

DOCUMENT

RBC

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RESISTANCE BRIDGE CALIBRATORS MODELS RBC100A & RBC400A

User Maintenance Manual/Handbook

Software Version: 2

Isothermal Technology Limited, Pine Grove, Southport, PR9 9AG, England
Tel: +44 (0)1704 543830 Fax: +44 (0)1704 544799 Internet: www.isotech.co.uk E-mail: info@isotech.co.uk

The company is always willing to give technical advice and assistance where appropriate. Equally, because of the programme of continual development and improvement we reserve the right to amend or alter characteristics and design without prior notice.

This publication is for information only.

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Guarantee

This instrument has been manufactured to exacting standards and is guaranteed for twelve months against electrical break-down or mechanical failure caused through defective material or workmanship, provided the failure is not the result of misuse. In the event of failure covered by this guarantee, the instrument must be returned, carriage paid, to the supplier for examination and will be replaced or repaired at our option.

FRAGILE CERAMIC AND/OR GLASS PARTS ARE NOT COVERED BY THIS GUARANTEE

INTERFERENCE WITH OR FAILURE TO PROPERLY MAINTAIN THIS INSTRUMENT MAY INVALIDATE THIS GUARANTEE

Recommendation

The life of your **ISOTECH** Instrument will be prolonged if regular maintenance and cleaning to remove general dust and debris is carried out.



ISOTHERMAL TECHNOLOGY LTD.
PINE GROVE, SOUTHPORT
PR9 9AG, ENGLAND

TEL: +44 (0) 1704 543830/544611

FAX: +44 (0)1704) 544799

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1. Introduction

1.1 Initial Inspection

The Resistance Bridge Calibrator (RBC) was fully inspected and carefully packed when it was shipped to you. As accidents can happen in transit, you are advised to unpack the unit and inspect it for any sign of shipping damage, and confirm that your delivery is in accordance with the packing note. If you find any damage or that part of the delivery is missing you should notify Isotech and the carrier immediately. If the unit is damaged you should keep the packaging for possible insurance assessment.

When you unpack the RBC, verify that the following items are included in the package and are in good order:

- This manual with the software password on the front of the CD label.
- The RBC instrument.
- A USB cable for connecting the RBC to your computer.
- A CD with the analysis software and an electronic copy of the manual.
- A calibration certificate for the RBC.

If you have any questions or comments relating to the RBC, the RBC software, or this manual, please contact Isotech.

1.2 Safety Instructions

- Please familiarise yourself with this manual before using the RBC.
- The RBCA series of bridge calibrators derive their power from the USB interface; no other external supply is required. Only voltages less than 1 V should be connected to the RBC resistor terminals; higher voltages risk damage to internal components. Higher voltages can be used under specific conditions only (see Sec. 9).
- We recommend the use of shielded cables for connecting the RBC to the bridge.

1.3 RBC History

The RBC calibrators were developed by the Measurement Standards Laboratory (MSL) of New Zealand, which operates within Industrial Research Ltd (IRL). IRL is one of New Zealand's national research institutes with responsibilities for the industrial application of science and engineering. IRL developed and patented the Resistance Bridge Calibrator, which is now licensed to Isothermal Technology Ltd (Isotech, UK). The RBC is available commercially exclusively from Isotech and its global network of distributors.

1.4 The RBC and this Manual

The Resistance Bridge Calibrator is a switched four-terminal resistor network, developed by MSL for the purpose of calibrating ac and dc resistance-thermometry bridges. There are two important parts to the RBC: the RBC instrument and the analysis software. The RBC instruments are sold in two forms: a manually operated desktop unit (RBC100M and RBC400M), and a computer operated unit in a standard-resistor can (RBC100A and RBC400A).

This manual provides a detailed description of the principles of the computer-operated RBCs, the software, and factors to consider in an uncertainty analysis.

The automatically operated calibrators, RBC100A and RBC400A, are engineered to calibrate the highest-accuracy thermometry bridges available, and have a specified maximum uncertainty of 1 $\mu\Omega$ (0.01 ppm for 100 Ω). The main engineering features include:

- The RBC is fully sealed and completely immersible in oil, to enable improved temperature control. The seal also prevents the ingress of moisture and degradation of electrical insulation.
- USB interface to enable fully automated calibrations.
- Low-power latching relays for the switching network to minimise the heat produced in the instrument.

- An improved set of base resistance values to enable a greater number of accessible complement combinations for most bridges.
- One resistance combination designed to be close to 100 Ω .
- Additional relays to allow the measurement of the combining network without opening the instrument.
- Improved four-terminal junction ensuring greater accuracy of series and parallel combinations.

In addition to the major hardware changes, the software has also been upgraded. The significant new features in the software include:

- The software optionally allows the automatic interfacing of resistance bridges, so bridge readings are no longer required to be entered manually. The use of the interface requires a user-written dynamic-link-library (.dll) file to interface the bridge so that any local interface system can be used. The manual describes the syntax and functionality required of the DLL file. Files for common models of resistance bridges are provided.
- The software produces a Microsoft Word® file for calibration reports and analysis summaries so that data can be copied and pasted into other documents or the formatting can be changed as required. This feature requires Word® to be installed on the computer.
- Full automation of the RBC enables the user to select combinations in advance, modify the measurement sequence, and compile averages of bridge readings.
- There are a number of minor improvements to the user interface. One of the most useful is being able to select a point in the graph to highlight and identify the resistor combination used for the measurement. At the same time the corresponding entry is highlighted in the data spreadsheet.

1.5 Software Installation and Getting Started

The analysis software is suitable for use with Microsoft Windows operating systems from Windows 95 up to and including Windows 7. To install the software, simply run the setup.exe file on the CD. The first time you run the RBC application, it will request a password. The password can be found on the front of the CD label. You can install as many copies as you wish so long as you have the password.

Users who are unfamiliar with the RBC and wish to get started quickly, should begin by reading Section 2.6, and the whole of Sections 4 and 6. These provide a minimal description of the RBC and the software, how to use them, and how to analyse the results. Users wanting to learn more of the principles of the RBC, software options, and the limitations in the RBC performance, can read the remainder of the manual at their convenience.

1.6 Updates, and Technical Support

Occasionally new versions of the software and manual will be released. The latest versions can be downloaded from the Isotech web site at www.isotech.co.uk.

If you have any questions about the application of the RBC or the software contact us by email at info@isotech.co.uk.

1.7 Further Information on the RBC

The following papers describe various aspects of the RBC operation, performance, and comparisons with alternative bridge calibration methods. Much of the information provided in this manual is based on the papers.

Operational principles of the RBC:

“A Simple Resistance Bridge Calibrator”, D R White, K Jones, J M Williams and I E Ramsey, *Cal. Lab. Magazine*, March/April, 33-37, 1998.

“A General Technique for Calibrating Metric Instruments”, D R White and MT Clarkson, Proc. 3rd Biennial Conf. Metrological Society of Australia 22-24 Sept. 1999, pp 179-183.

“A General Technique for Calibrating Indicating Instruments”, D R White, M T Clarkson, P Saunders, H Yoon, *Metrologia*, **45**, 199-210, 2008.

Electronic principles of the RBC:

“A Simple Resistance Network for the Calibration of Resistance Bridges”, D R White, K Jones, J M Williams and I E Ramsey, *IEEE Trans. Instrument. Meas.*, **IM-42**, 5, Oct 1997, 1068-1074.

DC performance of the RBC:

“A Resistance Network for Verifying the Accuracy of Resistance Bridges”, D R White and J M Williams, Presented to CPEM '96, *IEEE Trans. Instrument. Meas.*, **IM-46**, 2, 329-332, 1997.

AC performance of the RBC:

“A Network for Verifying ac Resistance Measuring Instruments”, K Jones, CPEM Conf. Digest, CPEM Washington DC, 6-10 July 1998 Ed. T L Nelson, pp 452-3.

Use of the RBC, the performance of different bridges, alternative methods:

“A Method for Calibrating Resistance Bridges”, D R White, Proceedings TEMPMEKO '96, 129-134.

“A Method for Calibrating Resistance Thermometry Bridges”, D R White, Proceedings NCSL '97, 471-479.

“Contribution of Uncertainties in Resistance Measurements to Uncertainty in ITS-90”, D R White, in *Temperature, its Measurement and Control in Science and Industry*, Vo 7, D C Ripple Ed., 321-326.

“Performance Assessment of Resistance Ratio Bridges Used for the Calibration of SPRTs”, G F Strouse and K D Hill, in *Temperature, its Measurement and Control in Science and Industry*, Vo 7, D C Ripple Ed., 327-332.

“Comparison of Test and Calibration Methods for Resistance Ratio Bridges”, S Rudtsch, G Ramm, D Heyer, and R Vollmert, Proc TEMPMEKO 2004, 773-780.

Copies of these papers are available on request.

The following international patents protect the RBC: New Zealand: 281731; USA: 5867018; United Kingdom: 2301501; Germany: 19581562.

2 Principles of the RBC

2.1 Introduction

In simplest terms the Resistance Bridge Calibrator (RBC) is a set of four resistors that can be connected in different configurations to generate a total of 35 distinct and inter-related four-terminal resistances. Measurements of the 35 different resistances in each of two possible ways yield 70 results, each with information about the behaviour of the bridge and the RBC. Since the RBC behaviour is completely determined by the values of the 4 base resistors, the 70 measurements provide up to 66 pieces of information about the behaviour of the bridge. This is enough information to determine the distribution of errors associated with the bridge readings, i.e., enough to calibrate the bridge.

This section of the manual explains the principles of the RBC in more technical detail.

Appendix C contains a short tutorial on ac resistance measurement.

2.2 Direct-Reading and Resistance-Ratio Bridges

All resistance bridges measure resistance by comparing an unknown resistance R_x with a reference or standard resistor R_s . Usually a current is passed through both resistors so that the ratio of the voltages generated is equal to the ratio of the resistances P :

$$P = R_x / R_s . \quad (2.1)$$

We make a distinction between **direct-reading** resistance bridges and **resistance-ratio** bridges.

Direct-reading resistance bridges present the result of the measurement as a resistance (in ohms). They do so by multiplying, either explicitly or implicitly, the measured resistance ratio, P , by the value of an internal reference resistance stored in the instrument's memory. The direct-reading bridges used for resistance thermometry typically have specified accuracies in the range 0.0002% to 0.01%, and are amongst the least expensive thermometry bridges. Because direct-reading bridges read in ohms, their calibration requires the use of at least one calibrated resistor with a value traceable to the SI ohm. The RBC software includes a feature that transfers the RBC calibration to the resistance bridge.

Resistance-ratio bridges are those that present the result of the measurement in the form of a dimensionless resistance ratio, as in Equation (2.1). The best thermometry bridges measure to better than 1 part in 10^8 , and cryogenic current comparator bridges used in electrical standards measure dc resistance ratios to about 1 part in 10^9 . Despite the high accuracies involved, which can be much greater than the absolute accuracy of any calibrated resistor, it is possible to calibrate these bridges by exploiting the fact that the bridges measure a resistance ratio, a number without units, so no reference to the SI ohm is required.

The calibration technique exploited by the RBC, called the combinatorial method, is an extension of two traditional methods for checking the performance of resistance bridges. These two methods are called a linearity check and a complement check.

2.3 The Linearity Check

Suppose we have two resistors, R_1 and R_2 , and a reference resistor R_s . By making separate ratio measurements of the resistance of R_1 and R_2 and the resistance of the two in series, we obtain three measured resistance ratios:

$$P_1 = R_1 / R_s + \xi_{P_1} , \quad (2.2)$$

$$P_2 = R_2 / R_s + \xi_{P_2} , \quad (2.3)$$

$$P_{12} = (R_1 + R_2) / R_s + \xi_{P_{12}} , \quad (2.4)$$

where $\xi(P)$ are the errors in the bridge readings. Ideally, if all of the errors $\xi(P_1)$, $\xi(P_2)$ and $\xi(P_{12})$ are zero, we should find that the sum of the individual measurements is equal to the measurement of the two resistors in series, so that

$$P_1 + P_2 - P_{12} = 0 . \quad (2.5)$$

In practice, the small errors in all three measurements due to errors in the resistance bridge readings give a result

$$P_1 + P_2 - P_{12} = \xi(P_1) + \xi(P_2) - \xi(P_{12}). \quad (2.6)$$

The right-hand side of Equation (2.6) depends only on the errors in the bridge readings, and should be near to zero. By comparing the readings in this way for a range of different resistors, used singly or in different series or parallel combinations, we can build up information about the pattern of errors in the bridge readings. Note that there is no need to know the exact value of the resistors; it is sufficient to know that they are stable for the duration of the measurements.

Under some circumstances the right-hand side of Equation (2.6) may be zero although each individual error term is not zero, indicating incorrectly that the bridge readings have no error. It turns out that Equation (2.6) can be zero for all combinations of bridge readings only when the bridge error is directly proportional to the bridge reading, i.e., when the error function $\xi(P)$ is a straight line through zero. Consequently, any form of non-linearity in the bridge error will be detectable from measurements of the form of Equation (2.6).

2.4 The ‘Reciprocal’ or ‘Complement’ Check for Resistance-Ratio Bridges

For direct-reading bridges, which read in ohms, calibration necessarily involves the use of a calibrated resistance with a value traceable to the SI ohm. With resistance-ratio bridges that accommodate an external standard resistor, it is possible to determine the absolute accuracy of the bridge without using calibrated resistors. Suppose we have two resistors R_x and R_s . There are two ways of using the bridge to measure their ratio. Firstly, by making a ‘normal’ measurement with R_x connected to the R_x terminals of the bridge, and R_s connected to the R_s terminals of the bridge, we get a measurement

$$P_1 = R_x/R_s + \xi(P_1). \quad (2.7)$$

Then we make a ‘reciprocal’ or ‘complement’ measurement by exchanging the two resistors, so that the resistor R_s is connected to the R_x terminals of the bridge, and *vice versa*. We get

$$P_2 = R_s/R_x + \xi(P_2). \quad (2.8)$$

Ideally, when the two errors are zero, the product of the two measurements is equal to 1:

$$P_1 P_2 = \frac{R_x}{R_s} \frac{R_s}{R_x} = 1. \quad (2.9)$$

In practice, the small errors $\xi(P_1)$ and $\xi(P_2)$ associated with each of the measurements cause the result to differ from 1.0 exactly. Since we know we can detect the non-linearities, we’ll assume that the errors are linear, i.e., proportional to the reading, so that $\xi(P) = \varepsilon P$. Then

$$P_1 P_2 = \left(\frac{R_x}{R_s} + \varepsilon \frac{R_x}{R_s} \right) \left(\frac{R_s}{R_x} + \varepsilon \frac{R_s}{R_x} \right), \quad (2.10)$$

hence

$$P_1 P_2 = 1 + \varepsilon^2, \quad (2.11)$$

so that the linear error can be measured. Note again that there is no need to know the exact value of the resistors; it is sufficient to know that they are stable for the duration of the sequence of measurements. The complement check can only be carried out on bridges that measure resistance ratio and accept an external standard resistor.

2.5 Turning Checks into a Calibration

The two important points to draw from the linearity and complement checks described above are:

- By combining the linearity and complement checks we can detect and build up information about all types of errors in the bridge readings.
- The values of the resistors are not critically important, i.e., the resistors do not need to be calibrated.

While the presence of errors is detectable from these measurements, the values of the errors are not uniquely determinable. We can see this by looking closely at Equation (2.6):

$$P_1 + P_2 - P_{12} = \xi(P_1) + \xi(P_2) - \xi(P_{12}).$$

On the right-hand side of the equation there are the three error terms, with one term associated with each of the three bridge readings. On the left-hand side there are also three terms representing the three resistor configurations, but one term is calculable from the other two. Therefore, there are in total five unknown variables in this equation: $P_1, P_2, \xi(P_1), \xi(P_2)$, and $\xi(P_{12})$. However, we have only three measurements, so we do not have enough information to uniquely determine the actual values of all five variables. Further, because there will always be an additional distinct value of $\xi(P)$ for every additional reading, no matter how many measurements we make, there will always be more unknowns than measurements. A system like this, which has more unknown variables than measurements, is said to be underdetermined.

There are two ways to make this system overdetermined, and hence make it possible to calculate the error in the bridge readings. Firstly, we can approximate the true error function of the bridge $\xi(P)$ by a simple algebraic equation. In this way we limit the number of variables represented on the right-hand side of Equation (2.6) to perhaps only 3 or 4 rather than one for every measurement we make. Secondly, we can use a small number of resistors to generate a very large number of inter-related resistance ratios, and this is the purpose of the RBC.

2.6 The Resistance Network

The RBC is a network of four four-terminal resistors (as shown in Figure 2.1). By connecting the various terminals of the network together in a variety of series and parallel combinations, the RBC will generate a total of 35 inter-related four-terminal resistances. The various configurations of the resistance network and the equations for the resulting resistances are shown in Table 2.1.

By measuring the resistance of the network in both the normal and complement (reciprocal) modes we obtain up to 70 inter-related measurements. The analysis software provided with the RBC helps reduce this information to a correction equation and an uncertainty in the corrected bridge readings.

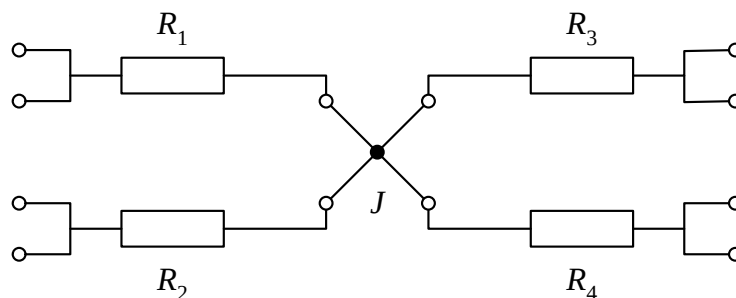


Figure 2.1: A simplified circuit diagram of the resistance network used in the RBC. R_1 to R_4 are the four base resistors and J is a four-terminal junction that allows the resistors to be connected together in such a way that they appear to be connected to a single point. The open circles indicate connection points.

