Beamex

Calibration White Paper

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Calibration uncertainty for non-mathematicians

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WORLD-CLASS CALIBRATION SOLUTIONS

Calibration uncertainty for non-mathematicians

This paper discusses the basics of uncertainty in measurement and calibration. It is not made for mathematicians or metrology experts, but rather for those of you who are planning and making practical measurements and calibrations in industrial applications.

Being aware of the uncertainty related to the measurement is a very fundamental concept. ***You should not really make any measurements unless you are aware of the related uncertainty.*** Generally speaking, it seems that the awareness and interest of uncertainty is growing, which is great.

The uncertainty of measurements can come from various sources, such as the reference measurement device used for making the measurement, from environmental conditions, from the operator making the measurements, and from many others sources.

There are several calibration uncertainty guides, standards and resources available, mostly full of mathematical formulas, so in this article I will try to keep the mathematic formulas to a minimum.

This is a practical guide to gain some general understanding in the great world of uncertainty in measurements and calibrations.

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Classic "piece of string" example

Let's start with an example to illustrate the measurement uncertainty in practice; the example is to give the same piece of a string to three persons (one at a time) and ask them to measure the length of that string. With no additional instructions given. They can all use their own tools and methods to measure it.

More than likely, as a result, you will get three somewhat different answers, such as:

- The first person says it is about 60 cm. He used a 10 cm plastic ruler, measured the string once and came to this conclusion.

- The second person says it is 70 cm. He used a three meter measuring tape and checked the results a couple of times to make sure he was right.

- The third person says it is 67.5 cm, with an uncertainty of ±0.5 cm. He used an accurate measuring tape and measured the string multiple times to get an average and standard deviation. Also, he tested how much the string stretches when it is pulled and noticed that this had a small effect on the result.

Even this simplified example shows that there are many things that affect the result of a measurement; the measurement tools that were used, the method/process that was used and the way the person did the job.

So, the question you should be asking yourself is:

When calibration work is performed at your plant, which of these three examples sound the most familiar to you?

What kind of "rulers" are being used at your site and what are the measuring methods/processes?

If you just measure something once without knowing the related uncertainty, the result is not worth much.

Very short terminology course

Let's take a very brief look into the essential terms related to this subject.

So, what is the ***uncertainty*** of measurement? We can simply say that it is the "doubt" of our measurement, meaning that it tells us how good our measurement is. Every measurement we make has some "doubt", and we should know how much this "doubt" is, in order to decide if the measurement is good enough for the purpose.

It is good to remember that ***error is not the same as uncertainty***. When we compare our device to be calibrated against the reference standard, the error is the difference between these two measurements. But the error does not have any meaning unless we know the uncertainty of the measurement.

So I would like to say that:

If you don't know the uncertainty of the measurement, don't make the measurement at all!

Too often we have seen, for example, that when a person is making an important temperature measurement in his process with, say, ±1.0 °C acceptance limit, and finds a maximum error of 0.5 °C, he is happy and says it "passes" and accepts the result. Although, after analyzing the calibration process, he could find that the total uncertainty of his measurement process is ±2.0 °C. So the way the calibration was done was not good enough for this application.

But ***as long as he did not know/care about the uncertainty, he could claim that it was a good "passing" calibration,*** although in reality, it failed.

From making a single measurement to knowing your standard deviation

So, what should you do to start the journey towards being aware of all the related uncertainties?

The first simple, yet good, practice is that when you normally make a measurement/calibration once, try instead to repeat the same measurement several times. Most likely you will discover small differences in the measurements between the repeats. But which measurement is the correct one?

Without diving too deep into statistics, we can say that it is not enough to measure only once. If you repeat the same measurement several times, you can find the average and the standard deviation of the measurement. So you will learn how much the results can differ between repeats. This means that you can find out what is the normal difference between measurements.

