In-situ Temperature Calibration Capability for Dimensional Metrology

Prem Rachakonda[1]
prem.rachakonda@nist.gov

Dan Sawyer[1]
daniel.sawyer@nist.gov

Bala Muralikrishnan[1]
bala.muralikrishnan@nist.gov

Chris Blackburn[1]
christopher.blackburn@nist.gov

Craig Shakarji[1]
craig.shakarji@nist.gov

Gregory Strouse[2]
gregory.strouse@nist.gov

Steve Phillips[1]
steven.phillips@nist.gov

[1]Semiconductor and Dimensional Metrology Division
[2]Sensor Science Division

National Institute of Standards and Technology
Gaithersburg, MD

Abstract: The Dimensional Metrology Group (DMG) at the National Institute of Standards and Technology (NIST) has developed a new in-situ temperature calibration system. This paper discusses the system components, an in-situ calibration procedure, the uncertainty sources involved in the calibration process, presents an uncertainty budget, and examines it with a Monte Carlo simulation. This system enables the DMG to perform quicker in-situ temperature calibration, at frequent intervals, with minimal downtime and provides better uncertainties in the dimensional measurements.

1. Introduction

The Dimensional Metrology Group (DMG) at the National Institute of Standards and Technology (NIST) has the capability to perform large range dimensional measurements in a facility called the Tape Tunnel. The Tape Tunnel is equipped with a 60 m long steel bench and a reference interferometer. Various artifacts and instruments, such as tape measures, optical cables,

laser trackers, laser distance meters etc. are calibrated against the reference interferometer. The relative uncertainty ($U_{k=2}$) in the displacement measurement is 2.4×10^{-7} [1].

A major component of this uncertainty is the uncertainty in measuring the temperature in the Tape Tunnel. There are 14 temperature probes installed along the length of the steel bench; two each at seven equidistant locations. One probe measures the air temperature and the other measures the material temperature (of the steel bench). Historically, calibrating these probes involved removing all the 14 probes and sending them to the NIST Thermodynamic Metrology Group. This process introduced a considerable amount of downtime to the DMG's measurement capabilities. This also introduced uncertainties due to a) variation in the contact geometry of the material probe with the steel bench during reinstallation, and b) variation in the resistances of the probe's cables due to pinching and/or elongation.

To address these issues, a new in-situ temperature calibration system was developed. This paper discusses the system components, an in-situ calibration procedure, the uncertainty sources involved in the calibration process, presents an uncertainty budget, and examines it with a Monte Carlo simulation.

2. Background

The accuracy of an interferometric measurement depends on the knowledge of the wavelength of light, which is a function of the refractive index of the air path of the laser. Any variations in the refractive index have to be applied to the calculation of the wavelength, to obtain a length measurement traceable to the International System (SI) of units. The factors that affect the refractive index of air are temperature, pressure, humidity and the composition of the gases in the air. The relationship between refractive index, temperature, pressure, and humidity is given by Edlen's equation [2, 3]. Among the parameters that affect the refractive index of air, temperature is the most critical, as shown in **Error! Reference source not found.**.

Parameter	Parameter change needed
Temperature	1.05 °C
Pressure	373 Pa ($\approx$ 2.8mm of Hg)
Relative Humidity	$\approx$ 100 %

Table 1. Parameter change needed for 10^{-6} variation in refractive index of air.

3. Thermistors and the Steinhart-Hart Equation

Thermistor probes are made out of doped polycrystalline ceramic materials that exhibit a large change in resistance for a relatively small change in temperature. These probes are highly stable, with a drift in the range of 5 m°C/year [4] to 20 m°C/year [5]. Though they are highly sensitive to temperature changes, they are non-linear and hence are used for a small range of temperature measurements, typically less than 10 °C.

Based on the relationship between their temperature and resistance, thermistors are categorized as Positive Temperature Coefficient (PTC) thermistors or Negative Temperature Coefficient (NTC) thermistors. The resistance of PTC thermistors increases with increasing temperature, whereas the resistance of NTC thermistors decreases with increasing temperature.

