Characterisation of a selection of AC and DC resistance bridges for standard platinum resistance thermometry

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Abstract

Accurate resistance bridges are used to measure the ratio between the resistance of standard platinum resistance thermometers and a reference (standard) resistor at the level of microkelvin in temperature terms, and as such play a critical role in the realization and dissemination of the ITS-90. For AC bridges, the ratio test unit has been available for some time, and for both AC and DC bridges the increasing availability of resistance bridge calibrators based on combinatorial calibration have increased the ease with which the accuracy and linearity of resistance bridges may be determined, under conditions which provide a realistic representation of the actual measurement setup. In this study, the performance of 14 resistance bridges which were available for testing at NPL, consisting of a range of manufacturers and types, has been evaluated and expressed in terms of the standard deviation of the bridge errors over a given range of ratios, namely *s*. In general the bridges are found to comply with the manufacturers' specifications. The uncertainty of *s* has also been determined using Monte Carlo techniques and is found to be of the order of 10% of *s* for most bridge types.

1. Introduction

Accurate resistance bridges are used to measure the ratio between the resistance of standard platinum resistance thermometers (SPRTs) and a reference, or standard, resistor at the level of μK in temperature terms, and as such play a critical role in the realization and dissemination of the International Temperature Scale of 1990 (ITS-90). The commercial availability of resistance bridge calibrators (RBCs) based on combinatorial calibration [1,2] has increased the rate at which the accuracy and linearity of temperature resistance bridges can be characterised [3]. This study has been performed for several reasons:

- The calibration of resistance thermometry bridges has been a long standing problem since the early 1960s when the first automatic resistance bridges were developed. There have only really been a few confidence building techniques (complement method, using calibrated resistors, and simple linearity checks). The lack of a means for properly calibrating thermometry bridges has left a weak link in the traceability chain of almost all contact thermometry measurements. The temperature measurement community has been fortunate that these bridges have been far better than is actually needed for routine calibrations. Even now, 50 years later, there are not many options, and currently only the RBC is suited to the more modern bridges exploiting new analogue to digital conversion (ADC) techniques.
- Previous comparison of the RBC and the ratio test unit (RTU – applicable only to particular AC bridges) [9,10] used the manual RBC with its attendant problems of poor temperature control (when used with the highest accuracy bridges it was being used well beyond its specified accuracy), and manual operation. It is time that a new comparison is carried out using the recent automatic and temperature controlled RBC.
- The analysis algorithm and the operating principles of the RBC are well documented, but there is little published validation of the RBC with respect to its uncertainty estimation.
- It is now 13 years since the last survey of resistance bridges [9], and new technologies have been introduced. It is timely to see how well manufacturers assess their own bridges.

The principles underlying the operation of the RBC are well documented [4-6]. While RBCs have been around for some time, their operation was manual and time-consuming, with up to a day of operator's time required to characterise one bridge. The recent availability of automatic RBCs [7] which do not require intervention by the operator has dramatically increased the amount of

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characterisation that can be performed in a given time frame, and opened up the possibility of exploring parameter space by e.g. studying the influence of bridge current, frequency, etc. [8]. This activity is important because it has been demonstrated that bridges with nominally identical specifications can exhibit wider than expected performance variations [9].

In this study the performance of a range of resistance bridges with varying specifications, from a number of different manufacturers, was evaluated with an automatic RBC and, where possible (i.e. for the AC bridges) an RTU with traceable calibration. The bridges were selected on the basis of their ready availability at NPL. The importance of using more than one method for this task has been demonstrated [10], at least for validation of the RBC measurements, although the RBC has evolved considerably since its first implementation.

2. Resistance bridge calibration

2.1 Resistance bridge calibrator (RBC)

The RBC was originally designed by D.R. White of the Measurement Standards Laboratory of New Zealand and has been around for some time [1-4]. Until recently the RBC operation was manual, with the user being required to set each resistance to be delivered. An automated version has recently become commercially available [7]. Prior to the advent of the RBC, checks of the bridge resistance ratio readings using resistors were limited to using a pair of calibrated resistors (limited by uncertainty in AC electrical standards and AC-DC effects), linearity methods (using resistors in series, which gives information on linearity at a few points but cannot identify actual errors since the system is underdetermined), and complement checks which examine the ratio of two resistors connected to the bridge and again by swapping the connections. The automation of the RBC has greatly increased the amount of information that can be collected on resistance bridge performance.

