F900 Performance Validation Report

Introduction

Work on validating the performance of the F900 started in October 1999 and continued until April 2001, during this time a large number of tests were performed. This report provides details of some of the key tests used to determine the more critical aspects of the F900's performance.

Unless stated otherwise, these tests were conducted in the company's main offices in Milton Keynes in which light industrial activities take place (including the use of 3-phase machinery). The work was carried out in the research and development department, which is not –air-conditioned, ambient temperatures therefore varied between about 16 and 30°C. This environment is not ideal for precision electrical measurement. It is therefore realistic to expect that the F900 should equal or exceed the performance indicated by these tests when used in most temperature laboratories, provided good measurement practices are employed.

Accuracy

A key performance parameter for the F900 is its accuracy since this ultimately limits the measurement uncertainty that can be achieved using the bridge. The high accuracy of ±20ppb claimed in the F900 specification is difficult to validate because of the uncertainty of the tests used and indeed the difficulty in finding artifacts for use in such tests. Three approaches were taken to validate the accuracy of the F900:

Internal Consistency Check: The F900 uses a ratio transformer to make the measurement (figure 1):

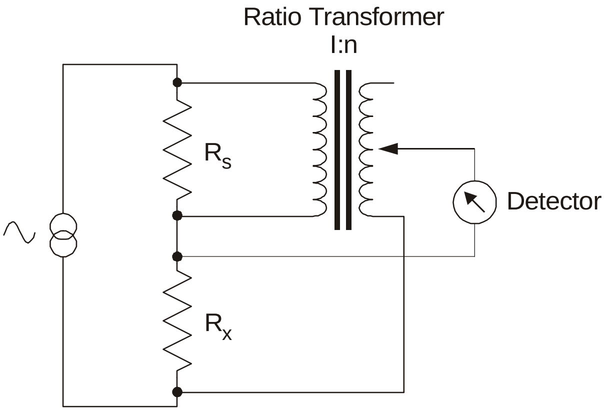

Figure 1: F900 Measurement Concept

The two resistances Rs and Rx carry the same current. The ratio transformer is used to balance the voltage developed across an unknown resistance (Rx) against that across a known standard resistance (Rs). Since the ratio of the voltage across the primary and secondary of an ideal transformer is equal to the turns-ratio (n), the ratio of the resistances Rx and Rs then equals the turns-ratio:

$$\mathit{At\ Balance}: \quad R_X = n\, R_S$$

The ratio transformer is actually a series of cascaded transformers. Each transformer has tappings in decimal intervals (10:1, 10:2 10:3….10:9) and provides one decade of resolution for the bridge. Since the tapped secondary comprises a number of individual windings, it is possible to connect any two of these windings 'back-to-back' and use a sensitive detector directly to measure the difference between them. From this we can calculate the linearity errors that would occur when the winding segments are built up into the complete secondary winding. However, this approach does not subject the windings to the common mode voltages they will experience in practice. This is important since the complex inter-winding capacitance relationships will inject current that depends on these common mode voltages. The approach used was therefore to connect all the segments of the secondary in their intended arrangement and to compare these with a reference winding. The ratio transformer has two 'extra' windings that normally drive subsequent decades and one of these was used as the reference in the measurement.

The most significant 'decade' actually provides a ratio up to 1.2 to give the required range for thermometry. This decade effectively determines the measurement linearity since it is here where the signals are greatest and therefore where any ratio errors have the most impact on the measurement. The winding inter-comparison was made on this decade in order to confirm the F900 measurement linearity; the results (with measurement uncertainties) are shown in figure 2:

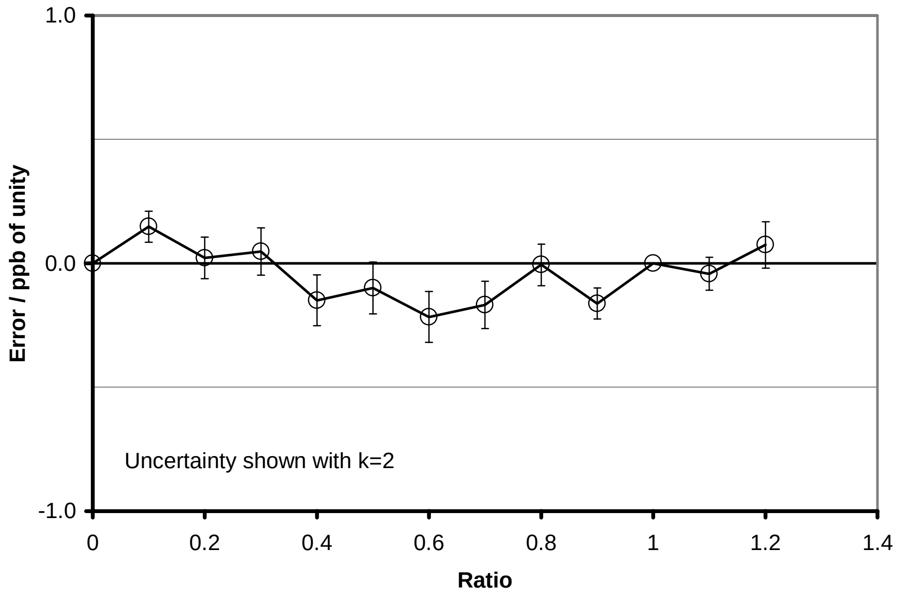

Figure 2: Non-Linearity Caused by Ratio Transformer Errors

This test confirms that the non-linearity caused by ratio errors in the transformer is less than 1ppb and is therefore insignificant compared with the specified performance of 20ppb.

This test measures linearity only; it does not check whether the full winding accurately provides a ratio of unity. Any errors in either the zero or unity ratio measurements further contribute to the total measurement accuracy achieved by the F900. However, it is straightforward to check ‘unity’ performance by connecting the potential terminal for R_X to R_S . It is also easy to check ‘zero’ performance by connecting a four-terminal short-circuit in place of R_X These test functions are built into the bridge and made available via front panel keys. They provide a simple and useful instrument performance check.

Complement Check: Although the F900 is equipped with a unity self test function, it is desirable to check the accuracy of the ratio measurements when using actual resistors. This can be achieved by connecting two resistors of similar value to the bridge and measuring the ratio, then swapping over the resistors and re-measuring the ratio. The ratios should be the reciprocal of each other so that the product of the two ratios should be unity. The measurement error is therefore half the difference between the product of the two ratios and unity.

Two Wilkins resistors were used in the tests. Although the temperature coefficient and power coefficient of these resistors are low, they are significant at the level of measurement (ppb) we are working at. The interruption of the power to the resistors whilst they are being swapped over manually causes the temperature and therefore the resistance of the resistors to change significantly followed by a relatively long recovery. This was overcome in the tests by using reed relays to swap over connections to the resistors within a few milli-seconds, a timeframe that is short enough to have no negligible impact on the resistance. The temperature coefficient of the resistors (2ppm/°C) mean that a 1mK change in temperature yields a 2ppb error. The resistors used in the test were therefore chosen to have matched temperature coefficients, they were used in a stable temperature environment and the measurements were taken quickly so as to minimize the effect of temperature coefficient on the measurement.

The result of complement checks in a number of F900s is shown in table 1:

F900 S/N	R1/R2	R2/R1	R1/R2xR2/R1	Error / ppb
7869005009	1.000037014	0.999963000	1.000000013	-6.5
7869001005	1.000035132	0.999964862	0.999999992	4
78669003007	1.000032194	0.999967804	0.999999997	1.5

Table 1: Complement Errors Measured on F900s

The complement checks confirm that the ratio accuracy of the bridge at unity is within specification.

