Performance assessment of resistance bridges and multimeters used at CMS

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Abstract. Automatic balancing ac resistance bridges, ASL F18 and F700, and HP 3458A multimeters are the measurement instruments used by Center for Measurement Standards (CMS) for the calibration of standard platinum resistance thermometers (SPRTs), industrial platinum resistance thermometers (IPRTs), and liquid-in-glass thermometers (LIG) respectively. The inherent non-linearity of these measurement instruments could be a significant source of uncertainty and the absolute accuracy is especially critical to the primary instrument. A resistance bridge calibrator RBC 100, manufactured by 2K electronics, is a resistor network for the purpose of assessing their linearity and absolute accuracies of the foregoing thermometry bridges and meters. Each thirty-five normal measurements gives the linearity with $4.781\times10^{-8}$, $4.982\times10^{-7}$, and $6.371\times10^{-5}$ for F18, F700, and HP 3458A, however this deteriorates to $2.661\times10^{-7}$ and $3.227\times10^{-6}$ for two bridges while considering both normal and complementary data. Additionally, the possible contributions from the F18 Bridge to the uncertainty of SPRT measurement at ITS-90 fixed points were investigated also.

1. Introduction
No matter what the fixed point or comparison calibration system, even liquid-in-glass system, all are concerned with the resistance thermometry in CMS. Accurate resistance thermometry requires the measurements of four-terminal resistances with high accuracy bridges or multimeters, however their characteristics, including linearity and accuracy, influencing the realization and transfer of temperature scale, previously relied on the manufacturers’ specifications and a simple check.
A resistance bridge calibrator (RBC), a Hamon-type resistance network, developed by the Measurement Standards Laboratory of New Zealand was used to assess the resistance instruments of our calibration systems recently. The results of the assessment are not used at CMS to correct the resistance instruments, but are used as a check for compliance with the assigned uncertainties and the manufacturer’s specifications.

2. Resistance Instruments
The resistance instruments used in this study constitute two automatic balancing ac resistance bridges, ASL F18 and F700, and one HP 3458A multimeter.
The ASL F18 automatic balancing ac resistance bridge is the resistance instrument for SPRTs fixed-point calibration system. The frequencies available are 30 Hz and 90 Hz. 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. Measurement conditions are $10^4$ gain, 0.1 Hz bandwidth, 30Hz frequency, 1 mA current, and 100 $\Omega$ reference resistor normally.
The ASL F700 automatic balancing ac resistance bridge is the resistance instrument for IPRTs comparison calibration system. The bridge operates at 1.5 times the local line frequency and is phase locked to it. The range of measurable ratios is from 0 to 3.999 times the value of the reference resistor with a resolution of 7.5 digits. Normally, $10^4$ gains, 0.1 Hz bandwidth, 1 mA current, and 100 $\Omega$ reference resistors are the measurement conditions.

The HP 3458A multimeter is the resistance instrument for the liquid-in-glass thermometer calibration system with 8.5 to 4.5 digit resolution and 1 mA current.

3. Resistance Bridge Calibrator

The resistance bridge calibrator is a set of four resistors that can be connected in different series and parallel combinations to generate a total of 35 distinct and inter-related four-terminal resistances over the range from 16.8 $\Omega$ to 130 $\Omega$. Furthermore, up to 35 complement ratios can be obtained by exchanging the unknown and standard connections to the bridge, but only 10 and 31 of them are within the F18 and F700 ac bridge resistance ranges respectively with a 100 $\Omega$ reference resistor. Table 1 gives the nominal resistance ratio values, including 35 normal and reciprocal ratio values, suitable for evaluating the performance of the F18 and F700 bridges.

The 35 normal ratio values listed in Table 2 times by 100 are the 35 nominal resistance values generated by RBC to assess the HP 3458A multimeter with its built-in resistor.

At CMS, the RBC which is not temperature controlled is used in the laboratory environment, which is temperature controlled within $(23\pm 3) ^\circ C$, has an accuracy of approximately 0.1 ppm of 100 $\Omega$ reference resistor and approaching 0.01 ppm under good laboratory control as stated in the operator manual.

Table 1. Nominal resistance ratios suitable for evaluating the performance of the F18 and F700 bridges.

| Normal Measurement used at F18 and F700 | Complement Measurement used at F18 | used at F700 |
|----------------------------------------|------------------------------------|-------------|
| 0.168 0.365 0.520 0.668 0.943         | 0.769 1.180 0.769 1.180 1.538 1.927 3.201 |
| 0.190 0.434 0.555 0.678 0.987         | 0.845 1.222 0.845 1.222 1.609 2.076 3.298 |
| 0.208 0.442 0.565 0.708 1.008         | 0.884 1.259 0.884 1.259 1.624 2.092 3.961 |
| 0.226 0.472 0.591 0.734 1.026         | 0.975 1.362 0.975 1.362 1.691 2.120 |
| 0.252 0.478 0.616 0.794 1.131         | 0.992 1.413 0.992 1.413 1.770 2.262 |
| 0.303 0.482 0.621 0.818 1.183         | 1.014 1.476 1.014 1.476 1.803 2.305 |
| 0.312 0.519 0.650 0.847 1.299         | 1.060 1.496 1.060 1.496 1.923 2.739 |

4. Results and Discussion

The 35 normal measurements of RBC will provide information only on the linearity of the resistance instruments and the inclusion of both normal and complement ratios in a bridge assessment can then determine the accuracy.