Resistance-ratio bridges simply indicate a resistance ratio, such as R_x / R_s, where R_x is the thermometer resistance and R_s is the standard, or reference, resistance. For all of these bridges, the reading is a dimensionless number, so there is no requirement for traceability to the SI ohm. Instead, the resistance ratio scale is fixed by the requirement that the measured ratio of two identical resistances should be equal to 1 exactly. For bridges that measure resistance ratio, this means that the RBC can be operated without calibration, and traceability to the SI ohm is not necessary.

As it is not practical to test the bridge with two identical resistors, an equivalent test can be performed using two non-identical but similar-valued resistances by comparing the readings for R_x / R_s and R_s / R_x; the product of the two readings should equal 1. This is the complement check. So long as both normal and complement (reciprocal) measurements are included amongst the RBC measurements, the analysis software will be able to determine the absolute accuracy of the bridge in respect of resistance ratio, and it is not necessary to know the values of the resistors.

When the RBC is used to calibrate a resistance ratio bridge, it is sufficient to know only approximate values for the four base resistors (i.e. to the nearest ohm), because the values are only used as starting values for the least-squares analysis of the measurement results. For the ARBC employed in this study, the values of the four base resistances are 79.332 Ω, 47.499 Ω, 36.59 Ω, and 28.242 Ω. Note that the output of the least-square analysis is not values for the RBC resistors, but dimensionless ratios of the RBC resistances with respect to the standard resistor: R_1/R_s, R_2/R_s, R_3/R_s, and R_4/R_s.

The unit used in this study was the Isotech RBC100A. Four base resistors may be combined in series and in parallel to yield 35 different four-wire resistances over the range from 15.9 Ω to 126.8 Ω. With a 100 Ω standard resistor, this means 35 ratios are available from 0.159 to 1.268. Measurement of these 35 ratios yields information on the linearity. Additionally, by swapping the RBC and standard resistor connections to the bridge, 35 additional reciprocal, or complement, ratios are available. Generally not all of these complement ratios are available within the range of a resistance bridge; for example, only 9 are available for typical use of the MicroK 70 bridge.

The best approach is to calculate a set of four 'best' values for the base resistors, which minimise the differences between the measured and calculated values for all combinations. This can be done conveniently using the method of least-squares. The least-squares algorithm finds values for R_1/R_S to R_4/R_S that minimise the variance of the differences between the measured and calculated values for all the resistance ratios:

$$s^2 = \frac{1}{N-\rho}\sum_{i=1}^{N}\left(P_{i,meas} - P_{i,calc}\right)^2 \qquad (1)$$

Where N is the number of measured ratios, $P_{i,meas}$ are the measured ratios, and $P_{i,calc}$ are the ratios calculated from the fitted values of R_1/R_S to R_4/R_S. The division by $N - \rho$ is done so that s^2 equals the variance of the differences between the measured and calculated values. The number $N - \rho$ is the number of degrees of freedom associated with the variance and is equal to the number of measurements, N, minus the number of fitted parameters, ρ. If all of the base resistances are treated as unknowns, then $\rho = 4$. The standard deviation, s, calculated from the data is a measure of the accuracy of the bridge when no corrections are applied to the readings.

Note that the minimisation of s^2 is non-trivial and should not be attempted using typical built-in spreadsheet algorithms; a robust algorithm should be used such as the downhill simplex method [13].

Corrections

It is also possible to include an expression which permits a correction to the bridge readings to account for some of the error in the readings. Equation (1) can be modified:

$$s^2 = \frac{1}{N-\rho}\sum_{i=1}^{N}\left(P_{i,meas} + \Delta P\left(P_{i,meas}\right) - P_{i,calc}\right)^2 \qquad (2)$$

Where $\Delta P(P_{i,meas})$ is the correction equation, and ρ is the number of parameters determined in the least-squares fit (i.e. the number of non-constant resistor values plus the number of fitted constants in the correction equation). The most general correction equation is

$$\Delta P\left(P_{i,meas}\right) = A + BP_{i,meas} + CP_{i,meas}^2 + DP_{i,meas}^3 \qquad (3)$$

This accounts for an offset in the bridge readings (A), a linear error ($P_{i,meas}$) directly proportional to the reading, and non-linear quadratic and cubic errors; this equation fits most large-scale errors encountered in bridge readings. Sometimes other expressions might be used; a saw-tooth function may be needed, particularly with AC bridges.

There is an important distinction between the terms ‘accuracy’ and ‘linearity’ [9]. In this study, ‘linearity’ refers to measurements performed with direct measurements only (no complement measurements), so that information on the linearity of the bridge can be obtained, but not a full calibration. In contrast, ‘accuracy’ refers to measurements performed with both direct and complement measurements, which enable a full calibration can be performed.

