VAISALA

CALIBRATION BOOK

DOC213538EN-B

Published By
Vaisala
www.vaisala.com

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Scope

In today's knowledge driven world we want to understand and control things based on real data. Performing measurements with measurement equipment is one part of this quest in various fields. However, having measurement equipment in place is only part of the picture. One should always make sure that the data produced by the measurement equipment is reliable and accurate. Naturally the measurement equipment must also fit the purpose and be used in a correct way.

This book was written to help the readers with the measurements they perform. The intent is to help the readers and their organizations determine the most appropriate activities that ensure the quality of their measurements. We hope this book provides the readers with a framework in which to place their own activities.

This book serves as a generic introduction to calibration. We discuss the rationale behind calibration, and the factors that affect the need to calibrate. The book also provides some specific information on calibration of relative humidity, dewpoint temperature, temperature, and barometric pressure.

Introduction

What Time Is It?

It is a simple question but the answer is not so simple. What time is it exactly and how do you know it?

Most people are used to calibrating and adjusting their watches whenever necessary. Working standards (i.e. clocks) are visible almost everywhere and making a comparison calibration is easy and almost an unconscious act. If the watch has drifted, we adjust it according to the reference that we trust. An official time is often available via television or Internet.

Calibration and adjustment against official time provides us the traceability for time. Imagine how the world would operate if we did not have a common source for time? Everybody would have his or her own interpretation of time. Trains and planes would leave by the definition of time the operating companies use, and passengers would either catch or miss their carriage depending on time on their wristwatches.

So perhaps calibration is not such a difficult topic. We actually do it in our private and working life all the time, and it is important, is it not?

The International System of Units (SI)

From global perspective all measurements are based on the globally agreed International System of Units (SI). This ensures that we use the same quantities, and that measurements performed with various types of equipment in various locations are comparable. The further we are from the International System of Units (SI) the higher uncertainty we have in the measurement in terms of absolute accuracy.

To learn more visit the website of International Bureau of Weights and Measures (BIPM) http://www.bipm.org/en/si/

Why the Measurements are Needed

Things are measured for the information the measurement provides, not for the sake of measuring itself. The key factor about measurement is to understand when it is important to truly know the reliability of measurement results.

The value of information determines the requirements for appropriate metrological confirmation processes. These requirements influence the choice of the measurement equipment and calibration practices.

How then do we define the value of information obtained? It comes from why you need the information the measurement provides. The following are some examples.

Measurement Results Have High Economical Impact

Example: Running parameters of a process are well known. A temperature difference of 0.1 °C from the optimum of 48 °C produces 1 % more unacceptable process outcome (i.e. scrap). It is quite easy to calculate financial effect of the error in the measurement.

The example above is also good for explaining the importance of traceability. The optimum temperature of the process should be based on a known temperature, not just based on the displayed value of one particular thermometer. The knowledge of optimum process conditions must be based on traceable measurements. This is highly important in the event that the thermometer fails and needs to be replaced with a new one.

In volume based trade the economical impact is simple: If you measure incorrectly, you also invoice incorrectly and may also end up with costly discussions with your customer.

Legislation or Other Industry Authorities May Require Measurement

Whether you buy potatoes for dinner or gasoline for your car, the companies who sell their products charging by volume are required to verify their instrumentations that act as basis for their invoicing. This protects the customer´s rights to get the correct volume of product, but also the supplier is getting the money for everything supplied.

There are also several standards and industry specific regulations that give advice and sometimes direct requirements for calibration.

Measurement Results are Connected to Health, Safety or Environmental Risks

Measurements may be in place to protect employees from occupational health hazards. There are various quantities measured, such as toxic concentrations for different gases. For example, working conditions must be kept under certain limits. Reliable measurements in this area are vitally important and no compromises should be made.

An example of a health risk is the manufacturing of food. The product must be sterilized in certain temperatures to kill bacteria. The measurements to prove this must be reliable.

Many health, safety, and environmental risk-related measurements are also required by legislation or industry standards.

Measurement Results are Used to Obtain Research Results

Researchers are working on creating new knowledge. In the scientific world one of the key factors is to get the desired results, but also to understand why, and how the results are accomplished. In many fields of research the ambient and process conditions, as well as end results, are measured and documented. After series of tests and trials, large amounts of data is analyzed to understand various phenomena and relations between them. Since all tests are not easily reproducible, is quite clear that false assumptions (such as faulty measurement results which are thought to be correct) can jeopardize an entire research. In research, calibration plays a vital role before, during and after tests.

Distributed Manufacturing

If you produce products in multiple locations it is important to use optimal setups for the highest possible yield and quality in all locations. If certain locations or machines have problems with a setup that works well on others, it is possible that the measurement results are not the same.

What if your subcontractors send you mechanical components that do not fit into where they are supposed to? Operating on tight tolerances requires that all participants in the chain have calibrated equipment. Otherwise you end up adjusting, taking a little bit away, then things start to fit. But what happens when you decide to change subcontractors? You start all over again.

A baking company tried to bake their popular bread in another bakery. The recipe is the same, the raw materials used are the same, and the oven was set to the same temperature. However, the taste and structure of the bread was not the same. This could be because, the measurement information from the scales were different, and the temperature sensors controlling the ovens were showing different values.

Traditionally, process industries would try to achieve the desired end result by trial and error, changing various parameters until the end result is acceptable. If the measurement equipment is calibrated properly, and the results are taken into account when using the recipes, the desired results could be reached immediately.

Calibration Practices in a Nutshell

- To put an effective calibration system in place you have to:
- Understand the value of information the measurements provide.
- Identify your measurement equipment.
- Set up appropriate processes for calibration of your measurement equipment.

1. Calibration Requirements

Requirements for calibration systems are usually set locally by legislation and regulations, customer expectations, or own internal needs.
In case the requirements are legally set, the calibration system must be designed to fulfill these requirements.

In case the customer expectations or own internal needs are to be fulfilled, there are several Quality Management Standards (QMS) from which to choose from. A few of them are: ISO 9000:2000, QS 9000, ISO/TS 16949:2002 and Good Laboratory Practice (GLP). These all state the minimum requirements and guidance for the maintenance of measurement equipment.

Under the selected QMS the measurement equipment maintenance system and actual calibration system is built.

In case more effective measurement equipment maintenance system is needed the ISO 10012, ANSI/NCSL Z540 or ISO/IEC 17025 is selected.

1.1. Quality Management Standards

Quality Management Standards like ISO 9000:2000, QS 9000, ISO/TS 16949:2002 and Good Laboratory Practice (GLP) all state the minimum requirements for the maintenance of measurement equipment.

ISO10012 Measurement Management Systems - Requirements for Measurement Processes and Measuring Equipment is specially designed for measurement equipment maintenance.

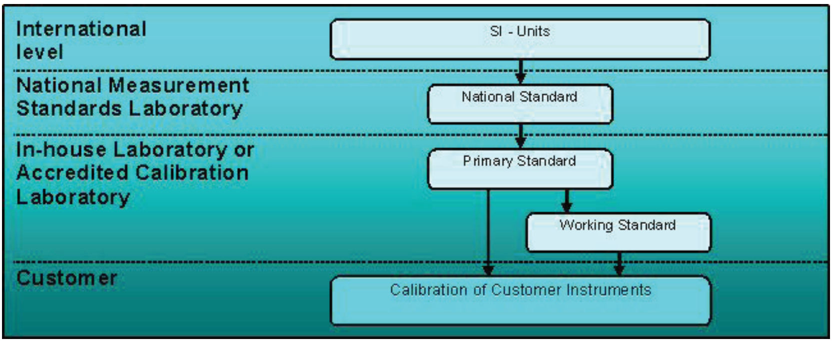
ISO/IEC 17025 General Requirements for the Competence of Testing and Calibration Laboratories, is a laboratory accreditation standard used globally.
ANSI/NCSL Z540 General Requirements for Calibration Laboratories and Measuring and Test Equipment, is a laboratory accreditation standard used alternatively in USA.

MIL-STD-45662A Calibration Systems Requirements, has been cancelled on February 27, 1995 and ISO 10012 or ANSI/NCSL Z540 is preferred if these requirements apply.

1.2. Traceability

Each calibration service provider must maintain an effective traceability chain. At the very least, the primary standard must be calibrated at an outside laboratory and then used for calibrations. In case the calibration service maintains working standards, all of them must be calibrated using primary standards including all supportive measurements.

- For instance, temperature of pressure balance is measured and the temperature correction is used for the pressure calculation. The thermometer used to measure this value must be calibrated.
- Another example is the measurement of the analog output of pressure transmitter with multimeters. The multimeter must be calibrated. To fulfill the definition of traceability all these measurements must also have valid uncertainty estimations.



Example of traceability chain

Ask for uncertainty when ordering calibration
Some commercial calibration services do not include uncertainty estimations into calibration certificates if not ordered separately. Some calibration services are not able to calculate uncertainty at all. One should always consider the competence of these services.

1.3. Calibration Documentation

In all of the QMS's the management of measurement equipment is based on regular calibrations at predefined intervals, including a documentation system by which this can be proven. This documentation system should contain as minimum:

1. Organization, management
   - Responsibilities, job descriptions, training plans and training records
   - Management review plan and records of the meetings

2. Register of measurement equipment
   - Each measurement equipment should be identifiable which means some kind of numbering system attached to the equipment
   - Register should contain the history of the equipment and the time for the next calibration

3. Archives containing issued calibration certificates. The certificates should be stored for the time documented in the QMS.

4. Procedures for faulty measurement equipment

5. Procedures for receiving customer feedback, solving complaints, corrective and preventive actions

6. Quality audit plan and records from previous audits, findings and corrective actions

Validity of Calibration

Calibration Certificate presents the performance of the measurement equipment at the time of calibration and the conditions during calibration.

After calibration the equipment should be sealed to protect the integrity of the calibration adjustments.

Recalibration Interval

The procedure for determining the recalibration interval should be defined in the QMS. The recalibration interval should be recorded into the measurement equipment maintenance system for each measurement equipment.

Each measurement equipment should have a sticker that states the next calibration date. The calibration laboratory can provide this if agreed with the customer.

There should be procedures in the QMS on how to handle and remove the measurement equipment from service when the calibration is overdue, or if the calibration sticker or calibration seal are broken or missing.

There should be procedures in the QMS of how the use of the most demanding measurements is secured.

Examples:

- Continuously using two independent measurement devices and comparing the readings
- Periodical comparison of a process unit with a working standard (Spot checking).

2.1. Metrology & Calibration Services

Traditionally, metrology was organized by the users of specific areas. The measurements related to trade and safety have been under legal metrology and regulated by the local legislation.

The purpose of legal metrology has been to ensure correct measurement results in trade to protect customers.

Scientific metrology has been developed freely in research institutes when doing physical research in order to develop more accurate measurement methods and equipment.

Besides these two 'paths' there has always been metrology cooperation inside different organizations. As an example the World Meteorological Organization (WMO) has developed and standardized the measurement equipment and techniques related to meteorological observations.

The basis of modern metrology is set in Convention of the Metre, which is a diplomatic treaty which gives authority to the General Conference on Weights and Measures (CGPM), the International Committee for Weights and Measures (CIPM) and the International Bureau of Weights and Measures (BIPM) to act in matters of world metrology, particularly concerning the demand for measurement standards of ever increasing accuracy, range, diversity, and the need to demonstrate equivalence between national measurement standards.

The backbone of metrology is the International System of Units (SI).

Metrology organizations are built to maintain and improve the International System of Units (SI) and provide accurate measurement and calibration services.

The International System of Units (SI) is maintained by BIPM (International Bureau of Weights and Measures) in France. The task of the BIPM is to ensure worldwide uniformity of measurements and their traceability to the International System of Units (SI).

National laboratories represent the top metrology level. They are responsible for maintaining and developing traceability and for providing the highest accuracy calibrations.

Accredited and other calibration services are then providing the traceability to the users.

International Cooperation

Legal Metrology

Legal metrology covers all the legislative, administrative and technical procedures established by or referenced by public authorities. It also covers all procedures implemented on their behalf in order to specify and to ensure, in a regulatory or contractual manner, the appropriate quality and credibility of measurements related to official controls, trade, health, safety and the environment.
The International Organization of Legal Metrology (OIML) is an intergovernmental treaty organization coordinating legal metrology.

The International Bureau of Legal Metrology (BIML) is the secretariat and headquarters of the OIML, ensuring both the day to day running of activities and the planning of longer term actions.

OIML has developed a worldwide technical structure that provides its members with metrological guidelines for the elaboration of national and regional requirements concerning the manufacturer and use of measurement equipment for legal metrology applications.

Regionally, the legal metrology is coordinated by Asia-Pacific Legal Metrology Forum (APLMF), Euro-Asian Cooperation of National Metrological Institutions (COOMET), Euro-Mediterranean Legal Metrology Forum (EMLMF), European Cooperation in legal metrology (WELMEC), Sistema Interamericano de Metrologia (SIM), and Southern African Development Community (SADCMEL).

The National Legal Metrology Bodies implement the legal metrology.

Metrology

National metrology institutes (NMI's) are essential when proving the uniformity of measurements and their traceability to the International System of Units (SI).

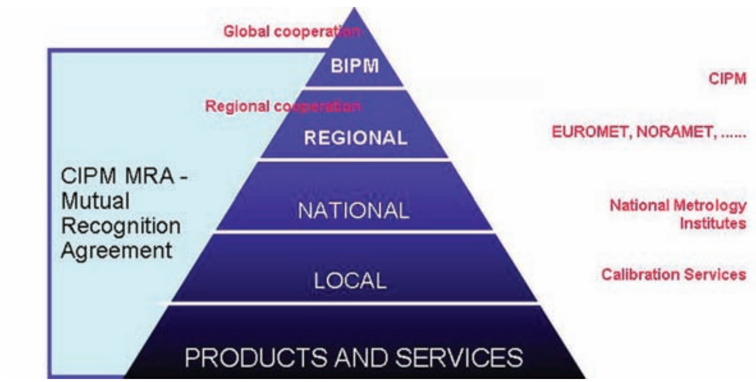
Currently, in 2006

- 64 institutes from 45 Member States
- 18 Associates of the CGPM
- and 2 international organizations that are covering a further 101 institutes designated by the signatory bodies

have signed so-called Mutual Recognition Arrangement (CIPM MRA) for national measurement standards and for calibration and measurement certificates issued by NMI's.

