RESISTANCE BRIDGE CALIBRATORS MODELS RBC100M & RBC400M

User Maintenance Manual/Handbook

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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.

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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.

1. Introduction

1.1 Initial Inspection

Our Packing Department uses custom designed packaging to send out your unit, but as accidents can still happen in transit, you are advised, after unpacking the unit, to 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 must notify us or our agent, and the carrier immediately. If the unit is damaged you should keep the packing 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.
- The RBC
- A CD with the analysis software and password
- A calibration certificate for the RBC

If the RBC is incomplete or damaged please notify your supplier or Isotech immediately. Also, if you have any questions or comments relating to the RBC, the RBC software, or the manual, please contact Isotech.

1.2 Safety Instructions

- Please familiarize yourself with the handbook before using the RBC
- The RBC is entirely passive and does not require connection to a power supply of any sort
- It should only be connected to the inputs of resistance bridges
- Only connect the RBC to separated extra low voltage circuits (SELV according to EN60950)
- We recommend the use of shielded connection cables to the bridge.
- If the RBC is moved from a relatively cold storage area to a warm area with a high dewpoint temperature, condensation can form on parts of the RBC, and this can lead to very low insulation resistances. This commonly happens, for example, when the RBCs are offloaded from cargo holds of aircraft. The inner case of the RBCs contains a small bag of desiccant to help prevent this happening when it is first shipped. If condensation is observed at other times, the RBC should be stored in a warm environment (< 40 °C) overnight. If the RBC is used in humid environments, it may be useful to occasionally remove the bag of desiccant and dry it at 150 °C for a few hours.

1.3 RBC History

The RBC calibrators are a result of research carried out at the Measurement Standards Laboratory (MSL) of New Zealand, which operates within Industrial Research Ltd of New Zealand (IRL). IRL is one of New Zealand's National research institutes focused on the industrial application of science and engineering.

IRL developed and patented the Resistance Bridge Calibrator which is now licensed by Isothermal Technology Ltd (Isotech). The RBC is available exclusively from Isotech and its global network of distributors.

1.4 The RBC and this Manual

The Resistance Bridge Calibrator is a 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 itself and the analysis software.

This manual provides a detailed description of the principles of the RBC, the principles of the software, and factors to consider in an uncertainty analysis. Details on the running of the software, software options and error messages can also be found in the Help menu of the RBC application.

The RBC100 (manually operated units sold after June 2007) has undergone several design changes to improve its electrical performance, to simplify manufacture and maintenance, and to better target the RBC application to bridges with uncertainties larger than 0.1 ppm. These include:

- Improved temperature coefficient (Section 8.2.6).
- Improved switch reliability (Section 8.2.3).
- Improved immunity to transient high humidity (Section 8.2.4).
- A greater number of accessible complement combinations (Section 3.4)
- One resistance combination designed to be close to 100 Ω (Section 3.4).
- A smaller case and lower cost (see Note 2 below).

Note 1: In order to gain the improved switch reliability, the RBC no longer has a combination indicator.

Note 2: Although this RBC100 or RBC400 has the same nominal specifications of the earlier models, its potential performance under ideal conditions is not quite as good. The typical performance of the new RBC is limited by a combination of ambient temperature control, the 4-terminal junction errors, and combining network errors to about 5 $\mu\Omega$ rms (10 $\mu\Omega$ max – see Section 8 for details). A fully computer controlled RBC with a target accuracy of 1 $\mu\Omega$ (max), is under development.

The latest version of the software has several new features:

- It allows fixed values for RBC resistances to calibrate (in ohms) direct reading resistance bridges,
- It will print a calibration certificate consistent with ISO 17025:1999 *General requirements for the competence of testing and calibration laboratories*,
- A new graph option that plots the residuals from the analysis and displays the calculated 95% confidence interval.

1.5 Software Installation and Getting Started

The analysis software provided is suitable for use with Microsoft Windows 3.1 or higher, Microsoft NT, and Vista. 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 with the CD. 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 Sections 3.1, 4.1, and the whole of Sections 6 and 7. 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 and the limitations in its 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.

D R White, M. T. Clarkson, P. Saunders, and H. Yoon, "A general technique for calibrating indicating instruments", 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.

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 resistors, the measurements provide 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 for those who would like to know more about 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

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

In this manual 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 ratio P by the value of the 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 allows the user to transfer the calibrated value of any of the RBC resistors to the resistance bridge.

Resistance-ratio bridges are those that present the result of the measurement in the form of Equation (2.1), that is, as a dimensionless resistance ratio. The best thermometry bridges measure to better than 1 part 10^8, and cryogenic current comparator bridges measure dc resistance ratios to about 1 part in 10^9. Despite the high accuracies involved, which are usually 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 simple dimensionless number, 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 called a linearity check and a complement check.

2.3 The Linearity Check

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

$$P_1 = R_1 / R_s + \xi(P_1), \qquad (2.2)$$

$$P_2 = R_2 / R_s + \xi(P_2), \qquad (2.3)$$

$$P_{12} = (R_1 + R_2) / R_s + \xi(P_{12}) . \qquad (2.4)$$

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

$$P_1 + P_2 - P_{12} = 0 \,. \tag{2.5}$$

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

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

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 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 sequence of measurements

Under some circumstances the right-hand side of Equation (2.6) may be zero although each 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 equation $\xi(P)$ 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,

$$P_1 = R_x / R_s + \xi(P_1) \,, \tag{2.7}$$

then by exchanging the two resistors and making a 'reciprocal' or 'complement' measurement,

$$P_2 = R_s / R_x + \xi(P_2) \,. \tag{2.8}$$

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

$$P_1 P_2 = \frac{R_x}{R_s}\frac{R_s}{R_x} = 1 \,. \tag{2.9}$$

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

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

hence

$$P_1 P_2 = (1+\varepsilon)^2 \,, \tag{2.11}$$

so that the linear error can be detected and 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: $P_1, P_2, \xi(P_1), \xi(P_2), \xi(P_{12})$. 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 a distinct value of $\xi(P)$ for every 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 resistance ratios, and this is exactly 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, 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.

