Calibration Coefficients and Thermistor Selection

ABSTRACT

Calibration coefficients for thermistors are determined by the Steinhart-Hart equation for a given thermistor, temperature region, and bias current. The Steinhart-Hart coefficients provide the best curve fit depending on which part of the thermistor range is being used. This will vary based on which bias current is supplied to the thermistor. Multiple options for bias current settings require multiple sets of calibration coefficients for the thermistor.

INTRODUCTION

Thermistors are devices whose resistance changes based on their temperature. The relationship between temperature and resistance is nonlinear, but well known. Thermistors are invaluable tools for accurately measuring temperature within a 50°C range of ambient temperature. A properly selected thermistor can measure temperature differences on the order of ±0.0005°C.

In order to properly choose a thermistor for a given application, a few factors must be taken into account. First, thermistors have a defined range of temperatures for which their behavior is characterized. This temperature range varies with the base thermistor resistance. Second, for most commercial controllers, there are two options for bias current, either 10μA or 100μA. [Variable bias current controllers introduce more noise into the sensor measurement.] These bias currents have been chosen to optimize the signal to noise ratio (SNR) across the range of readable voltages. Finally, there is a lower limit on voltages that can be accurately read. Thus, choosing a thermistor requires knowledge of the temperature range that is to be measured, the bias current available from the controller, and the lowest voltage that can accurately be recorded.

The voltage, current, and resistance are related through Ohm's law,

$$V = IR\,, \qquad (1)$$

where V is the voltage (in Volts), I is the current (in Amps), and R is the resistance (in Ohms).

The temperature is related to the resistance through the Steinhart-Hart equation (third order approximation),

$$\frac{1}{T} = A + B[\ln(R)] + C[\ln(R)]^3\,, \qquad (2)$$

where T is the temperature (in Kelvin), R is the resistance (in Ohms), and A, B, C are the Steinhart-Hart coefficients. The Steinhart-Hart coefficients are determined on a case-by-case basis, as they depend on the thermistor being used, the temperature range under consideration, and the bias current being supplied to the thermistor.

The third order approximation to the Steinhart-Hart equation provides the optimal compromise between computational requirements and best fit. The inclusion of a square term would be more computationally taxing (extra appearance of R), and worsens the fit, so the square term is discarded. For more details regarding the quantitative nature of the fits, please see **Reference 2**.

PROPERLY CHOOSING A THERMISTOR

In practice, the method of measuring the temperature of a thermistor is achieved by measuring the voltage difference across the thermistor. The bias current driving the resistor is known, the voltage measured, so **Eq. 1** is used to determine the resistance. **Eq. 2** is then used to calculate the temperature of the thermistor.

The resistance as a function of temperature is known for commercially available thermistors, and is given in their data sheets. The user has the option of which bias current to send to the thermistor. For a given thermistor, there will be an overlap region, where both the 10μA and 100μA bias currents will work. The reason that there are different calibration coefficients for the same thermistor is simple: one set of coefficients curve fit to the 10μA bias current range, while the other set curve fit to the 100 μA bias current range.

Figure 1 below shows the resistance of two Wavelength thermistors as a function of temperature. The TCS610 is a 10kΩ thermistor, while the TCS651 is a 100kΩ thermistor.

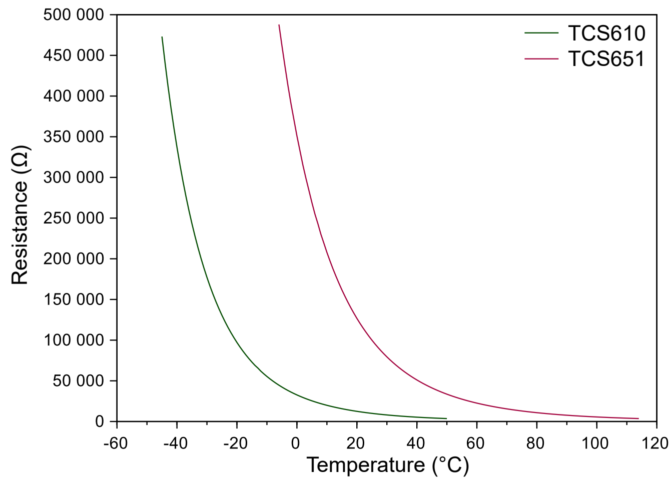

Figure 1. TCS610 and TCS651 resistance versus temperature.

Note that the relationship between the resistance and temperature is nonlinear for both cases.

The bias current overlap is shown in **Figure 2** and **Figure 3**. For the TCS610, the overlap goes from -8°C to 13°C. For the TCS651, the overlap spans 41°C to 67°C.

