Comparison CCEM-K8 of DC Voltage Ratio: Results

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***Abstract*—Fifteen National Metrology Institutes have participated in dc voltage ratio comparison CCEM-K8. The method followed to normalize the participants' results, the calculation of the key comparison reference values and the comparison results are reported for the two mandatory ratios of the comparison, 1000 V/10 V and 100 V/10 V.**

***Index Terms*—DC voltage ratio, international comparisons, key comparisons, voltage divider.**

I. INTRODUCTION

THE need for a key comparison of dc voltage ratio was recognized by the Comité International d'Electricité et Magnetisme (CCEM) at its 20th meeting, in June 1995. Its purpose was to compare the scaling capabilities in dc voltage of the National Metrology Institutes (NMI) up to 1000 V. After preliminary studies carried out at IEN [1], it was decided to use a Datron 4902S voltage divider (s/n 20 335) as the travelling standard. The divider has 100, 10-kΩ resistive elements, each made up of two parallel 20-kΩ bulk metal foil resistors. It can divide a maximum input voltage of 1000 V in multiples of 10 V, up to 100 V, and in multiples of 100 V up to 900 V. Trimmers are provided on the instrument but, after a preliminary adjustment, they were sealed and no further adjustment was made. On this divider, the measurements of the voltage ratios 1000 V/10 V and 100 V/10 V were mandatory. Measurements of other ratios were optional. The standard conditions for temperature and humidity were: $\mathrm{T} = (23 \pm 0.5)^{\circ}\mathrm{C}$ and $\mathrm{H} = (45 \pm 5)\%$. Corrections for deviations from these conditions were to be applied by the pilot laboratory.

The comparison started in October 1998, with IEN as the pilot, but in November, while at the second participant, the travelling standard had a failure, which forced the replacement of its base 10-V section [2]. After repair, the circulation was re-started at the end of February 1999 and was finished in June 2001, with fourteen NMIs having participated, in addition to the pilot. In the following, the processing of the comparison data and the results are presented for the mandatory measurements. More detailed information and the results for the optional measurements can be found in the comparison final report [3].

II. BEHAVIOR OF THE TRAVELLING STANDARD

Calibrations of the divider at IEN were carried out by measuring the individual resistive sections: each section of the 10×100 V or of the 10×10 V resistive chains was successively compared with a transfer resistor by means of a Kelvin double bridge with lead compensation. Fig. 1 shows the IEN measurements of the basic ratios 1000 V/100 V and 100 V/10 V after repair of the divider, corrected for deviation from standard ambient conditions.

After day 135, the data show a change of drift, for which two different interpretations are proposed: i) a specific and unknown event causing the change ii) a gradual stabilization of the divider after repair, which would support an exponential behavior. In Fig. 1, linear and exponential interpolations are compared, showing a significant difference for the 1000 V/100 V ratio, where linear interpolation is to be preferred.

During the preliminary characterization work [1], temperature and humidity coefficients, C_T and C_H, were evaluated by multiple linear regression of the measurements taken at IEN under different ambient conditions. After repair, this work had to be repeated, using the control measurements carried out at IEN during the comparison. The coefficients of the mandatory ratios, before and after the change of drift, are given in Table I, where the values "before" correspond to ten measurements and the values "after" correspond to 26 measurements. Table I also reports the standard deviation s of the multiple linear regression; the values of s will be taken to be the standard uncertainty to be associated with the travelling standard. From the values of s and from Fig. 1, it is clear that the data, after the change of drift, are more scattered than before. This could be attributed to the increased number and extension of movements between

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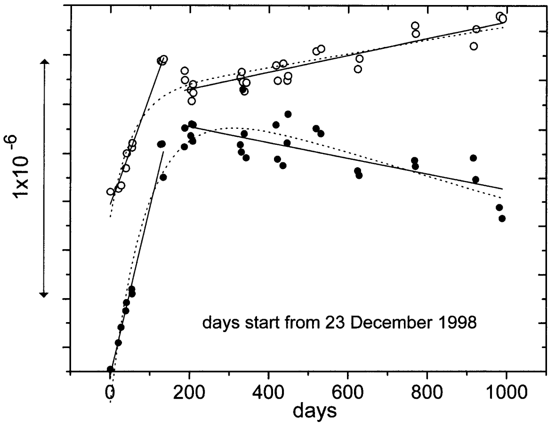

Fig. 1. Behavior of the ratios 1000 V/100 V (open circles) and 100 V/10 V (solid circles), as shown by measurements at the pilot laboratory.

laboratories; only one laboratory carried out its measurements before the change.

