Performance Assessment of Resistance Ratio Bridges used for the Calibration of SPRTs

Gregory F. Strouse[1] and Kenneth D. Hill[2]

[1]*National Institute of Standards and Technology, Gaithersburg, MD, USA.*
[2]*National Research Council of Canada, Ottawa, Canada*

Abstract. Automatic balancing dc and ac resistance ratio bridges are the primary measurement devices used by National Measurement Institutes for the calibration of standard platinum resistance thermometers (SPRTs) on the International Temperature Scale of 1990 (ITS-90). Performance assessment of these resistance ratio bridges is critical to the determination of both the uncertainties of the measurements and for identifying if a resistance bridge is exhibiting non-compliant behavior. NIST and NRC investigated the performance of 18 resistance ratio bridges consisting of 14 ASL F18s, 2 ASL F900s, and 2 MI 6010Bs. The assessment techniques included the use of an AEONZ resistance bridge calibrator, an ASL ratio test unit, and complements checks. Additionally, the possible effects from using different ac frequencies were investigated. This paper presents the methods of assessment employed, indicates the performance results obtained for the 18 resistance ratio bridges, describes the determination of measurement uncertainties, and assesses the contribution to the calibration uncertainty of SPRT measurements at ITS-90 fixed points.

INTRODUCTION

Resistance ratio bridges, whether ac or dc, are the principal instruments used by National Measurement Institutes (NMIs) to calibrate standard platinum resistance thermometers (SPRTs) at the defining fixed points of the International Temperature Scale of 1990 (ITS-90). Performance assessments of the resistance ratio bridges facilitate estimation of the uncertainties arising from the resistance measurement. Such components are included in the overall uncertainty budgets assigned to the realization of the ITS-90 fixed-point cells and to the calibration of SPRTs at both the National Institute of Standards and Technology (NIST) and the National Research Council of Canada (NRC).

Several methods are used to assess the uncertainties arising from use of the resistance ratio bridges. They include: a Hamon-type resistance network [AEONZ resistance bridge calibrator (RBC)]*, a ratio turns tester [ASL ratio test unit (RTU)], ratio complements checks, ac quadrature/frequency dependence, and measurement repeatability. The four uncertainty components derived from the performance assessment include non-linearity, ratio error, ac quadrature/frequency dependence, and repeatability. The results of the assessment are not used at either NIST or NRC to "calibrate" or "correct" the resistance ratio bridge, but are used as a check for compliance with the assigned uncertainties and the manufacturer's specifications.

The performance characteristics of eighteen resistance ratio bridges were studied to quantify the range of values that might be expected.

RESISTANCE RATIO BRIDGES

The resistance ratio bridges used in this study constitute two ac models and one dc model. Normally, NIST and NRC use ac resistance ratio bridges for the measurement and calibration of SPRTs. Table 1 lists the resistance ratio bridges that were assessed. For those resistance ratio bridges that do not belong to either NIST or NRC, the serial number is replaced with a letter identifier. The resistance ratio bridges investigated included fourteen Automatic System Laboratories (ASL) F18s (8 NIST, 6 NRC), two ASL F900s (1 NIST, 1 NRC), and two Measurement International (MI) 6010Bs (2 NIST).

The two models of the ac resistance ratio bridges (ASL F18 and ASL F900) use an inductive voltage divider technique to ratio the unknown resistance (e.g. SPRT) to a known resistance (calibrated reference resistor). The frequencies available are either 30 Hz or 90 Hz for 60 Hz mains. The range of measurable ratios is from 0 to 1.299 times the value of the reference resistor with a resolution of 9.5 digits for the ASL F18 and 10.5 digits for the ASL F900. For the ac resistance ratio bridges, the nominal measurement conditions were 10^4 (F18) and 10^5 (F900) gain, 0.1 Hz (F18) and 0.2 Hz (F900) bandwidth, 30 Hz frequency, current of 1 mA, and a 100 Ω reference resistor.

