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A comparison of the 10 kΩ reference standards of the BIPM and the National Metrology Laboratory, (NML), Dublin, Ireland was carried out from February to June 2002. Two BIPM 10 kΩ travelling standards, B10K07 and B10K11 were shipped to the NML by air courier. The BIPM measurements of the travelling standards were carried out by comparison with BIPM 10 kΩ reference standards using a Warshawsky bridge. The BIPM 10 kΩ reference standards are calibrated in terms of a 100 Ω reference resistor whose value is known with respect to the BIPM Quantized Hall Resistance (QHR) standard. The NML measurements were carried out using a Measurements International Limited 6000A resistance bridge to compare the 10 kΩ travelling standards with its 10 kΩ reference resistors. The values of the 10 kΩ reference resistors are known by extrapolation of their secular behaviour based on the results of previous comparisons with the BIPM at the 10 kΩ level. The measuring current in the 10 kΩ resistors was 0.5 mA for both laboratories. Results of all NML and BIPM measurements were corrected to 23 °C and 101325 Pa for the dependence of the resistances of the travelling standards on ambient temperature and pressure.

Figures 1 and 2 show the measured values obtained for the two standards by the two laboratories. The BIPM values and uncertainties are calculated for the reference date, the mean date of the NML measurements (16 March 2002), from linear least-squares fits. Those of the NML are calculated from the mean of the measured values.

Table 1 lists the results and the component uncertainty contributions for the comparison NML/BIPM. Table 2 lists the uncertainties of maintenance and measuring equipment at the BIPM and Table 3 lists the uncertainties of maintenance and measuring equipment at the NML.

The following elements are listed in Table 1:

(1) the mean resistance value R_{NML} of each resistor measured by the NML;
(2) the type-A uncertainty due to the instability of the resistors and the measuring equipment, computed as the standard uncertainty of the mean value;

(3) the type-B uncertainty component due the measuring equipment of the NML. This uncertainty is partially correlated between the different travelling standards used for a comparison and the contributions that are completely or at least partially correlated are indicated by asterisks (*) in Table 3 ;

(4-6) the corresponding quantities for the BIPM;

(7) the difference ($R_{\mathrm{NML}} - R_{\mathrm{BIPM}}$) for each resistor, and (8) the clearly uncorrelated (type-A) part of the uncertainty;

(9) the result of the comparison which is the mean of the differences of the calibration results for the different standards;

the uncertainty of the transfer, estimated by two methods:

(10) the standard deviation of the mean value of the results, from the different resistors, counting only the type-A uncertainties of the individual results;

(11) the *a posteriori* uncertainty, which is the standard deviation of the mean of the two different results, s_{M};

(12) the total uncertainty of the comparison, which is the root-sum-square of the type-A and type-B uncertainties.

In Table 1, the type-A uncertainties are negligible compared to the estimated type-B uncertainties. We compare these with the *a posteriori* uncertainty estimated by the standard deviation of the mean of the results from the two travelling standards, line 11. (With only two travelling standards, the uncertainty of the standard deviation of the mean is comparable to the value of the standard deviation of the mean itself.) If the *a posteriori* uncertainty is significantly different from the type-A uncertainty, as is the case here, we assume either that a standard has changed in an unusual way (but the BIPM measurement results before and after transporting the travelling standards, Figure 1 and Figure 2, show no evidence of this) or that some factors listed in the type-B uncertainty budget for the NML can give rise to residual errors that differ among the travelling standards. The correlations between the type-B uncertainties when measuring different standards are unknown. As usual, the larger of the two uncertainties, here the *a posteriori* uncertainty, is retained to evaluate the total comparison uncertainty.

The final results of the comparison are presented as the difference between the value assigned to a 10 kΩ standard by each laboratory. The difference between the value assigned by the NML, at the NML, R_{NML}, and that assigned by the BIPM, at the BIPM, R_{BIPM}, for the reference date is

$$R_{\mathrm{NML}} - R_{\mathrm{BIPM}} = 0.07\ \mathrm{m}\Omega\ ;\ u_{\mathrm{c}} = 5.9\ \mathrm{m}\Omega \text{ on } 2002/03/16,$$

where u_{c} is the combined type-A and type-B standard uncertainty from both laboratories.

This is a most satisfactory result. The difference between the values assigned to the travelling standards by the two laboratories is much less than the standard uncertainty associated with the difference.