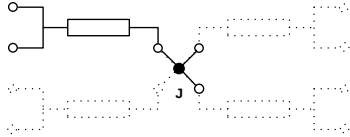
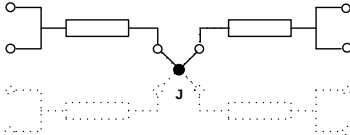
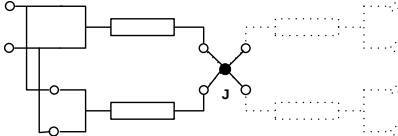
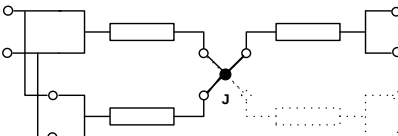
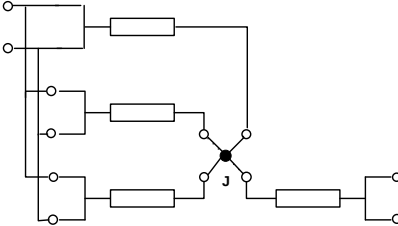
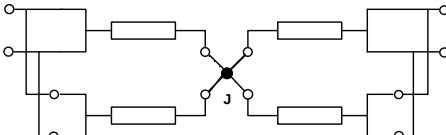
	Network Resistance	Network Connection
1	R1	
2	R2	
3	R3	
4	R4	
5	R1+R2	
6	R1+R3	
7	R1+R4	
8	R2+R3	
9	R2+R4	
10	R3+R4	
11	R1//R2	
12	R1//R3	
13	R1//R4	
14	R2//R3	
15	R2//R4	
16	R3//R4	
17	R1+R2//R3	
18	R1+R2//R4	
19	R1+R3//R4	
20	R2+R1//R3	
21	R2+R1//R4	
22	R2+R3//R4	
23	R3+R1//R2	
24	R3+R1//R4	
25	R3+R2//R4	
26	R4+R1//R2	
27	R4+R1//R3	
28	R4+R2//R3	
29	R1+R2//R3//R4	
30	R2+R1//R3//R4	
31	R3+R1//R2//R4	
32	R4+R1//R2//R3	
33	R1//R2+R3//R4	
34	R1//R3+R2//R4	
35	R1//R4+R2//R3	

Table 2.1: The 35 combinations of the resistor network. Column one is the combination number that is used as the index throughout this manual and the software. Column two is a description of the combination, where the symbols + and // mean series and parallel connections, respectively. Column three shows how the network is connected to realise the combinations.

2.7 Why the RBC Works for AC Measurements

The network used in the RBC exploits many of the principles employed in Hamon build-up resistors, a closely related device commonly used in electrical-standards laboratories. Traditionally, such resistance networks have been used only for dc measurements because stray capacitances and inductances in the network introduce frequency-dependent errors causing the inter-relationships between the resistors to depart from ideal. However, because these defects are almost purely reactive (i.e., 90° out of phase with the ac sensing current), in thermometry bridges they have only a second-order effect on the measured resistance (the real part of the impedance). Thus, effects that introduce errors in the complex impedance of say 1 part in 10^4 , cause errors of less than 1 part in 10^8 in the value of the resistance. This property, combined with the freedom from needing to know the values for the base resistors, means that the RBC can be used on any bridge that measures resistance ratio or conductance ratio, whether it uses a dc, ac or switched-dc sensing current. Section 8 discusses in detail the uncertainties arising in the use of the RBC, including ac effects.

2.8 Limitations in the Use of the RBC

Not all bridges will accommodate all 70 possible measurements with the RBC. There are four possible restrictions.

Direct-reading bridges, and bridges that operate with an internal standard resistor only

With bridges that use only an internal reference resistor or only read directly in ohms, none of the complement ratios can be measured. This means the principles outlined in the complement check (Section 2.4) cannot be used to determine the absolute accuracy of the bridge. Instead, at least one of the four RBC base resistance values must be known. Alternatively, the network can be used to check the non-linearity of the bridge, and the absolute accuracy determined using an additional measurement with a calibrated resistance standard. Note that thermometry bridges are used to measure the $R(T)/R(0\text{ }^{\circ}\text{C})$ relationship for platinum thermometers via separate measurements of $R(T)$ and $R(0\text{ }^{\circ}\text{C})$ made with the same bridge and standard resistor, so linearity is the most important attribute of a thermometry bridge.

Bridges with a restricted range of external standard resistor

Some bridges will accommodate an external standard resistor, but only if it has a resistance very close to a nominal value such as 10 Ω , 100 Ω or 1000 Ω . In these cases there may be one RBC setting with a resistance within that range. Therefore, only one complement measurement may be possible. All current models of the RBC have one combination that is close to 100 Ω . One complement measurement (in addition to the set of normal ratios) is sufficient to determine the absolute accuracy; however, the more complement ratios included in the calibration, the lower the uncertainty in the calibration constants determined by the analysis.

Bridges with a limited range

In order to accommodate all 70 possible ratios realised by the RBC, a bridge must typically be able to measure ratios up to, and sometimes above, 4.0. With bridges that measure ratios up to 1.3 or 1.6, for example, typically 40 to 50 of the 70 ratios will be within the range of the bridge. The range of resistance ratios available also depends on the value of the standard resistor chosen. The values of the base resistances in the RBCs have been chosen to maximise the total number of combinations, for a variety of bridges, when the bridge is used with a 100 Ω standard resistor.

Bridges with a wide range

Some bridges are designed to operate over a wide range of resistance ratios, up to 10 or more. In these cases the range of normal ratios and complement ratios may not overlap. As a consequence the estimate of the linear error in bridge readings (see Sec. 5.2) is likely to have a high uncertainty associated with it. If you require a good measure of the absolute accuracy, if possible, choose a value of the standard resistor that ensures that the range of normal measurements and complement measurements overlap.

The RBC100 and RBC400 bridge calibrators have been optimised for 25 Ω and 100 Ω thermometry bridges, respectively, so that all of the normal ratios and a large number of the complement ratios are within the range of typical bridges. They have also been designed to test as much of the bridge circuitry as possible. Accordingly, the resistance values have been chosen to ensure that every ratio is different and that every numeral (0–9) of every digit in the bridge reading is exercised as much as is practicable. In this way, the RBC will demonstrate not only that the output systems (visual display and digital interface if used) are working correctly, but also that the various switches that interconnect the internal voltage or current dividers are working correctly.

Appendix B lists the nominal values of all 70 ratios realised by the RBCs.

2.9 Accuracy of the RBC

For direct-reading resistance bridges, the factor limiting the accuracy of the calibration is usually the uncertainty in the values of the RBC base resistances. If you have access to a national standards laboratory, the RBC resistances can usually be measured with uncertainties below 100 $\mu\Omega$ (~1 ppm).

For resistance-ratio bridges, there are three main factors limiting the accuracy of the RBC: (i) the stability of the resistors against changes in ambient temperature; (ii) errors in the four-terminal junction; and (iii) errors in the combining network. The latter two effects are controlled by design to limit the maximum error on any one combination to a few micro-ohms. However, the temperature of the resistors in the RBC is determined by laboratory conditions.

For both types of bridge calibration, the temperature stability of the RBC is important. For this reason the RBCs have been designed for immersion in temperature-controlled oil baths. Temperature control of the bath to within 0.03 $^{\circ}\text{C}$ is sufficient for the RBC to achieve the specified accuracy of 0.01 ppm.

The RBCs can also be used as bench-top instruments. In laboratories with time-proportioning PID (proportional, integral, differential) control for the air-conditioning system, an accuracy of about 0.1 ppm should be achieved easily. In laboratories with On/Off control systems, which typically have a forced hysteresis of 1 $^{\circ}\text{C}$ or more, some care may be required to avoid direct air flow from the air vents to achieve an accuracy of 0.1 ppm. A full uncertainty analysis for the RBCs is provided in Section 8 of this manual.

3. Traceability and Calibration of the RBC

The resistance bridge calibrator is an unusual instrument; for some applications, it does not require calibration. There are, however, a number of factors that must be considered in order to ensure that a bridge calibration using the RBC is valid. There are three aspects of a calibration procedure that any calibration must address: (i) the nature of the reference standard; (ii) the conditions under which the instrument under test will be used; and (iii) the measurement uncertainty.

3.1 The Reference Standard

As noted in Section 2.2, there are two main classes of resistance bridges to be considered from a calibration perspective: direct-reading resistance bridges, and resistance-ratio bridges. These two classes must be treated differently in respect of the reference standard.

Direct-Reading Resistance Bridges

Because direct-reading bridges indicate a reading in ohms, they all require calibration results to be traceable to the SI ohm. To establish traceability with the RBC, it is sufficient to have a traceable value for any one of the RBC resistors. Usually, the most convenient resistors to have calibrated are those closest to 100 Ω (R_1 on the RBC100A, R_3 on the RBC400A).

Direct-reading resistance bridges tend to be at the lower accuracy end of the range of bridges available, typically with accuracies of about 0.01% to 0.0002%. Calibration of the RBC resistors for this level of accuracy should not be difficult (see Sections 8.3 and 8.4 for discussion of the various sources of uncertainty in the RBC), and for some applications the value supplied on the RBC certificate will be sufficient.

Ideally, if you have available a calibrated standard resistor with a low uncertainty (1 ppm or lower) and a calibrated high-quality resistance-ratio bridge, the RBC can be calibrated in-house. Otherwise, the RBC should be calibrated by a laboratory accredited to ISO17025 for the calibration of resistors. The values from the RBC certificate supplied with the RBC could also be used, but it should be kept in mind that the resistors will drift with time, perhaps as much as 1–2 parts per million per year, sometimes more in the first year. The long-term stability of these resistors should be checked regularly so the drift can be tracked. The value provided on the certificate when you received with the RBC should be the starting value on your record.

To use the base resistor values when calibrating a direct-reading resistance bridge, the latest resistor values should be entered into the *RBC Information* dialog box under the *Settings* menu of the software (see Section 6), and the corresponding check-box in the dialog box should be checked to tell the analysis software that the values are constant and not values to be fitted by the least-squares analysis. The analysis software will then give the corrections to the bridge reading in ohms. It is sufficient to have just one of the RBC base-resistor values measured and set to constant in the software.

Resistance-ratio bridges

Resistance-ratio bridges simply indicate a resistance ratio, such as R_x/R_s . For all of these bridges, the reading is a dimensionless number, and because the reading is simply a number, 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 1.0 exactly. For resistance-ratio bridges, this requirement replaces the traceability link to the SI ohm, and means that the RBC can be operated without calibration.

Rather than testing the bridge with two identical resistors, which is impractical, an equivalent test can be made with two non-identical but similar-valued resistances by comparing readings for R_x/R_s and R_s/R_x ; the product of the two readings should equal 1.0. This is the complement check described in Section 2.4. Note that it is not necessary to know the values of the resistors to carry out this test. 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.

When the RBC is used to calibrate a resistance-ratio bridge, it is sufficient to insert approximate values for the four base resistors into the *RBC Information* dialog box under the *Settings* menu of the software (e.g., to the nearest ohm), because the values are required only as starting values for the least-squares analysis of the measurement results. None should be set to constant values. Note that the output of the least-squares 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 analysis output also provides the user with a correction equation expressed in terms of resistance ratio.

To measure a resistance with a resistance-ratio bridge, you will require the calibrated bridge and a calibrated standard resistor connected to the bridge as an external standard. The unknown resistance is given by the product of the (dimensionless) resistance ratio indicated by the bridge when measuring the unknown resistor, and the value of the standard resistor. The traceability to SI ohms is therefore via the standard resistor, not the bridge and RBC.

3.2 Measurement Conditions

A measurement made with a calibrated resistance bridge is strictly only traceable if the conditions under which the bridge is calibrated are the same as the conditions under which it is used.

Good examples of situations where calibration conditions are not maintained during both calibration and use are applications using the transformer-based bridges with an ‘autocal’ feature. Usually the autocal operation compares the various windings on the transformers and makes software corrections so that all the transformer ratios are self consistent. Sometimes this type of process is called a ‘self calibration’, but it is strictly a self adjustment. While this type of operation greatly improves the performance of the bridge in several important respects, it is not an independent proof of performance. For example, it is possible for stray impedances and faults to become apparent only when the bridge is connected via the normal external connections to the bridge. Additionally, the windings on the transformers, and the stray impedances about them, may be energised in a manner that does not duplicate the situation in normal use. Hence, the stray currents that give rise to errors in the readings may be different during the auto-adjustment and when the bridge is used.

The RBC method is one of the few bridge calibration methods capable of evaluating the performance of a bridge under exactly the same conditions as when it is used. For the same reason, when calibrating a bridge with the RBC, the bridge operating conditions (sensing current, frequency, bandwidth, resistance range, etc) should be the same as expected to apply in use. The conditions should be recorded on the calibration certificate for the bridge (see the *Bridge Information* and *Certificate Settings* dialog boxes under the *Settings* menu of the software).

3.3 Uncertainties

A traceable calibration also requires an objective assessment of the uncertainties in the indications of the device under test. This must include the uncertainties in the device under test (the bridge), as well as the various factors associated with the reference instrument. For the RBC there are four main factors that contribute to the uncertainties in the reference. These factors are explained in detail in Sections 8.3 and 8.4, but in summary:

The combining network is a set of resistors associated with each of the main RBC resistors that ensures that the currents through the RBC resistors are distributed correctly when the RBC is used for parallel combinations. These resistors are trimmed at the time of manufacture to ensure the RBC achieves its specified accuracy.

The Hamon junction (also called a four-terminal junction) is a device that connects the four RBC resistors in such a way that they all appear to be connected to a single point. Departures from ideal affect all combinations, and are characterised by the ‘cross-resistances’ of the Hamon junction.

Ambient temperature: While it is often not necessary to know the exact values of the RBC resistors when calibrating a bridge, it is essential that the resistors retain the same value for all of the measurements. The small temperature coefficients of the resistors in combination with ambient temperature changes give rise to variations in the measurements that will be apparent in the statistical analysis of the results.

Insulation resistance: The operation of the RBC also assumes that the four resistors are completely independent and isolated. The very slight electrical leakages that occur across the surface of printed circuit boards and switches introduce small errors.

For most applications, the RBC-related uncertainty is dominated by the effects of ambient temperature variations.

Further, most of the remaining errors tend to be distributed more or less at random through the various RBC combinations so they are observed as a contribution to the measured standard deviation of bridge errors. In this respect the RBC is failsafe; a bridge calibration will not yield uncertainties as low as, say, 1×10^{-8} in resistance ratio unless the cumulative effect of all of the errors in the RBC is also less than 1×10^{-8} .

Even if the RBC is used only for calibrating resistance-ratio bridges, it should be subject to regular checks to ensure that it continues to perform at its best and does not limit the assessment of the performance of bridges under test. Instructions for care and maintenance of the RBC include measurements of the insulation resistance and combining network, and are given in Section 9.

4 Making Measurements

The Resistance Bridge Calibrators are designed primarily for calibrating low-frequency (less than 100 Hz) thermometry bridges, including so-called switched-dc bridges. They employ a five-wire guarded electrical definition similar to that used by resistors for electrical resistance standards measurements. Connections to the RBC are made via the five terminals on the top of the instrument (see the photo on the front cover of this manual). A schematic diagram for the RBC, including the switches, the combining network, the four-terminal junction, and all of the latching relays, is shown in Figure 4.1.

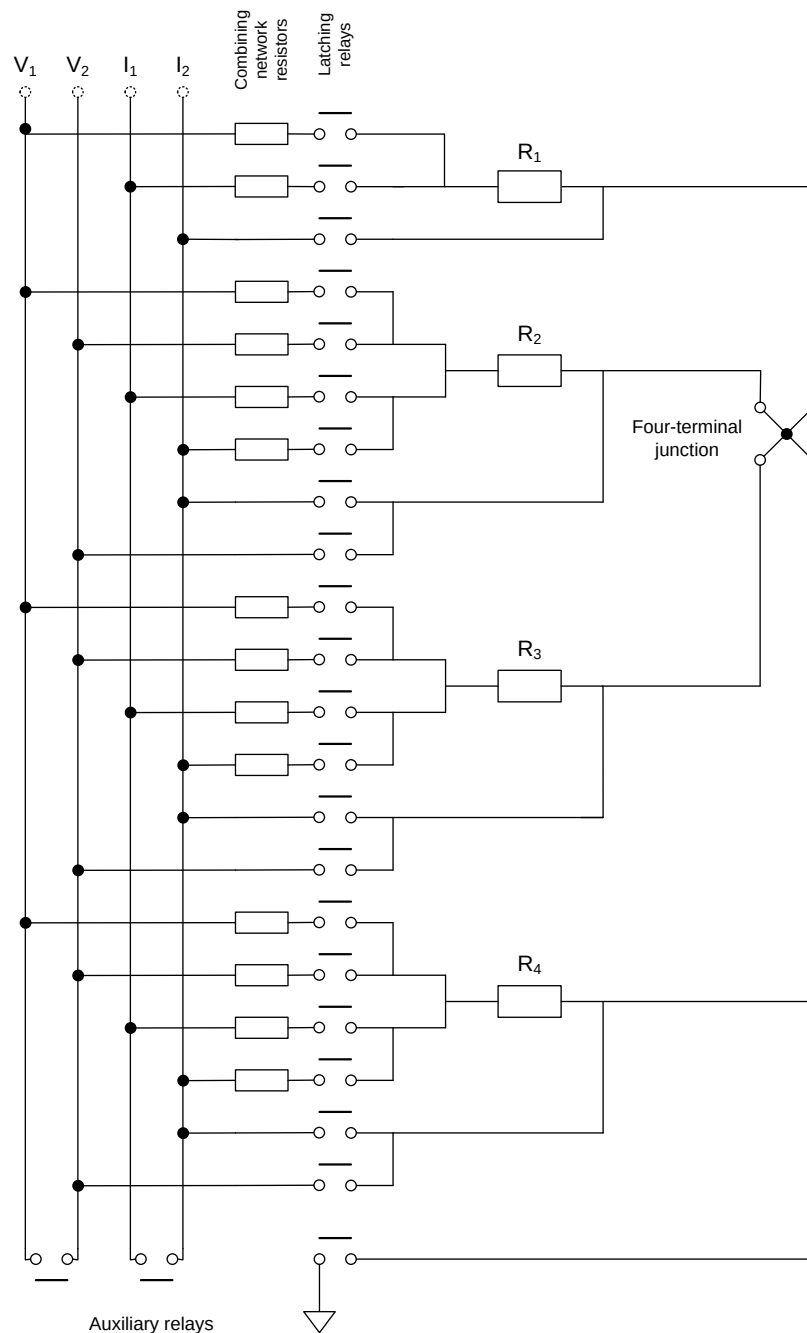


Figure 4.1: A simplified schematic diagram of the RBC showing the 4 base resistors (R_1 to R_4), all of the combining network resistors, the four-terminal junction and the three auxiliary switches that make possible external electrical testing of the RBC.