In order to have comparable data, it had been established by the comparison protocol that the voltage had to be applied to the divider for at least 5 or 10 min (for ratios 100 V/10 V and 1000 V/10 V, respectively) before taking the measurements, in order for the device to stabilize. But, with the measurement technique used at IEN, only one section of the divider at a time is powered during the measurements, while with other methods, all the divider sections are powered. To verify if any effect due to the dissipated power could occur, a direct comparison between a Fluke 752 divider and the Datron divider was performed. Before starting the measurements, the Fluke was powered for at least 12 h, while the Datron was left unpowered. Then, the Datron was connected in parallel to the voltage supply and the output of a detector, monitoring the voltage difference of the two dividers at the 10-V taps, was recorded for at least 2 h. The resulting drift was less than two parts in 10^8 of the voltage on the 10-V taps.

III. LABORATORY MEASUREMENTS

The laboratory results were given as relative deviations of the divider's ratios (input/output) from nominal. To obtain normalized data, the following steps were taken:

1) correction of the original result d_l for temperature and humidity, to obtain the corrected result $d_{0,l}$;
2) calculation of the difference Δ_l between the corrected laboratory result and the corresponding interpolated pilot laboratory result;
3) addition, to the laboratory standard uncertainties u_A (type A) and u_B (type B), of a contribution $u(T,H)$ due both to the correction in step 1) and to the uncertainty of the values of temperature and humidity;
4) addition of the uncertainty contribution s due to the travelling standard.

Tables II and III report the laboratory ambient conditions, the original results d_l, the corrected and the normalized results $d_{0,l}$ and Δ_l, the various uncertainty contributions, and the global standard uncertainty $u_{G,l}$. In these tables, ν_l are the degrees of freedom as given by the laboratories (for LCIE, in the absence of information, an infinite number was assumed) and $\nu_{G,l}$ are the effective degrees of freedom associated with $u_{G,l}$. Details of the calculation of $\nu_{G,l}$ are given in the comparison final report [3].

TABLE I
TEMPERATURE AND HUMIDITY COEFFICIENTS (WITH STANDARD UNCERTAINTY IN PARENTHESIS) AND STANDARD DEVIATION S

Ratio	C_T (10^{-6}/°C)	C_H (10^{-6}/p.u.)	s (10^{-6})
1000V/10V before	-0.081 (0.030)	0.0096 (0.0044)	0.088
1000V/10V after	-0.026 (0.016)	-0.0015 (0.0013)	0.092
100V/10V before	-0.291 (0.021)	0.0031 (0.0031)	0.063
100V/10V after	-0.214 (0.014)	-0.0095 (0.0012)	0.083

IV. COMPARISON RESULTS

To the results of Tables II and III, the results of the pilot laboratory must be added, to obtain the complete sets of data from which the two Key Comparison Reference Values (KCRV) can be calculated. Of course, for IEN, the normalized results are $\Delta_{\text{IEN}} = 0$. The IEN average ambient conditions during the whole comparison are given in Table IV and the uncertainty contributions in Table V. In this table, the contribution of the travelling standard, evaluated from the measurements after the change of drift, is reduced by the square root of 26, which is the number of these measurements.

In principle, all laboratories should contribute to the KCRV, because laboratory measurements of voltage ratios are mutually independent. However, Tables II and III suggest that some of the participants' differences Δ_l are not compatible with the corresponding global uncertainties $u_{G,l}$. This observation can be put in more quantitative terms by the calculation of the so called Birge ratio R_B, given by

$$R_B = \frac{\sqrt{\dfrac{\sum_{l=1}^{n} W_l(\Delta_l-\Delta_w)^2}{n-1}}}{\sqrt{\dfrac{1}{\sum_{l=1}^{n}\frac{1}{u_{G,l}^2}}}}. \qquad (1)$$

Here, the weighted variance in the numerator is calculated from the $n = 15$ laboratory results, whose weighted mean is Δ_w, while the weighted variance in the denominator is calculated from the laboratory global uncertainties. If all laboratory uncertainties were assessed correctly, R_B would be close to one. Instead, even excluding NPL, for which Δ_l is large, it is found that for ratio 1000 V/10 V $R_B = 1.71$ and for ratio 100 V/10 V $R_B = 1.88$.

