

Guidance on the computation of calibration uncertainties

Jérôme Duvernoy (France)

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Chairperson, Publications Board
World Meteorological Organization (WMO)
7 bis, avenue de la Paix
P.O. Box 2300
CH-1211 Geneva 2, Switzerland

Tel.: +41 (0) 22 730 8403
Fax: +41 (0) 22 730 8040
E-mail: Publications@wmo.int

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FOREWORD

The Guide to the Expression of Uncertainty in Measurement makes a simple and clear statement stipulating that for any measurement of a physical quantity to be useful, it is essential to associate a quantitative value indicating the quality of the measurement made. Provision of information regarding the quality of a meteorological observation enables confident assessment of the suitability of that observation for its' intended purpose, whether, for example, weather forecasting, climate trend analysis, or any other of the numerous WMO application areas. Without the benefit of information quality, we cannot have this confidence.

In this context, the quality assurance of meteorological observations and traceability of measurements to the International System of Units (SI) have been identified as important matters to be addressed by the WMO Integrated Global Observing System (WIGOS).

At its 16th session, the WMO Commission for Instruments and Methods of Observation (CIMO) emphasized clearly the need to determine the uncertainty of observations of basic meteorological parameters by implementing an instrument calibration strategy at national, regional and global levels. Although not the first time such a recommendation has been made by CIMO, this latest call was broader than before, as it includes in its scope other types of measurements, including those from remote sensing instruments such as lidar and weather radar.

This report, prepared by Dr J. Duvernoy (France) during his chairmanship of the CIMO Expert Team on Regional Instrument Centres, Calibration and Traceability, provides a simplified guide to help the staff of Regional Instrument Centres (RICs) and national calibration laboratories to establish their own detailed methods for determining calibration uncertainties. It does this by reviewing the main rules for determining uncertainty and providing concrete examples implemented in Regional Instruments Centers (RICs) in a number of regional associations. By directly addressing the computation of calibration uncertainty, the report complements a series of Instruments and Observing Methods (IOM) publications available on the WMO website which are related to metrology in meteorology, including calibration techniques and facilities.

On behalf of CIMO, I wish to express my sincere gratitude to the primary author of this report, J. Duvernoy, for the development of this document and I am convinced that it will provide valuable support to the RICs and national calibration laboratories in addressing their vital task of ensuring the quality of our observations.



(Prof. B. Calpini)

President

Commission for Instruments and Methods of Observation

1 INTRODUCTION

The fundamental reference document to perform the uncertainties calculation is the Guide to the Expression of Uncertainty in Measurement (GUM)¹. This Guide expressed the need of uncertainty by:

“When reporting the result of a measurement of a physical quantity, it is obligatory that some quantitative indication of the quality of the result be given so that those who use it can assess its reliability. Without such an indication, measurement results cannot be compared, either among themselves or with reference values given in a specification or standard. It is therefore necessary that there be a readily implemented, easily understood, and generally accepted procedure for characterizing the quality of a result of a measurement, that is, for evaluating and expressing its uncertainty.”

This IOM report demonstrates by examples how to conduct a process to evaluate uncertainty. This report will not give standard uncertainty for pressure, temperature or humidity calibration, but will try to give you the way to perform your own uncertainty computation.

The formal definitions of the term used in “uncertainty of measurement” may be found in the VIM² (JCGM200:2012, definition 2.26) and the major definitions are also expressed in the CIMO Guide WMO N°8³.

The International System of Units (SI) may be seen as the backbone of metrology. 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 Metrology Institutes (NMI) 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 then provide the traceability to the users.

An uncertainty budget should include the measurement model (mathematical relation among known quantities) of a measurement, estimates, and measurement uncertainties associated with the quantities in the measurement model, covariance, type of applied probability density functions, degrees of freedom, type of evaluation of measurement uncertainty, and any coverage factor. Measurement uncertainty comprises, in general, of many components. The most common are described below, but the first step of uncertainty calculation is to clearly understand the calibration process and to list exhaustively the uncertainty components associated to this particular calibration process.

Accreditation requires additional processes and documentation and, most importantly, evidence that laboratory personnel have been trained and have mastered the processes and methods to be accredited.

Since procedures and methods are likely to change more frequently than the management aspects of the accreditation, the methods are usually not included in the management manual. However, there is specific reference to the procedures and methods used in the management manual. As it is unlikely that all aspects of the accreditation will be covered once the quality management system is introduced, it is recommended that a preaudit should be conducted and coordinated with the certifying agency. The first step, to be sure that the

calibration laboratory system is ready for preparing accreditation, is to fill up the self-evaluation scheme provided by WMO as an IOM report⁴ [“Evaluation Scheme for Regional Instrument Centres and Other Calibration Laboratories”](#).

