XIX IMEKO World Congress
Fundamental and Applied Metrology
September 6–11, 2009, Lisbon, Portugal

PREDICTION OF THE OUTPUT VOLTAGE OF DC VOLTAGE STANDARDS

Damir Ilić, Alan Šala, Ivan Leniček

Faculty of Electrical Engineering and Computing (FER), Zagreb, Croatia,
damir.ilic@fer.hr; alan.sala@fer.hr; ivan.lenicek@fer.hr

Abstract – In this paper we report some methods which upgrade the measurement uncertainty evaluation in analysis of the prediction of the output voltage of DC Reference Standards (Fluke 732A at 1 V, 1,018 V and 10 V levels). The monitoring of long-term stability of Zener-based voltage reference standards is one of the main tasks of Primary Electromagnetic Laboratory (PEL), which is a part of the Faculty of Electrical Engineering and Computing of the University of Zagreb, and a holder of national standards of voltage in Croatia. The long-term stability of its DC Reference Standard has been analysed according to the calibration data obtained in different laboratories over a period of more than twenty years. The weighted least-squares fitting was used and the regression coefficients were calculated, by which the maintained voltages at all three outputs can be predicted for a moment of interest. This approach significantly reduces the uncertainties of the maintained voltages.

Keywords: DC reference voltage standard, least-squares analysis, long-term drift.

1. INTRODUCTION

During the last decades, in numerous national metrology institutes, and from recently as well in PEL, dc voltage standards based on the Josephson effect (JAVS) have been used for voltage maintenance [1-4]. For transfer of that physical value to the measuring instruments, or to the laboratories not having the Josephson standard, the Zener-based dc voltage reference standards (DCRS) have been frequently used [5-10]. Their relative time stability at the 10 V output is ±30 μV/year, and at the lower levels 1,018 V and 1 V it is ±12 μV/year, for the widely used type Fluke 732A[1], but is also similar for other types of such standards. The specific feature of these voltage standards is that the output voltage change can be reliably approximated by the curve-fitting, particularly regression line, whereas the associated uncertainty is reduced by increasing the number of calibrations and decreasing the time interval in which they are being made. This approach makes it possible to calculate the predicted value of output voltage (at any level) for a particular day, which is the main (or basic) information of interest of their use as the source of stable and known voltage.

The reference voltage standard of PEL is of Fluke 732A type with 10 V, 1,018 V and 1 V outputs (further in paper abbreviated as RU), and since 1987 it was regularly calibrated. The characterization of it (i.e. calculation of the parameters of the fitted curves for the available history data of its output voltages) is very important: it that way the relative uncertainty of the maintained voltage can be reduced, even down to the range of $1\cdot10^{-7}$ for all three outputs.

Furthermore, a few other DCRS of type Fluke 732A and 732B forms a group standard of voltage. History of all calibrations gives the individual drift rate of each output voltage, and using this drift rate the output voltage can be predicted for the respective date. A voltage standard to be calibrated and the group of four DCRS are connected to the voltage comparator with 16 inputs. This comparator is made up of magnetically latching relays and is connected to the controlling computer via an optoisolated serial interface [11]. The relays connect DC reference standards in such a way that the difference voltage of every two inputs can be routed to a developed digital nanovoltmeter **η***PEL* [12].

Since December 2006, PEL was equipped with the commercial JAVS of Supracon [13], and the latest calibration of RU and other standards were made using this system, as it can be seen from the results presented in Tables I to III. Nevertheless, the DCRS are still important for the routine comparisons and calibrations of other voltage standards, as well as other high-resolution equipment, and the prediction of their voltage is crucial for proper use.

2. PREDICTION OF VOLTAGE VALUES

On one hand, prediction of the voltage values on the basis of the average drift during the last few calibrations is limited by the short-term stability of the electronic voltage standard itself, since the almost linear long-term drift of the voltage is superimposed by random fluctuations. Typical deviations from the predicted values over a six months period are lower than ±100 nV for the 1 V and 1,018 V outputs, and less than ±500 nV for the 10 V output. Random fluctuations or 1/*f* noise of all standards give autocorrelated measurements and scatter the daily measurements.

---

[1] Brand names are used for purpose of identification. Such use does not imply endorsement by authors nor assume that the equipment is the best available.

