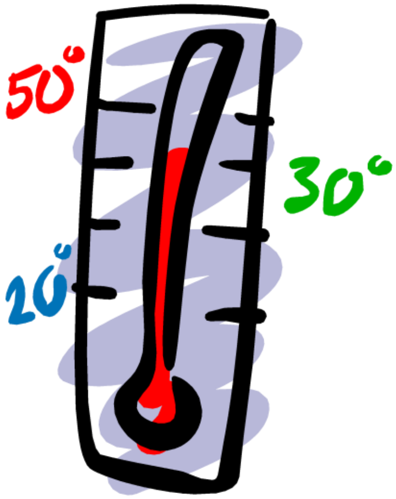

arroyo instruments

APPLICATION NOTE AN-021

Determining Temperature Accuracy

September 25, 2023

Temperature accuracy can mean different things depending on the context

First, let's start with a few definitions of accuracy:

- **Absolute accuracy** – as the name implies, the ability to achieve an actual absolute temperature at the measurement point
- **Relative accuracy** – the accuracy of a change in temperature. For example, how accurately does adjusting the set point from 25°C to 26°C create a 1°C change?
- **Repeatability** – how accurately can the system return to the same set point?
- **Uniformity** – how even is the temperature across the cold plate?
- **Stability** – how accurately can the system return to the same set point?

Most people, when thinking of temperature accuracy, mean absolute accuracy, but depending on the application, absolute accuracy may not even be particularly important. Instead, the ability to repeat the measurement at the same temperature (repeatability) or determine the temperature sensitivity of the device (relative accuracy) is more important.

Don't confuse accuracy with stability, which is an entirely different measurement. While the two are related, stability measures the change in temperature across time, not the absolute temperature at any given moment. You can have a low accuracy system that is highly stable and vice versa.

For some systems, you also need to consider the difference in measurement accuracy versus control accuracy. For controllers that use an analog-based control loop, the temperature control accuracy is often different than the temperature measurement accuracy due to variations in the analog circuitry. Arroyo Instruments uses a digital feedback system, so the measurement and control accuracy are the same.

Finally, the measurement conversion formula can be a source of absolute accuracy errors. For example, the Steinhart-Hart equation is used to convert thermistor resistance into temperature, and a similar Callendar-Van Dusen equation is used for RTDs. A poor fit of the coefficients (or simply the wrong coefficients) can introduce additional measurement errors.

The goal of this document is to equip you with enough knowledge to identify the different types of accuracy measurements, understand what is important to your application, and help you minimize those errors. There are calculations and mathematical models for computationally estimating thermal errors, but that is beyond the scope of this document. Instead, the focus is on identifying and understanding the sources of errors, minimizing those errors where possible, and ultimately evaluating those errors through experimental testing.

Authors note: this document refers to the temperature-controlled surface as the “cold plate,” as many applications are for controlling the waste heat of an active DUT (such as laser or LED) by cooling, but it is really a “temperature controlled plate,” it can both heated and cooled… but that’s a long phrase and “cold plate” is easier to read.

Absolute Accuracy

Absolute accuracy is, by far, the most difficult to measure. Many variables come into play when evaluating absolute accuracy, some that can be controlled by sensor or instrument selection, and some that are part of the mechanical design of the thermal platform.

The two main elements that are independent of the thermal platform (fixture) are:

1. Instrument measurement accuracy – most instruments measure in the sensors “native units,” such as resistance for thermistors or RTDs, or voltage for LM335s. A formula is then used to convert the measurement from the native measurement, such as resistance, into temperature.
2. Sensor accuracy at the specific temperature – many sensors change in accuracy over their operating range. Thermistors, for example, are generally more accurate in the lower region of their operating range.

The balance of the error sources is integral to the design of the fixture and device, below a list of the most common. All of these can be present in both the DUT and the fixture:

3. Thermal interfaces – how many mating surfaces (such as device to cold plate) are there between the DUT and the sensor, and what is the quality (thermistor resistance) of those interfaces?
4. Materials – what are the materials the heat will be travelling through? Copper is much more thermally conductive than aluminum, but the latter is far more commonly used because it is a easier to machine.
5. Thermal load – larger thermal loads will create higher temperature differentials through the materials and create larger temperature across the thermal interfaces.
6. Ambient loading on DUT – a difference between ambient temperature and control temperature will cause heat exchange through the air, cooling or heating the exposed faces of the DUT. The greater the difference between ambient temperature and control temperature, the greater the heat exchange and influence on the DUT.
7. Ambient loading on sensor – if any portion of the sensor is exposed to air, the air will influence the sensor measurement, increasing as the temperature differential increases. Burying the sensor in a hole significantly reduces this sensitivity, but even the wires leading into the sensor can influence the sensor measurement, particularly under high temperature differences, as the wires are cooled by ambient and act as a heat sink to the sensor.
8. Proximity of sensor to DUT – the closer the sensor can be placed to the DUT, the better the performance. A tightly coupled sensor reduces the materials and interfaces between the sensor and the DUT, reducing possible error sources.

