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REPORT TO THE COMITÉ CONSULTATIF D'ÉLECTRICITÉ ON THE 1987 INTERNATIONAL COMPARISON OF ONE-OHM RESISTANCE STANDARDS AT THE BIPM AND THE RESULTING AGREEMENT AMONG DETERMINATIONS OF R_H

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REPORT TO THE COMITÉ CONSULTATIF D'ÉLECTRICITÉ ON THE 1987 INTERNATIONAL COMPARISON OF ONE-OHM RESISTANCE STANDARDS AT THE BIPM AND THE RESULTING AGREEMENT AMONG DETERMINATIONS OF $\underline{R}_H$

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Résumé - C'est lors de sa 17e session (septembre 1986) que le Comité Consultatif d'Electricité a demandé au BIPM d'organiser une comparaison internationale d'étalons de résistance de 1 Ω, limitée aux laboratoires qui mesurent la résistance de Hall quantifiée $\underline{R}_H$ ou qui réalisent des déterminations absolues de l'ohm. Le but principal de cette comparaison était d'évaluer l'accord existant entre les mesures de $\underline{R}_H$ réalisées par les différents laboratoires en fonction de leur représentation de l'ohm, $\underline{\Omega}_{LAB}$.

Onze laboratoires nationaux (CSIRO, ETL, IMM, LCIE, NBS, NIM, NPL, NRC, OFMET, PTB, VSL) ainsi que le BIPM ont participé à cette comparaison. Chaque laboratoire a fait parvenir au Bureau deux ou trois étalons voyageurs de 1 Ω (31 étalons au total). Ces 31 étalons, ainsi que les 6 étalons du Bureau qui matérialisent la représentation de l'ohm du BIPM ($\underline{\Omega}_{69-BI}$) ont été comparés à deux étalons de transfert du BIPM, fabriqués par le CSIRO et ayant de très faibles coefficients de température et de pression. Ces comparaisons ont été réalisées à l'aide d'un comparateur cryogénique de courants continus. Le même dispositif de mesure [7] a été utilisé pour rattacher les deux étalons de transfert à $\underline{R}_H$, immédiatement avant et après la comparaison.

Les différences $\underline{\Omega}_{LAB} - \underline{\Omega}_{69-BI}$ ont été évaluées à la date centrale de la comparaison (20 octobre 1987) avec une incertitude totale qui, à une exception près, est de l'ordre de 0,03 µΩ. La valeur de $\underline{\Omega}_{69-BI}$ en Ω, déduite de la comparaison avec le CSIRO et de la détermination de l'ohm réalisée par ce laboratoire, diffère de moins de 0,01 µΩ de la valeur attendue, calculée par extrapolation des résultats des comparaisons précédentes. Ceci confirme le fait que $\underline{\Omega}_{69-BI}$ dérive linéairement et indique également un bon accord entre l'ancien et le nouveau dispositif de mesure du BIPM.

La moyenne et l'écart-type pondérés des valeurs de $\underline{R}_H$ en $\underline{\Omega}_{69-BI}$, déduites des mesures de $\underline{R}_H$ en $\underline{\Omega}_{LAB}$ et en $\underline{\Omega}_{69-BI}$ réalisées dans les onze laboratoires nationaux et au BIPM, sont :

$$\underline{R}_H = 25\,812{,}8\,[1 + (2{,}059 \pm 0{,}021) \times 10^{-6}]\,\underline{\Omega}_{69-BI}\ (20\text{-}10\text{-}1987).$$

Les valeurs de $\underline{R}_H$ en $\underline{\Omega}_{69-BI}$, correspondant à cinq des six laboratoires qui annoncent une incertitude relative inférieure ou égale à $3{,}6 \times 10^{-8}$ sur la mesure de $\underline{R}_H$ en fonction de leur représentation de l'ohm, ainsi que la valeur extrapolée de la moyenne pondérée de mesures de $\underline{R}_H$ en $\underline{\Omega}_{69-BI}$ rapportées au 1er janvier 1986 [8], sont toutes incluses dans un intervalle de $6{,}6 \times 10^{-8}$. Cet accord excellent démontre qu'il est maintenant possible d'utiliser l'effet Hall quantique pour réaliser une représentation de l'ohm invariable et reproductible à quelques 10^{-8} près.

Abstract - In order to evaluate the agreement among determinations of the quantized Hall resistance, R_H, at the request of the CCE the BIPM organized and conducted an international comparison of one-ohm resistance standards among twelve laboratories. The weighted mean and standard deviation are $R_H = 25\,812{,}8\,[1 + (2{,}059 \pm 0{,}021) \times 10^{-6}]\,\Omega_{69-BI}$ on October 10, 1987. Values and uncertainties for R_H in Ω_{LAB} and for $\Omega_{LAB} - \Omega_{69-BI}$ are given.