The automatic balancing dc resistance ratio bridge model (MI 6010B) uses a direct current comparator technique to ratio the unknown resistance (e.g. SPRT) to a known resistance (calibrated reference resistor). The reversal period ranges from 4 s to 60 s. The range of measurable ratios is from 0.001 to 13 times the value of the reference resistor with a resolution of 11 digits. For the dc resistance ratio bridges, the nominal measurement conditions were reversal periods ranging from 4 s to 32 s, current of 1 mA, and a 10 Ω reference resistor.

ASSESSMENT TECHNIQUES

The assessment techniques used to characterize the performance of the resistance ratio bridges include the use of a switchable resistance network (AEONZ RBC), a ratio turns unit (ASL RTU), ratio complements check, ac quadrature/frequency dependence, and measurement repeatability. The ASL RTU is only compatible with the ac resistance ratio bridges.

TABLE 1. Performance assessment results for NIST and NRC tested resistance ratio bridges at 1 mA.

NIST tested resistance ratio bridges

Resistance ratio bridge	**AEONZ RBC**		**ASL RTU**	**Ratio Complements Check**	**AC Quadrature/ Frequency Dependence**	**Measurement Repeatability**
s/n	Non-linearity $\times 10^6$	Ratio Error $\times 10^6$	Ratio Error $\times 10^6$	Ratio Error $\times 10^6$	$\times 10^6$	$\times 10^6$
F18 1166-5/104	**0.02**	**0.02**	**0.05**	**0.03**	**0.02**	**0.002**
F18 2847-001/187	0.03	0.03	0.07	0.05	0.02	0.002
F18 1356-2/143	0.03	0.08	0.09	0.01	0.02	0.002
F18 926-2/046	0.04	0.07	0.10	0.10	0.02	0.003
F18 1343-005/141	0.06	0.13	0.08	0.07	0.02	0.003
F18 631-5/024	0.05	0.06	0.06	0.04	0.03	0.002
F18 A	0.20	0.86	0.37	0.37	0.02	0.005
F18 B	0.04	0.20	0.21	0.19	0.02	0.007
F900 4137-002/168	0.02	0.02	0.01	0.01	0.01	0.002
MI 6010B C	0.11	0.09	N/A	0.30	N/A	0.004
MI 6010B D	0.47	0.51	N/A	0.46	N/A	0.006

NRC tested resistance ratio bridges

Resistance ratio bridge	**AEONZ RBC**		**ASL RTU**	**Ratio Complements Check**	**AC Quadrature/ Frequency Dependence**	**Measurement Repeatability**
s/n	Non-linearity $\times 10^6$	Ratio Error $\times 10^6$	Ratio Error $\times 10^6$	Ratio Error $\times 10^6$	$\times 10^6$	$\times 10^6$
F18 1131-5/089	0.02	0.06	0.07	0.03	-	-
F18 846-02/041	0.04	0.05	0.10	0.03	-	-
F18 631-2/022	**0.03**	**0.03**	**0.07**	**0.01**	-	-
F18 631-2/021	0.06	0.18	0.12	0.05	-	-
F18 2847-002/158	0.04	0.17	0.12	0.24	-	-
F18 1356-004/145	0.06	0.22	0.21	0.21	-	-
F900 7869-005/009	0.03	0.03	0.04	0.03	-	-

Resistance Bridge Calibrator

The commercially-available AEONZ (now 2K Electronics) RBC was originally designed and built by D. R. White of the Measurement Standards Laboratory of New Zealand [1-3]. The RBC uses four base resistors wired similarly to Hamon build-up resistors [4]. Using the various series and parallel combinations of the four base resistors, the RBC gives 35 different four-wire resistances over the range from 16.8 Ω to 129.9 Ω. These 35 resistances are used to assess the non-linearity of the resistance ratio bridge. Additionally, up to 35 possible reciprocal values are available to quantify the ratio error. However, only 10 of these reciprocal values are within the ac bridge resistance range of 0.0 Ω to 129.9 Ω with a 100 Ω reference resistor. The measurement of all possible resistance ratios verifies that the resistance ratio bridge properly activates the internal relays used to set the number of turns to achieve balance. Table 2 gives the nominal resistance ratio values (35 normal and 10 reciprocal) suitable for evaluating the performance of the ASL F18 and ASL F900 resistance ratio bridges.