Let’s beak down these various elements:

Instrument measurement accuracy

This is one of easiest to evaluate, as it's a specification that should be provided by the instrument manufacturer. Because different sensors are measured differently, each sensor input will have its own specification.

For example, the Arroyo Instruments 5305 TECSource has a thermistor measurement accuracy of 0.05% of reading plus 5Ω. For a 10kΩ thermistor operating at 25°C, this means a measurement accuracy of ±10Ω. At 25°C, a thermistor sensitivity is 430 Ω/°C. If the measurement error is ±10Ω, that translates into an instrument temperature accuracy of ±0.023°C.

However, consider the same thermistor measurement at 70°C: typical thermistor resistance is about 1750Ω, so measurement accuracy is ±5.88Ω. With thermistor sensitivity only 57 Ω/°C, that translates into a temperature accuracy of ±0.1°C.

Sensor accuracy

Similar to instrument measurement accuracy, sensor accuracy is typically provided by the manufacturer. In the case of the thermistor used in all Arroyo Instruments products, the manufacturer specifies an accuracy of ±0.1°C across the range of 0°C to 70°C.

Other sensors will have differing measurement accuracies. For example, the RTD sensor used in the Arroyo Instrument high temperature products (those going to 150°C) meets EN60751 Class B requirements, which states an accuracy of ±(0.3°C + 0.005 * T), where T is the absolute value of temperature (i.e., disregard sign). For example, at 25°C, that would translate into an accuracy of ±0.425°C, while at 70°C, accuracy would be 0.65°C, and at 150°C, accuracy would be 1.05°C.

Thermal interfaces

A thermal interface is any seam, joint, or surface-to-surface contact between two materials. Consider a solid block of aluminum. For heat to move from one side to the other within the block, you only need to consider the thermal conductivity of the material itself. However, if you were to slice the block in half and press the two halves back together, you have now created a thermal interface that will slow down the conduction of heat from one side to the other.

The thermal resistance can be lowered by:

- Improving flatness
- Reducing roughness
- Use of thermal interface materials (such as thermal grease or pads)
- Soldering

Materials

Different metals have different thermal conductivity ratings, below are some common materials used in cold plates as well as a few common materials (latter three) for device packaging.

Material	Thermal conductivity [W/mK]
Aluminum	237
Copper	401
Kovar	17
Tungsten-Copper (CuW)	180 to 300[1]

Molybdenum-Copper (MoCu)	165 to 260[1]

[1] Depending on formulation

The higher the thermal conductivity, the better the heat transfer, and therefore lower thermal gradients between the DUT and the sensor.

Thermal load

Thermal load (waste heat generated by the DUT) itself is not a source of temperature error, but greater thermal loads increase the errors caused by thermal resistance of the interfaces and materials the heat needs to travel through. As such, higher thermal loads will create larger thermal gradients between the sensor and the DUT. Further, higher thermal loads will make the cooling system work harder and will enhance any areas of uneven thermal transfer, creating lateral temperature differentials (temperature differences across the width and depth of the cold plate or device).

Ambient loading on DUT

When the air temperature is significantly different than the control temperature, the air will act as a thermal load on the DUT and cold plate. The greater the temperature difference, the greater the impact. For many laser applications, the laser is controlled at 20°C or 25°C, which is typically near the ambient temperature. Under these conditions, ambient loading is kept to a minimum. However, for many LED applications, where the DUT is heated as high as 150°C, the ambient impacts can be substantial. This can create a cooling effect on the DUT, lowering the actual temperature at the DUT.

Ambient loading on Sensor

In a similar way, large differences between ambient and control temperatures will affect the sensor. This is particularly true if the sensor is surface mounted with a significant portion of the sensor exposed to air. However, even when the sensor is mounted into a hole in the cold plate, the wires of the sensor can act as a cooling “heat sink,” drawing heat down the wires and cooling the sensor. Where possible, the sensor should be buried 1” [2.5cm] or more into the cold plate, with the wires and sensor fully potted with thermal grease or thermally conducting epoxy.

Proximity of sensor to DUT

Like thermal load, proximity is itself not a contributor to total temperature error, but when a sensor is placed as close as possible to the DUT, it minimizes material and thermal interfaces between the DUT and the sensor, which then minimizes temperature error. A sensor that is located on the same thermal platform as the critical measurement point (laser chip, LED, etc.) and as close as possible, will have the smallest temperature error. Further, if the DUT is enclosed in a hermetically sealed package (such as TO-can, butterfly package, HHL package, etc.), it significantly reduces the ambient loading on the sensor.

