltage standards [1], [2], have been used for voltage source and voltage maintenance. For the transfer of that physical value to measurement instruments, as well as for the comparison of Josephson standards, the Zener-diode-based voltage standards are used. They have replaced the chemical sources with saturated electrolytes known as Weston standard cells. Chemical sources have been in use since the beginning of the century and have a number of shortcomings, like for instance a nonlinear and relatively high voltage temperature coefficient ($4 \times 10^{-5}$/K), temperature and load hysteresis, sensitivity to vibration, etc. [3].

The experiments with own designs of the Zener diode standards started in various laboratories at the beginning of the 1970's [4] and have continued until today [5]. At the beginning of the 1980's the commercial designs of these sources appeared on the market, the most famous among them being the dc reference standard Fluke 732A (DCRS) with 10, 1, and 1.018 V outputs. According to the manufacturer's data its voltage temperature coefficient at the 10 V output is $\approx 5 \times 10^{-7}$/K, time stability $\pm 0.5 \times 10^{-6}$/month or $\pm 3 \times 10^{-6}$/year, and load and temperature hysteresis are negligible [6], [7]. The specific feature of this voltage standard is that the output voltage change can be reliably compensated by regression line, i.e., the calibration data can be statistically processed, whereas the uncertainty of regression line slope coefficient is reduced by increasing the number of calibrations and time interval in which they are being made [8].

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TABLE I
Parameters of the Regression Line for Eight DCRS Fluke 732A ($t = 0$ on January 1, 1987)

| DCRS | A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|---|
| $a_i/10^{-6}$ | - 1.09 | - 1.51 | - 0.96 | 1.50 | 1.10 | 0.55 | - 2.21 | 1.26 |
| $b_i/(10^{-6}$/month) | 0.016 | 0.018 | 0.14 | 0.051 | 0.17 | 0.11 | - 0.004 | 0.11 |
| $s_{yi}/10^{-9}$ | 51 | 20 | 38 | 65 | 120 | 108 | 3.5 | 10 |
| $s_{bi}/(10^{-9}$/month) | 6 | 5 | 5 | 8 | 15 | 12 | 1 | 2 |

At the beginning of 1987, the manufacturer presented one DCRS to the Faculty of Electrical Engineering (ETF), now the Faculty of Electrical Engineering and Computing (FER), of Zagreb University for the purpose of conducting research with a voltage balance ETF-84 [9]. Today, this source is used as the national voltage standard of the Republic of Croatia. On the basis of the comparison results of the Fluke (Fluke Primary Standards Lab), NIST (National Institute of Standards and Technology), and PTB (Physikalisch-Techniche Bundesanstalt) laboratories, the time stability of that source (denoted as "A") at the 10 V output was analyzed.

## II. DCRS Comparisons

### *A. Calibration in Fluke and NBS Laboratories*

The "A" voltage standard (DCRS-A) was calibrated at the manufacturer from October 24, 1986 to January 13, 1987 [10]. During that time at the 10 V output all together 110 comparisons with the voltage maintained in the Fluke laboratory were made, and the value of the voltage expressed for January 15, 1987 was 10.0000012 $V_{\mathrm{NBS}}$ (9.9999892 $V_{\mathrm{BI\text{-}76}}$) with a relative uncertainty of $0.23 \times 10^{-6}$ ($1\sigma$). The parameters of the related regression line $Y = a + bt$ are also given. They are shown in Table III with designation "Fluke," where $a_{\mathrm{A}}$ is a constant expressed as a relative deviation from 10 V, $b_{\mathrm{A}}$ is the regression line slope coefficient, $s_{\mathrm{bA}}$ is a standard deviation of that coefficient, $s_{\mathrm{yA}}$ is a standard deviation of the values measured around the regression line, $N$ is the number of data, and $\bar{t} = \Sigma t_i / N$ is the mean value of independent variable. These data are shown in Table I with the designation A, as the deviation from 10 $V_{\mathrm{BI\text{-}76}}$.