I. INTRODUCTION

In September 1986, the 17th meeting of the Comité Consultatif d'Electricité (CCE) expressed its intention to meet in September 1988 to recommend an internationally accepted value for the quantized Hall resistance, R_H, to be used from January 1, 1990 by national standards laboratories to maintain representations of the ohm by means of the quantum Hall effect. To aid it in setting a conventional value of R_H as close as possible to the best estimates of its SI value and to evaluate the international uniformity to be gained by its implementation, the CCE requested the Bureau International des Poids et Mesures (BIPM) to carry out an international comparison of one-ohm resistance standards limited to those laboratories measuring R_H or making absolute determinations of the ohm. The measurements at the BIPM were carried out using new equipment and procedures outlined in Section II. In Section III we present the results of each determination of R_H in terms of the local laboratory representation of the ohm (Ω_{LAB}), the difference $\Omega_{LAB} - \Omega_{69-BI}$ and the resulting values of R_H in Ω_{69-BI}. The corresponding uncertainty estimates as well as some estimates of the a posteriori uncertainty in travelling standards are also given in Section III. In Section IV we discuss some general conclusions of this comparison.

II. EXPERIMENTAL PROCEDURES AND EQUIPMENT

A. Requested procedural rules

Among the laboratories solicited, eleven responded affirmatively, indicating that they would provide a link between their travelling standards and their own determination of $\underline{R}_H$, the absolute ohm, or both. The eleven participating national laboratories were the following:

CSIRO, Division of Applied Physics (CSIRO), Lindfield;
Electrotechnical Laboratory (ETL), Ibaraki;
Institut de Métrologie D.I. Mendéléev (IMM), Leningrad;
Laboratoire Central des Industries Electriques (LCIE), Fontenay-aux-Roses;
National Bureau of Standards (NBS), Gaithersburg;
National Institute of Metrology (NIM), Beijing;
National Physical Laboratory (NPL), Teddington;
National Research Council of Canada (NRC), Ottawa;
Office Fédéral de Métrologie (OFM), Wabern;
Physikalisch-Technische Bundesanstalt (PTB), Braunschweig;
Van Swinden Laboratorium (VSL), Delft.

Thus, including the BIPM, twelve laboratories took part in the comparison.

Each participant was requested to send three one-ohm travelling standards along with values of their temperature and pressure coefficients at 20 °C and 101 325 Pa (the reference values), precise but "preliminary" values of the travelling standards and estimates of their drift rates. It was hoped that the latter two data could help uncover possible unusual behavior of the travelling standards in case of mishaps in transport. This proved to be useful in two cases and we recommend that in future comparisons laboratories endeavor to have ready several back-up travelling standards which have been measured at the same time as those sent to the BIPM and which can replace the travelling standards in case of need. The laboratories were informed that the BIPM's measurements would be made at a current of 50 mA. All final results are meant to be referred to this value of current. Laboratories measuring at different currents were requested to correct their results to this value.

B. Equipment at the BIPM

The equipment and procedures used at the BIPM differed greatly from the previous comparison [1]. The six one-ohm standards, the mean of which defines our representation of the ohm, designated Ω_{69-BI}, were treated almost in the same way as the travelling standards. All resistors, including those of the BIPM were compared to two transfer resistors, 905 and 907, designed and built by the CSIRO [2], to have small temperature and pressure coefficients and, for these reasons, introducing lower uncertainty than Ω_{69-BI} itself. The most important new equipment is the resistance bridge based on a cryogenic current comparator (CCC) [3], [4]. The CCC bridge permits the establishment of an accurately known, adjustable ratio of current passing through one-ohm resistors in separate circuits. This current ratio, which is maintained rigorously constant by feedback from a SQUID, and the measured difference in voltage drops across the resistors, give the ratio of their resistances. A desktop microcomputer acquires and treats voltmeter readings, switches current polarities, calculates resistance ratios and stores data.

The equipment for measuring the temperature and pressure is also new. A calibrated platinum resistance thermometer is located in a fixed position in the oil bath containing the transfer standards and the resistors to be measured. The reference junctions of 12 copper-constantan thermocouples are closely coupled thermally to the thermometer. The second junction of each thermocouple pair is placed in the thermometer wells of the resistors in the bath. Temperature differences between the thermometer and the oil at the centers of the resistors are determined from digital nanovoltmeter readings. The estimated type A uncertainty is 0,25 mK. (All uncertainties here are one-standard-deviation estimates.) The atmospheric pressure is measured with an uncertainty of about 10 Pa with a calibrated digital manometer, Crouzet model 2100, equipped with an IEEE-488 bus.

Because of the importance of $\underline{\Omega}_{69-BI}$ as an international reference used, for example, as an auxiliary constant in the adjustment of the fundamental physical constants [5], it was considered advisable to compare results obtained with the new CCC-based bridge with those from the BIPM's old double bridge. This was done in a comparison of one-ohm travelling standards from the NPL, in April 1987. Mean results from the two systems differed in relative value by less than 1×10^{-8}, an amount rather less than the uncertainty of the double bridge. The final result, deduced from the CCC measurements, of three travelling standards was that, on April 24, 1987 [6]:

$$\underline{\Omega}_{NPL} - \underline{\Omega}_{69-BI} = (0,34 \pm 0,02)\ \mu\Omega .$$

The uncertainty is the root-sum-square of the combined type A and type B components. It is an indication of the accuracy we expected to achieve in the present comparison.