2.2 Ratio Test Unit (RTU)

The RTU is an inductive three-core inductive ratio transformer with electronically increased input impedance [10,14,15], manufactured by ASL. The divider winding is connected directly to the BNC (Bayonet Neill–Concelman) connectors on the front of the (AC) bridge. The RTU directly provides a resistance ratio which tests the bridge only. The expanded uncertainty (coverage factor $k = 2$, 95% coverage probability) of the ratio error given by the RTU used in this study, serial number 007538/02, ranges from 4×10^{-8} at a ratio of 0, up to 7×10^{-8} at a ratio of about 1.2. The output of the RTU can be adjusted by means of an internal trim-pot which is a potential source of drift, so the RTU is regularly calibrated against a sophisticated apparatus based on inductive voltage dividers at the Physikalisch-Technische Bundesanstalt (PTB). The RTU measurements made in this study were carried out by ASL. The unit has a calibration which is traceable to electrical standards at PTB in Braunschweig.

3. Experiment

The object of this study is to characterise a range of commercially available temperature resistance bridges. Bridges were selected from those available in the temperature and humidity laboratories at the National Physical Laboratory (NPL). These were the ASL F700, F700A, F18 and F900; Isotech MicroK 70, 100, and 500; MI 6010T; and Fluke 1595A.

All the bridges considered measure resistance ratios, so there is always a need for a reference, or standard, resistor. In general this standard resistor is traceably calibrated so that in principle the resistance of the SPRT is also traceably determined. For all measurements a 100 Ω reference resistor was used, and a measuring current of 1 mA. The AC bridges were operated at 25 Hz frequency, 10^4 gain (F18) and 10^5 gain (F900), 0.1 Hz bandwidth (F18) and 0.2 Hz bandwidth (F900). The accuracy of the bridges, in terms of resistance ratio, specified by the manufacturers is $\pm$ 0.5 x 10^{-6} (F700/F700A), $\pm$ 0.1 x 10^{-6} (F18), $\pm$ 0.02 x 10^{-6} (F900), $\pm$ 0.07 x 10^{-6} whole range with 0.017 x 10^{-6} for ratios 0 to 0.25 and 0.95 to 1.05 (microK 70), $\pm$ 0.1 x 10^{-6} (microK 100), $\pm$ 0.5 x 10^{-6} (microK 500), < 0.05 x 10^{-6} (MI 6010T), $\pm$ 0.2 x 10^{-6} (Fluke 1595A).

The RBC and the reference resistors (Tinsley, serial number 222106, 99.999437 Ω, calibration traceable to NPL) were immersed in a Hart Scientific 7108 stirred oil bath maintained at 20 °C with a peak-to-peak stability of better than 0.01 °C.

The number of measurements performed at each resistance was arranged such that the total measuring time was about 12 hours. For the AC bridges, this corresponds to 40 measurements per resistance, for the MI6010T 50 measurements, and for the microK DC bridges about 400 measurements. Deviations from these figures indicate constraints on time available for using the equipment. RBC operation and data acquisition was automatic, with the exception of the MI 6010T where RBC operation and data acquisition was performed manually as communication could not be established with the bridge via the general purpose interface bus (GPIB) port. Direct measurements were performed with the RBC connected to the thermometer input terminals (R_x) on the bridge and the standard resistor connected to the R_s terminals. Complement measurements were performed by swapping the R_x and R_s connections to the bridge.

For some of the AC bridges, the RBC results were compared with the results of the RTU where these were available. The RTU is conceptually different to the RBC: with the RBC, the resistance bridge under test measures the ratio of the resistance of the various RBC combinations, to the resistance of the standard resistor. Because the standard resistance is a constant scale factor, the various mathematical relations relating the RBC combinations apply also to the measured resistance ratios. The RTU provides direct information on the bridge performance, ignoring all other contributions to the error (e.g. standard resistor, electromagnetic interference, and cable effects), while the RBC provides information on the bridge performance as used in actual measurement conditions since it effectively replaces the SPRT – leaving all other parts of the measurement process unchanged.

4. Results

The RBC100A was employed for these tests. By combining four resistors having nominal values 79.332 Ω, 47.499 Ω, 36.59 Ω, and 28.242 Ω, 35 ratios are available. In addition, 9 complement ratios were available in the ratio range up to about 1.26.

The software provided with the RBC was used to determine the variance between the measurements and the fitted values of resistance ratio. The fitted values of resistance ratio were determined by parameterising the four resistance ratios P_1 to P_4 (R_1/R_S to R_4/R_S), yielding the variance s^2 [1], as given in Equation 1. The standard deviation s for various bridges is given in Table 1. In all cases the overall measurement time was comparable.