The vertical axis on both plots below (Voltage) ranges from 0 to 5V. This is a common sensor input range for OEM products. The range for instruments, however, commonly ranges from 0 to 10V.

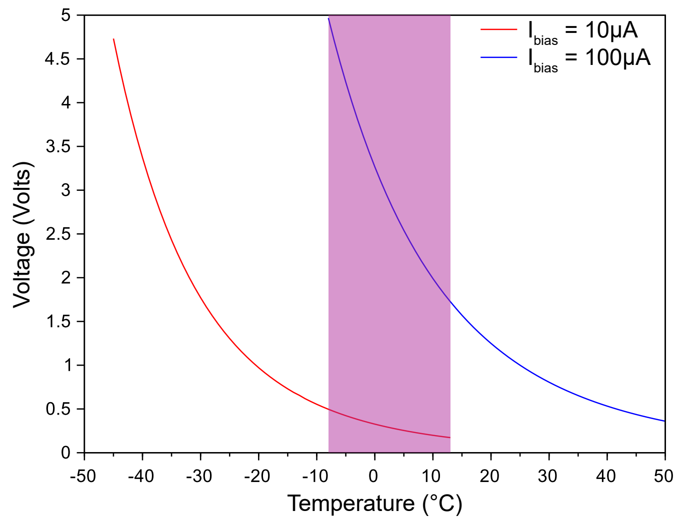

Figure 2. Voltage as a function of temperature for two available bias current settings for the TCS610 thermistor. The overlap region between the two is shaded in purple.

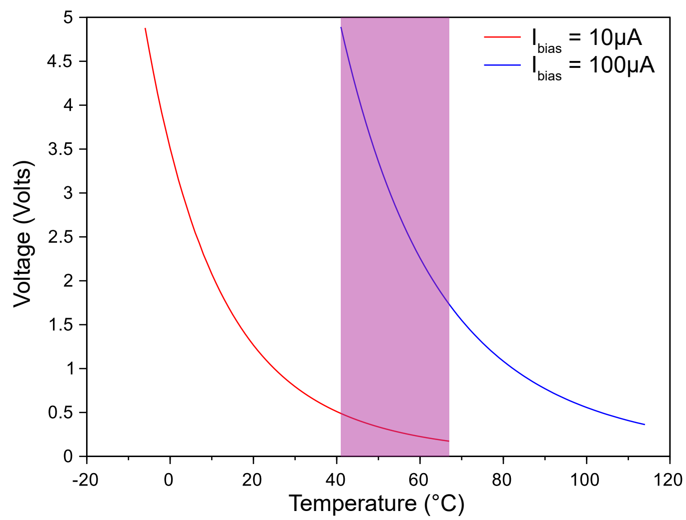

Figure 3. Voltage as a function of temperature for two available bias current settings for the TCS651 thermistor. The overlap region between the two is shaded in purple.

EXAMPLE 1:

Consider a case where temperature measurement in the range of ±40°C is desired. Wavelength offers a thermistor that spans that range (TCS610). Within this temperature range, there will need to be a bias current change (around 0°C), see **Figure 2**. From the range -40 to 0°C, the 10µA bias current would be chosen. This will give voltage readings from 3.372V (at 40°C) to 0.326V (at 0°C). For the positive values of temperature, we would choose to use the 100µA bias current. Correspondingly, we would measure voltages of 3.266V and 0.532V at 0°C and 40°C, respectively. Doing this, all of the measured voltages would be high enough to be measured accurately using one sensor across the entire range.

Example 1 is an indicator of the importance of bias current when dealing with thermistors. Generally, a temperature range would be selected such that a bias current change is not required if designing an OEM product. Instruments auto-range the bias current. As seen from Ohm's Law, with the resistance being fixed, if we increase the current supplied by a factor of 10, the voltage must also change by a factor of 10. Thus, the bias current can be used to boost (or lower) the voltage being read directly.

