Bath Calibrations

ISF calibration of 29 March 2012

Consider the ISF calibration from 29 March 2012, which from Dick Friesen's spreadsheet of 22 Feb 2013 gave the results in the first two columns of the following table. The Callendar-Van Dusen (CVD) equation for a PRT can be written in the following form:

$$\frac{R_T}{R_0} = 1 + \alpha(1 + \frac{\delta}{1.e2})T - \frac{\alpha\delta}{1.e4}T^2 \left\{ +\frac{\alpha\beta}{1.e6}T^3 - \frac{\alpha\beta}{1.e8}T^4 \right\} \tag{1}$$

where R_T is the PRT resistance at temperature T, R_0 is the resistance at 0°C, \alpha is the temperature sensitivity expected to be 0.003925, $\delta = 1.46$ and $\beta = 0$ for $T < 0$°C and 0.1 otherwise. A fit to the measurements in which only R_0 and α were allowed to vary and δ and β were held at the preceding values produced the smallest RMS errors from the tabulated values for $R_0 = 50.0082$and $\alpha = 0.0039128$, and with these values (1) produces the values shown in the third column of the table, with the deviations shown in the fourth column. The deviations are very small except at the lowest two temperatures. Fitting while excluding the lowest three temperatures produced essentially the same fit, so these deviations are not distorting the fit to a significant degree. Because it is more difficult to maintain bath uniformity at lew temperature, I thinki it is preferable to use the CVD fit results instead of the measurements to avoid possible errors arising from conduction and/or bath non-uniformity at the lowest temperatures. However, the departures are not in the direction I would have expected (with measurements being too high in temperature); instead, as shown in the last column, the departures ΔT (the deviations in resistance translated into corresponding deviations in temperature) are negative at the lowest temperatures. Even the largest deviation corresponds to a temperature error of <0.05°C, so these measurements are in very good agreement with the values from the CVD equation.

Table 1: ISF calibration of 2012 (first two columns), the resistance values that result from Equation (1) using the fit to these calibration values, the deviation between the measurements and the fit, and the corresponding error in temperature (ΔT) that would result if the CVD result is correct and the measured resistance is used.

| ISF PRT	TTHR1	CVD fit	Deviation	ΔT
°C	Ω	Ω	Ω	C
-60.028	37.979	37.987	-0.008	-0.047
-50.043	39.997	40.001	-0.004	-0.023
-40.047	42.010	42.011	-0.001	-0.009
-30.058	44.015	44.014	0.001	-0.001
-20.076	46.011	46.011	0.000	+0.001
-10.088	48.003	48.002	0.001	-0.000
-0.101	49.988	49.988	0.000	-0.003
9.889	51.968	51.969	-0.001	-0.005
19.873	53.942	53.943	-0.001	-0.003
29.866	55.914	55.913	0.001	+0.006

The CVD equation (1) can then be used to calculate resistance values at specific temperatures for use during the on-board calibrations.. The following table shows the values that result from (1) using the fit to the ISF calibration:

Table 2: Corresponding values of temperature and resistance determined from Eq. (1) using the fit parameters determined from the 2012 ISF calibration. These would be appropriate values to use during on-board calibration.

Temperature, °C	Resistance, Ω
-70	35.971
-60	37.994
-50	40.010
-40	42.021
-30	44.027
-20	46.026
-10	48.020
0	50.008
10	51.991
20	53.968
30	55.939
40	57.905

ISF Calibration of 8 March 2011

Comparison to the calibration of the same sensor a year earlier provides an indication of the stability of the sensor. The fit to those measurements gave $R_0 = 50.076$ and $\alpha = 0.003754$. The latter is a somewhat larger deviation than expected from the nominal 0.003925 and the 0.0039128 from the 2012 calibration. The following figure shows that this calibration differs significantly (by up to 4C) from the 2012 calibration and the departure is largest at low temperature. The inconsistency of this calibration with the CVD equation also suggests that errors occurred at the low temperatures.
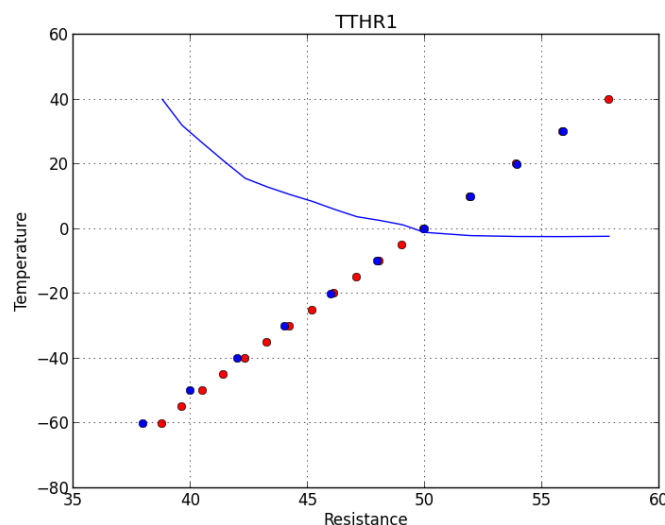