A typical standard shows a standard deviation (of ten daily measurements) of about 30 nV for the 1 V and 1,018 V outputs, and about 300 nV for the 10 V output. Typical observed limiting value of Allan deviation at 1 V and 1,018 V level was 20 nV, and at 10 V it was 100 nV.

On the other hand, the output voltage of a DCRS depends on several variables. The functional dependence can be given as [14]:

$$U(t,T,p,h) = f(t,T,p,h) + s(t) + g(T - T_0) + \\ + j(p - p_0) + k(h - h_0) \quad , \qquad (1)$$

where: t is time, constant values T_0, p_0, h_0 represent reference values of temperature, pressure and humidity, respectively, and term $s(t)$ represents an influence of $1/f$ noise. The temperature coefficient of RU is determined to be approximately −7 (nV/V)/ºC of ambient temperature change and is included in the correction of data. During the past years none or neglected seasonal effects dependences has been observed, so the humidity dependence $k(h - h_0)$ term claimed to be insignificant. Pressure coefficient of this standard is below 0,4 (nV/V)/hPa, so it is also almost negligible, and therefore the simplified mathematical model can be written:

$$U_{\mathrm{RU}}(t) = U_{\mathrm{P}}(t) \pm \Delta U \, . \qquad (2)$$

With ΔU we denoted here a short-term stability of the electronic voltage standard itself (or a random fluctuation) which is superimposed to its long-term drift, denoted by $U_{\mathrm{P}}(t)$. The data for ΔU, as pointed out earlier in this section, can be gathered for each output level by the measurement of its voltage for a shorter (a few days) or longer period of time (a month, for example, or even longer), and once defined and measured it is not expected to change dramatically from time to time. In other words, we can consider this influence more or less the same and as something that scatters daily measurements and enlarges the uncertainties of the output voltage. However, we would like to concentrate to the prediction of the voltage for a particular day of interest, $U_{\mathrm{P}}(t)$, which we can explain as a long-term drift associated to the output voltage. For the voltage standards with two or more outputs, with the main voltage level of 10 V, and other voltage levels of 1,018 V and 1 V obtained by the internal voltage divider, a long-term drift can be different, and usually is different, for each of the output of the same DCRS.

We would determine the $U_{\mathrm{P}}(t)$ by the analysis of the past calibration data for our reference voltage standard (RU) for all three outputs. In such analysis more data obtained through the history could give more confidence about the behaviour of the standards and prediction for the future, but also could lead to the misleading having in mind that some effects of changes, happen many years before, are maybe not representative for today's characteristics and could influence the prediction of the future changes and associated uncertainties. From that point of view someone could reject or introduce less or more history data, and therefore a different prediction will be a consequence. Although the analysis is performed on one particular item, it could be representative for such type of standards.

2.1. 10 V level

Calibration data at the 10-volt level of DCRS-RU are presented in Table I. In the second column, the identification of calibration laboratory is given, followed by the calibration voltage values and the relative deviation from the nominal value, where $\delta U_{10} = (U_{10}/U_{10\mathrm{n}} - 1)$; U_{10} is the actual voltage at the 10-volt output and $U_{10\mathrm{n}} = 10$ V. This relative deviation is given in μV/V (parts per million or 10^{-6}). In the last column, the associated relative uncertainty is given. The first three rows (no. *, **, and ***) represent the calibration results for year 1987 (from January to December). After the thorough examination of all results on all three outputs, the definite conclusion is that these calibration results could be rejected for several reasons: (i) there is a gap of 7 year between these results and the beginning of series of regular calibrations started in 1994; (ii) the corresponding results from 1987 for 1,018 V and 1 V outputs exhibit relatively large changes from the following results, which is pointed out in the following subsections 2.2 and 2.3; (iii) at this moment we have more calibration data and it is reasonable to reject the oldest ones to obtain smaller uncertainties of prediction for nowadays.

Table I. Calibration data for DCRS-RU at the 10 V output (the starting day $t = 0$ corresponds to 1994-5-15, and last to 2009-3-1).