The thermistors used in the DMG's Tape Tunnel are of the NTC variety. The relationship between the resistance (R) in ohms and the temperature (T) in Kelvin of an NTC thermistor is given by the Steinhart-Hart equation [6, 7],

$$\frac{1}{T} = \sum_{i=0}^{n} A_i (\ln(R))^i. \tag{1}$$

Equation **Error! Reference source not found.** is derived using fundamental principles of solid state physics. Since thermistors are polycrystalline semiconductor devices, the density of the carriers (therefore conductivity) increases exponentially with the temperature. Hence, the relationship between the resistance (R) and the absolute temperature (T) may be represented by [7, 8],

$$\frac{1}{R} = F e^{\left(\frac{-\Delta E}{2kT}\right)}, \tag{1}$$

where F is a proportionality constant, ΔE is the electrical conduction activation energy, and k is the Boltzmann's constant. Equation 1 may then be rewritten as

$$\frac{1}{T} = A_0 + A_1 \ln(R), \tag{2}$$

where $A_0 = ln(F) \times (2k / \Delta E)$ and $A_1 = (2k / \Delta E)$. The grain boundaries and doping of the semiconductor can change the relationship shown in Eq. (2). To account for such cases, Steinhart and Hart [6] used a series expansion, shown in Eq. (1). It was also found that there is no loss in precision by terminating the expansion after $n = 3$. Moreover, ignoring A_2 proved to be statistically insignificant [10] and thus Eq. (1) reduces to

$$\frac{1}{T} = A_0 + A_1 \ln(R) + A_3 (\ln(R))^3. \tag{3}$$

4.   Calculation of the Coefficients of the Steinhart-Hart Equation

The Steinhart-Hart equation is a widely used relationship between the temperature and resistance and is hard wired into many commercial instruments. The calibration process involves measuring temperatures and resistances at multiple known temperatures and calculating the values of A_0, A_1, and A_3 in Eq. (4).

Prior to calibrating the probes in the DMG's Tape Tunnel, the errors in the temperature values of the 14 thermistor probes are compared against the budgeted uncertainty ($U_{k=2}$) of

±90 m°C. This comparison is performed using a reference thermometer, which was previously calibrated by the NIST Thermodynamic Metrology Group, with an uncertainty ($U_{k=2}$) of 6.8 m°C. If any of these errors fall outside the budgeted uncertainty ($U_{k=2}$) of ±90 m°C, the probes will require calibration.

To perform the calibration, the three coefficients (A_0, A_1, and A_3,) in Eq. (4) are required to be calculated. For this purpose, the temperature on the reference thermometer and the resistances of the Tape tunnel's thermistors are recorded for at least three different temperature values (set by a stable heat source). This will result in three linear equations, which may then be solved to obtain A_0, A_1 and A_3.

Even though three points are sufficient to calculate the coefficients, in practice, five points are chosen around a desired temperature point. This is to improve the uncertainty of the temperature measurements and allow for redundancy. These five points result in five sets of linear equations of the form $MX = T$, where

$$M = \begin{bmatrix} 1 & \ln(R^1_{TEST}) & [\ln(R^1_{TEST})]^3 \\ \vdots & \ddots & \vdots \\ 1 & \ln(R^n_{TEST}) & [\ln(R^n_{TEST})]^3 \end{bmatrix}, X = \begin{bmatrix} A_0 \\ A_1 \\ A_3 \end{bmatrix}, \text{ and } T = \begin{bmatrix} 1/T^1_{REF} \\ \vdots \\ 1/T^n_{REF} \end{bmatrix}. \quad (5)$$

In the above equation, the temperature is in the Kelvin scale, the resistance is in Ohms and n = 5 (the number of calibration points). Since the Tape Tunnel's set point temperature is 20 °C, the five calibration points are chosen to be 18 °C, 19 °C, 20 °C, 21 °C and 22 °C. The coefficient matrix X may then be solved using the following matrix operations,

$$X = [M^T M]^{-1} [M^T T]. \quad (4)$$

A Monte Carlo simulation was performed to understand the effect of using more than five calibration points ($n > 5$). The simulation indicated that increasing the number of calibration points from $n = 5$ to $n = 7$ changes the value of the thermistor's measured temperature by 2 μ°C. Such a change in the measured temperature is insignificant for the requirements of the DMG's Tape Tunnel and indicates that five calibration points ($n = 5$) are sufficient.

5.   Hardware and Software Components

The architecture of the DMG's temperature calibration system relies on commercial off-the-shelf components and custom calibration routines. Below is a list of components that were used in this system[†] and are depicted in **Figure 1**.