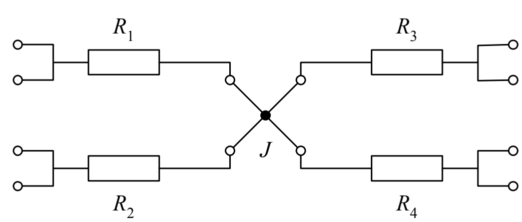


Figure 2.1: A simplified circuit diagram of the resistance network used in the RBC. R_1 to R_4 are the four base resistors and *J* is a four-terminal junction that allows the resistors to be connected together in such a way that they appear to be connected to a single point. The open circles indicate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

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.

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 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, which may be a calibrated RBC. Note that thermometry bridges are used to measure the $R(T)/R(0\ °C)$ relationship for platinum thermometers via separate measurements of $R(T)$ and $R(0\ °C)$ made with the same bridge and standard resistor, so linearity is the most important attribute of a thermometry bridge.

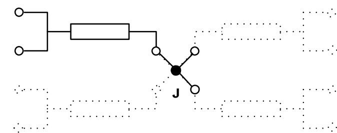
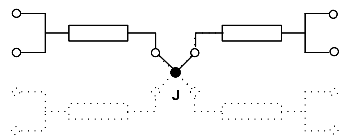
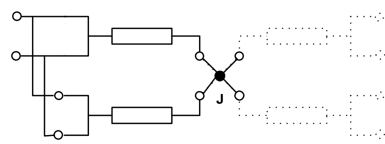
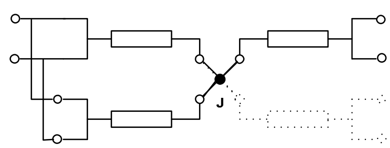
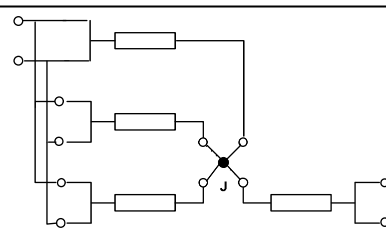
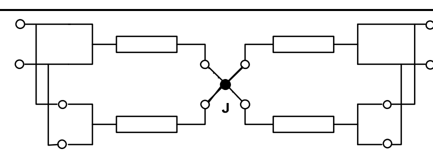
	Network Resistance	Network connection
1 2 3 4	R1 R2 R3 R4	
5 6 7 8 9 10	R1+R2 R1+R3 R1+R4 R2+R3 R2+R4 R3+R4	
11 12 13 14 15 16	R1//R2 R1//R3 R1//R4 R2//R3 R2//R4 R3//R4	
17 18 19 20 21 22 23 24 25 26 27 28	R1+R2//R3 R1+R2//R4 R1+R3//R4 R2+R1//R3 R2+R1//R4 R2+R3//R4 R3+R1//R2 R3+R1//R4 R3+R2//R4 R4+R1//R2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

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 10Ω, 100Ω or 1000Ω. In these cases there may be one RBC setting with a resistance within that range. Therefore only one complement measurement may be possible. All models of the RBC have one combination that is close to 100Ω. 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 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 100Ω 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 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, respectively, optimised for 25Ω and 100Ω thermometry bridges, 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 practical. 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 100μΩ (~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 a few micro-ohms. However, the temperature of the resistors in the RBC is determined by laboratory conditions.

For both types of calibration, the temperature stability of the RBC is important. In laboratories with time-proportioning PID (Proportional, Integral, Differential) control for the air-conditioning system, the specified accuracy of 0.1 ppm should be achieved easily. In laboratories with On/Off control systems, which typically have a forced hysteresis of 1°C or more, some care may be required to avoid direct air flow from the air vents to achieve of the specified accuracy. 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 2.1, 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 they indicate a reading in ohms, all direct reading bridges require the 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 100Ω (R_1 on the RBC100, R_2 on the RBC400).

Direct-reading resistance bridges tend to be at the lower accuracy end of the range of bridges available, typically with accuracies of about 2×10^{-6} in resistance ratio (2 ppm) to 10^{-4} in resistance ratio (100 ppm). Calibration of the RBC resistors for this level of accuracy should not be difficult (see Section 8.4 for discussion of the various sources of uncertainty), and for some applications the value supplied on the RBC certificate will be sufficient.

Ideally, if you have a calibrated standard resistor with a low uncertainty (1 ppm or lower) and a high-quality resistance-ratio bridge in-house, the calibration of the RBC can be done in-house. Otherwise, you should get the RBC resistors calibrated by a laboratory that is accredited to ISO17025 for the calibration of standard resistors. You could also take the values from the RBC certificate supplied with the RBC, 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 you can track any drift. 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 put into the RBC software (see Section 6.), and the corresponding check-box in the dialogue 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 values measured and set to constant in the software.

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 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. As described in Section 2 of this manual, the principle behind the complement check can be extended to the RBC. So long as both normal and complement 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 software (e.g., 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 (see Sec. 6). 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 resistors - 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 all of the same reasons, when calibrating the bridge with the RBC, the bridge operating condition (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.

