UT-ONE Accuracy with External Standards

by Valentin Batagelj

Batemika UT-ONE is a three-channel benchtop thermometer readout, which by itself provides excellent accuracy in precise temperature measurements and calibrations. Nevertheless, in some special applications, an improvement in the accuracy of the thermometer readout may be required. UT-ONE with its flexible design and three input channels provides the possibility to connect the external standard (most commonly a reference resistor), which removes most of the internal short-term and long-term drift.

This application note provides some guidelines for the implementation of the external standards and the accuracy analysis for the two specific case studies. All accuracy analysis applies to readout only and does not include the accuracy of the thermometer probe.

This application note will focus on the resistance part of the UT-ONE readout only. Similar conclusions can be drawn also for the voltage part, but as regarding the implementation of external standards, use of external voltage reference is more difficult and will most often not result in significantly improved accuracy.

1 Implementation of the external standard in the UT-ONE thermometer readout

External standard for the resistance part of the thermometer readout is a precise reference resistor. A precise reference resistor must have good long term stability and low temperature coefficient. Reference resistor can be placed in a thermally-stabilized enclosure, such as an oil bath or an air chamber. Alternatively, if temperature coefficient is low and its value is known, the temperature of the reference resistor can be measured and temperature correction can be applied to the resistor reference value.

Figure 1: Batemika R210A precise reference resistor

Reference resistor must be regularly calibrated in order to determine its resistance value, as well as to estimate the uncertainty and in particular the long term drift.

To implement the reference resistor as the external standard in UT-ONE, connect it to one of the main inputs in the same way as a resistance thermometer. Then use the UT-ONE user interface to set the reference value and temperature coefficient for the resistor on the selected channel. Note that you can specify a different reference resistor for each of the input channels. Refer to the UT-ONE user manual for more information on configuring external standards.

If you provide the temperature coefficient of the reference resistor, UT-ONE will use the internal temperature TJ to automatically calculate the temperature correction of the reference resistance. The correction will be effective only if the resistor is placed near the UT-ONE and in stable laboratory conditions. If the resistor is placed in a thermally-stabilized enclosure, set the temperature coefficient to 0. This will effectively disable the automatic temperature correction.

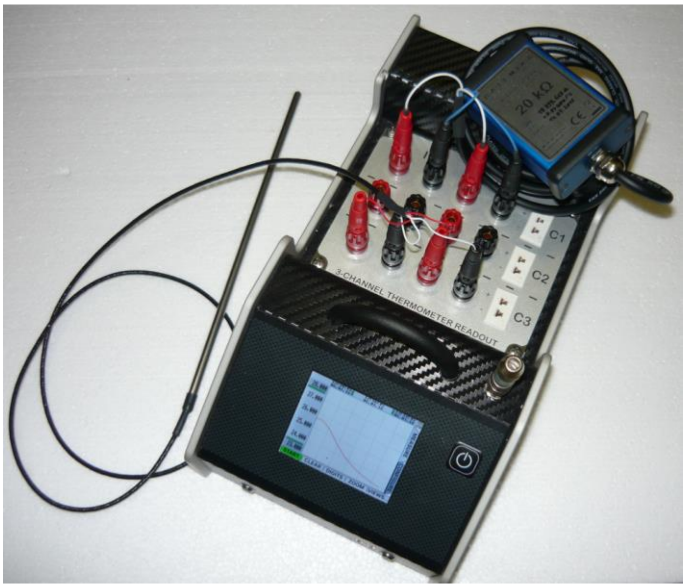

Figure 2: UT-ONE with reference resistor connected to channel C1

You may now perform measurements with the external standard. After you initiate the measurement with the external standard, the measurement circuit will first measure the unknown resistance R_x and subsequently the reference resistance R_s. UT-ONE will then compare the measured reference resistance to its temperature-corrected reference value and make the necessary adjustment to the unknown resistance. This procedure effectively removes most of the internal short and long term drift, which in most cases significantly improves the accuracy of the measurement.

2 UT-ONE accuracy specifications

Accuracy specification of any thermometer readout is a generally either a complex or an oversimplified problem. The main issue is related to the fact that a thermometer readout is basically a measurement instrument for the measurement of electrical resistance and electrical voltage, and its basic accuracy and also calibration relates to resistance and voltage, and not directly to temperature. However, the end user of the thermometer readout is interested in the accuracy expressed in temperature for the particular probe type. Unfortunately, the transformation of resistance/voltage accuracy to temperature is not straightforward and depends on thermometer probe characteristics, especially the probe sensitivity and range. The UT-ONE User manual provides accuracy specifications for each resistance/voltage range, as well as convenient graphs with temperature accuracy over complete temperature range for selected thermometer probe types under specified conditions.

Accuracy specification for any thermometer readout can be divided in three major components, namely the effective resolution, linearity and drift (short and long term). There are several other minor components, but they can be safely included within the short-term drift. Combined accuracy is calculated as the geometric sum of the individual components. For the sake of this application note, a Monte Carlo simulation was designed to calculate the accuracy values presented in graphs.

2.1 Effective resolution

Effective resolution provides the measure for the random scatter (noise) of the resistance readings. Effective resolution is calculated as the standard deviation *s* of a large number *N* of resistance readings (typically 1000 readings or more) of a stable resistance value.