No.	Lab.	t/day	U_{10}/V	δU_{10}/(μV/V)	u/(μV/V)
*	Fluke	-2677	9,9999086	-9,14	0,23
**	NIST	-2647	9,9999087	-9,13	0,13
***	PTB	-2346	9,9999114	-8,86	0,20
1	PTB	0	9,9999162	-8,38	0,08
2	PTB	862	9,9999180	-8,20	0,08
3	PTB	1620	9,9999200	-8,00	0,05
4	PTB	2435	9,9999236	-7,64	0,05
5	PTB	3266	9,9999281	-7,19	0,05
6	PTB	4037	9,9999309	-6,91	0,05
7	PEL	4585	9,9999340	-6,60	0,05
8	PTB	4725	9,9999345	-6,55	0,05
9	PEL	4769	9,9999348	-6,52	0,05
10	PEL	5404	9,9999364	-6,36	0,05

The long-term drift for this output can be represented by the regression line

$$U_{10}(t) = K + at \, . \qquad (3)$$

Analysis is performed using the weighted least-squares method [15], with weights $p = k_p/u^2$ (k_p is a self-chosen constant, and u stands for uncertainties of the calibration data), and the coefficients of regression line are calculated by solving the following system of equations, where Gauss's notation is used for the sums; for instance, $[p] = \sum_{i=1}^{n} p_i$:

$$\begin{aligned} [p]K + [pt]a &= [pU_{10}] \\ [pt]K + [pt^2]a &= [ptU_{10}] . \end{aligned} \qquad (4)$$

In Table IV, the calculated coefficients of the regression line K and a are presented for this voltage level, together with some other parameters and for two other voltage levels.

The standard deviation of a data from the regression line, the so called parameter m, is calculated with the following expression:

$$m = \sqrt{\frac{[pvv]}{n-z}} \ , \tag{5}$$

where v is the difference between the calibration value and the regression value for a particular t, n is the number of data and z is the number of unknowns. The sum $[pvv]$ can be also noted in the form $[pv^2]$, which is mathematically equal, but the first manner is more common.

It is not of interest only to calculate the predicted value of voltage, but also the associated uncertainty of such prediction. Therefore, for the regression line, the uncertainty of the predicted voltages (marked generally u_P) for a particular date (t_P), according to the regression function, can be calculated as follows:

$$u_P = m\sqrt{\frac{1}{[p]}\left(1+\frac{\left(t_P[p]-[pt]\right)^2}{[p][pt^2]-[pt]^2}\right)} \ . \tag{6}$$

In Fig. 1, the calibration data and the calculated regression line for the 10-volt level are presented. The predicted voltage is calculated for September 11, 2009 ($t_P = 5598$ days), and the same data are also given in Table IV in subsection 2.4.

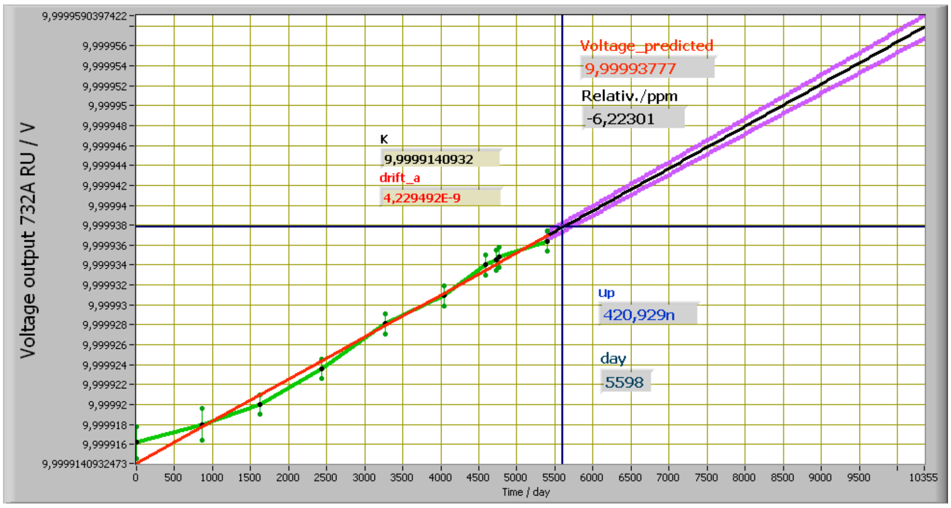

Fig. 1. Calibration data, associated uncertainties and the regression line for DCRS-RU at the 10-volt level (the starting day corresponds to May 15, 1994).