RESISTANCE VERSUS TEMPERATURE RESPONSE
TCS610 10 kΩ THERMISTOR @ 25°C

10 µA TEMPERATURE RANGE: -45 to +13°C
100 µA TEMPERATURE RANGE: -8 to +50°C

TEMP (°C)	R_T (Ω)	VOLT (V) (10 µA)	VOLT (V) (100 µA)
-45	473200	4.732	
-44	441800	4.418	
-43	412600	4.126	
-42	385600	3.856	
-41	360500	3.605	
-40	337200	3.372	
-39	315500	3.155	
-38	295400	2.954	
-37	276700	2.767	
-36	259300	2.593	
-35	243100	2.431	
-34	228000	2.280	
-33	213900	2.139	
-32	200800	2.008	
-31	188600	1.886	
-30	177200	1.772	
-29	166500	1.665	
-28	156600	1.566	
-27	147300	1.473	
-26	138600	1.386	
-25	130500	1.305	
-24	122900	1.229	
-23	115800	1.158	
-22	109200	1.092	
-21	103000	1.030	
-20	97130	0.971	
-19	91660	0.916	
-18	86540	0.865	
-17	81730	0.817	
-16	77220	0.772	
-15	72980	0.729	
-14	69000	0.690	

TEMP (°C)	R_T (Ω)	VOLT (V) (10 µA)	VOLT (V) (100 µA)
-13	65260	0.652	
-12	61750	0.617	
-11	58450	0.584	
-10	55340	0.553	
-9	52420	0.524	
-8	49670	0.496	4.967
-7	47080	0.470	4.708
-6	44640	0.446	4.464
-5	42340	0.423	4.234
-4	40170	0.401	4.017
-3	38120	0.381	3.812
-2	36200	0.362	3.620
-1	34380	0.343	3.438
0	***32660***	***0.326***	***3.266***
1	31040	0.310	3.104
2	29510	0.295	2.951
3	28060	0.280	2.806
4	26690	0.266	2.669
5	25400	0.254	2.540
6	24180	0.241	2.418
7	23020	0.230	2.302
8	21920	0.219	2.192
9	20890	0.208	2.089
10	19900	0.199	1.990
11	18970	0.189	1.897
12	18090	0.180	1.809
13	17260	0.172	1.726
14	16470		1.647
15	15710		1.571
16	15000		1.500
17	14320		1.432
18	13680		1.368

TEMP (°C)	R_T (Ω)	VOLT (V) (10 µA)	VOLT (V) (100 µA)
19	13070		1.307
20	12490		1.249
21	11940		1.194
22	11420		1.142
23	10920		1.092
24	10450		1.045
25	***10000***		***1.000***
26	9572		0.957
27	9165		0.916
28	8777		0.877
29	8408		0.840
30	8056		0.805
31	7721		0.772
32	7402		0.740
33	7098		0.709
34	6808		0.680
35	6531		0.653
36	6267		0.626
37	6015		0.601
38	5774		0.577
39	5545		0.554
40	5326		0.532
41	5116		0.511
42	4916		0.491
43	4725		0.472
44	4543		0.454
45	4368		0.436
46	4201		0.420
47	4041		0.404
48	3888		0.388
49	3742		0.374
50	3602		0.360

Figure 4. Image of the TCS610 thermistor datasheet. The two bias current ranges described in Example 1 are highlighted in yellow (10µA) and pink (100µA).

Additionally, how the voltage accross the thermistor is measured varies depending on the temperature controller. At Wavelength Electronics, components and modules are analog devices, while instruments have analog-to-digital converters built-in.

When using components or modules, it is best to stay 1V away from the upper voltage limit, and 0.5V away from the lower voltage limit. Coming too close to the limits that are set by the unit is not advised, as issues such as non-linearity and reverse poling can skew measurements, or damage the unit.

When using instruments, it is recommended that a 0.5V buffer is given to both the upper and lower maximum voltages. If the voltage comes too near the limit, issues arise from the analog-to-digital converters in the circuitry inside the instrument. These issues may skew the measurement, and give inaccurate temperature readings.

These buffers are not standard for all units, but are basic guidelines that apply to most scenarios. Depending on the unit chosen, the buffer zone may be closer to the limit. See the corresponding datasheet of the driver being used for more information.

EXAMPLE 2:

Consider a case where temperature measurement in the range of ±5°C is desired. Again, we could use the TCS610 thermistor for this application. From the TCS610 datasheet, we see that for this temperature range, we could use either a 10µA or 100µA bias current. Both would work well in this case. The choice depends on the ability to measure voltages. If the volt-meter has the capability to measure voltages up to 5V, then the 100µA bias current would be a good choice (lower SNR). But, if the volt-meter can only measure voltages up to 4V, then the 10µA bias current would be the proper choice. See **Figure 5** for an illustration.

Example 2 shows why knowing what voltages you can accurately measure is important. This is another factor which determines which thermistor is proper for your application, and which bias current option you should choose.