It is suggested to make a measurement multiple times, even up to ten times, for it to be statistically enough reliable to calculate the standard deviation. These kind of uncertainty components, that you get by calculating the standard deviation, are called the ***A-type uncertainty.***

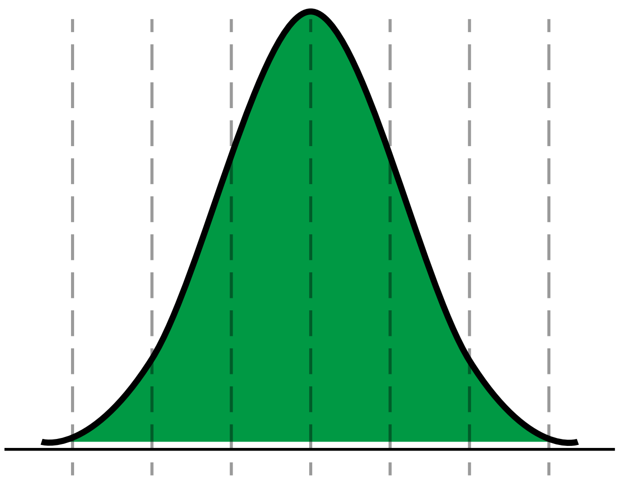


Diagram: Standard deviation

You may say: ***What???*** - Always repeating the same measurement ten times is just not possible in practice!

Luckily you don't always need to make ten repeats, but you should still experiment with your measurement process by sometimes making several repeats of the same measurement. This will tell you what the typical deviation of that whole measurement process is and you can use this knowledge in the future as an uncertainty component related to that measurement, even if you just make the measurement once during your normal calibration.

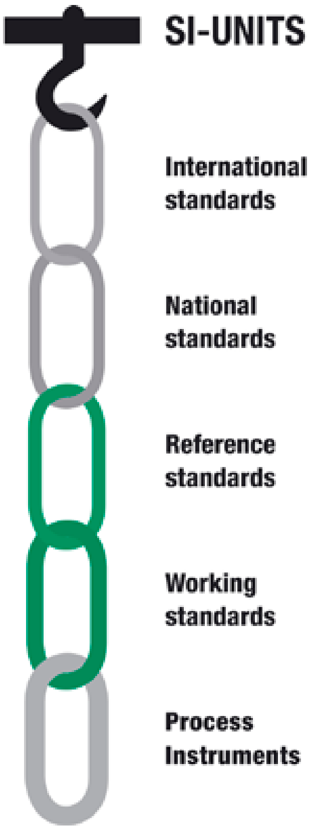
Imagine that you would perform a temperature measurement/calibration multiple times and you would learn that there could be a ±0.2 °C difference between the repeats. Next time you would make the same measurement, even if you would then make it just once, you would be aware that there is this ±0.2 °C possible difference, so you could take it into account and don't let the measurement go too close to the acceptance limit.

So if you keep calibrating similar kinds of instruments over and over again, it is often enough to make the measurement just once and use the typical experimental standard deviation. Of course you need to do your homework and make the measurements and the calculations to find out the typical standard deviation of that instrument type and that calibration process.

In summary, ***you should always be aware of the standard deviation of your calibration process – it is one part of the total uncertainty.***

Your reference standard (calibrator) and its traceability

Often, ***one of the biggest sources of uncertainty comes from the reference standard*** (or calibrator) that you are using in your measurements/calibrations. Naturally to start with, ***you should select a suitable reference standard*** for each measurement. It is also important to remember that it is not enough to use the manufacturer's accuracy specification for the reference standard and keep using that as the uncertainty of the reference standards for years. Instead ***you must have your reference standards calibrated regularly*** in a calibration laboratory that has ***sufficient capabilities (uncertainty small enough)*** to calibrate the standard and to make it traceable. Pay attention to the total uncertainty of the calibration that the laboratory documented for your reference standard. Also, you should ***follow the stability of your reference standards*** between its regular calibrations. After some time, you will learn the true uncertainty of your reference standard and you can use that information as the uncertainty of your reference standard in your calibrations.



Other uncertainty sources

In the previous section I suggested that you repeat the measurement several times. But how about if you ask ***a few of your colleagues to repeat that same measurement?*** Do you all get the exact same results? Often there are some differences between the different persons making the measurement. So, does it mean that the person making the measurement also have an effect to uncertainty? – yes, it does. This is especially the case if the instructions are not at an appropriate level.

What if you make the same test and this time you ***use different kind of reference standards (calibrators) to make the measurement?*** Again, most likely you will find differences. And if the reference standards have different levels of accuracy (uncertainty) you may even see relatively big differences. Often the reference standard (or calibrator) used to make the measurement can be ***one of the biggest sources of uncertainty!***

Different environmental conditions may add additional uncertainty in certain calibrations.