In this figure, the red dots are the 2011 calibration and the blue ones the 2012 calibration. The blue line shows the error that would result from using the 2011 calibration, multiplied by a scale factor of 10, if the 2012 calibration is the correct answer. (I.e., the departure is about 4C at the lowest temperature and lowest resistance.)

Because of the rather large difference at low temperature and the inconsistency with expected PRT behavior, I think it is best to discount this calibration rather than assume that the probe itself changed.

## RAF Calibration of 3 Mar 2011, Low-T Bath

The CVD coefficients for this calibration are 50.021 and 0.003665, so the sensitivity coefficient α is significantly smaller than the expected value of 0.003925. The following plot shows that this is rather inconsistent with the ISF 2012 calibration, and use of this calibration would lead to significant errors at low temperature if the 2012 ISF calibration is correct, and this calibration would produce temperature readings too low by up to 5C (although only by about 3C at -50, the usual low-T range for total temperature in GV flight).
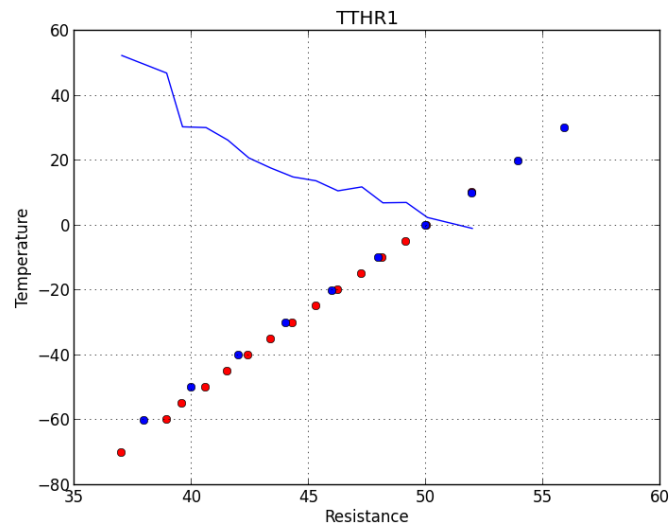
Red dots: RAF calibration in the low-T bath, 3 Mar 2011. The blue dots are thoe measurements from the ISF 2012 calibration, and the blue line is the temperature error (scaled by a factor of 10) that would result from using the 3 Mar 2011 calibration if the ISF calibration is correct.

RAF Calibration of June 2010, "Old Bath"

The CVD fit parameters for this calibration are 50.18 and 0.003715. The following figure shows this calibration is comparison to the 2012 ISF calibration, and shows that significant errors would result from the use of this calibration if the 2012 ISF calibration or the predictions of the CVD equation are correct. The error is up to 3C at -30C.
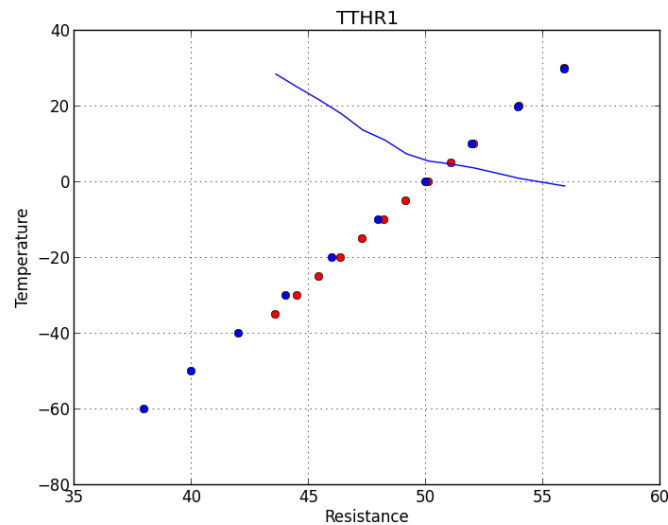
Red dots: RAF Calibration of June 2010, old bath. Blue dots: ISF calibration of 2012. Blue line: error that would result from using this calibration, if the 2012 calibration is correct.