Existing components:

1. Seven birdcage thermistors, to measure air temperature.
2. Seven disk thermistors, to measure the temperature of the material.
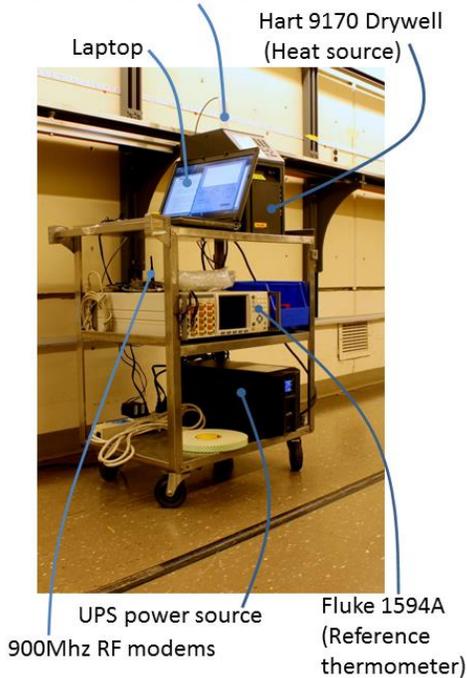

[†] Disclaimer: Commercial equipment and materials are identified here in order to adequately specify certain procedures. This identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

3. Two Hart 1560 (Black Stacks) connected to the 14 thermistor probes.
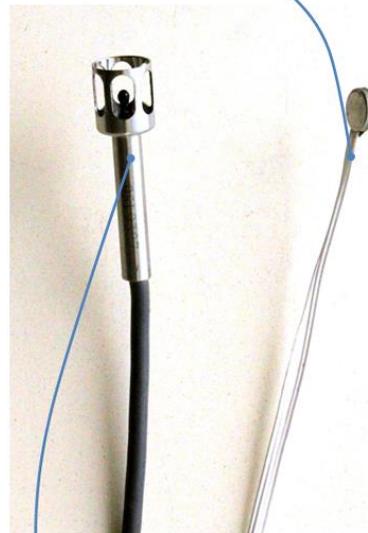
Calibration components (on a mobile steel cart):

1. Fluke 1594A Super Thermometer along with Fluke 5660-S precision, ultra stable thermistor probe, calibrated by the NIST Thermodynamic Metrology Group.
2. Heat source: Fluke 9170 metrology well (drywell).
3. Four radio frequency (RF) modems, 1 W/900 MHz (Xtend-PKG).
4. Uninterruptible power supply (UPS), rated for 1000 W/1440 VA to power the equipment on the steel cart.
5. Laptop running either Windows or Linux, with MATLAB Compiler Runtime (MCR).
6. Development PC with MATLAB, with Instrumentation toolbox.
7. Custom made cylindrical inserts/adapters, to accommodate the reference probe and the test thermistors.

Figure 1. NIST Tape Tunnel temperature calibration system on a cart.

Figure 2. Thermistor probes.

6.   Calibration Procedure

At each location of the pair of thermistors, the calibration procedure is described in the following steps. **Figure 3** depicts a screenshot of a typical measurement in progress.

1. The thermistors probes under test are first removed from their measurement locations in the Tape Tunnel and are inserted into the drywell using the custom aluminum

adapter. Since the tape tunnel has two probes per location along its length, two probes are inserted at the same time to increase the throughput of the calibration process.

2. The probe of the reference thermometer is inserted into the drywell using the same custom aluminum adapter.

3. The assembly of the aluminum adapter and the probes is insulated from the environment using cellulose rubber.

4. The calibration routine is started on the laptop, which goes through the following steps:

   a. The drywell is set to 17 °C until it reaches stability, as an initializing routine. This initializing routine has been observed to produce lower uncertainties in the measured temperature and resistance values. It should be noted that the drywell relies on its internal sensor to indicate the stability on its display screen. However the drywell's internal sensor may not be calibrated and it does not consider the effects of thermal loading (aluminum inserts and the probes). Instead of relying on the drywell's internal sensor, the DMG's temperature calibration system relies on the reference thermometer to indicate stability. The recording of the measurements (for all the probes/thermistors) begins only after the reference thermometer's standard deviation of a sequence of 100 measurements is below 1.2 m°C.

   b. The drywell is set to 18 °C (first calibration point) until it reaches stability. Then the temperature from the reference probe (T), the resistances and the temperatures measured by the test probes (R and $T2$ respectively) are recorded. About 300 measurements are recorded to reduce the influence of random noise.

   c. Step b is repeated for 19 °C, 20 °C, 21 °C and 22 °C and the corresponding data files are stored.

   d. If the errors[†] in the temperature values measured by the test probes ($T2$) are within the budgeted uncertainty ($U_{k=2}$) of ±90 m°C, the procedure is terminated.

   e. If the comparison in step d fails, the stored data files are post-processed using Eq. (4) and the new calibration coefficients are calculated for each probe.

   f. The test probes' instrumentation is updated with these new coefficients.