The accreditation procedure consists of assessments by an expert panel (external to the organization), which includes a representative from the certifying agency. The assessment panel will focus on two main areas, namely the documentation and the facilities included in the scope of the accreditation.

The most important part is the assessment of documentation that covers the uncertainty analysis of calibrations.

2 GENERAL CONSIDERATIONS

Reading the definition, “calibration is an operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication” (JCGM200:2012, definition 2.39), it is assumed that uncertainty comes from three main sources: The reference used (measurement standard), the unit under calibration (UUC) (measurement result) itself, and the calibration process used (under specified conditions). The major 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 stability of pressure generation, the temperature uniformity in a climate chamber during a temperature calibration or the pressure correction used in a dew-point calibration.

The uncertainty in the result of a measurement generally consists of several components which may be grouped into two categories according to the way in which their numerical value is estimated:

- A. those which are evaluated by statistical methods,
- B. those which are evaluated by other means.

There is not always a simple correspondence between the classification into categories A or B and the previously used classification into “random” and “systematic” uncertainties. The term “systematic uncertainty” can be misleading and should be avoided.

Any detailed report of the uncertainty should consist of a complete list of the components, specifying for each the method used to obtain its numerical value. The uncertainty of measurement associated with the input estimates is evaluated according to either a 'Type A' or a 'Type B' method of evaluation.

The Type A evaluation of standard uncertainty can be applied when several 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. In this case the standard uncertainty is

the experimental standard deviation of the mean that follows from an averaging procedure or an appropriate regression analysis.

The Type B evaluation of standard uncertainty is the method of evaluating the uncertainty by means other than the statistical analysis of a series of observations. Typically, the standard uncertainty is evaluated by scientific judgement based on all available information, by previous measurement data, by experience with or general knowledge of the behaviour and properties of relevant materials and instruments, by manufacturer's specifications; by data provided in calibration and other certificates or by uncertainties assigned to reference data taken from handbooks.

To meet the needs of some industrial and commercial applications, as well as requirements in the areas of health and safety, an expanded uncertainty U is obtained by multiplying the combined standard uncertainty u_c by a coverage factor k . The intended purpose of U is to provide an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand. In meteorology the factor k is based on the coverage probability or level of confidence required, such that in many cases the coverage probability corresponds to approximately 95 %.

3 UNCERTAINTY CALCULATION

3.1 Uncertainty of measurement estimating procedure

The following is a guide to the use of this document in practice. This procedure is part of a generic document from the European co-operation for Accreditation and titled "Evaluation of the Uncertainty of Measurement in Calibration.

- (a) Express in mathematical terms the dependence of the measurand (output quantity) Y on the input quantities X_i according to the following equation:

$$Y = f(X_1 + X_2 + \dots + X_N) \quad (\text{eq. 1})$$

In the case of a direct comparison of two standards the equation may be very simple, e.g.:

$$Y = X_1 + X_2 \quad (\text{eq. 2})$$

- (b) Identify and apply all significant corrections.
- (c) List all sources of uncertainty in the form of an uncertainty analysis in accordance with the GUM:

$$u^2(y) = \sum_{i=1}^N u_i^2(y) \quad (\text{eq. 3})$$

The quantity $u_i(y)$ ($i = 1, 2, \dots, N$) is the contribution to the standard uncertainty associated with the output estimate y resulting from the standard uncertainty associated with the input estimate x_i :

$$u_i(y) = c_i \cdot u(x_i) \quad (\text{eq. 4})$$

where c_i is the sensitivity coefficient associated with the input estimate x_i , i.e. the partial derivative of the model function f with respect to x_i , evaluated at the input estimates x_i ,

$$c_i = \frac{\partial f}{\partial x_i} = \left. \frac{\partial f}{\partial X_i} \right|_{X_1=x_1, \dots, X_N=x_N} \quad (\text{eq. 5})$$

The sensitivity coefficient c_i describes the extent to which the output estimate y is influenced by variations of the input estimate x_i . It can be evaluated from the model function f by equation (1) or by using numerical methods, i.e. by calculating the change in the output estimate y due to a corresponding change in the input estimate x_i of $+u(x_i)$ and $-u(x_i)$ and taking as the value of c_i the resulting difference in y divided by $2 u(x_i)$. Sometimes it may be more appropriate to find the change in the output estimate y from an experiment by repeating the measurement at e.g. $x_i \pm u(x_i)$.