RAF Calibration of March 2009, Old Bath?

For this calibration the CVD coefficients are 50.216 and 0.003708. These are reasonably consistent with other RAF calibrations but not with the 2012 ISF calibration or expectations from the CVD equation. The plot for this calibration, in similar format as those for other calibrations, is shown below. As for most of the other calibrations, significant errors (up to 4C) would result from use of this calibration, if the ISF 2012 calibration is correct.
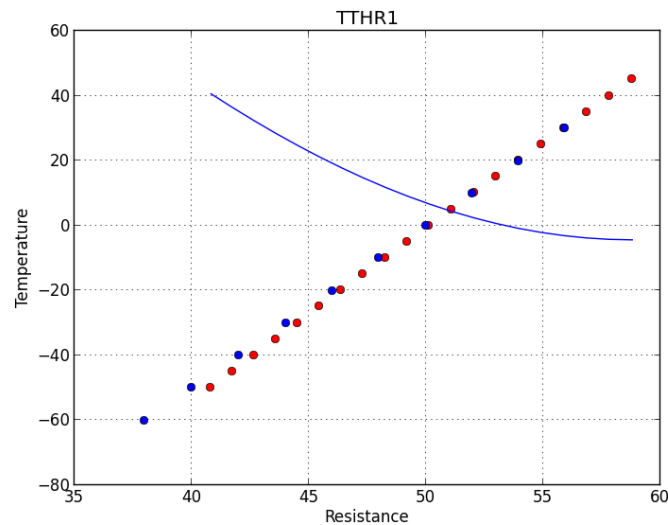
Red dots: RAF calibration of 2009-03; blue dots: ISF calibration of 2012. Blue line: error that would result from use of this calibration if the 2012 ISF calibration is correct.

Summary, Bath Calibrations

The sensitivity coefficient (formally, the temperature coefficient of resistance) determined from the bath calibrations is consistently low compared to the expected value, except for the 2012 ISF calibration, as shown in the following table:

Calibration	α
CVD and Goodrich value	0.003925
ISF 2012	0.003912
ISF 2011	0.003754
RAF Cold-T bath Mar 2011	0.003665
RAF old bath 2010-6	0.003715
RAF cold bath 2010-6	0.003754
RAF old bath 2009-03	0.003708

Except for the 2012 ISF result, these coefficients appear suspiciously small and will lead to errors of 4C or more at the lowest temperatures measured by the GV, if the 2012 ISF calibration is correct. That appears to me to be the favored interpretation because of the similarity between the measured value of α and the value expected for a PRT. This coefficient can exhibit some variability as is higher for higher purity of platinum and absence of strain in the element. Some PRT sensors are designed commercially to have sensitivity coefficients of 0.00385, and some high-quality PRTs have also been made with coefficients of about 0.0039. Lower coefficients such as those shown

for the RAF calibrations are clearly inconsistent with expectations for a high-quality PRT, and the last result (2012) suggests that the value has not decreased from damage or degradation but instead results from mis-measurement.

It would be interesting to compare these results to the DLR and NIST calibrations.

Tentative Recommendations:

1. Stop using repeated calibrations in the baths, which are more likely to introduce errors. Instead, periodically check that the sensor has not changed significantly, but use either the CVD equation with nominal values or the CVD equation with values from the 2012 ISF calibration unless there is evidence that the probe has changed significantly. The RAF calibrations are consistent enough that they could be used for monitoring for change, but they should not be used for determining resistance values for the onboard calibration.

2. Confirmation of the 2012 ISF calibration would be useful, because it is an outlier vs other calibrations even though it appears to be most consistent with CVD. Evidence from the NIST and DLR calibrations would be useful in this regard.

3. A new temperature scale was introduced in 1990 that affects measurements such as this. It goes by the name ITS-90 and is described in NIST Tech Note 1265. A somewhat incomplete study of this suggests that the differences it might introduce are <0.1°C in the most extreme cases we will encounter, so I have not included these changes for now. At some time it may be worth considering more carefully how the redefinition of the temperature scale (which brings it more in line with the thermodynamic scale and so better for our purposes) might affect our measurements. There are services that will provide calibration to IST-90 temperature, and it may be worth sending a sensor to a company for such calibration. We need to specify the temperature range of interest to avoid having the expense of a full calibration over the IST-90 range. Key thresholds are 29C (the melting point of gallium) and -38C (the triple point of mercury). Extending below 38C may require going to the triple point of Argon, which is -189C, and it may be impractical and unwise to expose the sensor to such a low temperature.

