19 May 2009

TO: File
FROM: Al Cooper
SUBJECT: A/D Calibration

0.0.1 General Comments

A new calibration was done for the 0-5V range of the A/D, using a wider temperature range, 16 different temperatures, and with higher-resolution recording of the board temperature than done before. The recorded temperature was that measured by the A/D board and so is the appropriate temperature that can represent the temperature dependence during operational measurements.

Three features of the calibration data affect how the calibration is determined:

1. The calibration data are "measured" vs "true" voltages, with the measured voltage determined from $V_m = 5C/2^{16}$ where C is the recorded count from the A/D. There are substantial variations, channel-to-channel, in the calibration, so the voltage calibration needs be considered before the data are averaged over channels to determine the temperature variation or to identify outliers.

2. The measurements for the first channel (TTHL2) for the second temperature (-9.8°C) appeared anomalously close to the results for the third temperature (-5.3°C), so there was probably an error made for this temperature set. These were excluded from the fits that follow.

3. For all channels, the temperatures 30°C and higher exhibited a strange behavior as shown in the following figure: Successive voltages alternated above and below the best-fit lines (linear or 4th-order) by an amount that corresponded to several counts (<5). For lower temperature, this behavior was not present and the fits were much better. I don't understand the source of this and have proceeded to use the data to determine calibrations for all measured temperatures. However, normal operating temperature is above 30°C so the source of this variation remains a (minor) concern.

There were two questions to be addressed using these calibration data: (1) is there significant non-linearity in the calibration at fixed temperature; and (2) how can the temperature dependence of the A/D be incorporated into data processing? The first figure shows that, for the 0-5V range, the non-linearity is insignificant compared to the more serious picket-fence behavior, and in any case will amount to only a few counts, so a linear calibration appears adequate. This note will focus on the temperature dependence and use a linear fit to represent the voltage conversion to counts.