The overview of the calibration data and calculated parameters show that the long-term drift (i.e. coefficient a) is equal to 1,55 µV/year, and an uncertainty $u_p = 0{,}42$ µV is associated to September 11, 2009. These results show that standard RU exhibit very small drift on this level, and that the prediction of its output value can be calculated with very small uncertainty.

One interesting point could be further rejection of the data. Thus, we can reject first data (no. 1 in Table I) and repeat the calculation for the set of data no. 2 to no. 10, after that reject first two data (no. 1 and no. 2) and repeat the calculation for the set of data no. 3 to no. 10, etc. Calculation of u_p for such restricted sets of data is presented in Fig. 2, where index k shows which data are introduced into the calculation. One has to have in mind that for the calculation of parameter m, the number of data n must be at least larger by one from the number of unknowns z, which in this case for $z = 2$ means $n \geq 3$. The smallest uncertainty u_p is obtainable using the set of data from no. 8 to no. 10, or in other words, when all history data except the latest three are rejected. There is no doubt that this approach would lead to the smallest uncertainty of prediction, but it is also more sensitive to the addition of new calibration data (i.e. the first next in the future). On the other hand, some attention has to be paid to the other voltage levels, and prior to rejection of the data one should takes into account that it is reasonable that past calibration data should be valuable for all three outputs, which means if we reject data for this level as "inappropriate" we should consider the rejection of the similar data (i.e. from the same time of calibration) for other voltage levels.

Distribution of calculated parameters u_p and dependency on history measurement interval of interest can be evaluated using Fig. 2, where the just mentioned rejection of data and calculation is used.

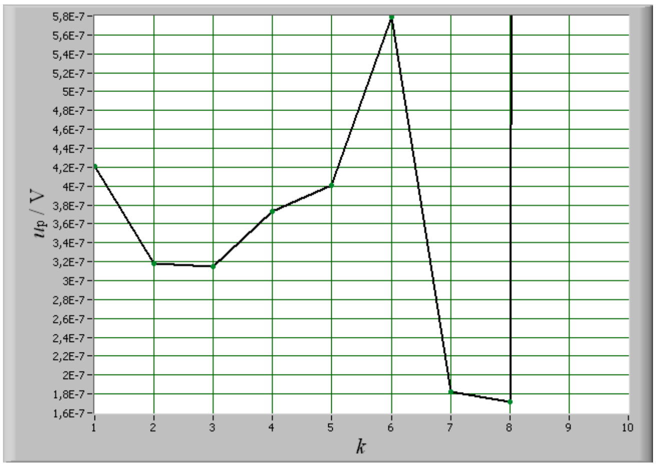

Fig. 2. Distribution of calculated uncertainties u_p of DCRS-RU at the 10-volt level (the index k shows which data are introduced in the analysis, and corresponds to the no. in Table I).

2.2. 1,018 V level

Calibration data for DCRS-RU at this level are presented in Table II, where the columns have the same meaning as described before. In the fifth column, the absolute deviations from nominal values are given ($\Delta U_{1018} = U_{1018} - 1{,}018$ V; U_{1018} is the actual voltage at the 1,018-volt output), while the uncertainties are given in the last column. The first two rows (no. * and **) represent the calibration results from year 1987 (with the starting day February 14). As explained in the previous subsection, after the thorough examination of all results on all three outputs, the definite conclusion is that these calibration results could be rejected for the mentioned reasons.

Table II. Calibration data for DCRS-RU at the 1,018 V output (the starting day $t = 0$ corresponds to 1994-5-15, and last to 2009-3-1).

No.	Lab.	t/day	U_{1018}/V	ΔU_{1018}/µV	u/µV
*	NIST	-2647	1,01798738	-12,62	0,13
**	PTB	-2346	1,01798388	-16,12	0,20
1	PTB	0	1,01796909	-30,91	0,06
2	PTB	864	1,01796617	-33,83	0,06
3	PTB	1620	1,01796438	-35,62	0,10
4	PTB	2434	1,01796301	-36,99	0,10
5	PTB	3258	1,01796224	-37,76	0,10
6	PTB	4038	1,01796145	-38,55	0,10
7	PTB	4725	1,01796125	-38,75	0,10
8	PEL	4768	1,01796118	-38,82	0,10
9	PEL	5404	1,01796067	-39,33	0,10

In Fig. 3, the calibration data and the calculated regression line for the 1,018-volt level are presented. It is immediately clear that the regression line does not fit the data correctly. If we calculate the uncertainty u_p in the same way like we did for 10-volt level, for the same particular day and using this regression line, we will obtained the data pointed out in Fig. 4. It is obvious that the uncertainty u_p will be smaller with the rejection of more data, and the smallest value is calculated for the last three results, but the predicted value of voltage is not in accordance with the latest calibration data (Fig. 3).