To be a member in the MRA, the NMI's have to prove their technical capability by participating into so called key comparisons.

BIPM maintains database of all NMI's including the measurement ranges and uncertainties approved.



Accreditation

Accreditation systems are developed for global recognition of laboratories and inspection facilities, thus facilitating acceptance of test, inspection and calibration data accompanying goods across national borders.

- ILAC (International Laboratory Accreditation Cooperation) and IAF (International Accreditation Forum, Inc.) are the main organizations for global cooperation of laboratory and inspection accreditation bodies working closely with the ISO (International Organization for Standardization).
- EA (European Accreditation) in Europe, NVLAP (National Voluntary Laboratory Accreditation Program) in North America and APLAC (Asian Pacific Laboratory Accreditation Cooperation) in Asia are the main regional coordinating organizations.

These organizations develop regionally the accreditation system with the national accreditation bodies by so called Multilateral Agreements (MLA) which provide a means for goods and services to cross regional boundaries and boundaries throughout the world.

What is the Accreditation Process?

A test report, inspection report, or a certificate issued by an accredited body in one country is recognized as equivalent to a report or a certificate issued by an accredited body in any of the countries signatories to the MLA. Accreditation bodies recognize that they operate in an equivalent way and that they deliver equivalent accreditations, providing the same level of competence and confidence.

The MLA makes accreditation a "passport" which facilitates access to international markets through co-operation with ILAC (International Laboratory Accreditation Co-operation) and IAF (International Accreditation Forum).

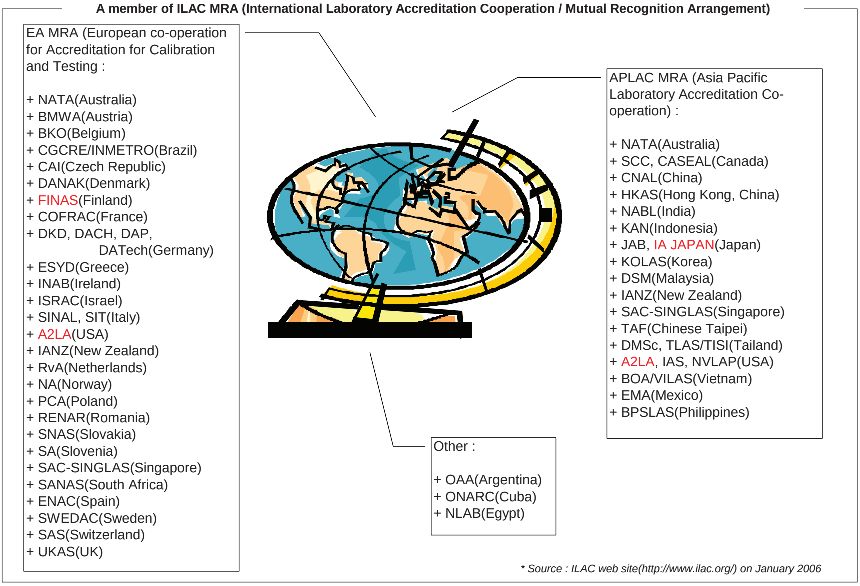
2.2. National Measurement Standard Laboratories

National Measurement Standard Laboratories are usually situated under the NMI's or they may be contract laboratories. Usually National Measurement Standard Laboratories are responsible for providing and organizing calibration services needed by local society.

The calibration services of the National Measurement Standard Laboratories may be limited to calibration of the highest grade primary standards.

2.3. Commercial Calibration Services

Accredited laboratories work according to ISO/IEC 17025 (ANSI/NCSL Z540 may be used also in USA) and the competence of the laboratories is ensured by third party accreditation.
The certificates issued by accredited laboratories are widely accepted through the MLA's written between the Accreditation organizations.



Signatories of ILAC MRA, Vaisala accreditations marked with red

Non-Accredited Calibration Services and Laboratories

Non-accredited calibration services are the major service providers containing most of the measurement equipment manufacturers calibration services and large amount of commercial calibration services.
Without accreditation the competence of these services is not proven and before use the competence should be confirmed by auditing the service.

2.4. In-House Calibration

Sometimes it is practical to maintain a in-house calibration system. This may be the case if the measurement equipment is difficult to transfer (calibration on site) or when the amount of calibrated equipment is high.

To set up an in-house calibration system, a suitable organization should be founded. The organization may contain just one person or a whole department with management and calibration staff.

In any case, the duties of the personnel should be recorded and adequate training provided.

Organization and Management

A simple in-house calibration function may be just one person nominated for the calibration tasks. In larger organizations the organization structure, management, responsibilities, job descriptions, training plans and training records should be documented.

These documents should also contain:

- Procedures for faulty measurement equipment
- Procedures for receiving customer feedback, solving complaints, corrective and preventive actions
- Quality audit plan and records of previous audits, findings, corrective and preventive actions
- Defined document retention times
- Comparison calibration plan and results of previous comparisons.

Technical Documentation

Technical documentation should contain reference equipment, facilities, conditions, verification and maintenance of the reference equipment.

Technical documentation should also contain:

- Traceability
- Uncertainty calculations
- Calibration instructions
- Stability of the reference equipment.

Choosing Reference Equipment

The selection of the reference equipment depends on the chosen calibration method and accuracy needed. Some considerations are as follows:

- Accuracy, the chosen reference must be accurate enough for the intended calibrations.
- Range, the measurement range of the chosen reference must cover the whole range needed.
- Calibration service, suitable calibration service must be available.
- Transportation, the reference should not be sensitive to be damaged during transportation.
- Usability, the reference should be suitable for the intended use and user friendly.

3. Calibration Activities

What is needed to set up an effective measurement equipment maintenance system?

Plan and decide

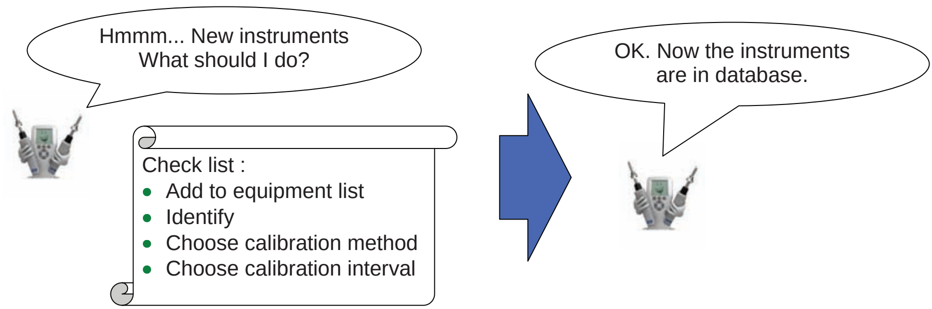
- List all measurement equipment
- Determine the need for calibration for each unit
- Choose calibration method and interval
- Identify each unit and its calibration status.

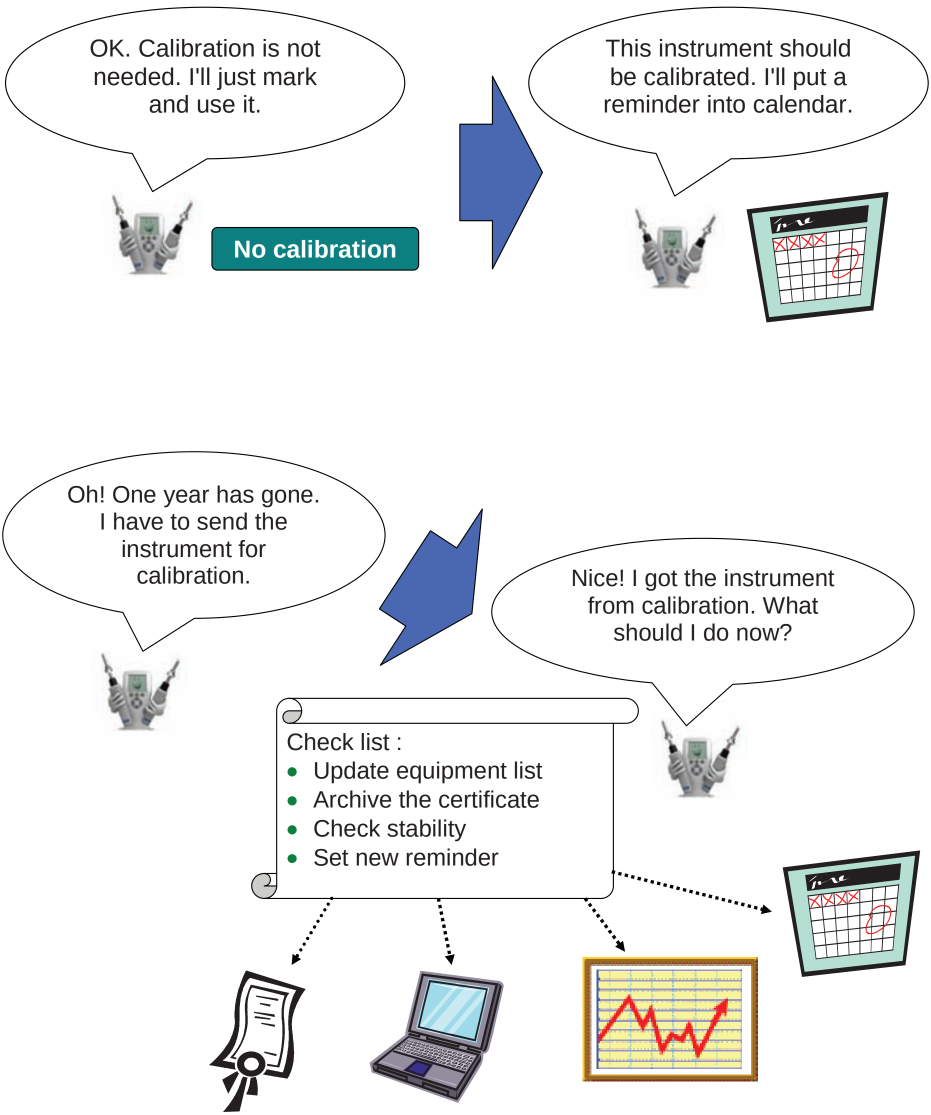
Act as planned

- Perform the calibrations as planned
- Keep record of the calibrations and calibration results

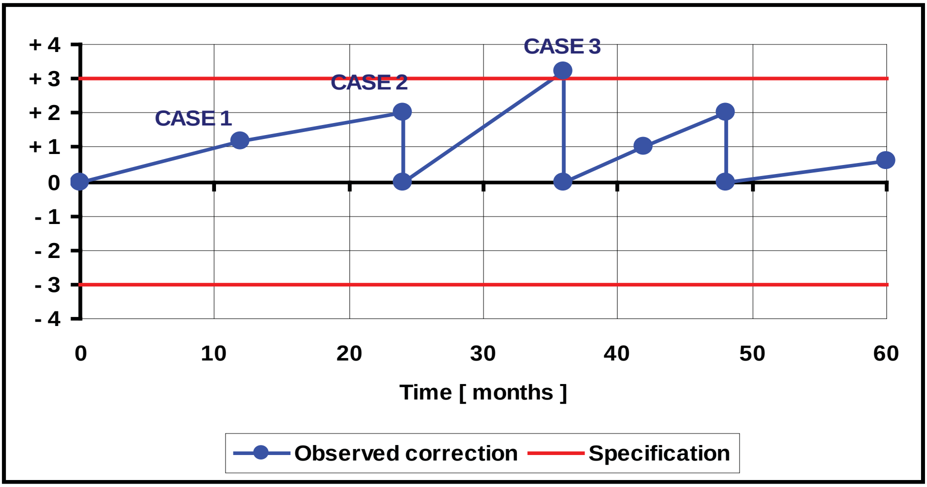
Analyze

- Check if the calibration results require corrective actions
- Adjust the calibration intervals if needed
- Review the effectiveness of the system periodically.




OK. Calibration is not needed. I'll just mark and use it.
No calibration
This instrument should be calibrated. I'll put a reminder into calendar.
Oh! One year has gone. I have to send the instrument for calibration.
Nice! I got the instrument from calibration. What should I do now?
Check list :
Update equipment list
Archive the certificate
Check stability
Set new reminder

What Should We Do with the Calibration Results?



Case 1:

- Instrument is in specifications, no adjustments: No actions.
- Please check the calibration curve if there is correction that should be taken into account before taking the instrument into service.

Case 2:

- Instrument is in specifications, adjusted: No actions.
- Sometimes it is practical to adjust the instrument during each calibration to maintain the optimum performance.

Case 3:

- Instrument is not in specifications, adjusted: Reduce calibration interval. Check if it was affecting the production. Check other similar instruments.

NOTE: If an instrument is not in specifications repeatedly, even if it has been adjusted, reject the instrument. Check other similar instruments.

3.1. Choosing Calibration Method

When Calibration is Needed

The need for calibration is determined for each measurement equipment before taken into use or when the way of using it is significantly changed. For each unit one of the following calibration schemes should be chosen:

Selecting Calibration Method

Calibration Scheme	Applicable Units
Regular calibration	For units used in daily service, when knowing the uncertainty and traceability is important
Calibration before use	For units used infrequently or which are not in active usage but held as spare equipment
	For new units
	For repaired units
Calibration if needed	For units used in other service than production, inspection, repairing or testing of products but which can be taken into such service if needed
Inspection before use	For units not calibrated but which should be inspected or adjusted before use (like adjustment of null detector)
No calibration	For units which do not need calibration

Laboratory and Field Calibration

Laboratory calibration is the most accurate method used for calibrating measurement equipment. Laboratory calibration offers uncertainties lower than that of field calibration. Effects of the environment are minimal and the number of factors influencing the calibration is reduced significantly.