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Bridge	Linearity: $s \times 10^{-6}$	Accuracy: $s \times 10^{-6}$	No. readings	Mfr accuracy $\times 10^{-6}$
F18 706-3/027	0.039	0.133	40	0.1
F18 012656/02	0.046	0.084	40	0.1
F18 1085/003/071	0.119	0.210	40	0.1
F18 012656/01	0.045	0.061	40	0.1
F900 09340/02	0.031	0.031	40	0.02
F900 03206/001	0.024	0.037	40	0.02
microK 70 13-P485	0.016	0.017	400	0.07
microK 70 10-P148	0.016	0.019	80	0.07
microK 100 09-P118	0.015	0.018	200	0.1
microK 500 08-P072	0.062	0.071	40	0.5
Fluke 1595A B22076	0.028	0.029	100	0.2
MI 6010T 990317	0.082	0.125	50	0.05
F700 1256 005 361	0.261	0.386	80	0.5
F700A 1337 004 444	0.203	0.234	50	0.5

Table 1: Summary of results for all bridges investigated in this study. All values in terms of bridge ratios. ‘Linearity’ values refer to the determination of *s* without the complement measurements; ‘Accuracy’ refers to the overall value of *s*, including both direct and complement measurements. ‘No. readings’ is the number of measurements performed at each ratio. Also shown (right column) is the nominal accuracy specified by the manufacturer.

Figure 1 shows typical calibrations for the MicroK 70, F900, and 1595A which exhibit comparable performance. Note that, for the two F900 bridges, the RBC results are broadly consistent with the RTU measurements. The two MicroK 70 bridges were also characterised with a (different) RBC by Metrosol Limited during manufacture and prior to shipping (green diamonds in Figure 1), and the results are comparable to the current RBC measurements. The F900 performance as indicated by the RBC is comparable with the findings of Joung et al. who examined the sensitivity of the bridge performance to the front panel settings [8]. Figure 2 shows typical calibrations for the F18, MicroK 500, and MI 6010T which all exhibit comparable performance. The F18 706-3/027 exhibits a linearly decreasing negative offset, which shows the utility of characterising the bridges with the RBC. The F18 012656/01 RBC measurements are consistent with the RTU measurements. Table 2 provides the values of the bridge ratio and corresponding sensitivity of a 25 Ω SPRT used with a 100 Ω standard resistor (1 Ω SPRT at the Ag fixed point), when measuring at the ITS-90 fixed points.

The Fluke 1595A in Figure 1 has a non-random pattern of residuals in the fits, which suggests a problem with insulation resistance giving rise to a quadratic error. The ASL F18 in Figure 2 has a linear pattern of residuals in the fits, which suggests a very linear bridge but poorly adjusted for zero and full scale, which is common in the F18.

We make a particular comment on the Measurements International MI-6010T. Conventional wisdom suggests that for best performance this bridge should be always operated at ratios larger than 1. Among other things, this has to do with the number of windings in the different arms of the bridge. The MI-6010T bridge has 800 windings in the standard resistor arm and 11264 windings in the RBC (or thermometer) arm. For the maximum resistance ratio of 1:14 this means 800:11264 windings, corresponding to 10264 steps. For resistance ratios below 1 we can only use a ratio of 800:1 which correspond to 799 steps. That means the RBC-based linearity test with direct and complement measurements will, in principle, always provide an inferior performance compared to the operation at optimum conditions (ratio between 1 and 14). To investigate this, measurements were made of the bridge performance with R_s values of 10 Ω, 25 Ω, and 100 Ω. The results indicate that changing R_s has limited impact on the quality of the direct measurements, while reducing R_s appears to substantially improve the complement measurements. The performance of the MI-6010T bridge when used with the three values of R_s is shown in Figure 3.