C. Procedure for comparison of two resistors

The comparison of two resistors begins with the measurements of the depth of oil above the top plates of the resistors in order to calculate the pressure of the oil. Then the platinum resistance thermometer is read, followed by readings of the two thermocouples and the manometer. The electrical measurement sequence consists in setting up the 50 mA current in the normal polarity and reading the voltage difference on a picovoltmeter, integrating over about two minutes. The current polarities are then reversed and the voltage measurements repeated. With the current polarities back in the original directions, a third set of voltage measurements is obtained. Using a linear interpolation technique, the resistance ratio is calculated. Polarity reversals are continued until a total of nine sets of voltage measurements are completed. Statistically these are considered as three independent determinations of the resistance ratio. In a typical run, the standard deviation of the mean of the three determinations is about 1 to 2×10^{-9}. The temperature and pressure measurements are repeated, the final results calculated and the data are stored.

The high resolution of the BIPM bridge allowed us to identify anomalous behavior associated with low leakage resistance (as little as 20 MΩ) in some one-ohm travelling standards.

D. Complete comparison scheme

Measurements of the travelling standards were carried out from September 24 to November 17, 1987. The mean date, to which all results will be referenced, is October 20, 1987. Each travelling standard was compared to the two transfer standards five times at intervals of about 11 days. A linear least-squares fit was calculated for the ratios of the resistance of each travelling standard to each transfer resistor. For 34 of the 37 participating resistors the average of the standard deviation of the predicted value of a travelling standard with respect to the transfer standards on the mean date of the comparison is $3,4 \times 10^{-9}$. Similar least-squares fits were made to data from seven comparisons of the resistors forming $\underline{\Omega}_{69-BI}$ to the two transfer standards. The drift rates, relative to $\underline{\Omega}_{69-BI}$, and their uncertainties were (- 0,23 ± 0,11) nΩ/d and (0,014 ± 0,08) nΩ/d. The standard deviations from the predicted values in $\underline{\Omega}_{69-BI}$ of the transfer resistors on the mean date were 2,3 nΩ and 1,5 nΩ. The fact that these uncertainties are comparable in magnitude to the type A uncertainty of a single comparison run implies that no significant random scatter arises from influences such as temperature and pressure which generally vary from run-to-run. To verify the absolute stability of the transfer standards, they were compared with a relative uncertainty of about 1×10^{-8} to the BIPM's quantum Hall resistance [7]. The result indicated changes of about 0,01 μΩ and 0,02 μΩ in the two standards. The relative drift of these two resistors throughout the comparison was confirmed by repeated direct comparisons.

It is difficult to generalize the type B uncertainties to assign to the measurement of a 1 Ω resistor in terms of $\underline{\Omega}_{69-BI}$ because of the great variation (factors of 500 or more) among temperature or pressure coefficients. In general, for rather good quality resistors we estimate equivalent 1-σ uncertainties of about 10 nΩ for effects of temperature and 10 nΩ for uncorrected influences of pressure. The uncertainties due to leakage resistance and the winding ratio are less than 1 nΩ. The uncertainty in the calibration of the resistive divider used to equilibrate the CCC by injecting a known current in the compensation winding is about 5 nΩ. This gives a total type B uncertainty of about 15 nΩ.

III. RESULTS*

Table I gives the results of the comparison of the one-ohm travelling standards with Ω_{69-BI}. The initial and return values of the travelling standards in Ω_{LAB} are listed in columns 2 and 3. In column 4 we give the value of the travelling standards in Ω_{LAB} on 1987-10-20. These are obtained using a linear interpolation between the initial and return measurements for all but two laboratories ; NBS and OFM provided predicted values of their travelling standards on 1987-10-20 based on linear least-square fits to results of measurements made before and after the BIPM measurements. The initial and return results for NBS were calculated from separate sets of 28 and 32 measurements carried out before and after the measurements at BIPM. Column 5 lists the values of the travelling standards in Ω_{69-BI} on 1987-10-20, as measured at BIPM using the procedure described in sections II.C and II.D. Column 6 gives the individual and mean values of $\Omega_{LAB} - \Omega_{69-BI}$ deduced from columns 4 and 5. The standard deviation of the mean value, s_M, is listed in column 7.

Table II summarizes the results of the comparison and the determinations of R_H. Data in the second column are supplied by the laboratories and should have been referred to October 20, 1987. In those cases where R_H in Ω_{LAB} was not referred to this date by the laboratory, we have specified the reference date. We assume that the change in Ω_{LAB} between the two dates is negligible. Two laboratories (OFM and PTB) reported values of R_H from measurements reported in 1986 [8] and extrapolated by those laboratories to the central

* Note added in proof. Portions of this report were presented at CPEM-88 in Tsukuba in June 1988 and preprints of the results were distributed to the participants in the comparison. The present version, put into final form on August 19, 1988, incorporates modifications of values communicated to us by participants during the period June 7 to August 18, 1988.

date of the comparison. In a departure from previous practice, the CSIRO reported its values of $\underline{R}_H$ and the travelling standards in terms of an $\underline{\Omega}_{LAB}$ maintained by standard resistors. Previously they had reported values in terms of the CSIRO's realization of the ohm by the calculable capacitor. The ETL does not maintain $\underline{\Omega}_{ETL}$ in the form of standard resistors. The uncertainty listed for them in column 2 is that for the determination of $\underline{R}_H$ in terms of a set of one-ohm-resistors.