4.1 Selecting Resistance Combinations

Once the bridge has been connected to the electrical measurement terminals of the RBC, and the computer is connected via the USB interface, the required resistance combinations of the RBC may be selected using any of three methods:

Set RBC Combination dialog box: A single RBC combination can be selected using the *Set RBC Combination* dialog box under the *Options* menu. Only a single combination can be selected, and if the RBC is connected to the computer via the USB interface, the selection will take immediate effect. This method for setting the combination is most useful when the calibration process is being set up, or the operator wishes to manually check a few combinations.

Data Window: Clicking the check boxes on the left-hand edge of the Data Window of the software will select the corresponding combinations to be measured during a measurement sequence. Each required combination must be selected. No action will be taken on these selections until the measurement sequence has been started by clicking on the *Start* button on the software's toolbar. For resistance-ratio bridges, starting a measurement sequence requires the standard resistor value to be entered into the *Bridge Information* dialog box.

RBC Combinations dialog box: Groups of the RBC combinations can be selected using the *RBC Combinations* dialog box (under the *Settings* menu). This dialog box enables the user to limit the range of resistance ratios or resistances measured to ensure that the combination is always within the range of the bridge. Different ranges can be selected for the normal and complement combinations. No action will be taken on these selections until the measurement sequence has been started by clicking on the *Start* button on the software's toolbar. For resistance-ratio bridges, limiting the range requires the standard resistor value to be entered into the *Bridge Information* dialog box.

4.2 Selecting the Measurement Sequence

Figure 4.2 shows the *Measurement Settings* dialog box (under *Settings* menu). The *Reading Settings* part of the dialog box enables the operator to manage the data acquisition from the bridge. It determines the number of initial readings to discard to eliminate transient or settling effects when the RBC combination is changed, the number of readings averaged for each recorded result, the time interval between each individual reading, and the number of times the complete list of selected RBC combinations is repeated. Repeating and averaging the complete RBC sequence helps to eliminate drift effects in the RBC and the standard resistor when very high resolution bridges are being calibrated (high resolution usually means long measurement times).

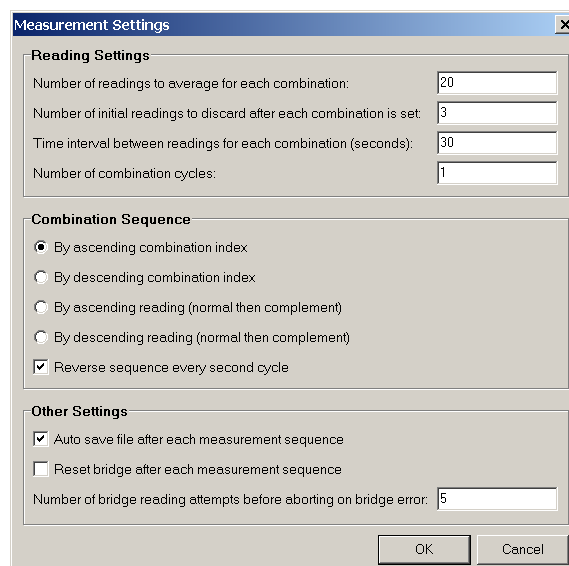


Figure 4.2: The *Measurement Settings* dialog box showing options for managing the acquisition and averaging of bridge readings, and the RBC combination sequences.

The *Combination Sequence* part of the dialog box determines the order in which the various combinations are set by the computer. The combination index refers to the number in the index column of the Data Window that identifies the RBC combination (see also Table 2.1). Using the combination index means that the combinations with the largest and smallest resistances are mixed up to some degree so that drifts in resistance will become apparent from the scatter (the standard deviation) of the readings. If the RBC combinations are run in order of ascending or descending reading, then the total measurement time might be reduced, but at the slight risk of drifts in resistance values being mistaken for non-linearity in the bridge readings. Generally the combination-index sequence should be used unless the RBC and standard resistor are in a demonstrably stable environment.

The *Other Settings* part of the dialog box enables the user to direct the computer to back up the measurement data after each measurement, to reset the bridge to its default settings after each measurement, which is required for the reliable operation of some bridges, and to specify the number of reading attempts before aborting the measurement cycle if a bridge reading error occurs.

4.3 Selecting the Bridge and Interface

To select the bridge and its interface, first open the *Bridge/Interface Settings* dialog box under the *Settings* menu. This dialog box lists all of the bridge interface files available for use. These files are dynamic link library files (DLL, all have a suffix .dll) written to interface specific bridges. DLLs are supplied with the RBCA to interface the ASL F900, ASL F18, ASL F17, ASL F700, ASL F250, MI 6015T and the MicroK and MilliK bridges. To load these DLL files into the software, first select the directory where they are located by clicking on the *Set Interface DLL Directory* button, and then load them by clicking on the *Add/Remove Interface DLLs* button. If the bridge does not have a DLL available, you can either use the keyboard DLL or write a DLL file for the bridge. Instructions for writing the DLL are given in Section 6.4.

Once you have the correct DLL listed in the dialog box, the bridge can be selected using the cursor. Once the interface is selected, a range of different bridge settings will appear on the left of the dialog box as shown in Figure 4.3. Depending on the functions integrated into the DLL you may be able to select the appropriate interface type, the bridge address on the interface, and some bridge settings such as the sensing current. Once you have entered all of the various settings you will be able to save these as default values for later use if required. The version of the selected DLL will appear below the DLL list box.

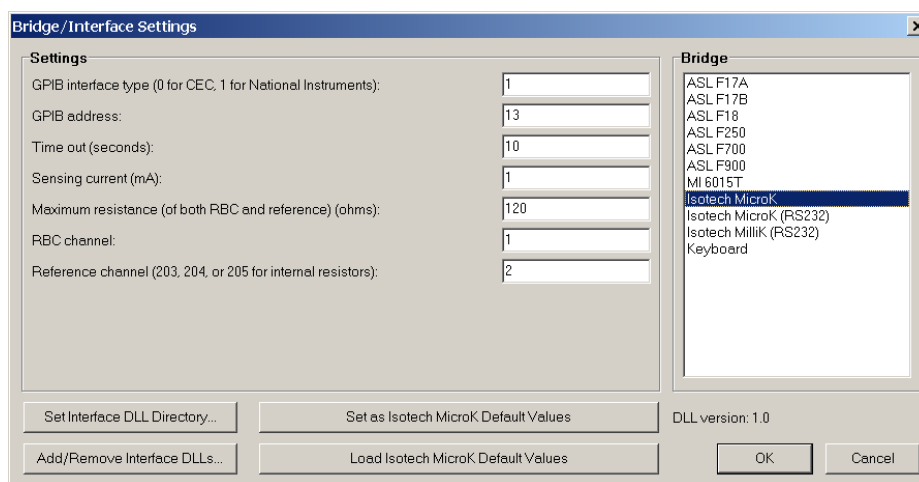


Figure 4.3: Example of the *Bridge/Interface Settings* dialog box with the interface file for the MI6015T bridge selected.

4.4 Making Measurements

Once all of the measurement settings have been entered, you will be able to start a measurement sequence by clicking on the *Start* button in the software's toolbar. If you have selected complement measurements, the computer will ask to you exchange the connections to the standard resistor and the RBC after it has completed the normal measurements.

5 Analysing the Results

Once all of the readings have been collected, the software will analyse the results when you click the *Calculate* button in the Analysis Window. For direct-reading resistance bridges, the simplest approach to the analysis is to compute the values for the 35 combinations of the resistance network from the known values of the four base resistances, and then compare these values with the values measured by the bridge under test. Setting all of the resistor values to constant in the *RBC Information* dialog box allows this option.

For sets of measurements that include both normal and complement measurements it is not necessary to know the values for any of the base resistances of the RBC. In this case, the software actively searches for the values for the resistors most consistent with the results. The same technique is applied to direct-reading resistance bridges in the cases when we only know values for some of the resistors. In this section we give an overview of the analysis technique.

5.1 The Least-Squares Fit

One approach to the analysis is to take the four measurements for the base resistors R_1 , R_2 , R_3 , and R_4 , use these values to calculate the values for the other combinations (e.g., $R_1 + R_2$), and compare the measured and calculated values for those combinations. The differences will give a very quick indication of the accuracy of the bridge.

A better 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 (a procedure known as fitting). We explain the process for resistance-ratio measurements, but an almost identical process applies to direct-reading measurements.

The least-squares algorithm finds values for R_1/R_s to R_4/R_s that minimise the variance (standard deviation squared) of the differences between the measured and calculated values for all the resistance ratios:

$$s^2 = \frac{1}{N - \rho} \sum_{i=1}^N (P_{i,\text{meas}} - P_{i,\text{calc}})^2. \quad (5.1)$$

In Equation (5.1) N is the number of measured ratios, $P_{i,\text{meas}}$ are the measured ratios, and $P_{i,\text{calc}}$ are the ratios calculated from the fitted values of R_1/R_s to R_4/R_s . Equation (5.1) also includes a division by $N - \rho$; this 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.

5.2 Including a Correction Equation

With some bridges it is advantageous to add corrections to the bridge readings to account for some of the error in the readings. If so, the least-squares problem is modified to include a correction equation:

$$s^2 = \frac{1}{N - \rho} \sum_{i=1}^N (P_{i,\text{meas}} + \Delta P(P_{i,\text{meas}}) - P_{i,\text{calc}})^2, \quad (5.2)$$

where $\Delta P(P_{i,\text{meas}})$ is the correction equation, and ρ is the number of parameters determined in the least-squares fit (equal to the number of non-constant RBC resistor values plus the number of fitted constants in the correction equation). Again, the factor $N - \rho$ is the number of degrees of freedom associated with the variance s^2 .

The most general correction equation is a cubic equation of the form

$$\Delta P(P) = A + BP + CP^2 + DP^3. \quad (5.3)$$

This equation accounts for an offset in the bridge readings (A), a linear or scale error (BP) directly proportional to the reading, an even-order non-linear error (CP^2) and an odd-order non-linear error (DP^3). This equation will fit most of the large-scale errors that are found in bridges. Figure 5.1 shows the result of the assessment of an ac resistance-ratio bridge with a fault that causes a cubic error in the readings. In addition to the general polynomial, Equation (5.3), the software includes a ‘sawtooth’ error model. This model assumes that the error is proportional to the fractional part of the bridge reading (if the bridge reading is a resistance ratio) or the fractional part of the bridge reading after it has been divided by 10, 100, 1000, etc depending on the maximum reading (if the bridge reads resistance directly). This type of behaviour occurs to some degree in all bridges based on decade voltage or current dividers, although it is not usually significant. An example of a bridge with a significant sawtooth error is shown in Figure 5.2.

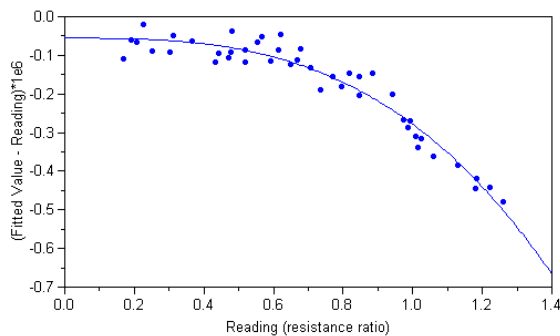


Figure 5.1: RBC100 results for a resistance-ratio bridge with a faulty input circuit that gives rise to a cubic error. This is abnormal behaviour for this bridge, which has a specified accuracy of $\pm 0.2 \times 10^{-6}$ (vertical scale in the graph is 0.7×10^{-6}).

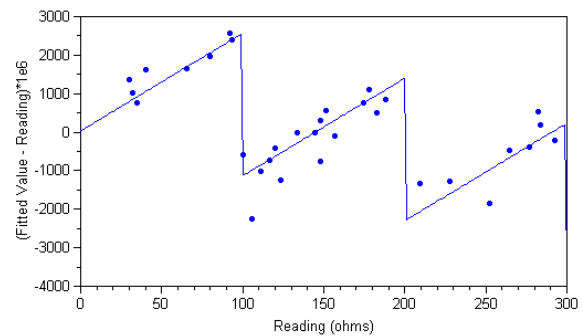


Figure 5.2: RBC400 results for a direct-reading resistance bridge exhibiting a sawtooth error. This is normal behaviour for this model of bridge, which has a specified accuracy of $\pm 10 \text{ m}\Omega$ (vertical scale in the graph is $7 \text{ m}\Omega$).

The software allows the operator to choose any combination of the five error functions for a correction equation. The only limitations are:

- to determine the value for the sawtooth term, the readings must cover a sufficient range so that the leading digit of the readings changes;
- to determine a value for the linear term (BP in Equation (5.3)), either one of the RBC base resistors must be known (direct-reading bridges) or both normal and complement measurements must be included in the set of measurements (resistance-ratio bridges).

In principle, only one complement measurement and one normal measurement are necessary to determine the linear term. However, the more measurements made the lower the uncertainty in the results. As a guide, at least 3 to 4 measurements should be made for each parameter fitted in the analysis. With 4 unknown resistances and several coefficients in the correction equation, the recommended minimum number of measurements is about 20.

The error model is selected in the Analysis Window by checking the appropriate check boxes. If none of the boxes are checked, the software assumes that the bridge is ideal, so only the four base ratios are fitted (as in Section 5.1). If a correction equation is required, then the appropriate terms should be selected.

As a first step in selecting the error model, run the analysis without any error model selected, and note the value of the standard deviation near the top of the Analysis Window. Next select a full cubic polynomial error model; Offset + Quadratic + Cubic + Linear (if appropriate), and repeat the analysis. If some of the t -ratios for the coefficients are greater than 2.5, and the standard deviation has decreased significantly, then there is a statistically significant error in the bridge. You can optimise the form of the correction equation by successively deselecting those correction terms that have the lowest t -ratios. Note too that some bridges may have sawtooth-shaped errors.

Our experience testing several hundred bridges suggests that most bridges do not need corrections applied. Further, if a correction is required and some of the t -ratios are large, greater than 10 say, then there may be a fault in the bridge. If you do find large t -ratios, use the graph or the data window to check that the measured bridge error is within the manufacturer’s specification.

5.3 The Uncertainties in Parameter Values, and Total Uncertainty

In addition to the values for the resistance ratios and the constants in the correction equation, the software also calculates uncertainties in the values. The uncertainties can be presented in the Analysis Window in three forms: as absolute uncertainties, relative uncertainties (uncertainty/parameter value), and as t -ratios (parameter value/uncertainty). The t -ratio form is suitable for a t -test for statistical significance of the parameter. Usually values of t greater than 2.5 indicate the term is significant and the bridge has an error. If the t -ratios are less than 2.5, the reduction in standard deviation (uncertainty in bridge readings) with a correction is usually marginal, and it is simpler to operate the bridge without corrections.

When printing the result summary or certificate, the software calculates the expanded uncertainty for the bridge readings. When **no correction equation is applied** the expanded uncertainty is calculated as

$$U = \pm ks, \quad (5.4)$$

where s is the standard deviation of the fit (Equation (5.1)) and k is the coverage factor determined from the Student t -distribution for $N - \rho$ degrees of freedom¹ and the level of confidence indicated in the *Certificate Settings* dialog box (the default is 95%).

When **a correction equation is applied** the expanded uncertainty in the corrected bridges readings is

$$U = \pm ks(1 + \rho/N)^{1/2}, \quad (5.5)$$

where, as before, s is the standard deviation of the fit (Equation (5.2)) and k is the coverage factor for $N - \rho$ degrees of freedom and the level of confidence indicated in the *Certificate Settings* dialog box. Note that the extra ρ/N term in Equation (5.5) accounts for the uncertainty in the correction.

When the Graph Window is in residuals mode, the confidence interval $\pm U$ is indicated on the graph. With a good choice of error model, the points in the residuals graph should be distributed randomly with very few points (perhaps one or two) outside the $\pm U$ band.

Note: For direct-reading bridges, it is assumed that the uncertainty in the measured values of the RBC base resistances is negligible compared to $\pm U$ and therefore does not contribute significantly. This is consistent with the policy of most ISO17025 accreditation bodies, which require reference standards to be at least a factor of 3 (sometimes 4 or 5) better than the instrument under calibration. At a factor of 3, the additional uncertainty would be less than 5% of U .

¹ See the ISO Guide to the Expression of Uncertainty in Measurement, 1995, for an explanation of terms.

6 Software Guide

This section briefly describes the tasks that can be carried out using the RBC software. Note that the software can be used with both manually operated RBCs (RBC100M, RBC400M) and automatic RBCs with the USB interface (RBC100A, RBC400A). Some of the features of the software will not be available with the manually operated RBC.