Field calibration is a quick and easy way of checking measurement equipment without having to remove it from the process or process area, remembering that proper stabilization times are allowed for both the UUC and the working standard.

Users must decide which is the most optimal method for their approach and this section will outline some advantages and disadvantages of both.

Equipment Required for Field Calibration

Field calibration requires a working standard as a reference. This working standard could be a hand-held or some other equipment that would be used to calibrate the instrument installed in the process.

The working standard is only used for calibration and should not be used in any part of the monitoring operation of the process. Care should be taken when handling the working standard and proper storage is required to ensure its functionality.

A calibrator can also be used in the field to produce a multi-point calibration. Some calibrators are stand alone reference standards. This means that there is no need for a separate working standard.

Working standards are generally calibrated at a higher level laboratory.

Advantages of Field One-Point Calibration

Field calibration offers the user the ability to calibrate the instrument in place. Leaving the instrument installed into the process eliminates any down-time that would incur while removing and re-installing the instrument from the process.

ATTENTION:
Before inserting a hand-held meter or other working standard into a process, make sure that the operating conditions do not exceed its specifications.

Calibration is made at one-point against the working standard by placing the working standard as close to the UUC as possible. Stabilization time must be allowed to reach temperature equilibrium between the working standard and the UUC. Attention must be paid to the proximity of the working standard to the UUC, temperature gradients, air flow, pressure differences, and any other factors that could influence the calibration results.

One-point calibration is an effective way to maintain a sensor's performance for operating conditions that do not vary. Sensors that are constantly maintained at one temperature, one humidity, one pressure and so on would be ideal cases for one-point calibration.

Disadvantages of Field One-Point Calibration

There are also disadvantages in field calibration that should be mentioned. Field calibrations with the instrument installed in the process limit the calibration curve to one point only. Many processes vary in conditions and the one-point calibration limits the curve over a small portion of the operating conditions.

Advantages of Field Multi-Point Calibration

Using a working standard and generator or chamber, which is able to produce various points enables the user to perform multi-point field calibration. The difference between one-point field calibration and multi-point field calibration is that the UUC must be removed from the process.

The time saved performing multi-point field calibration to that of laboratory calibration can be significant.

Disadvantages of Field Multi-Point Calibration

Field calibration generally carries a higher calibration uncertainty than laboratory calibration.

Labor and traveling costs may be significantly higher than in laboratory calibrations. In laboratory the reference equipment are usually constantly available and several instruments may be calibrated simultaneously.

Example of salt solution chamber for humidity instrument calibration

Field Spot Checking

Spot checking is a quick and easy way to determine proper operation of a unit. Spot checking should not be confused with field calibration. They are very similar in the respect that a reference equipment is placed near the sensor that is being checked and the readings are compared to that of the installed instrument. In spot checking stabilization time is not as crucial as it is in field calibration, and therefore time used for the checking is much shorter.

Spot-checking can be viewed as a good addition to measurement equipment maintenance. For example if a unit is calibrated annually in a laboratory, it could be subject to spot checking every 3 months.

Guidelines should be set up before commencing with the spot checking of instruments. There should be pre-established limits to determine potential actions taken.

Examples of Potential Actions

Error	Potential Action
0 %...1 %	No actions needed
1 %...3 %	Perform one-point field calibration
3 %...5 %	Perform multi-point field or laboratory calibration
>5 %	Unit needs to be serviced

3.2. Determining the Calibration Interval

The decision on the calibration interval must always be made by the user, however there are common practice guidelines available.

Typical Calibration Interval

The typical calibration interval can be chosen from the values given as example. The variation in values tells the shorter calibration intervals chosen for critical equipment and accordingly the longer values used for not so critical equipment.

Typical calibration intervals

Measurement equipment	Month					
	6	9	12	24	36	60
Mechanical pressure meters				■	■	
Precision barometers	■	■	■			
Barometers		■	■	■		
Liquid-in-glass thermometers					■	■
Resistive temperature sensors and thermoelements/thermometers	■	■	■	■		
Dewpoint meters			■	■		
Humidity meters	■	■	■			
Active electrical meters			■	■		
Passive electrical meters				■	■	■
Length measurement equipment			■	■	■	■
Length measurement equipment with electrical display	■	■	■	■		

■ suitable calibration interval

Lengthening the Calibration Interval

When the measurement equipment has stability surveillance long enough the calibration interval can be lengthened. Lengthening can be made when there have been at least 3 calibrations performed in a 12-month time period and the unit has remained within specification. Before lengthening the calibration interval, the user should ensure that the maximum calibration intervals were not exceeded, or, that the calibration interval is not lengthened for critical equipment.

The calibration interval can also be lengthened if the equipment is used with other more stable measurement equipment or if the application allows lower accuracy than the manufacturers specifications grant for the normal calibration interval.

Shortening the Calibration Interval

When measurement equipment has drifted more than its specifications allow, the following procedures should be performed:

- In cases where the drift is caused by misuse or breakage, the cause and fault should be corrected.
- In cases where the unit has drifted without a clear cause, the calibration interval should be shortened to half of its original length.
- Consider whether the calibration intervals of other similar equipment should be shortened.

3.3. Choosing Calibration Points

A one-point calibration is a typical on-site calibration. It is a good stability monitoring check to be made between full calibrations. The one-point calibration may be used to adjust the equipment using an offset-correction.

A full calibration should cover the entire measurement range with 5 or more points equally spaced to verify the linearity of the unit. The calibrated range can be smaller than the actual measurement range if the equipment is used within the limited range. In such a case it is good practise to somehow identify the range the unit is calibrated to since it must not be used outside the calibrated range.

Sensors having hysteresis should be calibrated using increasing and decreasing values with equal change rates of the quantity and stabilization times.

3.4. Calibration Methods by the User

There are numerous ways to calibrate measurement equipment. Manufacturers of measurement equipment develop what they may consider the best method for specific equipment. Calibration laboratories that provide services for all equipment measuring a certain quantity have their own internal calibration methods. Metrologists focus strictly on calibration develop procedures and equipment that solely aim to achieve the lowest possible uncertainties.

Whatever method is chosen it should be based on a proper understanding of the requirements in relation to traceability, accuracy and costs.

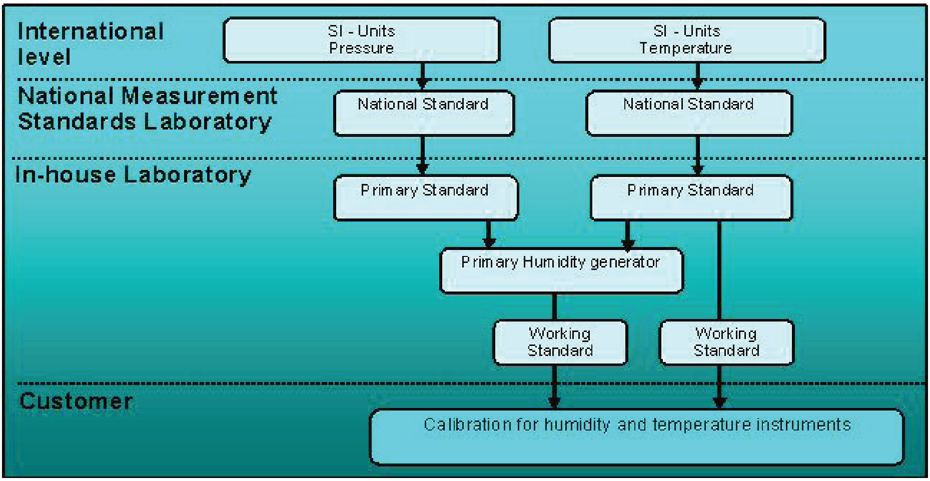
Users of measurement equipment that are interested in performing calibration themselves must either purchase or develop their own calibration equipment. Purchasing of calibration equipment should be considered a major investment.

Not only will it require the capital for the equipment itself but also the need for training of personnel (including back-up personnel), development of procedures, calculation of uncertainties and development of methods for calibrating the equipment itself. This may require extensive resources and time, and should be seriously thought out before the purchase is made.

How to handle the calibration of in-house calibration equipment itself should be thought out as well. How and where is the reference standard calibrated? Calibrators are very elaborate and will require a highly accurate calibration in order to maintain their specified accuracy. Outsourcing the calibration of the reference standards is typically an optimal approach. However, the expense can be high and the turnaround time can be long. This means downtime for the user's normal calibration.

Purchasing of even more measurement equipment will be required to bring the calibration of almost all measurement equipment in house. There may always be equipment that requires calibration from outside sources. Users may opt to send references directly to a National laboratory. This is the typical method for a high-end laboratory. Calibration at a National laboratory can be very expensive and may have an extremely long turnaround time.

The calibration traceability chain can be very confusing, especially when more links are added. Below is an example of a traceability chain for installed humidity and temperature units.



Example of humidity and temperature instruments traceability chain

Temperature Equilibrium

The often spoken term “temperature equilibrium” is important but usually impossible to reach in most calibrations. When temperature equilibrium occurs, all of the components in the system are at same temperature and no heat flows occur.

Usually there are heat-producing elements in the system like motors, electronics, operator or light sources. Also note that the heat radiated from the operator´s body is a heat producing element.

To minimize the errors due to temperature differences, the system should be allowed to stabilize for a sufficient amount of time, so that all parts of the system have reached their own equilibrium:

- Ensure that the electronics have been powered long enough to reach their nominal operating temperature.
- Ensure that the environment (air conditioning and lighting) is stable. No spot lights or sun should be shining directly into the measurement area.
- The number and variation of people in the measurement area is limited to a minimum, and the measurement system is protected from the heat produced by the operator if needed.

Stabilization and Sampling

After a new measurement point is adjusted the whole calibration system and the sensors must be stabilized before measurement.

Different parts of the system stabilize at different rates. The whole system should be stabilized before measurements are made. If only the reference is monitored and found to be stable, the Unit Under Calibration (UUC) may still be not stabilized.

In cases where the measurement system is not stable, sampling should be used to ensure a good representation of the quantity being measured, not just a single measurement at one point.

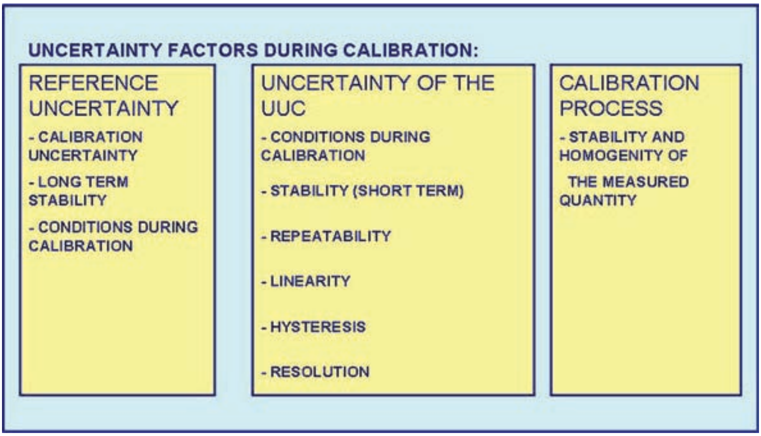
The number of samples should be large enough. Typically ten samples are adequate but if the system has a lot of variation, up to 100 samples at a reasonable interval should be taken to cover the full variation.

Uncertainty Estimation

Uncertainty comes from three main sources: The reference used, the unit under calibration (UUC) itself, and the calibration process used.

Some of the uncertainty factors are listed below:

- Uncertainty of the reference is composed of calibration uncertainty, long-term and short-term stability, resolution and the effect of influence quantities.
- Uncertainty of the UUC is composed of repeatability, linearity, hysteresis and short-term stability, resolution and the influence quantities.
- The calibration process itself may cause uncertainty; like the uncertainty of the height correction used in a pressure calibration, the temperature uniformity in a climate chamber during a temperature calibration or the pressure correction used in a dewpoint calibration. For more information, see Appendix C.



Presenting the results

Typically the results are presented in a table showing the reference reading, UUC reading, correction (or error) and uncertainty values. Additionally a graph of the results may be produced. Good calibration certificate always presents the following as minimum:

- Calibrated item
- Calibration place and operator
- Calibration method and conditions during calibration
- Traceability of the measurement results
- Measurement results, uncertainty and coverage factor
- Results before and after adjustment (if adjusted)
- Number of pages and signature(s).

Correction - Error - Deviation - Difference

Be careful when interpreting the calibration results:
Error = Reading - Reference value
Correction = Reference value - Reading

Deviation or difference can be calculated either way.

VAISALA
MEASUREMENT STANDARDS LABORATORY
ACCREDITED CALIBRATION LABORATORY

FINAS

CERTIFICATE OF CALIBRATION SAMPLE

Example of calibration certificate

4. Calibration in Practice

This chapter will look at practical calibration for measurement equipment of relative humidity, dewpoint temperature, temperature, and pressure.

4.1. Humidity Calibration

Choosing reference equipment

The reference equipment needed depends on the measurement range, accuracy needed, and calibration method chosen.

Moist Air (Gas) Generation Methods

Two Temperature (2t) Generators

In two temperature generators the gas is saturated in a saturator. The dew-point temperature is the saturation temperature corrected for possible pressure differences between the saturator and the measurement chamber. Dewpoint temperature is calculated using the formula 1.

- ✓ A two-temperature generator is the most accurate humidity generator and is used widely as the realization equipment for dewpoint temperature calibrations in national measurement standard laboratories.
- ✓ The effect of the enhancement factor is very small and the uncertainty in the dewpoint temperature due to the uncertainty of the enhancement factor is usually negligible.
- ✗ The two-temperature generator is very slow in use. The temperature of the whole generator is changed before each measurement point, typically one measurement point per day is reached with this generator.

Two Pressure (2p) Generators

In a two-pressure generator, the gas is saturated in a saturator at a higher pressure and then released at a lower pressure for measurement. Dewpoint temperature is calculated using formula 1.