TABLE 2. Nominal resistance ratios (≤1.299) suitable for evaluating the performance characteristics of the ac resistance ratio bridges.

Nominal resistance ratio values				
0.168	0.190	0.208	0.226	0.252
0.303	0.312†	0.365†	0.434	0.442
0.472	0.478	0.482†	0.519	0.520
0.555	0.565	0.591	0.616	0.621
0.650	0.668	0.678	0.708	0.734
0.769*	0.794	0.818†	0.845*	0.847
0.884*	0.943	0.975*	0.987	0.992*
1.008	1.014*	1.026	1.060*	1.131
1.181*	1.183	1.222*	1.259*	1.299

†Base resistors ratio values
*Reciprocal ratio values

The network has a stated accuracy of better than 1 part in 10^8 for ac resistance ratio bridges and 1 part in 10^9 for dc resistance ratio bridges [1]. The manufacturer specifies a periodic maintenance check of the insulation resistance, nominal values of the four base resistors, and four-wire connections. The four base resistors are not thermostatically controlled and the temperature coefficient of resistance of those resistors is 3 parts in 10^6 per °C. To meet the stated accuracy, the temperature instability of the resistors should not exceed 10 mK during the measurements. The RBC used by NIST is placed in an insulated box and the temperature is monitored with a platinum resistance thermometer. At NRC, the RBC is used in the laboratory environment as received from the manufacturer. Software for calculating the non-linearity and the ratio error is provided with the device.

The dc resistance ratio bridge measurements require only the 35 normal resistance ratio values to determine non-linearity. The 35 reciprocal values are used to measure the ratio error.

Ratio Turns Unit

The ASL RTU is designed to provide 14 distinct resistance ratio values ranging from 0.000 000 000 to 1.181 181 182. These ratio values are generated from the inductive voltage divider contained within the RTU in integer multiples of elevenths. Table 3 gives the nominal ratios supplied by the RTU.

TABLE 3. Nominal resistance ratios provided by the ASL RTU.

Nominal resistance ratio values		
0.000 000 000	0.090 909 091	0.181 818 182
0.272 727 273	0.363 636 364	0.454 545 455
0.545 454 545	0.636 363 636	0.727 272 727
0.818 181 818	0.909 090 909	1.000 000 000
1.090 909 091	1.181 818 182	

The RTU allows the user to verify four parameters that check the operational compliance of the ac resistance ratio bridge with the manufacturer's specifications. The checks ensure: 1) that the correct number of turns were wound on the inductive voltage divider of the user's ac resistance ratio bridge, 2) that the implementation of the internal relays to set the number of turns to achieve balance is performed properly, 3) that the non-linearity of the ac resistance ratio bridge is within specification, and 4) that the effect of uneven lead resistance (up to 100 Ω) does not compromise the measurement. Since the RTU supplies the 14 ratios from the internal inductive voltage divider, no subsequent calibration of the RTU is necessary. No external reference resistors are required for these measurements.

Complements Check

The ratio complements check method is another means of verifying the ratio error of resistance ratio bridges and is independent of the calibration values of the reference resistors used. A two-way complements check, using two resistors nominally of the same value (e.g. two 100 Ω), is performed by measuring the normal and reciprocal resistance ratio values of the two reference resistors. The ratio error is determined from the equation:

$$\delta(10^6) = \frac{[(1-(R_1/R_2)(R_2/R_1)]\,x\,10^6}{2} \qquad (1)$$

where the R quotients are the measured ratios; and R_1 and R_2 are nominally 100 Ω for an ac or 10 Ω for a dc resistance ratio bridge, respectively

A three-way complements check using the ratios of three different resistors (e.g. 10 Ω, 25 Ω, and 100 Ω) permuted is a simple method to assess the non-linearity of the resistance ratio bridge [5].

