EMF – Electromotive Force
RF – Radio Frequency
RMS – Root Mean Square

Abbreviations

Potential errors that can affect temperature measurement accuracy

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The ability to measure the temperature of a system accurately and with the required resolution depends on a variety of factors. While the first step in estimating the errors in a system is the sensor and instrument calibration, to really determine accuracy, it is important to look at the quantifiable factors that affect accuracy: the uncertainty of the measurement.

Uncertainty of the measurement is simply the estimate of all the errors associated with the measurement. By accounting for all the uncertainties of the measurement a total uncertainty is estimated. This article explains where or how errors can occur. It then explains the two classes of errors that exist, and details specific errors and a brief explanation of each. It ends with an explanation of the methodology for combining the uncertainties to determine the overall accuracy.

Where errors occur

Design errors: These are errors of design and occur prior to sensor installation. For example, whether or not the sensor can be mounted on or near the sample to be measured could be a design error. If it is too far away, there can be a thermal lag and offset due to thermal conductance of the sample. Design errors also apply to the physical construction of the sensor. This affects the reproducibility of the sensor over thermal cycling. Some sensors are more fragile than others and more prone to damage due to physical stress.

Installation and environment errors: This would include installation errors and environmental effects. Choice of wire material, wire gauge, 2-lead vs 4-lead configuration, physical configuration of the wire, locations of heat sinking, placement of the sensor, Other interactions include thermal radiation, magnetic fields, and ionising radiation.

Operation and instrumentation errors: Instrumentation is a crucial component to the total quality of the measurement. The excitation level, thermal EMFs/current reversal, instrument resolution, and accuracy all affect the measurement. Additionally, grounding errors and RF noise coupling can introduce noise to the measurement.

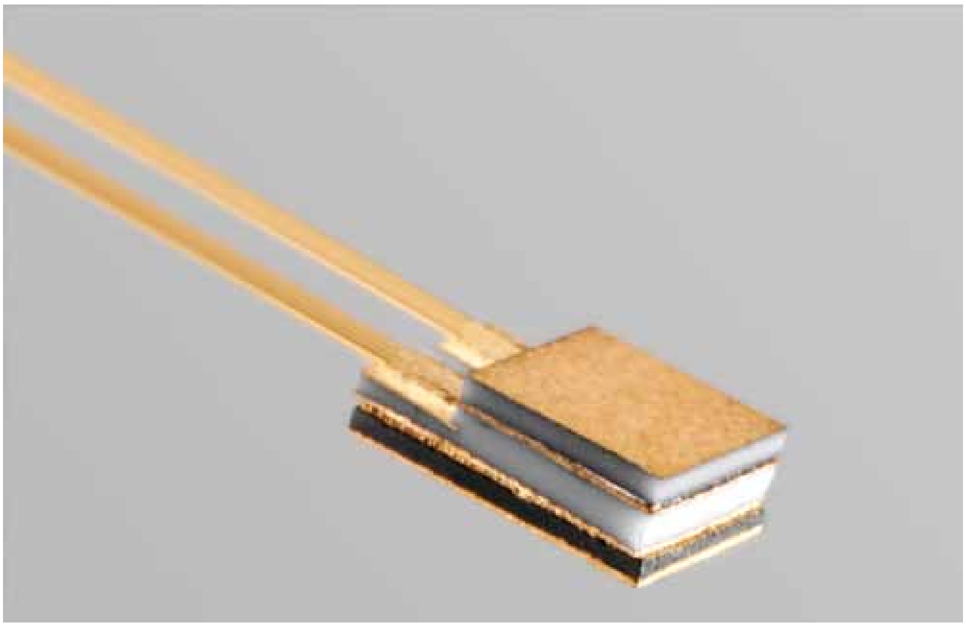
Two classes of errors

Type A - random errors: These can be evaluated by statistical methods. Most random errors are the result of instrumentation: uncertainty in the current source and voltage measurements. Other random errors are the actual assignment of a temperature (transferring ITS-90 or PLTS-2000), and interpolation errors.

Type B - systematic errors: These can be evaluated by other means. Design, installation, and environmental errors are systematic. For example, sensors in magnetic fields will create an offset to the measurement. This offset can be estimated from prior information or directly measured by other means (isothermal measurements with and without field). RF noise can also cause both random errors (eg current noise) and systematic errors (eg self-heating).