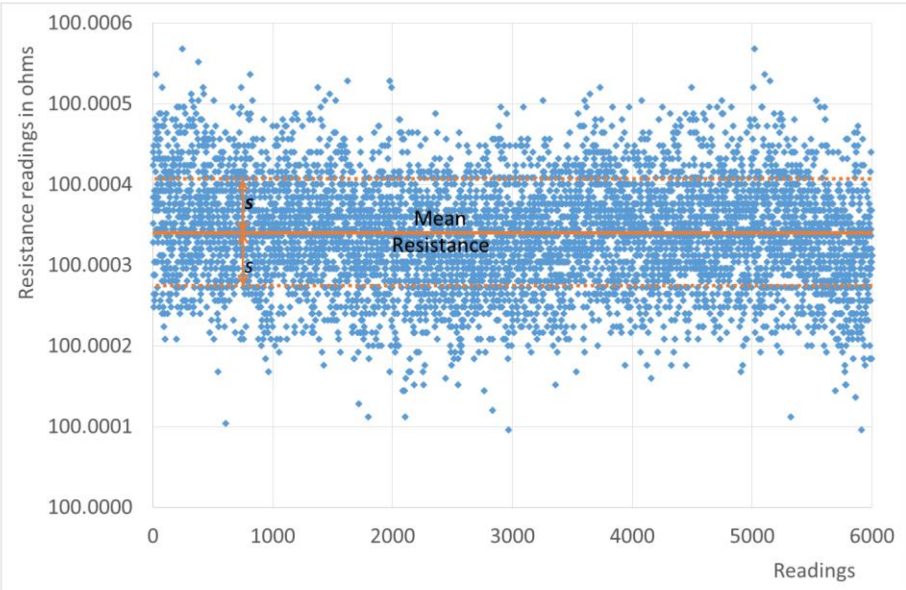

Figure 3: Scatter of resistance readings (range R3, 15 samples, N=6000)

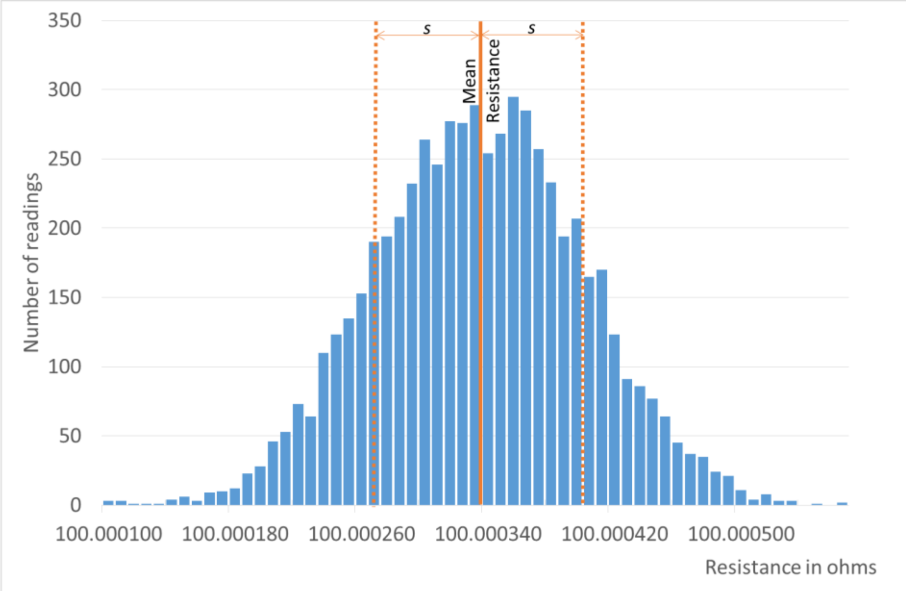

Figure 4: Histogram of resistance readings (range R3, 15 samples, N=6000)

UT-ONE effective resolution depends on the selected measurement range, measurement current and internal averaging. Effective resolution for each measurement range at 2 second internal averaging and normal measurement current is specified in the UT-ONE user manual.

Measurement resolution can be improved by increasing internal averaging and therefore acquisition time for one reading. If you double acquisition time, the effective resolution will be improved by a factor of √2. When using single readings, you can adjust the acquisition time by specifying the number of samples that are acquired internally and produce one reading. A typical value of 15 samples will result in the acquisition time of 2 seconds.

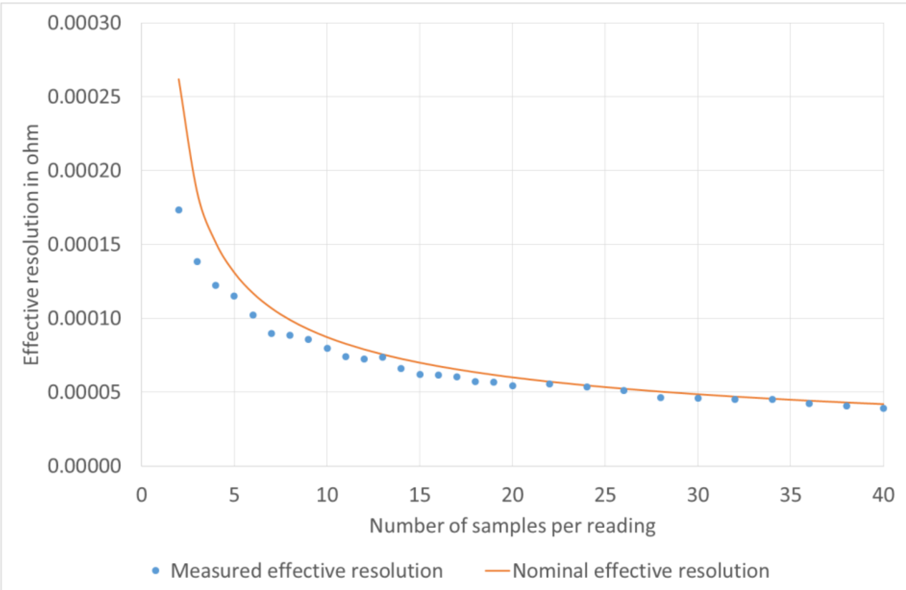

Figure 5: Relation between effective resolution and number of samples per reading (range R3, N=500)

Reducing the measurement current will worsen the effective resolution. If you decrease the measurement current by √2, the effective resolution will increase by √2 (approximately 40%).