AC Quadrature /Frequency Dependence

The ac quadrature effects/frequency dependence of an ac resistance ratio bridge is estimated from the difference between the low frequency (30 Hz) and the high frequency (90 Hz) measurements of both the SPRT and a reference resistor.

Measurement Repeatability

The measurement repeatability is determined by making two similar measurements using the resistance ratio bridge. The first method is to measure a thermostatically controlled (±10 mK) reference resistor over at least a 10 h period to determine the repeatability of only the resistance ratio bridge. The second method is to measure an SPRT in either a H_2O triple-point cell or a Ga triple-point cell over at least a 10 h period to determine the repeatability of the measurement system under nominal SPRT calibration conditions. For either method, the repeatability is expected to be within 4 μΩ peak-to- peak.

RESULTS AND UNCERTAINTIES

Non-Linearity

The RBC results from Table 1 show that for the NIST and NRC resistance ratio bridges the non-linearity values do not exceed 6 parts in 10^8, and 3 parts in 10^8, for the NIST and NRC ASL F18 and ASL F900, respectively. The letter-identified resistance ratio bridges give values that do not exceed 2 parts in 10^7, and 5 parts in 10^8, for the ASL F18 and MI 6010B, respectively. The NIST repeatability of four RBC non-linearity measurement sets was 1 part in 10^8 for the ASL F18 and F900 and 2 parts in 10^8 for the MI 6010B. The manufacturer's linearity specifications are 1 part in 10^8, 2 parts in 10^9, and 1 part in 10^8 for the ASL F18, ASL F900, and MI 6010B, respectively.

The non-linearity component is calculated from the 35 normal (non-reciprocal) values obtained with the RBC (Type A). Table 1 gives the non-linearity values for the 18 resistance ratio bridges as the standard deviation determined by the analysis software. The non-linearity uncertainty components given in Table 4 are the non-linearity values given in Table 1 in bold type in the column labeled RBC non-linearity.

Ratio Error

The AEONZ RBC results from Table 1 show that for the NIST and NRC resistance ratio bridges the ratio error values do not exceed 2.2 parts in 10^7, and 3 parts in 10^8 for the ASL F18 and ASL F900, respectively. The letter-identified resistance ratio bridges give ratio error values that do not exceed 8.6 parts in 10^7, and 5.1 parts in 10^7, for the ASL F18 and MI 6010B resistance ratio bridges, respectively. The NIST repeatability of four RBC ratio error measurement sets was 2 parts in 10^8 for the ASL F18 and F900 and 3 parts in 10^8 for the MI 6010B. The manufacturer's accuracy specifications are 1 part in 10^7, 2 parts in 10^9, and 1 part in 10^7, for the ASL F18, ASL F900, and MI 6010B, respectively.

The ASL RTU results from Table 1 for the NIST and NRC ac resistance ratio bridges show that the ratio error does not exceed 2.1 parts in 10^7 and 4 parts in 10^8, for the ASL F18 and ASL F900, respectively. The letter-identified resistance ratio bridges give values that do not exceed 3.7 parts in 10^7 for the ASL F18 resistance ratio bridges. The NIST repeatability of four RBC ratio error measurement sets was 2 parts in 10^8 for the ASL F18 and F900.

The ratio error uncertainty component (Type A) is the result obtained using the RBC, verified by the results from the ASL RTU for the ac bridges and the two-way ratio complements check. The ratio error uncertainty components given in Table 4 are the ratio error values from Table 1 given in bold type in the column labeled RBC ratio error. Figures 1 and 2 give examples of the results from the RBC, the RTU, and the complements check measurements for an ASL F18 and an ASL F900, respectively. Figure 3 gives an example of the results from the RBC measurements for a MI 6010B.