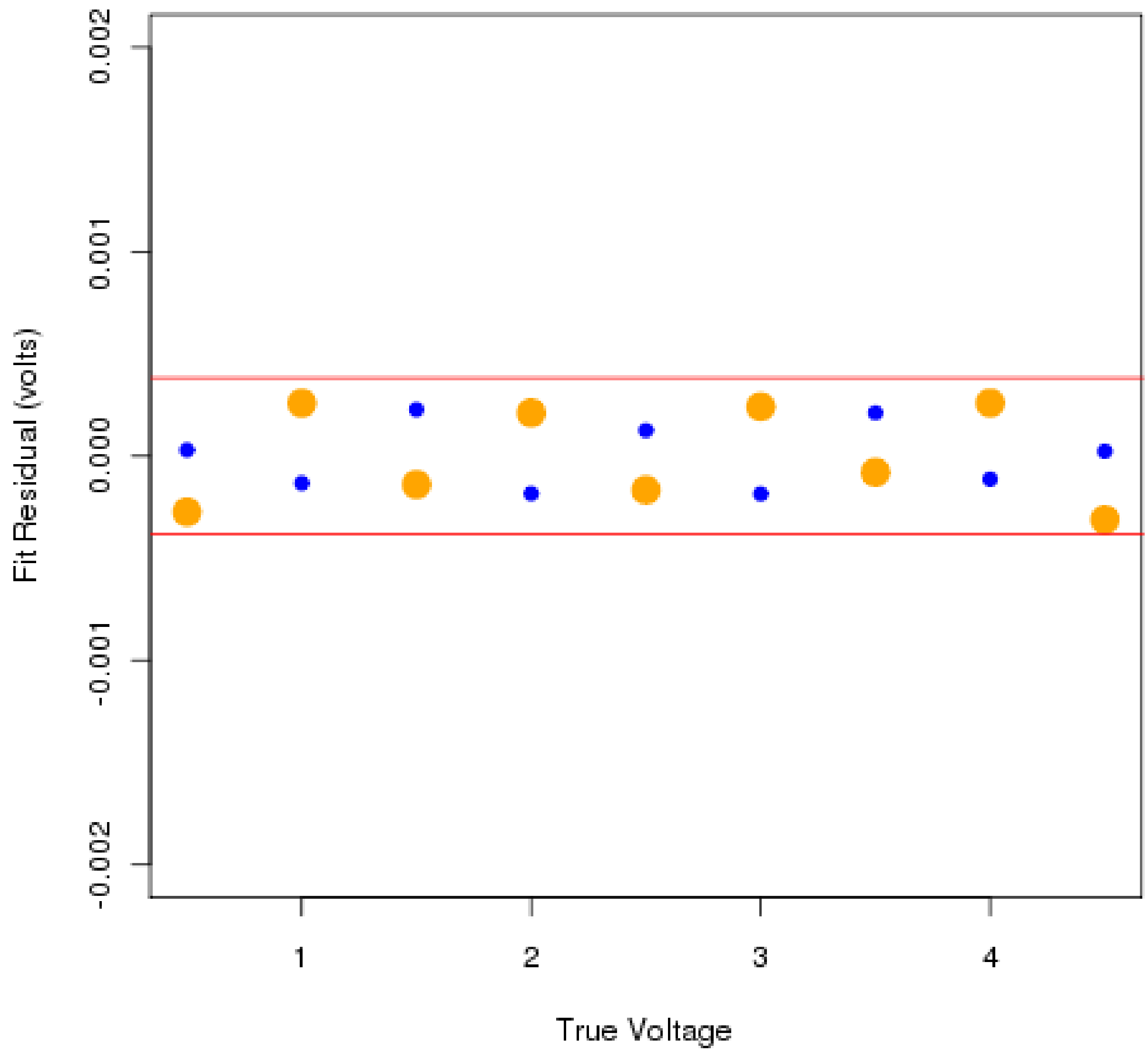

Figure 1: Residuals for fits to the volbge calibration, for a linear fit (large orange dots) and a 4th-order fit (small blue dots), as a function of the true voltage, for the first channel. The measurements for T=40°C were used for this plot. The red lines show deviation limits corresponding to ±5 counts. All four channels showed this behavior, for T>40°C.

0.0.2 The approach

The 12th temperature, near 40°C, was taken as a reference, and deviations in voltage for other temperatures were calculated to determine a functional relationship. The approach taken was as follows:

1. For each channel, determine a voltage calibration at the reference temperature (in the form $V_t = f(V_m)$ where V_t is the true voltage and V_m is the voltage determined from the recorded counts as described above. This is the fit that is needed to determine true voltage values from the measurements. For fits of higher order, this avoids having to invert the fit as would be necessary if the measured voltage were determined as a function of the true voltage, as would be a more usual approach.

2. For a given true voltage V_t, determine how the measured voltage changes with temperature, and represent that change by $\delta(V_t, T) = V_m(V_t, T) - V_m(V_t, T^*)$ where T^* is the selected reference temperature. If the deviation function δ can be determined as a function of true voltage and temperature, then the calibration function can be expressed in the form $V_t = f(V_m(V_t, T) - \delta(V_t, T))$.

3. The temperature dependence determined from the calibration can be used to find a functional representation of the voltage changes with temperature. Figure 2 shows the variations with temperature of the measurements for all nine voltages, from 0.5 V (cyan dots) to 4.5 V (orange dots). Similar plots for all four channels looked the same, so initially the four were averaged and used to determine a channel-independent temperature correction by fitting quadratic polynomials to the data for each temperature.

4. Figure 3 shows a sample calibration (for 2.5V). To check if a single calibration could represent all voltages after normalization, Fig. 4 was constructed by combining the fits for all 9 true voltages. There is significant variation, especially for the lower voltages, that will make it necessary to use a voltage-dependent representation of the function $\delta(V_{T,}T)$.

These results could be used in processing, for example, in this way:

1. Measured quantities are V_m and T.

2. The calibration can be represented by the functions $f_n(V_m, T^*)$ and $\delta(V_t, T)$. The index n refers to the channel number, so there will be a calibration function f for each channel and there will be nine functions δ_j for each of the true voltages.

3. The function δ is a continuous function of temperature, but the dependence on V_t must be represented in some way. V_t isn't known until the calibration is applied, but adequate accuracy for determining δ could be obtained by using the calibration for T^* to determine a first estimate of V_t. That can be used to determine the functions δ_{j-1} and δ_j bracketing the actual V_t, and they can then be used with linear interpolation between them to determine the value of δ. That value leads to an estimate of V_t that could be refined by iteration if necessary.