When you implement the external standard, the noise from the measurement of the reference resistance will propagate in the measurement result, resulting in the worsened effective resolution. The effect depends on the ratio between the unknown and reference resistance. The resulting effective resolution can be estimated as:

$$Effective\ resolution\ with\ e.s. = \sqrt{\frac{R_s^2 + R_x^2}{R_s^2}} \cdot Effective\ resolution\ without\ e.s.$$

2.2 Linearity error

Linearity describes the deviation of the instrument characteristics from a linear curve. The instrument is typically calibrated/adjusted at one point, typically somewhere between 50% and 100% of the measurement range. Ignoring all other errors, the instrument is perfectly accurate at this calibration point. If the instrument was perfectly linear, this would imply that the instrument is perfectly accurate across the entire measurement range. However, due to linearity errors, small deviations can be observed as we move away from the calibration point.

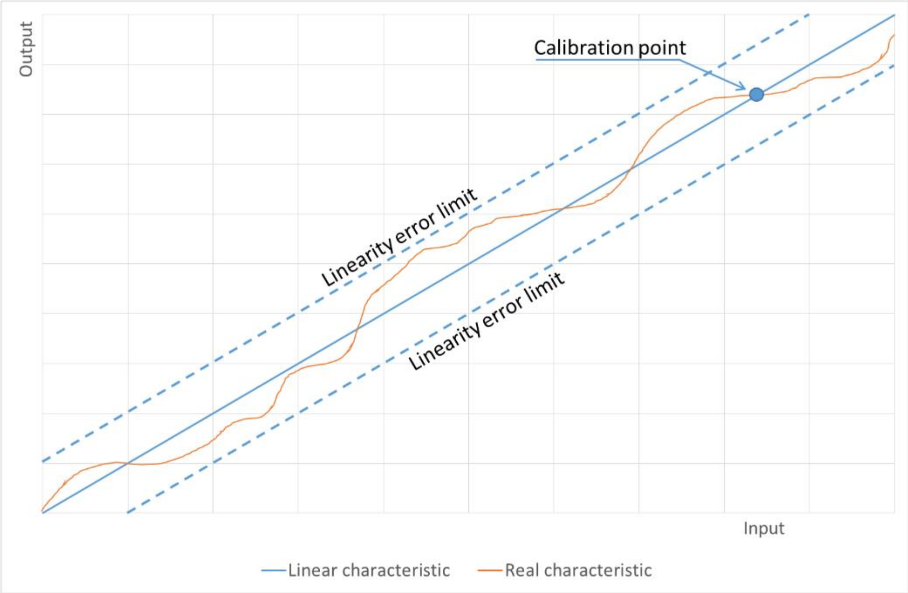

Figure 6: Linearity error limit (not to scale!)

UT-ONE linearity is specified in the UT-ONE user manual as a fixed linearity error limit over the entire measurement range. This is a conservative estimation, as the linearity error is typically smaller at low values and near the calibration point.

UT-ONE linearity error has no predictable shape, but tends to be stable over time. For selected measurement ranges, a linearity correction is determined and implemented for each unit, which results in a significantly improved linearity.

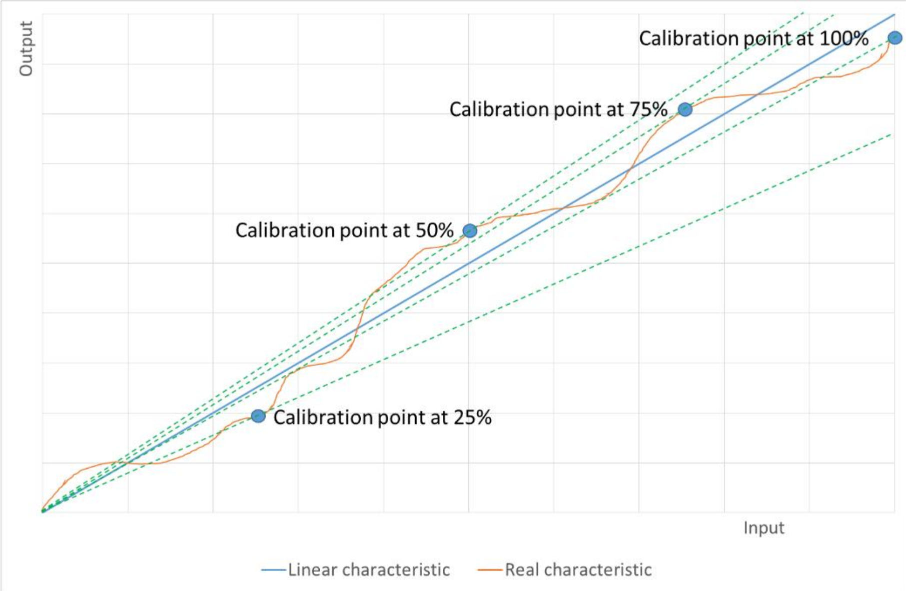

Figure 7: Contribution of linearity error at different calibration points (not to scale!)