- (d) Calculate the standard uncertainty $u(x_i)$ for repeatedly measured quantities
- (e) For single values, e.g. resultant values of previous measurements, correction values or values from the literature, adopt the standard uncertainty where it is given or can be calculated.
- (g) Calculate for each input quantity x_i the contribution $u_i(y)$ to the uncertainty associated with the output estimate resulting from the input estimate x_i according to equations and sum their squares to obtain the square of the standard uncertainty $u(y)$ of the measurand. If input quantities are known to be correlated, this procedure must be adapted.
- (h) Calculate the expanded uncertainty U by multiplying the standard uncertainty $u(y)$ associated with the output estimate by a coverage factor k .

The combined standard uncertainty of a measurement result is taken to represent the estimated standard deviation of the result. It is obtained by combining the individual standard uncertainties u_i , whether arising from Type A or Type B evaluation.

$$u_c^2(y) = \sum_{i=1}^n u_i^2(y) \quad (\text{eq. 6})$$

The quantity u_i ($i = 1, 2, \dots, N$) is the contribution to the standard uncertainty associated with the output estimate y resulting from the standard uncertainty associated with the input estimate as described in sections c); d) and e).

Calibration laboratories should state an expanded uncertainty of measurement U , calculated by multiplying the standard uncertainty $u_c(y)$ by a coverage factor k .

- (i) Report the result of the measurement comprising the estimate y of the measurand, the associated expanded uncertainty U and the coverage factor k in the calibration certificate in accordance with accreditation standards.

To be more adapted to meteorology, some examples dealing with specific meteorological cases are shown in the following chapters. It is also fully recommended to refer to EA bibliography.

3.2 Uncertainty examples

The three examples presented in the next chapter are extracted from the Indonesian (BMKG Badan Meteorologi Klimatologi dan Geofisika) Calibration Laboratory, the Slovenian (Agencija Republike Slovenije za okolje) and the French (Meteo-France) Regional Instrument Centres. They are related to pressure, temperature and humidity calibrations. These examples are used from session 4 (pressure), session 5 (temperature) to session 6 (humidity). An example from the Australian RIC (Bureau of Meteorology) is also available in Annex. It should be noted that the BOM RIC uses degree of freedom to estimate the coverage factor.

The calculation of the degrees of freedom drives the uncertainty analysis in terms of confidence. The greater the degrees of freedom the higher is confidence in the parameter. The degrees of freedom are used to calculate the coverage factor.

$$v_{\text{eff}} = \frac{u_c^4(y)}{\sum_{i=1}^N \frac{u_i^4(y)}{v_i}} \quad (\text{eq. 7})$$

This method is explained in the Appendix G of the GUM. To facilitate the reading, this example is available as a comparison in the annex.

The uncertainties derived for each case uses methods described in the GUM.

It is highly recommended that these examples should be considered only as examples for some components and not as the absolute truth. The uncertainty must be evaluated for each calibration process.

4 PRESSURE CALIBRATION

This document derives the expanded 95 % confidence interval uncertainties for pressure instruments calibrated by the system. The specific case presented is the inspection instruments (silicon barometer) calibrated against working references (quartz barometer). A calibration for a barometer consists of testing it across the range 700 hPa to 1050 hPa in three ascending and three descending passes, at 50 hPa steps against a reference standard as shown in figure 1.