- ✓ The two pressure generator is faster as the saturator is maintained in constant temperature and the dewpoint setting is achieved through pressure changes.
- ✗ The effect of the enhancement factor is significant and the uncertainty in dewpoint temperature due to the uncertainty of the enhancement factor is also significant.
- ✗ The measurement range is limited as the enhancement factor is known only up to 2 MPa (20 bar, 290 psi). In cases where the saturator and measurement temperatures are at 23 °C and the measurement pressure is one atmosphere (1013.25 hPa) the minimum dewpoint temperature of the generator would be -16 °C frostpoint or -17.9 °C dewpoint.

Combined Two Temperature (2t), Two Pressure (2p) Generators

In combined two temperature, two pressure generators, both the temperature and pressure of the saturator are adjustable. With this arrangement the range of the generator may be extended with reasonable saturator pressures. Dewpoint temperature is calculated using formula 1.

These generators use the same principle where gas is saturated in a saturator at pressure p_{sat} and at temperature t_{sat} and dewpoint temperature $t_{d,sat} = t_{sat}$. Dewpoint temperature at measurement chamber (at pressure p_{meas}) is then calculated:

Formula 1

$$f(p_{sat}, t_{d,sat}) \cdot e_w(t_{d,sat}) = \frac{p_{sat}}{p_{meas}} \cdot f(p_{meas}, t_{d,meas}) \cdot e_w(t_{d,meas})$$

Explanations	
f(psat,td,sat)	the enhancement factor of moist gas at psat and td,sat
ew(td,sat)	the saturation vapor pressure of moist gas at td,sat
f(pmeas,td,meas)	the enhancement factor of moist gas at pmeas and td,meas
ew(td,meas)	the saturation vapor pressure of moist gas at td,meas

Divided Flow Generators

In divided flow generators, dry gas is separated into two or more flow paths and one of them is then fed through a saturator. The measured gas is then a mixture of the saturated and dry gas.

ⓘ To reach low dewpoint temperatures, the mixing can be done several times by adding more dry gas into the path. This is called dilution method.

ⓘ In very low dewpoint ranges, the saturator can be replaced with a dilution element which produces constant flow of water molecules into the gas flow.

ⓘ In very high dewpoint ranges the saturator can be replaced with an evaporation element where water is heated to produce steam which is then added to the gas flow.

✓ A divided flow generator response is fast.

Dry Gas Supplies

A dry gas supply is needed for these generators. Different types of high pressure or drying agent (desiccant) dryers are available. It is important to choose a supply that has a lower dewpoint than the lowest measured dewpoint value and a flow capacity needed for the generator.

ⓘ To avoid saturator contamination a filter is recommended after the gas supply.

Saturated Salt Solutions

This method generates air of a desired humidity by equilibrating air with a saturated aqueous solution of salt kept at a constant temperature within a closed container. The relative humidity of the air in the equilibrium state with the saturated aqueous solution of salt is determined by the kind of salt and the temperature of the solution. Air of a desired humidity can be generated by choosing the salt.

Example of salt solution calibrator

Climate Chambers

A climate chamber is usually a chamber with an air circulator and heat and moisture control systems. It is usually easy to use and does not need to be filled with liquid. However, stability and uniformity of temperature and humidity inside the chamber are usually not so good.

Reference Equipment

Gravimetric hygrometers are the most accurate reference equipment. 2t generators are commonly used in national laboratories. 2p and 2t/2p generators are usually not classified as reference equipment.

Dewpoint meters or condensing hygrometers are the most commonly used reference equipment. In this meter the gas sample is fed into the measurement chamber where the sensing element is cooled until dew/frost occurs. The temperature of the surface is then measured with Pt-100 sensor element installed into the sensing element.

- ✓ Dewpoint meters are generally stable and accurate equipment.
- ✗ Dewpoint meters are quite slow in stabilization after humidity changes.
- ✗ Sometimes dewpoint meters do not find the dewpoint at all and need the operator to fix the problem.
- ✗ In ranges from 0 to -20 °C the dew may be in the form of water, or ice, or both, which may cause significant error if it is not noticed.
- ✗ Dewpoint meters need periodic cleaning.
- ✗ Dewpoint meters may need an additional cooling system for the lowest measurement points.
- ✗ The temperature of the additional coolant may affect the dewpoint meter reading causing significant errors.

Comparison of the Generators and References:

Generators	Accuracy	Stability	Use	Automa-tization	Maintenance	Price
2t generator	✓✓✓	✓✓✓	✗✗✗	✗✗	✓	✗
2p generator[1]	✓✓	✓✓	✗	✓✓	✓	✗
2t/2p generator[1]	✓	✓✓	✓✓✓	✓✓	✓	✓
Divided flow generator[1]	✓	✓✓	✓✓	✓✓	✓✓✓	✓✓
Saturated salt solution	✗	✓	✓	✗✗✗	✓	✓✓✓
Climate chamber	✓	✓	✓✓	✓✓	✓✓✓	✗
Reference Meters	**Accuracy**	**Stability**	**Use**	**Automa-tization**	**Maintenance**	**Price**
Gravimetric hygrometer	✓✓✓	✓✓✓	✗✗✗	✗✗✗	✗✗	✗✗✗
Dewpoint meter	✓✓	✓✓	✓	✓	✗	✗

1 In some cases, the generators may be used as references with extra careful operation and a separate control equipment monitoring the output of the generator.

✓ Good ... ✓✓✓ very good

✗ No good ... ✗✗✗ not suitable

ⓘ ... Information

❢ ...Remarkable point

Relative Humidity Calibration

Relative Humidity (U)

Relative humidity is the ratio of the partial water vapor pressure (pw) to the water vapor saturation pressure (pws) at a particular temperature. It is measured as a percentage:

Formula 2

$$\text{Relative humidity}\,[\%RH] = \frac{p_w}{p_{ws}} \cdot 100$$

Relative humidity is strongly temperature-dependent. Pressure will also change the relative humidity. For example, if a process is kept at a constant temperature, the relative humidity will increase by a factor of two if the pressure is doubled.

Other Definitions of Humidity:

Absolute Humidity (a)

Absolute humidity refers to the mass of water in a unit volume of moist air at a given temperature and pressure.

Usually expressed as grams per cubic meter (or grains per cubic foot) of air, it can easily be confused with mixing ratio.

Mixing Ratio (r)

Mixing ratio is the ratio of the mass of water vapor to the mass of dry gas. It is dimensionless but often expressed in grams per kilogram (or grains per pound) of dry gas. It is mainly used in drying processes or ventilation systems for calculating water content when the mass flow of gas is known.

Saturation Vapor Pressure of Water (p_{ws})

The maximum pressure that water vapor can exist at a particular temperature. The higher the temperature, the more water vapor the gas can hold.

Dewpoint Temperature (t_d)

Dewpoint is the temperature at which air becomes saturated when cooled and begins to condense, forming dew. At 100 % relative humidity the ambient temperature equals the dewpoint temperature. The lower the dewpoint temperature as compared to the ambient temperature, the lesser the risk of condensation and consequently, the drier the gas. Dewpoint is not temperature dependent, but it is affected by pressure.

Frostpoint Temperature (t_f)

If the dewpoint temperature is below freezing, the term frostpoint temperature is sometimes used. Frostpoint temperature is always higher than dewpoint temperature for the same humidity. This is because the saturation vapor pressure of ice is smaller than the saturation vapor pressure of water.

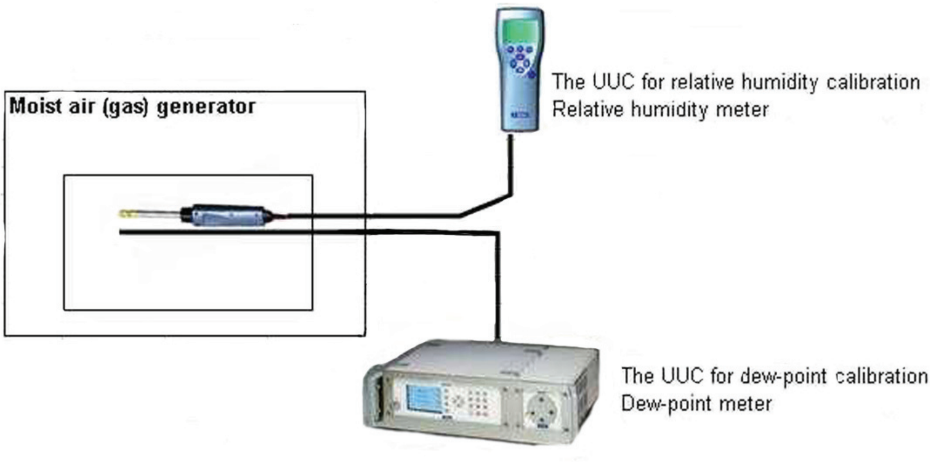
Relative Humidity Calibration Methods

Preparations

Perform a chemical purge if the sensor has this function. Allow the humidity sensor to stabilize to laboratory conditions.

Using a Moist Air (Gas) Generator as Reference

Place the UUC into the chamber of a humidity generator, or supply moist air (gas) generated by a humidity generator into the UUC. This enables comparing the indicated value of the UUC in order to calibrate it to the value of the humidity generator.



Example: Using reference generator (Relative humidity and dewpoint)

ATTENTION:

Consider temperature and humidity distribution, and airflow inside the chamber, place the hygrometer in an effective location.

Pay attention to heat generation of equipment that will be brought into the chamber simultaneously.

Using a Dewpoint Meter or Hygrometer as Reference

Dewpoint Meter

Place the UUC into the chamber of a dewpoint generator, or, supply moist air (gas) generated by a dewpoint generator into the UUC. This enables comparing the indicated value of the UUC in order to calibrate it to the value of the dewpoint and temperature generator. When using a dewpoint meter as reference for a relative humidity calibration, a reference thermometer is needed.

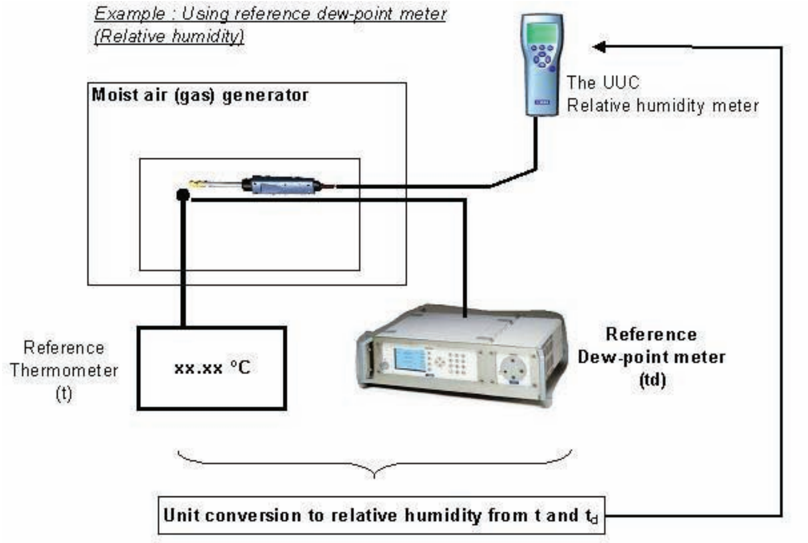
Unit Conversion

When calibrating a relative humidity meter by comparing it to a dewpoint meter, it is necessary to convert the dewpoint values to relative humidity values.

Formula 3

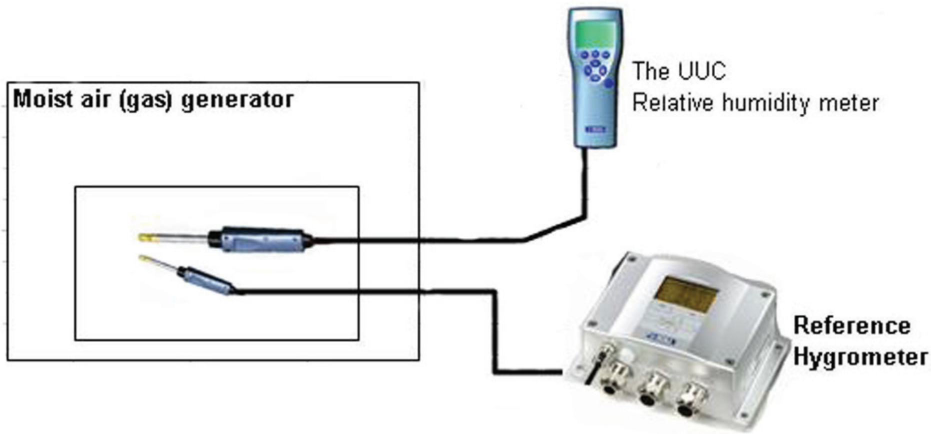
$$U_w = \frac{f(p_t, t_d) \cdot e_s(t_d)}{f(p_t, t_t) \cdot e_s(t_t)} \cdot 100\ \%$$

Temperature values and pressure values in the chamber are indispensable for calculation. Enhancement factor [f] is often handled as f = 1.



Hygrometer

Place both the UUC and the reference hygrometer into the chamber of a humidity generator, or, supply moist air (gas) generated by a humidity generator to both the UUC and the hygrometer. This enables comparing the indicated value of the UUC to the value of the reference hygrometer.



Example: Using reference hygrometer (Relative humidity)

Consideration Before Calibration Work:

- *Shorten the connecting tube from the generator to the hygrometer as much as possible.*
- *When calibrating two or more hygrometers simultaneously, connect moist air supply tubes from the generator directly to each hygrometer.*
- *Keep flow rates constant.*
- *If the dewpoint of the air generated by a generator becomes higher than the room temperature, apply heat insulation to the piping to avoid condensation.*

One-Point Calibration

In a one-point calibration the reference sensor and calibrated sensor are placed closely together in a stable environment. After stabilization the readings can be taken. A one-point calibration may also be done in a process where the reference sensor is placed near the UUC sensor in actual process conditions.

In case the one-point calibration is made in room conditions the reference and calibrated sensor must be protected from direct light sources, like lighting or sun, and stabilization should be ensured with a fan circulating air to the sensors.