Under these circumstances, the KCRV is more safely estimated by the arithmetic mean, and not by the weighted mean. The associated standard uncertainty will be the standard deviation of the mean. To improve the accuracy of the estimation, those laboratories which, with high probability, are not members of the same statistical distribution, as the other laboratories

TABLE II
1000 V/10 V: RESULTS OF THE LABORATORIES, DIFFERENCES FROM PILOT LABORATORY AND UNCERTAINTIES

Lab	Date	T (°C)	δT (°C)	H (%)	δH (%)	d_l (10^{-6})	$d_{0,l}$ (10^{-6})	Δ_l (10^{-6})	u_A (10^{-6})	u_B (10^{-6})	ν_l	$u(T,H)$ (10^{-6})	s (10^{-6})	$u_{G,l}$ (10^{-6})	$\nu_{G,l}$
LCIE	17/03/99	22.9	0.1	45	5	-3.9	-3.908	0.367	0	0.15	1.E6	0.028	0.088	0.176	94
SP	04/06/99	22.7	0.4	48	5	-3.79	-3.793	-0.069	0.019	0.14	5784	0.010	0.092	0.169	244
NPL	20/08/99	20	1	50	5	-7.64	-7.710	-3.990	0.03	0.35	211	0.050	0.092	0.367	232
CEM	19/09/99	22.3	0.2	43	2	-2.89	-2.911	0.808	0.03	0.26	20	0.012	0.092	0.278	24
KRISS	25/10/99	22.2	0.35	45	1.2	-3.664	-3.685	0.032	0.008	0.013	16	0.014	0.092	0.094	24
CSIRO	08/01/00	20.9	0.14	52	1	-3.58	-3.624	0.089	0.02	0.13	14	0.034	0.092	0.164	28
NIM	10/04/00	23	0.3	40	3	-3.96	-3.968	-0.260	0.11	0.11	37	0.008	0.092	0.181	56
VNIIM	29/07/00	24	0.52	59	1.7	-4.162	-4.115	-0.413	0.007	0.033	54	0.025	0.092	0.101	30
NIST	12/10/00	23.6	0.3	30	5	-3.68	-3.687	0.011	0.05	0.24	6250	0.023	0.092	0.263	1215
NRC	02/11/00	23	0.08	27	6	-3.503	-3.530	0.167	0.08	0.094	20	0.024	0.092	0.155	39
MSL	06/01/01	19.8	0.29	48	4.3	-3.69	-3.768	-0.074	0.11	0.041	9	0.050	0.092	0.157	23
CSIR	01/03/01	23.7	0.5	49	5	-4.02	-3.996	-0.305	0.1	0.3	222	0.015	0.092	0.330	244
NPLI	07/04/01	23	1	45	10	-2.97	-2.970	0.719	0.19	0.3	70	0.017	0.092	0.367	78
NMIJ	01/06/01	23	0.2	45	1	-3.802	-3.802	-0.116	0.012	0.107	1556	0.003	0.092	0.142	120

TABLE III
100 V/10 V: RESULTS OF THE LABORATORIES, DIFFERENCES FROM PILOT LABORATORY, AND UNCERTAINTIES

Lab	Date	T (°C)	δT (°C)	H (%)	δH (%)	d_l (10^{-6})	$d_{0,l}$ (10^{-6})	Δ_l (10^{-6})	u_A (10^{-6})	u_B (10^{-6})	ν_l	$u(T,H)$ (10^{-6})	s (10^{-6})	$u_{G,l}$ (10^{-6})	$\nu_{G,l}$
BNM	17/03/99	22.9	0.1	45	5	-3.8	-3.829	0.210	0	0.12	-	0.019	0.063	0.137	128
SP	04/06/99	22.7	0.4	48	5	-3.63	-3.666	-0.089	0.023	0.094	628	0.057	0.083	0.140	119
NPL	20/08/99	20	1	50	5	-7.79	-8.383	-4.781	0.02	0.19	289	0.133	0.083	0.247	113
CEM	19/09/99	22.3	0.2	43	2	-2.856	-3.024	0.587	0.04	0.19	11	0.029	0.083	0.213	15
KRISS	25/10/99	22.2	0.35	45	1.2	-3.331	-3.502	0.121	0.009	0.006	45	0.045	0.083	0.095	32
CSIRO	08/01/00	20.9	0.14	52	1	-3.43	-3.812	-0.165	0.02	0.11	13	0.035	0.083	0.144	29
NIM	10/04/00	23	0.3	40	3	-3.86	-3.907	-0.230	0.07	0.11	34	0.041	0.083	0.160	60
VNIIM	29/07/00	24	0.52	59	1.7	-4.485	-4.139	-0.427	0.022	0.026	50	0.068	0.083	0.113	40
NIST	12/10/00	23.6	0.3	30	5	-4.04	-4.054	-0.318	0.05	0.19	3584	0.050	0.083	0.219	744
NRC	02/11/00	23	0.08	27	6	-3.504	-3.671	0.072	0.03	0.016	11	0.040	0.083	0.098	37
MSL	06/01/01	19.9	0.29	45	4.3	-3.07	-3.738	0.025	0.06	0.008	8	0.061	0.083	0.119	40
CSIR	01/03/01	23.7	0.5	49	5	-4.52	-4.333	-0.552	0.1	0.14	82	0.068	0.083	0.203	115
NPLI	07/04/01	23	1	45	10	-2.84	-2.84	0.953	0.22	0.37	63	0.135	0.083	0.459	77
NMIJ	01/06/01	23	0.2	45	1	-3.694	-3.694	0.116	0.004	0.01	260	0.025	0.083	0.087	26