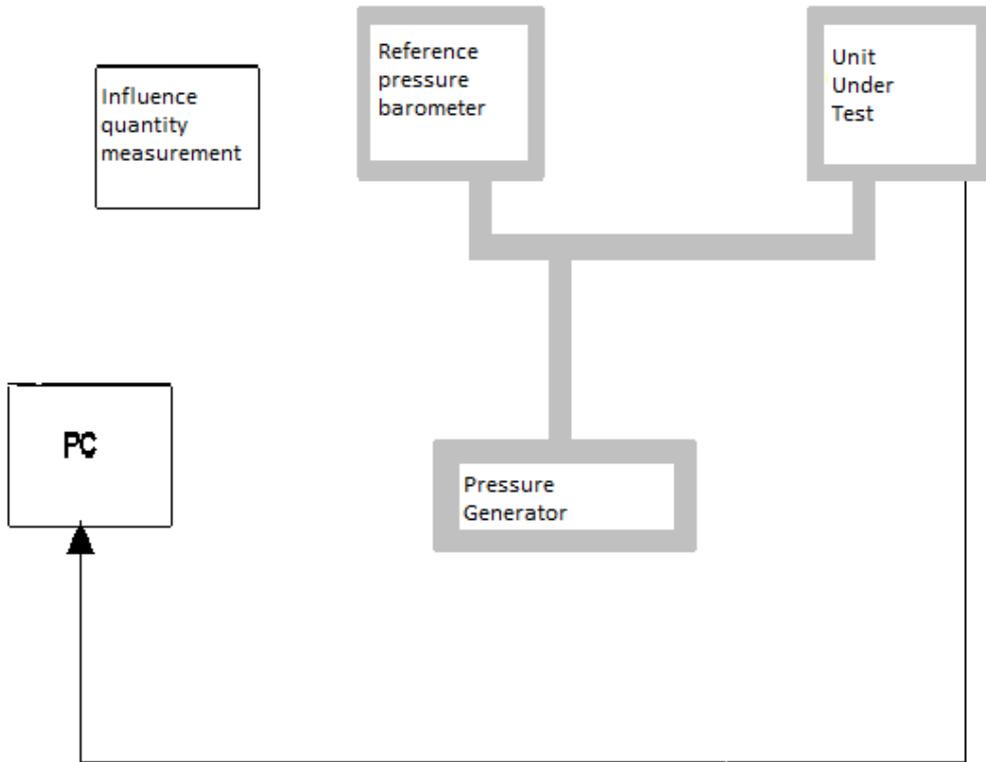


Figure 1: Pressure calibration scheme

It should be noted that a second example dealing with pressure calibration comes from the BOM RIC and uses degree of freedom to estimate the coverage factor. This method is explained in the Appendix G of the GUM. To facilitate the reading of this report, this example has been published for comparison in the annex.

4.1 Introduction

This document derives the expanded 95% confidence interval uncertainties for pressure instruments calibrated by the system. The case of a working standard calibrated against the laboratory reference is presented.

A calibration for a barometer consists of testing it across the range 700 hPa to 1050 hPa in three ascending and three descending passes, at 50 hPa steps against a reference standard. The pressure is generated by a pressure generator (CPC 6000) using an inside pump for low and high pressures. This process generates six sets of results for each point across the range with less at the turning points at the end of each pass. This is due to the difficulty in achieving an increasing pressure point at the lowest turning point pressure or a decreasing pressure at the top turning point of the range. These results are processed to derive both the corrections and an uncertainty for the barometer.

For each pass at each test point 10 measurements are collected. These measurements are used to determine an average correction at the test point during that pass. The spread of these measurements around the average are then used as the measure of the reference repeatability. The maximum difference between any three averages at the same point, from different passes, is used as the reproducibility for the barometer under calibration at that point.

For the uncertainty calculation, the reference uncertainty, maximum repeatability and reproducibility from all test points, is combined with the barometer's resolution and its maximum drift rate between calibrations. The constructed uncertainty will be applicable for use over its operating range during its calibration period. If the determined uncertainty exceeds the required operational uncertainty, it is replaced.

A quartz barometer is the laboratory primary barometer laboratory standard. The calibration of the piston gauge by the Australian Bureau of Meteorology provides traceability to S.I..

The calibration has been performed following the calibration procedure. The reference barometer and Unit Under Calibration are connected through pressure pipe to the CPC 6000 pressure generator. All equipment is settled in an appropriate table in the calibration laboratory and in the ambient temperature $21^{\circ} \pm 2^{\circ}\text{C}$.

Following the VIM definition, the calibration is "an operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication".

The uncertainty model is:

$$C = P_{\text{ref}} - P_{\text{UUC}} \quad (\text{eq. 8})$$

where:

P_{Ref} The reading from the reference barometer including potential corrections deriving from its certificate.

P_{UUC} The reading from the unit under calibration.

C The correction of the unit under calibration.

C is the correction obtained at each point from the corrected reading of the reference and the instrument being calibrated.

This model gives uncertainty components separated into 4 categories.

- Uncertainty coming from the reference (Type A and B component),
- Uncertainty coming from the measurement chain if needed (Type B component)
- Uncertainty coming from the generation (Type B component)
- Uncertainty coming from the Unit Under Calibration (Type A component for repeatability and Type B component for adjustment).

These categories are developed below as:

- Uncertainty coming from the reference barometer

The pressure measurement is vitiated by errors due to the reference barometer and the pressure generation.