[†] The term "errors" here, is defined as the difference in the measured temperature values of the probes under test and that of the reference thermometer.
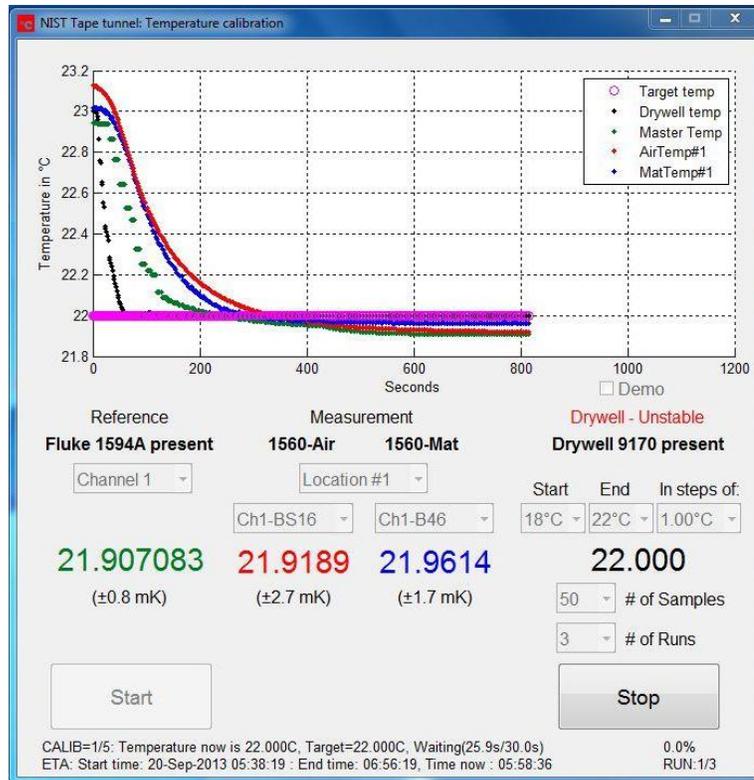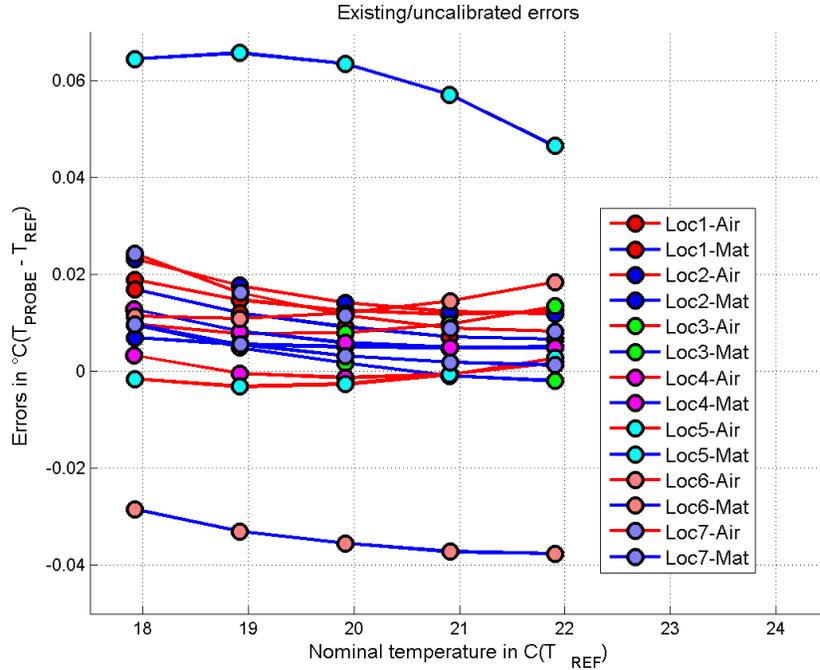
Figure 3. Screen shot of the NIST Tape Tunnel calibration software.