The first time you run the RBC software, it will request a password. The password can be found on the front of the CD.

6.1 Software capabilities

The software has three main windows; the Data Window, the Graph Window, and the Analysis Window.

The **Data Window** is a spreadsheet listing the switch settings and combination number for each combination, a summary of all of the measurements, the corrections (if calculated), and the residual differences between the measured and calculated measurements. The results may be ordered according to RBC combination number or descending value. The spreadsheet can be copied (under the *Edit* menu) and pasted into other applications including Microsoft Word and Excel. A single column of data can also be copied from other applications into the spreadsheet. Only the readings column can be edited by the user.

The **Graph Window** gives a graphical representation of the bridge errors. It has two modes selectable under the *Graph* menu; one with the bridge errors and correction equation plotted, and a second with the residual errors from the least-squares fit and the calculated expanded uncertainty for the bridge readings. The graph may be copied and pasted as a picture into other applications. Data is only plotted in the graph once an analysis calculation has been successfully completed.

The **Analysis Window** specifies the model for the bridge error and summarises the results of the least-squares fit to that model. The uncertainties in the model parameter values can be set to one of three different forms using the *Options* menu.

The Data, Analysis and Graph windows are fully user adjustable, so can be tiled or overlaid according to user preference. The fonts and column positions in the Data and Analysis Windows can be adjusted, and the range, gridlines, axis titles in the Graph Window can be changed. These settings are stored in the RBC.ini file on the computer and can be reset to default values simply by deleting the RBC.ini file. If you delete the file you will need to re-enter the software password the first time you restart the software. The password is located on the inside back cover of this manual.

Once an analysis has been completed there are several ways of exporting the results. The *Print Results* option (under *File* menu) prints a complete summary of the bridge calibration including: job and report numbers, the RBC identification and resistance values, bridge identification and settings, client identification, a tabular summary of measurements and results, a graphical summary of the results and least-squares fit, and a list of the values and uncertainties calculated by the software. The RBC, bridge, client and certificate details are entered into the software via the *Settings* menu. If Microsoft Word is loaded onto your computer, you can also produce a Word file for the results summary by selecting the *Generate Microsoft Word Files on Printing* setting under the *Options* menu. Word files are generated in the background and are saved in the current directory.

The *Print Certificate* option (under *File* menu) prints a calibration certificate for the bridge. The correction equation used in the certificate is the one currently selected in the Analysis Window. Before you can print the certificate, you must also fill in all the information in the *Bridge Information*, *Client Information* and *Certificate Settings* dialog boxes. The certificate should be printed onto company letterhead and, if the various dialog boxes are filled in correctly, it will comply with ISO17025. If Microsoft Word is loaded onto your computer, you can also produce a word file for the Certificate by selecting the *Generate Microsoft Word Files on Printing* setting under the *Options* menu. Word files are generated in the background and are saved in the current directory.

The *Export Results* option under the *File* menu allows the user to export the result summary to a text file. The file includes all of the various settings for the RBC and the software. The text file generated with this option also records the standard deviations of bridge readings, information that is not available from the Data Window.

6.2 A Quick-Start Guide

To use the software you will need to:

1. Connect the RBC to the bridge.
2. Start the RBC application.
3. Enter the resistor values for the RBC into the *RBC Information* dialog box (under the *Settings* menu), and the RBC type to 'manual' or 'automatic'. If you are calibrating a direct-reading resistance bridge and have traceable values for any of the RBC resistors, set at least one of the values to constant. If you do not set one of the values to constant, the software will determine non-linearity, but not the scale error. The RBC values can be saved as default values or stored with a descriptor (e.g., the RBC serial number) if you have more than one RBC. If you are calibrating a resistance-ratio bridge and plan to include complement measurements, do not set any of the resistor values to constant.
4. Set the standard resistor value in the *Bridge Information* dialog box (under the *Settings* menu). If the standard resistor value and the RBC resistor values are entered before you take readings, then the Fitted Value column of the Data Window will indicate the expected value for the reading. This may be helpful for checking that the RBC switch settings are correct as you progress through the calibration. Note that if you select **ohms** or **k ohms** for the bridge units, the software assumes that the bridge is direct-reading and sets the value for the standard resistor to 1 ohm or 1 kilo-ohms.
5. Select the appropriate bridge from the *Bridge/Interface Setting* dialog box on the *Settings* menu. Choose the Keyboard interface if you want to enter the readings into the software manually.
6. Select the set of combinations you require and the measurement settings, and press the *Start* button on the application's toolbar. Note that it is not necessary to enter all 70 possible RBC readings. However, the more measurements you are able to include the lower the uncertainty in the results. For a manual RBC, the software will prompt you to set the appropriate RBC combination before each set of readings, otherwise these will be set automatically.
7. For the first run through the analysis of the measurements, make sure **none** of the error-model terms in the Analysis Window have been selected. Click on the *Calculate* button in the Analysis window.

You should now have a graph showing the error in the bridge for each reading. If you have made any mistakes in the switch settings on the RBC there will be one or two data points on the graph that look very different from the overall trend. If you click on outlying points in the Graph Window, the software will highlight the point and highlight the corresponding row in the Data Window. You can then check whether you have made a mistake by repeating the measurement, re-entering the data, and clicking calculate again.

When you have run a calculation, the Analysis Window will also indicate the standard deviation in the bridge readings near the top of the Analysis Window. Typically, with a successful calibration run, this uncertainty value will be less than half of the manufacturer's specified accuracy.

8. Now check to see if a correction equation might be useful. First select the first four polynomial terms under the error model in the Analysis Window. Click the *Calculate* button. If you do not have one of the RBC resistors set to a constant (direct-reading calibrations) or both normal and complement measurement results entered (resistance-ratio calibrations), then an error dialog box will pop up and you will have to deselect the linear term in the error model.
9. After the calculation you should have a Graph Window showing the calculated errors in the bridge, and the Analysis Window showing the values for the constant in the correction equation, their uncertainties, and the standard deviation of bridge errors with the correction applied. Under the *Graph* menu, you can change the graph to show residuals from the fit or the total bridge error. You can also change the format and titles of the two graph axes.

10. After you have trialled a number of different error models, you can print a result summary and a calibration certificate for the bridge. The model selected for a certificate should be a good compromise between the minimum possible uncertainty and as simple a calibration equation as practical. Section 5 of this manual, which describes the analysis process, gives some guidelines. To enter the information required for the certificate you will need to fill in all of the relevant text boxes in the *RBC Information*, *Bridge Information*, *Client Information*, and *Certificate Settings* dialog boxes, all of which can be found under the *Settings* menu.

6.3 The Least-Squares Fit

As described in Section 5, the least-squares algorithm finds values of the base ratios R_1/R_s to R_4/R_s , and values for the coefficients of the correction equation that minimise the variance of the differences between measured and calculated values for bridge readings:

$$s^2 = \frac{1}{N - \rho} \sum_{i=1}^N (P_{i,\text{meas}} + \Delta P(P_{i,\text{meas}}) - P_{i,\text{calc}})^2. \quad (5.2)$$

A good analogy is that the algorithm searches for the lowest point on a surface. For a geographical surface, there are two coordinates: longitude and latitude. For the least-squares surface there are at least four co-ordinates corresponding to the values of R_1/R_s to R_4/R_s and the coefficients of the correction equation. The height of the surface corresponds to the value of s^2 in Equation (5.2). The least-squares surface may be quite complicated with hills, valleys and holes, but usually with one very deep hole corresponding to the best fit of the model to the data. Because the surface is complicated, and there may be several holes and valleys, it is important that the algorithm is directed to start the search for the minimum near where the deepest hole is expected to be found. This means the software must have starting values for the resistance ratios and the correction constants.

For resistance-ratio bridges the values entered into the *RBC Information* dialog box are the starting values for the search for the minimum variance. All of the check boxes in the *RBC Information* dialog box should be left unchecked so the program can search for the best values. With resistance-ratio bridges the value of the standard resistor used with the bridge must also be entered into the *Bridge Information* dialog box.

For direct-reading bridges at least one of the RBC resistor values must be set to the known value and the corresponding check box checked to indicate that it is a constant. Usually, the lowest uncertainty is obtained by choosing one or two of the base resistors with values nearest that of the standard resistor. Any values for the base resistances left unchecked in the *RBC Information* dialog will be adjusted by the algorithm to obtain the best fit to the measurements.

For both direct-reading bridges and resistance-ratio bridges, the starting values for the coefficients of the correction equation are set to zero, since the errors are expected to be small.

Once the algorithm has identified the best values for the base ratios and coefficients, it calculates the uncertainties in these values. This information is obtained by investigating the curvature of the s^2 surface near the bottom of the hole. If, for example, the hole is very deep and narrow, then the co-ordinates of the position of the hole (the R_1/R_s to R_4/R_s values) can be determined accurately.

Users wishing to verify the software by comparing the results with those from another least-squares algorithm should recognise that the least-squares problem set by Equation (5.2) is a difficult non-linear problem requiring a robust algorithm. In particular, there are some cases when the solve functions found in spreadsheet applications fail to correctly locate the minimum. For more details on the algorithm employed by the software, which is nicknamed amoeba because of the way it searches for the minimum, see the reference in the footnote².

6.4 Automatic Bridge Readings

The RBC software communicates with resistance bridges via interface dynamic link libraries (DLLs). A separate DLL for each bridge is required. Some DLLs are supplied with the RBC software. Users of the software may wish to write their own DLLs for bridges where no other DLL is available or to add functionality and replace the existing DLLs. The DLLs can be written in any software language, provided they conform to the requirements set out below.

² For detailed description of the algorithm, see Press W.H., Flannery B.P., Teukolsky S.A., and Vetterling W.T., "Numerical Recipes: The art of Scientific Computing", Cambridge University press, London 1986.

An example DLL written in Pascal for an ASL F18 bridge is given in Appendix D.

Each DLL file must provide seven procedures identified by the following names:

```
GetVersion  
GetBridgeName  
GetParamDescriptions  
GetError  
OpenInterface  
CloseInterface  
GetReading
```

A description of each procedure with parameter listings written in Delphi Pascal is given below. Note that in Pascal, the PChar type is a pointer to a null-terminated string of 8-bit characters, so the parameters defined in the procedure headings in other languages must be compatible with this type. Also note that **stdcall** is a calling convention in which the parameters are passed on the stack from right-to-left and are automatically removed from the stack upon returning. Words in bold typeface below are Pascal reserved words.

```
procedure GetVersion(var Version:PChar); stdcall;
```

This procedure returns the version of the DLL in the Name parameter. The version of the selected DLL is displayed in the RBC software below the DLL list box in the right hand side of Figure 4.3.

```
procedure GetBridgeName(var Name:PChar); stdcall;
```

This procedure returns the name of the bridge in the Name parameter. The name of the bridge is used in the RBC software to identify the bridge being calibrated, as shown in the list box in the right hand side of Figure 4.3.

```
procedure GetParamDescriptions(var Description1, Description2,  
    Description3, Description4, Description5, Description6, Description7,  
    Description8, Description9, Description10:PChar); stdcall;
```

In order for the RBC software to communicate in a flexible way with the bridge being calibrated, provision is made for the user to specify up to 10 different parameter values. The procedure `GetParamDescriptions` returns a description of each parameter required to be passed to the DLL. If fewer than 10 parameters are required, the unused `Description` parameters should be assigned a null string. These parameter descriptions are used to generate the list of descriptions for the text boxes on the left hand side of the dialog box of Figure 4.3.

```
procedure GetError(var Error:Boolean; var ErrorDescription:PChar); stdcall;
```

This procedure is called by the RBC software to determine whether or not an error has occurred during the execution of one of the DLL procedures. The parameter `Error` should be set to `TRUE` if an error has occurred, in which case the parameter `ErrorDescription` should contain a description of the error to provide information to the user of the RBC software. Provision must be made within the DLL to reset the `Error` parameter to `FALSE` after the call to this procedure has been made by the RBC software. This can be done using an error flag variable that is global to the DLL.

```
procedure OpenInterface(var Parameter1, Parameter2, Parameter3, Parameter4,  
    Parameter5,Parameter6, Parameter7, Parameter8, Parameter9,  
    Parameter10:PChar); stdcall;
```

The parameters `Parameter1` to `Parameter10`, corresponding to the descriptions returned from the procedure `GetParamDescriptions` above, are passed from the RBC software to the DLL in the form of strings. The `OpenInterface` procedure should check the validity of each parameter. If all parameters contain valid values, the procedure should then open the interface and initialise the bridge. If not, then the error flag should be set to `TRUE` and the appropriate error description should be set, both to be returned when the RBC software calls the `GetError` procedure.

```
procedure CloseInterface; stdcall;
```

This procedure returns the bridge to local (so the user can change bridge settings on the front panel of the bridge) and closes the interface to the bridge. If an error occurs during this operation, the error flag should be set to `TRUE` and the error description should be set.

```
procedure GetReading(var Reading:PChar); stdcall;
```

This procedure carries out a single reading of the bridge and returns the value formatted as a string in the `Reading` parameter. The procedure should carry out error checking before returning the reading, and ensure that the returned `Reading` string corresponds to a valid numerical value. If an error occurs, the error flag should be set to `TRUE` and the error description should be set.

7 A Bridge Calibration Procedure

This section provides a simple outline of a calibration procedure. It is intended to be a guide only so should be modified to suit your laboratory's needs and QA system.

Step 1: Determine the relevant specifications of the bridge.

- What is its range, in terms of either resistance or resistance ratio? Ensure that the range of the RBC will cover a good sample of the range of measurements likely to occur in use.
- What is its expected accuracy? Ideally the accuracy of the RBC should be at least a factor of 3 better than the bridge. This ensures that the uncertainties due to the RBC do not contribute significantly to the calibration uncertainty.
- If the bridge reads only in terms of ohms or measures resistance ratio with an internal standard resistor only, then to assess the absolute accuracy of the bridge (as opposed to non-linearity only) you must have a calibration value for at least one of the RBC resistance values.
- For resistance-ratio bridges, an external standard resistor should be used if possible. Choose a standard resistor with a value that ensures the range of normal and complement values overlap. A standard resistance of 100 Ω works well for both the RBC100-A and RBC400-A. A standard resistance of 25 Ω can also be used with an RBC100-A to calibrate bridges that read ratios up to 4.0. An overlap in the normal and complement ranges will minimise the uncertainty in the value of the linear correction term, if it is determined.

Step 2: Simple inspection

Connect the RBC to the bridge and switch both instruments on. Confirm that both the bridge and the RBC are functioning correctly by comparing the bridge readings for 3 or 4 of the RBC combinations with the numbers expected (Appendix B). The Data Window of the software will display the expected ratios for your RBC once you've filled out the details in the *RBC Information* dialog box and entered a value for the standard resistor in the *Bridge Information* dialog box. Note that if you select ohms or kohms for the bridge units the value for the standard resistor will be set to 1 Ω or 1 k Ω by default.

Step 3: The Measurements

By following the instructions of Section 4, either manually or automatically acquire bridge measurements for the resistance ranges required. If you wish to assess the absolute accuracy of a resistance-ratio bridge, exchange the connections to the RBC and the standard resistor to enable the complement (reciprocal) ratios to be measured.

In order to ensure a high level of confidence in the results of the analysis, try to take at least 20 measurements in total, preferably including at least 5 complement ratios. The more measurements you are able to include, the lower the uncertainty in the results.

For thermometry bridges with specified accuracy > 0.1 ppm, a full selection of normal and complement measurements can usually be made within 1 or 2 hours, depending on the settling time of the bridge. For bridges with specified accuracies < 0.1 ppm, the measurements may take more than 8 hours and the measured uncertainties may be limited by the uncertainties in the RBC (see Section 8 for a detailed uncertainty analysis).

Step 4: Analysis

First: Run the least-squares-fit tool with all of the error-model terms switched off; the calculation then assumes that the bridge is ideal. Clicking the *Calculate* button will cause the software to evaluate the results without using a correction equation. Record the value of the standard deviation calculated from the fit. If both the bridge and the RBC are in good order the standard deviation should be at least a factor of 2 better than the specified accuracy for the bridge and there should be no conspicuous non-linearity or strong pattern in the residual errors on the graph.

Second: With some bridges it may be advantageous to apply corrections to the bridge readings. To determine the best values for the corrections run the analysis with the appropriate correction equation terms switched on. As a first trial select the general cubic error model (Equation (5.3)) with all four polynomial error terms. If the bridge exhibits any non-linearity the standard deviation with this fit will be significantly less than that obtained without the correction equation.

Third: If the bridge has been found to exhibit non-linearity, all of the error model terms should be trialled to determine the equation that yields the best compromise between the lowest standard deviation and the fewest number of fitted parameters. As a guide, the *t*-ratio for all the parameters used in a correction equation should be greater than 2.5. If a *t*-ratio is smaller than 2.5, it is likely that the corresponding term of the equation is not important, so can be deselected. A few bridges have been found to exhibit sawtooth shaped error curves.

Experience with a wide range of bridges has shown that many bridges do not require a correction equation at all. If a bridge is faulty, then the type of the correction equation may give clues to the nature of the faults. A bridge with a low input impedance or poor isolation will typically have a square law (quadratic) error. An ac bridge with a unwanted input capacitance or inductance will typically have a cubic error.

Step 5: Reporting.

A hard copy summary of the measurements and analysis is obtained by selecting the *Print Results* option in the *File* Menu. If the bridge has been found to be satisfactory the *Print Certificate* command may be used to produce a calibration certificate for the bridge. To produce a certificate, the software will expect the information identifying the owner of the bridge, the calibration laboratory, and a description of the bridge. If the *Bridge Information* and *Certificate Settings* dialog boxes have been filled correctly, the certificate will comply with ISO 17025 *General requirements for the Competence of Testing and calibration Laboratories*.