Full Calibration

To perform a full range calibration, controlled temperature and humidity generation equipment are needed. A humidity generator, climate chamber or a saturated salt solution calibrator may be used.

In a full calibration, the measurement points (usually 3 or more points) are selected equally spaced throughout the measurement range and usually performed from the lowest humidity to the highest humidity. These measurements are then repeated backwards from the highest humidity to the lowest humidity.

Common Mistakes

Temperature Equilibrium is Not Reached

In case the Unit Under Calibration (UUC) has been recently moved from some other environment into the measurement environment, it may not have had sufficient time to stabilize to the temperature of the measurement conditions. This may cause up to 6 %/ °C error in the relative humidity value.

Stabilization Time is Not Sufficient

After changing the humidity value of the reference, the UUC must have enough stabilization time at the new humidity value (sometimes the equipment may have very different response or stabilization times).

Hysteresis is Not Taken into Account

Some sensors have significant hysteresis behavior. Significant errors may occur if the measurements are carried out by only changing the humidity values in one direction.

The Temperature or Humidity is Measured in a Different Location Than the UUC Sensor

An error will occur if there is temperature difference between the reference sensor and the UUC sensor.

Dewpoint Temperature Calibration

Dewpoint temperature (t_d) and frostpoint temperature (t_f) are used to present the amount of water in a gas, usually air, but also in other gases. Typically the lowest measured t_f values vary from -100 to -60 °C and highest measured t_d values vary from 60 to 85 °C.

The thermodynamic dewpoint temperature t_d of moist air, at pressure p, and mixing ratio r, is the thermodynamic temperature where the mixing ratio r_w of the saturated air (against water) are equivalent.

Formula 4

$$r = r_w(p, t_d)$$

The correspondence between dewpoint temperature t_d, mixing ratio r and pressure p is:

Formula 5

$$e'_w(t_d) = \frac{r}{\frac{M_v}{M_a} + r} \cdot p = x_v \cdot p \quad \text{or} \quad e'_w(t_f) = \frac{r}{\frac{M_v}{M_a} + r} \cdot p = x_v \cdot p$$

Explanations	
e'w(td)	saturation vapor pressure of saturated air (against water) at dewpoint temperature td
e'w(tf)	saturation vapor pressure of saturated air (against ice) at frostpoint temperature tf
Mv	molar mass of water vapor
Ma	molar mass of dry air
xv	mole fraction of the water vapor

Dewpoint Temperature Calibration Methods

Dewpoint temperature calibration is a typical comparison calibration where the reading of the UUC is compared to the value of reference generator or reference meter at selected dewpoint temperatures.

Preparations

Before calibration the entire measurement system must be purged of water vapor. Usually, this is done by flushing the system with dry gas. The drying process can be accelerated by heating the tubing during flushing.

ⓘ The measurement system, tubing and fittings must be of a suitable material for the measurement range. For the lowest dewpoints, use electro-polished stainless steel tubing with a minimum number of fittings, preferably welded connections or leak free fitting types.

ⓘ If the measured dewpoint temperature is near or above room temperature, heat the system before starting humidity generation to avoid condensation in the system.

Calibration

Select the measurement points (usually 3 or more points) equally spaced throughout the measurement range. The calibration is usually performed beginning with the lowest dewpoint temperature and proceeding to the highest dewpoint temperature. The measurement of hysteresis with condensing type dewpoint meters is not necessary. Other type sensors would need the hysteresis measurement but it is difficult to produce at the lowest dewpoint temperatures due to extremely long stabilization times. In these cases the hysteresis should be estimated and added into the uncertainty estimations.

After changing the dewpoint temperature the stabilization time must be sufficient to allow the measurement system, reference and the UUC to reach equilibrium.

Common Mistakes

Condensation in the System

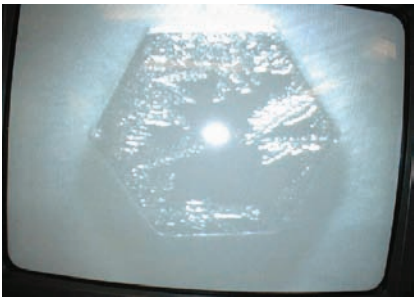
- ✗ If condensation occurs, the dewpoint temperature reading, after condensation, is lower than the true reading.
- ✗ When condensed water remains in the system, the dewpoint temperature readings, after condensation, are higher than the true reading.
- ⓘ To avoid these errors - always heat the complete system at least 5 degrees Celsius above the highest generated dewpoint temperature before starting humidity generation.

Faulty Condensation in the Dewpoint Meter

- ✗ Sometimes condensation in a dewpoint meter forms a large crystal and part of the mirror has no condensation at all.
- ✗ Sometimes condensation is water or ice or a mixture of both.
- ⓘ How to avoid these errors - always use the mirror microscope to investigate the dew layer on the mirror. It should be constant and smooth over the whole surface. Ensure that the microscope covers the full mirror and not just a part of it. In case the dew is not satisfactory, the mirror should be heated until it dries, cleaned if needed and re-cooled to get a new dewpoint value.

Two Examples of Faulty Condensation

Condensation occurs over half of mirror, one large crystal and rest without condensation. This was measured at -60 °C dew-point and this fault was about 1.5 °C error in dewpoint.



This was measured at -60 °C dewpoint and this fault was about 1 °C error in dewpoint.

4.2. Temperature Calibration

Thermodynamic Temperature (T_{90}) is one of the basic units in The International System of Units (SI) and the Kelvin [K] is a basic unit.

Kelvin is defined using the following equation:

Formula 6

$$1\ K = \frac{T_{tp}}{273.16}$$

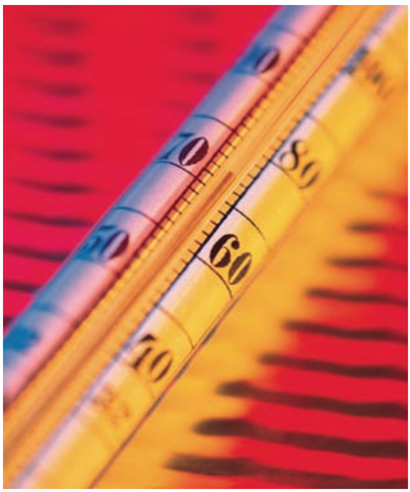
Explanations	
Ttp	the thermodynamic temperature at the Triple Point of Water [K]
Celsius and Fahrenheit (t)	derived quantities in The International System of Units (SI) and they are defined using the following equations (formula 7 and 8)

Formula 7

$$t[°C] = T[K] - 273.15\ K$$

Formula 8

$$t[°F] = 1.8 \cdot t[°C] + 32$$



As the thermodynamic temperature itself is not a practical unit of measurement, the realization of temperature is made using the International Temperature Scale, ITS-90. The scale is based on so called fixed points such as triple points, freezing points or melting points of pure materials. The thermodynamic temperatures at these points are determined experimentally and the values are agreed upon by all those who use this scale. Between these points so called interpolation equipment is used, in range from -259 to 962 °C a 25.5 ohm Standard Platinum Resistance Thermometer (SPRT) is used. This is a specially designed and manufactured platinum thermometer that follows closely the interpolation equations presented in the ITS-90. Typically SPRT 25 is used up to 420 °C or 660 °C and a specially designed High Temperature Platinum Resistance Thermometer (HTPRT) is used at the higher temperatures.

ITS-90 Temperature Scale

Between 0.65 K and 5.0 K, T_{90} is defined in terms of the vapor-pressure temperature relations of ^3He and ^4He.

Between 3.0 K and the triple point of neon (24.5561 K), T_{90} is defined by means of a helium gas thermometer calibrated at three experimentally realizable temperatures having assigned numerical values (defining fixed points) and using specified interpolation procedures.

Between the triple point of equilibrium hydrogen (13.8033 K) and the freezing point of silver (961.78 °C) T_{90} is defined by means of Standard Platinum Resistance Thermometers calibrated at specified sets of defining fixed points and using specified interpolation procedures.

Above the freezing point of silver (961.78 °C) T_{90} is defined in terms of a defining fixed point and the Planck radiation law.

Choosing Reference Equipment

The reference equipment needed depends on the accuracy needed and the calibration method chosen. In the case of a one-point calibration, only a reference thermometer is needed. In case of a fixed-point calibration or a full calibration, temperature generation equipment is also needed.

Numerous different thermometers are available. Typically resistive sensors, either platinum sensors or thermistors are used as the sensor, and they are attached to a display unit or digital multimeter.

Liquid-in-glass thermometers may also be used. Thermocouples are used as references only at higher temperatures.

Radiation thermometers are developing rapidly and can already be used from room temperature up to extremely high temperatures. The accuracy of those is, however, limited and in this book we are not considering them as reference equipment.

Temperature Generation Methods

Fixed Points

Fixed point calibration should be chosen when the best available accuracy is needed.

ⓘ In a full fixed-point calibration, the points needed for each range are defined and the interpolation equations are given in the ITS-90 scale documentation.

ⓘ Sometimes it is practical to use one or a few fixed points as regular in-house stability test. If drift in the sensor is observed, then send the sensor for a full calibration.

! In cases where fixed-point calibration was chosen, the full system should be chosen to support the highest accuracy calibrations.

✓ The best available accuracy is achieved with Fixed Points.

✗ Fixed Points are expensive and complex to use.

Calibration Baths

Calibration baths are usually especially designed baths or tanks with a deep chamber and high circulation using alcohol, water or oil as a medium, depending on the temperature. Salt is also used at the highest temperatures. Especially designed, so-called, Micro Baths are also available for smaller thermometers.

✓ The best available stability and uniformity of temperature is achieved with the best calibration baths.

! The stability of the bath may be improved with an especially designed temperature stabilization block.

! Each sensor should be tested for optimum immersion. Test is done by simply calibrating the end points while immersing the sensor, for example, at 5 cm increments. Once the results remain the same for the next immersion level, the correct immersion level has been found for this kind of sensor.

✗ Some thermometer sensors are not immersible into a liquid medium without proper protection.

METHANOL is Highly Toxic

Most bath manufacturers recommend methanol, but good industrial grade ethanol is usually suitable for all baths, please ask your local supplier.

- *If methanol is used the work space should be ventilated and the bath operators or other people should not be exposed to the fumes during filling, operation or changing of the fluid.*
- *Storage and disposal of all bath fluids should be done according to the local regulations.*

Climate Chamber

- ⓘ A climate chamber is usually a chamber with an air circulator and a heat control system. Sometimes, humidity may also be controlled.
- ✓ A climate chamber is usually easy to use and does not need any liquid filling.
- ✓ A climate chamber is suitable for the calibration of large thermometers. With a window on the door they also can be used for chart recorders or thermometers having only a visual display.
- ✗ Stability and uniformity of temperature inside the chamber is usually poor.
- ! Stability and uniformity of temperature inside the chamber may be improved by placing a special measurement chamber inside the climate chamber.

Dry Block Calibrators

- ⓘ A dry block calibrator is a small calibration furnace with a vertical well for thermometer sensors and they usually have a very low immersion depth. The measurement range is usually from room temperature up to 650 °C but some equipment can go down to -40 °C.
- ✓ The dry block calibrator is portable, usually easy to use and does not need any liquid filling.
- ✗ Low immersion depth, suitable only for very thin sensors.

Ovens

- ⓘ Ovens are used at higher temperatures. Only specially designed vertical calibration ovens with several temperature controlled zones should be used for calibration.
- ✓ Ovens reach the highest calibration temperatures.
- ✗ An oven without air circulation will have high temperature gradients and the gradients should be investigated carefully before use.

Temperature Sensing Equipment

SPRT Thermometers

SPRT thermometers are resistive sensors with typically 25.1 to 25.5 Ω nominal resistance to used in the range from -259 to 962 °C.

- ✓ The best available temperature measurement accuracy is achieved with an SPRT-25 thermometer calibrated at fixed points.
- ✓ The best available temperature measurement accuracy is achieved with an SPRT-25 thermometer calibrated at fixed points.
- ✗ An SPRT thermometer is an extremely fragile piece of equipment and needs careful operation.
- ✗ An SPRT-25 thermometer usually requires the use of the triple point of water.
- ✗ Calculations of SPRT-25 thermometer are complex.
- ✗ Needs an accurate resistance measurement bridge.

Pt-100 Sensor or Precision Thermistor

Pt-100 sensors or precision thermistors are generally used in the range from -100 to 200 °C.

- ✓ Pt-100 sensors or precision thermistors are usually robust and easy to use.
- ✗ Stability of a Pt-100 sensor is not known before it has undergone several calibrations.
- ✗ Stability of the sensors may be monitored with regular calibrations at ice-point (0.00 °C).

Liquid-in-Glass Thermometers

Liquid-in-glass thermometers may be used in the range from -200 to 500 °C.

ⓘ In liquid-in-glass thermometers, the expansion of a selected liquid in comparison to temperature is used to measure temperature. The liquid may be an organic liquid in the lowest temperatures, for example mercury/thallium down to -56 °C and mercury down to -38 °C.

✓ Liquid-in-glass thermometers are generally stable allowing up to a three year calibration interval.

✗ The use of mercury is not allowed in several countries.

✗ Liquid-in-glass thermometers are fragile and the measurement range is limited.

ⓘ Liquid-in-glass thermometers are usually used as a pair of two thermometers.

ⓘ Different kinds of liquids are used, but only mercury or mercury/thallium thermometers are reliable.

✗ Liquid-in-glass thermometers are difficult to read and require a trained observer.

Temperature Display Units

In cases where the sensor has an electrical output, it is usually measured with a resistance bridge, thermometer display unit or digital multimeter.

Resistance Bridges

In a resistance bridge, the measured resistance is compared to a reference resistance, either internal or external.

- ⓘ A conventional resistance bridge is manual, but modern bridges are possible to automate.
- ✓ Most accurate resistance measurement method.
- ✗ Does not give direct temperature readings.
- ✗ Needs calibrated reference resistance.

Thermometer Display Units

There are many different especially designed thermometer display units to choose from.