Column 3 lists the value of $\underline{\Omega}_{LAB} - \underline{\Omega}_{69-BI}$ at the standard conditions of temperature, pressure and power dissipation stated in Section I.A. The uncertainties are combinations of type A and type B uncertainties and correspond to those of column 6 of Table III.

In column 4 we give the value deduced for $\underline{R}_H$ in $\underline{\Omega}_{69-BI}$ on the central date of the comparison. The values and uncertainties are deduced from the two previous columns except for the uncertainty for the LCIE, who measured the transfer standards directly in terms of $\underline{R}_H$.

The results of column 4 are presented graphically in Fig. 1 along with a value of the weighted mean and standard deviation. The weights were the reciprocals of the variances from column 4 of Table II. The final result is

$$\underline{R}_H = 25\ 812{,}8\ [1 + (2{,}059 \pm 0{,}021) \times 10^{-6}]\ \underline{\Omega}_{69-BI} \text{ on 1987-10-20 .} \qquad (1)$$

The above calculation gives a large weight to the BIPM's determination of $\underline{R}_H$ since its transfer uncertainty is zero. Recalculating a weighted mean and standard deviation without the BIPM results gives

Without BIPM:

$$\underline{R}_H = 25\ 812{,}8\ [1 + (2{,}048 \pm 0{,}031) \times 10^{-6}]\ \underline{\Omega}_{69-BI} \text{ on 1987-10-20,} \qquad (2)$$

i.e. a result practically identical to that obtained with the BIPM values. We see no reason to delete the BIPM results and we take the first value for the final result of this comparison.

The value of $\underline{R}_H$ in (1) can be compared with the corresponding weighted mean value from the results in [8] which are referred to the date of 1986-01-01. For the OFM and the PTB, the 1986 results are already included in (1); so we deleted them in the calculation of the 1986 value. To extrapolate $\underline{\Omega}_{69-BI}$ from 1986-01-01 to 1987-10-20 we use the results of (6) below. This gives for the 1986 $\underline{R}_H$ value extrapolated to 1987-10-20:

$$\underline{R}_H = 25\ 812{,}8\ [1 + (2{,}034 \pm 0{,}044) \times 10^{-6}]\ \underline{\Omega}_{69-BI} \text{ on 1987-10-20 .} \qquad (3)$$

This is in good agreement with the 1987 value in (1).

The uncertainties listed in column 3 of Table II were derived from the components given in Table III. Data in the second and third columns were provided by the participants. The fourth column gives the standard deviation of the mean calculated from the values of $\underline{\Omega}_{LAB} - \underline{\Omega}_{69-BI}$ deduced from each travelling standard. The type B uncertainties are estimated as described in Section II.D.

The histogram in Fig. 2 indicates the scatter obtained in the value of $\underline{\Omega}_{LAB} - \underline{\Omega}_{69-BI}$ obtained from travelling standard $\underline{i}$ with respect to the mean value of $\underline{\Omega}_{LAB} - \underline{\Omega}_{69-BI}$ obtained from all travelling standards from a given laboratory. The two travelling standards from one laboratory are deleted since one of them, we do not know which one, underwent an unusually large change. For the data in Fig. 2, the pooled standard deviation is 0,034 μΩ. This is an estimate of the transfer uncertainty of the travelling standards. It is noteworthy that if the same analysis is made using only the results from the seven transfer standards made by the CSIRO, the corresponding pooled standard deviation is 0,010 μΩ.

The value of $\underline{\Omega}_{LAB} - \underline{\Omega}_{69-BI}$ on 1987-10-20 from the CSIRO, combined with the value of $\underline{\Omega}_{LAB}$ in terms of the CSIRO realization of the ohm by the calculable capacitor, namely, $\underline{\Omega}_{LAB} - \Omega = (0{,}030 \pm 0{,}005)$ μΩ, allows us to calculate a value for $\underline{\Omega}_{69-BI}$ in Ω, based on the CSIRO determination of the ohm, for 1987-10-20. The value is

$$\underline{\Omega}_{69-BI} - \Omega = -\,(1{,}731 \pm 0{,}017)\ \mu\Omega \ . \tag{4}$$

The above uncertainty is only that component of the total uncertainty (types A and B combined) which is expected to vary in time. From previous results [9], we would have expected

$$\underline{\Omega}_{69-BI} - \Omega = -\,(1{,}738 \pm 0{,}011)\ \mu\Omega \ , \tag{5}$$

a remarkably good agreement. From the results and uncertainty in (4), and all of the previous data linking $\underline{\Omega}_{69-BI}$ to the CSIRO determination of the ohm [9], we have recalculated a weighted, linear, least-squares fit. The result is

$$\underline{\Omega}_{69-BI} - \Omega = \underline{a} + \underline{b}\,\underline{t} \ , \tag{6}$$

where $\underline{a} = -\,(1{,}733 \pm 0{,}007)$ μΩ ,
$\underline{b} = -\,(0{,}0614 \pm 0{,}0011)$ μΩ/a ,
$\underline{t}$ is time, in years, measured from 1987-10-20 ,

and all uncertainties are of type A only.