In the ideal adjustment, linear characteristic is determined in such manner that residual linearity error are as small as possible and within the linearity error limits. To achieve this, a large number of calibration points would have to be measured and a fitting procedure should be implemented. In practice, only a single calibration point is measured to determine the linear characteristics. Note that the selection of calibration point has a significant influence on the adjustment accuracy. As presented in Figure 7, calibration point should be selected as high as possible, preferably near the range nominal limit. If calibration point is selected under 50% of the range nominal limit, linearity error can be propagated in a very large adjustment error at higher values.

2.3 Drift

Drift is a change of instrument characteristics over time. Note that drift is inherent to any measurement instrument and is the main reason that instruments require recalibration in regular intervals.

Drift can be described as short term or long term drift. Short term drift describes random and often reversible changes over a period of a few hours to a few days. Long term drift describes slow and often irreversible changes over a longer period of time, typically one year. UT-ONE short term and long term drift is specified in the accuracy specifications in the UT-ONE user manual.

Implementing the external standard will remove most of the internal short term and long term drift. Note that the reference resistor also has a specified uncertainty and drift, which must be taken into account instead of the internal drifts. Drift component is the dominant component of the UT-ONE accuracy specification in most practical measurement applications, so its reduction using the external standard will result in a significant improvement of the combined UT-ONE accuracy.

3 Thermistor 10k case study

For the first case study we will examine the case of a NTC thermistor probe with nominal resistance of 10 kohm at 25 °C. The temperature range is from 0 °C to 30 °C, which corresponds to resistance range between approximately 33 kohm and 8 kohm. The application requires best achievable accuracy, preferably bellow 1 mK.

There are several possible approaches to achieve the specified goal, but here we will described our recommended procedure. Considering the resistance range, we will set the measurement range to fixed manual range of 40 kohm (no autoranging). We will set the measurement current to normal value (20 µA). We will use the reference resistor as the external standard. Three values of the reference resistor and an option with no external standard will be evaluated in order to determine their influence on the combined accuracy. Acquisition time will be set to 4 seconds (15 samples).

Effective resolution is under 0.1 mK, which in this case represents a negligible contribution. Adding an external standard worsens the effective resolution, in particular for the 10 kohm reference resistor. For this case study, the effective resolution without external standard was set to 0.025 ohm.

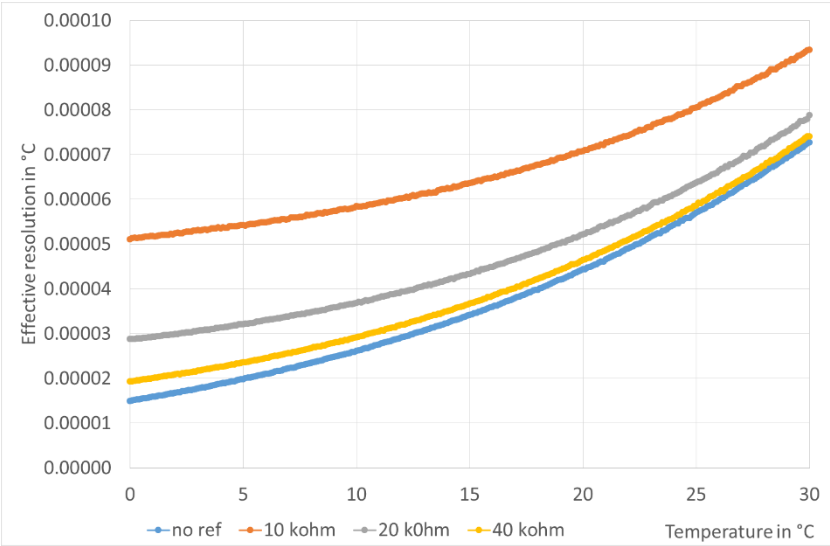

Figure 8: Effective resolution for thermistor probe under given configuration

Implementation of the external resistor significantly reduces the drift component of the UT-ONE accuracy. For this case study, a 20 ppm drift was used for the configuration without the external standard and the accuracy of the reference resistors was set to 3 ppm. Note that the drift component is independent of the value of the reference resistor.

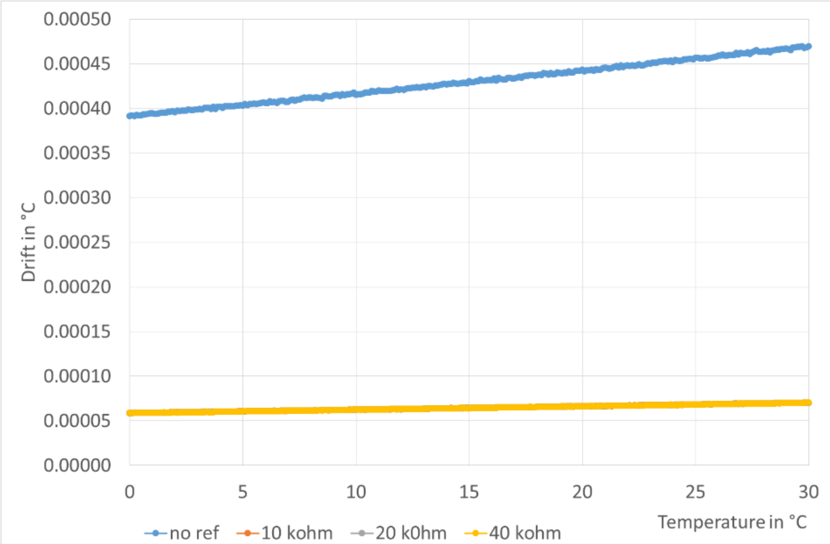

Figure 9: Drift for thermistor probe under given configuration

Linearity error is increased when using the external standards, in particular for the lower values of reference resistors. With the significantly decreased drift contribution, linearity becomes the dominant contribution in the combined uncertainty. For this case study, linearity contribution was 5 ppm of measurement range (0.2 ohm).