As a baseline, the instrument and sensor accuracies simply add together to get the best-case performance. Continuing the thermistor and RTD examples from earlier, here are example accuracies across temperatures:

T	Thermistor Instrument ± °C	Sensor ± °C	Total ± °C	RTD Instrument ± °C	Sensor ± °C	Total ± °C
0	0.013	0.100	0.113	0.326	0.3	0.626
25	0.023	0.100	0.123	0.336	0.425	0.761
70	0.100	0.100	0.200	0.354	0.65	1.004
150				0.387	1.05	1.437

The RTD sensor is significantly less accurate, particularly due to the sensor accuracy, but even the instrument measurement accuracy is three times that of the thermistor. RTDs provide an extremely wide range of operation, but because of that, they do not perform as well as sensors with a narrower operating range.

Once the instrument accuracy is known, you can begin evaluating the other error contributors. The following is good practice for minimizing additional measurement errors:

- Limit the number of thermal interfaces between the sensor and device
- Use thermal grease or other thermal interface materials to improve conductivity through and thermal interfaces, but pay attention to greases (particularly silicon-based) if your system is particularly sensitive to outgassing contamination
- Place the sensor as close to the device as possible
- Avoid exposing the sensor directly to air
- Use copper or other highly thermally conductive materials

Because of the many variables that contribute to temperature measurement error, it is exceptionally difficult in complex thermal systems to quantify these errors without significant experimental testing. There are mathematical models used for estimating temperature gradients though various materials and thermal interfaces, but those calculations are beyond the scope of this document. The goal is to provide you with enough details to identify the main areas of measurement error and help reduce those as best as possible.

Relative accuracy

Relative accuracy is often as important that absolute accuracy, particularly when using temperature to adjust the operation of the DUT, such as wavelength tuning a laser's light output though changes in temperature. In most cases, the range of relative accuracy is much smaller than the measurement range of the sensor.

For example, many lasers can be tuned using temperature. By shifting the operating temperature by 1°C, the resulting wavelength of the laser will shift by several tenths of a nanometer, so a common test is to measure the wavelength at a lower temperature, say 20°C, then raise the temperature to 25°C and take a second wavelength measurement. The accuracy of the relative change of 5°C is far more important than if the laser is at exactly 20°C or 25°C absolute temperature, as the point of the measurement is to determine nanometers per degree C.

While a sensor may have an absolute offset error of several tenths of a degree, that offset is generally similar across a narrow temperature range. For example, a RTD sensor at 25°C may have a maximum sensor error of ±0.425°C, but the change in error from 20°C to 25°C is going to be far smaller. In other words, if the actual temperature error of an RTD at 25°C was +0.4°C, the error at 20°C is going to be very close to +0.4°C as well… say, for example, +0.38°C. The difference in those two errors, 0.02°C, is going to be your relative accuracy.

Repeatability

Repeatability can be another important characteristic of a temperature controller. Repeatability is the ability to test at a given temperature, turn off the system, come back tomorrow, and return to that same temperature. A system with excellent absolute accuracy, has, by definition, excellent repeatability. However, even a system with very poor absolute accuracy can be highly repeatable, and for some applications, repeatability is more important: the ability to consistently repeat the same temperature over time ensures that whatever measurements are being made can be directly compared without regard to absolute accuracy.

For example, consider an incoming inspection of a batch of lasers needs to be performed. Prior testing with this system has established pass/fail criteria. So long as the system can accurately repeat the same temperature used during that prior testing, the absolute temperature of the laser is not critical. It may be a degree or two off, but repeatability is within a few hundredths of a degree, creating a consistent thermal environment over time.

Uniformity

Another critical consideration in temperature measurement is the uniformity of the cold plate. Absolute accuracy, relative accuracy, and repeatability are typically referenced to the temperature sensor itself, which is normally located near the middle of the cold plate. However, uniformity measures the differences in temperature across the cold plate and can be significantly different depending on operating conditions.

Many of the same factors that influence absolute accuracy also influence uniformity:

1. Materials
2. Thermal load
3. Ambient loading

Materials

> As described above, different metals have different thermal conductivity ratings. Materials with better thermal conductivity will transfer heat faster and lower temperature gradients across the plate.

Thermal load

> The location and density of the thermal load will directly impact the uniformity of the plate. Dense thermal loads, such as small, single-emitter high-power laser diodes, inject heat into a relatively small area of the cold plate, creating a hot spot where the temperature at that location will be well above the surrounding area. Conversely, laser or LED arrays that feature multiple smaller thermal loads but may be just as much heat as the single-emitter laser example will inject heat into the cold plate across a much larger area, reducing the temperature variations across the plate.
>
> Further, high thermal loads will create wider temperature differences across the plate for two reasons: one, the heat is never uniform, and will always cause hotter regions; and two, the TECs

must work harder to dissipate the heat, causing cooler areas (when cooling) where the TECs are active.