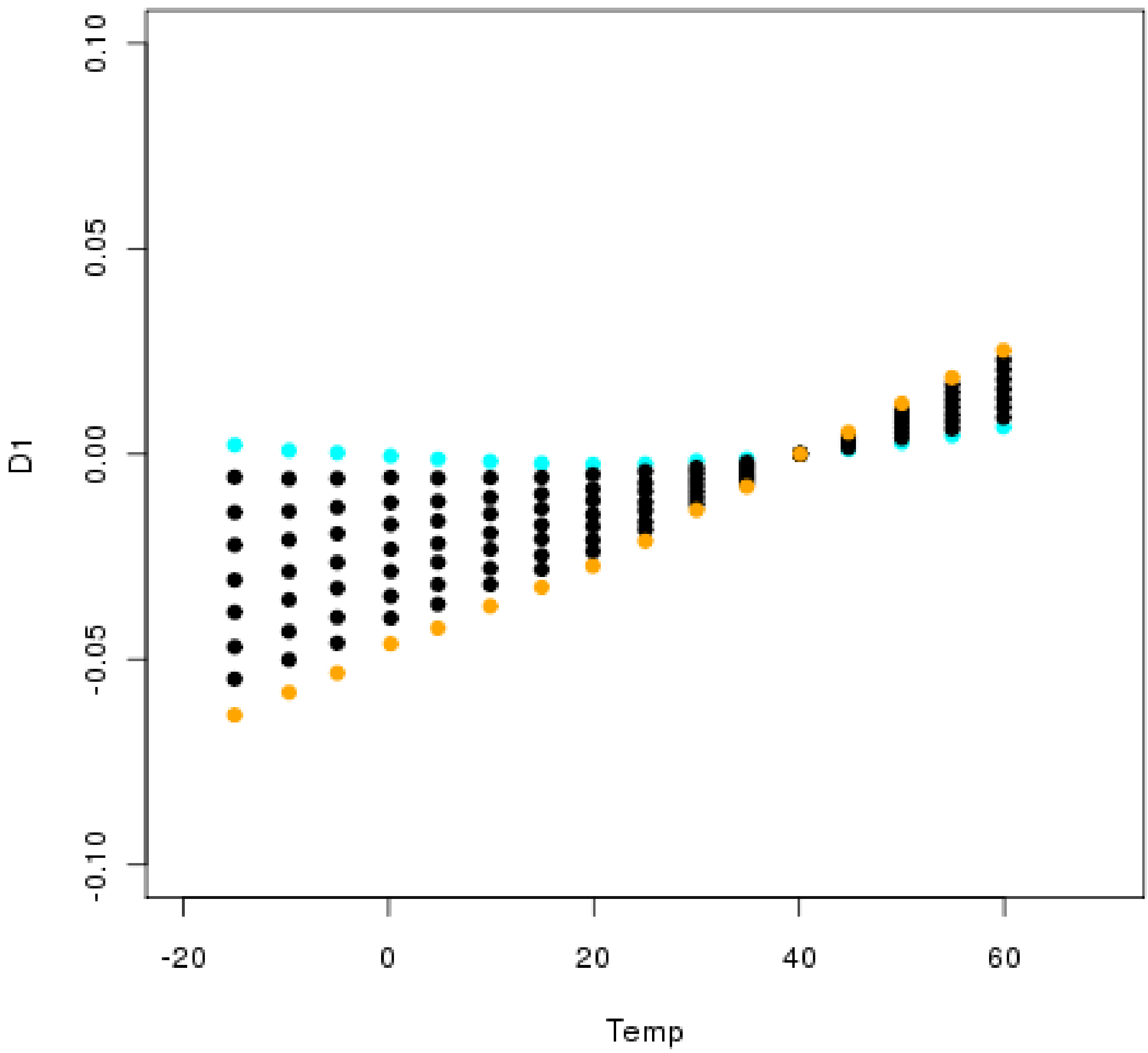

Figure 2: Deviations in measured voltage as a function of temperature, relative to measurements at 40°C, for the 9 voltages from 0.5 (cyan) to 4.5 (orange) V. This is for channel 1 (TTHL1), but all four channels are similar.