If you need to read some form of analog display (analog gauge, temperature meter), you have limited ***readability***, i.e. you can only read it to certain accuracy and there is a possibility to read it incorrectly (wrong viewing angle) which ads uncertainty. In case of digital readouts, the ***resolution*** (number of decimals) is always limited, which causes uncertainty (you can only read to the last decimal).

There are different technical aspects in the calibration process, applications and quantities that create additional uncertainties. For example in temperature calibration, it is imperative to wait long enough for the temperature to stabilize and to assure proper probe immersion into temperature block; in flow calibration you need to ensure a stabile flow; in pressure calibration you must avoid any leaks and have a stabile pressure, etc. Generally, any fluctuations or changes in the variable to be measured will cause additional uncertainty.

There are also some ***random variables*** that throw in some additional spices to the soup.

Also, you can use the ***experimental standard deviation*** mentioned earlier as one uncertainty component.

So we can shortly ***summarize*** these additional sources of uncertainty:

- Device under test
- Reference standard (calibrator)
- Method/process for making the measurements/calibrations
- Environmental conditions
- The person(s) making the measurements
- Additional uncertainty components depending on the quantity being measured/calibrated

All of these above listed uncertainty components are referred as the ***Type B uncertainty***.

Adding uncertainties together => combined uncertainty

The type A (standard deviation) is something you can calculate, but often some of the various type B uncertainties needed to be estimated. Once standard deviation is calculated and the various Type B uncertainties are estimated, it is time to add them together. Before that you need to make sure that all uncertainties are in the same quantity/unit. Also, the uncertainties should be having the same ***coverage factor/ confidence level.***

When you add together uncertainty components that are independent from each other, don't just sum them all together, that would make a too pessimistic (worst-case) result. Instead, add the components together using ***the root sum of the squares*** method. That means, square each component, then sum them together and finally take a square root of the total sum. Although I said no formulas, maybe it is anyhow easier to understand this with a relatively simple formula:

Total uncertainty =

$$\sqrt{u_{(1)}^2 + u_{(2)}^2 + \ldots + u_{(n)}^2}$$

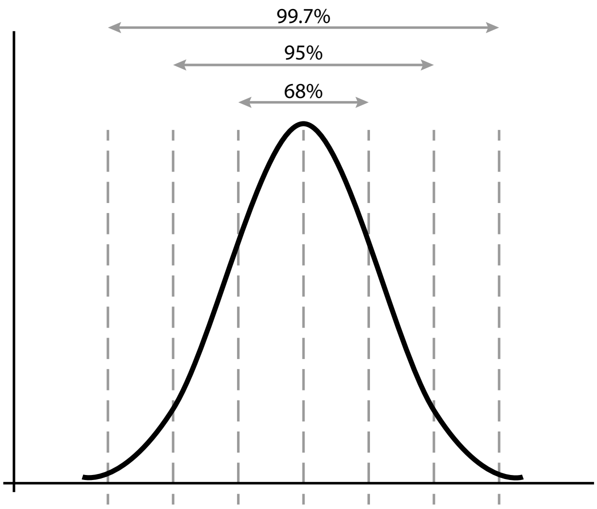
Where each "u" is one independent uncertainty component.

Coverage factor/confidence level

When uncertainty is determined, it is typically multiplied with a ***coverage factor (k)***. Most often the combined uncertainty is multiplied with 2 (k=2 or 2 sigma). This multiplication is done in order to have greater ***confidence level*** of the result. When the coverage factor of 2 is used, it equals a confidence level of 95%. This is done because we are dealing with statistical data and according ***normal (Gaussian) distribution*** 95% of the results are within the 2 sigma range. So in practice, using the 2 sigma, 95% of the results will be within the given uncertainty budget. Different sigma values give the following confidence levels:

- 1 sigma (k=1) = 68% confidence level (68% of the results are within)
- 2 sigma (k=2) = 95% confidence level
- 3 sigma (k=3) = 99.7% confidence level

Normal (Gaussian) distribution



When you add different uncertainty components together, make sure they are all the same 1 sigma values before adding them.

Expanded uncertainty

Before the combined uncertainty component is published, you need to multiply the result with the selected sigma value in order to get the required confidence level. After you have done the multiplication, what you get is called ***expanded uncertainty***, i.e. uncertainty with certain confidence level included.