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 Section 8, 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 various 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 are 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 not limit the assessment of the performance of bridges under test. Instructions for care and maintenance of the RBC includes measurements of the insulation resistance and combining network, and are in Section 9.

4. Making Measurements

The Resistance Bridge Calibrators are designed primarily for thermometry bridges, and employ a four-terminal coaxial definition, i.e. one coaxial lead connects the two current terminals of the resistor; the other coaxial lead connects the two voltage terminals (see Appendix C). Connections to the RBC are made with 50Ω BNC connectors.

Once the bridge has been connected to the RBC, the required resistance combinations of the RBC may be selected using the 8 toggle switches on the front panel of the RBC, and bridge readings recorded. A circuit diagram for the RBC that includes the switches is shown in Figure 4.1. Amongst the large number of possible switch settings there are 86 settings that yield one of the 35 possible resistances of interest. There are two techniques for determining the appropriate switch settings.

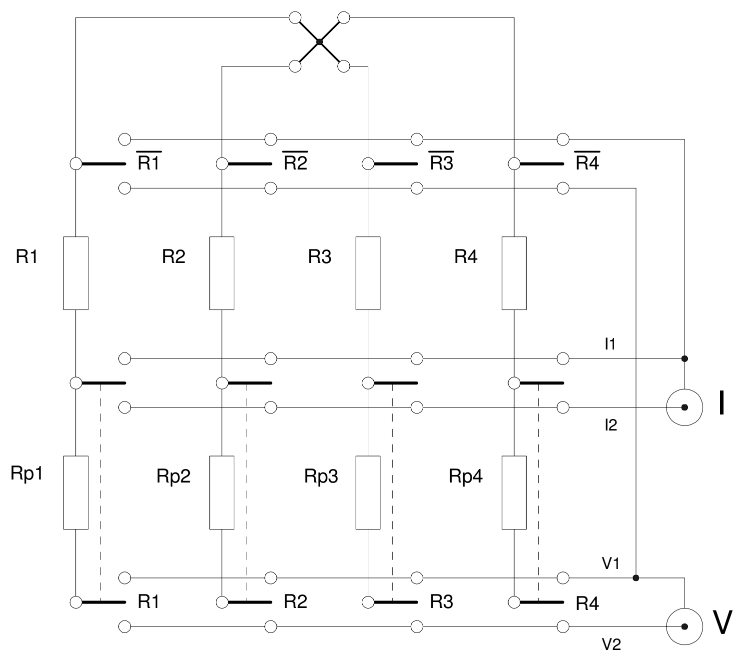


Figure 4.1: A circuit diagram of the RBC showing the 4 base resistors (R1 to R4), the four potential sharing resistors (Rp1 to Rp4), the 8 switches and the two BNC connectors.

4.1 Selecting Resistance Combinations using the Combination Table

All of the switches have three positions: up and down (which make connections) and centre (no connection). The switch positions for 35 of the valid combinations are shown in Table 4.1 with U or D indicating that the switch should be in the up or down position respectively. Where there is no entry in the table the corresponding switch should be in the centre position. This table is also presented in the data window of the software.

RBC Combination Table									
Combination		**Switch settings**							
Number	**Description**	**R1**	**R2**	**R3**	**R4**	$\overline{R1}$	$\overline{R2}$	$\overline{R3}$	$\overline{R4}$
1	R1	U					U	D	
2	R2		U			U		D	
3	R3			U		U	D		
4	R4				U	U	D		
5	R1+R2	U	D						
6	R1+R3	U		D					
7	R1+R4	U			D				
8	R2+R3		U	D					
9	R2+R4		U		D				
10	R3+R4			U	D				
11	R1//R2	U	U					U	D
12	R1//R3	U		U			U		D
13	R1//R4	U			U		U	D	
14	R2//R3		U	U		U			D
15	R2//R4		U		U	U		D	
16	R3//R4			U	U	U	D		
17	R1+R2//R3	U	D	D					
18	R1+R2//R4	U	D		D				
19	R1+R3//R4	U		D	D				
20	R2+R1//R3	D	U	D					
21	R2+R1//R4	D	U		D				
22	R2+R3//R4		U	D	D				
23	R3+R1//R2	D	D	U					
24	R3+R1//R4	D		U	D				
25	R3+R2//R4		D	U	D				
26	R4+R1//R2	D	D		U				
27	R4+R1//R3	D		D	U				
28	R4+R2//R3		D	D	U				
29	R1+R2//R3//R4	U	D	D	D				
30	R2+R1//R3//R4	D	U	D	D				
31	R3+R1//R2//R4	D	D	U	D				
32	R4+R1//R2//R3	D	D	D	U				
33	R1//R2+R3//R4	U	U	D	D				
34	R1//R3+R2//R4	U	D	U	D				
35	R1//R4+R2//R3	U	D	D	U				

Table 4.1: Switch settings for the RBC. The table lists one of the valid sets of switch settings for each of the 35 RBC combinations. There are a total of 86 switch settings that realise valid four terminal resistances with the RBC although only 35 are listed here. The combination indicator on the front panel of the RBC will indicate the combination number for any of these 35 combinations.

4.2 Selecting the Resistance Combinations by Rule

Once familiar with the RBC, it is quicker to select the combinations without reference to the table. The naming of the switches is designed to aid the selection of combinations. Figure 4.2 is a diagrammatic aid to memory for setting the switches.