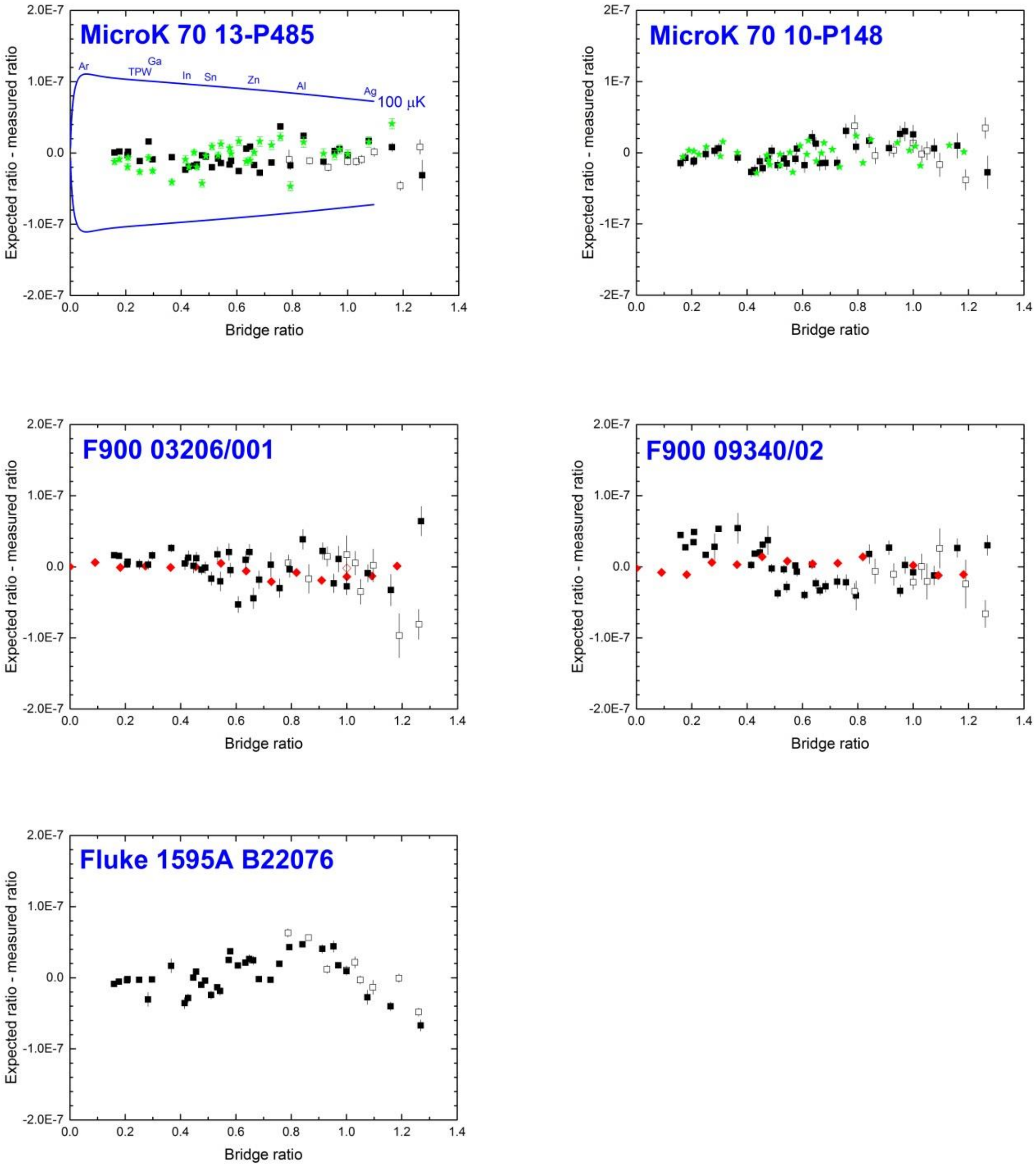

Figure 1: Bridge error as a function of bridge ratio (F900, microK 70, 1595A). Filled squares: direct measurements; open squares: complement measurements; green stars: direct measurements of the same bridge during pre-shipping tests with a different RBC, provided by Metrosol; red diamonds: ratio test unit measurements performed by ASL. Blue line in top left graph shows the ratio difference corresponding to a temperature difference of 100 μK (100 Ω standard resistor).