7.   Results and Uncertainty Analysis

The errors in the temperatures for the 14 probes, as reported by their instrumentation with the existing set of coefficients, are shown in **Figure 4**. It can be observed that two of the probes' errors appear to be systematically biased in comparison to the errors of the other probes. However, it should be noted that the magnitude of the errors of these two probes is within -40 m°C and +66 m°C, which is within the budgeted uncertainty ($U_{k=2}$) of ±90 m°C. These errors may be attributed to mechanical damage that could have occurred after the previous calibration was performed.

The primary sources of uncertainty for this temperature measurement may be categorized as below:
1. The reference thermometer (reference probe and the instrumentation),
2. Test thermometer (thermistor probes and the instrumentation),
3. The heat source/drywell, and
4. Errors due to the least-squares fit.

Figure 4. Existing errors in the thermistors' temperature measurement.

Error! Reference source not found. lists the different sources of uncertainty, their corresponding values, distributions and their corresponding contribution to the expanded uncertainty. Adding all the uncertainty terms in a root-sum-of-squares (RSS) manner will give a combined standard uncertainty (u_c) of 19.7 m°C, and using a coverage factor of $k = 2$ yields an expanded uncertainty of 39.5 m°C.

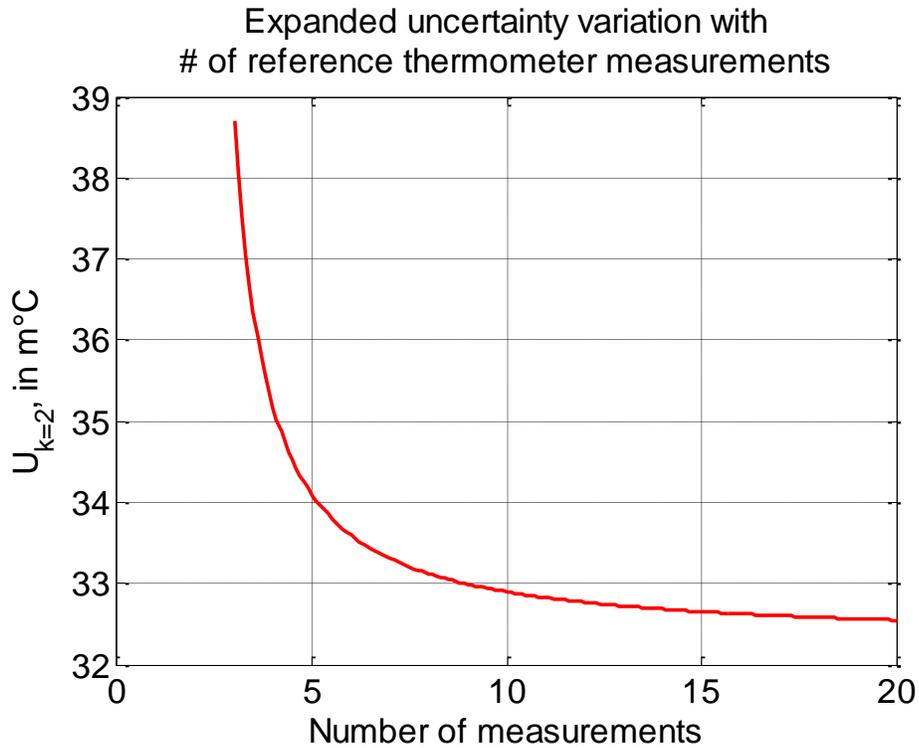|	Source of Uncertainty	u_i (m°C)	Type	Distribution	Contribution[‡]
1	Reference probe: Calibration Bath uncertainty	1.2	B	Gaussian	0.4 %
2	Reference probe: Calibration report uncertainty	12.6	B	Gaussian	40.8 %
3	Reference probe: Probe drift ($\approx$ 3 months[†])	0.7	B	Uniform	0.1 %
4	Reference probe: Instrument uncertainty	0.0	B	Uniform	0.0 %
5	Drywell: Radial uniformity	5.8	B	Uniform	8.6 %
6	Drywell: Axial uniformity (50 % of actual range)	7.8	B	Uniform	15.6 %
7	Test probes: Probe drift/year (Air thermistors)	11.5	B	Uniform	33.9 %
8	Test probes: Instrument uncertainty	1.5	B	Uniform	0.6 %
9	Fit: Measurement residuals	0.01	A	Gaussian	0.0 %
	Combined standard uncertainty (u_c)	19.7			
	Expanded uncertainty ($U_{k=2}$)	39.5			

Table 2. Sources of uncertainty of the temperature measurement.