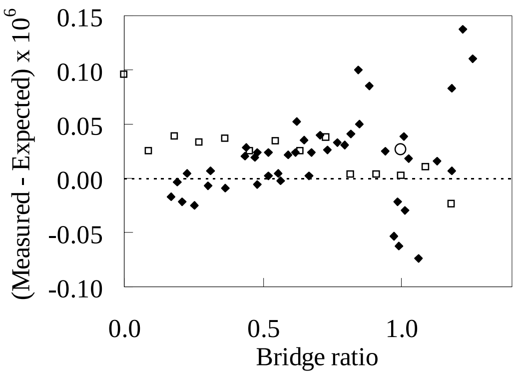

FIGURE 1. Results from the AEONZ RBC (closed diamonds), ASL RTU (open squares), and the ratio complements check (open circle) measurements for ASL 18 846-02/041.

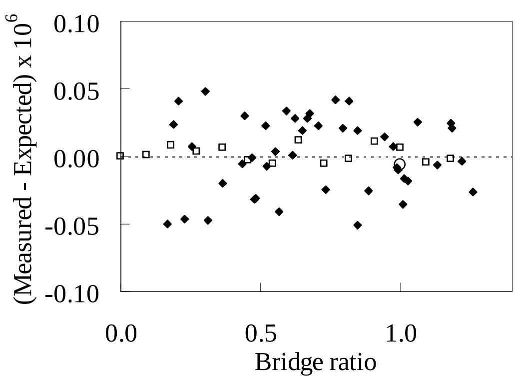

FIGURE 2. Results from the AEONZ RBC (closed diamonds), ASL RTU (open squares), and the ratio complements check (open circle) measurements for ASL F900 4137-002/68.

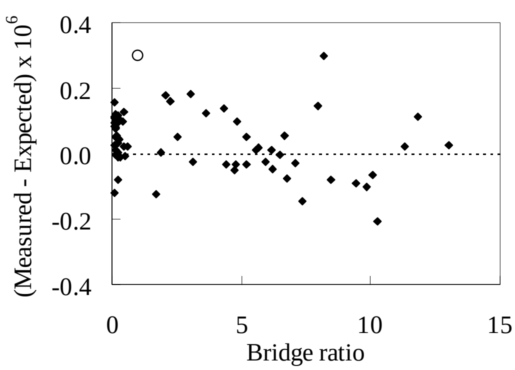

FIGURE 3. Results from the AEONZ RBC (closed diamonds), and the ratio complements check (open circle) measurements for MI 6010B C.

AC Quadrature /Frequency Dependence

The ac quadrature/frequency dependence uncertainty component is calculated from the fractional change between the low (30 Hz) and high (90 Hz) frequency measurements of an SPRT as measured in a H_2O triple point cell. Table 1 gives the results of the ac quadrature/frequency dependence values of the 9 ac resistance ratio bridges characterized at NIST. The ac quadrature/frequency dependence uncertainty component given in Table 4 is calculated by dividing the ac quadrature/frequency dependence value (given in bold type) from Table 1 by $\sqrt{3}$.

Measurement Repeatability

The measurement repeatability uncertainty component is calculated as the standard deviation of the measurements (Type A standard uncertainty) of either an SPRT over a 10 h period. Table 1 gives the results (standard deviation of the measurements) of the measurement repeatability. The measurement repeatability uncertainty component given in Table 4 is the measurement repeatability value in bold type from Table 1. Figure 4 gives an example of the nominal measurement repeatability for the two ac resistance ratio bridges measuring a 25 Ω reference resistor.