The reference barometer is calibrated by the BOM on several points over the calibration range (700 to 1100 hPa).

The use of the reference barometer causes uncertainties from:

- Calibration u_{Pref}
- Interpolation $u_{interpol}$
- Drift u_{drift}
- Repeatability u_{repeat}
- Temperature influence u_{temp}
- Resolution u_{resol}

We will consider that repeatability and reproducibility are grouped and determined by the biggest experimental standard deviation u_{repeat} or by the measurement extent (Max- Min). The hysteresis component is also taken into account. $u_{hysteresis}$.

- Uncertainty due to the measurand

The uniformity of the generation depends on two components:

- The height difference between the reference and the UUT, u_{alti}
- The generator stability u_{stab}

- Uncertainty due to the Unit Under Calibration

If the Calibration Laboratory proceed to barometer adjustment, the associated component is included into the uncertainty budget: u_{adjust} .

The Unit Under Calibration introduces the uncertainty component due to its repeatability:

u_{UUCrep} .

If the covariance is neglected, the uncertainty is estimated as

$$u^2(C) = u^2(P_{Ref}) + u^2(P_{UUC}) \quad (\text{eq. 9})$$

4.2 Uncertainties components linked to reference standard

- u_{Pref}

The calibration is performed with the reference of the BMKG calibration laboratory Paro 745 . This component (Type B) is given reading the BOM calibration certificate as ± 0.023 hPa at a 95% confidence interval with a coverage factor of 2.

$$u_{\text{Pref}} = \frac{U_{\text{calibration}}}{2} \quad (\text{eq. 10})$$

$$u_{\text{Pref}} = \frac{0.023 \text{ hPa}}{2} = 0.012 \text{ hPa} \quad (\text{eq. 11})$$

The result comes from the last BOM calibration certificate. $u_{\text{Pref}} = 0.012$ hPa

- u_{drift}

The drift rate of the working references (Quartz Instrument) is specified in its purchase specification by the manufacturer as < 0.10 hPa per year. This is a very conservative estimate and further work by the manufacturer has reduced this figure.

The drift from the reference barometer between two external calibrations is estimated from the two last calibration certificates. For a given point, the maximum difference (absolute value) is calculated from the corrections of each certificate Δc . The uncertainty component is estimated by dividing this difference by $\sqrt{3}$.

$$u_{\text{drift}} = \frac{\text{Max}(\Delta c)}{\sqrt{3}} \quad (\text{eq. 12})$$

It is checked if this difference is lower than the previous calculated value. If not the case, the previous value is kept.

In this case the value has been computed between 2011 and 2012 as:

$$u_{\text{drift}} = \frac{0.083 \text{ hPa}}{\sqrt{3}} = 0.048 \text{ hPa} \quad (\text{eq. 13})$$

- u_{interpol}

The calibration of the reference barometer is performed at given points. However, its use require points spread continuously along the whole range. The interpolation between two points are performed linearly. The doubt introduce by the interpolation is estimated according BNAE (Bureau de Normalisation de l'Aéronautique et de l'Espace, French Standardization Bureau for Aeronautic and Space) recommendation, as:

$$u_{\text{interpol}} = \sqrt{2} \cdot s_{\text{rep}} = 2.9 \text{ Pa in this example.} \quad (\text{eq. 14})$$

- u_{temp}

The reference barometer has been calibrated by the BOM at a given temperature (see the calibration certificate). During a BMKG calibration process, it is not fully guaranteed that the temperature is exactly the same, but it remains in a given range. It is known that the reference quartz barometer is temperature compensated but a bias remains. This value has been estimated using manufacturer data. This value is divided by $\sqrt{2}$, making the assumption that the temperature dependency is following an Arcsine law.

$$u_{temp} = 0.0008\% \text{F.S.}/^{\circ}\text{C} / \sqrt{2} = 0.0008/100 * 1034 * 4 / \sqrt{2}, ^{\circ}\text{C} = 0.024 \text{ hPa} \quad (\text{eq. 15})$$

- u_{resol}

The barometer display shows a digit equals to a Pa. With a RS connexion this resolution is decreased to 0.1 Pa.

The resolution of the working references is:

± 0.001 hPa with a coverage factor of $1/2/\sqrt{3}$;

$$u_{resol} = \frac{0.001}{2 \cdot \sqrt{3}} = 0.0003 \text{ hPa} \quad (\text{eq. 16})$$

and is used as the range of a square distribution in the uncertainty calculation.