Series combinations (see Table 4.1 combinations 5 – 10 and 17 – 35)
For those combinations that require series connections, only the switches labelled R1, R2, R3 and R4 are required, with at least one switch in the up position and one in the down position. For example, the $R_1 + R_2$ combination may be selected by setting the R1 switch up and the R2 switch down (or *vice versa*). If another resistor is required to be in parallel with one of the two resistors then the corresponding switches should be set to the same position. For example the $R_1 + R_2//R_3$ combination may be selected with the R1 switch up and the R2 and R3 switches down.

Non-series combinations (see Table 4.1 combinations 1 – 4 and 11 - 16)
For those combinations that require no series connection, connections must be made to the four-terminal junction. In these cases at least one of the switches R1, R2, R3, or R4 must be switched up, with none of these switches in the down position. Additionally, two of the switches marked $\overline{\mathrm{R1}}, \overline{\mathrm{R2}}, \overline{\mathrm{R3}}$, or $\overline{\mathrm{R4}}$ must be used with one switched up and one switched down. These switches select the connections to the four-terminal junction. The restriction on the choice of which two of the four switches must be used is: if any of the switches R1, R2, R3, or R4 are selected then the corresponding switch $\overline{\mathrm{R1}}, \overline{\mathrm{R2}}, \overline{\mathrm{R3}}$ or $\overline{\mathrm{R4}}$ must **not** be used (a bar or overscore above a variable name is the conventional logic symbol for **not**). Thus $\overline{\mathrm{R1}}$ should **not** be used if R1 is used.

For example, the R_1 combination may be selected by switching R1 up, and using any two of the $\overline{R2}, \overline{R3}$, or $\overline{R4}$ switches with one switched up and the other switched down.

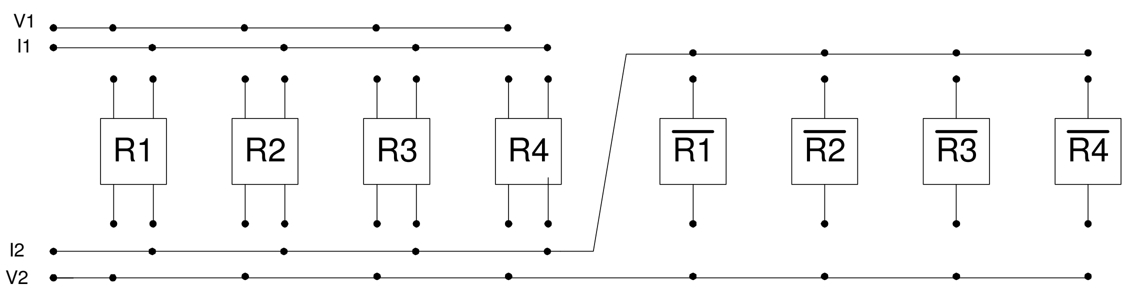


Figure 4.2: A simple representation of the RBC. The four switches labelled R1, R2, R3 and R4 make connections between the 'free' ends of the four resistors and the BNC connectors. With the switches up, the resistors are connected to V1, I1, with the switches down connections are made to V2 and I2. The four switches labelled $\overline{\mathrm{R1}}, \overline{\mathrm{R2}}, \overline{\mathrm{R3}}$, or $\overline{\mathrm{R4}}$ make connections between the four-terminal junction and the V2 and I2 terminals of the BNC connectors. When used, these switches must be used in pairs with one switch up and one switch down. Connections must be made to all 4 BNC terminals.

5. Analysing the Results

Software is provided with the RBC to aid in the analysis of the measurements. The software uses a spreadsheet format to record and present the results. 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. The analysis software 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 we search for values for the resistors that are most likely to explain 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 ratios R_1/R_S, R_2/R_S, R_3/R_S, and R_4/R_S, calculate the values for the other combinations, and compare them to the measured values for the those combinations. This will give a very quick indication of the accuracy of the bridge.

A better approach is to calculate a set of 'best' values for the base ratios R_1/R_S, R_2/R_S, R_3/R_S, and R_4/R_S that 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). The computer finds values for R_1/R_S to R_4/R_S that minimise the variance of the differences between the measured and calculated values for all the resistance ratios:

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

In Equation (5.1) N is the number of measured ratios, $P_{i,meas}$ are the measured ratios, and $P_{i,calc}$ are the ratios calculated from the fitted values of R_1/R_S to R_4/R_S. 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. $\rho = 4$ if all of the base resistances are unknown. The standard deviation s 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:

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

where $\Delta P(P)$ is the correction equation, and ρ is the number of parameters determined in the least squares fit (equal to 4 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

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

This equation accounts for an offset in the bridge readings (A), a linear error (BP), 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 is reading resistance). 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.

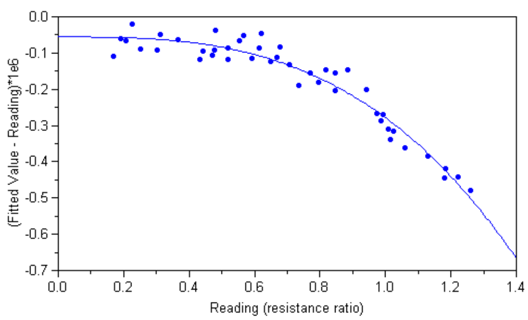


Figure 5.1: RBC100 results for a resistance ratio bridge with a faulty input circuit that gives rise to a cubic error. This is abnormal behaviour for this bridge, which has a specified accuracy of $\pm 0.2 \times 10^{-6}$ (vertical scale in the graph is 0.7×10^{-6}).