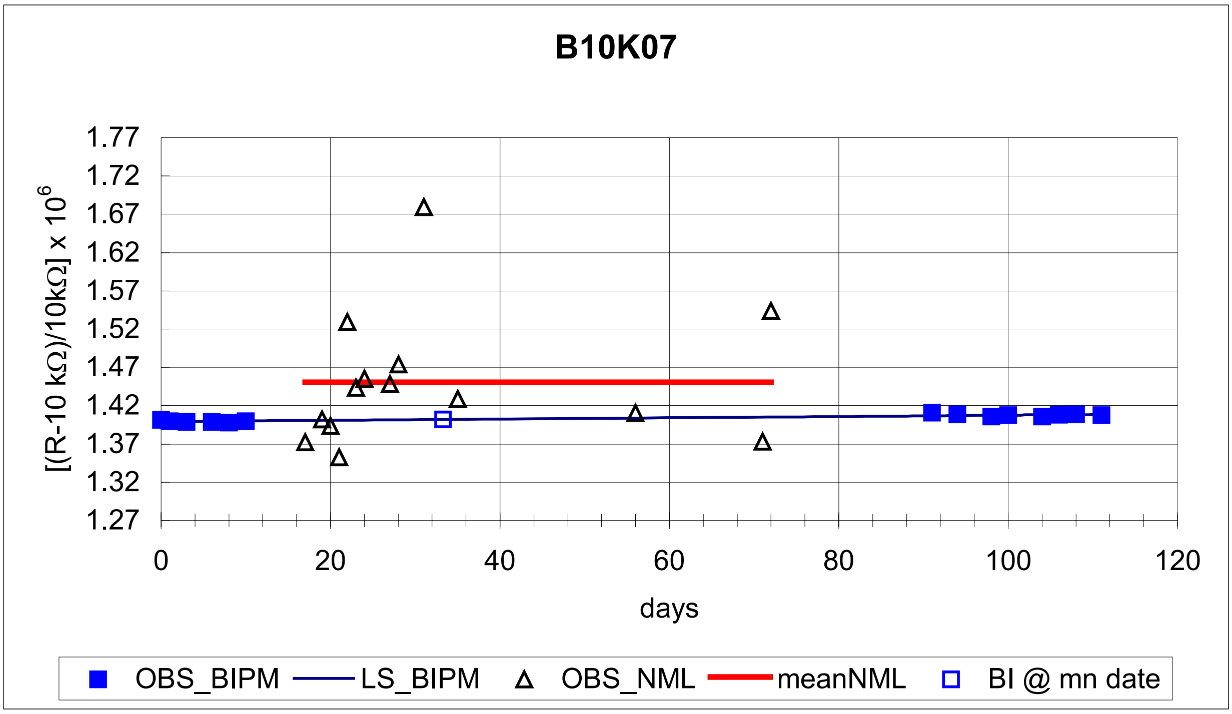

Figure 1. Relative deviation from the nominal 10 kΩ value of the resistance of B10K07 vs time: a linear least-squares fit (LS) to the BIPM measurements and the mean of the NML measurements.