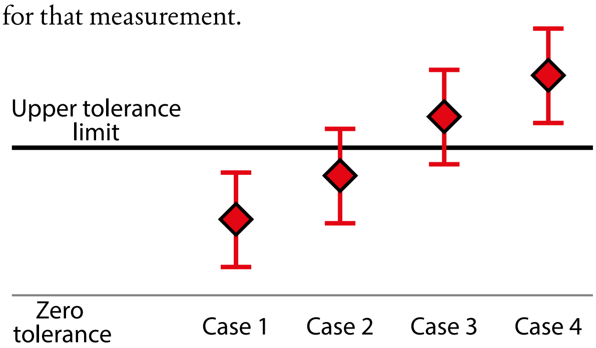
How to express uncertainty in results or calibration certificate

In your calibration results, you should express the uncertainty as ± value and also mention the coverage factor/confidence level. For example you can say that the temperature is: 20.5 °C with uncertainty ±0.1 °C (k=2).

Compliance statement – pass or fail

Most often the calibration of an instrument includes an acceptance criteria, i.e. there are limits within which the result is considered being ***passed*** and outside of which it is considered being ***failed***. There are different interpretations if/how the uncertainty should be taken into account when deciding for Pass/Fail.

Let's use some examples to study different cases. In the below picture, the diamond shape illustrates the measurement result and the line above and below indicates the total uncertainty for that measurement.



We can interpret these different above cases as following:

- **Case 1:** This is pretty clearly within the tolerance limits, even when uncertainty is taken into account. So we can state this as a good "Pass" result.
- **Case 4:** This is also pretty clear case. The result is outside of the tolerance limits, even when uncertainty is taken into account. So we can state this being a bad or "Fail" result.
- **Case 2** and **Case 3:** These cases are a bit more difficult to judge. Sure it seems that in case 2 the result is within the tolerance while in case 3 it is outside, especially if you don't care about the uncertainty. But taking the uncertainty into account, we can't really say this with confidence.

There are regulations (for example; ILAC G8:1996 - Guidelines on Assessment and Reporting of Compliance with Specification; EURACHEM / CITAC Guide: Use of uncertainty information in compliance assessment, First Edition 2007) for how to state the compliance of calibration. These guides suggests to state a result as passed only when the error added with uncertainty is less than the acceptance limit. Also, they suggest to state failed only when the error added (or subtracted) with the uncertainty is bigger than the acceptance limit. When the result is closer to the acceptance limit than half of the uncertainty, it is suggested to be called an "undefined" situation, i.e. you should not state pass or fail.

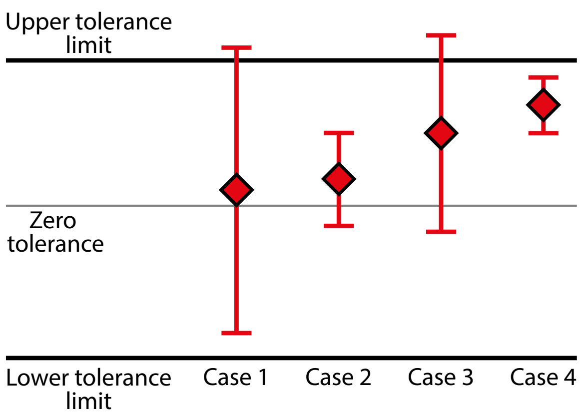
We have seen many people interpreting the uncertainty and pass/fail decision in many different way over the years. In practice, the uncertainty is most often not taken into account in the pass/fail decision, but it is anyway very important to be aware of the uncertainty, when making the decision.

Uncertainty examples

In the graphics below, there are some examples of what different uncertainties can mean in practice.

The cases 1 and 2 have the same measurement result, so without uncertainty we would consider these being the same level measurements. But when the uncertainty is taken into account, we can see that case 1 is really terrible because the uncertainty is simply too large to be used for this measurement with the given tolerance limits.

Looking at case 3 and 4 it seems that the case 3 is better, but with uncertainty we can see that it is not good enough for a pass statement, while the case 4 is.



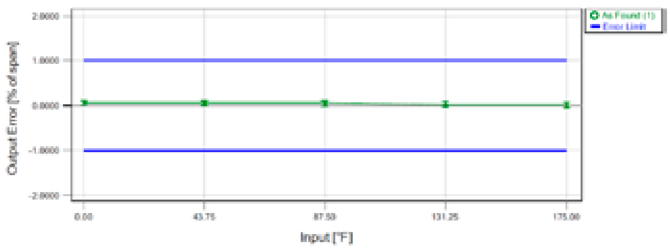
Again I want to point out that ***we need to know the uncertainty before we can judge a measurement result.*** Without the uncertainty calculation the above cases 1 and 2 look similar, although with uncertainty taken into account they are very different.