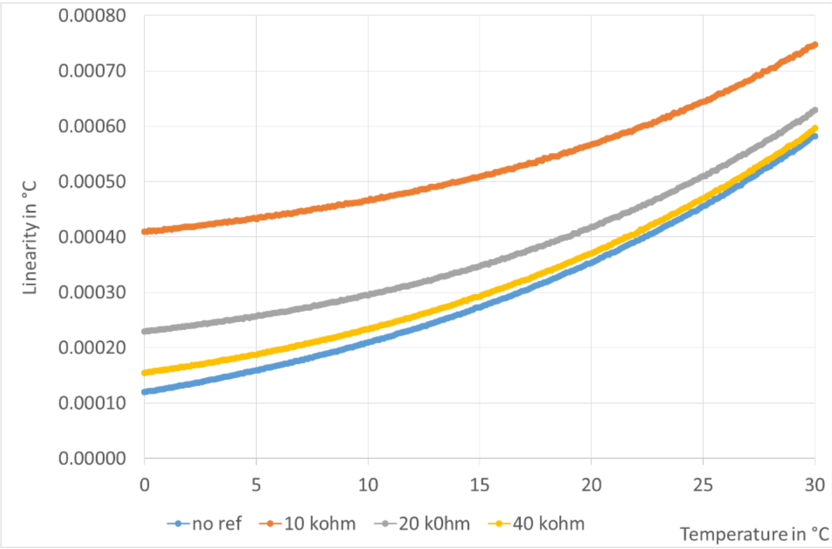

Figure 10: Linearity for thermistor probe under given configuration

The combined accuracy is shows that the accuracy is below the target value of 1 mK. Best results are obtained with the 40 kohm reference resistor, followed closely by the 20 kohm reference resistor. Note that using a 10 kohm reference resistor provides no improvement compared to the configuration without external resistors.

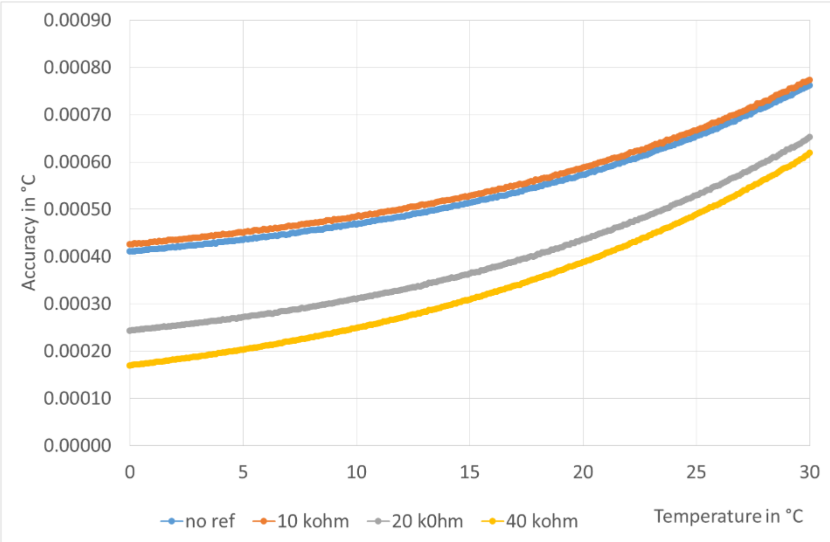

Figure 11: Combined accuracy for thermistor probe under given configuration

As a conclusion, for this case study, the optimal configuration would include the 40 kohm or 20 kohm reference resistor, used as an external standard. In this case, the combined accuracy is less than 0.7 mK over the entire temperature range.

Note that if the thermistor probe was calibrated and then used with the same UT-ONE unit, a large part of the linearity error would be corrected within the thermistor Steinhart-Hart correction equation. In this case the advantage of reduced drift with the implementation of the external standards would become even more significant and the combined accuracy of the UT-ONE unit would be even lower.