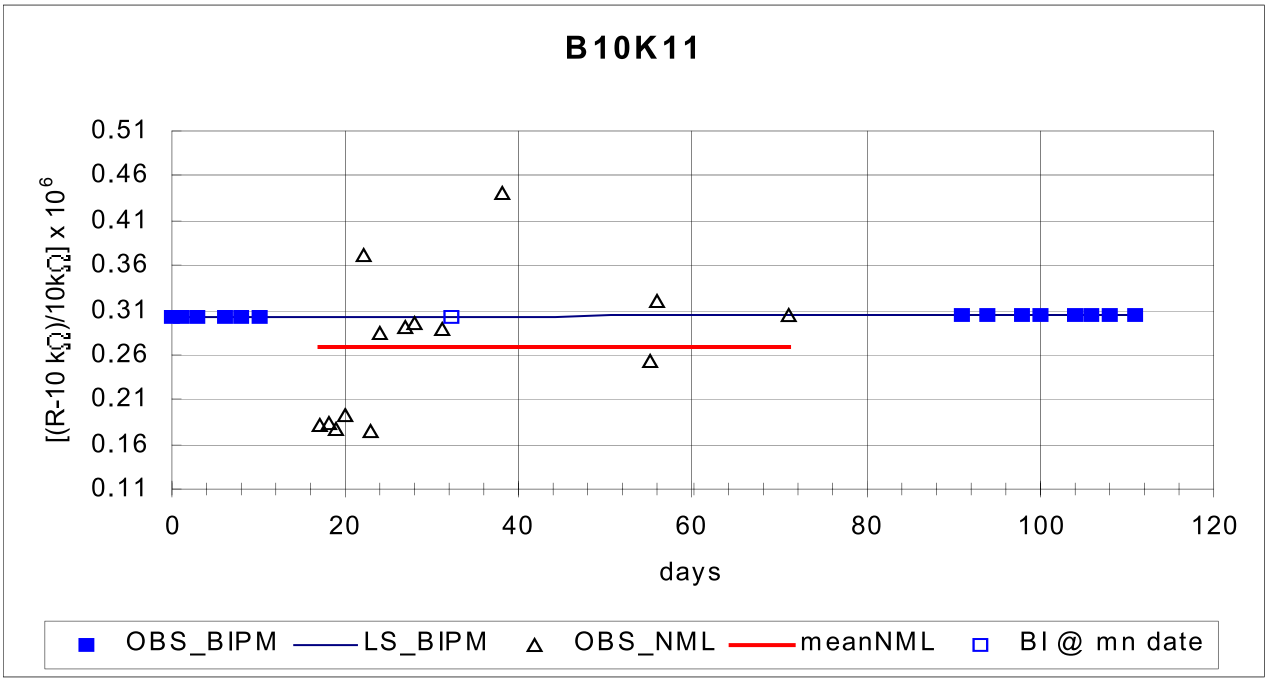

Figure 2. Relative deviation from the nominal 10 kΩ value of the resistance of B10K11 vs time: a linear least-squares fit (LS) to the BIPM measurements and the mean of the NML measurements.

Table 1. Results of the NML/BIPM bilateral comparison of 10 kΩ standards using two BIPM travelling standards: mean date 16 March 2002. Uncertainties are 1-σ estimates.
The combined type-A uncertainty is $w=[r^2+t^2]^{1/2}$, the expected transfer uncertainty is $x=[w_{07}^2+w_{11}^2]^{1/2}/2$ and the total combined uncertainty is $y=[s^2+u^2+x^2]^{1/2}$.

			B10K07	B10K11	
1	NML	$(R - 10\,000\ \Omega)$/mΩ	14.50	2.68	
2		type-A uncertainty/ mΩ	0.23	0.21	r
3		type-B uncertainty/ mΩ	5.9		s
4	BIPM	$(R - 10\,000\ \Omega)$/mΩ	14.02	3.02	
5		type-A uncertainty/ mΩ	0.006	0.005	t
6		type-B uncertainty/ mΩ	0.15		u
7		$(R_{\mathrm{NML}} - R_{\mathrm{BIPM}})$/ mΩ	0.48	-0.34	
8		combined type-A uncertainty/ mΩ	0.231	0.213	w
9		$< R_{\mathrm{NML}} - R_{\mathrm{BIPM}} >$/ mΩ	0.07		
10	expected type-A transfer uncertainty/ mΩ		0.16		
11	s_{M} of difference for 2 resistors/ mΩ		0.41		x
12	total uncertainty in comparison / mΩ		5.9		y

Table 2. Estimated type-B standard uncertainties, relative to the nominal value, for 10 kΩ calibrations with the BIPM equipment. A relative uncertainty of 1×10^{-8} corresponds to 0.1 mΩ.

Realization of $R_H(2)$	2×10^{-9}
Ratio of resistance of transfer resistor to $R_H(2)$	6×10^{-9}
DC/AC difference (at 1 Hz) of transfer resistor	2×10^{-9}
Comparison of transfer resistor to reference resistors	5×10^{-9}
Imprecision in the values of the reference resistors (including uncertainties in extrapolated resistance values and residual power, temperature and pressure effects)	10×10^{-9}
Comparison of the travelling standards to the reference resistor	5×10^{-9}
Uncertainty in the temperature correction for the travelling standard	2×10^{-9}
Uncertainty in the pressure correction for the travelling standard	4×10^{-9}
rss total	15×10^{-9}

Table 3. Estimated standard uncertainties, relative to the nominal value, for 10 kΩ calibrations with the NML equipment. A relative uncertainty of 1×10^{-8} corresponds to 0.1 mΩ. Asterisks (*) indicate components that are either completely correlated or probably significantly correlated when measuring different travelling standards.

Extrapolated value of the 10 kΩ reference standard*	50×10^{-8}
Bridge ratio	30×10^{-8}
Effects of temperature	1×10^{-8}
Leakage resistance effects	10×10^{-8}
rss total	59×10^{-8}