- ⓘ If the Pt-100 sensor or thermistor is connected to a thermometer, they should be calibrated as a pair, and the calibration coefficients stored in the memory of the thermometer.
- ✓ Gives direct temperature reading, no additional calculations needed.

Digital Multimeters

A digital multimeter may be used to measure the resistance of the temperature sensor.

- ✗ If the resistance of the Pt-100 sensor or thermistor is measured during the calibration with multimeter and the coefficients for the calibration equation are given on the certificate, the following should be taken into consideration:
- ⓘ Proper calibration of the resistance range of the multimeter.
- ⓘ The measurement current should not exceed the recommended current of the sensor to avoid self-heating.

Comparison of the Calibration Methods, Generators and References:

	Accuracy	Stability	Use	Automatization	Maintenance	Price
Calibration Methods						
Full fixed point calibration	✓✓✓	✓✓✓	✗✗✗	✗✗✗	✗✗✗	✗✗✗
Single fixed point calibration	✓✓✓	✓✓✓	✗✗✗	✗✗✗	✗✗✗	✗
Comparison calibration in bath	✓✓	✓✓	✓✓	✓✓	✓	✗
Temperature Generation						
Fixed points	✓✓✓	✓✓✓	✗✗✗	✗✗✗	✗✗✗	✗✗✗
Calibration baths	✓✓	✓✓	✓✓	✓✓	✓	✗
Climate chamber	✓	✓	✓✓	✓✓	✓✓✓	✓
Dry block calibrator	✓✓	✓	✓✓✓	✓✓	✓✓✓	✓✓✓
Ovens	✓	✓	✓✓✓	✓✓✓	✓✓✓	✓
Reference Sensor						
SPRT thermometer	✓✓✓	✓✓✓	✗	✗	✗✗	✗✗✗
Pt-100 sensor or precision thermistor	✓✓	✓	✓✓✓	✓✓	✓✓✓	✓
Liquid-in-glass thermometer	✓	✓✓✓	✗	✗✗✗	✓✓✓	✓✓✓
Display Unit						
Resistance bridge	✓✓✓	✓✓✓	✗✗	✗✗	✗✗	✗✗✗
Thermometer	✓✓	✓✓	✓✓✓	✓✓✓	✓	✓
Digital multimeter	✓	✓	✓	✓✓✓	✓✓✓	✓✓✓

✓ Good ... ✓✓✓ very good

✗ No good ... ✗✗✗ not suitable

ⓘ ... Information

! ...Remarkable point

Temperature Calibration Methods

A temperature calibration may be a fixed point calibration, or, a comparison calibration, where the reference value and the UUC value are compared at selected temperatures.

A temperature calibration may be done as a one-point calibration, or, a full range calibration. Sometimes it is also practical to calibrate the UUC for only part of the measurement range, if the overall range is larger than the temperature range used.

Fixed Point Calibration

In a fixed point calibration, the reference is a so-called fixed point cell which when operated properly produces a fixed temperature value. The cell has a thermometer well into which the sensor is placed and the reading taken.

Several fixed point values may be measured and the coefficients solved for the correction equation.

The most common fixed point is the triple point of water which produces temperature of 0.01 °C. Traditionally ice-point (0.00 °C) is used like a fixed point but it does not have that status in ITS-90 scale.

One-Point Calibration

Traditionally the ice-point (0.00 °C) is used as a control or adjustment point for some thermometers.

The stability of liquid-in-glass thermometers and platinum sensors are controlled with frequent ice-point measurements and appropriate corrections calculated.

In one-point calibration the reference sensor and UUC sensor are placed closely together in a stable temperature environment. After stabilization the readings are taken. A one-point calibration may also be done in a process where the reference sensor is placed near the UUC sensor in actual process conditions.

In cases where the one-point calibration is made at room temperature the reference and calibrated sensor must be protected from direct light sources, like lighting or sun, and stabilization should be ensured with a fan circulating air to the sensors.

Full Calibration

To perform a full range calibration, a controlled temperature generator is needed. This may be a calibration bath, climate chamber or dry block calibrator.

In full calibration the measurement points (usually 3 or more points) are selected equally spaced throughout the measurement range. These are usually performed beginning with the lowest temperature and proceeding to the highest temperature. Hysteresis of modern temperature sensors is negligible and does not need to be measured.

After changing the temperature set-point, the stabilization time must be sufficient to allow the medium, reference and the UUC to reach equilibrium.

Calibration in a Fixed Point Cell

The UUC sensor is immersed into the thermometer well of the fixed cell, the cell is prepared and the reading of the UUC sensor is taken.

ⓘ Sensor construction and dimensions should be suitable to fixed point calibration.

Calibration in Calibration Bath

The reference and UUC sensor are immersed into the bath, and after stabilization, the reading of the reference and UUC sensor are taken.

ⓘ Sensor construction and dimensions should be suitable for bath calibration.

ⓘ The sensor may have to be protected before immersing into the bath liquid.

Calibration in Climate Chamber or Dry Block Calibrator

The reference and UUC sensor are placed into the calibration chamber and after stabilization, the reading of the reference and UUC sensors are taken.

In this case, the thermal contact between air and the sensor is weak, in comparison to a calibration in liquid, and heat conducted through the connecting wires may cause large errors.

Common Mistakes

System Not Stabilized Before Measurement

✗ In cases where system is not stabilized before taking measurements, the reference and the UUC reading may differ significantly as the sensors have different time constants and follow the change at different rates.

ⓘ To avoid these errors, carefully wait for the system to stabilize before taking any measurements.

Heat Conducted via Sensor Wires

✗ In cases where the sensor is not immersed deep enough into the temperature chamber, heat is conducted via the wires and significant errors can occur. This may happen in baths, dry wells, ovens and climate chambers.

ⓘ To avoid these errors, calibrate the sensor at end point temperatures while immersing the sensor, for example, at 5cm increments. Once the results remain the same for the next immersion level, the correct immersion level has been found for this kind of sensor.

4.3. Pressure Calibration

The measurement scale of pressure is very wide (from 10^{-8} to 10^{8} Pa). The nature of pressure itself and the measurement methods vary depending on the scale. Pressure can also be measured using different gases or liquids. This makes the measurement of pressure very different. The amount of pressure may need to be known as an absolute pressure, gage pressure, positive or negative differential pressure and can be expressed using various units like Pa, psi, mmHg, Torr, atm and so on.

In the lowest pressure ranges, we are speaking about detecting a few particles in the measurement system. In the highest pressure ranges we are speaking about large and even dangerous forces generated inside the measurement system.

This chapter concentrates on a small part of the pressure range used in Vaisala Barometers and Pressure Transmitters, from 50 to 1300 hPa.

The tendency of expansion of a compressed gas or liquid is called pressure p [Pa] and it is defined using equation:

Formula 9

$$p = \frac{F}{A}$$

In a system the pressure p is the fraction of the force F [N] caused by the tendency of expansion of the compressed gas (or liquid) against surface and the area of that surface A [m^2].

Most pressure equipment in this pressure range measure the force that affects the pressure sensor.

Choosing Reference Equipment

Pressure Balance (known also as Piston Gage), Mercury Manometer or Electrical Transfer Standard may be used as reference equipment in the pressure range from 50 hPa to 1300 hPa.

Conventional Pressure Balance

In conventional pressure balance weights are loaded on top of a piston. The mass together with the local gravity produces a downward force. This force causes pressure relative to the area of the piston against the bottom of the piston. To measure the pressure, the balance pressure supply is connected to the bottom of the pressure balance and adjusted so that the piston is floating - at this point the pressure in the system is equal to the pressure produced with the weights and piston.

- ✓ The best available accuracy is achievable with the best Pressure Balances.
- ✓ Pressure Balances are extremely stable equipment allowing even three year calibration interval depending on the accuracy needed.
- ✗ The local gravity has to be measured for pressure calculation (local gravity can be calculated instead of measurement if the accuracy demand is not critical).
- ✗ Pressure Balance is temperature dependent and needs stable conditions.
- ✗ When operating Pressure Balance in absolute pressure mode a calibrated Vacuum Meter is needed.
- ✗ The operation of the Pressure Balance is manual, therefore a trained operator is needed.
- ✗ Needs periodical cleaning.
- ✗ The pressure calculations are very complex (including residual pressure, gravity, temperature corrections, and uncertainty estimation).

Digital Pressure Balance

In so called digital pressure balance, the piston is placed on a load cell and the force is measured with the load cell.

- ✗ Needs daily gain calibration with a calibration mass.
- ✗ Needs periodical cleaning.

Mercury Manometer

In mercury manometer the measured pressure is lifting mercury in column and the height of the mercury column is measured with various means. Traditionally, a scale is attached and the readings are observed manually. Modern mercury manometers use ultrasonic or laser measurement systems for the measurement height of the column.

- ✓ Mercury manometers are generally stable equipment allowing even three year calibration intervals depending on the construction (so called dual cistern manometers).
- ✗ Mercury is highly toxic and needs to be installed in a ventilated room.
- ✗ Mercury gets contaminated and needs to be periodically cleaned.
- ✗ The density of mercury changes due to the amount of dissolved air, therefore, the dissolved air needs to be removed periodically.
- ✗ The local gravity has to be measured for pressure calculations (local gravity can be calculated instead of the measurement if the accuracy demand is not critical).
- ✗ Mercury is very temperature dependent and needs stable conditions.
- ✗ The pressure calculations are very complex (gravity and temperature corrections).
- ✗ Mercury evaporates slowly and it needs to be refilled periodically (so-called single cistern manometers). As the mercury evaporates the readings will drift accordingly and it needs to be recalibrated after refilling. Due to the evaporation these manometers should be calibrated annually.
- ✗ The vacuum on the dual cistern manometer should be periodically pumped to keep it low enough.
- ✗ The reading of the Mercury Manometer is manual, and needs a trained observer.
- ✗ Mercury Manometers are extremely difficult to transfer for calibration and are not suitable as traveling standards.

Electrical Transfer Standard and Electrical Transfer Standard Integrated into a Pressure Controller

Electrical transfer standards have a sort of sensor attached with the display unit or with the digital output.

- ✓ Electrical transfer standards are generally easy to use and easy to transport.
- ✓ Best electrical transfer standards are as accurate as high class pressure balances.
- ✓ Electrical transfer standards integrated into pressure controllers are easy to automate.
- ✗ The reference should not be sensitive to damage during transportation.
- ✗ The reference adjusted for optimum accuracy during calibration.
- ✗ At least two references are needed for cross-checking and checking before and after transportation.

Comparison of the References:

	Accuracy	Stability	Use	Automatization	Maintenance	Price
Conventional pressure balance	✓✓✓	✓✓✓	✗✗✗	✗✗	✗✗	✗✗
Digital pressure balance	✓✓	✓✓	✓✓	✓	✓✓	✗
Mercury manometer	✓	✓✓	✗✗✗	✗✗✗	✗✗✗	✓
Electrical transfer standard, low accuracy	✓	✓	✓✓✓	✓✓	✓✓✓	✓✓✓
Electrical transfer standard, high accuracy	✓✓	✓	✓✓✓	✓✓	✓✓✓	✓
Electrical transfer standard integrated to pressure control-ler, low accuracy	✓	✓	✓✓✓	✓✓✓	✓✓✓	✗✗
Electrical transfer standard integrated to pressure control-ler, high accuracy	✓✓	✓	✓✓✓	✓✓✓	✓✓✓	✗✗✗

✓ Good ... ✓✓✓ very good

✗ No good ... ✗✗✗ not suitable

ⓘ ... Information

! ...Remarkable point

Pressure Calibration Methods

Pressure calibration is a comparison calibration where the reference value and the UUC value are compared at selected pressures.

Pressure calibration may be performed as one-point calibration or full range calibration. Sometimes it is also practical to calibrate the UUC for a part of the measurement range if the range is larger than the used pressure range.

One-Point Calibration at Atmospheric Pressure

In one-point calibration, no pressure generating system is needed, the reference and the UUC are just placed at same level and readings are taken at stable conditions.

Mercury manometers or electrical transfer standards may be used as references in a one-point calibration.

In this case the pressure gradient should be monitored and be sufficiently slow to avoid errors in readings (If the integration times of the reference and the UUC are different the pressure gradient will cause error).

The result of a one-point calibration is usually offset-correction that is added to the reading of the UUC. Some UUC's can be adjusted at the calibration point.

One-point calibrations are useful for barometers and for periodical checking of pressure equipment, in addition to the one-point calibration, the full calibration should be carried out at regular intervals.

Full Calibration

When performing a full calibration, a pressure generating system is needed. The reference and the UUC are connected into a closed pressure system at the same level and the readings are taken at adjusted pressure levels.

In full calibration the measurement points (usually from 5 to 11 points) are selected equally spaced from the measurement range. The calibration is performed for increasing and decreasing pressures using the same pressure adjustment rate and stabilization times to measure the hysteresis of the UUC.

When changing the pressure, the maximum pressure change rate should not be exceeded to avoid damages. Rapid pressure changes also cause adiabatic temperature changes in the system causing long stabilization times.

Pressure balance, mercury manometer or electrical transfer standard may be used as a reference in full calibration.

Pressure can be adjusted using a simple hand pump, vacuum pump and pressure supply with adjustment valves or a pressure controller. Sometimes the references may be integrated into the pressure controller.

✓ If a pressure controller is used the calibration can be fully automated.

In this case the pressure system should be leak free and should be tested before each calibration to avoid errors in readings. Leaks may cause large errors and should be corrected before starting the calibration.

ⓘ The results of full calibrations are usually correction curves from where the correction at measurement points is taken and added to the reading of the UUC. Some UUC's can be adjusted using offset and gain corrections, leaving the unlinearity not corrected while some units can be adjusted for optimum linearity and accuracy.

Common Mistakes

Leak in Pressure System

✗ Leaks in the system may cause significant errors.

ⓘ How to avoid these errors - before starting the calibration, perform a leak test at the highest and lowest measured pressure each time new equipment is added to the system. A leak test may be performed by adjusting the pressure, closing system and monitoring the reference reading if the pressure remains. In case leaks occur, they should be fixed before calibration.

