Determining the Uncertainties Associated with Mapping

By Dubhaltach Mac Lochlainn, National Standards Authority of Ireland (NSAI) – National Metrology Laboratory (NML), www.NSAI.ie/nml

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In order to ensure the accuracy of the mapping process, a detailed uncertainty analysis should be performed on the measurements. By determining the contributions to the uncertainty of measurement, and listing them in what is known as an uncertainty budget, an assessment can be made of the quality of the measurements.

As per international best practice [1], uncertainty is normally represented by a single value, which is calculated by combining estimates of all the factors which contribute to the overall uncertainty of measurement. This value is calculated using the following formula:

$$U_{total} = \sqrt{{u_1}^2 + {u_2}^2 + {u_3}^2 \ldots\ldots + {u_n}^2}$$

Where U_{total} is the total uncertainty and u_x are the individual uncertainty components. This value is then multiplied by $k = 2$, to provide 95% confidence in the uncertainty estimate, as per normal statistical techniques.

Each uncertainty component is either obtained by statistical means (type A contributions) or by other means, such as a specification provided by a manufacturer (type B components). Type A contributions are already statistically normalised, whilst as type B contributions need to be divided by $\sqrt{3}$ to convert from rectangular to normal distributions. Some, or all of the instrument and probe characteristics may be obtained from the manufacturer, in which case their empirical evaluation is not required.

The components detailed below should be accounted for in the uncertainty budget for mapping. They are inserted into the uncertainty budget as a plus or minus (±) value, and represent the characteristics of the instrument and probes used in the mapping process.

Calibration Uncertainty

All instruments used in a mapping process should be calibrated by an accredited laboratory, who provide a value for the uncertainty of calibration on their certificates. If the thermometer readout and probes are calibrated separately, uncertainties for each should be included in the budget. The uncertainty value obtained from the calibration certificate is stated at 95% (k = 2) confidence, and therefore needs to be divided by two to obtain the normalized value.

Instrument Resolution

The accuracy of measurements displayed by the readout are dependent on the resolution of the display. For example, if the true value is 4.95°C, but the resolution is 0.1°C, the display will indicate 5.0°C. Conversely, if the true value is 4.94°C, the display will indicate 4.9°C. For this reason, half the resolution of the readout should be incorporated into the uncertainty budget.

Drift

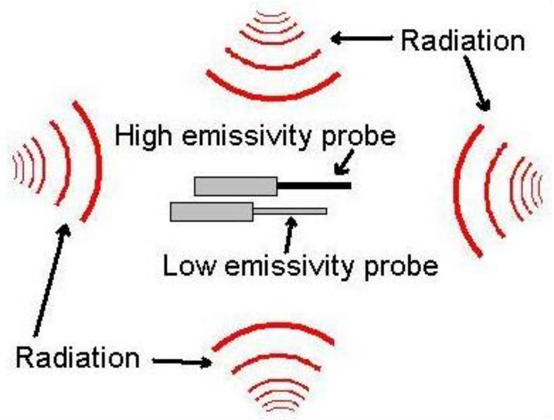
The accuracy of all instruments change over time. The conditions of use (such as the treatment of the probes and temperature extremes to which they are exposed) will affect this rate of change. The manufacturer will normally be able to give an estimate of the expected drift on a particular instrument. An alternative source for this information is the calibration history. Two or more sets of calibration measurements can be compared in order to determine the maximum expected drift between calibrations. This value can then be incorporated into the uncertainty budget.

Repeatability

There are many factors which affect a set of measurements, leading to variation when the same conditions are replicated and repeat measurements are taken. This is mainly due to environmental variation (temperature, humidity, electrical noise). In order to quantify this value, two sets of measurements can be taken under the same conditions, and the difference between them taken as the uncertainty component.

Radiation Effect

This is the influence of thermal radiation on the probe temperature, which could lead to erroneous readings with respect to the air temperature in the enclosure. For temperatures from 0°C to 50°C, the radiation effect can be assumed to make a maximum contribution of 0.3°C to the measurement uncertainty [2]. Beyond this range, the effect can be evaluated by comparing identical probes whose emissivities have been altered in an enclosure. The easiest way of doing this is by painting one probe matt black, and polishing the other, and placing both in the centre of the enclosure. The difference between the readings is a measure of the radiation effect.



Hysteresis (for Pt100 Probes only)

Like all sensors, temperature probes may be influenced by the direction in which the temperature change is occurring. If not available from the probe manufacturer, this effect is assessed by measuring temperature set points in both ascending and descending order with the same probe, using a stable calibration medium. The difference between the readings at any one temperature is the hysteresis effect for that probe.