The data are shown in Fig. 3. The error bars represent the total uncertainties assigned by the CSIRO to each point. The results in (6) can be used to express the result of the weighted value of $\underline{R_H}$ from (1) in Ω. The result is

$$\underline{R_H} = 25\ 812{,}8\ [1 + (0{,}326 \pm 0{,}067) \times 10^{-6}]\ \Omega\ , \qquad (7)$$

where we have included the type B uncertainty of 0,062 $\mu\Omega$ estimated by the CSIRO for its ohm determination [10].

IV. CONCLUSIONS

The limited international comparison of one-ohm resistances standards yields values of $\underline{\Omega_{LAB}} - \underline{\Omega_{69-BI}}$ having typical total uncertainties of about 0,03 $\mu\Omega$, a value nearly equal to the typical random scatter of 0,034 $\mu\Omega$. The comparison with the CSIRO resulted in a value for $\underline{\Omega_{69-BI}}$ in Ω, based on the CSIRO determinations of the ohm, which was very close to the anticipated value, reconfirming the predictibility of $\underline{\Omega_{69-BI}}$ with a completely new measurement system at the BIPM.

The weighted mean and standard deviation of the values of $\underline{R_H}$ in $\underline{\Omega_{69-BI}}$, deduced from measurements of $\underline{R_H}$ in $\underline{\Omega_{LAB}}$ made in the 12 participating laboratories are :

$$\underline{R_H} = 25\ 812{,}8\ [1 + (2{,}059 \pm 0{,}021) \times 10^{-6}]\ \underline{\Omega_{69-BI}} \text{ on } 1987\text{-}10\text{-}20\ .$$

The values of $\underline{R}_H$ for five of the six laboratories claiming a relative uncertainty of 3,6 × 10^{-8} or less in their measurements of $\underline{R}_H$ in terms of Ω_{LAB} as well as the extrapolated value of the weighted mean of $\underline{R}_H$ from 1986 all lie within an interval of 6,6 × 10^{-8}. This excellent agreement demonstrates that it is now possible to use the quantum Hall effect to realize a representation of the ohm having a world-wide reproducibility and stability in time of a few parts in 10^8.

ACKNOWLEDGEMENT

We thank all of our colleagues in the national laboratories who participated in the resistance comparison and who provided values of $\underline{R}_H$.

CAPTIONS

Table I. Values $\underline{R}$ of the travelling standards in Ω_{LAB} and Ω_{69-BI} and corresponding values, in μΩ, of the differences $\Omega_{LAB} - \Omega_{69-BI}$ on 1987-10-20. $\underline{s}_M$ is the standard deviation of the mean, in μΩ, of the differences $\Omega_{LAB} - \Omega_{69-BI}$.

Table II. Measured values of $\underline{R}_H$ on 1987-10-20 in terms of Ω_{LAB} and in terms of Ω_{69-BI} using the results of the comparison. Values are expressed as $\underline{R}_H = 25\,812{,}8\ (1 + \underline{\Delta} \times 10^{-6})\ \Omega_j$, where $\Omega_j = \Omega_{LAB}$ or Ω_{69-BI}.

Table III. Uncertainties in $\Omega_{LAB} - \Omega_{69-BI}$ in parts in 10^8.

Fig. 1. Values of $\underline{R}_H$ in $\underline{\Omega}_{69-BI}$ on 1987-10-20 expressed as fractional deviations from 25 812,8 $\underline{\Omega}_{69-BI}$. The error bars surrounding each datum represent the uncertainty in $\underline{R}_H$ in $\underline{\Omega}_{LAB}$ (smaller) and the uncertainty in $\underline{R}_H$ in $\underline{\Omega}_{69-BI}$. The solid horizontal line and parallel dashed lines represent the weighted mean and standard deviation. The datum represented by an open square and bar is the weighted average and standard deviation of the corresponding 1986 value extrapolated using the known drift of $\underline{\Omega}_{69-BI}$.

Fig. 2. Dispersion of $\underline{\Omega}_{LAB}$ - $\underline{\Omega}_{69-BI}$ for the 1987 limited international comparison of resistance.

Fig. 3. Variation in time of $\underline{\Omega}_{69-BI}$ deduced from determinations of the ohm at the CSIRO. The error bars represent the total combined uncertainty of each determination. The line results from a weighted fit taking into account only the component of the total uncertainty which is expected to vary in time.

Table I

Values R of the travelling standards in Ω_{LAB} and Ω_{69-BI} and corresponding values, in μΩ, of the differences $\Omega_{LAB} - \Omega_{69-BI}$ on 1987-10-20. s_M is the standard deviation of the mean, in μΩ, of the differences $\Omega_{LAB} - \Omega_{69-BI}$.