Comparison with a Traceable IVD: Although the design calculations and measurements on the ratio transformer indicate that the F900 achieves the stated accuracy, we wanted to find some way of providing a performance check for the whole instrument that was traceable to national standards. For this, a ratio test unit (RTU) was used, which is an inductive voltage divider (IVD) of our own design that is used as a company reference standard. The RTU provides ratios in integer multiple of elevenths, this particular ratio set is useful in that it exercises all the digits of every decade when used over the range zero to unity and thereby provides a thorough check of the ratio tappings. The RTU was sent to PTB, the national standards laboratory of Germany for calibration.

The F900 was compared with the RTU using the PTB assigned values and the result is shown in figure 3. The difference or ‘error’ between the nominal or design values for the RTU ratios and those assigned by PTB is also shown in figure 3. The uncertainties (k=2) for both measurements are shown by the ‘error bars’. Interestingly, the F900 ‘error’ is a mirror image of the calibration ‘error’ determined by PTB. This suggests that the calibration ‘errors’ determined in this test are the result of ‘errors’ in the values assigned by PTB in their calibration and are not real. This does not mean that the PTB values are wrong since the nominal or design values for the RTU are comfortable within the uncertainties declared by PTB.

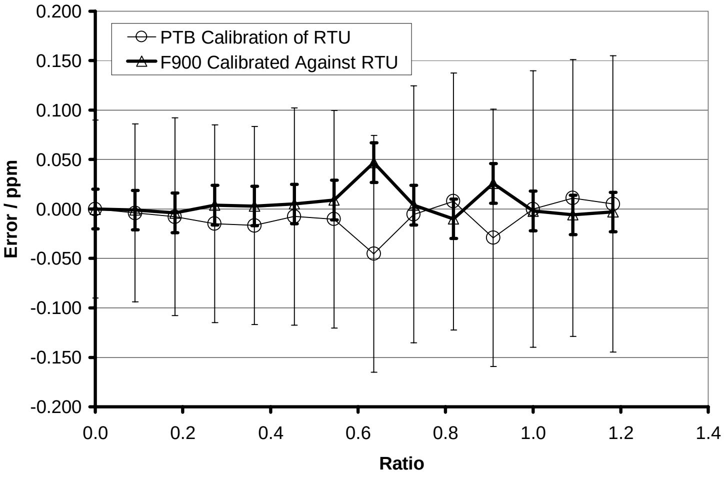

Figure 3: Error Plots for F900 vs. RTU & RTU vs. PTB standards

With the uncertainties available on the PTB calibration of the RTU, it is not possible to use this test alone to confirm the accuracy of the F900. However, the striking mirror image relationship between the two results in figure 3 together with the design calculations for the RTU support the view that it is legitimate to use the nominal RTU ratios in the test. If we use the nominal design values for the RTU in the calibration test, we find that the errors are very small (figure 4). The maximum error is only 14ppb and the standard deviation is 5ppb:

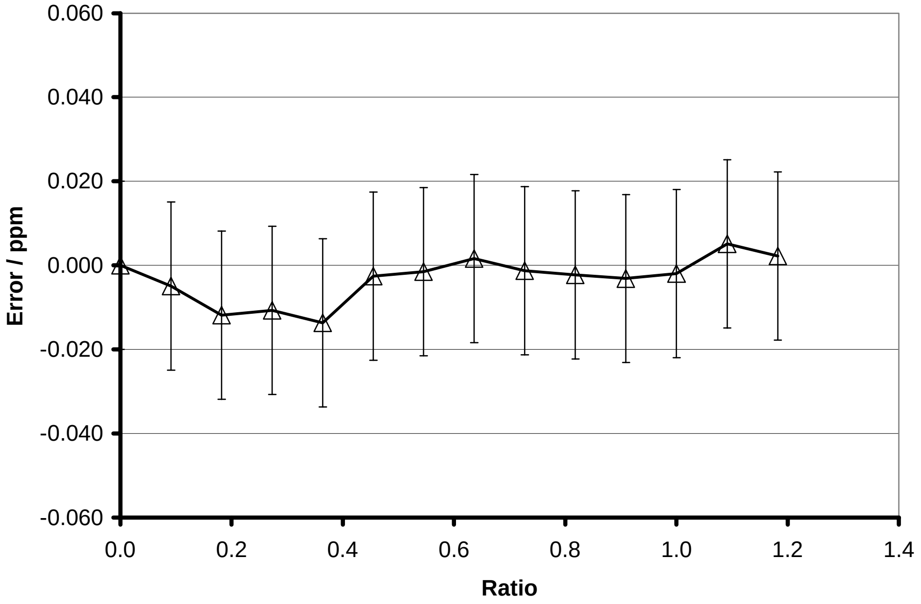

Figure 4: Comparison Between F900 and RTU (Nominal Values)

The internal consistency checks confirm that the linearity of key components within the F900 measurement system easily achieve the stated 20ppb accuracy. Additionally, the comparison of the F900 against the RTU indicates that the linearity of the complete F900 instrument is within its specification.

Noise

Although not part of the formal specification of the instrument, the noise performance of the F900 is vital in determining the measurement uncertainty that can be achieved with this equipment.

The F900 measures resistance ratio by balancing the voltage across the known and unknown resistances using a ratio transformer. The complex electronics surrounding the transformer are there to ‘bootstrap’ the transformer so that the magnetising currents in the transformer do not load the resistances significantly as this would lead to measurement errors. These circuits do not directly form part of the measurement circuit so their contribution to noise is limited to the noise on the very small bias currents drawn by the amplifiers that are connected to the potential leads of the resistance Rs.

The null balance detector used also contributes to the measurement noise. The bridge impedance is matched to the noise impedance of the detector using a transformer in order to optimize measurement noise. For an ideal transformer, any resistance ‘seen’ through a transformer has its impedance transformed by n^2:1. The detector system noise (referred to the detector amplifier input) can be viewed as an equivalent voltage noise (v_N) and current noise (i_N) as shown in figure 5:

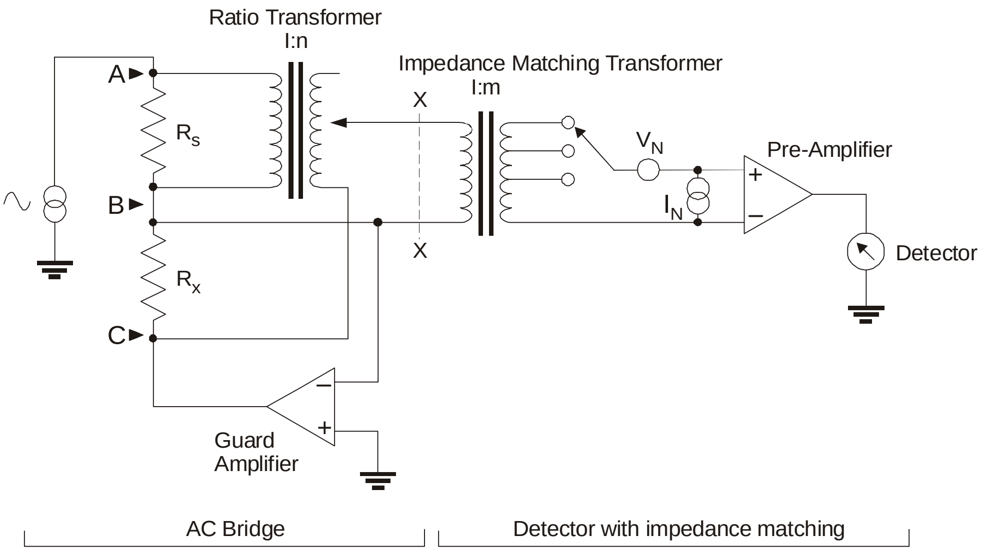

Figure 5: Noise Matching System Used in F900

The easiest way to determine the contribution of detector noise to the total measurement noise is to refer the detector noise components to position X-X. At this point the impedance of the bridge is:

$$R_B = R_X + n^2 R_S$$

Note: when measuring low resistances (high temperature SPRTs or cryogenic applications), the lead resistances are significant and need to be included in the calculation of bridge impedance. For the purpose of this analysis they are ignored, so the noise V_N at X-X is given by:

$$V_N{}^2 = \left(m\, i_N\ R_B\right)^2 + \left(\frac{v_N}{m}\right)^2$$

The optimum (lowest $V_N{}^2$) value for m (transformer setting) is determined by differentiating this expression w.r.t. m and setting this to zero to yield:

$$\textit{Minimum noise when}:\quad m^2 R_B = \frac{v_N}{i_N}$$

Considering that an ideal transformer transforms any impedance by n^2, this is equivalent to stating that optimum noise performance is achieved when the transformer matches the detector ‘noise’ impedance to the measurement circuit impedance. This noise matching facility enables the F900 to approach the fundamental Johnson Noise limit over the normal resistance measurement range used in thermometry. For example, the fundamental Johnson noise on a 25.5Ω SPRT at 0°C measured with a 0.5Hz bandwidth is 893pV and the measurement noise achievable with a properly configure F900 is equivalent to only 958pV (only 7% above the fundamental limit).

An Excel spreadsheet has been produced that calculates the theoretical noise figure for the F900 for any operating conditions (this can be supplied to F900 customers to assist in predicting uncertainty budgets). These predict that for a 10Ω resistance measured at 25°C the F900 (set to 10Ω impedance) would exhibit an RMS ratio noise of 62ppb at 0.7071mA and 9ppb at 5mA. The corresponding measurements were made using Wilkins standard resistors in a temperature stabilized oil bath, with the results shown in table 1:

Test Current	**Calculated RMS Noise**	**Measured RMS Noise**
0.7071mA	62ppb	57ppb
5mA	9ppb	5ppb

Table 1: Calculated and Measured Noise Figures

The measurements confirm that the noise performance of the F900 is as predicted by the design calculations and closely approaches the fundamental Johnson Noise limit.

Bridge Current Accuracy

The accuracy of the bridge current is important because of the self-heating effect in an SPRT. This causes the resistance of the SPRT at a given temperature to be dependent on the measurement current to an extent that is significant at the target uncertainty level of 20ppb. The accuracy of the bridge current is therefore important if the SPRT is to be used as a transfer standard thermometer at a stated current or if the bridge current is to be varied to allow extrapolation back to the zero-power resistance.

The bridge current was measured using a Keithley Model 2000 multi-meter to measure the voltage developed across a calibrated Wilkins Resistor. The errors between the measured and expected current for all bridge setting are shown in table 2:

Bridge Setting / mA	Error / %
50√2	0.01
50	-0.01
20√2	0.01
20	-0.01
10√2	0.02
10	0.05
5√2	-0.02
5	-0.04
2√2	-0.03
2	-0.04
√2	-0.01
1	0.02
0.5√2	0.01
0.5	-0.01
0.2√2	0.00
0.2	-0.01
0.1√2	0.02
0.1	0.05

Table 2: Bridge Current Error

This test confirms that the current accuracy is comfortably within the specified Ω±0.1%.

Conclusion

As stated at the beginning of this report, the above test results are a limited selection of the extensive tests carried out on the F900 over the last 18 months. However, these tests are the ones that address the most important performance criteria for this instrument (accuracy, noise and bridge current accuracy). These tests confirm the performance of the F900 to be well within its performance specification.

The F900 is designed to be as immune to environmental effects (particularly electrical noise and temperature) as possible. It should therefore be possible for users to achieve the specified performance. It is however important for users to set up the F900 correctly in order to achieve this performance. In particular, users must set the bridge gain correctly (as documented in the user manual) – F18 users are prone to get this part wrong, as this is different from the F18 because of the increased accuracy of the F900 bridge.