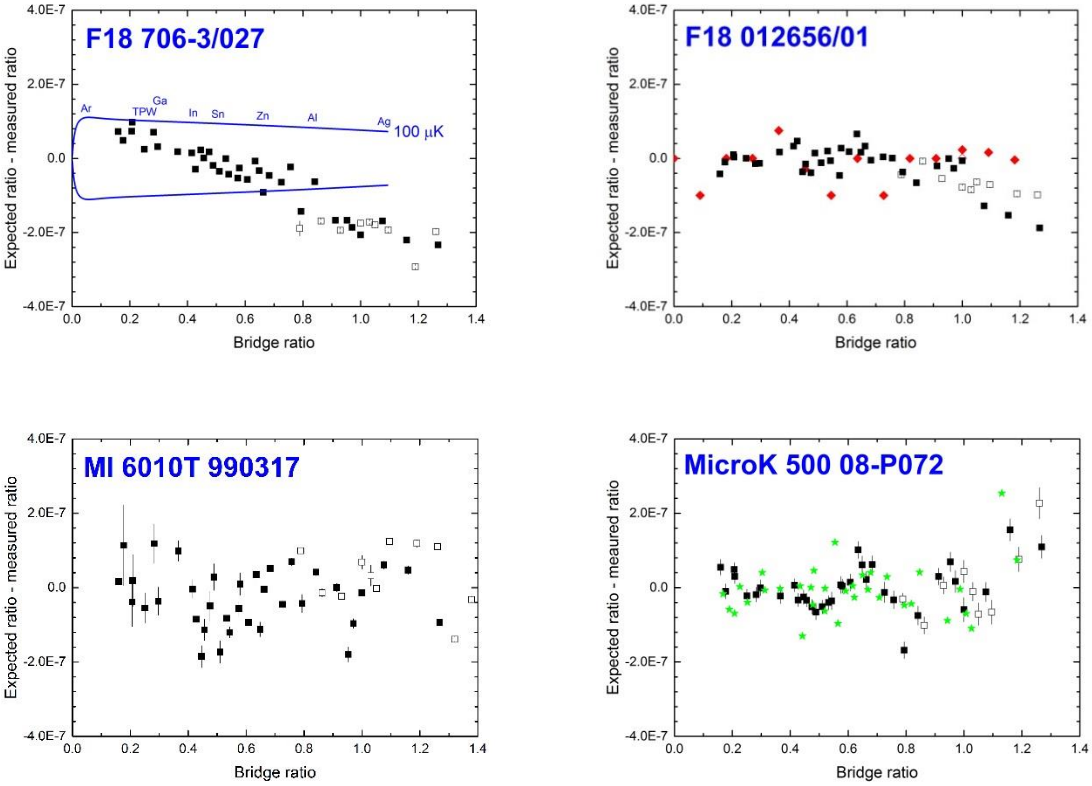

Figure 2: Bridge error as a function of bridge ratio (F18, MicroK 500, and MI-6010T). Symbols as in Figure 1.

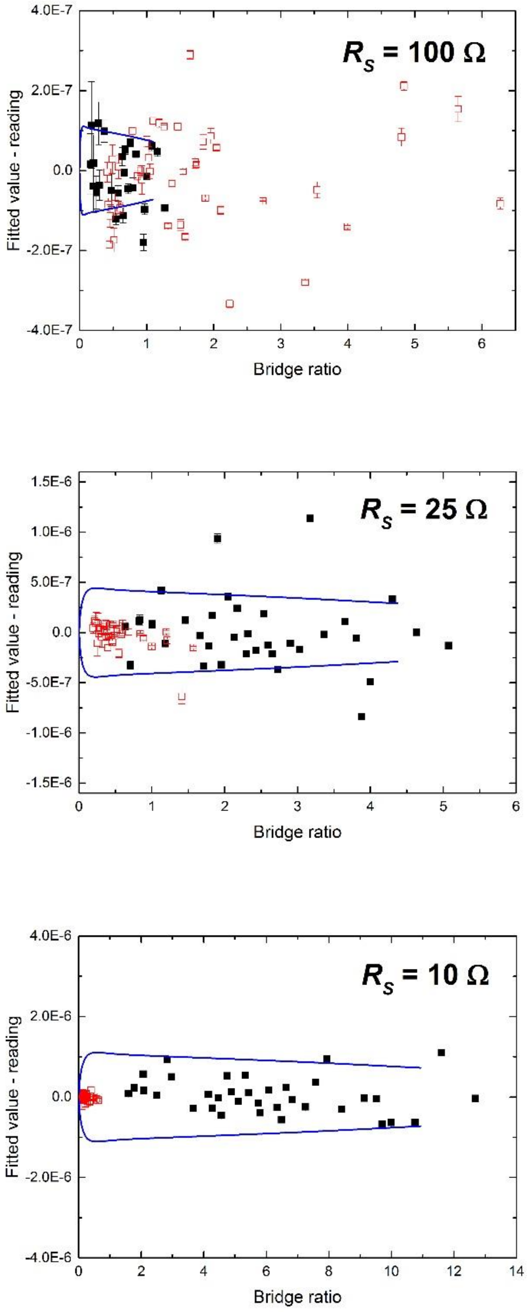

Figure 3: Results for the MI6010T bridge for different values of R_s, as indicated in the graphs. Closed points: direct measurements; open points: complement measurements. Blue line shows the ratio difference corresponding to a temperature difference of 100 μK.