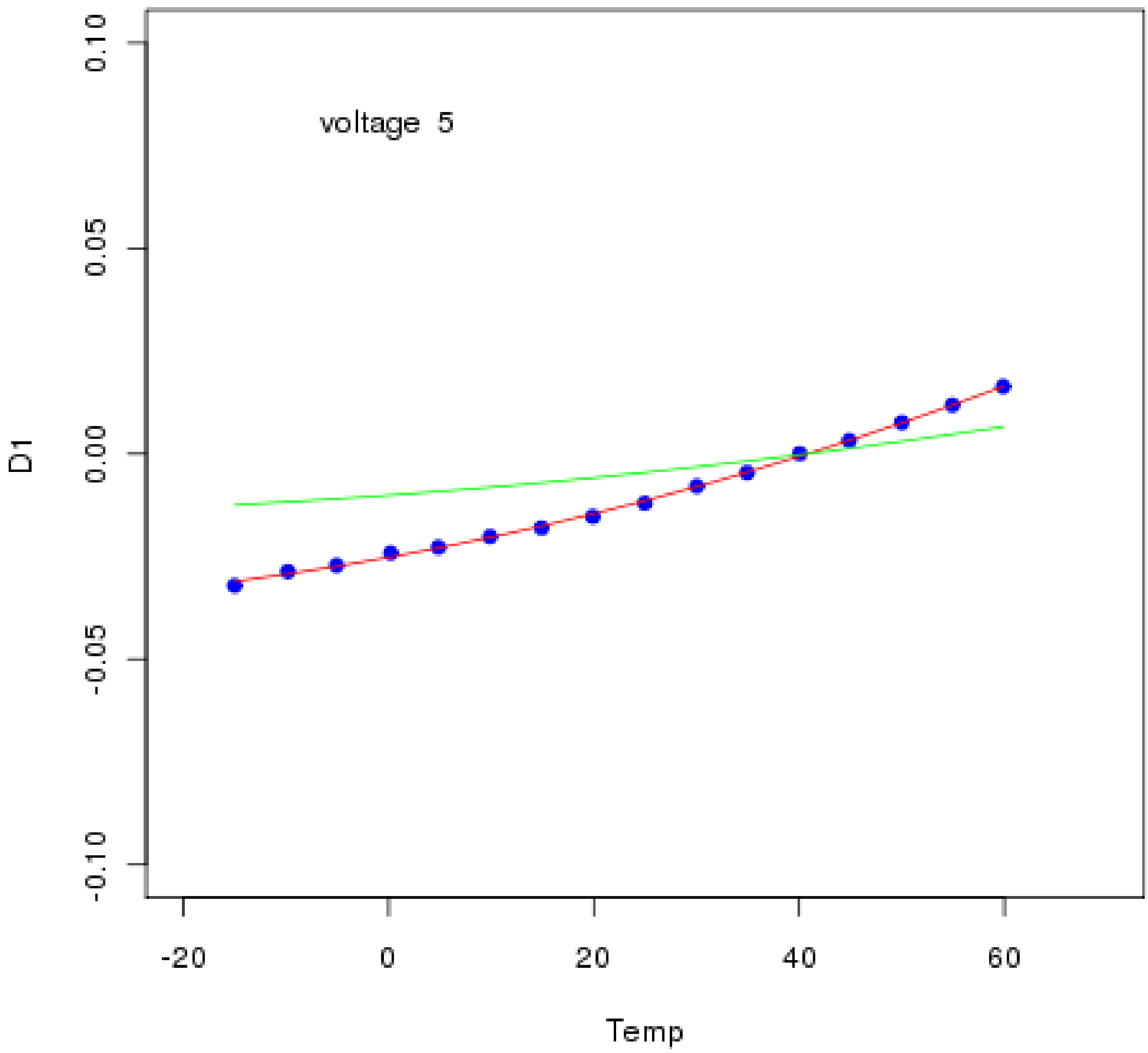

Figure 3: The average temperature dependence for the 2.5V measurements for all channels (blue dots) and the quadratic fit to the data (red line). The green line shows the same fit after normalizing by the true voltage, to obtain a normalized representation of the temperature variation.