Self-Heating

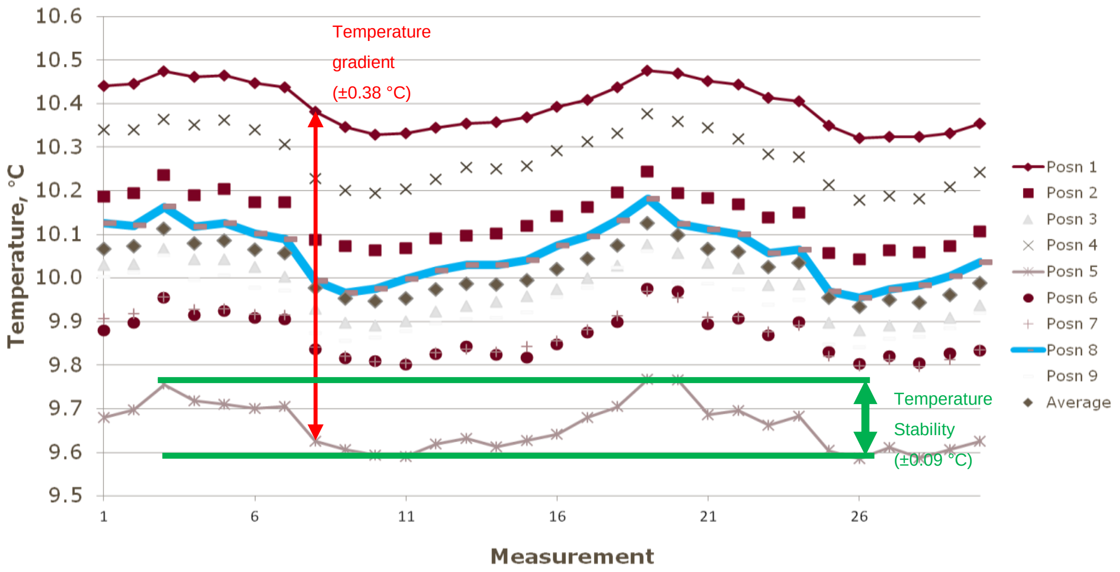
The current passing through a probe has the effect of heating it, and therefore gives an artificially high reading. A value for the self-heating effect can normally be obtained from the manufacturer. Alternatively, a zero power analysis will determine the difference in readings due to varying the probe current input. This can then be extrapolated back to give the value which would be obtained if zero current were used.

Temperature Gradients

Significant variations in temperature occur from one point to the next within the enclosure. These variations should be factored into the uncertainty, to account for variations in the whole volume of the enclosure. The data obtained during the mapping process can be used to calculate the gradients, based on the maximum of the differences between the measured points within the working space at a moment in time. Alternatively, where the uncertainty is being estimated at each location separately (such as where monitoring is carried out using multiple probes), a small separation (approximately 1 cm) between two probes may be used to give a value for the local gradients within the vicinity of the probe.

Stability

Temperature variations can occur within an enclosure in time, which contribute to the uncertainty of measurement during the mapping process. The stability can be evaluated using data obtained during the mapping process, and should consist of a minimum of 30 readings over a period of 30 minutes.



Loading Effect

The proportion of volume consisting of air can lead to variations in the stability and response of the probes. If the loading effect is to be factored into the uncertainty, it is done by taking measurements at each location in both the loaded and unloaded state. If the mapping is to cover only one state, this should be noted in the report, and the loading effect need not be included in the uncertainty budget.

Overall Uncertainty

The uncertainty statement should specify:

- Which of the above components have been left out of the uncertainty budget.
- Whether the uncertainty is for individual locations (as is the case when the enclosure is monitored), or for the entire chamber.

Example of Expanded Uncertainty for Mapping

The uncertainty budgets below have been developed for two different mapping scenarios. Each budget is carried out as per the Guide to the expression of Uncertainty in Measurement, published by the BIPM [1], giving the expanded uncertainty at the bottom. Budgets should be prepared for each temperature at which mapping is carried out.

The first budget applies to an enclosure which is monitored by internal probes. The reference probes were placed next to the monitoring probes and the mapping relates to the individual measuring locations within the enclosure. The load in the enclosure varies, therefore the loading effect has been included in the uncertainty.