The formatting for the certificate and the text for the certificate can be changed via the *Certificate Information* dialog box (under the *Settings* menu).

If the bridge does not meet the expected specification or is not fit for purpose, a certificate should not be produced.

8 Evaluating Uncertainties in RBC measurements

8.1 Introduction

This chapter describes the effects associated with the RBCs and the most common of the effects associated with resistance bridges that give rise to errors in the measurements. The uncertainty analysis described here has three purposes:

- To explain the factors that limit the accuracy of the RBC.
- To determine the expected performance of the RBC in any particular case.
- To aid in the recognition of faulty bridges.

For all bridge calibrations the contributions to the total uncertainty, expressed as a standard deviation, σ , can be associated with either the bridge, the connecting cables, or the network .

$$\sigma_{\text{total}}^2 = \sigma_{\text{RBC}}^2 + \sigma_{\text{cables}}^2 + \sigma_{\text{bridge}}^2 . \quad (8.1)$$

The various contributions to these terms are discussed below.

Note: the terms cited in Equation (8.1) should **not** be added to the measured variance as determined from the analysis of the results (Equations (5.1) or (5.2)). The variance s^2 returned from the analysis of the measurements is an experimental determination of σ_{total}^2 . Ideally, if all factors have been correctly considered, the two variances σ_{total}^2 (Equation (8.1)) and s^2 as determined from the measurements (Equations (5.1) and (5.2)) should be approximately equal. If s^2 is found to be significantly greater than σ_{total}^2 , then the bridge under test or the RBC may be faulty.

8.2 Summary of the Most Significant Sources of Uncertainty

Tables 8.1 summarises the sources and magnitude of the major uncertainties due to all the effects that contribute to the uncertainty in RBC measurements on resistance-ratio bridges. The values have been calculated for an RBC100A used with a switched-dc bridge operating with a 1 mA sensing current and a 100 Ω standard resistor. The table shows the RBC100A is capable of standard uncertainties better than 1 $\mu\Omega$ (0.01 ppm of 100 Ω), and usually better if the RBC temperature is stable. Figure 8.1 shows the results of an assessment of a switched dc bridge with a RBC100A using a 3 mA sensing current, yielding a standard deviation of residuals of 160 n Ω (1.6 ppb of 100 Ω).

Table 8.1: Summary of the most significant sources of uncertainty due to the RBC.

Source	Maximum error / n Ω	Standard uncertainty / n Ω	Basis for numerical uncertainty evaluation
Four-terminal junction	50	20	Measurements of cross resistance of manufactured junctions
Combining network	50	20	Measurements of the combining networks of several RBCs
Ambient temperature	300	120	Based on 10 mK peak-to-peak temperature variation and maximum temperature coefficient of $\pm 0.3 \times 10^{-6} / ^\circ\text{C}$
Insulation resistance	100	50	Based on minimum of 0.1 T Ω , across the terminals of different base resistors
Drift	300	100	Based on 1 ppm drift per year drift rate and measurement over 1 day
TOTAL	< 1000	160	

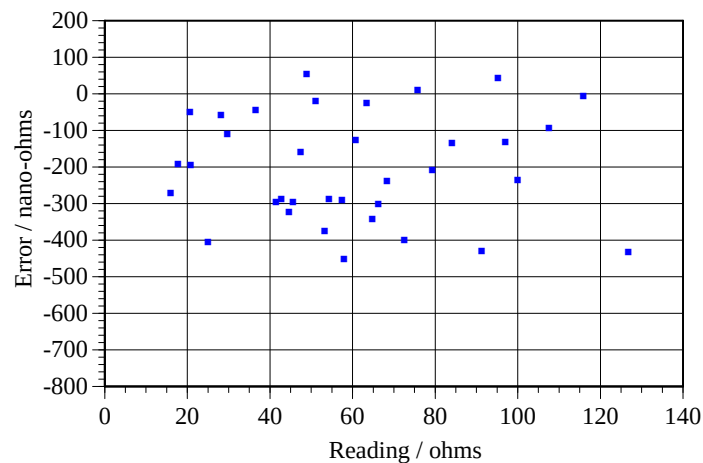


Figure 8.1: Results of an assessment of a high-quality dc resistance bridge using an RBC100A showing a bridge offset of – 200 nΩ. The standard deviation of the residual errors is 160 nΩ. Full scale on the graph corresponds to 1 μΩ.

8.3 Sources of Uncertainty in the RBC for dc Measurements

8.3.1 Thermal emfs

Thermal emfs are the small voltages generated in conductors due to the Seebeck effect. The emfs are a side-effect of heat flow in the conductor and occur only where there are temperature gradients along the conductors. The emfs become apparent when different metals, which generate different emfs, are used in a closed circuit. For measurements made at room temperature, the voltages are normally of the order of a few microvolts (a few parts in 10^5 at 100 Ω and 1 mA sensing current). With care, the effects can be reduced to a few tenths of a microvolt, but for highest accuracy resistance measurements they must be eliminated. This is usually done by periodically reversing the sensing current. With the sensing current flowing in one direction, the unwanted effects might add to the reading, and in the other direction they would subtract from the reading. The average of the two readings should therefore be free of the errors. This procedure typically reduces thermal emf errors to a few parts in 10^{10} , depending on the ambient temperature stability. Most high-accuracy dc bridges exploit this technique by using a switched-dc or square-wave sensing current. AC bridges avoid the thermal emfs in the same way by using a low-frequency sinusoidal sensing current (typically in the range 10 Hz to 400 Hz).

8.3.2 Four-terminal Junction Cross-resistance

A four-terminal junction is a terminal block with four terminals connected in such a manner that when a current is passed through any two terminals there is no voltage developed across the other two terminals. This means that resistors connected to the block appear to be connected at a single point. In practice, the junction is not ideal and the non-ideal behaviour can be represented in terms of two ‘cross resistances’. For the junction used in the RBC100A and RBC400A, the cross-resistances are typically less than 50 nΩ. The standard deviation of the cross-resistance errors for all 35 combinations is typically less than 20 nΩ (less than 2 parts in 10^{10} at 100 Ω).

Further information on the modelling and measurement of the cross-resistances of four-terminal junctions can be found in the paper by Riley³.

³ J C Riley. "The Accuracy of Series and Parallel Connections of Four Terminal Resistors", *IEEE Trans Instrum Meas*, IM-16, 3, pp 258-68, 1967.

8.3.3 Combining Network

In order to realise the parallel combinations of the network used in the RBC, a low- resistance connection must be made between each of the terminals of the resistors (see the figures in Table 2.1). Because the resistance of the connections is not zero in practice, the currents through each of the resistors may not be divided according to their resistance. If the currents are not distributed correctly then the measured resistance of parallel combinations will be in error. One solution is to introduce known resistances into the current leads so that the currents are distributed properly. The same effect can also be achieved by introducing combining resistors into the potential leads, or into both the current and potential leads for a greater effect, and that is what has been done for the RBC100A and RBC400A (see Figure 4.1). With the combining network in place, the values for the parallel combinations of two and three resistors are given below.

For the two-resistor case

$$R(R_1 \parallel R_2) = \frac{R_1 R_2}{R_1 + R_2} \left[1 + \frac{N_2}{D_2} \right], \quad (8.2)$$

where

$$N_2 = R_1 R_2 \left(\frac{R_{p1}}{R_1} - \frac{R_{p2}}{R_2} \right) \left(\frac{R_{c1}}{R_1} - \frac{R_{c2}}{R_2} \right) \quad (8.2a)$$

and

$$D_2 = \left(R_1 + R_2 + \frac{R_{p1} + R_{p2}}{R_{p1} + R_{p2} + R_{c1} + R_{c2}} \frac{R_{c1} + R_{c2}}{R_{p1} + R_{p2} + R_{c1} + R_{c2}} \right) R_{p1} + R_{p2} + R_{c1} + R_{c2} . \quad (8.2b)$$

For the three-resistor case

$$R(R_1 \parallel R_2 \parallel R_3) = \frac{R_1 R_2 R_3}{R_1 R_2 + R_1 R_3 + R_2 R_3} \left[1 + \frac{N_3}{D_3} \right], \quad (8.3)$$

where

$$\begin{aligned} N_3 = R_1 R_2 R_3 & \left[\left(R_{p1} + R_{c1} + \frac{R_{p1} R_{c1}}{R_1} \right) \left(\frac{R_{p2}}{R_2} - \frac{R_{p3}}{R_3} \right) \left(\frac{R_{c2}}{R_2} - \frac{R_{c3}}{R_3} \right) \right. \\ & + \left(R_{p2} + R_{c2} + \frac{R_{p2} R_{c2}}{R_2} \right) \left(\frac{R_{p1}}{R_1} - \frac{R_{p3}}{R_3} \right) \left(\frac{R_{c1}}{R_1} - \frac{R_{c3}}{R_3} \right) \\ & \left. + \left(R_{p3} + R_{c3} + \frac{R_{p3} R_{c3}}{R_3} \right) \left(\frac{R_{p1}}{R_1} - \frac{R_{p2}}{R_2} \right) \left(\frac{R_{c1}}{R_1} - \frac{R_{c2}}{R_2} \right) \right] \end{aligned} \quad (8.3a)$$

and

$$\begin{aligned} D_3 = & R_1 R_2 + R_1 R_3 + R_2 R_3 \left[(R_{p1} + R_{c1})(R_{p2} + R_{c2}) + (R_{p1} + R_{c1})(R_{p3} + R_{c3}) + (R_{p2} + R_{c2})(R_{p3} + R_{c3}) \right] \\ & + R_{c1} R_{c2} + R_{c1} R_{c3} + R_{c2} R_{c3} \left[R_1(R_{p2} + R_{p3}) + R_2(R_{p1} + R_{p3}) + R_3(R_{p1} + R_{p2}) \right] \\ & + R_{p1} R_{p2} + R_{p1} R_{p3} + R_{p2} R_{p3} \left[R_1(R_{c2} + R_{c3}) + R_2(R_{c1} + R_{c3}) + R_3(R_{c1} + R_{c2}) \right] \\ & + \left(R_{c1} R_{c2} + R_{c1} R_{c3} + R_{c2} R_{c3} \right) \left(R_{p1} R_{p2} + R_{p1} R_{p3} + R_{p2} R_{p3} \right) \end{aligned} \quad (8.3b)$$

where: R_1 , R_2 and R_3 are the base resistors;

R_{p1} , R_{p2} and R_{p3} are the potential sharing resistors;

R_{c1} , R_{c2} and R_{c3} are the current sharing resistors;

and the symbol $\parallel$ is used to indicate that resistors are connected in parallel.

Equations (8.2) and (8.3) show that when $R_{p1}/R_1 = R_{p2}/R_2$, $R_{c1}/R_1 = R_{c2}/R_2$, and $R_{c3}/R_3 = R_{c3}/R_3$, there is no error in the parallel combinations. The RBC is manufactured to ensure that these conditions are closely met. The potential sharing resistances are in the range $1\ \Omega$ to $3\ \Omega$, and the resistances are matched so that the error in the parallel combinations is less than $0.05\ \mu\Omega$ (1ppb of $100\ \Omega$). The standard deviation of the combining network errors is typically less than $0.02\ \mu\Omega$.

Note that the expressions given for the combining network errors in Equations (8.2) and (8.3) are different from those given in the operator manual for the manually operated RBCs. In the manually operated RBCs the current sharing resistances are very small (a few milliohms) so that the combining network performs satisfactorily without the additional resistors⁴.

8.3.4 Leakage Resistance (see also Section 8.4)

Another factor that may affect the long-term performance of the RBC is the quality of the insulating materials used in the RBC components. In particular, the insulation resistances are strongly affected by humidity. Typically the insulation resistance ranges from $10^{11}\ \Omega$ to $10^{13}\ \Omega$ for relative humidity in the range 70 % RH to 40 % RH. The automatic RBC's are sealed in an airtight can so the humidity and the insulation resistances are normally at the upper end of these ranges. In most environments the insulation resistance causes negligible error.

For normal RBC combinations, the leakage resistance R_L appears in parallel with the network resistance R_N so that the measured ratio P_{meas} is

$$P_{\text{meas}} = \frac{1}{R_s} \frac{R_N R_L}{R_N + R_L} \quad (8.4)$$

$$\approx \frac{R_N}{R_s} - \left(\frac{R_N}{R_s} \right)^2 \frac{R_s}{R_L} = \frac{R_N}{R_s} - P^2 \frac{R_s}{R_L}, \quad (8.5)$$

so that a small error, with a quadratic dependence on resistance ratio, P , occurs. The worst case occurs with the largest of the series combinations (usually $R_1 + R_2$). Then the difference between the measured and calculated values for the resistance is

$$R(R_1 + R_2)_{\text{meas}} - R(R_1 + R_2)_{\text{calc}} = \frac{-(R_1 + R_2)^2}{R_s R_L}, \quad (8.6)$$

which leads to a relative error in the measurement of

$$\varepsilon = \frac{-(R_1 + R_2)}{R_L}. \quad (8.7)$$

To achieve an accuracy of 0.01 ppm at $100\ \Omega$, which is required for the RBC100-M and RBC400-M calibrators, the various insulation resistances have to be greater than $10^{10}\ \Omega$. In most environments, the insulation resistances are greater than $10^{11}\ \Omega$ so the errors are negligible. As a matter of long-term care, the insulation resistances in the RBC should be checked occasionally to ensure that they do not contribute significantly to the uncertainty (see Section 9).

⁴ If the current sharing resistors, R_{c1} , R_{c2} , R_{c3} are assumed to be much smaller than R_{p1} , R_{p2} , R_{p3} , then equations (8.2) and (8.3) simplify to the equations given in the operator manual for the RBC100M and RBC400M:

$$R(R_1 \parallel R_2) \approx \frac{R_1 R_2}{R_1 + R_2} \left[1 + \left(\frac{R_1 R_2}{R_1 + R_2} \right) \left(\frac{R_{p1}}{R_1} - \frac{R_{p2}}{R_2} \right) \left(\frac{R_{c1}}{R_1} - \frac{R_{c2}}{R_2} \right) \left(\frac{1}{R_{p1} + R_{p2}} \right) \right]$$

and

$$R(R_1 \parallel R_2 \parallel R_3) \approx \frac{R_1 R_2 R_3}{R_1 R_2 + R_1 R_3 + R_2 R_3} \left[1 + \frac{R_1 R_2 R_3}{R_1 R_2 + R_1 R_3 + R_2 R_3} \left(R_{p1} \left(\frac{R_{p2}}{R_2} - \frac{R_{p3}}{R_3} \right) \left(\frac{R_{c2}}{R_2} - \frac{R_{c3}}{R_3} \right) \right. \right. \\ \left. \left. + R_{p2} \left(\frac{R_{p1}}{R_1} - \frac{R_{p3}}{R_3} \right) \left(\frac{R_{c1}}{R_1} - \frac{R_{c3}}{R_3} \right) + R_{p3} \left(\frac{R_{p1}}{R_1} - \frac{R_{p2}}{R_2} \right) \left(\frac{R_{c1}}{R_1} - \frac{R_{c2}}{R_2} \right) \right) \frac{1}{R_{p1} R_{p2} + R_{p1} R_{p3} + R_{p2} R_{p3}} \right]$$

8.3.5 Power coefficients

When a current is passed through a resistor heat is dissipated. The resulting change in temperature causes a small change in the value of the resistance. A simple thermal model of a resistor shows that the resistance changes in response to sensing current according to

$$R(I_0) = R(1 + \alpha h R I_0^2), \quad (8.8)$$

where α is the temperature coefficient of the resistor, h is the thermal resistance between the resistor and the ambient environment, and I_0 is the sensing current. With most resistance bridges the excitation is provided by a constant current source so that the sensing current for the series combinations is the same as that for the single-resistor combinations, and no error occurs. However, for the parallel combinations the current is divided between the resistors and the self-heating is reduced.

The effect of the self-heating in resistor R_1 will affect the measured parallel combination of $R_1//R_2$ according to

$$R(R_1 // R_2)_{\text{meas}} - R(R_1 // R_2)_{\text{calc}} = -\frac{R_1^3 R_2^2 (R_1 + 2R_2)}{(R_1 + R_2)^4} \alpha h I_0^2, \quad (8.9)$$

where I_0 is the sensing current used for all measurements. In practice, the self-heating is complicated by the thermal time constants of the resistors, which are several minutes. If the measurements are carried out in a short time, with the resistors allowed to return to ambient temperature between measurements, the self-heating effects will be less than that implied by Equation (8.9).

For the resistors used in the RBC100A and the RBC400A, and sensing currents less than 3 mA, the power coefficients contribute less than 1ppb uncertainty.

8.3.6 Temperature Control

The most significant contribution to the RBC uncertainty is due to the combination of the finite temperature coefficients of the resistors and variations in the ambient temperature. The resistors used in the RBC have temperature coefficients within $\pm 0.3 \times 10^{-6}/^\circ\text{C}$ over the range 10°C to 30°C .

In laboratories with time-proportioning PID control for the air-conditioning system, an accuracy of 0.1 ppm should be achieved easily. In a laboratory temperature controlled to within 1°C , the maximum variation in the resistances will be about 1 part in 10^7 , leading to a standard uncertainty of about 0.03 ppm. This is near the practical limit of performance of the RBC100A and RBC400A calibrators.

Ideally, the RBC should be placed within a temperature controlled oil bath, and the instrument cases have been designed for this purpose. Control of the bath to within 10 mK should ensure the resistance variations are within 0.003 ppm peak-to-peak, or near 1 ppb rms.

Note: if ambient temperature variation is a concern, then measurements with the RBC should be made in the sequence as directed by the analysis software. Readings should not be made in either an increasing or decreasing order of resistance, as this may, depending on the sign of the resistor temperature coefficients, cause the variations due to temperature to be indistinguishable from bridge error and the resulting uncertainty calculated from the measurements may be unduly optimistic, and any correction equations may be in error. The software also has a feature allowing measurement sequences to be repeated in both the forward and reverse directions so that drift effects can be averaged further.