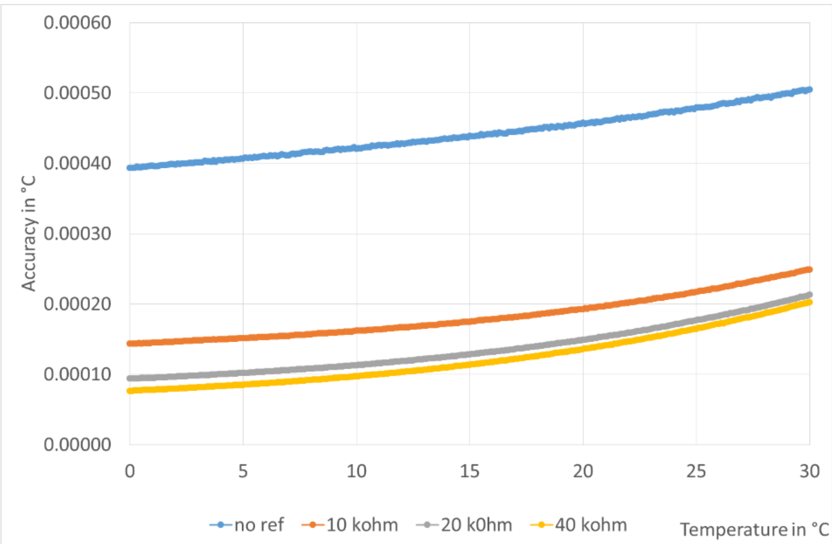

Figure 12: Combined accuracy for thermistor probe calibrated and used with the same UT-ONE unit

4 Pt-25 case study

For the second case study we will examine the case of a Pt-25 SPRT probe with nominal resistance of 25 ohm at 0.01 °C. The temperature range is from -200 °C to 600 °C, which corresponds to resistance range between approximately 4 ohm and 80 ohm. The application requires best achievable accuracy, preferably bellow 2 mK. For this case study, three different configurations will be presented.

4.1 Configuration A

To start, we will try a configuration similar to the one used in the previous case study. Considering the resistance range, we will set the measurement range to fixed manual range of 100 ohm (no autoranging). We will set the measurement current to normal value (1 mA). We will use the reference resistor as the external standard. Three values of the reference resistor and an option with no external standard will be evaluated in order to determine their influence on the combined accuracy. Acquisition time will be set to 4 seconds (15 samples).

Effective resolution is rather large, especially in the case of 25 ohm and 50 ohm reference resistors. In this configuration, the effective resolution without external standard was set to 0.00007 ohm.

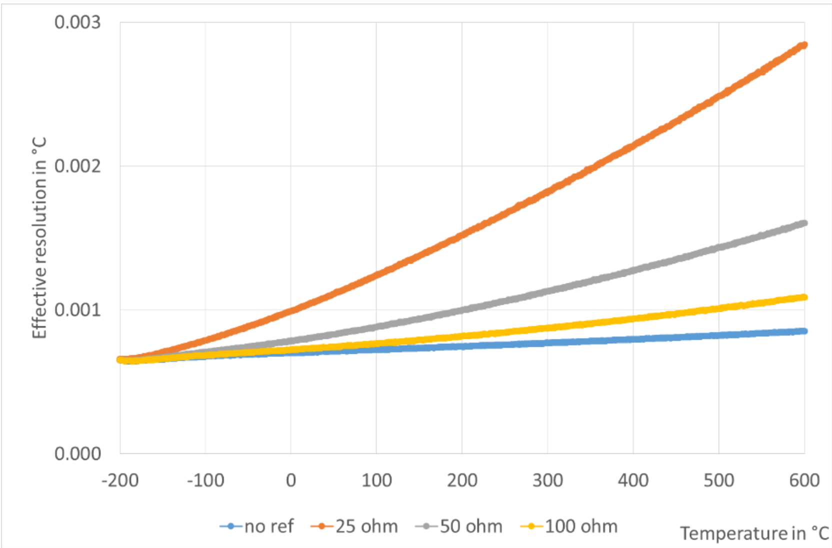

Figure 13: Effective resolution for Pt-25 probe for configuration A

Drift is the dominant contribution to UT-ONE accuracy in the configuration without the external standard. Without the implementation of the external standard, the target accuracy is not achievable. Note that the drift component is independent of the value of the reference resistor. For this case study, a 15 ppm drift was used for configuration without external standard and 2 ppm was used for the accuracy of the reference resistors.

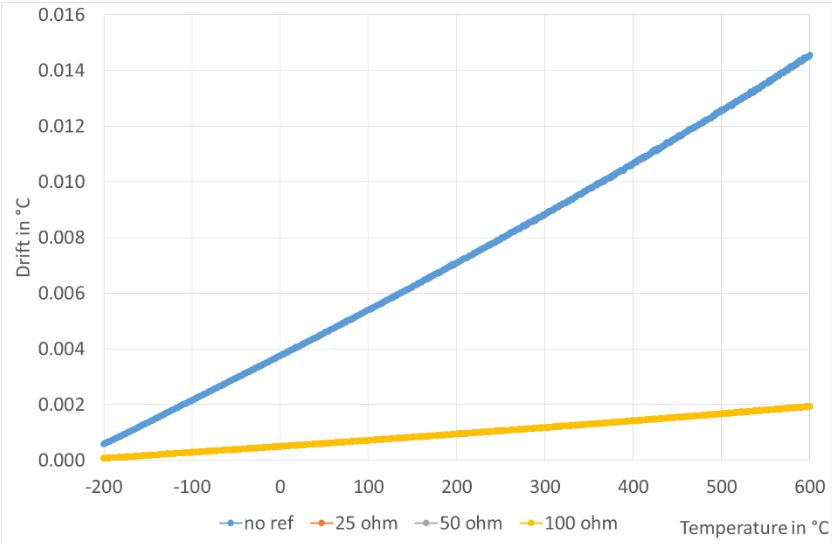

Figure 14: Drift for Pt-25 probe for configuration A

Linearity error is significantly increased when using external standards, so the only realistic option is the use of a 100 ohm resistor. For this case study, linearity contribution was set to 1 ppm of measurement range (0.0001 ohm).