TEMP (°C)	R_T (Ω)	VOLT (V) (10 µA)	VOLT (V) (100 µA)
-5	42340	0.423	4.234
-4	40170	0.401	4.017
-3	38120	0.381	3.812
-2	36200	0.362	3.620
-1	34380	0.343	3.438
0	***32660***	***0.326***	***3.266***
1	31040	0.310	3.104
2	29510	0.295	2.951
3	28060	0.280	2.806
4	26690	0.266	2.669
5	25400	0.254	2.540

Figure 5. TCS610 datasheet for ±5°C. Highlighting shows how voltage varies depending on the bias current chosen.

EXAMPLE 3:

Consider a case where temperature measurement at 50°C is desired. This falls into the usable range for many different thermistors. If the TCS10K5 (a 10kΩ thermistor) and the TCS651 (a 100kΩ thermistor) are both available, which is the correct choice? Both of the thermistors have 50°C in their temperature ranges for a 100µA bias current selection. The distinction comes when looking at the voltage output of the thermistors at 50°C. The TCS10K5 will yield a voltage of 0.360V (see **Figure 6**), while the TCS651 will output a voltage of 3.359V (see **Figure 7**). Thus, the TCS651 would be the correct choice for this scenario, since it gives a mid-range voltage output.

TEMP (°C)	R_T (Ω)	VOLT (V) (10 µA)	VOLT (V) (100 µA)
50	3602		0.360

Figure 6. TCS10K5 datasheet for 50°C.

TEMP (°C)	R_T (Ω)	VOLT (V) (10 µA)	VOLT (V) (100 µA)
50	33590	0.335	3.359

Figure 7. TCS651 datasheet for 50°C.

EXAMPLE 4:

Consider a case where keeping the load at a temperature of 10°C is critical. You have a TCS610 and a TCS651 thermistor to monitor the temperature. Which thermistor should you choose? In this case, the important parameter is the slope of the graph ($\Delta V/\Delta T$) around 10°C, as shown in **Figure 2** and **Figure 3**. The steeper the slope, the more sensititive the voltage response is at that point. The TCS651, which has the steeper slope, will be able to monitor voltage changes (and thus temperature changes) with greater resolution than the TCS610.

Alternatively, looking at the datasheet, you can back out the same information by looking at the resistance as a function of temperature. The bigger the difference in *R* between two temperature increments, the more sensitive the measurement will be. This is illustrated in **Table 1** below. The ΔR/ΔT column shows the sensitivity of the thermistor for a one degree temperature change. For this temperature choice, the TCS651 has more than an order of magnitude more sensitivity.

TCS610			**TCS651**		
Temp (°C)	**R_T (Ω)**	**ΔR/ΔT (Ω/°C)**	**Temp (°C)**	**R_T (Ω)**	**ΔR/ΔT (Ω/°C)**
9	20,890	990	9	219,000	11,200
10	19,900		10	207,800	
11	18,970	930	11	197,600	10,200

Table 1. The sensitivity (ΔR/ΔT) of both a 10kΩ and a 100kΩ thermistor shown about 10°C. The 100kΩ thermistor is more sensitive in this temperature region.

HELPFUL HINTS

- Know the required operating temperature. This will allow you to determine other operating parameters (bias current and measurable voltage) prior to selecting a thermistor.
  - Temperature region and experimental parameters impact thermistor choice.
  - Commercially available products generally have either a 10μA or 100μA bias current option.
  - Measurable voltage depends on the volt-meter being utilized and internal error circuit.
- If using an OEM product, select a temperature range that will avoid the need for a bias current change. Instruments auto-select the bias current range.
- The desired temperature range should be in the middle of one of the bias current ranges. For example, if you wish to measure temperature at 20°C, choose a thermistor that has a bias current range of 0 to 40°C, not one that has a range of -20 to 20°C.
- Select a temperature range that has high enough voltages at the lower temperature limit, and low enough voltages at the higher temperature limit (volt-meter dependent choice).

SUMMARY

There are multiple sets of calibration coefficients for thermistors due to their wide operating range. As the temperature increases, the resistance decreases. For a fixed bias current, the decreasing resistance causes the measured voltage to decrease. Thus, at a specified point, the bias current must be increased to allow the voltage across the thermistor to be measured accurately.

The calibration coefficients are determined by the Steinhart-Hart equation. Each thermistor has a different operating range, and different sets of calibration coefficients.

One set of calibration coefficients are determined by a curve fit for a 10μA bias current, and the other set are determined by a curve fit for a 100μA bias current.

USEFUL REFERENCES

1. Thermistor Basics
2. Calibration curves for thermistors. Steinhart, John S. & Hart, Stanley R. *Deep Sea Research and Oceanographic Abstracts* **15** (1968)
3. TCS610 Product Page
4. TCS651 Product Page

KEYWORDS
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