Ambient loading

As with absolute accuracy measurements, when the air temperature is significantly different than the control temperature, the air will act as a thermal load on the DUT and cold plate. Areas of ther cold plate that are directly exposed to air will be impacted the greatest. As noted above, for many laser applications, the laser is controlled at 20°C or 25°C, which is typically near the ambient temperature and therefore not a significant impact. However, for many LED applications where the DUT is heated as high as 150°C, the ambient impacts can be substantial, causing asymmetric cooling of the cold plate and increasing non-uniformity.

Stability

Stability is the measurement of the change of temperature over time. In a perfectly thermally stable environment where the ambient temperature does not change and the thermal load from the device under test remains perfectly constant, the one could use the stability specification of the controller alone to determine system stability. However, as with accuracy measurements, stability measurements have several factors that play into determining overall system stability:

1. Controller stability – what is the native instability of the controller itself?
2. Temperature sensor sensitivity -- how sensitive is the sensor to changes in temperature?
3. Thermal time constant – systems with a long thermal time constant (how slowly or quickly that move with a given change of load or cooling) are inherently harder to stabilize.
4. Variable thermal load – if the thermal loads change, either due to changes in ambient conditions or changes in heat from the DUT will create instability.
5. Stability timeframe – how long is the stability window? In other words, over how much time is a particular stability calculated? One hour and 24 hours are common time frames, but your application may be require significantly longer evaluations.

Let's look into each of these points in more detail…

Controller stability

A temperature controller should have a stability specification that dictates performance over a certain timeframe. For example, many Arroyo Instruments controllers are specified at 0.004°C over one hour and 0.01°C over 24 hours using a thermistor and responsive load. There is also the consideration of the ambient sensitivity (often called the "temperature coefficient") of the controller, typically specified in ppm/°C. For example, the 5305 TECSource has a specification of 50 ppm/°C, which translates into roughly 0.00125°C/°C. These two specifications form the best possible performance your system will see.

Temperature sensor sensitivity

Sensor sensitivity, particularly when trying to achieve highly stable systems, can play a role in system stability. Thermistors, when operating in their higher sensitivity ranges (such as 25°C for a 10kΩ thermistor) provide an excellent signal-to-noise measurement that can be used to accurately discern very small changes in temperature. And RTD, on the other hand, is a great sensor for very wide (or hot) temperature operation but has a much lower temperature sensitivity. Lower sensitivities translate into higher instabilities.

Thermal time constant

The system thermal time constant effectively measures how sluggish the system is to thermal inputs. Systems with large thermal time constants are inherently more difficult to stabilize as the reaction time to changes in loading (DUT or ambient) is longer, making the determination of ideal PID settings for the control loop far more difficult. Reducing mass, reducing the number of thermal interfaces and moving the sensor closer to the DUT are a few ways to lower the thermal time constant and create a more responsive system.

Variable thermal load

Variable thermal loads can have the greatest impact to system stability, particularly when the changes are significant. Load changes may be due to HVAC cycling (changing ambient air loading) or changes in the DUT thermal load itself. Either of these will have corresponding impacts on the fixture by raising or lower the total load and requiring the controller to respond by adjusting the temperature control loop. Systems with large thermal time constants will have an very difficult time in responding quickly to changes in thermal loads, increasing system instability. Isolating the fixture from ambient effects (placing it in an enclosure, for example) can lead to significant improvements to stability. While minimizing/eliminating changes to DUT thermal loads may not be possible given the requirements of the application, making gradual (instead of sudden) changes allows the controller to more easily keep up with the changes and minimize significant changes in temperature (and therefore stability).

Stability timeframe

Longer stability timeframes will create greater instability. One hour stability will nearly always be better than 24-hour stability. A one-week stability is likely to be similar to 24-hour stability, although simple things like the HVAC not running on weekends come into play. As the timeframe widens to months, the calibration performance of the instrument itself may start to come into play, as instruments drift away from their original calibration values.

Summary

As can be seen above, determining absolute accuracy is the most challenging. However, for many applications, absolute accuracy may not be critical… excellent relative accuracy combined with good repeatability may provide the necessary accuracy needed for an application.

The Arroyo Instruments controllers are highly accurate and minimize their contribution to the total measurement error. They also provide a highly stable control loop to minimize changes in temperature over time, and have excellent long-term repeatability. Sensor errors can be the most obvious contributor to overall error, but as explained above, there are many other sources of measurement error, with varying degrees of difficulty in mitigating.

Contact Arroyo Instruments if you need additional help in understanding your temperature control problem, or for recommendations on what controllers, fixtures, or sensors would best meet your application.