Why the Reference and UUC Should be at the Same Level
Hydrostatic pressure effects any pressure system and in case the reference and UUC are at different levels the appropriate correction should be used.

5. Vaisala Calibration Services

Calibration is one of Vaisala's core operations. We have a wide range of calibration services available for customers.

Vaisala calibration services enable you to get the best possible performance from your units.

For further information, please contact Vaisala sales office or service center. Contact information as well as information on our services is available at Vaisala website **www.vaisala.com**.

Calibration Services

Relative humidity, dewpoint temperature, barometric pressure and carbon dioxide calibration services are available globally from our regional service centers. We cooperate with world class courier companies to make international logistics fast and trouble-free.

Accredited Calibration Services

Accredited calibrations for measurement instruments are needed when formal third party recognition for calibration is required. This recognition is required for instruments used as reference standards, and to meet various demands from different authorities.

Vaisala has accredited calibration services for Vaisala pressure, temperature, dewpoint and humidity instruments. Services are available through regional service centers, and available for both already installed units and together with delivery of new units.

Calibration certificates are issued in compliance with the requirements of the ISO/IEC 17025 and recognized by all the major international accreditation organizations.

Vaisala Service Center	European Service Center	Asian Service Center	North American Service Center
Location, laboratory code	Helsinki, Finland K008	Tokyo, Japan 0123	Boston, MA, USA 112765
Accreditation symbol	FINAS Finnish Accreditation Service	ilac-MRA IAJapan JCSS	A2LA ACCREDITED
Accredited Quantities			
Relative humidity	■	■	■
Temperature	■		■
Dewpoint		■	■
Barometric pressure	■		

■ Available

Customized Maintenance Services

Vaisala has the flexibility to offer customized maintenance services that are suitable for your specific needs. We will work with you to design a superior solution.

Service Center Locations

On-line Technical Support

If you need technical support, please contact
helpdesk@vaisala.com

European Service Center

Vaisala Instruments Service
Vanha Nurmijärventie 21
01670 Vantaa
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Phone: +358 9 8949 2658
Fax: +358 9 8949 2295
E-mail: instruments.service@vaisala.com

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E-mail: china.service@vaisala.com

Appendix A: Terminology

Accreditation (Laboratory)

Formal recognition that a laboratory is competent to carry out specific tests or calibrations.

Notes:

1. Accreditation is normally awarded following successful laboratory assessment and is followed by appropriate surveillance.
2. The competence of the laboratory is stated in the accreditation decision, covering: best measurement capability, physical quantity, calibration method and measurement range.

Accuracy (of Measurement)

Closeness of the agreement between the result of a measurement and a true value of the measurand.

Notes:

1. “Accuracy” is a qualitative concept.
2. The term precision should not be used for “accuracy”.

Adjustment (of a Measurement Instrument)

Operation of bringing a measurement instrument into a state of performance suitable for its use.

Note: Adjustment may be automatic, semiautomatic or manual.

Calibration

Set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measurement instrument or measurement system, or values represented by a material measure or a reference material, and the corresponding values realized by standards.

Notes:

1. The result of a calibration permits either the assignment of values of measurands to the indications or the determination of corrections with respect to indications.
2. A calibration may also determine other metrological properties such as the effect of influence quantities.
3. The result of a calibration may be recorded in a document, sometimes called a Calibration Certificate or a Calibration Report.

Correction

Value added algebraically to the uncorrected result of a measurement (reading) to compensate for systematic error.

Notes:

1. The correction is equal to the negative of the estimated systematic error.
2. Since the systematic error cannot be known perfectly, the compensation cannot be complete.

Correction Factor

Numerical factor by which the uncorrected result of a measurement is multiplied to compensate for systematic error.

Note: Since the systematic error cannot be known perfectly, the compensation cannot be complete.

Indicating Instrument

Digital Measurement Instrument

Measurement instrument that provides a digitized output or display.

Note: This term relates to the form of presentation of the output or display, not to the principle of operation of the instrument.

Analog Measurement Instrument

Measurement instrument in which the output or display is a continuous function of the measurand or of the input signal.

Note: This term relates to the form of presentation of the output or display, not to the principle of operation of the instrument.

Displaying

Indicating Device

Part of a measurement instrument that displays an indication.

Notes:

1. This term may include the device by which the value supplied by a material measure is displayed or set.
2. An analogue displaying device provides an analogue display: a digital displaying device provides a digital display.
3. A form of presentation of the display either by means of a digital display in which the least significant digit moves continuously, thus permitting interpolation, or by means of a digital display supplemented by a scale and index, is called a semi-digital display.
4. The English term readout device is used as a general descriptor of the means whereby the response of measurement instrument is made available.

Indicating (Measurement) Instruments

Measurement instrument that displays an indication.

Example: Analog indicating voltmeter, digital frequency meter, micrometer.

Notes:
1. The display may be analogue (continuous or discontinuous) or digital.
2. Values of more than one quantity may be displayed simultaneously.

A displaying measurement instrument may also provide a record.

Drift (Long-Term Stability)

Slow change of a metrological characteristic of a measurement instrument.

End Point Linearity

The closeness to which the calibration curves can be adjusted to approximate the specified straight line so that the upper and lower range values of both input and output curves coincide.

Error

Result of a measurement (reading) minus a true value of the measurand.

Note: Since a true value can not be determined a conventional true value is used.

Hysteresis Error

The maximum deviation between the two calibration curves of the measured variable as obtained by an upscale going traverse and a downing traverse over the full range and subtracting the value of dead band.

Linearity Error

The absolute value of the maximum deviation between the calibration curve and the specified straight line.

Note: Linearity error should be qualified. When expressed simply as linearity, it is assumed to be independent linearity error.

Random Error

Result of a measurement minus the mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions.

Notes:
1. Random error is equal to error minus systematic error.
2. Because only a finite number of measurements can be made, it is only possible to determine an estimate of random error.

Hysteresis

The property of a device whereby it gives different output values in relation to its input values depending on the directional sequence in which the input values have been applied.

Note: Hysteresis is calculated as correction downwards - correction upwards.

Independent Linearity

The closeness to which the calibration curve can be adjusted to approximate the specified straight line so that the maximum deviation is minimized (best fit).

Linearity

The closeness to which a calibration curves approximates a specified straight line.

Note: Linearity should be qualified. When expressed simply as linearity, it is assumed to be independent linearity.

Material Measure

Device intended to reproduce or supply, in a permanent manner during its use, one or more known values of a given quantity.

Example: Weight, standard electrical resistor or capacitor, gauge block, standard signal generator and reference material.

Measurand

Particular quantity subjects to measurement.

Measurement Equipment

Measurement equipment are equipment used in measurement and they may be actively measurement instruments like measurement instruments, -transducers, -sensors or material measures like weights, standard resistor or capacitors, gauge blocks or reference materials and so on.

Measurement or Measurement System

Complete set of measurement instruments and other equipment assembled to carry out specified measurements.

Example: The equipment needed in thermometer calibrations that may contain the reference thermometer, reference sensor, calibration bath, ice-point, computer and so on.

Note: The system may include material measures and chemical reagents. A measurement system that is permanently installed is called a measurement installation.

Measurement Instrument

Instrument that is intended to be used to make measurements, alone or in conjunction with supplementary device(s) like sensors.

Measurement Transducer

Device that provides an output quantity having a determined relationship to the input quantity.

Example: Thermocouple, current transformer, strain gauge, pH electrode.

Recording Device

Part of a measurement instrument that provides record of an indication.

Recording (Measurement) Instrument

Measurement instrument that provides a record of the indication.

Example: Barograph, chart recorder, data logger.

Notes:
1. The record (display) may be analog (continuous or discontinuous line) or digital.
2. Values of more than one quantity may be recorded (displayed) simultaneously.
3. A recording instrument may also display an indication.

Reference, (Measurement) Standard, Etalon

Material measure, measurement instrument, reference material or measurement system intended to define, realize, conserve or reproduce a unit or one or more values of a quantity to serve as a reference. The references may be named by the function they have like:

International (Measurement) Standard

Standard recognized by an international agreement to serve internationally as the basis for assigning values to other standards of the quantity.

National (Measurement) Standard

Standard recognized by a national decision to serve, in a country, as the basis for assigning values to other standards of the quantity.

Primary Standard

Standard that is designated or widely acknowledged as having the highest metrological qualities and whose value is accepted without reference to other standards of the same quantity.

Secondary Standard

Standard whose value is assigned by comparison with a primary standard of the same quantity.

Reference Standard

Standard, generally having the highest metrological quality available at a given location or in a given organization, from which measurements made which are derived.

Transfer Standard

Standard used as an intermediary to compare standards.

Travelling Standard

Standard, sometimes of special construction, intended for transport between different locations.

Working Standard

Standard that is used routinely to calibrate or check material measures, measurement instruments or reference materials.

Repeatability (of Results of Measurements)

Closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement.

Notes:

1. These conditions are called repeatability conditions.
2. Repeatability conditions include the same measurement procedure, observer, measurement instrument used under the same conditions and location and repetition is made over a short period of time.
3. Repeatability may be expressed quantitatively in terms of the dispersion characteristics of the results.

Reproducibility (of Results of Measurements)

Closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement.

Notes:

1. A valid statement of reproducibility requires specification of the conditions changed.
2. The changed conditions may include: principle of measurement, method of measurement, observer, measurement instrument, reference standard, location, conditions of use and time.
3. Reproducibility may be expressed quantitatively in terms of the dispersion characteristics of the results.
4. Results are here usually understood to be corrected results.

Response Time

Time interval between the instant when a stimulus is subjected to a specified abrupt change and the instant when the response reaches and remains within specified limits around its final steady value.

Sensor

Element of a measurement instrument or measurement chain that is directly affected by the measurand.

Example: Pt-100 sensor element, humidity sensor.

Note: In some fields the term “detector” is used for this concept.

Stability/Unstability

Ability of a measurement instrument to maintain constant its metrological characteristic with time.

Notes:

1. Short-term stability (noise) is usually attributed to time periods less than 24 hours and long-term stability (drift) to longer time periods.
2. Where stability with respect to a quantity other than time is considered, this should be stated explicitly.

Systematic Error

Mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions minus a true value of the measurand.

Notes:

1. Systematic error is equal to error minus random error.
2. Like true value, systematic error and its causes cannot be completely known.

Traceability (of Measurement)

Property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties.

Notes:

1. The concept is often expressed by the adjective traceable.
2. The unbroken chain of comparisons is called a traceability chain.

Uncertainty (of Measurement)

Parameter associated with the result of a measurement, which characterizes the dispersion of the values that could reasonably be attributed to the measurand.

Notes:

1. The parameter may be, for example, a standard deviation (or a given multiple of it), or the half-width of an interval having a stated level of confidence.
2. Uncertainty of measurement comprises, in general, many components. Some of these components may be evaluated from the statistical distribution of the results of series of measurements and can be characterized by experimental standard deviations. The other components, which can also be characterized by standard deviations, are evaluated from assumed probability distributions based on experience or other information.
3. It is understood that the result of the measurement is the best estimate of the value of the measurand, and that all components of uncertainty, including those arising from systematic effects, such as components associated with corrections and reference standards, contribute to the dispersion.

This definition is that of the "Guide to the expression of uncertainty in measurement" in which its rationale is detailed (see, APPENDIX C).

Appendix B: Abbreviations

A2LA	American Association for Laboratory Accreditation, USA
APLAC	Asian Pacific Laboratory Accreditation Cooperation
APLMF	Asia-Pacific Legal Metrology Forum
BIML	Bureau International de Métrologie Légale (International Bureau of Legal Metrology)
BIPM	Bureau International des Poids et Mesures (International Bureau of Weights and Measures)
CGPM	Conférence Générale des Poids et Mesures (General Conference on Weights and Measures)
CIPM	Comité International des Poids et Mesures (International Committee for Weights and Measures)
COOMET	Euro-Asian Cooperation of National Metrological Institutions
DMM	Digital multimeter
EA	European Accreditation
EMLMF	Euro-Mediterranean Legal Metrology Forum
GLP	Good Laboratory Practice
HTPRT	High Temperature Platinum Resistance Thermometer
IAF	International Accreditation Forum, Inc.
ILAC	International Laboratory Accreditation Cooperation
ISO	International Organization for Standardization
JCSS	Japan Calibration Service System
MLA	Multilateral Agreement
MOU	Memorandum of Understanding
MRA	Mutual Recognition Arrangement
NIST	National Institute of Standards and Technology, USA
NMI	National Metrology Institute
NPL	National Physical Laboratory, UK
NVLAP	National Voluntary Laboratory Accreditation Program
OIML	Organisation Internationale de Métrologie Légale (International Organization of Legal Metrology)
PRT	Platinum Resistance Thermometer
PTB	Physikalisch-Technische Bundesanstalt
QMS	Quality Management Standard
SADCMEL	Southern African Development Community
SI	Système International d'Unités (International System of Units)
SIM	Sistema Interamericano de Metrologia
SPRT	Standard Platinum Resistance Thermometer
UUC	Unit Under Calibration
UUT	Unit Under Test
WELMEC	European Cooperation in Legal Metrology

Appendix C: Uncertainty Calculation

Uncertainty may be calculated in several ways. The reliability of the given uncertainty often depends more on the professionalism of the person performing the calculation than on the calculation method used.

Two common mistakes in uncertainty calculations are:

- Giving only the calibration uncertainty of the reference equipment and “forgetting” the long-term stability of the reference and uncertainties caused by the calibration process and unit under calibration.
- “Forgetting” some uncertainty components to get “suitable” uncertainty values.

It is almost impossible to evaluate the reliability of the given uncertainty unless the calibration is performed by an accredited calibration laboratory. The uncertainty estimations of accredited calibration laboratories are always inspected by qualified technical specialists.

In the following some practical examples are given for people who are developing calibration systems and uncertainty estimations or evaluating suppliers calibration systems.

The examples given in this appendix are made according to EA-4/02 “Expression of the Uncertainty of Measurement in Calibration”.