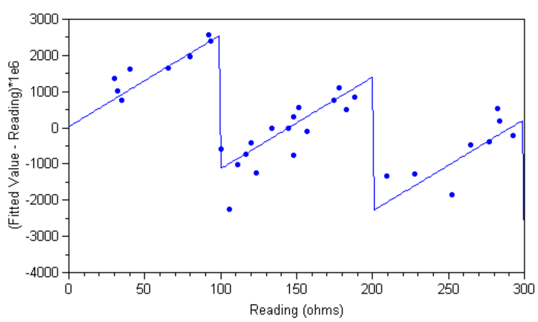


Figure 5.2: RBC400 results for a direct reading resistance bridge exhibiting sawtooth error. This is normal behaviour for this model of bridge, which has a specified accuracy of ± 10 mΩ (vertical scale in the graph is 7 mΩ).

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 (ratio bridges).

In principle only one complement measurement and one normal measurement are necessary to determine the linear term, however the more measurements are 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 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 in 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 some benefit from using a correction equation with the bridge. You can optimise the form of the correction equation by deselecting those correction terms that have the lowest *t*-ratios.

If some of the *t*-ratios are very large then there may be a fault in the bridge. Check by using the graph or the data window that the bridge error is within the manufacturer's specification for the bridge. Note too that some bridges may have sawtooth shaped errors.

5.3 The Uncertainties in Parameter Values, and Total Uncertainty

In addition to the values for the parameters 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 of the corresponding form.

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

$$U = \pm ks \qquad (5.4)$$

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 freedom[1] and the level of confidence indicated in the Certificate Settings dialog (the default is 95%).

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

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

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. 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, 1993, for an explanation of terms)

6. Software Guide

This section briefly describes the tasks that can be carried out using the RBC software. The details on how to carry out these tasks are given in the Help menu of the software.

The first time you run the RBC software it will request a password. The password can be found on the inside of the back cover of this manual and with the CD.

6.1 Software capabilities

The **data window** in the RBC application is a spreadsheet that lists; the switch settings and resistance network combination 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 measurement. The spreadsheet can be copied (under 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; 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 as a windows metafile (*.wmf – see the Graph menu) into other applications.

The **analysis window** specifies the model for the bridge error and summarises the results of the least squares fit to that model.

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.

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 Info, Client Info and Certificate Settings dialogs. The certificate should be printed onto company letterhead and, if the various dialogs are filled in correctly, will comply with ISO17025.

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 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.

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 Windows application.

3. Enter the resistor values for the RBC into the RBC Info. dialog, and the standard resistor value into the Bridge Info. dialog. If these numbers are entered before you take readings then column 5 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. Note that if you select ohms or k ohms for the bridge units, the value for the standard resistor used by the software will be set to 1 ohm or 1 k ohms by default.

4. Enter bridge readings into the reading column of the data window. Note that it is not necessary to enter all 70 readings. However the more measurements you are able to include the greater the confidence in the results.

5. Select an error model in the analysis window (deselecting all error terms is a good first choice).

6. Click on the calculate button.

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

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

A good analogy is that the program searches for the lowest point on a surface. The co-ordinates for the position on the surface correspond to the values of R_1/R_S to R_4/R_S and the coefficients of the correction equation, while the height of the surface corresponds to the value of s^2. The surface may be quite complicated and have hills, valleys and deep holes, 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 program is directed to start the search for the minimum near to where the deepest hole is expected to be found.

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

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 unchecked values for the base resistances will be adjusted by the program to obtain the best fit to the measurements.

For both direct-reading bridges and ratio bridges, the starting values for the coefficients of the correction equation are set to zero, since the bridge should be very nearly ideal.

Once the program has identified the best values for the base ratios and coefficients it proceeds to calculate 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 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. More details on the algorithm employed by the software, which is nicknamed amoeba because of the way it searches for the minimum, may be found in the Help menu under the topic amoeba.

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 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 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 and RBC400. A standard resistance of 25 Ω can also be used with an RBC100 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 Info. dialog and entered a value for the standard resistor in the Bridge Info. dialog. 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 kΩ by default.

Step 3: The Measurements

In the sequence given by the combination number (Table 4.1), set the combination on the RBC, wait for the bridge to indicate a balanced reading, and then record the reading in the appropriate cell on the data window. Record all of the readings for all of the normal ratios that are within the bridge range.

If you wish to assess the absolute accuracy of a ratio bridge, exchange the connections to the RBC and the standard resistor to enable the complement or complement ratios to be measured. Repeat the sequence of RBC combinations and record all of the readings for the complement ratios that are within the range of the bridge.

In order to ensure a high level of confidence in the results of the analysis, try to take at least 30 measurements in total. The more measurements you are able to include, the greater the greater the confidence in the results.

For thermometry bridges with specified accuracy greater than 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 below 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).

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. Pushing the calculate button will cause the software to evaluate the results according to Equation (5.1). Note the value of the standard deviation calculated from the fit. If the both the bridge and the RBC are in good 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 results analysis with the appropriate correction equation terms switched on. As a first trial select the general cubic error model 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 switched off. 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 least-squares fits with a variety of the correction equations may give clues to the nature of the faults.

Step 5: Reporting.

A hard copy summary of the 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 Info and Certificate Settings dialogs have been filled correctly, the certificate will comply with ISO 17025 *General requirements for the Competence of Testing and calibration Laboratories*.

If the bridge does not meet the expected specification 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 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, and
- 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

$$\sigma^2{}_{total} = \sigma^2{}_{RBC} + \sigma^2{}_{cables} + \sigma^2{}_{bridge} \,. \qquad (8.1)$$

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 $\sigma^2{}_{total}$.