- u_{repeat}

During each calibration, the span of measurement (Max-Min) is calculated, for each ascending and descending test point average. The reading span describes the spread of the corrections around each of the test points recorded. The maximum span at any test point is used in the uncertainty calculation for the repeatability of the working barometer.

The worst case extend shown by the Quartz Instrument used as reference by the laboratory is less than ± 0.02 hPa. In expanded uncertainty terms this is:

$$u_{repeat} = 0.02 \text{ hPa} \quad (\text{eq. 17})$$

This figure is used for the repeatability in this uncertainty analysis. It is considered that repeatability and reproducibility are grouped and determined by the highest the measurement span (Max- Min).

- $u_{hysteresis}$

The hysteresis component is estimated as equal to the greatest difference between ascending and descending modes. As the BOM calibration certificate does not include ascending and descending data, it is assumed that the hysteresis component is included in the final uncertainty budget.

4.3 Uncertainty due to the pressure generation

- u_{alti}

This component is introduced by the pressure of the gas column being in the pressure tube between the devices settled at different heights. This component due to the difference of pressure between the Height H_2 against the Height H_1 equals to:

$$\Delta p_{\text{altitude}} = \rho g (H_1 - H_2) \quad (\text{eq. 18})$$

where

g is the standard gravity (9,80665 m.s⁻²)

considering $\rho_{\text{azote}} \sim \rho_{\text{air}}$, it is assumed that $\rho = 1,2 \text{ kg.m}^{-3}$

According to the BNAE recommendation, the uncertainty on pressure is given by:

$$(u_{\text{alti}})^2 = \left[\frac{\partial p}{\partial \rho} \right]^2 u^2(\rho) + \left[\frac{\partial p}{\partial (H_1 - H_2)} \right]^2 u^2(H_1 - H_2) + \left[\frac{\partial p}{\partial g} \right]^2 u^2(g) \quad (\text{eq. 19})$$

In BKMG the level are considered as identical. However it remains an uncertainty component on the level measurements:

$$u_{\text{alti}} = \left[\frac{\partial p}{\partial (H_1 - H_2)} \right] u(H_1 - H_2) = \rho g u(H_1 - H_2) \quad (\text{eq. 20})$$

Considering an altitude uncertainty equals to 10 cm it comes:

$$u_{\text{alti}} = 0.0117 \text{ hPa} \quad (\text{eq. 21})$$

The respective uncertainty component is obtained by divided this value by 3:

$$u_{\text{alti}} = 0.004 \text{ hPa} \quad (\text{eq. 22})$$

- u_{stab}

The generator stability has been studied in a separated document. This document shows the results of pressure generator characterization. The pressure generator is a CPC 6000 model from WIKA, it is coupled to an external barometer. The characterization was made in the BKMG calibration laboratory. The test covers the following parameters: - response time and stability in the full range used by the BKMG laboratory, as 700 to 1050 hPa. This characterization is in coherence with the calibration uncertainty calculation. The tests have been realized at the ambient temperature. To increase the uncertainty, the tests was repeated at different days. The worse uncertainty was kept. The manufacturer claimed a generation precision equals to +/- 0.01% of the Full scale using an internal reference, meaning a generation range equals to 0.11 hPa.

This characterization has two main aims. The first one is to verify the manufacturer specification. The second is to provide the stability component for the uncertainty budget.

The value obtained is: $u_{\text{stab}} = 0.012 \text{ hPa}$

4.4 Uncertainty due to Unit Under Calibration

- **Resolution**

The resolution of the instrument is:

$$u_{UUCres} = \frac{0.1hPa}{2\sqrt{3}} = 0.03 \text{ hPa} \quad (\text{eq. 23})$$

and is considered the range of a square distribution for the uncertainty calculation.

- **Repeatability**

As was done for the calibration of the working references, the extend of measurements is calculated for each ascending and descending test point average. The maximum extend at any test point is used in the uncertainty calculation for the repeatability of the inspection instrument. As 3 cycles are done, this value is divided by 1.69⁵.

$$u_{UUCrep} = \frac{Extend}{1.69} \quad (\text{eq. 24})$$

This figure is used for the repeatability in this uncertainty analysis.