Immediately after that, from January 22 to March 9, 1987, the DCRS-A was calibrated in the NBS (National Bureau of Standards, now NIST) [11], and on the basis of 29 com-

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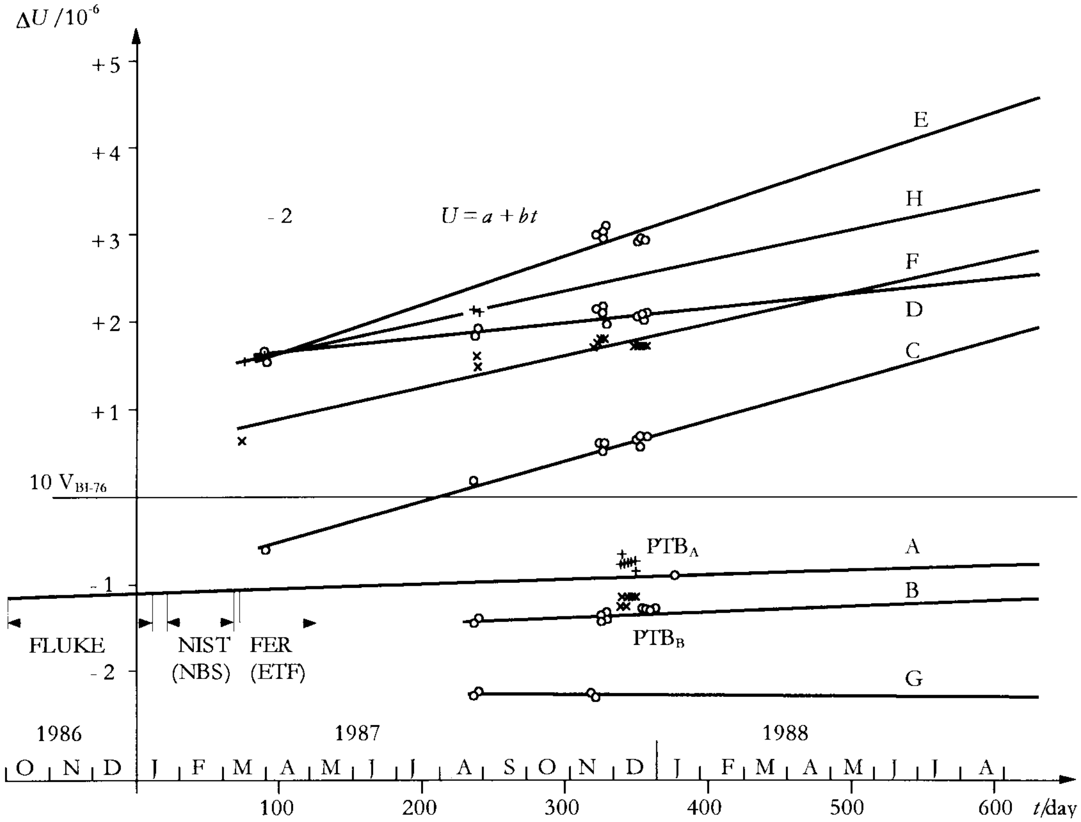


Fig. 1. Regression lines for DCRS-A, B, C, D, E, F, G, and H (parameters are written in Table I).

TABLE II
RESULTS OF COMPARISONS BETWEEN DCRS-A AND B WITH C THROUGH F (ALL VALUES ARE IN $10^{-6}$)

| December 12, 1987 | | November 26, 1987 | | December 22, 1987 | |
|---|---|---|---|---|---|
| $\Delta_A$ | - 0.79 | $\Delta_{A1}$ | - 2.94 | $\Delta_{A2}$ | - 2.92 |
| $\Delta_B$ | - 1.13 | $\Delta_{B1}$ | - 3.26 | $\Delta_{B2}$ | - 3.16 |
| $\Delta_{Ac}$ | - 0.95 | $\Delta_{A1c}$ | - 2.78 | $\Delta_{A2c}$ | - 2.86 |
| $\Delta_{Bc}$ | - 1.30 | $\Delta_{B1c}$ | - 3.14 | $\Delta_{B2c}$ | - 3.22 |
| $\Delta_A - \Delta_B$ | 0.34 | $\Delta_{A1} - \Delta_{B1}$ | 0.32 | $\Delta_{A2} - \Delta_{B2}$ | 0.24 |
| $\Delta_{Ac} - \Delta_{Bc}$ | 0.35 | $\Delta_{A1c} - \Delta_{B1c}$ | 0.36 | $\Delta_{A2c} - \Delta_{B2c}$ | 0.36 |
| $\Delta_A - \Delta_{Ac}$ | 0.16 | $\Delta_{A1} - \Delta_{A1c}$ | - 0.16 | $\Delta_{A2} - \Delta_{A2c}$ | - 0.06 |
| $\Delta_B - \Delta_{Bc}$ | 0.17 | $\Delta_{B1} - \Delta_{B1c}$ | - 0.12 | $\Delta_{B2} - \Delta_{B2c}$ | 0.06 |