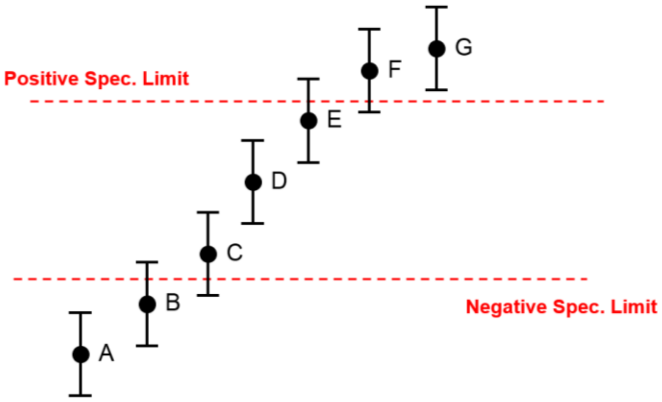
Input Quantity	Max Variation	Probability Distribution	Divisor	Uncertainty Contribution
	(±°C)			(±°C)
System Calibration	0.024	Normal	2	0.012
System Drift	0.050	Rectangular	√3	0.029
Resolution	0.005	Rectangular	√3	0.003
Repeatability	0.032	Rectangular	√3	0.018
Hysteresis	0.021	Rectangular	√3	0.012
Self-Heating	0.002	Rectangular	√3	0.001
Radiation Effect	0.025	Rectangular	√3	0.014
Stability	0.094	Rectangular	√3	0.054
Loading Effect	0.358	Rectangular	√3	0.207
		Standard Uncertainty		0.218
		Expanded uncertainty (k = 2)		0.436

The next budget applies to a mapping carried out on the empty working volume of an enclosure, using nine probes. In this case, the loading effect has not been accounted for, and this should be stated on the report.

Input Quantity	Max Variation	Probability Distribution	Divisor	Uncertainty Contribution
	(±°C)			(±°C)
System Calibration	0.024	Normal	2	0.012
System Drift	0.050	Rectangular	√3	0.029
Resolution	0.005	Rectangular	√3	0.003
Repeatability	0.032	Rectangular	√3	0.018
Hysteresis	0.021	Rectangular	√3	0.012
Self-Heating	0.002	Rectangular	√3	0.001
Radiation Effect	0.025	Rectangular	√3	0.014
Stability	0.094	Rectangular	√3	0.054
Loading Effect	0.299	Rectangular	√3	0.097
		Standard Uncertainty		0.186
		Expanded uncertainty (k = 2)		0.372

Although it is not always possible to quantify all the components listed above, a reasonable estimate should be given for each, and they should be kept in mind when purchasing new measurement equipment. The largest components in most uncertainty budgets are the stability, gradients and loading effect, all of which can be assessed during the mapping process and do not require any additional specialist equipment.

Where pass/fail criteria are being determined through the mapping process, the uncertainty of the measurements should be included in the results. In particular, where measurements are found to be close to the specification limit, it is important that the uncertainty of measurement is considered before a pass/fail statement is made. For example, in the figure below, a series of measurements are displayed (the black dots), along with their respective uncertainties (the error bars above and below each measurement).



In this illustration, only measurement D would meet the specifications. Measurements A and G are the only measurements which are definitely beyond the specification, but all others may either be in, or out of specification.

This guide does not intend to provide an exhaustive explanation of measurement uncertainty, but merely touches on the areas relating to temperature mapping. For a more comprehensive understanding of uncertainty, guidance and resources are available from National Metrology Institutes and accreditation bodies [3, 4].

References

1. JCGM 100:2008 Joint Committee for Guides in Metrology., “Guide to the expression of uncertainty in measurement,” 12 April 2008. [Online]. Available: www.bipm.org.
2. Deutscher Kalibrierdienst, “DKD-R 5-7,” 13 07 2004 (English Translation: 2009). [Online]. Available: http://www.dkd.eu/dokumente/Richtlinien/dkd_r_5_7_e.pdf. [Accessed 13 April 2016].
3. S. Bell, “A Beginner's Guide to Uncertainty of Measurement,” 08 2001. [Online]. Available: https://www.wmo.int/pages/prog/gcos/documents/gruanmanuals/UK_NPL/mgpg11.pdf. [Accessed 14 April 2016].
4. JCGM 106:2012 Joint Committee for Guides in Metrology, “Evaluation of measurement data – The role of measurement uncertainty in conformity assessment,” 10 2012. [Online]. Available: http://www.bipm.org/utils/common/documents/jcgm/JCGM_106_2012_E.pdf. [Accessed 14 April 2016].