	$(\frac{R}{\Omega_{LAB}} - 1)\ 10^{-6}$			$(\frac{R}{\Omega_{69-BI}} - 1)\ 10^{-6}$	$\Omega_{LAB} - \Omega_{69-BI}$ in μΩ	
Standard	Initial	Return	1987-10-20	1987-10-20	1987-10-20	s_M in μΩ
			PTB			
	1987-09-24	1987-12-15				
730951	- 25,670	- 25,880	- 25,736 6	- 24,505 7	+ 1,230 9	
730955	- 23,363	- 23,396	- 23,373 5	- 22,075 0	+ 1,298 5	
692273	- 20,016	- 20,199	- 20,074 0	- 18,846 4	+ 1,227 6	
					+ 1,252 3	0,023 1
			CSIRO			
	1987-09-02	1988-01-01				
S-60650	+ 29,411	+ 29,510	+ 29,450 2	+ 31,213 7	+ 1,763 5	
S-60657	- 1,470	- 1,427	- 1,453 0	+ 0,305 2	+ 1,758 2	
S-64144	- 9,976	- 9,899	- 9,945 5	- 8,184 7	+ 1,760 8	
					+ 1,760 8	0,001 5
			NRC			
	1987-08-26	1987-12-27				
336435	- 3,19	- 3,39	- 3,279	- 4,771 0	- 1,492	
336436	- 5,10	- 5,34	- 5,207	- 6,722 3	- 1,515	
336437	- 4,11	- 4,27	- 4,182	- 5,649 9	- 1,468	
					- 1,492	0,013 6
			NIM			
	1987-08-27	1988-02-04				
127BZ13	- 11,55	- 11,72	- 11,607 0	- 11,236 4	0,370 6	
601BZ13	- 26,20	- 26,32	- 26,240 2	- 25,803 7	0,436 5	
645BZ13	- 23,77	- 23,69	- 23,743 2	- 23,245 7	0,497 5	
					0,434 9	0,036 7
			NBS			
	1987-08-22	1988-01-05				
77	+ 5,966	+ 5,892	+ 5,934	+ 6,128 5	+ 0,194 5	
S-60659	+ 2,349	+ 2,342	+ 2,346	+ 2,595 0	+ 0,249 0	
S-60906	+ 6,708	+ 6,718	+ 6,712	+ 6,987 2	+ 0,275 2	
					+ 0,239 6	0,023 8

Table I (end)

Standard	$(\frac{R}{\Omega_{LAB}} - 1)\ 10^{-6}$ Initial	$(\frac{R}{\Omega_{LAB}} - 1)\ 10^{-6}$ Return	$(\frac{R}{\Omega_{LAB}} - 1)\ 10^{-6}$ 1987-10-20	$(\frac{R}{\Omega_{69-BI}} - 1)\ 10^{-6}$ 1987-10-20	$\Omega_{LAB} - \Omega_{69-BI}$ in $\mu\Omega$ 1987-10-20	s_M in $\mu\Omega$
			LCIE			
	1987-08-10	1988-01-25				
732525	- 22,690	- 22,688	- 22,689	- 21,577 6	+ 1,111 4	
732530	- 22,880	- 22,885	- 22,882	- 21,782 4	+ 1,099 6	
732532	- 22,660	- 22,652	- 22,657	- 21,559 2	+ 1,097 8	
					+ 1,102 9	0,004 3
			ETL			
	1987-09-05	1988-02-04				
70C111	+ 0,938	+ 0,688	+ 0,864 0	+ 2,825 0	+ 1,961 0	
70C122	+ 5,248	+ 5,088	+ 5,200 6	+ 7,093 4	+ 1,892 8	
72C202	- 2,622	- 2,802	- 2,675 3	- 0,779 4	+ 1,895 9	
					+ 1,916 6	0,022 2
			VSL			
	1987-10-25	1988-04-23	1987-11-16 Ω_{LAB}	1987-11-16 Ω_{69-BI}	(1987-11-16)	
1773191	- 24,277	- 24,347	- 24,285 5	- 23,689 6	+ 0,595 9	
1805643	- 21,814	- 21,879	- 21,821 9	- 21,207 4	+ 0,614 5	
					+ 0,605 2	0,009 3
			NPL			
	1987-09-04	1987-12-17				
L-713	+ 49,126	+ 49,145	+ 49,134 4	+ 49,448 0	+ 0,313 6	
S-60652	+ 54,156	+ 54,176	+ 54,164 8	+ 54,525 8	+ 0,361 0	
S-60656	+ 11,700	+ 11,714	+ 11,706 2	+ 12,078 0	+ 0,371 8	
					+ 0,348 8	0,017 9
			OFM			
	1987-09-10	1988-01-17				
1624034	- 26,790	- 26,821	- 26,805	- 26,550 4	+ 0,254 6	
1844266	- 25,982	- 26,027	- 26,005	- 25,723 6	+ 0,281 4	
					+ 0,268 0	0,013 4
			IMM			
	1987-09-09	1988-03-09				
710	- 5,140	- 5,190	- 5,151	- 3,747 4	+ 1,403 6	
922	+ 12,760	+ 12,790	+ 12,767	+ 14,438 7	+ 1,671 7	
					+ 1,537 7	0,134 1

Table II. Values of R_H expressed as $R_H = 25\ 812{,}8\ (1 + \Delta \times 10^{-6})\ \Omega_j$, where $\Omega_j = \Omega_{LAB}$ or $\Omega_{69\text{-}BI}$.