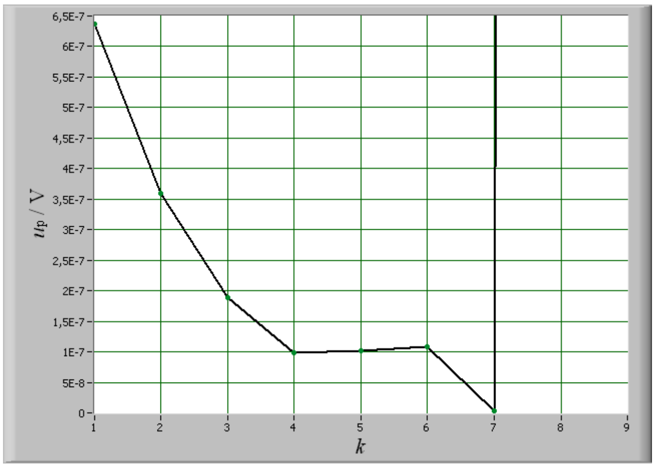

Fig. 4. Distribution of calculated uncertainties u_p of DCRS-RU at the 1,018-volt level (the index k shows which data are rejected in the analysis, and corresponds to the no. in Table II).

This confirms that the regression line is inappropriate curve for this voltage level. Therefore for the further analysis, instead of regression line, the weighted 3rd order polynomial is considered:

$$U_{1018}(t) = K + at + bt^2 + ct^3, \tag{7}$$

and to calculate the unknowns K, a, b and c, the following system of equations needs to be solved:

$$\begin{aligned}
[p]K + [pt]a + [pt^2]b + [pt^3]c &= [pU_{1018}] \\
[pt]K + [pt^2]a + [pt^3]b + [pt^4]c &= [ptU_{1018}] \\
[pt^2]K + [pt^3]a + [pt^4]b + [pt^5]c &= [pt^2U_{1018}] \\
[pt^3]K + [pt^4]a + [pt^5]b + [pt^6]c &= [pt^3U_{1018}] .
\end{aligned} \tag{8}$$

As well as for the system (4), the Gauss's notation is used for the sums, and p stands for the particular weights. This system can be expressed in the matrix form as $\boldsymbol{Nx} = \boldsymbol{n}$, where $\boldsymbol{N}$ is the matrix of coefficients of normal equations (sums on the left sides), $\boldsymbol{x}$ is the vector of unknowns and $\boldsymbol{n}$ is the vector of absolute members (sums on the right sides).

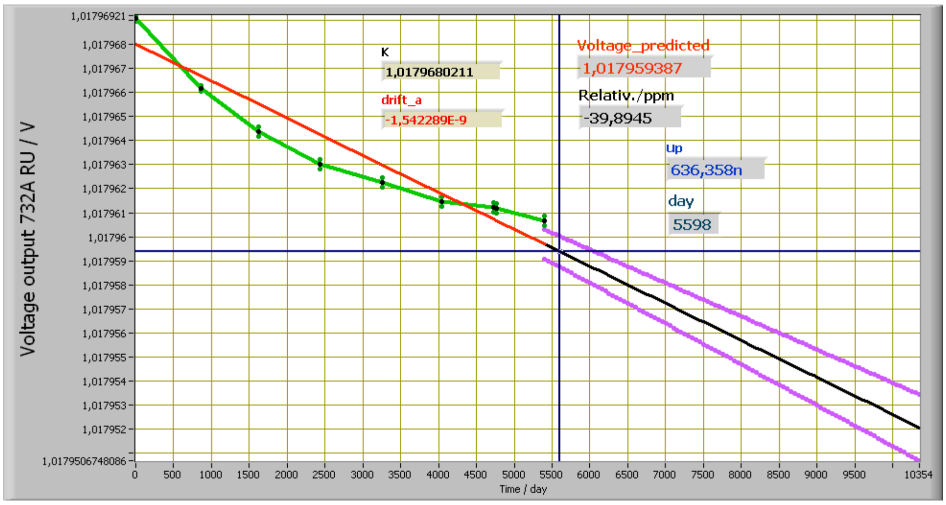

Fig. 3. Calibration data, associated uncertainties and the regression line for DCRS-RU at the 1,018-volt level (the starting day corresponds to May 15, 1994).