Specific errors that could affect measurement

- Installation: Installation errors can include location of sensor and control heater, mounting methods and materials, and type of electrical connection wire.
- Placement of sensor: the sensor should be placed in a location that will minimise thermal lag with respect to the control heater and experiment. The use of a thermal medium such as grease will enhance the thermal connection and decrease thermal lag. Poor thermal design of the overall apparatus can produce measurement errors and result in poor control stability.
- Electrical connection: The choice of electrical lead materials and gauge size affect the amount of heat conducted into the system and to the sensor. If leads are not properly heat sunk, they will introduce a heat load into the sensor. This affects the sensor's measurement and can also affect the sample. It can bias the reading of temperature as well as directly affect the temperature if the heat leak is great enough. Installation as a 2-lead as opposed to 4-lead electrical measurement will introduce an offset due to uncompensated lead resistance.
- -Lead versus 4-lead: The dominant source of error in a 2-lead resistance measurement is usually the resistance of the lead wires connecting the current source to the temperature sensor. The equivalent error the lead resistance represents depends on the sensor type and sensor sensitivity. In order to eliminate the effects of lead resistance, a 4-lead measurement (*see Figure 1*) is normally used. Two of the leads, I+ and I–, supply current to the sensor, while the other two leads, V+ and V–, connect to a high impedance voltmeter. The reason this measurement scheme



works is that the IR drop in the current leads is not measured, and the voltage drop in the voltage leads is extremely small due to the very small current required by the voltmeter to make the voltage measurement. Even inherently 2-lead devices should be connected in a 4-lead measurement scheme.

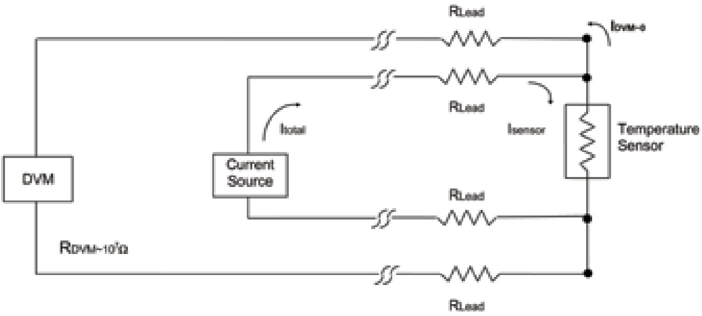


Figure 1: 4-Lead connection configuration for electrical resistance measurement.

Instrumentation: In addition to the sensor calibration, the instrumentation used to perform the temperature measurement must also be calibrated. Most often this instrumentation consists of a current source and a voltmeter. Like other electronic components, their calibration degrades with time and manufacturers typically provide accuracy specifications stated for a given period such as six months or one year. The effect of each is discussed below. Note that in the end result the offsets are excitation level dependent.

- Effect of current source accuracy: Because resistance temperature sensors are linearly dependent upon the current source accuracy, this is more important for them than for diode sensors where the response is nonlinear. For resistance sensors, an error in current measurement is inversely related to the resultant measurement error of resistance: $R - \Delta R = V/(I + \Delta I) \approx (V/I)(1 - \Delta I/I) = R - R(\Delta I/I)$ where I is the current setting, ΔI is the variation from that setting, and $\Delta R = R\Delta I/I$.
  The temperature error, ΔT, due to current source uncertainty, ΔI, is then $\Delta T = \Delta R/(dR/dT)$.
- Effect of voltage measurement accuracy: for diodes, the effect of voltage measurement accuracy on resultant temperature measurement is not difficult to calculate, provided that diode sensitivity is known for the temperature of in-terest. The potential temperature error, ΔT_V is $\Delta T_V = \Delta V/[dV/dT]$.
  For resistive temperature sensors such as platinum or CernoxTM, the potential temperature error, ΔT_R, is $\Delta T_R = \Delta R / [dR/dT] = [\Delta V/I] / [dR/dT]$ since from Ohm's law, $\Delta V = I\Delta R$.
- Self-heating: Any difference between the temperature of the sensor and the environment the sensor is intended to measure produces a temperature measurement error or uncertainty. Dissipation of power in the temperature sensor will cause its temperature to rise above that of the surrounding environment. Power dissipation in the sensor is also necessary to perform a tem-perature measurement. Minimisation of the temperature measurement uncertainty thus requires balancing the uncertainties due to self-heating and output signal measurement.
  Self-heating is really a combination of sensor design and instrumentation. The primary reason for self-heating offsets at low temperatures is the thermal boundary resistance between the active sensor element and its surroundings. At temperatures below 50 K the thermal boundary resistance has a very strong inverse cubic relationship with temperature. This forces the instrumentation to be capable of sourcing a small excitation and measuring a small volt-age signal. The optimum excitation power will be a function of sensor, resistance, and temperature.

Environmental concerns: Environmental changes like magnetic fields, ionising radiation, or changes in the pressure, humidity, or chemistry of the environment can create a systematic bias in the temperature measurement.

Thermoelectric and zero offset voltages: Voltages develop in electrical conductors with temperature gradients even when no current is allowed to flow as a result of the thermoelectric effect. Thermoelectric voltages appear when dissimilar metals are joined and joints are held at different temperatures. Typical thermoelectric voltages in cryogenic measurement systems are on the order of tens of microvolts. Thermal EMFs in the sensor leads and connections have a larger effect on resistance measurements as compared to diode measurements because diode signal levels are much larger (typically a few tenths of a volt at room temperature to several volts at 4,2 K). For resistance measurements, performing current reversal eliminates the effect of thermoelectric voltages.