8.3.7 Lead Resistances

Some bridges exhibit a sensitivity to lead resistances. In these cases there will be small but negligible effects due to the potential sharing resistors in the RBC. The effects should always be insignificant since bridges that exhibit lead resistance sensitivity also exhibit a large non-linearity due to low input impedances, and these effects will be at least an order of magnitude greater than the lead resistance effects.

8.3.8 Temporal Drift

For the RBC100A and RBC400A calibrators the effects of temporal drift are small. The resistors have a relative stability of about 1 ppm per year so will drift typically only 3 ppb over a 24-hour period. Assuming a linear drift the uncertainty introduced into the RBC measurements should be less than 1 ppb.

8.4 Sources of Uncertainty in the RBC for ac Measurements

When calibrating ac bridges, there are a number of effects that introduce errors that must be considered in addition to the dc effects listed above.

8.4.1 The Combining Network

For ac applications the inductance of the combining network must be considered. The sharing resistor inductance at high frequencies increases the impedance of the combining network and destroys the matching of the combining network. If the time constants for the components of the combining network are identical, the sensing current will continue to be distributed correctly and no error occurs. The errors that arise therefore depend on the differences in the electrical time constants:

$$\Delta R_{\text{meas}} = \frac{-R_1 R_2}{(R_1 + R_2)^2} \left(\frac{L_{p1}}{R_1} - \frac{L_{p2}}{R_2} \right) \left(\frac{L_{c1}}{R_1} - \frac{L_{c2}}{R_2} \right) \left(\frac{R}{R_p} \right) 2\pi f^2, \quad (8.9)$$

where the L_p are the inductances of the respective sharing components, and R/R_p is the nominal ratio of base resistances to their potential sharing resistance. For the RBC100 the maximum error is estimated to be of the order of

$$\Delta R_{\text{meas}} = -1.0 \times 10^{-9} f^2, \quad (8.10)$$

where the frequency is measured in kHz. For the RBC400 the effects are smaller. For resistance thermometry bridges operating at frequencies less than 100 Hz, the errors are negligible.

8.4.2 Base Component Reactance

The well-known formulae for series and parallel combinations of resistances are exact for dc resistances and complex impedances. However, ac resistance bridges measure the real part of the complex impedance. The assumption of the series representation of impedance (Appendix C) ensures that for impedances in series the relationship

$$\text{Re}(Z_1 + Z_2) = \text{Re}(Z_1) + \text{Re}(Z_2) \quad (8.11)$$

is always true. However, the corresponding relationship for parallel impedances,

$$\text{Re } Z_1 Z_2 / (Z_1 + Z_2) = \left[\text{Re}(Z_1) \text{Re}(Z_2) / \text{Re}(Z_1) + \text{Re}(Z_2) \right], \quad (8.12)$$

is an approximation. For impedances that have a low reactance, i.e. are predominantly resistive and have only small series inductance or parallel capacitance, and at low frequencies, the approximation is extremely good. For inductive components, typical for resistors of less than a few hundred ohms, the errors are

$$\Delta R_{\text{meas}} = \frac{R_1 R_2}{(R_1 + R_2)^2} \left(\frac{L_1}{R_1} - \frac{L_2}{R_2} \right)^2 2\pi f^2. \quad (8.13)$$

This equation has the same form as Equation (8.9) above for the combining network error, and is typically a factor of 30 smaller, so is practically negligible.

A similar problem arises when complement ratios are included in a bridge assessment. The implicit assumption (Appendix C, Equation (C8))

$$\text{Re}(Z_x / Z_s) = 1 / \text{Re}(Z_s / Z_x) \quad (8.14)$$

is strictly satisfied only when the ratio Z_x/Z_s is real. For an accuracy of $1:10^8$ it is sufficient for the phase angles of the reference resistor and the resistance network in the RBC to be matched to within $1:10^4$. When including complement measurements in a bridge assessment the reference resistor should have a small ac-dc difference, a condition satisfied by high-performance film resistors and ac resistance standards of the Wilkins⁵ design, for all practical frequencies up to 10^4 rad/s.

8.4.3 Dielectric Losses, Stray Inductance, and Capacitance

When ac sensing currents are used with the RBC, the fields around the conductors in the RBC induce losses in the various insulating materials used in the construction of the RBC. This dielectric loss effect is very similar to the cable dielectric loss (Section 8.4.1) but much smaller, so is negligible. Similarly, the remaining ac effects due to stray inductances, stray capacitances, and the changing ac definition of the resistors with some combinations have a very small second-order effect that is negligible compared to the other ac errors.

8.5 Effects due to the Connecting Cables

The effects due to the capacitance of the cables connecting the bridge to the RBC are the most significant contributors to uncertainty in ac applications. The main effects are due to cable capacitance and dielectric loss.

With a bridge that realises a four-terminal coaxial connection to the network, the admittances of the coaxial cables connecting the bridge to the network are indistinguishable from the admittance of the network itself. Although this effect is not strictly attributable to either the network or the bridge, a poor set of cables will affect the ability of the network to expose errors in the bridge. The effect is most pronounced for the highest resistance combinations. For the series combinations the error is

$$R(R_1 + R_2)_{\text{meas}} - R(R_1 + R_2)_{\text{calc}} = -2R_1R_2 \left(\frac{1}{R_C} + \omega C_C \tan \delta_C \right) - 3R_1R_2(R_1 + R_2)\omega^2 C_C^2, \quad (8.15)$$

where R_C is the insulation resistance of the cable, C_C is the capacitance of the cable and δ_C is the loss angle of the capacitance.

The first term of Equation (8.15) involving R_C is the dc term due to the cable leakage resistance. The effect is identical to the RBC leakage resistance effect discussed in Section 8.2.4 above. It usually dominates the leakage effects in the RBC by a factor of 10 or more.

The second term of Equation (8.15) involving the loss angle of the cable is the most significant term for low-frequency ac operation and for the RBC400 introduces maximum relative error of the order of

$$2.5 \times 10^{-8} f, \quad (8.16)$$

where f is the frequency is in kHz.

At frequencies above 100 Hz or so, the frequency-squared term of Equation (8.15) dominates, introducing a maximum relative error in the RBC400 of the order of

$$2.5 \times 10^{-7} f^2, \quad (8.17)$$

where, again, the frequency is in kHz. The errors for the RB100 are smaller by a factor of 3 and 10 respectively, because of the lower resistances.

⁵ Resistors made to Wilkins' design are available from Tinsley Instruments (UK) and Automatic Systems Laboratories (UK).

8.6 Sources of Uncertainty Associated with the Bridge

8.6.1 Johnson Noise

The ultimate limit to the resolution of a bridge is determined by the thermal noise generated in all resistances, known as Johnson or Nyquist noise. The noise voltage generated by a resistor R is characterised by a mean square voltage

$$\overline{V_t^2} = 4kTR\Delta f, \quad (8.18)$$

where T is the temperature of the resistor and Δf is the bandwidth of the measuring system. A useful rule of thumb is that a $100\ \Omega$ resistor generates noise with an amplitude of $0.4\ \text{nV rms}$ for a $0.1\ \text{Hz}$ bandwidth. For many bridge designs the uncertainty in resistance due to Johnson noise is

$$\sigma^2 = \frac{4kTR_x\Delta f}{I_0^2} \left(1 + \frac{R_x}{R_s}\right), \quad (8.19)$$

which for a $0.1\ \text{Hz}$ bandwidth, $R_s = R_x = 100\ \Omega$ and a $1\ \text{mA}$ sensing current, I_0 , yields an uncertainty of approximately $0.6\ \mu\Omega$ (6 parts in 10^9). The noise imposes a compromise between the resolution, which improves with decreasing bandwidth, and measurement time, which increases with reduced bandwidth. The theoretical limit on the resolution of a bridge is determined by the relation $\Delta f\tau > 0.5$, where τ is the measurement time in seconds.

8.6.2 Detector Noise

In all bridges a detector is required to determine when the bridge is in balance. The detector itself is usually a major contributor to noise in the bridge readings. The noise in all detectors may be characterised by an equivalent input noise current spectral density i_n and an equivalent input noise voltage spectral density v_n . The effect on the resolution of the bridge varies with bridge design but always has the form

$$\sigma^2 = \frac{v_n^2 + N^4 i_n^2 R_x^2}{N^2 I_0^2} \Delta f \left(1 + \frac{R_x}{R_s}\right), \quad (8.20)$$

where N is a coupling constant. In some bridge designs the detector is transformer-coupled to the bridge so that the noise current and noise voltage can be optimised for a particular bridge impedance. In this case the factor N includes the turns-ratio for the transformer. If the turns-ratio is optimised for the minimum noise, the variance (Equation (8.20)) simplifies to

$$\sigma^2 = \frac{2v_n i_n R_x \Delta f}{I_0^2} \left(1 + \frac{R_x}{R_s}\right). \quad (8.21)$$

In a well-designed high-resolution bridge operating close to the thermal noise limit, this term should be of a similar magnitude or smaller than that for the thermal noise (Equation (8.19)). Indeed, the two terms are easily added, so that the sum is

$$\sigma^2 = \frac{4kTR_x\Delta f}{I_0^2} \left(1 + \frac{R_x}{R_s}\right) \left(1 + \frac{v_n i_n}{2kT}\right). \quad (8.22)$$

Thus, the criterion for a bridge to be limited only by thermal noise in the resistors is that $v_n i_n < 2kT$. The detector noise is often the major contributor in most bridges but is difficult to quantify because the bridge manufacturers do not usually supply the information on the detector noise voltage and current. For further information on noise and noise matching refer to the paper by Netzer⁶

⁶ Yishay Netzer, "The design of low noise amplifiers", *Proc. IEEE*, **69**, 728-741, (1981).

8.6.3 Quantisation Noise

Quantisation error is the difference between an analogue signal and its representation as a digital number. If an instrument has a resolution of Δ in its reading (equivalent to 1 count in the least significant digit), then the quantisation error (the truncated part of the reading) for any reading will always be less than $\pm \Delta/2$. For instruments with other forms of noise (e.g. Johnson noise) the quantisation error is random (on average it does not bias the readings) and contributes to the variance according to

$$\sigma^2 = \frac{R_s^2 \Delta^2}{12}, \quad (8.23)$$

or equivalently the resolution is limited to about 0.29 (1-sigma) of the least significant digit.

8.6.4 Electromagnetic Interference (EMI)

In addition to the various types of noise generated within the bridge circuit, noise may also be introduced by external agencies via electromagnetic radiation. Ideally, the contribution from external sources should be zero but in some cases it is difficult to avoid. For low-frequency instruments the most serious sources are magnetic and often associated with mains power supplies. Interference often occurs at multiples of mains frequencies (e.g. 50 Hz, 100 Hz, 150 Hz,...) so high-resolution ac bridges are usually operated at frequencies away from the mains harmonics (e.g. 25 Hz and 75 Hz) to avoid the interference. Nevertheless interference may still occur at multiples of mains sub harmonics e.g. 12.5 Hz, 15 Hz, 37.5 Hz....) caused for example by the multi-pole electric motors used to drive stirrers in standard resistor baths and thermometer calibration baths. True synchronous motors and universal motors should therefore be avoided for such applications. Induction motors should be preferred since they slip behind the mains-frequency by about 3% and generate interference that is usually just outside the bandwidth of ac bridges. Compressed air driven motors will generate very little interference.

In general, low frequency magnetic fields are difficult to shield, and the best way of reducing the interference is to eliminate the source or separate the source from the instrument by as much distance as possible.

For further advice on eliminating EMI refer to the book by Ott⁷

8.6.5 Bridge Non-linearities

In all bridge assessments with the RBC a part of the measured standard deviation will be due to the non-linearity of the bridge. If the non-linearity occurs over a wide range of readings and changes slowly with reading then a calibration equation will remove most of the effect. If, however, the non-linearity changes very rapidly with reading then the effects will be similar to the effects of noise, and contribute to the standard deviation even when a correction equation is used. In most instruments these 'differential non-linearities' are similar in magnitude to the least significant digit on the bridge so will cause an increase in the variance similar to that due to the quantisation noise (Section 8.5.3).

⁷ Ott H W, "Noise Reduction Techniques in Electronic Systems", New York, Wiley & Sons, 1976.

9 Maintenance

One of the features of the RBC100A and the RBC400A is that they are passive devices and fail-safe. If at any time a RBC is faulty then it is very unlikely that a calibration of a bridge will yield a satisfactory result. That is, if either the bridge or the RBC is faulty, then the standard deviation for the measurement will be larger than expected. There are two groups of faults that may occur gradually in the RBC and only slowly affect its performance, and therefore, may not be easily recognised. For this reason it is recommended that the RBC be subject to periodic checks to ensure continued good performance. These can be carried out in-house if the facilities are available; otherwise a calibration should be sought from Isotech. These simple checks should be carried out regularly, e.g., after 1 year from new, then no less frequent than every five years, or whenever there are suspicions that the RBC might be faulty.

9.1 Maintenance Checks and Calibration

9.1.1 Insulation Resistance Checks

These tests require an insulation meter able to measure resistances above $10^{11} \Omega$. Insulation testers such as Meggers are **not** suitable. For the purposes of these tests the RBCs should **not** be subjected to voltages in excess of 5 V. Measurements should be carried out with the relative humidity below 70% RH.

- With all of the RBC switches open, measure the resistance between each pair of the V1, V2, I1, and I2 terminals (6 measurements in total).
- With the switches set to the $R_1 + R_2$ combination, measure the resistance between any one of the V1, V2, I1, and I2 terminals and the metal case (1 measurement).

For all measurements, the resistance should be more than $10^{11} \Omega$, for which the error in the RBC combinations is about 1 part in 10^9 . Typical values for the insulation resistance are in excess of $10^{12} \Omega$.

9.1.2 Combining Network Checks

These checks require a four-terminal resistance bridge or four-terminal-resistance meter with an accuracy of better than 0.1 m Ω .

- Measure the resistance of each of the four base resistances. This can be done as the RBC would be used normally. The values, measured at room temperature, should be within 0.0005% of those listed on the calibration certificate.
- Measure the sharing resistances of the combining network. Each sharing resistance includes relay contacts and must be measured as four-terminal resistance. The measurements can be done by connecting the RBC to a bridge in the normal manner. A separate software application is available to select the appropriate switches of the network so that all 16 of the combining resistors can be measured. The error caused by the network errors can be calculated using Equations (8.2) and (8.3). A detailed technical procedure is available from Isotech.

9.2 Repair

There are no user serviceable parts within the RBC. If the RBC is found to be faulty contact Isotech immediately.

Appendix A: Specifications

Electrical and Mechanical Specifications	RBC100A	RBC400A
Corresponding thermometer resistance R_0 (Ω)	25	100
Suitable R_s values at 1:1 ratios (Ω)	25, 100	100
Resistance range, $R_{\min} - R_{\max}$ (Ω) (Note 1)	16 –127	43 – 346
Nominal accuracy ($\mu\Omega$) (Note 2)	1	4
Temperature coefficient (ppm/ $^{\circ}\text{C}$)	± 0.3	± 0.3
Combining network mismatch (max., $\mu\Omega$) (Note 3)	0.1	0.4
Four-terminal junction cross resistance (max., $\mu\Omega$)	0.05	0.05
Sensing current (max. mA)	5	3
Power requirements	5V, via the USB cable. Idle current typically less than 5 mA, switching currents less than 200 mA.	
Connections	Signal: Five-terminal guarded dc, spade lugs. Digital Control: USB.	
Size	88 mm diameter, 140 mm high. Identical to Tinsley type standard resistors.	
Software specifications		
Operating system	Windows 95, 98, 2000, 7 XP, NT, Vista compatible	
Minimum hardware requirements	486/66 PC, 8MB RAM, SVGA 800×600 monitor	
Features (Note 4):	Tabular presentation of data. Least-squares analysis for calibration equation. Graphical presentation of results. Word compatible job summary and calibration certificate. Import and export of data from other applications. Fully automatic measurements. Interface to resistance bridges.	

Notes:

- (1) Other resistance ranges may be available on request. Low resistance ranges have higher temperature coefficients and are not as accurate.
- (2) The accuracy specification is expressed as the maximum error in any of the series or parallel combinations with respect to the resistance of the base resistors. The specification assumes that the RBC is maintained in an environment with a peak-to-peak temperature variation of no more than 1 $^{\circ}\text{C}$.
- (3) The combining network mismatch is measured at time of manufacture and reported on the calibration certificate supplied with the RBC.
- (4) The latest version of the software is available on request.