For the calculation of uncertainty of the predicted voltage on a particular day, the matrix of weight coefficients $\boldsymbol{Q}$, which is the inverse matrix of $\boldsymbol{N}$, i.e. $\boldsymbol{Q} = \boldsymbol{N}^{-1}$, is the most important. According to the least-squares theory, the uncertainties are calculated using the following equation:

$$u_{\mathrm{P}} = m \cdot [Q_{11} + 2t_{\mathrm{P}}Q_{12} + t_{\mathrm{P}}^{2}(2Q_{13} + Q_{22}) + 2t_{\mathrm{P}}^{3}(Q_{14} + Q_{23}) + \\ + t_{\mathrm{P}}^{4}(2Q_{24} + Q_{33}) + 2t_{\mathrm{P}}^{5}Q_{34} + t_{\mathrm{P}}^{6}Q_{44}]^{1/2} , \quad (9)$$

where Q_{11}, Q_{12}, …, Q_{44} are the elements of matrix $\boldsymbol{Q}$, and m is calculated by (5) (having in mind that in this case $z = 4$). In other words, if we want to implement weighted 3rd order polynomial for the best approximation of the long-term drift of DCRS, we will need at least 5 calibration data for the analysis.

The calculated unknowns, as well as the predicted voltage value and its uncertainty for September 11, 2009, are also given in Table IV.

2.3. 1 V level

The calibration data for DCRS-RU at the 1-volt level are presented in Table III, where all columns have the same meaning as described for the previous tables. An exception is the fifth column, where deviations from the nominal value are given ($\Delta U_1 = U_1 - 1$ V; U_1 is the output voltage).

Table III. Calibration data for DCRS-RU at the 1 V output (the starting day $t = 0$ corresponds to 1994-5-15, and last to 2009-3-1).

No.	Lab.	t/day	U_1/V	ΔU_1/μV	u/μV
*	NIST	-2647	0,99998925	-10,75	0,13
**	PTB	-2346	0,99998945	-10,55	0,20
1	PTB	0	0,99998791	-12,09	0,06
2	PTB	864	0,99998807	-11,93	0,06
3	PTB	1620	0,99998806	-11,94	0,10
4	PTB	2433	0,99998839	-11,61	0,10
5	PTB	3258	0,99998873	-11,27	0,10
6	PTB	4036	0,99998888	-11,12	0,10
7	PEL	4586	0,99998927	-10,73	0,10
8	PTB	4724	0,99998931	-10,69	0,10
9	PEL	4768	0,99998929	-10,71	0,10
10	PEL	5404	0,99998938	-10,62	0,10

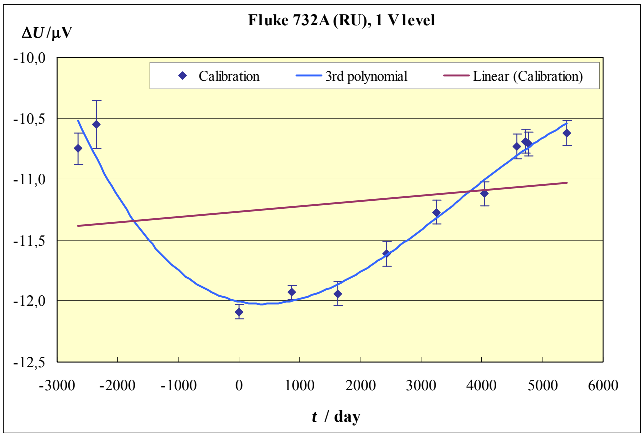

Fig. 5. Distribution of calculated uncertainties u_{p}, of DCRS-RU at the 1-volt level ($t = 0$ corresponds to May 15, 1994).