General

- The statement of the result of a measurement is complete only if it contains both the values attributed to the measurand and the uncertainty of measurement associated with that value.
- The uncertainty of measurement is a parameter, associated with the result of a measurement, which characterizes the dispersion of the values that could reasonably be attributed to the measurand.

Uncertainty is given using the same unit and precision as the measurement result.

Example: 75.5 %RH ± 2.0 %RH, (k = 2)
The statement of the result of a measurement is complete only if it contains both the values attributed to the measurand and the uncertainty of measurement associated with that value.

Uncertainty types

There are two different methods on evaluating uncertainty:

1. Type A method is based on statistical methods.
2. Type B method is based on other methods.

Type A Evaluation of Standard Uncertainty

The Type A evaluation of standard uncertainty can be applied when several (10) independent observations have been made for one of the input quantities under the same conditions of measurement.

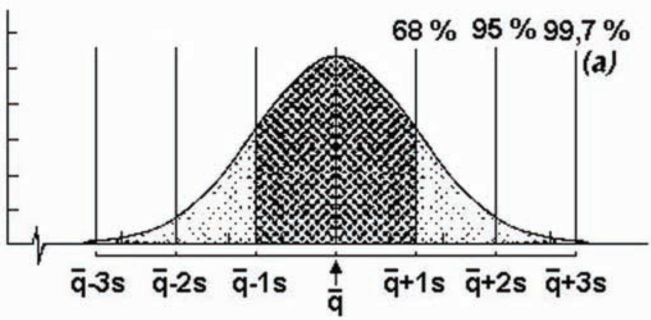
- If there is sufficient resolution in the measurement process there will be an observable scatter or spread in the values obtained.

Example: 75.03, 75.00, 75.03, 75.01, 75.00, 75.02, 75.06, 75.05, 75.04, 75.06

- The average of the observed values is 75.03
- The standard deviation of the observed values is 0.02
- The estimate of the repeatedly measured input quantity is the **arithmetic mean** (q) or the **average** of the individual observed values.

The uncertainty of measurement associated with the estimate is evaluated as the **experimental standard deviation**. The term **standard deviation** is used.

One **standard deviation** represents 68% of the possible deviation of the samples.



Type B Evaluation of Standard Uncertainty

Formula 10

$$u = \frac{\left(\frac{1}{2} \cdot (a_+ + a_-)\right)}{\sqrt{3}}$$

The Type B evaluation of standard uncertainty is the evaluation of the uncertainty associated by means other than the statistical analysis of a series of observations. Values belonging to this category may be derived from:

- Previous measurement data
- Experience with or general knowledge of the behavior and properties of materials and instruments
- Manufacturers specifications
- Data provided in calibration and other certificates
- Uncertainties assigned to reference data taken from handbooks

If only upper and lower limits a+ and a- can be estimated for the value of the quantity. A probability distribution with constant probability distribution density between these limits (rectangular probability distribution) has to be assumed for the possible variability of the input quantity.

- If the resolution is poor and no actual variation can be found the type B evaluation method should be used.

Example 1: 75.0, 75.0, 75.0, 75.0, 75.0, 75.0, 75.1, 75.1, 75.0, 75.1

- The average of the observed values is 75.03
- The standard deviation of the observed values is 0.05
- In this case the standard deviation would give acceptable estimate for the uncertainty. However, in a case where the measured values are all the same, the type B should be used.

Example 2: 75.0, 75.0, 75.0, 75.0, 75.0, 75.0, 75.0, 75.0, 75.0, 75.0

- The average of the observed values is 75.00
- The standard deviation of the observed values is 0.00 that is of course not true as we know the measured values are somewhere between 74.95 and 75.05 and that why the type B should be used. In this case the calculation would be:

Formula 11

$$u = \frac{\left(\frac{1}{2} \cdot (0.05 + (-0.05))\right)}{\sqrt{3}} = \frac{0.05}{\sqrt{3}} = 0.023$$

- In this case the minimum value for uncertainty would be 0.023.

Typical Uncertainty Factors

Typically uncertainty is composed from the uncertainties of the reference, calibration and unit under calibration. Refer to the following terms below:

- **Reference:**
  Calibration uncertainty from certificate
  Long-term stability
  Short-term stability + effect of environmental conditions
  Resolution, linearity, hysteresis

- **Calibration:**
  Deviation of the measurement results
  Effect of environmental conditions

- **Unit Under Calibration:**
  Resolution
  Short-term stability + effect of environmental conditions
  Hysteresis
  Linearity
  Repeatability

Examples of Determining Uncertainty Factors

Long-Term Stability of the Reference Equipment

The reference must have at least two calibrations before the long-term stability can be determined.

For example, the reference resistor was first calibrated at a 6 month interval. To get the first uncertainty estimation, the following will be calculated:

- 6 month drift was converted to 12 month drift:
- 5.4 ppm / Time between calibrations · 1 year = 10.4 ppm / year

This is type B uncertainty and can be converted to a standard uncertainty by dividing it by the square root of three

Formula 12

$$10.4\ \text{ppm} / \sqrt{3} = 6.0\ \text{ppm}$$

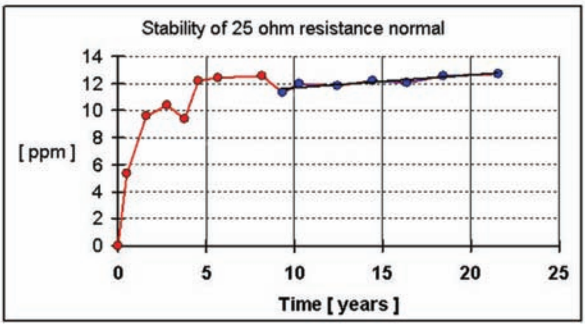
In table below the uncertainties are calculated from the actual measurement data:

Long-term Uncertainty of the Reference Resistor:

Calibration	Time [years]	Time Between Calibrations [years]	Observed Drift [ppm]	Drift/Year [ppm]	Uncertainty [ppm]
1	0.0		0.0		
2	0.5	0.52	5.4	10.4	±6.0
3	1.6	1.12	4.2	3.8	±2.2
4	2.8	1.15	0.8	0.7	±0.4
5	3.8	1.02	-1.1	-1.1	±0.6
6	4.6	0.75	2.8	3.8	±2.2
7	5.6	1.09	0.2	0.2	±0.1
8	8.2	2.53	0.1	0.1	±0.0
9	9.4	1.18	-1.2	-1.0	±0.6
10	10.3	0.94	0.6	0.6	±0.4
11	12.4	2.12	-0.1	-0.1	±0.0
12	14.4	2.02	0.4	0.2	±0.1
13	16.4	1.95	-0.1	-0.1	±0.0
14	18.5	2.07	0.5	0.2	±0.1
15	21.6	3.08	0.2	0.1	±0.0

Sometimes it is difficult to say if the variation is due calibration uncertainty or long-term stability.

After several calibrations the long-term drift can be estimated from the measurement data (see the seven latest results in the figure below).



When this kind of stable situation is reached there is no need to update the uncertainty estimations annually as long as the drift remains smaller in recalibrations.

Uncertainty of the Reference Equipment Caused by Temperature

There are three sources of uncertainty caused by temperature:

1. At the time of calibration the temperature of the reference resistor is given with an estimation of ± 0.05 °C. This uncertainty was not included in the calibration uncertainty. Therefore, the uncertainty due to the calibration temperature is:

   Formula 13

   $$u = 0.05\ °C \cdot \alpha = 0.05\ °C \cdot 0.82 \cdot 10^{-6}\ \Omega °C^{-1} = 4.1 \cdot 10^{-8}\ \Omega$$

   Where α is the temperature coefficient of the reference resistor.
2. The uncertainty caused by the uncertainty of the temperature coefficient of the reference resistor. The coefficient $\alpha = 0.75 \cdot 10^{-6}\ \Omega\ °C$ is given by the manufacturer without any estimation of uncertainty. To define the uncertainty, the coefficient was measured and the uncertainty estimated, the measured coefficient was found to be $\alpha = 0.82 \cdot 10^{-6}\ \Omega\ °C^{-1} \pm 0.03 \cdot 10^{-6}\ \Omega\ °C^{-1}$.
   The calibration temperatures vary from 22.4 to 23.7 °C and the temperature during use may vary from 19.5 to 20.5 °C. This means that the maximum temperature difference is 4.2 °C. The resistance uncertainty due to the uncertainty of the temperature coefficient is:
   $4.2\ °C \cdot 0.03 \cdot 10^{-6}\ \Omega\ °C^{-1} = 0.13 \cdot 10^{-6}\ \Omega$.
3. The uncertainty caused by the temperature uncertainty of the reference resistor during use. The temperature is measured but the temperature varies according to room temperature (from 19.5 to 20.5 °C). It is estimated that the uncertainty of the measured temperature value is 0.3 °C. The resistance uncertainty due to the uncertainty of the temperature is:
   $0.3\ °C \cdot 0.82 \cdot 10^{-6}\ \Omega \cdot C^{-1} = 0.25 \cdot 10^{-6}\ \Omega$.

Correlation of Uncertainty Factors

When estimating the uncertainty factors one must also estimate if the factors are correlated. In case the factors correlate it must be taken into account by using appropriate correlation factors.

In these examples all uncertainty factors are considered not to be correlated.

Combining Uncertainty Factors

The 'old' uncertainty calculation method is the square root of the sums of squares of the components:

Formula 14

$$u = \sqrt{u_1^2 + u_2^2 + \ldots u_n^2}$$

Explanations

$u_1 \ldots u_n$	the uncertainty components determined using the methods A or B
u	**the combined uncertainty** representing 68% confidence level (k = 1)

Measurement Model

The 'modern' uncertainty calculation is based on measurement model where all the uncertainty factors are presented as corrections. The uncertainties of these corrections are multiplied with the appropriate sensitivity coefficients before calculating the square root of the sums of squares of the components:

Formula 15

$$t_{correction} = \left(t_{reference} + \delta t_{reference}\right) - \left(t_{reading} + \delta t_{reading}\right)$$

Explanations

δtreference and δtreading	the corrections

After all the corrections are determined the uncertainty is calculated using uncertainty budget.

Uncertainty Budget

Example of a measurement model used in temperature calibration:

Formula 16

$$b + \delta t_{dev} + \delta t_{rnd} = \frac{\sum_{i=1}^{n}\left[\left(t_{ref,i} + \delta t_{ref}\right) - \left(t_{read,i} + \sum \delta t_{read}\right)\right]}{n} + \delta t_{stab} + \delta t_{hom}$$

$$b = \frac{\sum_{i=1}^{n}\left[\left(t_{ref,i} + \delta t_{ref}\right) - \left(t_{read,i} + \sum \delta t_{read}\right)\right]}{n} + \delta t_{stab} + \delta t_{hom} - \delta t_{dev} - \delta t_{rnd}$$

After all uncertainty factors are estimated, a uncertainty budget must be built.

Normal probability means type A uncertainty and Rectangular means type B uncertainty.

Formula 17

$$R_t = R_{cal} + \delta R_{cal,t} + \delta R_{stab} + \delta R_{\alpha} + \delta R_t$$

Explanations

R_{cal}	the value given in calibration
$\delta R_{cal,t}$	the correction due temperature uncertainty in calibration
δR_{stab}	the correction due stability of the reference resistor
$\delta R\alpha$	the correction due uncertainty of the temperature coefficient
δR_t	the correction due uncertainty of the temperature of the reference resistor

Formula 18

$$\delta R_t = (t_{cal} - t) \cdot \alpha$$

Explanations

t_{cal}	the temperature during calibration, tcal = 23.45 °C
t	the measured temperature, tcal = 20.28 °C
α	the temperature coefficient of the reference resistor, $\alpha = 0.82 \cdot 10^{-6}\ \Omega\ °C^{-1}$

Uncertainty Budget

Quantity Xi	Estimate xj	Standard Uncertainty u (xj)	Probability Distribution	Sensitivity coefficient cj	Uncertainty Contribution u(yi) [Ω]
Rcal	25.000017 Ω	$5.0 \cdot 10^{-6}$ Ω	normal	1	$5.0 \cdot 10^{-6}$
δRcal, t	0.000000 Ω	0.05 °C	normal	$0.82 \cdot 10^{-6}$ Ω °C^{-1}	$4.1 \cdot 10^{-8}$
δRstab	0.000000 Ω	$1.8 \cdot 10^{-6}$ Ω	rectangular	1	$1.8 \cdot 10^{-6}$
δRα	0.000000 Ω	$0.03 \cdot 10^{-6}$ Ω °C^{-1} $\cdot 3.17$ °C	special	1	$9.5 \cdot 10^{-7}$
δRt	-0.0000026 Ω	0.3 °C	rectangular	$0.82 \cdot 10^{-6}$ Ω °C^{-1}	$2.5 \cdot 10^{-7}$
Rt	25.000014 Ω				
			Combined uncertainty		$5.0 \cdot 10^{-5}$
			Expanded uncertainty (k=2)		$1.0 \cdot 10^{-4}$

Expanded Uncertainty

The **combined uncertainty (u)** is multiplied with a **coverage factor (k)** to get the **expanded uncertainty (U)**.

The value for coverage factor k = 2, means that the **confidence level** of the expanded uncertainty is 95 %. The expanded uncertainty is given with the measurement result and coverage factor.

Example: 75.5 %RH ± 2.0 %RH, (k = 2)

Presenting Uncertainty

No rounding is made in sub-calculations. The uncertainty is usually given with two significant digits after the decimal point:

1000.22 hPa ± 0.15 hPa instead of 1000.22 hPa ± 0.15127 hPa.

The expanded uncertainty may be rounded downwards if the rounded amount is less than 5% of the uncertainty value. All other values should be rounded upwards.

± 0.106 hPa should be rounded to ± 0.2 hPa instead of ± 0.1 hPa, which as 5% of 0.106 hPa is 0.0053 hPa and if rounded to ± 0.1 hPa the rounded part 0.006 > 0.0053 hPa.

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