The process of calibrating the reference thermometer (Fluke 5660-S and Fluke 1594A) by the NIST Thermodynamic Metrology Group involved comparing it with their master thermometer at

---

[‡] Contribution percentage = $(u_i / u_c)^2$
[†] The reference thermometer was calibrated three months prior to the calibration procedure in the Tape Tunnel.

three points. It should be noted that performing such a calibration at a greater number of data points would significantly improve the expanded uncertainty of the system. **Figure 5** shows that increasing the number of calibration points (from three to 20), lowers the value of the expanded uncertainty by 6.1 m°C. The cost of such a calibration has diminishing returns.

Figure 5. Variation in the expanded uncertainty of the reference thermometer vs. the number of measurements obtained in its calibration.

8.   Monte Carlo Simulation Based on the Uncertainty Parameters

A Monte Carlo simulation was performed by generating 1000 random data points for temperature and resistance based on the values in **Error! Reference source not found.**. **Error! Reference source not found.** lists the uncertainties and their coverage intervals.

Number	Nominal Temp.	Expanded uncertainty ($U_{k=2}$)	Coverage interval
1	17.917 °C	39.7 m°C	94.40 %
2	18.919 °C	39.6 m°C	96.50 %
3	19.916 °C	37.9 m°C	96.50 %
4	20.909 °C	38.7 m°C	95.90 %
5	21.907 °C	38.9 m°C	96.00 %

Table 3. System uncertainty at various temperatures, based on Monte Carlo simulation.

9.   Conclusions

The new in-situ calibration system developed at the NIST Dimensional Metrology Group, achieves an expanded uncertainty of ±39.5 m°C, with a downtime of about two days to calibrate all of the 14 temperature probes. The requirements to train an operator to perform these calibrations are minimal. Even though this uncertainty value is less than the budgeted expanded uncertainty for the Tape Tunnel (±90 m°C), the effect of these error sources can be further reduced by correcting its calibration parameters of the reference thermometer, by using better insulation techniques, by using higher quality inserts, by and measuring the sources of errors, instead of relying on the manufacturer's specifications.

10. References

[1] C. Blackburn, D. Sawyer, and C. Shakarji, "Common-Path Method for Laser Tracker Ranging Calibration," *Journal of the CMSC, Vol. 9, No. 1, Spring 2014.*.

[2] B. Edlen, "The Refractive Index of Air," *Metrologia*, vol. 2, no.2, pp. 77-80, 1965.

[3] A. Slocum, "*Precision Machine Design*", Society of Manufacturing Engineers (SME), pp. 198, 1992.

[4] Specifications of the "5640 Series Thermistor Standards Probes" http://us.flukecal.com/products/temperature-calibration/probessensors/5640-series-thermistor-standards-probes?quicktabs_product_details=2 (Retrieved March 10, 2014)

[5] "Specifications for YSI Precision Thermistors and Probes" http://www.advindsys.com/Manuals/YSIManuals/ YSICatalog-1998.pdf (Retrieved March 10, 2014)

[6] J. Steinhart and S. Hart, "Calibration curves for thermistors," *Deep Sea Research and Oceanographic Abstracts*, vol. 15, no. 4, . 497-503, 1968.

[7] T. McGee, "*Principles and Methods of Temperature Measurement*", Wiley & Sons, pp. 209, 1988.

[8] J. Shakelford, "*Introduction to Materials Science for Engineers*", Prentice Hall, pp. 624, 2008.

[9] M. Matus, "Temperature Measurement in Dimensional Metrology – Why the Steinhart-Hart Equation works so well," *Proceedings of MacroScale 2011*, Wabern, Switzerland, October 2011.

[10] M. Sapoff, "Thermistor Thermometers," Section 32.3 in The Measurement, Instrumentation and Sensors Handbook, J. Webster, ed., pp. 32-25 – 32-41, CRC Press, 1999.