The first two rows of Table III (no. * and **) represent the calibration results from year 1987 (with the starting day February 14), and all calibration data are given in Fig 5. The change of the output voltage at this level exhibits rise from starting point $t = 0$, while the previous behaviour shows drop of the output voltage. From the data pointed in Fig. 2 it is obvious that the regression line does not match the whole set of data (it is better to say it is completely out of range for the future prediction of voltage), and to cover all data some other models should be considered. However, as explained before, the time interval between the last calibration in 1987 and following in 1994 is seven years, and the need to use reasonable modelling for long-term drift (or as simple as possible) leads to the conclusion that these first two data should be rejected for further analysis, having also in mind that this is appropriate for two other voltage levels as well.

Thus, the calibration data for 1-volt output are approximated with the regression line

$$U_1(t) = K + at , \quad (10)$$

and the analysis was done in the same way as it was for 10-volt level, but of course using the corresponding data at this level. This also means that the uncertainty u_{P} of the predicted voltage is calculated for a particular date t_{P} (September 11, 2009) using (6), and all results are presented in Table IV.

Furthermore, considering the rejection of data we can perform the same calculation of dependence of uncertainty u_{p} on the truncation of the past calibration data, in the same way like we did for 10-volt level. The results are given in Fig. 6, and are very similar to those presented in Fig. 2. The smallest uncertainty u_{p} is obtainable using the set of data from no. 7 to no. 10, or in other words, when all history data except the latest four are rejected. For this case it would lead to the lower u_{P}, but basically the rejection of data is just in opposite to have as much information about the particular standard as is possible, and the more history data give more confidence in the expected future changes. Therefore, the smaller u_{P} is not utmost condition to be fulfilled, because by taking into account more data some sort of “averaging” is implemented into the calculation.

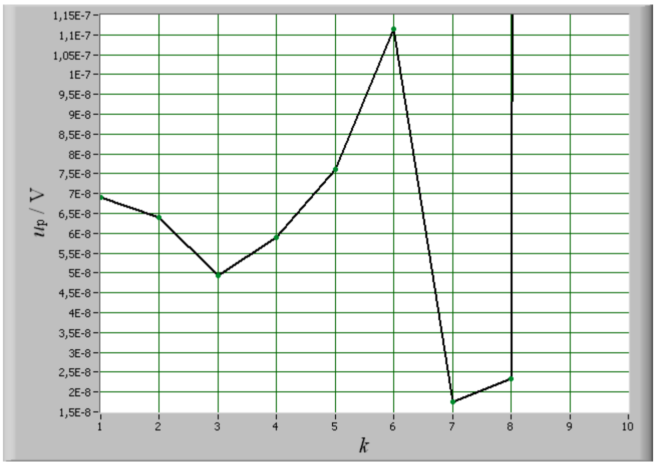

Fig. 6. Distribution of calculated uncertainties u_{p} of DCRS-RU at the 1-volt level (the index k shows which data are introduced in the analysis, and corresponds to the no. in Table III).

2.4. Analysis of results

In Table IV, the summary results are given for all three outputs, calculated in the way described in the previous three sections. For analysis only data from no. 1 (in Tables I to III) are taken into account, and the predicted values of voltage U_P are calculated for the last day of this IMEKO World Congress, September 11, 2009 ($t_P = 5598$ days), as well as associated uncertainties u_P.

Table IV. Calculated coefficients of the weighted regression models (regression line for 1 V and 10 V, and 3rd order polynomial for 1,018 V) for DCRS RU at all outputs and the prediction of voltages on September 11, 2009 ($t_P = 5598$ days).

	1 V	**1,018 V**	**10 V**
K/V	0,99998782	1,01796909	9,9991410
a/(μV/year)	0,107	−1,459	1,545
b/(μV/year^2)	/	0,101	/
c/(μV/year^3)	/	−0,003	/
m/μV	0,080	0,052	0,744
U_P/V	0,99998945	1,01796055	9,99993777
u_P/μV	0,069	0,099	0,421