In this example, the value equals to: $u_{UUCrep} = 0.012 \text{ hPa}$

- $u_{adjustment}$

If needed, the component related to the adjustment is estimated as the resolution multiplied by $\sqrt{2}$, so:

$$u_{adjustment} = \sqrt{2} * u_{UUCres} \quad (\text{eq. 25})$$

4.5 Expanded measurement uncertainty

The uncertainty budget relative to the calibration means (reference and generator) is then obtained with the following equation:

$$u_{cal} = \sqrt{u_{Pref}^2 + u_{drift}^2 + u_{interpol}^2 + u_{temp}^2 + u_{resol}^2 + u_{repeat}^2 + u_{hysteresis}^2 + u_{alti}^2 + u_{stab}^2} \quad (\text{eq. 26})$$

Where u_{cal} is the combined standard uncertainty. The expanded calibration uncertainty is:

$$U_{cal} = 2 * u_{cal} \quad (\text{eq. 27})$$

The extended uncertainty for calibration means is obtained on the whole calibration range, then from 700 to 1050 hPa.

The uncertainty budget relative to the working standard calibration is then obtained with the following equation:

$$U = 2 * \sqrt{u_{cal}^2 + u_{UUCres}^2 + u_{UUCrepeat}^2 + u_{adjustment}^2} \quad (\text{eq. 28})$$

This uncertainty is given in the calibration certificate. All components are expressed and valued in the following table:

Quantity	Brief description	Standard uncertainty	Distribution	Sensitivity coefficient	Uncertainty contribution
u_{Pref}	Reference calibration	1.2 Pa	normal	1	1.2 Pa
u_{drift}	Drift Reference	4.8 Pa	rectangular	1	4.8 Pa
$u_{interpol}$	Interpolation	2.9 Pa	rectangular	1	2.9 Pa
u_{Temp}	Temperature sensibility	2.4 Pa	Arcsine	1	2.4 Pa
u_{resol}	Reference resolution	0.03 Pa	rectangular	1	0.03 Pa
u_{repeat}	Reference repeatability	2 Pa	rectangular	1	2 Pa
u_{alti}	Altitude difference	0.4 Pa	rectangular	1	0.4 Pa
u_{stab}	Generator stability	1.2 Pa	rectangular	1	1.2 Pa
u_{UUCres}	UUC resolution	0.3 Pa	rectangular	1	0.3 Pa
$u_{UUCrepeat}$	UUC repeatability	1.2 Pa	rectangular	1	1.2 Pa
Expanded measurement uncertainty U (k=2)					13.6 Pa

Table 1: Field Instrument uncertainty

The expanded uncertainty of a field instruments when they leave the laboratory can be stated as the standard uncertainty $U=0.136$ hPa with a coverage factor of 2.

5 TEMPERATURE CALIBRATION

5.1 Introduction

Pt100 resistance thermometer is used as the working temperature standard in the calibration laboratory. Stable temperature medium is a liquid bath with a working range from -40°C to 50°C . Data acquisition is performed via multimeter and GPIB interface or RS232 interface in the personal computer data base. Ambient temperature and relative humidity is monitored during calibration in one place and its influence appropriately evaluated. Reference Pt 100 four-wired is connected to the multimeter. In many cases, the requirements for the ambient conditions - especially the ambient temperature - are given in the specifications of the electrical devices. A calibrated thermometer is also needed for the measurement of the ambient temperature. The instrument of ambient temperature is fixed close to the measuring equipment where such influence is effective. A corresponding chart is presented in figure 2.

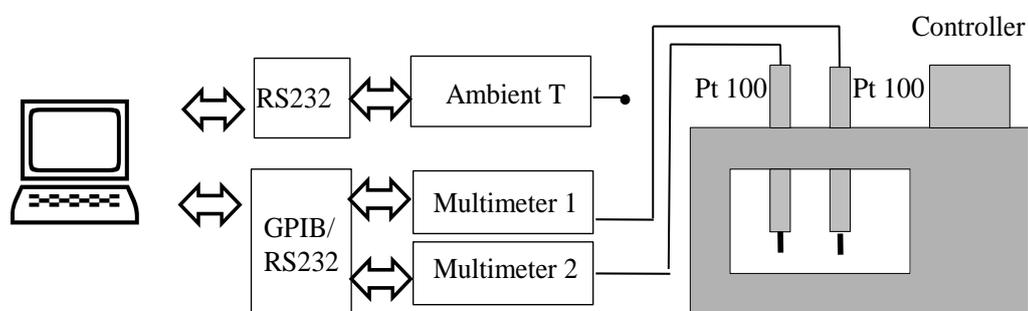


Figure 2: PRT calibration with platinum resistance thermometer as a reference

The measurement uncertainty in the calibration of a thermometer depends on the calibration method used, the uncertainty contribution of the standards, the characteristics of the measuring equipment used and the characteristics of the device under calibration. No general instructions for the measurement uncertainty of certain thermometer types can therefore be given. The examples of measurement uncertainty calculation cannot be directly implemented to any calibration actually carried out but uncertainty contributions must carefully be evaluated in each individual case.