Appendix B: Combination Tables

Table of Combinations: RBC100-M			
RBC component nominal values (ohms)			
R1	79.3316		
R2	47.4995		
R3	36.5896		
R4	28.2421		
Nominal resistance values for combinations with $R_s = 100.0000$ ohms			
Combination Number	Combination	Normal ratio value	Reciprocal ratio value
5	R1+R2	1.268311	0.788450
6	R1+R3	1.159212	0.862655
7	R1+R4	1.075737	0.929595
17	R1+R2//R3	1.000000	1.000000
18	R1+R2//R4	0.970429	1.030472
19	R1+R3//R4	0.952708	1.049639
29	R1+R2//R3//R4	0.912660	1.095698
8	R2+R3	0.840891	1.189215
1	R1	0.793316	1.260532
9	R2+R4	0.757416	1.320278
20	R2+R1//R3	0.725399	1.378552
21	R2+R1//R4	0.683270	1.463550
10	R3+R1//R2	0.663001	1.508294
23	R3+R4	0.648318	1.542454
22	R2+R3//R4	0.634387	1.576324
30	R2+R1//R3//R4	0.607720	1.645494
26	R4+R1//R2	0.579526	1.725548
24	R3+R1//R4	0.574171	1.741640
27	R3+R2//R4	0.543010	1.841587
25	R4+R1//R3	0.532825	1.876788
28	R3+R1//R2//R4	0.510685	1.958155
31	R4+R2//R3	0.489105	2.044549
2	R2	0.474995	2.105286
32	R1//R2+R3//R4	0.456497	2.190595
33	R4+R1//R2//R3	0.446387	2.240208
34	R1//R3+R2//R4	0.427518	2.339085
35	R1//R4+R2//R3	0.414959	2.409875
3	R3	0.365896	2.733015
4	R1//R2	0.297105	3.365818
11	R4	0.282421	3.540809
12	R1//R3	0.250404	3.993547
13	R1//R4	0.208275	4.801341
14	R2//R3	0.206684	4.838301
15	R2//R4	0.177114	5.646095
16	R3//R4	0.159392	6.273824

Table of Combinations: RBC400-M

RBC component nominal values (ohms)

R1	216.8144
R2	129.8168
R3	100.0000
R4	77.1862

Nominal resistance values for combinations with $R_s = 100.0000$ ohms

Combination Number	Combination	Normal ratio value	Reciprocal ratio value
5	R1+R2	3.46631	0.28849
6	R1+R3	3.16814	0.31564
17	R1+R4	2.94001	0.34014
7	R1+R2//R3	2.73301	0.36590
18	R1+R2//R4	2.65220	0.37705
19	R1+R3//R4	2.60377	0.38406
29	R1+R2//R3//R4	2.49431	0.40091
8	R2+R3	2.29817	0.43513
1	R1	2.16814	0.46122
20	R2+R4	2.07003	0.48308
23	R2+R1//R3	1.98253	0.50441
9	R2+R1//R4	1.86739	0.53551
21	R3+R1//R2	1.81199	0.55188
22	R3+R4	1.77186	0.56438
30	R2+R3//R4	1.73379	0.57677
10	R2+R1//R3//R4	1.66091	0.60208
24	R4+R1//R2	1.58385	0.63137
25	R3+R1//R4	1.56922	0.63726
2	R3+R2//R4	1.48405	0.67383
31	R4+R1//R3	1.45622	0.68671
26	R3+R1//R2//R4	1.39571	0.71648
33	R4+R2//R3	1.33673	0.74809
27	R2	1.29817	0.77032
3	R1//R2+R3//R4	1.24761	0.80153
34	R4+R1//R2//R3	1.21998	0.81968
28	R1//R3+R2//R4	1.16841	0.85586
35	R1//R4+R2//R3	1.13409	0.88176
11	R3	1.00000	1.00000
32	R1//R2	0.81199	1.23154
12	R4	0.77186	1.29557
14	R1//R3	0.68436	1.46122
4	R1//R4	0.56922	1.75679
13	R2//R3	0.56487	1.77032
15	R2//R4	0.48405	2.06589
16	R3//R4	0.43562	2.29557

Appendix C: AC Resistance Tutorial

C.1 Definition of Resistance for dc Measurements

The electrical resistance of a device is defined by the energy that is dissipated when a current flows through the component. For dc measurements the resistance is given directly by Ohm's law:

$$R = V/I, \quad (C1)$$

where V is the voltage across the device and I is the current flowing through it.

If a resistor has only two lead wires, the resistance of the leads is indistinguishable from the resistance of interest. Therefore, for the highest accuracy dc measurements it is necessary to eliminate the effects of lead resistances by using a 'four-terminal definition' of resistance as shown in Figure C1. The four-terminal definition requires the measuring current to flow only in one pair of leads, and for the voltage to be measured between the other pair of leads.

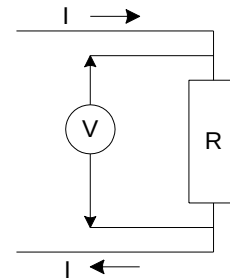


Figure C1: A Four terminal resistor.

C.2 Definitions of Resistance for ac Measurements

For ac measurements the definition of resistance is more complicated. With ac systems part of the energy 'conducted' by a device is carried by the magnetic and electric fields surrounding the component. If an external object alters those fields then the value of the resistance may also be altered. Thus, for the highest accuracy ac measurements it is necessary to limit the extent of the fields so that they are immune to external influences. This is achieved in practice by using coaxial connections to the component. There are a variety of coaxial connections (or definitions) possible⁸. The definition used for the connection to the RBC is known as a 'four-terminal coaxial' definition and is shown in Figure C2. Note that equal currents flow on the inner and outer conductors of the current leads so there is no magnetic field outside the cable. Similarly the electric field is contained entirely within the outer conductors of the two cables.

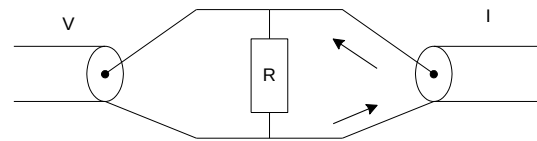


Figure C2: A four-terminal coaxial resistor.

The four terminal coaxial definition is suited only for the measurement of resistive components and at dc or low frequencies. For this reason it is very commonly found on ac resistance thermometry bridges. The main limitation in the definition is the capacitance of the two cables that shunt the component.

In general, the ac resistance of a component is not equal to the dc resistance because stray inductances and capacitances modify the distribution of the current through the component and alter the dissipation. For any component the power dissipated is

$$P = \text{Re}(VI) = |V||I|\cos(\theta), \quad (C2)$$

where $\cos(\theta)$ is the power factor of the component and θ is the 'phase angle' of the component, i.e., the difference between the phases of the voltage and current. The power may also be expressed in terms of the voltage only or the current only, by defining the conductance G and resistance R according to

$$P = \text{Re } V^2/Z = V^2G, \quad (C3)$$

⁸ For a complete descriptions of the definitions and their limitations see "Coaxial ac Bridges" by B P Kibble and G H Rayner. (Adam Hilger, 1984).

and

$$P = \operatorname{Re}(I^2 Z) = I^2 R. \quad (\text{C4})$$

These two definitions correspond to two different, but equivalent, representations of the component as shown in Figure C3. Note that in general R is not equal to $1/G$ and both R and G are frequency dependent.

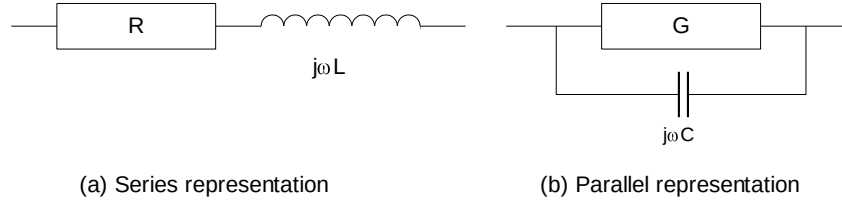


Figure C3: The series and parallel representation of a complex impedance (a) or admittance (b). In the series representation (a) the dissipative element is a resistance, in the parallel representation (b) the dissipative element is a conductance.

For the purposes of the uncertainty analysis the series equivalent representation (Figure C3 (a) and Equation (C4)) is assumed throughout this manual, since most ac bridges measure resistance according to this definition:

$$R = \operatorname{Re} V/I. \quad (\text{C5})$$

By using the definition of resistance given by Equation (C4) or (C5) it can be shown that the ac resistance of a pure resistance with a small series inductance and parallel capacitance is given by

$$R_{ac} = \frac{R_{dc}}{1 + (2\pi f R_{dc} C)^2}, \quad (\text{C6})$$

where f is the frequency of the ac current. Note that there are other effects that give rise to ac-dc differences in resistance⁹. Equation (C6) enables us to determine the effects of stray capacitances (in particular, the capacitance of the cables shown in Figure (C2)) on an ac resistance measurement. For $R = 200 \Omega$, $C = 200 \text{ pF}$ (corresponding approximately to a pair of 1 metre long coaxial cables) and $f = 90 \text{ Hz}$, the difference between the ac and dc resistance is about 1 part in 10^9 . Thus for many ac resistance measurements the four-terminal coaxial definition is perfectly satisfactory.

One of the consequences of the difference between the series and parallel representations of a component (Figure C3) is that the complement check (Section 2.2.1) is not as simple for ac bridges, as described in Section 2.2.2. AC resistance bridges measure the real part of the ratio of two complex (but predominantly resistive) impedances:

$$P = \operatorname{Re} \left(\frac{Z_x}{Z_s} \right). \quad (\text{C7})$$

Note that in this measurement Z_x is measured as a series equivalent and Z_s as a parallel equivalent component. When they are exchanged for the complement check the representation of each component will be changed and the values of resistance will be different. It follows that a complement check using the two impedances on an error free ac bridge will yield

$$P_1 P_2 = \cos^2(\theta_1 - \theta_2) \approx 1 - \frac{(\theta_1 - \theta_2)^2}{2}, \quad (\text{C8})$$

where $\theta_1 - \theta_2$ is the difference between the phase angles of the two impedances. An accurate complement check with an ac bridge therefore requires the phase angles of the components used to be matched to better than 10^{-4} , which is easily achieved in practice.

⁹ See the paper by Wilkins and Swan, "Precision ac/dc resistance standards", *Proc. IEE*, **117**, 4, April 1970, pp 841-848.

Note that both Equations (C6) and (C8) show that the ac defects in an otherwise pure resistance only have a second-order effect on resistance measurements. This is the principle that makes the RBC useful. Traditionally, devices like the Bridge Calibrator (in particular Hamon build-up resistors) have been used only for dc measurements. However, so long as the stray inductances and capacitances are small relative to the resistances in the RBC, and the ac frequency is not too high, the errors due to ac effects described here can be kept well below 1 part in 10^8 for most ac measurements. A fuller analysis of the uncertainties is given in Section 8.

Appendix D: Example DLL for an ASL F18 Bridge

In this example, written for Delphi Pascal, comments are given in blue italics between parentheses { }. The DLL, when compiled, has the file name 'F18Interface.dll'. Note that the DLL code includes a unit called GPIB, which is used to communicate with GPIB cards. This unit can be included in each DLL written for different bridges. In addition, the procedures SoftDelay, ValidReal, and ValidInteger, used internally to the DLL, can be copied into each different DLL. The only procedures that need to be rewritten for a new DLL are GetVersion, GetBridgeName, GetParamDescriptions, GetError, OpenInterface, CloseInterface, and GetReading. Much of the code deals with error checking, leading to sometimes lengthy procedures.

```
library F18Interface;
```

```
uses
```

```
{The following are units provided in the Delphi environment}
```

```
SysUtils,  
Classes,  
Dialogs,  
Windows,  
Forms,
```

```
{The GPIB unit enables communication via CEC or National Instruments interface  
cards. This unit is printed below}
```

```
GPIB in '..\Communications\GPIB\GPIB.pas',
```

```
{The following two units are provided by CEC and National Instruments, respectively,  
and contain the actual calls to the interface cards}
```

```
CECGPIB in '..\Communications\GPIB\CEC\CECGPIB.pas',
```

```
NIGPIB in '..\Communications\GPIB\National Instruments\NIGPIB.pas';
```

```
var
```

```
ErrorOccurred:Boolean; {Global error flag variable}  
ErrorStr:string; {Global error description variable}  
GPIBAddress:SmallInt; {GPIB address of the bridge, supplied from the  
RBC software via the OpenInterface procedure}  
GPIBInterfaceType:TGPIBInterfaceType; {Defined in the GPIB unit below}
```

```
{.....}
```

```
procedure SoftDelay(DelayTime:LongWord);
```

```
{This procedure is used internally to the DLL. It invokes a delay for DelayTime  
milliseconds.}
```

```
var
```

```
startTime:LongWord;
```

```
begin
```

```
startTime:=GetTickCount; {GetTickCount returns the number of  
milliseconds since Windows was started}
```

```
repeat
```

```
Application.ProcessMessages; {This allows processing of Windows  
messages during the delay}
```

```
until GetTickCount-startTime>DelayTime;
```

```
end;
```

```
{.....}
```

```
function ValidReal(S:string;MinB:Char;Min,Max:Extended;
```

```
MaxB:Char;ErrorMessage:string;var Valid:Boolean):Extended;
```

```
{This function is used internally to the DLL. It checks the that string parameter S  
contains a valid real number between the limits Min and Max. The parameter MinB can be  
'(' for an open lower limit, '[' for a closed lower limit, or 'i' for a minus infinity  
lower limit. Likewise MaxB can be ')', ']', or 'i' specifying the upper limit. If S  
does contain a valid real number, its value is returned as a numerical value.  
ErrorMessage is passed to this function in the event that there may be an error.}
```

```
var
```

```
value:Extended;  
code:Integer;
```

```
begin
```

```
Valid:=True;
```

```

if S='' then
    Valid:=False;
if Valid then
begin
    Val(S,value,code); {Converts string S into a real or integer value.
                        code is returned as 0 if S contains a string that
                        can be converted to a valid number of the same type
                        as the parameter value (in this case Extended),
                        otherwise code is returned as non-zero}
    if (code<>0) or (S[1]='.') or ((S[1]='-') and (S[2]='.')) then
        Valid:=False
    else
    begin
        if MinB='[' then
            if value<Min then
                Valid:=False;
        if MinB='(' then
            if value<=Min then
                Valid:=False;
        if MaxB=']' then
            if value>Max then
                Valid:=False;
        if MaxB=')' then
            if value>=Max then
                Valid:=False;
    end;
end;
if not Valid then
begin
    value:=0;
    ErrorStr:=ErrorMessage;
end;
    ValidReal:=value;
end;

{.....}

function ValidInteger(S:string;Min,Max:Integer;
    ErrorMessage:string;var Valid:Boolean):Integer;
{This function is used internally to the DLL. It is similar to ValidReal, but checks
that S contains a valid integer in the range from Min to Max (inclusive).}
var
    code,value:Integer;
begin
    if S='' then
        Valid:=False;
    if Valid then
    begin
        Val(S,value,code);
        if code=0 then
        begin
            if (value<Min) or (value>Max) then
                Valid:=False
            end
        else
            Valid:=False;
        end;
        if not Valid then
        begin
            value:=0;
            ErrorStr:=ErrorMessage;
        end;
        ValidInteger:=value;
    end;

    {.....}

procedure GetVersion(var Version:PChar); stdcall;
{Returns the version of the DLL for information in the RBC software.}
begin
    StrCopy(Version,'1.0');
    ErrorOccurred:=False;

```

```

end;

{.....}

procedure GetBridgeName(var Name:PChar); stdcall;
{Returns the name of the bridge for identification in the RBC software.}
begin
    StrCopy(Name,'ASL F18');
    ErrorOccurred:=False;
end;

{.....}

procedure GetParamDescriptions(var Description1, Description2,
    Description3, Description4, Description5,Description6, Description7,
    Description8, Description9, Description10:PChar); stdcall;
{Returns descriptions for up to 10 parameters required to be passed from the RBC software to this DLL - in this case, only 3 parameters are needed.}
begin
    StrCopy(Description1,'GPIB interface type (0 for CEC, 1 for National
        Instruments):');
    StrCopy(Description2,'GPIB address:');
    StrCopy(Description3,'Time out (seconds):');
    StrCopy(Description4,'');
    StrCopy(Description5,'');
    StrCopy(Description6,'');
    StrCopy(Description7,'');
    StrCopy(Description8,'');
    StrCopy(Description9,'');
    StrCopy(Description10,'');
    ErrorOccurred:=False;
end;

{.....}

procedure GetError(var Error:Boolean; var ErrorDescription:PChar); stdcall;
{Returns the error status to the RBC software.}
begin
    Error:=ErrorOccurred; {Sets the Error parameter to the value of the error flag}

    if ErrorOccurred then
        StrPCopy(ErrorDescription,ErrorStr)
    else
        StrCopy(ErrorDescription,'');
        ErrorOccurred:=False; {Resets the error flag back to FALSE}
end;

{.....}

procedure OpenInterface(var Parameter1, Parameter2, Parameter3, Parameter4,
    Parameter5, Parameter6, Parameter7, Parameter8, Parameter9,
    Parameter10:PChar); stdcall;
{Checks the interface and bridge parameters sent from the RBC software and initialises the interface and the bridge if all parameters are valid. In this case, only the first 3 parameters are needed.}
var
    valid:Boolean;
    value:Integer;
    number,timeOutTime:Extended;
    S:string;
begin
    valid:=True;
    S:='Invalid GPIB interface type. The value must be 0 or 1.';
    {S contains the error message, passed to the ValidInteger procedure in the next line, should the parameter Parameter1 contain an invalid value - in this case Parameter1 must be either '0' or '1'}
    value:=ValidInteger(Parameter1,0,1,S,valid);
    if valid then
        begin
            GPIBInterfaceType:=TGPIBInterfaceType(value);
            S:='Invalid GPIB address. The address must be an integer from 0 to 32.';
            value:=ValidInteger(Parameter2,0,32,S,valid);