LAB	Δ and uncertainty for R_H in Ω_{LAB} on 1987-10-20	value and uncertainty for $\Omega_{LAB} - \Omega_{69\text{-}BI}$ on 1987-10-20, in µΩ	Δ and uncertainty for R_H in $\Omega_{69\text{-}BI}$ on 1987-10-20
BIPM	not applicable	not applicable	2,069 ± 0,015
CSIRO/NML	0,340 ± 0,030 [a]	1,761 ± 0,015	2,101 ± 0,034
ETL [b]	0,247 ± 0,080	1,917 ± 0,027	2,164 ± 0,084
IMM	0,197 ± 0,070 [c]	1,538 ± 0,136	1,735 ± 0,153
LCIE	0,942 ± 0,036	1,103 ± 0,037	2,045 ± 0,041 [d]
NBS	1,843 ± 0,012	0,240 ± 0,028	2,083 ± 0,031
NIM	1,193 ± 0,372 [e]	0,435 ± 0,050	1,628 ± 0,375
NPL	1,712 ± 0,025	0,349 ± 0,027	2,061 ± 0,037
NRC	3,711 ± 0,066	-1,492 ± 0,036	2,219 ± 0,075
OFM	1,906 ± 0,121	0,268 ± 0,032	2,174 ± 0,125
PTB	0,569 ± 0,120	1,252 ± 0,031	1,821 ± 0,122
VSL	1,263 ± 0,030 [f]	0,605 ± 0,027 [g]	1,868 ± 0,040

[a] CSIRO reported its results in terms of an Ω_{LAB}; they deduced $\Omega_{LAB} = 1\Omega + 0{,}030\ \mu\Omega$, with a type A uncertainty of 0,005 µΩ, for the period 1987-08-24 to 1988-03-02.

[b] ETL did not use an intermediate group of resistors corresponding to an Ω_{LAB}; values of their travelling standards were determined directly in terms of the QHE using $R_H = 25\ 812{,}806\ 4\ \Omega_{ETL}$.

[c] using $\Delta = 0{,}190 \pm 0{,}070$ on 1988-04-21 and assuming (0,015 ± 0,010) µΩ/a for the drift rate of Ω_{IMM}.

[d] relative uncertainties of $3{,}6 \times 10^{-8}$ for R_H in terms of travelling standards and $2{,}0 \times 10^{-8}$ for travelling standards in terms of $\Omega_{69\text{-}BI}$.

[e] referred to 1988-05-01.

[f] referred to 1987-12-20.

[g] referred to 1987-11-16.

Table III. Relative uncertainties in $\Omega_{LAB} - \Omega_{69\text{-}BI}$ in parts in 10^8.

LAB	value of $\Omega_{LAB} - \Omega_{69\text{-}BI}$ µΩ	uncertainty for travelling standards in Ω_{LAB} ; type		value of σ_m for the transfer; type A	uncertainty for travelling standards in $\Omega_{69\text{-}BI}$; type B	RSS total uncertainty
CSIRO	1,761	1	A&B	0,2	1,1	1,5
ETL	1,917	0	-	2,2	1,5	2,7
IMM	1,858	1,5	A&B	13,4	1,5	13,6
LCIE	1,103	3,3	B	0,4	1,5	3,7
NBS	0,240	1	B	2,4	1,1	2,8
NIM	0,435	3	A&B	3,7	1,5	5,0
NPL	0,349	1,7	A&B	1,8	1,1	2,7
NRC	-1,492	3	A&B	1,4	1,5	3,6
OFM	0,268	2,5	A&B	1,3	1,5	3,2
PTB	1,252	2	A&B	2,3	1,5	3,1
VSL	0,605	2,1	B	0,9	1,5	2,7