TABLE IV
AVERAGE TEMPERATURE AND HUMIDITY AT IEN

Ratio	T_m (°C)	δT (°C)	H_m (%)	δH (%)
1000/10	23.2	0.5	45.9	5
100/10	23.2	0.5	45.9	5

TABLE V
UNCERTAINTY CONTRIBUTIONS OF IEN

Ratio	u_A (10^{-6})	u_B (10^{-6})	ν_l	$u(T,H)$ (10^{-6})	$s/\sqrt{26}$ (10^{-6})	$u_{G,l}$ (10^{-6})	$\nu_{G,l}$
1000/10	0.053	0.108	600	0.01	0.018	0.122	128
100/10	0.043	0.090	500	0.07	0.016	0.123	104

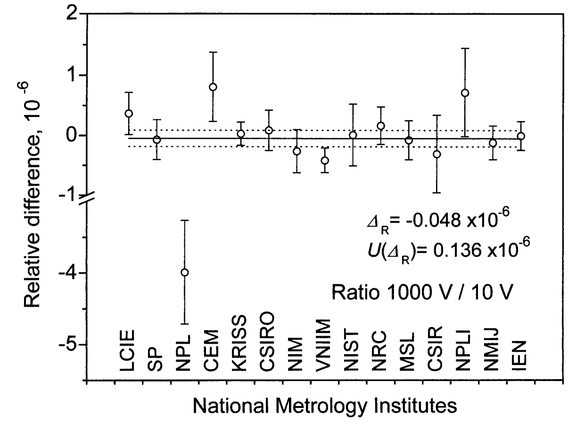

Fig. 2. Results for ratio 1000 V/10 V. The horizontal solid line represents the reference value. All uncertainties correspond to a confidence level of 95%.

were not included in the calculation. These laboratories were selected by using the median Δ_{med} as a robust estimator of the KCRV and the Median of Absolute Deviations (MAD) as a robust estimator of the deviation from the median. In the equation

$$S(\text{MAD}) = 1.4826 \cdot \text{ median } \{|\Delta_l - \Delta_{\text{med}}|\} \qquad (2)$$

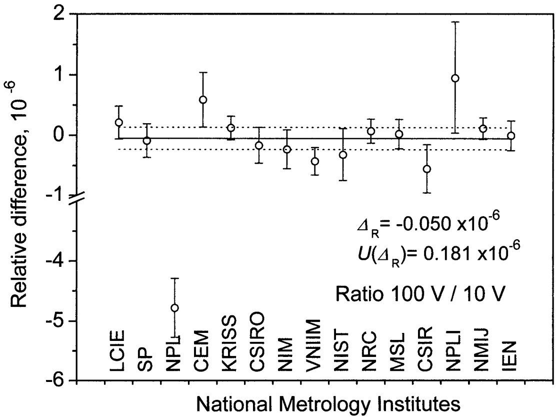

Fig. 3. Results for ratio 100 V/10 V. The horizontal solid line represents the reference value. All uncertainties correspond to a confidence level of 95%.