```

```

end;
if valid then
begin
  GPIBAddress:=value;
  S:='Invalid time out. Time out must be from 0 to 65 seconds.';
  number:=ValidReal(Parameter3,['',0,65,'],S,valid);
end;
if valid then
begin
  timeOutTime:=number;
  {The next four lines call procedures in the GPIB unit}
  InitialiseGPIB(GPIBInterfaceType);
  GPIBInterface.SetInputTerminator(10); {#10 (linefeed) is the character
                                         returned from the F18 that
                                         indicates the termination of the
                                         read string on the GPIB bus}

  GPIBInterface.SetTimeOutTime(timeOutTime);
  GPIBInterface.SendToDevice('AU CHK0 MET0 ONL ',GPIBAddress);
  valid:=not GPIBError; {GPIBError is defined and set in the GPIB unit}
  {Note: ErrorStr is not set here because the GPIB unit displays an
   error message when a GPIB error occurs}
end;
ErrorOccurred:=not valid;
end;

{.....}

procedure CloseInterface; stdcall;
{Sets the bridge to local and closes the interface.}
begin
  if GPIBInterface<>nil then
  begin
    GPIBInterface.SendToDevice('OFL ',GPIBAddress); {Command for F18 to
                                                         return to local}

    ErrorOccurred:=GPIBError;
    ErrorStr:='';
    CloseGPIB; {In the GPIB unit}
  end;
end;

{.....}

procedure GetReading(var Reading:PChar); stdcall;
{Returns a single reading from the bridge.}
var
  code:Integer;
  balanceCondition:string[1];
  bridgeReading:string;
  theReading:Extended;
  balanced:Boolean;
begin
  SoftDelay(3000); {3 second delay}
  GPIBInterface.SendToDevice('D ',GPIBAddress); {Command for F18 to send
                                                    a reading}

  if not GPIBError then
  begin
    SoftDelay(3000); {Another 3 second delay}
    {The next line reads a string from the F18}
    GPIBInterface.GetDataFromDevice(bridgeReading,GPIBAddress);
    if not GPIBError then
    begin
      {The next line removes the first character from the F18 string
       and copies a maximum of the next 11 characters into the variable
       Reading. In the absence of errors, Reading should now contain the
       numerical value of the bridge reading.}
      StrPCopy(Reading,Copy(bridgeReading,2,11));
      if StrLen(Reading)=0 then
      begin
        ErrorOccurred:=True;
        ErrorStr:='String from the F18 cannot be decoded.'
      end
      else

```

```

begin
  Val(Reading,theReading,code);
  if code<>0 then
    begin
      ErrorOccurred:=True;
      ErrorStr:='String from the F18 cannot be decoded.'
    end
  else
    begin
      {The 13th character of the string returned from the F18
      indicates the balance condition of the bridge - this DLL
      ignores the balance condition, but this could be modified if
      it were desired to only retain balanced readings}
      balanceCondition:=Copy(bridgeReading,13,1);
      Balanced:=balanceCondition='B';
      ErrorOccurred:=False;
    end;
  end;
end
else
begin
  ErrorOccurred:=True;
  ErrorStr:='';
end;
end
else
begin
  ErrorOccurred:=True;
  ErrorStr:='';
end;
end;
end;

{.....}

exports

  GetBridgeName index 1,
  GetParamDescriptions index 2,
  GetError index 3,
  OpenInterface index 4,
  CloseInterface index 5,
  GetReading index 6;

{.....}

begin
end. {End of the DLL}

```

The following unit implements calls to either a CEC GPIB card or a National Instruments GPIB card.

```

unit GPIB;

interface

uses
  CECGPIB, NIGPIB; {These two units are provided by CEC and National Instruments, respectively}

type
  TGPIBInterfaceType = (CEC, NI); {Identifies the type of GPIB card}

{Ancestor class for a general GPIB object}
  TGPIBInterface = class(TObject)
    DeviceName: string;
    constructor Create;
    destructor Destroy; override;
    procedure SendToDevice (Command: string; Address: SmallInt); virtual;
    procedure GetDataFromDevice (var TheData: string; Address: SmallInt);
      virtual;
    function ProcessGPIBStatus (Status: Integer;
      var Successful: Boolean): Boolean; virtual;
    procedure SetToLocal (Address: SmallInt); virtual;
    procedure SetInputTerminator (ASCIICode: Integer); virtual;
    procedure SetTimeOutTime (TheTime: Extended); virtual;
    procedure ClearDevice (Address: SmallInt); virtual;
    procedure SetToRemote (Address: SmallInt); virtual;
    procedure TransmitToBus (Command: string); virtual;
    procedure SerialPollDevice (Address: SmallInt; var PollByte: Byte);
      virtual;
  end;

{Descendent class for a CEC GPIB object}
  TCECInterface = class(TGPIBInterface)
    constructor Create;
    destructor Destroy; override;
    procedure SendToDevice (Command: string; Address: SmallInt); override;
    procedure GetDataFromDevice (var TheData: string; Address: SmallInt);
      override;
    function ProcessGPIBStatus (Status: Integer;
      var Successful: Boolean): Boolean; override;
    procedure SetTimeOutTime (TheTime: Extended); override;
    procedure TransmitToBus (Command: string); override;
    procedure SerialPollDevice (Address: SmallInt; var PollByte: Byte);
      override;
  end;

{Descendent class for a National Instruments GPIB object}
  TNIInterface = class(TGPIBInterface)
    Board, EOS: Integer;
    constructor Create;
    destructor Destroy; override;
    procedure SendToDevice (Command: string; Address: SmallInt); override;
    procedure GetDataFromDevice (var TheData: string; Address: SmallInt);
      override;
    function ProcessGPIBStatus (Status: Integer;
      var Successful: Boolean): Boolean; override;
    procedure SetToLocal (Address: SmallInt); override;
    procedure SetInputTerminator (ASCIICode: Integer); override;
    procedure SetTimeOutTime (TheTime: Extended); override;
    procedure ClearDevice (Address: SmallInt); override;
    procedure SetToRemote (Address: SmallInt); override;
    procedure TransmitToBus (Command: string); override;
    procedure SerialPollDevice (Address: SmallInt;
      var PollByte: Byte); override;
  end;

procedure InitialiseGPIB (GPIBInterfaceType: TGPIBInterfaceType);
procedure CloseGPIB;

```

```

var
  GPIBInterface:TGPIBInterface;
  NumRetries:Integer;
  GPIBError:Boolean; {Global variable used to indicate whether or not a
                      GPIB error has occurred}

implementation

uses
  Forms, Windows, SysUtils;

{.....}

procedure InitialiseGPIB(GPIBInterfaceType:TGPIBInterfaceType);
{This procedure initialises either a CEC interface or a National Instruments
interface.}
begin
  case GPIBInterfaceType of
    CEC:GPIBInterface:=TCECInterface.Create;
    NI: GPIBInterface:=TNIInterface.Create;
  end;
end;

{.....}

procedure CloseGPIB;
begin
  GPIBInterface.Free;
end;

{.....}

{Procedures for the general GPIB interface object}

procedure TGPIBInterface.ClearDevice(Address: SmallInt);
begin
  {Does nothing, as the descendent procedure will always be called}
end;

{.....}

constructor TGPIBInterface.Create;
begin
  inherited Create; {Assigns memory and initialises the data type}
  DeviceName:='';
  GPIBError:=False;
end;

{.....}

destructor TGPIBInterface.Destroy;
begin
  inherited Destroy;
end;

{.....}

procedure TGPIBInterface.GetDataFromDevice(var TheData: string;
      Address: SmallInt);
begin
end;

{.....}

function TGPIBInterface.ProcessGPIBStatus(Status: Integer;
      var Successful: Boolean): Boolean;
begin
end;

{.....}

```

```

procedure TGPIBInterface.SendToDevice(Command: string; Address: SmallInt);
begin
end;

{.....}

procedure TGPIBInterface.SerialPollDevice(Address: SmallInt;
    var PollByte: Byte);
begin
end;

{.....}

procedure TGPIBInterface.SetInputTerminator(ASCIICode: Integer);
begin
end;

{.....}

procedure TGPIBInterface.SetTimeOutTime(TheTime: Extended);
begin
end;

{.....}

procedure TGPIBInterface.SetToLocal(Address: SmallInt);
begin
end;

{.....}

procedure TGPIBInterface.SetToRemote(Address: SmallInt);
begin
end;

{.....}

procedure TGPIBInterface.TransmitToBus(Command: string);
begin
end;

{.....}

{Procedures for the CEC GPIB interface object}

constructor TCECInterface.Create;
const
    SystemController=0;
var
    status:Integer;
begin
    inherited Create;
    Initialize(21, SystemController); {Sets system controller to address 21}
    SetTimeOutTime(12);
    Transmit('REN', status); {REN - remote enable}
end;

{.....}

destructor TCECInterface.Destroy;
var
    status:Integer;
begin
    Transmit('GTL', status); {GTL - go to local}
    inherited Destroy;
end;

{.....}

procedure TCECInterface.GetDataFromDevice(var TheData: string;
```

```

Address: SmallInt);
{This procedure reads a string from the device with the specified GPIB address and
returns the string in the parameter TheData.}
var
  len:Word;
  status:Integer;
  successful:Boolean;
begin
  if not GPIBError then
  begin
    repeat {Command is repeated up to 5 times in the case of error}
      {Enter is the CEC command for returning a string from the device}
      Enter(TheData,255,len,Address,status); {255 is the maximum length
                                             for the returned string}
    until ProcessGPIBStatus(Longint(status),successful);
    if not successful then
      TheData:='';
    GPIBError:=not successful;
  end;
end;

{.....}

function TCECInterface.ProcessGPIBStatus(Status: Integer;
var Successful: Boolean): Boolean;
{This function processes the status information about the interface.}
var
  errorMessage,title:string;
  stopRetrying:Boolean;
begin
  Successful:=False;
  stopRetrying:=False;
  case Status of
    0 :Successful:=True;
    1 :errorMessage:='Illegal IEEE command syntax.';
    2 :errorMessage:='Tried to send or receive data when not a talker or
                    listener.';
    4 :errorMessage:='A quoted string or END found in IEEE LISTEN or
                    TALK list.';
    8 :errorMessage:='Timeout. (Instrument not responding.)';
    16 :errorMessage:='Unknown IEEE command.';
    32 :Successful:=True;
    64 :errorMessage:='Interface command not within interface
                    capability.';
  end;
  if not Successful then
  begin
    Inc(NumRetries);
    if (NumRetries>5) or (Status=8) then {Allow the command to be repeated up
                                         to 5 times before giving up}
    begin
      NumRetries:=0;
      GPIBErrorMessage:=errorMessage;
      stopRetrying:=True;
    end
    else
      stopRetrying:=False;
    end
  else
  begin
    NumRetries:=0;
    stopRetrying:=True;
  end;
  Application.ProcessMessages;
  ProcessGPIBStatus:=stopRetrying;
end;

{.....}

procedure TCECInterface.SendToDevice(Command: string; Address: SmallInt);
{This procedure sends the string Command to the device with the specified GPIB
address.}

```

```

var
    status:Integer;
    successful:Boolean;
begin
    if not GPIBError then
    begin
        repeat
            CECGPIB.Send(Address,Command,status);
        until ProcessGPIBStatus(Longint(status),successful);
        GPIBError:=not successful;
    end;
end;

{.....}

procedure TCECInterface.SerialPollDevice(Address: SmallInt;
    var PollByte: Byte);
var
    status:Integer;
    successful:Boolean;
begin
    repeat
        SPoll(Address,PollByte,status);
    until ProcessGPIBStatus(Longint(status),successful);
    GPIBError:=not successful;
end;

{.....}

procedure TCECInterface.SetTimeOutTime(TheTime: Extended);
begin
    SetTimeOut(Round(TheTime*1000));
end;

{.....}

procedure TCECInterface.TransmitToBus(Command: string);
var
    status:Integer;
    successful:Boolean;
begin
    if not GPIBError then
    begin
        repeat
            Transmit(Command,status);
        until ProcessGPIBStatus(Longint(status),successful);
        GPIBError:=not successful;
    end;
end;

{.....}

```

{Procedures for the National Instruments GPIB interface object}

```

procedure TNIInterface.ClearDevice(Address: SmallInt);
var
    successful:Boolean;
begin
    repeat
        DevClear(Board,Address);
    until ProcessGPIBStatus(MakeLong(iberr,ibsta),successful);
    GPIBError:=not successful;
end;

{.....}

constructor TNIInterface.Create;
var
    successful:Boolean;
begin
    Board:=0;
    repeat
        SendIFC(Board); {Interface clear}
    until ProcessGPIBStatus(MakeLong(iberr,ibsta),successful);
    if successful then
        repeat
            SetTimeOutTime(12);
        until ProcessGPIBStatus(MakeLong(iberr,ibsta),successful);
    GPIBError:=not successful;
end;

{.....}

destructor TNIInterface.Destroy;
var
    successful:Boolean;
begin
    repeat
        ibonl(Board,0); {Places the interface offline}
    until ProcessGPIBStatus(MakeLong(iberr,ibsta),successful);
    GPIBError:=not successful;
    inherited Destroy;
end;

{.....}

procedure TNIInterface.GetDataFromDevice(var TheData: string;
    Address: SmallInt);
var
    successful:Boolean;
    someData:array[0..255] of Char;
begin
    if not GPIBError then
        begin
            repeat
                NIGPIB.Receive(Board,Address,someData,255,EOS);
            until ProcessGPIBStatus(MakeLong(iberr,ibsta),successful);
            if ibcnt>0 then {ibcnt is the number of bytes read}
                someData[ibcnt]:=#0; {Ensures the string is null-terminated}
                TheData:=StrPas(someData); {Converts to a Pascal-type string}
                GPIBError:=not successful;
            end;
        end;
end;

{.....}

function TNIInterface.ProcessGPIBStatus(Status: Integer;
    var Successful: Boolean): Boolean;
var
    errorMessage:string;
    stopRetrying:Boolean;
begin
    Successful:=True;
    if (HiWord(Status) and ERR)=ERR then

```

```

begin
    Successful:=False;
    stopRetrying:=False;
    errorMessage:='Error code '+IntToStr(LoWord(Status));
    case LoWord(Status) of
        0 :errorMessage:=errorMessage+' : DOS error.';
        1 :errorMessage:=errorMessage+' : Board must be Controller in
            Charge.';
        2 :errorMessage:=errorMessage+' : No listeners detected.';
        3 :errorMessage:=errorMessage+' : Board not addressed correctly.';
        4 :errorMessage:=errorMessage+' : Invalid argument specified.';
        5 :errorMessage:=errorMessage+' : Board should be system
            controller.';
        6 :errorMessage:=errorMessage+' : I/O operation aborted (Time
            out).';
        7 :errorMessage:=errorMessage+' : Invalid interface board
            specified.';
        10 :errorMessage:=errorMessage+' : I/O operation already
            running.';
        11 :errorMessage:=errorMessage+' : Board does not have requested
            capability.';
        12 :errorMessage:=errorMessage+' : Error returned from file
            system.';
        14 :errorMessage:=errorMessage+' : Command error on bus.';
        15 :errorMessage:=errorMessage+' : Serial poll response byte
            lost.';
        16 :errorMessage:=errorMessage+' : SRQ is still asserted.';
        20 :errorMessage:=errorMessage+' : The return buffer is full.';
    else
        errorMessage:=errorMessage+' : Unknown error.';
    end;
    Inc(NumRetries);
    if (NumRetries>5) or (LoWord(Status)=6) then
    begin
        NumRetries:=0;
        GPIBErrorMessage:=errorMessage;
        stopRetrying:=True;
    end
    else
        stopRetrying:=False;
    end
    else
    begin
        NumRetries:=0;
        stopRetrying:=True;
    end;
    ProcessGPIBStatus:=stopRetrying;
end;

{.....}

procedure TNIInterface.SendToDevice(Command: string; Address: SmallInt);
var
    successful:Boolean;
begin
    if not GPIBError then
    begin
        repeat
            NIGPIB.Send(Board,Address,Command,Length(Command),NLEnd);
        until ProcessGPIBStatus(MakeLong(iberr,ibsta),successful);
        GPIBError:=not successful;
    end;
end;

{.....}

procedure TNIInterface.SerialPollDevice(Address: SmallInt;
var PollByte: Byte);
var
    pollB:SmallInt;
    successful:Boolean;
begin

```

```

repeat
    NIGPIB.ReadStatusByte(Board,Address,pollB);
    PollByte:=Lo(pollB);
until ProcessGPIBStatus(MakeLong(iberr,ibsta),successful);
GPIBError:=not successful;
end;

{.....}

procedure TNIInterface.SetInputTerminator(ASCIICode: Integer);
begin
    EOS:=ASCIICode;
end;

{.....}

procedure TNIInterface.SetTimeOutTime(TheTime: Extended);
var
    successful:Boolean;
    value:Integer;
begin
    if TheTime<=10e-6 then value:=T10us
    else if TheTime<=30e-6 then value:=T30us
    else if TheTime<=100e-6 then value:=T100us
    else if TheTime<=300e-6 then value:=T300us
    else if TheTime<=1e-3 then value:=T1ms
    else if TheTime<=3e-3 then value:=T3ms
    else if TheTime<=10e-3 then value:=T10ms
    else if TheTime<=30e-3 then value:=T30ms
    else if TheTime<=100e-3 then value:=T100ms
    else if TheTime<=300e-3 then value:=T300ms
    else if TheTime<=1 then value:=T1s
    else if TheTime<=3 then value:=T3s
    else if TheTime<=10 then value:=T10s
    else if TheTime<=30 then value:=T30s
    else value:=T100s;
    repeat
        ibtmo(Board,value); {Set timeout time}
    until ProcessGPIBStatus(MakeLong(iberr,ibsta),successful);
end;

{.....}

procedure TNIInterface.SetToLocal(Address: SmallInt);
var
    addressList:AddrList4882_t; {Defined in NIGPIB unit}
    successful:Boolean;
begin
    addressList[0]:=Address;
    addressList[1]:=NoAddr;
    repeat
        EnableLocal(Board,addressList);
    until ProcessGPIBStatus(MakeLong(iberr,ibsta),successful);
end;

{.....}

procedure TNIInterface.SetToRemote(Address:SmallInt);
var
    addressList:AddrList4882_t; {Defined in NIGPIB unit}
    successful:Boolean;
begin
    addressList[0]:=Address;
    addressList[1]:=NoAddr;
    repeat
        EnableRemote(Board,addressList);
    until ProcessGPIBStatus(MakeLong(iberr,ibsta),successful);
end;

{.....}

procedure TNIInterface.TransmitToBus(Command: string);

```



```
var
    successful:Boolean;
begin
    repeat
        SendCmds(Board,Command,Length(Command));
    until ProcessGPIBStatus(MakeLong(iberr,ibsta),successful);
end;

{.....}

end. {End of GPIB unit}
```