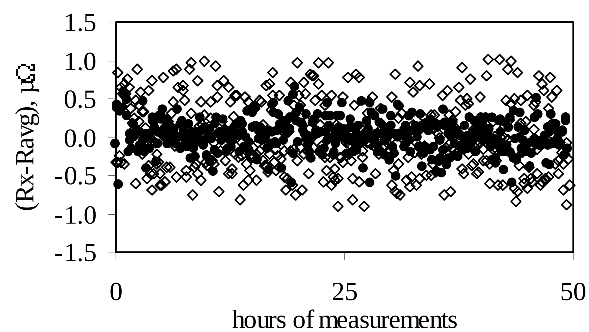

FIGURE 4. Measurement repeatability of an ASL F18 (open diamonds) and ASL F900 (closed circles) for a 25 Ω reference resistor.

As described in the text above, Table 4 gives the values of uncertainty [u(resistance ratio), *k*=1] that NIST and NRC assign to their respective ac resistance ratio bridges used for the ITS-90 calibration of SPRTs. These four uncertainty components are used in conjunction with other uncertainty components to assign overall uncertainties to the respective NIST and NRC realized ITS-90 fixed-point cells. The uncertainties assigned to the fixed-point cells are then used to estimate the overall uncertainties of the respective NIST and NRC calibrated SPRTs.

TABLE 4. Uncertainty values [u(resistance ratio), *k*=1] that NIST and NRC assign to their respective ac resistance ratio bridges used for the ITS-90 calibration of SPRTs.

Uncertainty Component	NIST	NRC
non-linearity $\times 10^6$	0.02	-
ratio error $\times 10^6$	0.02	0.03
ac quadrature/frequency dependence $\times 10^6$	0.01	-
measurement repeatability $\times 10^6$	0.002	-

SPRT Calibrations

The uncertainty contribution of the two resistance ratio bridges used at NIST and NRC, respectively, in the normal calibration of SPRTs on the overall uncertainty assigned to the fixed-point cells ranges from 93% at the H_2O TP to 1 % at the Ag FP. Table 5 gives the uncertainties that both NIST and NRC assign to their measurement systems, fixed-point cells and the ratio of the two columns.

TABLE 5. Uncertainties [u(resistance ratio), *k*=1] assigned to the resistance ratio bridges and the fixed-point cells overall at both NIST and NRC.

NIST			
Fixed-Point Cell	**Measurement System, mK**	**Fixed-Point Cell, mK**	**Ratio, %**
Ar TP	0.04	0.07	43
Hg TP	0.04	0.08	38
H_2O TP	0.04	0.04	93
Ga MP	0.04	0.04	93
In FP	0.04	0.07	43
Sn FP	0.04	0.14	21
Zn FP	0.04	0.25	12
Al FP	0.04	0.40	8
Ag FP	0.04	0.58	5

NRC			
Fixed-Point Cell	**Measurement System, mK**	**Fixed-Point Cell, mK**	**Ratio, %**
Ar TP	0.03	0.15	20
Hg TP	0.03	0.08	38
H_2O TP	0.03	0.04	75
Ga MP	0.03	0.12	25
In FP	0.03	0.13	23
Sn FP	0.03	0.38	8
Zn FP	0.03	0.14	21
Al FP	0.03	0.53	6
Ag FP	0.03	2.48	1

CONCLUSION

The various tests described here provide useful information regarding the performance characteristics and measurement system uncertainties of the resistance ratio bridges used in the calibration of SPRTs by ITS-90 fixed-point cells. As a general rule, the RBC, RTU, and complements checks are in agreement at a level of a few parts in 10^8. Where this is the case, we can have high confidence in the performance results obtained and in the corresponding measurement uncertainties attributed to the resistance ratio bridge. Every resistance ratio bridge user should be equipped to carry out periodic complements checks to ensure that the instrument is functioning within specification near a ratio of 1. The RTU is simple, stable, rapid in operation, and is well suited to validate ac bridge operation. The RBC provides a wide range of resistances and is equally adept at verifying the operation of both ac and dc resistance ratio bridges.

REFERENCES

* Any commercial instrument identified in this paper used to adequately specify the measurement procedure does not imply product recommendation by NIST or NRC.

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