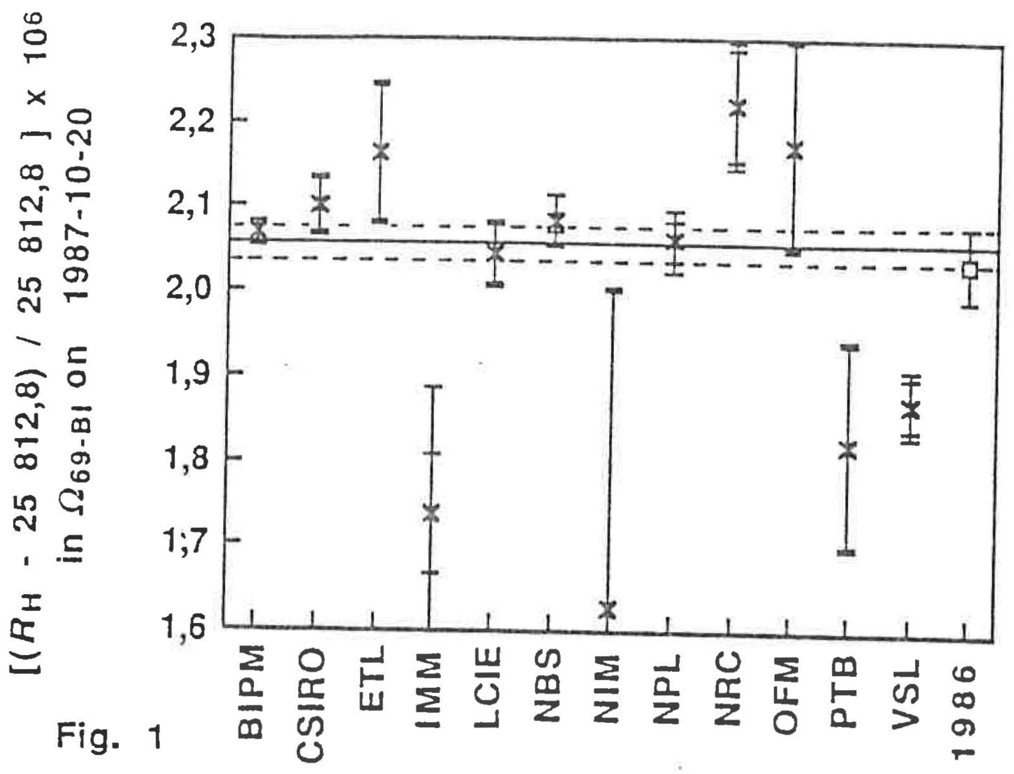

Fig. 1

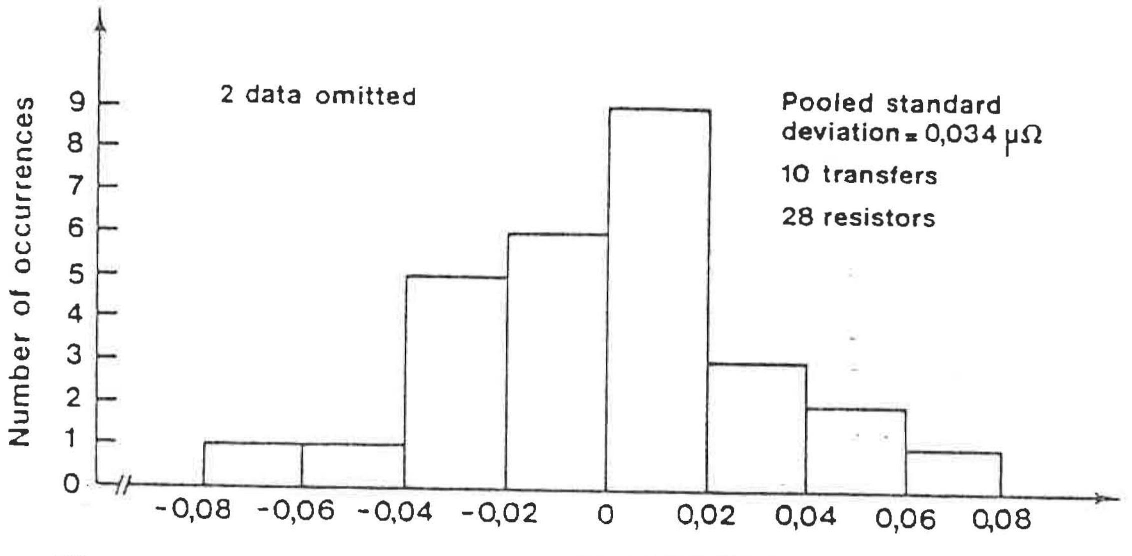

Fig. 2 $(\Omega_{LAB} - \Omega_{69-BI})_i - (\overline{\Omega_{LAB} - \Omega_{69-BI}})$ (μΩ)

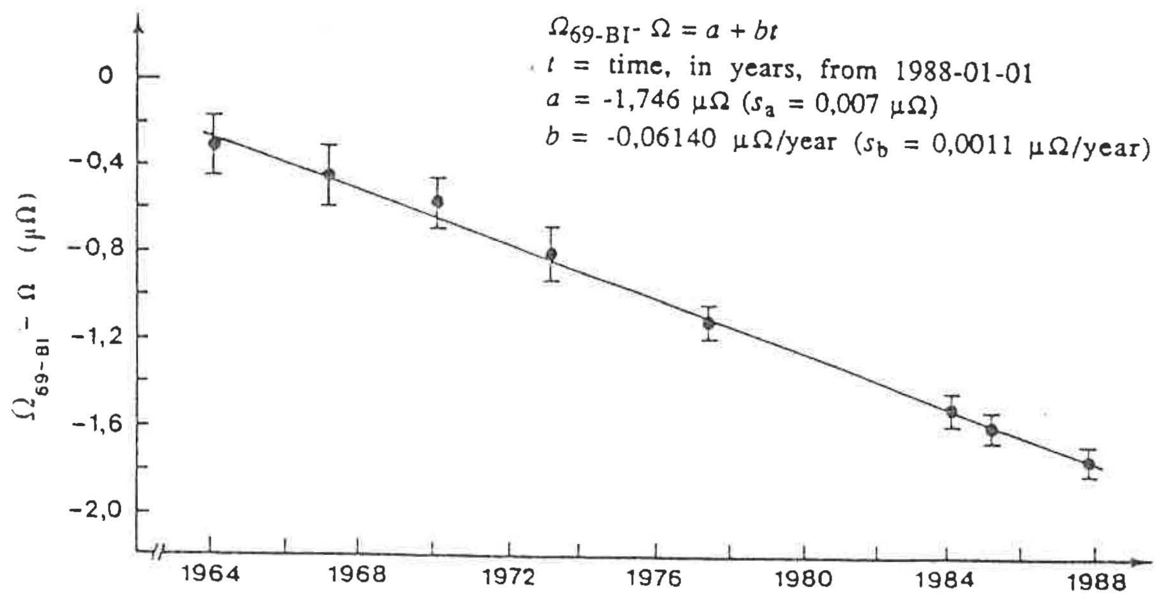

Fig. 3

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