3. CONCLUSION

First of all, the performed analyses of the change of output voltages at the 10-volt, 1,018-volt and 1-volt levels of DCRS-RU showed that they are much smaller than the maximum allowed from the manufacturer specifications. For the use of such standard as the reference one, it is ultimately needed to calculate (or predict) the output value of its voltage for any level and for any particular day of interest. To be able to do that, a model for curve fitting is needed which approximates the real change of voltage. It was shown that the oldest calibration data for all three levels should be reasonable rejected from further analysis. However, since the weighted 3rd order polynomial is better regression function than regression line for 1,018-volt output, it is assumed that all other past calibration data should be left in the valuable data set and no more truncation were done. Therefore, from the presented analysis, a reliable and powerful regression functions can be used to calculate the voltage of all three outputs for any particular day of interest, and associated uncertainty of such prediction as well. In that way our reference standard can be used for the calibration of other voltage standards. Although it was done for one particular item, presented calculation can be done for any standard of interest.

REFERENCES

[1] R. Pöpel, "The Josephson effect and voltage standards," *Metrologia*, vol. 29, pp. 153-174, 1992.

[2] D. Reymann, T. J. Witt, G. Eklund, H. Pajander, H. Nilsson: “Comparison of the Josephson Voltage Standards of the SP and the BIPM”, *IEEE Trans. Instrum. Meas.*, vol. IM-46, no. 2, pp. 220-223, April 1997.

[3] R. Behr, J. Niemeyer, A.S. Katkov: “Comparison of the Josephson Voltage Standards of VNIIM and PTB”, *IEEE Trans. Instrum. Meas.*, vol. IM-50, no. 2, pp. 203-205, April 2001.

[4] J. Kohlmann, F. Müller, O. Kieler, R. Behr, L. Palafox, M. Kahmann, J. Niemeyer: “Josephson series arrays for programmable 10-V SINIS Josephson voltage standards and for Josephson arbitrary waveform synthesizers based on SNS junctions”, *IEEE Trans. Instrum. Meas.*, vol. IM-56, pp. 472-475, 2007.

[5] T.J. Witt, D. Reymann, D. Avrons: “The stability of some Zener-diode-based voltage standards”, *IEEE Trans. Instrum. Meas.*, vol. IM-44, no. 2, pp. 226-229, April 1995.

[6] D. Vujević, D. Ilić, “Stability of Some DC Reference Standards”, *IEEE Trans. Instrum. Meas.*, vol IM-48., no. 6, pp. 1081-1084, December 1999.

[7] T.J. Witt: “Maintenance and dissemination of voltage standards by Zener-diode-based instruments”, *IEE Proc.-Sci. Meas. Technol.*, vol. 149, no. 6, November 2002.

[8] T. Funck, E. Pesel, P. Warnecke: “Calibration of electronic voltage standards at the PTB”, *Metrologia*, vol. 29, May 1998.

[9] T.J. Witt: “Measurements of the temperature dependence of the output voltages of some Zener diode based voltage standards”, *IEE Proc.-Sci. Meas. Technol.*, vol. 145, no. 4, July 1998.

[10] R. Kletke: “Maintaining 10V DC at 0,3 ppm or better in your Laboratory”, Fluke Corporation, Everett, Washington.

[11] A. Šala, D. Ilić, I. Leniček: “Simple and reliable system for accurate maintenance of voltage standards”, *Proceedings of the 16th IMEKO TC-4 Symposium*, vol. II, pp. 783-787, Florence, Italy, September 22-24, 2008.

[12] A. Šala, D. Ilić, I. Leniček: “High Accuracy Digital Nanovoltmeter For Maintenance Of Voltage Standards”, *Proceedings of the RMO 2008; 20th International Metrology Symposium*, pp. 159-163, Cavtat, Dubrovnik, Croatia, November 12-15, 2008.

[13] R. Behr, D. Ilić, A. Šala: “Bilateral direct comparison of Josephson array voltage standards of the PTB (Germany) and PEL (Croatia): Draft B report for EUROMET.EM-S28”, Metrologia, 2008, 45, Tech. Suppl., 01011.

[14] O. Power, J. Walsh: “Investigations of the long and medium-term drift of Zener-based voltage standards”, *IEEE Trans. Instrum. Meas.*, vol. IM-54, no. 1, pp. 330-336, February 2005.

[15] D. Ilić, D. Vujević, "Analysis of the long term stability of the Zener-based reference voltage standards", *Digest of the HMD 18th Metrology Symposium*, pp. 59, Cavtat, Croatia, October 8-10, 2001.