TABLE III
PARAMETERS OF THE REGRESSION LINE FOR DCRS-A AT THE 10 V OUTPUT OBTAINED IN THE FLUKE LABORATORY (DENOTED AS FLUKE), CALCULATED FROM ALL INDIVIDUAL VALUES MEASURED FOR A PARTICULAR DAY (ALL), AND FROM THE MEAN VALUES OF INDIVIDUAL CALIBRATIONS EXPRESSED FOR THE RESPECTIVE MEAN DATE, INCLUDING WEIGHT FACTORS (WEIGHT); $t = 0$ ON OCTOBER 24, 1986

| Parameters | $a_A/10^{-6}$ | $b_A/(10^{-6}/\text{year})$ | $s_{yA}/10^{-6}$ | $s_{bA}/(10^{-6}/\text{year})$ | $\bar{t}$ /day | $N$ |
|---|---|---|---|---|---|---|
| Fluke | - 9.188 | 0.196 | 0.051 | $7.6 \times 10^{-2}$ | 36.9 | 110 |
| All | - 9.167 | 0.107 | 0.064 | $2.8 \times 10^{-3}$ | 243.6 | 157 |
| Weight | - 9.121 | 0.099 | 0.048 | $1.5 \times 10^{-3}$ | 1781.0 | 87 |

parisons with the voltage maintained in NBS, for the mean date of February 14, 1987 the expressed voltage value was 10.0000013 $V_{NBS}$ (9.9999893 $V_{BI\text{-}76}$) with a relative uncertainty of $0.13 \times 10^{-6}$ ($1\sigma$). The DCRS-A was under continuous supply delivered to the ETF (FER) in Zagreb, Croatia.

## B. FER Comparison

During 1986/87 several laboratories in ex-Yugoslavia obtained DCRS. They will be marked as B–H. The DCRS-A was compared at the 10 V output with the DCRS-F and H on March 18, 1987, and on April 1 with the DCRS-C, D and E. In the period from the August 26–28, 1987, a circular comparison was made with all the DCRS's. The differences in voltage were measured by electronic microvoltmeter with an analog display. The error of the instrument at the ranges of 10 $\mu$V , 30 $\mu$V, and 100 $\mu$V did not exceed ±1% of the measured value.

On the assumption that the DCRS-A at the 10 V output at a certain day has the value predicted by its regression line $\Delta U_A = -1.09 \times 10^{-6} + 0.016 \times 10^{-6}$/month ("Fluke"), expressed by deviation with respect to 10 $V_{BI\text{-}76}$ with $t = 0$ relevant for January 1, 1987, on the basis of the comparison results the regression lines of other DCRS's were calculated and shown in Fig. 1. The parameters of these lines are given in Table I from which it is obvious that the regression line slope coefficients of all eight DCRS's is several times smaller than the declared voltage stability $\pm 0.5 \times 10^{-6}$/month, which is a very interesting piece of information.