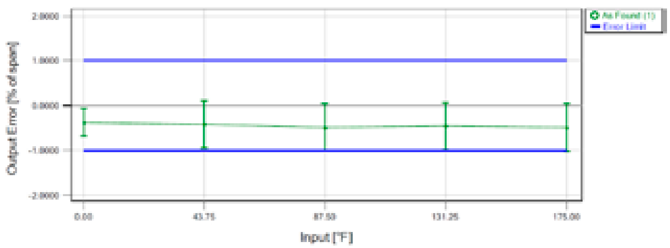
A real-life example

Below is a real-life example where the same RTD temperature transmitter has been calibrated using two different calibrators. This graphics were produced using [Beamex CMX calibration management software]. You can easily see that in the first case, the results is very good and also the green vertical uncertainty line is very short indicating a very small uncertainty. In the second case you can see that the result is a little bit worse, but the uncertainty of that calibrator is much worse.

Well, needless to say, that the first case is done with a Beamex calibrator… ;-)

Anyhow, when you see the uncertainty graphically it is very easy to notice the significance of it.





TUR / TAR ratio vs. uncertainty calculation

The ***TUR (test uncertainty ratio)***, or ***TAR (test accuracy ratio)***, is often mentioned in various publications. In short this means that if you want to calibrate a 1% instrument and you want to have 4:1 ratio, your test equipment should be 4 times more accurate, i.e. having 0.25% accuracy, or better. Some publications suggest that having a TUR/TAR ratio large enough, there is no need to worry about uncertainty estimation/calculation. The quite commonly used ratio is 4:1. Some guides/publications do also have recommendations for the ratio.

Most often the ratio is used as in the above example, i.e. just to compare the specifications of the DUT (device under test) and the manufacturer's specifications of the reference standard. ***But in that scenario you only consider the reference***

standard (test equipment, calibrator) specifications and you neglect all other related uncertainties. While this may be "good enough" for some, calibrations, this system does not take some of the biggest uncertainty sources into account. So it is highly recommended to make the uncertainty evaluation/calculation of the whole calibration process.

We also get asked quite regularly: "How many times more accurate should the calibrator be, compared to the device to be calibrated?". While some suggestions could be given, there isn't really any correct answer to that question. Instead you should be aware of the total uncertainty of your calibrations. And of course, it should reflect to ***your needs!***

SOME USEFUL RELATED RESOURCES

- EA-4/02 - Evaluation of the Uncertainty of Measurement in Calibration
- ILAC G8:1996 - Guidelines on Assessment and Reporting of Compliance with Specification
- EURACHEM / CITAC Guide: Use of uncertainty information in compliance assessment, First Edition 2007
- ISO/IEC 17025:2005 - General requirements for the competence of testing and calibration laboratories
- ISO 9001:2015 - Quality management systems -- Requirements
- ISO 10012:2003 - Measurement management systems -- Requirements for measurement processes and measuring equipment
- JCGM 101:2008 - Evaluation of measurement data — Guide to the expression of uncertainty in measurement

SUMMARY

I hope this paper helped to give some practical understanding of the uncertainty subject.

To very shortly summarize the key take-outs of some of the main topics:

- Be sure to distinguish "error" and "uncertainty"
- Experiment by making multiple repeats of measurements to gain knowledge of the typical deviation
- Use appropriate reference standards (calibrators) and make sure they have a valid traceability to national standards and that the uncertainty of the calibration is known and suitable for your applications
- Consider if the effect of the environmental conditions have a significant effect to the uncertainty of your measurements
- Be aware of the readability and display resolution of any indicating devices
- Study the specific important factors of the quantities you are calibrating
- Familiarize yourself with the "root sum of the squares" method to add independent uncertainties together
- Be aware of the coverage factor / confidence level / expanded uncertainty, of the uncertainty components
- Instead, or in addition to the TUR/TAR ratio, strive to be more aware of all the related uncertainties
- Pay attention to the total uncertainty of the calibration process before making pass/fail decisions

If you have any comments or questions, and I hope you do, we are very happy to hear from you!
Contact us, www.beamex.com or marketing@beamex.com