Ideally if all factors have been correctly considered, the two variances $\sigma^2{}_{total}$ (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 $\sigma^2{}_{total}$, 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 uncertainties all of the effects that contribute significantly to the uncertainty in RBC measurements on resistance ratio bridges. The values have been calculated for an RBC100 used with a bridge operating at 75 Hz, with a 1 mA sensing current and a 100 Ω standard resistor. A detailed explanation of the effects is given in following sections.

Source	**Maximum error /μΩ**	**Standard uncertainty /μΩ**	**Basis for numerical evaluation**
Junction cross resistance	3.5	2	Measurements of manufactured junctions
Combining network	2	0.5	Based on measurements on RBCs.
Temperature coefficients	3	1	Based on 1 °C peak-to-peak temperature control and maximum TC of 0.1×10^{-6}/ °C
TOTAL	**< 10**	**<3**	

Table 8.1: Summary of the most significant sources of uncertainty in RBC measurements.

Table 8.1 indicates that the RBC100 is capable of standard uncertainties better than 3 μΩ (0.03 ppm of 100 Ω). For direct reading resistance bridges the uncertainty is dominated by the uncertainty in the calibrated values of the RBC resistances, which typically limits measurements to about 0.0001% (1ppm) at 100 Ω.

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 when there are temperature gradients along the conductors. 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 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 the thermal emf errors to a few parts in 10^{10}, depending on the ambient temperature stability. Most high-accuracy dc bridges exploit this technique. AC bridges avoid the thermal emfs in the same way by using a low frequency sinusoidal sensing current.

8.3.2 Four-terminal Junction Cross-resistance

A four-terminal junction is a terminal block with the 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. In practice the junction is not ideal and the non-idealities can be represented in terms of two 'cross resistances'. For the junction used in the RBC, the cross-resistances are typically less than 3.5 $\mu\Omega$. The standard deviation of the errors for all 35 combinations is typically less than 2 $\mu\Omega$ (less than 2 parts in 10^8 at 100 Ω).

Further information on the cross-resistances of four-terminal junctions can be found in the paper by Riley2.

8.3.3 Combining Network

In order to realise the parallel combinations of the network, a low resistance connection must be made between each of the terminals of the resistors (Table 3.1). Because the resistance of the connections is not zero in practice, the currents through each of the resistors may not be divided, as expected, 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 sharing resistors into the potential leads, or into both the current and potential leads for a greater effect. In practice, it is sufficient to have sharing resistors in the potential leads and ensure that the current leads have as low a resistance as is practical (see Figure 4.1). Under these conditions the measured values for the parallel combinations of two and three resistors are

$$R(R_1\,//\,R_2) = \frac{R_1 R_2}{R_1 + R_2}\left[1 + \left(\frac{R_1 R_2}{R_1 + R_2}\right)\left(\frac{R_{p1}}{R_1} - \frac{R_{p2}}{R_2}\right)\left(\frac{R_{c1}}{R_1} - \frac{R_{c2}}{R_2}\right)\left(\frac{1}{R_{p1} + R_{p2}}\right)\right] \tag{8.2}$$

and

$$\begin{aligned} R(R_1\,//\,R_2\,//\,R_3) = \frac{R_1R_2R_3}{R_1R_2 + R_1R_3 + R_2R_3}\Bigg[1 + \frac{R_1R_2R_3}{R_1R_2 + R_1R_3 + R_2R_3}\Bigg(R_{p1}\left(\frac{R_{p2}}{R_2} - \frac{R_{p3}}{R_3}\right)\left(\frac{R_{c2}}{R_2} - \frac{R_{c3}}{R_3}\right) \\ + R_{p2}\left(\frac{R_{p1}}{R_1} - \frac{R_{p3}}{R_3}\right)\left(\frac{R_{c1}}{R_1} - \frac{R_{c3}}{R_3}\right) + R_{p3}\left(\frac{R_{p1}}{R_1} - \frac{R_{p2}}{R_2}\right)\left(\frac{R_{c1}}{R_1} - \frac{R_{c2}}{R_2}\right)\Bigg)\frac{1}{R_{p1}R_{p2} + R_{p1}R_{p3} + R_{p2}R_{p3}}\Bigg] \end{aligned} \tag{8.3}$$

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 // is used to indicate that resistors are connected in parallel.

2 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.

The potential sharing resistances are in the range 1 Ω to 3 Ω, and the resistances are matched so that the error in the measured ratios is less than 2.0 $\mu\Omega$ (0.02ppm of 100 Ω) and the standard deviation of the combining network errors is typically 0.5 $\mu\Omega$ or less.

Because the matching of the sharing resistors may change with time, the values of various resistances in the RBC and in particular the contact resistances of the switches, which are a part of the sharing resistances, should be checked periodically to ensure that they are stable and that the match is satisfactory. The calibration certificate supplied with the RBC provides a summary of the sharing resistances and the rms error introduced by the combining network based on measurements carried out at the time of calibration.

Note: the switches used in the RBC are susceptible to mechanical damage. Excessive loading of the switch levers (e.g. through automation), or dropping of the RBC onto a floor or bench, can cause misalignment of the switch mechanism leading to intermittent poor contact and combining network errors that may be as large as a few tens of micro-ohms. Poor switch contacts effect only combinations that have the base resistors in parallel combinations (combinations 11-35) and are evident from high standard deviations for repeated readings of a single combination.