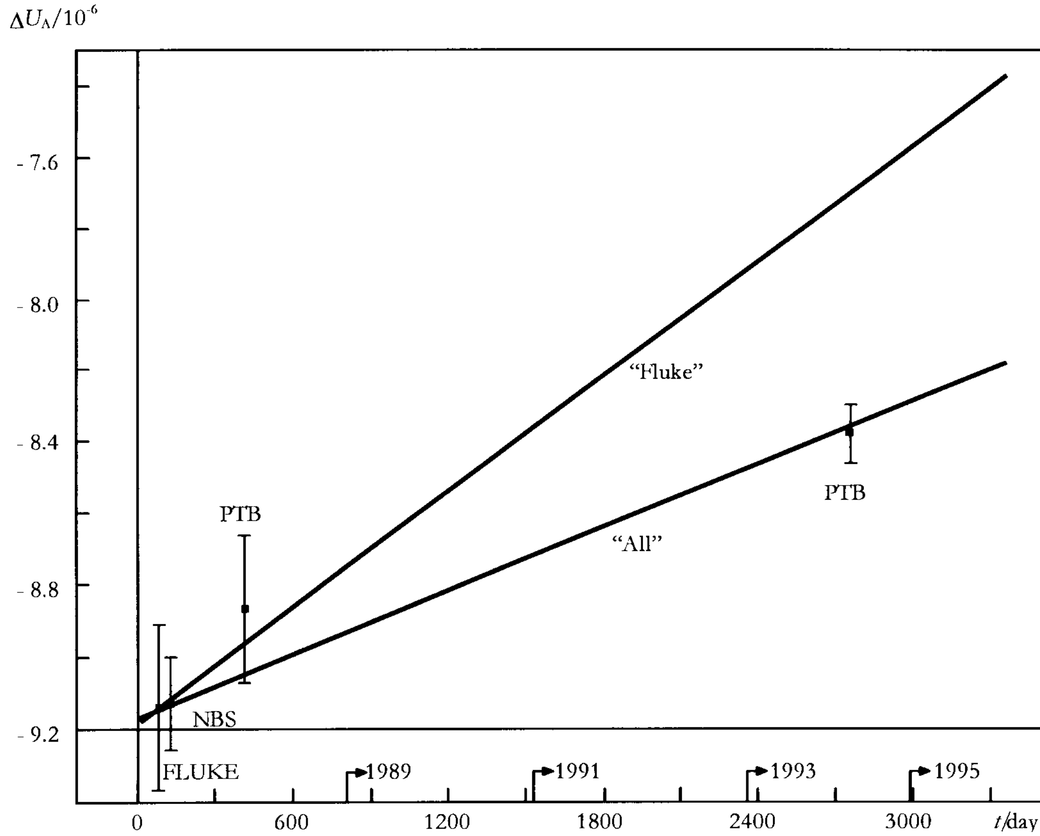


Fig. 2. Results of the comparisons of DCRS-A and regression line for 10 V output (parameters are written in Table III).

### C. First Comparison in PTB

To verify the voltage stored in these standards, a comparison test was made between the DCRS-A and B with the voltage maintained in the PTB. Before going to the PTB, and upon returning, the DCRS-A and B were compared to the DCRS-C to F. The mean date of comparison prior to going to the PTB was November 26, 1987. The mean date after coming back was December 22, 1987. From the data in Table I, the mean linear regression line was calculated for the DCRS-C to F: $\Delta U_{\mathrm{CF}} = 0.548 \times 10^{-6} + 0.12 \times 10^{-6}$/month. This regression line is almost identical to the regression line denoted with F, and is not therefore shown in Fig. 1.

In Table II, the comparison data are listed, where (respectively, from 10 $V_{\text{BI-76}}$): $\Delta_{\mathrm{A}}$, $\Delta_{\mathrm{B}}$—deviations of the DCRS-A and B measured at the PTB with the mean date December 12, 1987; $\Delta_{\mathrm{Ac}}$, $\Delta_{\mathrm{Bc}}$—deviations of the DCRS-A and B calculated from the regression line for December 12, 1987; $\Delta_{\mathrm{A1}}$, $\Delta_{\mathrm{B1}}$—mean values of deviations of the DCRS-A and B with the DCRS-C to F, measured before leaving for the PTB; $\Delta_{\mathrm{A2}}$, $\Delta_{\mathrm{B2}}$—same deviations measured upon returning from the PTB; $\Delta_{\mathrm{A1c}}$, $\Delta_{\mathrm{B1c}}$—deviations of the DCRS-A and B calculated from the mean value regression line $\Delta U_{\mathrm{CF}}$, with the mean date November 26, 1987; $\Delta_{\mathrm{A2c}}$, $\Delta_{\mathrm{B2c}}$—same deviations calculated for December 22, 1987. The comparison of the data prior to going to the PTB and upon returning, shows that the difference between the measured and calculated values is less than $0.2 \times 10^{-6}$ and, i.e., that the systematic errors during the circular comparison of DCRS's are on the level of $0.1 \times 10^{-6}$.

The comparison of DCRS-A in the PTB was done from December 8 to 17, 1987, during which eight comparisons with the voltage maintained in the PTB were made [12]. For the mean calibration date December 12, 1987, with an uncertainty of $0.2 \times 10^{-6}$ $(1\sigma)$, the expressed value of the voltage at the 10 V output was 9.9999921 $V_{\text{BI-76}}$, i.e., deviation of $\Delta_{\mathrm{A}} = -0.79 \times 10^{-6}$, whereas according to the regression line ("Fluke") for that date it should be $\Delta_{\mathrm{Ac}} = -0.95 \times 10^{-6}$.

### D. Second Comparison in PTB

After 1991 the DCRS-B to F were not accessible to our laboratory. Unfortunately, for several years it was not possible to perform the calibration of DCRS-A. Through the kind services of the PTB, the comparison of the DCRS-A with the voltage maintained in this laboratory was enabled from May 9 to 20, 1994 [13]. On the basis of ten comparisons at the 10 V output the mean voltage of 9.9999162 V with an uncertainty of $0.077 \times 10^{-6}$ $(1\sigma)$ was obtained.

## III. Analysis of DCRS-A Stability

Since January 1, 1990, for the representation of volt unit (V), the Josephson constant $K_{\text{J-90}}$ has been used [14]. Therefore, the values of the maintained voltage in the NIST and PTB were corrected with respect to the ratio between the units $V_{\mathrm{NIST}} = (1 - 9.264 \times 10^{-6})$ V and $V_{\mathrm{PTB}} = (1 - 8.065 \times 10^{-6})$ V, and all the DCRS-A comparison data obtained at the 10 V output prior to January 1, 1990 were recalculated on the basis of these ratios.