Also, the instrumentation can have a zero offset (the signal value measured with no input to the measuring instrument). The zero offset can drift with time or temperature and is usually included in the instrument specifications.

Grounding: Improper grounding of instruments or grounding at multiple points can allow current flows which result in small voltage offsets. The current flow through ground loops is not necessarily constant, resulting in a fluctuating voltage. Current can flow in the ground loop as it acts as a large aperture for inductive pick-up. Also, current can result if there is a potential difference due to multiple grounds.

Ac signal interference (RF noise): Signal leads and cables are very susceptible to interference from unwanted ac signals in the RF frequency range. They act like antennas and pick up noise from computers, monitors, instrumentation, radio broadcasts, and other sources. Signals are either inductively coupled or capacitively coupled. The induced signals circulate as noise current in the measurement leads and distort measurements. There are other concerns when diodes are used as the sensing element. The greatest concern relates to leads external to the cryostat. Ideally, the cryostat itself acts as the shield for all wiring internal to it. However, it is still possible for cross-talk between different signal leads. Power leads for control heaters and signal leads for temperature measurement should be kept far apart.

Measurement errors in diodes due to ac interference: Wiring techniques are especially important when using diodes because noise currents produce a shift in measurement. Because diodes have a nonlinear voltage response to the changing current, the shift is seen as a lower measured voltage corresponding to a higher measured temperature. The temperature error in noisy systems can be as high as several tenths of a kelvin.

Thermal (Johnson) noise: Thermal energy produces random motions of the charged particles within a body, giving rise to electrical noise. The minimum root mean square (RMS) noise power available is given by $P_n = 4kT\,\Delta f_n$, where k is the Boltzmann constant and Δf_n is the noise bandwidth. Peak-to-peak noise is approximately five times greater than RMS noise. Metallic resistors approach this fundamental minimum, but other materials produce somewhat greater thermal noise. The noise power is related to current or voltage noise by the relations: $I = [P_n/R_d]^{0.5}$ and $V = [P_n\,R_d]^{0.5}$.

Calibration uncertainty: Commercially calibrated sensors should have calibrations traceable to international standards. The best accuracy attainable is represented by the ability of national standards laboratories. The calibration uncertainty typically increases by a factor of three to 10 between successive devices used to transfer a calibration.

Calibration fit interpolation uncertainty: Once a calibration is performed, an inter-polation function is required for temperatures that lie between calibration points. Use of an interpolation function adds to the measurement uncertainty.

The additional uncertainty due to an interpolation function can be gauged by the ability of the interpolation function to reproduce the calibration points. Each calibration can be broken up into several ranges to decrease the fitting uncertainties. Typical uncertainties introduced by a properly calculated interpolation function are on the order of one tenth the calibration uncertainty.

Combining measurement uncertainties

Estimating the quality of a measurement involves the following steps:

- Identify the relevant sources of measurement uncertainty.
- Change the units of all uncertainties to temperature.
- Combine all of the uncertainties using the root sum of squares method. Examples of source of measurement uncertainties affecting the accuracy, but not the precision of a measurement include offset voltages and calibration uncertainties.

Both random and systematic uncertainties are treated in the same way. Finding statistical data suitable for addition by quadrature can be a problem; instrument and sensor specifications sometimes give maximum or typical values for uncertainties. Two approaches may be taken when dealing with maximum uncertainty specifications. The conservative approach is to use the specification limit value in the combined uncertainty calculation. The less conservative approach is to assume a statistical distribution within the specification limits and assume the limit is roughly three standard deviations, in which case one third of the specification limit is used in uncertainty calculations. The manufacturer may be able to supply additional information to help improve uncertainty estimates.

Conclusion

Once the sources of measurement uncertainty are identified, they must be converted to the equivalent temperature uncertainty. This will require some knowledge of the sensor characteristic in terms of resistance or voltage and the sensitivity dR/dT or dV/dT. Note that these quantities are temperature dependent and the overall uncertainty is temperature dependent. Resistive errors can be converted to temperature error using $\Delta T=\Delta R/(dR/dT)$ while a voltage error can be converted to temperature error using $\Delta T=\Delta V/(dV/dT= \Delta V/(I\times dR/dT)$. Finally, the errors can be combined into one overall uncertainty value using:

$$u_{total} = \sqrt{u_1^2 + u_2^2 + u_3^2 + \cdots + u_n^2}$$

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This article is a partial reprint of a paper from Lake Shore Cryotronics, Inc. The full paper is available at http://www.lakeshore.com/pdf_files/Appendices/LSTC_appendixE_I.pdf.

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