Point	t_{90} / °C	Bridge ratio	Sensitivity / K^{-1}
TP Ar	-189.344	0.054	0.00109
TP Hg	-38.8344	0.211	0.00101
TPW	0.01	0.250	0.00100
MP Ga	29.7646	0.280	0.00099
FP In	156.599	0.402	0.00095
FP Sn	231.928	0.473	0.00093
FP Zn	419.527	0.642	0.00087
FP Al	660.323	0.844	0.00080
FP Ag	961.78	1.072	0.00071

Table 2: Bridge ratios for SPRTs and sensitivities at selected ITS-90 fixed points, assuming a 100 Ω reference resistor except for the freezing point of silver where a 1 Ω reference resistor is assumed.

5. Uncertainty

Only the uncertainties associated with the RBC are considered here; the RTU measurements are included for completeness in this study and as a check against the RBC measurements. The standard uncertainty of the traceable 100 Ω standard resistor calibration is typically 2.5 μΩ, though since the exact value of R_s is not important, only the sensitivity of the resistor to temperature variations in the maintenance bath are considered. The bath has a peak-to-peak temperature stability of 8 mK corresponding to a standard uncertainty of 2.31 mK; with a temperature coefficient of resistance of 1.8×10^{-4} Ω / °C this yields an uncertainty associated with R_s of 416 nΩ. The uncertainty of the fitted resistance provided by the RBC (R_x) is 160 nΩ [7,11]. Propagating the uncertainty associated with these two quantities when calculating the bridge ratio R_x / R_s yields a standard uncertainty in the bridge ratio error of up to about 5.6×10^{-9} in the resulting bridge ratio (when used with a 100 Ω standard resistor), varying slightly with bridge ratio and standard resistor value. The variation of this uncertainty with bridge ratio is shown in Figure 4. The contribution is summed in quadrature with the Type A uncertainty, represented by the standard deviation of the mean of fitted ratio errors at a particular bridge ratio [9].

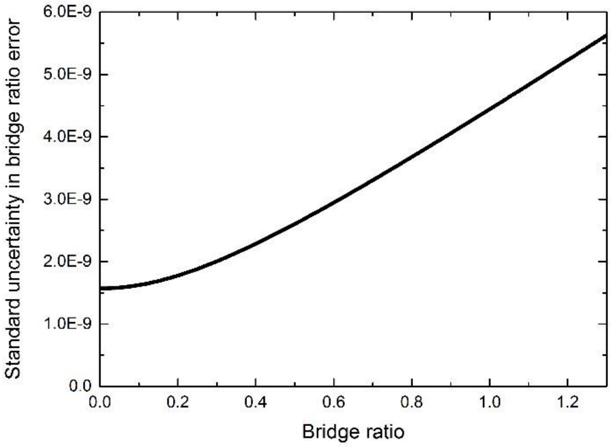

Figure 4: Uncertainty in the bridge error uncertainty arising from relevant contributions from the RBC and the standard resistor.

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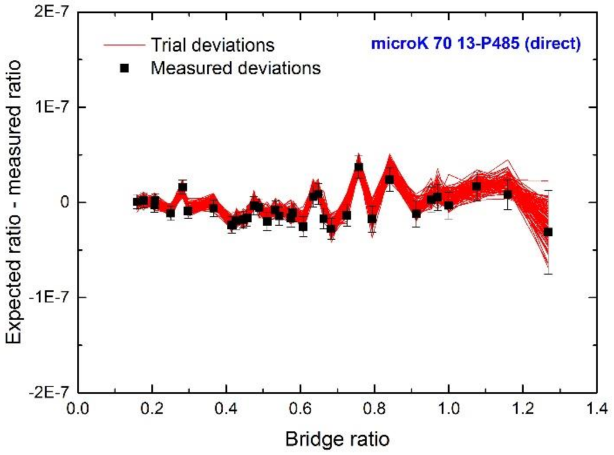
The minimisation of s^2 in (1) by least-squares is a non-trivial, non-linear problem requiring a robust algorithm. To evaluate the uncertainty in the determination of s^2, a Monte Carlo simulation was developed, to evaluate the distribution of s^2 arising from the (random) uncertainty in the 35 measured resistance ratios. The uncertainty ($k = 1$) at each ratio, as described above, is taken to be the sum in quadrature of the RBC and R_S contributions and the standard deviation of the mean of readings at that ratio. The outline of the algorithm used is comparable to that described by one of the authors in a previous publication [12]. The minimisation of s^2 for each set of 35 trial ratios was performed using the downhill simplex method of Nelder and Mead [13] using custom FORTRAN 77 code. Starting values for the four RBC resistances were taken as their nominal values: 79.332 Ω, 47.499 Ω, 36.59 Ω, and 28.242 Ω. The Monte Carlo simulation was also written using FORTRAN 77. The results are shown in Figure 5; the red lines are linear interpolations between the points to highlight representative deviations arising from the dispersion of values at each point due to the random uncertainty. It is then possible to evaluate the resulting dispersion of the values of s. The method was trialled with the MicroK 70 13-P485 and F18 012656/01 measurements (direct connection only). The mean value of s over all trials (100,000 sets of 35 ratios) for the MicroK is 1.72×10^{-8}, with a standard deviation of 0.15×10^{-8}, and for the F18, 4.52×10^{-8} with a standard deviation of 0.13×10^{-8}. The expanded uncertainty of s ($k = 2$) may then be taken as 0.30×10^{-8} or about 17 % for the MicroK 70, and 0.26×10^{-8} or about 6 % for the F18.