The change of the DCRS-A voltage at the 10 V output can be reliably predicted by means of the regression line obtained from the DCRS-A comparison data from particular laboratories [10]–[13], because this type of standard is characterized by linear change of voltage with time. These data will be analyzed using two different approaches in order to find out possible differences.

In the first approach (denoted as "All") the input data include all individual values measured for a particular day of DCRS-A calibration, i.e., the total number of input data is $N = 157$ (110 Fluke, 29 NBS, 8 $PTB_1$ and 10 $PTB_2$). The starting day $t = 0$ corresponds to October 24, 1986, and the last day $t = 2765$ to May 20, 1994. The parameters of the regression line calculated according to these data and expressed as a deviation from 10 V are given in Table III.

The second approach to calculating regression line parameters (denoted as "Weight") is based on the mean values of individual calibrations, expressed for the respective mean date. Only the calibration result obtained in the Fluke laboratory refers to the last calibration date, because of the larger number of data obtained during a longer period of time. Due to the difference between the units $V_{\rm NBS}$, $V_{\rm PTB}$, and $V$, the following corrected values are included into calculation: $U = 9.9999086$ V (January 15, 1987), $U = 9.9999087$ V (February 14, 1987), $U = 9.9999115$ V (December 12, 1987), and $U = 9.9999162$ V (May 14, 1994). The uncertainties of these values are $0.23 \times 10^{-6}$, $0.13 \times 10^{-6}$, $0.20 \times 10^{-6}$, and $0.077 \times 10^{-6}$ ($1\sigma$), respectively. Due to different uncertainties of the input data, the following weight factors are assigned to them: 6, 19, 8, and 54, respectively. During the calculation of regression line parameters, the influence of weight factors is included so that for a particular date instead of recording one voltage value, the number of the same values which corresponds to the number of respective weight factor is being recorded, e.g., thus, for February 14, 1987, it is taken that the voltage $U = 9.9999087$ V has been measured 19 times. Therefore, there is all together $N = 87$ data, the beginning $t = 0$ corresponds to the previous calculation, whereas $t = 2759$ corresponds to the last date. The parameters of the regression line calculated in such way are also given in Table III.

In Fig. 2, two regression lines are shown: the first one (denotation "All") calculated following the first approach in the analysis of the DCRS-A calibration data, and the second one (denotation "Fluke") defined by calibration performed in the Fluke laboratory (line A in Fig. 1). The regression line calculated following the second approach in the data analysis is not presented for the sake of better figure layout, since it is very close to the regression line denoted with "All." The slope coefficient of the "All" line ($\approx 0.1 \times 10^{-6}$/year) is almost two times smaller than the slope coefficient of the "Fluke" line, which does not mean that any of these values is incorrect, because when taking into account the standard deviations of these coefficients, then even within the $1\sigma$ interval their good matching is achieved. Comparing the two presented lines, it becomes obvious that by repeating calibration of the standard, and by using the data collected during several years, a more reliable prediction of the voltage change with time can be made, because the parameter $s_{\rm bA}$ of the line "All" is about 30 times smaller than the same parameter of the line "Fluke." The previous statement is also confirmed by the standard deviations of the regression lines calculated according to the known expression [8]

$$s_Y = s_y \sqrt{\frac{1}{N} + \frac{(t - \bar{t})^2}{\sum (t_i - \bar{t})^2}} \tag{1}$$

for January 1, 1996, i.e., for $t = 3356$ days. If the first calibration made in the Fluke laboratory had not been followed by other calibrations, then according to that regression line the calculation for the given day would have been made with $s_Y = 0.69 \times 10^{-6}$, and for the line "All" with $s_Y = 0.025 \times 10^{-6}$.

## IV. Conclusion

The comparison of eight DCRS Fluke 732A shows that particular regression lines have the annual change of voltage at the 10 V output several times smaller than that allowed in the specifications, and that only one DCRS has a negative regression line slope coefficient, whereas the slope coefficient of the other seven DCRS is positive. Analyzing the calibration data of one DCRS in the Fluke, NIST and PTB laboratories during the time period of more than seven years, it has been discovered that no significant differences exist between two different approaches: the first one that takes into account daily data, and the second one which introduces into the calculation the mean values expressed for the mean calibration date and calculated with weights. By means of the regression line obtained on the basis of the DCRS comparison it is possible to predict reliably voltage changes within the time period of at least one year.

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