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. For normal ratios the leakage resistor R_L appears in parallel with the network resistance R_N so that the measured ratio P_m is

$$P_m = \frac{1}{R_S}\frac{R_N R_L}{R_N + R_L} \qquad (8.4)$$

$$\approx \frac{R_N}{R_S} - \left(\frac{R_N}{R_S}\right)^2 \frac{R_S}{R_L} = \frac{R_N}{R_S} - P^2\frac{R_S}{R_L} \qquad (8.5)$$

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

$$R(R_1+R_2)_{meas} - R(R_1+R_2)_{calc} = \frac{-(R_1+R_2)^2}{R_S R_L} \qquad (8.6)$$

which leads to a relative error in the measurement of

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

To achieve an accuracy of 0.1 ppm at 100 Ω, which is required for the RBC100 and RBC400 calibrators, the various insulation resistances have to be greater than 10^{10} Ω. In practice most of the insulation resistances in the RBC are much greater than 10^{11} Ω so the errors are negligible.

Note: If the RBC is move from a relatively cold storage area to a warm area with a high dewpoint temperature, condensation can form on parts of the RBC. This commonly happens, for example, when the RBCs are offloaded from cargo holds of aircraft. The inner case of the RBCs contains a small bag of desiccant to help prevent this happening when it is first shipped. If condensation is observed at other times, the RBC should be stored in a warm environment (< 40 °C) overnight.

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). In humid environments, it may be useful to occasionally remove the bag of desiccant and dry it at 150 °C for a few hours.

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

$$R(I_0) = R(1+\alpha hRI_0^2) \quad (8.8)$$

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

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

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 (8.9).

For the resistors used in the RBCs, and sensing currents less than 5 mA, the power coefficients contribute less than 3 parts in 10^9 uncertainty.

8.3.6 Temperature Control

One of the most significant contributions to the RBC uncertainty is due to the combination of the temperature coefficients of the resistors and variations in the ambient temperature. The resistors used in the RBC have temperature coefficients within $\pm 0.1 \times 10^{-6}$/°C over the range 0°C to 50°C, and are typically within $\pm 0.05 \times 10^{-6}$/°C at temperatures in the range 20°C to 23°C.

In laboratories with time-proportioning PID control for the air-conditioning system, the specified 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 3 parts in 10^8, leading to maximum errors of about 0.03 ppm and an uncertainty (1 sigma) of about 0.01 ppm. This is near the practical limit of performance of the RBC100 and RBC400 calibrators.

In laboratories with On/Off control systems, which typically have a forced hysteresis of 1 °C or more, care should be taken to avoid direct air flow from air vents.

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.

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 resistances 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 RBC100 and RBC400 calibrators the effects of temporal drift are negligible. The resistors have a relative stability of about 10^{-6} per year so will drift typically only 1 part in 10^{9} over an 8-hour period.

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:

$$\frac{-R_1R_2}{(R_1+R_2)^2}\left(\frac{L_{p1}}{R_1}-\frac{L_{p2}}{R_2}\right)\left(\frac{L_{c1}}{R_1}-\frac{L_{c2}}{R_2}\right)\left(\frac{R}{R_p}\right)(2\pi f)^2 \tag{8.9}$$

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

$$-1.0\times 10^{-9} f^2 \tag{8.10}$$

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

$$\mathrm{Re}(Z_1+Z_2)=\mathrm{Re}(Z_1)+\mathrm{Re}(Z_2) \tag{8.11}$$

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

$$\mathrm{Re}\left[Z_1Z_2/(Z_1+Z_2)\right]=\left[\mathrm{Re}(Z_1)\,\mathrm{Re}(Z_2)/(\mathrm{Re}(Z_1)+\mathrm{Re}(Z_2))\right] \tag{8.12}$$

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, which is typical for resistors of less than a few hundred ohms, the errors are

$$\frac{R_1R_2}{(R_1+R_2)^2}\left(\frac{L_1}{R_1}-\frac{L_2}{R_2}\right)^2(2\pi f)^2 \tag{8.13}$$

This equation has the same form as Equation (8.9) above for the combining network error, and is typically a factor of 30 or more 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))

$$\mathrm{Re}(Z_X/Z_S)=1/\mathrm{Re}(Z_S/Z_X) \tag{8.14}$$

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 Wilkins[3] 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 insulting 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

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

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 (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 (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

$$2.5\times10^{-8} f \qquad (8.16)$$

where f is the frequency is in kHz.

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

$$2.5\times10^{-7} f^2 \qquad (8.17)$$

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.

3 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

$$\overline{V_t^{\,2}} = 4kTR\Delta f \tag{8.18}$$

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 Ω resistor generates noise with an amplitude of 0.4 nV rms for a 0.1 Hz bandwidth. For many bridge designs the uncertainty in resistance due to Johnson noise is

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

which for a 0.1 Hz bandwidth, $R_S = R_x = 100\ \Omega$ and a 1mA 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

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

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

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

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

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

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 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 Netzer4

4 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 ± Δ/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 form 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 Ott5

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).

5 Ott H W , "Noise Reduction Techniques in Eectronic Systems", New York, Wiley & Sons, 1976

9 Maintenance

One of the features of the RBC is that it is essentially a passive device 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 in the RBC, which may only slowly affect the RBC 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 an ISO 17025 accredited laboratory or through Isotech. These simple checks should be carried out regularly, 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 100 V.