The resistance values of four base resistors certificated by the Measurement Standards Laboratory of New Zealand are 81.8190 $\Omega$, 48.1791 $\Omega$, 36.5170 $\Omega$, and 31.2412 $\Omega$. The analysis proceeds by minimizing the variance between the measured and the fitted values for all the available combinations of the four base resistors:

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

where $P_{i,\text{meas}}$ are the measured values, $P_{i,\text{calc}}$ are the values calculated from the fitted values of four base resistors, $N$ is the number of measured values, and $N-\rho$ is the degrees of freedom associated with the variance. Figures 1 to 3 give the fitted results from 35 normal measurements for ASL F18, ASL F700, and HP3458A respectively.
The results from Table 2 show that the standard deviation of the residuals for non-linearity assessment are 4.781 parts in $10^8$ for ASL F18 and 4.982 parts in $10^7$ for ASL F700. It is apparent that the non-linearity results of F18 and F700 aren’t within the specifications, $<\pm0.01$ ppm and $<\pm0.25$ ppm respectively, stated by manufacturer. The linearity of HP3458A multimeter, showing the same order as F700, is 63.71 $\mu\Omega$. 

**Figure 1.** Fitted results from 35 normal measurements for ASL F18.

**Figure 2.** Fitted results from 35 normal measurements for ASL F700.

**Figure 3.** Fitted results from 35 normal measurements for HP3458A.
The accuracy assessment results are 2.661 parts in $10^7$ for ASL F18 and 3.227 parts in $10^6$ for ASL F700 and exhibits beyond the specifications also, $<\pm0.1$ ppm and $<\pm0.5$ ppm respectively, stated by the manufacturer.

Table 2. Performance assessment results for F18 and F700 ratio bridges and HP3458A multimeter.

| Resistance instrument | Non-linearity       | Accuracy              |
|-----------------------|---------------------|-----------------------|
| ASL F18               | $4.781 \times 10^{-8}(\text{Resistance ratio})$ | $2.661 \times 10^{-7}(\text{Resistance ratio})$ |
| ASL F700              | $4.982 \times 10^{-7}(\text{Resistance ratio})$ | $3.227 \times 10^{-6}(\text{Resistance ratio})$ |
| HP3458A               | $6.371 \times 10^{-5} \Omega$                   |

The uncertainties resulted from the non-linearity and non-accuracy of F18 ratio bridges in the normal calibration of SPRTs are therefore more than the original values provided by the manufacturer and amend to estimate from $4.781 \times 10^{-8} \times \text{ratio value} \times \frac{dT}{dR} \times \frac{1}{2\sqrt{3}}$ and $2.667 \times 10^{-7} \times \text{ratio value} \times \frac{dT}{dR} \times \frac{1}{2\sqrt{3}}$ formulae. The uncertainty contribution of F18 on the overall uncertainty assigned to the fixed-point calibration system at CMS is 64.5 % at the H$_2$O TP to 7.7 % at the Ar TP as shown in Table 3.

Table 3. Uncertainties (k=1) assigned to the F18 bridge, the calibration system and the contribution percentage.

| Fixed point | Uncertainty resulted from the F18 bridge, mK | Uncertainty of the calibration system, mK | F18 bridge uncertainty contribution percentage |
|-------------|--------------------------------------------|------------------------------------------|-----------------------------------------------|
| Ag FP       | 0.54                                       | 2.71                                     | 19.9 %                                       |
| Al FP       | 0.41                                       | 1.99                                     | 20.4 %                                       |
| Zn FP       | 0.27                                       | 0.71                                     | 38.1 %                                       |
| Sn FP       | 0.27                                       | 0.58                                     | 46.7 %                                       |
| In FP       | 0.14                                       | 0.49                                     | 27.5 %                                       |
| Ga MP       | 0.09                                       | 0.23                                     | 40.8 %                                       |
| H$_2$O TP   | 0.08                                       | 0.12                                     | 64.5 %                                       |
| Hg TP       | 0.07                                       | 0.27                                     | 24.6 %                                       |
| Ar TP       | 0.03                                       | 0.35                                     | 7.7 %                                        |

5. Conclusion

The linearity and accuracy of F18 and F700 resistance ratio bridges, assessed by the 2K RBC are all beyond the specifications stated by the manufacturer. The HP3458A multimeter has similar linearity to the F700 bridge. The uncertainty attributed to the performance characteristics of the bridge ratio plays an important role on the calibration of SPRTs by ITS-90 fixed-point cells, especially at the triple point of water with a contribution percentage of 64.5 %. It is apparently important that the resistance instrument users should carry out periodic assessment to obtain the real performance characteristics of them.

References

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