4. If further investigation supports the 2012 ISF calibration and the direct use of the CVD equation with nominal coefficients, it would then be best to use the values in Table 2 above for the onboard calibrations. The calibrations still incorporate the performance of the preamp and other circuitry, which may introduce non-linearities. The following points apply to these calibrations:

   (a) If resistance box settings restrict entries to increments of 0.01Ω, this is not a serious concern because the error introduced by an error of 0.005Ω corresponds to an error in temperature of only about 0.03C.

(b) Present calibrations show complex variations not represented well by power-law equations except at high order. Use of the present quadratic form introduces significant error vs the calibration points, and some other approach should be used. Interpolation, either linear or Lagrange, or a different functional form should be explored. This would be a complication in nimbus but appears to be needed.

(c) As for the bath cals, developing a good calibration for a particular A-D board and staying with that calibration unless there is clear evidence of a change would be preferable to the current practice of frequently changing the calibration based on the latest result. That probably introduces frequent errors and variability from project to project that is not real.

Inverting Existing Calibrations

Assume we have the set used for cal: {Ti, Ri}. The calibration then gives {Ti, Vi} via {Ri, Vi}. If, instead, should have used {Ti', Ri} where Ti' is e.g. from CVD

1. need Ri data from calibration. These are in the email from rbf on 2/22

2. change Ti -> Ti' and re-fit to get {Ti', Vi}

3. already have the resistances in python TCal.py

4. problem is that an inversion is needed: Have r=CVD(T), need T=CVD^-1(R). Need to invert the Callendar-Van Dusen equation, Eq. (1). A suitable rearrangement of (1) gives a form that can be the basis for an iterative solution (verified to converge to machine double-precision is 5-6 iterations):

$$T = \left(\frac{R_T}{R_0} - 1\right) \frac{1}{\alpha\left(1 + (\delta/1.e2)\right)} + \frac{1}{(1 + \delta/1.e2)} \left\{ \frac{\delta}{1.e4}T^2 - \frac{\beta}{1.e6}T^3 + \frac{\beta}{1.e8}T^4 \right\}$$

5. Then, for the pre-PREDICT cal, the adjusted temperatures that correspond to the resistances used are {-65.32, -56.38, -47.41, -38.09, -28.48, -18.98, -9.67, 0.08, 9.96} instead of {-70, -60, ... 10}. The fit to these, replacing (-89.225, 25.933, -0.078795), is (-82.44, 22.71, 0.297). The standard error for this fit is 0.024, so (unlike the previous calibration) the quadratic fit is adequate.

The following plot compares the two calibrations and shows that, at low temperature, the differences are substantial. Even at normal GV total temperatures (usually -50C or higher), the difference can be around 2C.
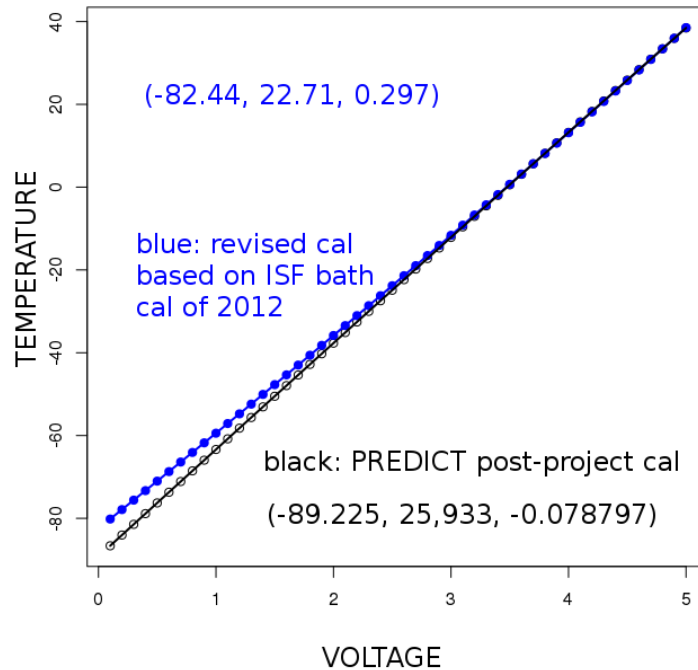
My plan now is to calculate a new temperature for the PREDICT ferry flight #1 by using the old cal to calculate the old voltage, then use the new cal to determine the new temperature, and see how that temperature works in the LAMS analysis.