- With all of the RBC switches in the centre position (not connected), measure the resistance between each pair of the V1, V2, I1, and I2 terminals (6 measurements in total).
- With all of the RBC switches in the centre position (not connected), measure the resistance between each of the V1, V2, I1, and I2 terminals and the metal case (4 measurements in total).
- With the Switches set to the R1+R2 combination, measure the resistance between any of the V1, V2, I1, and I2 terminals and the metal case (1 measurement).

For all 11 measurements, the resistance should be more than $10^{11}\ \Omega$.

Note: If the RBC is moved from a relatively cold storage area to a warm area with a high dewpoint temperature, condensation can form on parts of the RBC, and this can lead to very low insulation resistances. This commonly happens, for example, when the RBCs are offloaded from cargo holds of aircraft. The inner case of the RBCs contains a small bag of desiccant to help prevent this happening when it is first shipped. If condensation is observed at other times, the RBC should be stored in a warm environment (< 40 °C) overnight. If the RBC is used in humid environments, it may be useful to occasionally remove the bag of desiccant and dry it at 150 °C for a few hours.

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 1 mΩ.

- Measure the resistance of each of the four base resistances. This can be done as the RBC would be used normally. The values should be within 0.005% of those listed on the calibration certificate.

- To measure the sharing resistances of the combining network, remove both the lid of the RBC and the inner plastic case. All of the sharing resistors are then accessible via test points on the two circuit boards. There are a total of 16 sharing resistances: current and potential resistances for each of two positions for each of the four base resistor switches (see Figure 4.1). Each sharing resistance includes switch contacts and must be measured as four terminal resistance. The error caused by the network errors can be calculated using Equations (8.2) and (8.3). A detailed technical procedure is available from MSL.

Note: the switches used in the RBC are susceptible to mechanical damage. Excessive loading of the switch levers (e.g. through automation), or dropping of the RBC onto a floor or bench, can cause misalignment of the switch mechanism leading to intermittent poor contact and combining network errors. Poor switch contacts are evident during these measurements resistance measurements for which the repeatability is worse than 1 mohm.

9.2 Repair

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

Appendix A: Specifications

Electrical and Mechanical Specifications	**RBC100**	**RBC400**
Corresponding thermometer resistance R_0 (Ω)	25	100
Suitable Rs values at 1:1 ratios (Ω)	25, 100	100
Resistance range, R_{min} - R_{max} (Ω) (Note 1)	16 - 127	43 - 346
Temperature coefficient (ppm/°C)	±0.1	±0.1
Combining network mismatch (maximum, rms, μΩ) (Note 2)	2.0, 0.5	4, 1
Accuracy (μΩ) (Note 3)	10	30
Sensing current (max. mA)	10	5
Power requirements	RBC is passive and requires no power supply.	
Connections	Four-terminal coaxial: two 50 Ω BNC connectors, one for current and one for voltage.	
Size	Height 2U (90 mm), width 42HP (212 mm), length 196 mm, suitable for rack mounting	

Software specifications	
Operating system	Windows 3.1, 95,98, 2000, 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 Creates complete job summary Creates calibration certificate Import and export of data from other applications.

Notes:

(1) Other resistance ranges may be available on request. Low resistance ranges have higher temperature coefficient and are not as accurate.

(2) The combining network mismatch is measured at time of manufacture and reported on the calibration certificate supplied with the RBC.

(3) The accuracy specification assumes that the RBC is maintained in an environment with a peak-to peak temperature variation of no more than 1 °C. The specification is expressed as resistance ratio with respect to R_{max}.

Appendix B: Combination Tables

Table of Combinations: RBC100			
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			
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

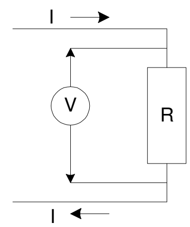
The electrical resistance of a device is defined by the energy that is dissipated when a current flows through the component. For dc measurements the resistance is given directly by Ohms law:

$$R = V / I \qquad \text{(C.1)}$$

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.

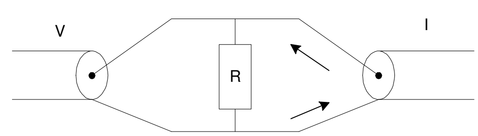
Figure C1: A Four terminal resistor.



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) possible6. 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

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

where $\cos(\theta)$ is the power factor of the component and θ is the 'phase angle' of the component, ie 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

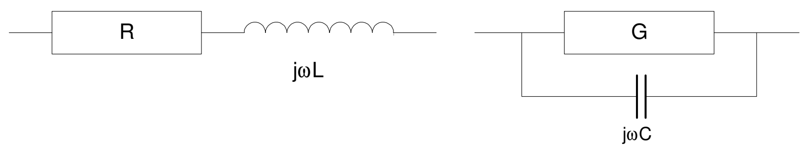
6 For a complete descriptions of the definitions and their limitations see "Coaxial ac Bridges" by B P Kibble and G H Rayner. (Adam Hilger, 1984).

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

and

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

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.



(a) Series representation (b) Parallel representation

Figure C.3: 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 C.3 (a) and Equation (C4)) is assumed throughout this manual, since most ac bridges measure resistance according to this definition:

$$R = \mathrm{Re}(V / I)\ . \qquad \text{(C5)}$$

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

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

where *f* is the frequency of the ac current. Note that there are other effects that give rise to ac-dc differences in resistance7. 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 $R = 200\Omega$, $C = 200$pF (corresponding approximately to a pair of 1 metre long coaxial cables) and $f = 90$ 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 C.4) 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

$$P = \mathrm{Re}\left(\frac{Z_x}{Z_s}\right) \qquad \text{(C7)}$$

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

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

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

where θ_1 - θ_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.

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 for 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.