Note that this result is consistent with the statistical prediction of the relative standard error in the standard deviation (i.e. the uncertainty in the uncertainty) should be $1/\sqrt{2\rho}$ which in this case, since $\rho = 4$, amounts to about 35 %, so the results are broadly consistent with this prediction.



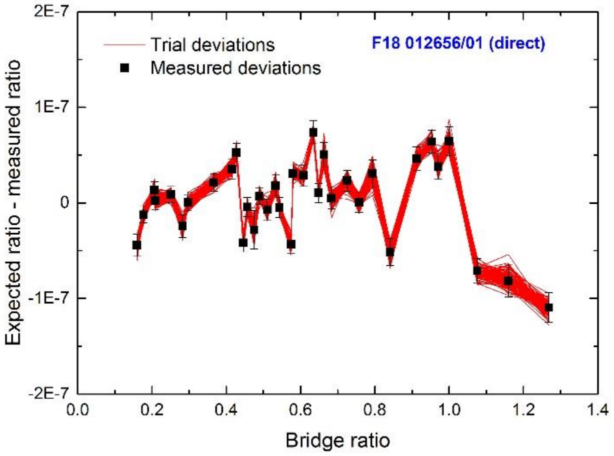


Figure 5: Square points: RBC calibration (errors bars represent two times the standard deviation of the mean, i.e. the expanded uncertainty of the value, k = 2) of the MicroK 70 13-P485 (top) and F18 012656/01 (bottom). Only direct measurements are considered – no complements. Red lines: Trial deviations, i.e. representative possible calibration points associated with the uncertainty of the resistance ratio measurements, as determined from the Monte Carlo calculation; only 100 trial sets of 35 values are shown for clarity. Lines are used to aid visualisation of the dispersion. Effectively this represents the range of results that could arise given the uncertainty of the bridge ratio measurements.

Conclusion

The performance of 14 bridges manufactured by WIKA (formerly ASL), Fluke, Isotech, and Measurements International has been measured using an automatic resistance bridge calibrator with unprecedented accuracy, and the results presented. The bridges were selected on the basis of their ready availability at NPL. A number of results have been cross-checked with other techniques including an independent bridge calibrator and a ratio test unit. In all cases, the different bridge calibration methods were found to be consistent. In general the performance of the bridges was found to comply with the manufacturers’ specifications. The main conclusions may be summarised as follows.

- The RBC provides a convenient means of calibrating high accuracy resistance-ratio bridges used in thermometry. Note that the fore-runner to the automatic RBC, namely the manual RBC, was not well suited to high accuracy bridges because of its lack of temperature control and the need for constant operator involvement for long periods (in excess of 8 hours) . This was fine for low accuracy bridges which take less than an hour to measure, but not high accuracy bridges. The RTU has limited availability (only a handful have been made) and is

only suitable for the F18 and F900, Also, the AC test unit developed by PTB [10,16] is only suited to the ASL range of AC bridges. The calibration of thermometry bridges is becoming increasingly problematic with the increasing prevalence of bridges with very low uncertainties and use of high-quality ADC and switched DC techniques (MicroK, Anton Paar, Fluke, and others) as well as MI bridges.
- The RBC and RTU give similar results where the measurements are comparable, giving confidence that both work as claimed. Note that one weakness of the RTU is that it uses the same transformer core as the F18/F900 series bridges, so it would not be unreasonable to expect similar errors in both, which would not be visible in the calibration.
- The uncertainly reported by the RBC software is consistent with Monte Carlo simulations, and also with usual formulae for the standard error in the variance.
- For the bridges tested here, the manufacturers seem to have a good understanding of the limitations of the instruments they produce, and the specifications are consistent with measured performance. There was some dispersion of the accuracy *s* for models of the same type, with values (in units of 10^{-6} bridge ratios) ranging from 0.061 to 0.210 (F18), 0.031 to 0.037 (F900), 0.017 to 0.019 (MicroK 70), 0.234 to 0.386 (F700).

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