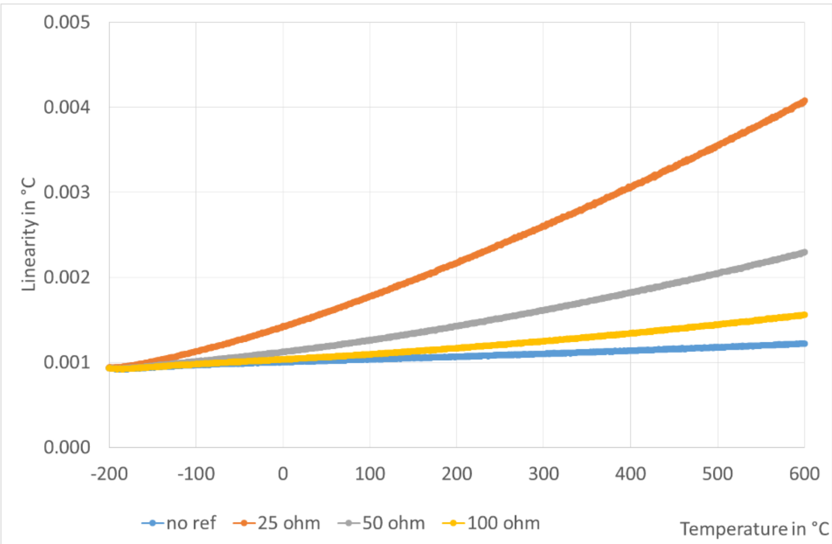

Figure 15: Linearity for Pt-25 probe for configuration B

The combined accuracy is significantly reduced by using the external standards, especially in the case of the 100 ohm reference resistor. The best accuracy is within approximately 3 mK over the entire temperature range, which is a satisfactory result for most practical applications. Note also that apart from implementing an external standard, no other special precautions were taken.

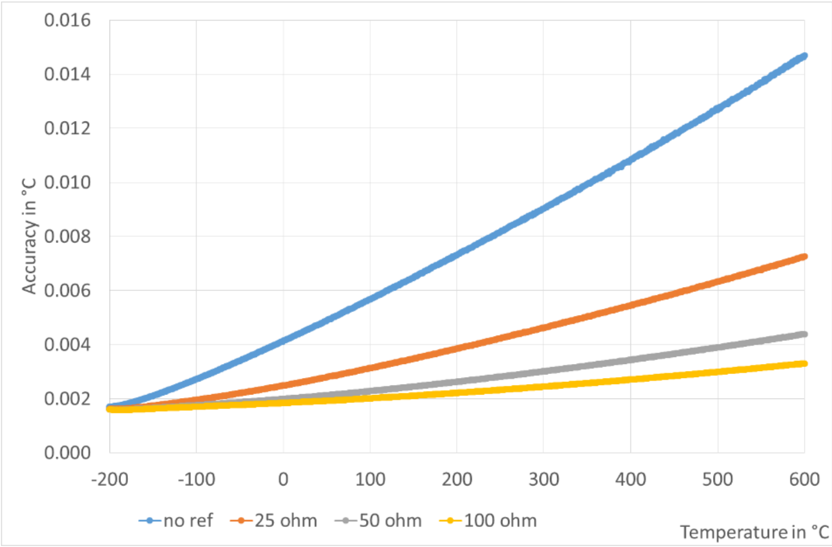

Figure 16: Combined accuracy for Pt-25 probe for configuration A

4.2 Configuration B

Although the accuracy obtained in the configuration A is very good, it still does not meet the target accuracy of 2 mK. In order to come closer to target accuracy, an optimized configuration B is required.

To improve the combined accuracy, the individual components have to be examined.

The effective resolution can be easily improved by increasing the acquisition time from 4 seconds to 10 seconds (40 samples). This improves the effective resolution by approximately a factor of 1.7, so the effective resolution in configuration without the external standard is equal to 0.000042 ohm. Further gains could be achieved by averaging several consecutive readings, but this would have a negligible influence on the combined accuracy.

The linearity is at 1 ppm and cannot be further improved.

The drift can be improved by using the reference resistor with 1 ppm accuracy. Note that this usually requires an ultra-precise reference resistor with excellent thermal stabilization.

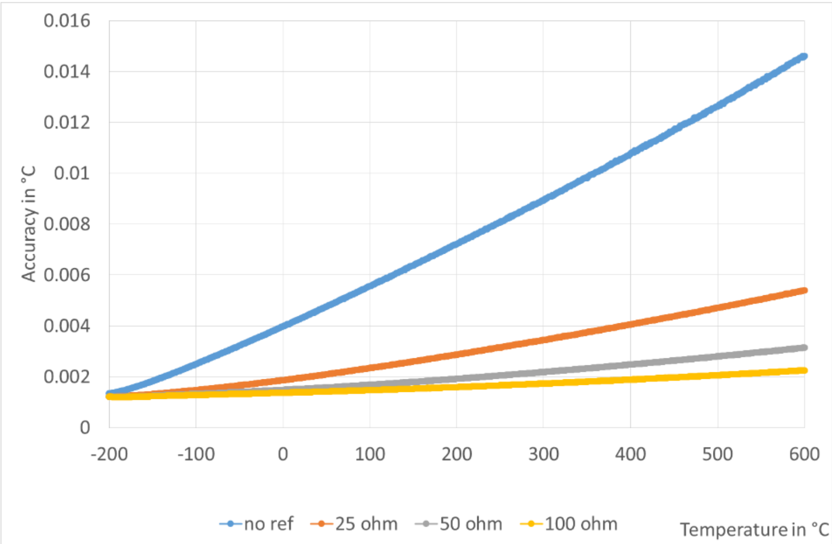

Figure 17: Combined accuracy for Pt-25 probe for configuration B

Optimized configuration resulted in a significantly improved combined accuracy, which is less than 2 mK over most of the temperature range. Accuracy is slightly worse than 2 mK only for temperatures above 500 °C. Note that the configuration B is designed for best accuracy and it may not be possible to achieve it on routine basis.