[4], the normalization coefficient 1.4826 is the inverse of the 75th percentile of a Gaussian distribution so that $S(\mathrm{MAD})$ gives the correct estimate of the standard deviation of the differences $(\Delta_l - \Delta_{\mathrm{med}})$, in the case of a Gaussian distribution. The criterion to select the participants not belonging to the distribution was

$$|\Delta_l - \Delta_{\mathrm{med}}| > 2.5 \cdot S(\mathrm{MAD}). \quad (3)$$

It is to be noted that the MAD criterion is based on the laboratory values and does not take into account the associated uncertainties, so that laboratories far from the median, but still compatible due to a large uncertainty, would also be discarded. By applying criterion (3) to the Δ_l values, after exclusion of NPL, it was found that also CEM and NPLI have to be excluded from the calculation of the KCRV for ratio 1000 V/10 V. For ratio 100 V/10 V, NPLI also has to be excluded. After selection, the arithmetic mean was chosen because the selection process, even if it decreases R_B, does not bring it much closer to one, due to the underestimated uncertainties of some of the remaining laboratories.

Figs. 2 and 3 show graphically the KCRV Δ_R and the results of the participants, with corresponding expanded uncertainties $U(\Delta_R)$ and $U_{G,l}$, evaluated for a confidence level of 95%. In the calculation of $U(\Delta_R)$ and $U_{G,l}$, the degrees of freedom were taken into account.

V. CONCLUSION

In spite of a failure and a change of drift of the travelling standard, comparison CCEM-K8 was completed successfully.

The results of NPL are quite far from the KCRV. After receiving the Draft A report, NPL made an investigation on the reason of the discrepancy and reported that it had been traced to the calibration of the NPL reference divider used for the comparison.

A brief description of the measurement methods used by the participants and their degrees of equivalence can be found in the comparison final report [3].

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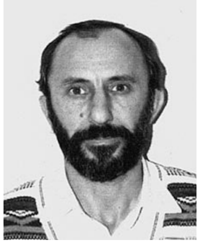
Since 1972, he has been with the Istituto Elettrotecnico Nazionale “Galileo Ferraris” (IEN), Torino, where he was initially involved in precision dc electrical measurements and in the development of the Josephson effect voltage standard. In 1986 and 1989, he was a Guest Scientist at the Electricity Division of the National Institute of Standard and Technology (NIST), Gaithersburg, MD. Since 1985, he has been engaged in the application of the quantum Hall effect for the reproduction of the unit of electrical resistance and, more recently, in voltage ratio measurements. From 1994 to 1998, he was in charge of the Electrical Metrology Department, IEN. Since 1999, he has been leading an IEN working group aimed at setting up a quality system for calibration and testing activity. He has been the chairman of the Euromet technical committee for Electricity and Magnetism.



Roberto Cerri was born in Torino, Italy, in 1956. He received the high school degree in electronics in 1978.

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Isabelle Blanc was born in Paris, France, in 1963. She received the Diplôme d’Ingénieur in mechanic-electricity from the Ecole Spéciale des Travaux Publics et de l’Industrie, France, in 1986.

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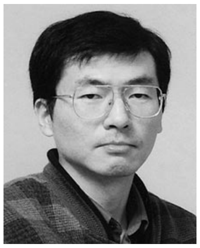

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He joined the National Standards Laboratory [now the National Measurement Laboratory (NML)], CSIRO, Linfield, Australia, in 1963 and has worked in electrical standards and related areas, including optical techniques for the measurement of high direct currents. In 1972, he was a guest worker in alternating-current standards at the Technion, Haifa, Israel. His main work at the NML has been in voltage standards, where he set up the Australian standard of voltage using Josephson arrays at the 1-V level and later at the 10-V level. He has also been involved in the Asia-Pacific Metrology Programme and in statistical aspects of high-accuracy metrology. He is an Electrical Assessor with the National Association of Testing Authorities and is a foundation member of the Metrology Society of Australia.

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He joined the Physics Division of the National Research Council of Canada, Ottawa, ON, in 1981. He became the Section Head of the Thermometry and Electrical Standards Section of the Laboratory for Basic Standards in 1986. His research concerns the Josephson volt, the quantum Hall effect, ac bridges, and cryogenic standards. He has been involved in fourteen international comparisons and has been the rapporteur of the Consultative Committee for Electricity and Magnetism three times.

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Eddie Tarnow was born in Johannesburg, South Africa, in 1960. He completed his two year compulsory military service and then received the National Higher Diploma for Technicians in electrical engineering, light current, through the Witwatersrand Technikon, South Africa.

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