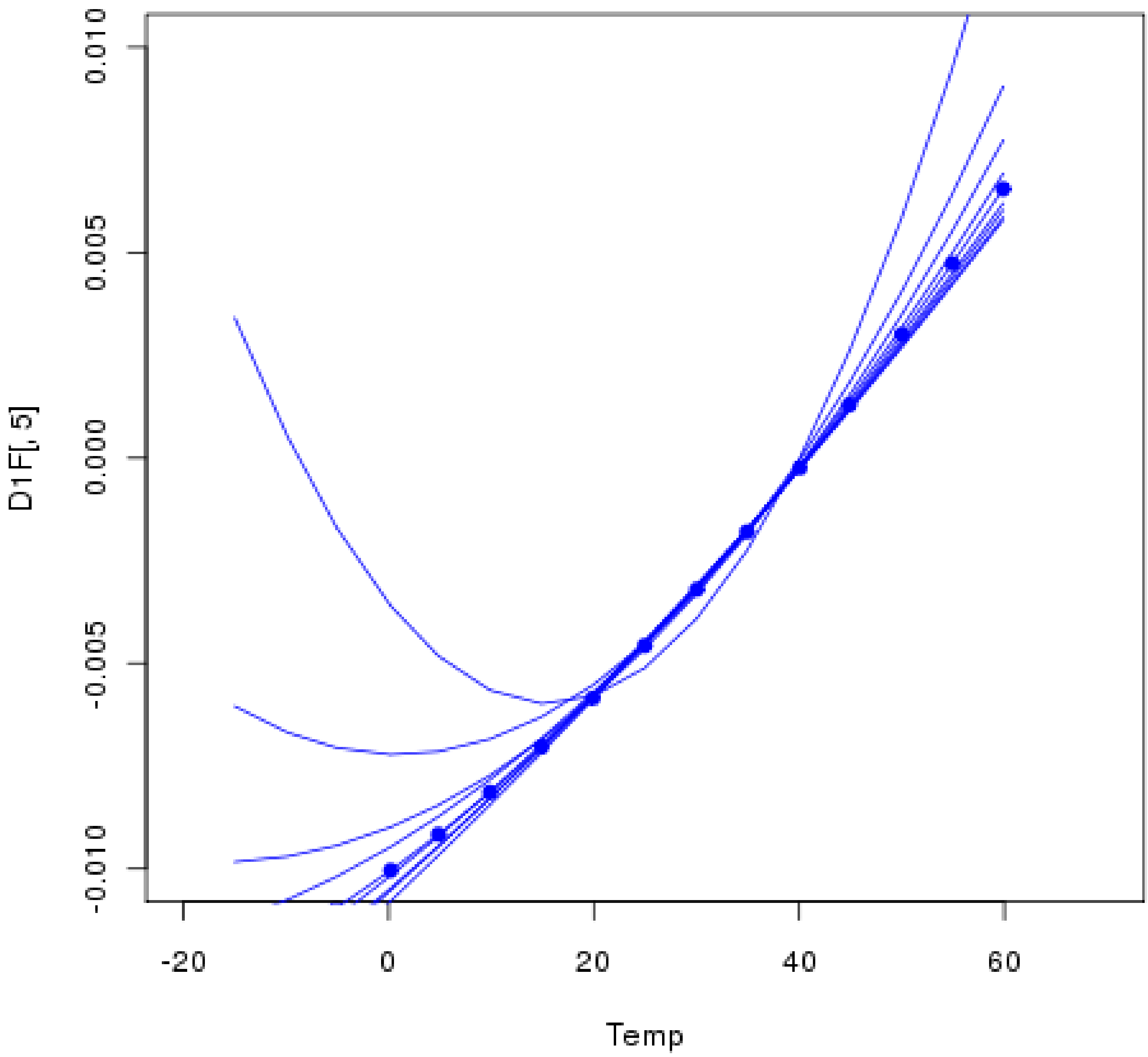

Figure 4: Combining the normalized calibration results for all nine "true" voltages. The blue dots represent the calibration for 2.5V, and the curves showing the greatest departure from the mean of other measurements and the greatest curvature are those for the lowest voltages.

The following tables contain the fit coefficients determined from the calibration:

Table 1: True voltage as a function of measured voltage, determined for T=40°C:

$$V_t = C_0 + C_1 V_m + C_2 V_m^2 + C_3 V_m^3 + C_4 V_m^4$$

Channel	C_0	C_1	C_2	C_3
0 [TTHL2]	-0.07450442	1.09376087		
1 [TTHL1]	-0.3005923	1.1382920		
2 [TTHR2]	-0.2517544	1.1309289		
3 [TTHR1]	-0.1598545	1.1144908		

Table 2: Voltage deviation function δ for each of the true voltages $V_{t,j}$ used in the calibration: $\delta_j = V_m(V_{t,j}, T) - V_m(V_{t,j}, T*) = A_0 + A_1 T + A_2 T^2$

V_t	A_0	A_1	A_2
0.5	-1.768949e-03	-1.566086e-04	5.010940e-06
1.0	-7.218792e-03	-8.230977e-06	4.673119e-06
1.5	-1.351594e-02	1.499760e-04	4.499533e-06
2.0	-1.900132e-02	2.957921e-04	4.223245e-06
2.5	-2.520223e-02	4.508312e-04	4.068070e-06
3.0	-3.063259e-02	5.960058e-04	3.779620e-06
3.5	-3.680750e-02	7.507708e-04	3.620800e-06
4.0	-4.228688e-02	8.962391e-04	3.362695e-06
4.5	-4.873845e-02	1.054765e-03	3.243052e-06

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