4.3 Configuration C

Another approach to improve the UT-ONE accuracy would be to reduce the measurement range. Pt-25 probes are often used as reference thermometers in calibration by comparison using calibration baths, which cover a range of up to 250 °C. In this particular case, we can set the UT-ONE measurement range to fixed manual range of 50 ohms. For the sake of this example, we set the acquisition time and resistor accuracy in the same way as in configuration A. Note that 100 ohm external resistor cannot be used, as it is out of 50 ohm range.

Effective resolution without external standard is considerably better on the lower measurement range and was set to 0.000035 ohm.

15 ppm drift was used for configuration without external standard and 2 ppm was used for the accuracy of the reference resistors. Note that this is the same as in configuration A.

Linearity error is 1 ppm of range, but as the range was reduced, the linearity error is also reduced to 0.00005 ohm.

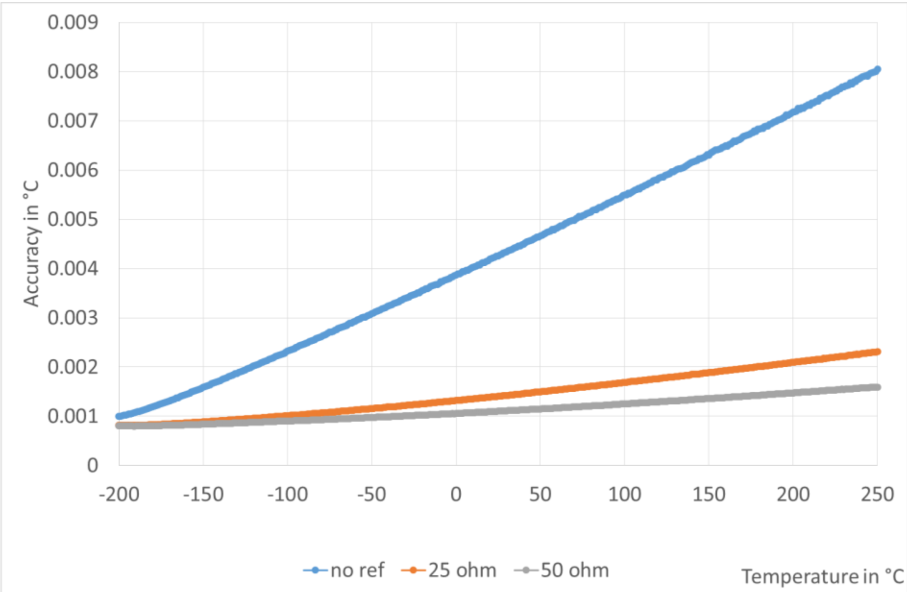

Figure 18: Combined accuracy for Pt-25 probe for configuration C

Combined accuracy for configuration C is well within the target accuracy of 2 mK, but only in a limited temperature range. The improvement is mainly due to improved effective resolution and linearity at the lower measurement range. It should also be noted that the error inherently increases with temperature, so reducing the temperature range will always improve the accuracy specification over entire range.

5 Conclusions

Implementation of the external standard significantly improves the accuracy of the UT-ONE thermometer readout. The value of the reference resistor has a significant influence on the resulting combined uncertainty and should be selected carefully. Note that some of the accuracy contributions are worsened by the implementation of the external standard. We do not recommend the use of reference resistors that are less than 50% of the nominal resistance range limit.

The implementation of the external standard can be summarized in a few simple steps:

1. Determine the thermometer probe and its required temperature range
2. Calculate the resistance limits for the probe temperature range
3. Select the lowest resistance range that covers the entire range for the selected probe. Set the resistance range to fixed manual range (no autoranging)
4. Select the value of the reference resistor. Ideally the value should be equal to the upper limit of the selected resistance range and no less than one half of this value. Note that you cannot measure the reference resistance that is higher than the selected resistance range.
5. Use the normal measurement current. Reduced current should be used only for special applications.
6. Use the 4 second acquisition time (15 samples). Increase it to 10 seconds only if the effective resolution is not satisfactory.
7. Always place the reference resistor near the UT-ONE unit. This way, the temperature correction of the reference resistance will be most effective. Alternatively, place the reference resistor in a thermally-stabilized enclosure and configure its temperature coefficient to 0.
8. Set the external standards configuration and start measuring.

Note that we recommend the use of fixed manual ranges instead of the autoranging in applications with external standards. Although autoranging or even manual selection of different ranges is possible, it will typically result in worse results (and possible overloaded measurements) compared to a simple fixed manual range. On the other hand autoranging is very useful in applications without the external standard, as it takes full advantage of the available accuracy for each measurement range.

The most useful values of external resistors would be:

- 25 ohm, 100 ohm and 400 ohm for the PRT range
- 1 kohm, 5 kohm and 20 kohm for the thermistor range

With this set of resistors you can cover each of the UT-ONE resistance ranges. Note that these values are also useful for the UT-ONE recalibration.