Platinum resistance thermometers are calibrated by the comparison method or in defined fixed points in the appropriate temperature scale. Combination of the two methods is also permissible. Comparison calibration of the resistance thermometers are calibrated in temperature-stabilized baths using reference/working thermometers, suitable electrical measuring devices must be used (ohmmeter, resistance measuring bridge, standard resistors) which must also have been traceably calibrated.

Comparison calibration is performed by measurement of the resistance of the instrument under calibration while it is exposed to a temperature.

Fundamentally, four instruments are required as follows:

- Reference standard
- Data acquisition for the reference standard
- Data acquisition for the instrument under calibration
- Temperature source

The technical requirements for the readout are the same for the instruments under calibration and the reference when calibrating PRTs against a reference PRT. If a multiplexing system is available, one readout device can usually be used for both. If the readout is designed for temperature calibration (not just temperature measurement) and has variable settings (current, timing, etc.), then certainly it can be used for both. If the readout is not designed for temperature calibration and/or a switching system is not available, then two or more readouts will probably be required. Before selecting a readout, review the information presented in the readouts section with regard to current settings, timing, multiplexing, etc. Best results will be obtained with readouts designed specifically for thermometer calibration.

A calibration bath/chamber cannot be considered as completely stable in time and homogeneous over its' entire volume, especially when temperature calibrations by comparison are performed at the best level of uncertainty. This represents a major contribution to the total uncertainty of a calibration procedure. In order to decrease this uncertainty contribution equalizing blocks can be used in calibration baths. The dimension of the block depends on the bath dimension.

- Homogeneity: A gradient is observed as a change of a temperature reading of a thermometer according to a change of its position inside a calibration bath. Basic gradients that can be observed are vertical and horizontal gradient. Because a lot of calibration baths have either a cylindrical shape or equalizing blocks inside it is sometimes more appropriate to define axial and a radial gradient. Uncertainty contribution of an axial gradient is determined as maximum temperature difference between two different positions in axial direction of an equalizing block. The radial gradient is a maximum temperature difference between two different positions in a radial direction.
- Stability: important characteristic of a bath is also short-term stability of a medium temperature. It strongly depends on type of regulation and flow of medium inside the bath. Since the calibration measurements are taken within short time interval, the short-time stability is relevant (ca. 30min). For the time stability of a bath, temperature deviations of a reference thermometer are observed.

The temperature, at which the calibration item is calibrated, is determined by measurement with the standard thermometer and by additional corrections, following the model below:

$$C = T_{\text{Ref}} - T_{\text{UUC}} \quad (\text{eq. 29})$$

where:

T_{Ref} The reading from the reference thermometer including potential corrections deriving from its certificate.

T_{UUC} The reading from the unit under calibration.

C The correction for the unit under calibration.

C is the correction obtained at each point from the corrected reading of the reference and the instrument being calibrated.

If the covariance is neglected, the uncertainty is estimated as

$$u^2(C) = u^2(T_{\text{Ref}}) + u^2(T_{\text{UUC}}) + u^2(T_{\text{RefAcq}}) + u^2(T_{\text{UUCAcq}}) + u^2(T_{\text{Bath}}) \quad (\text{eq. 30})$$

where:

- $u(C)$ is uncertainty of the correction,
- $u(T_{\text{Ref}})$ is uncertainty component linked to reference thermometer,
- $u(T_{\text{UUC}})$ is uncertainty component linked to unit under calibration,
- $u(T_{\text{RefAcq}})$ is uncertainty component linked to data acquisition of reference thermometer (bridge, multimeter...),
- $u(T_{\text{UUCAcq}})$ is uncertainty component linked to data acquisition of thermometer under calibration (bridge, multimeter...),
- $u(T_{\text{Bath}})$ is uncertainty component linked with the bath (homogeneity, time stability).

5.2 Uncertainty components linked to reference thermometer - T_{ref}

- u_{Trc} : standard uncertainty in the calibration of the reference thermometer. It presents information on expanded uncertainty of reference standard in the appropriate temperature range. If calibration certificate of reference standard holds information on corrections, then they should be applied but normally only expanded uncertainty is calculated:

Example: calibration expanded uncertainty: 0.020 °C (k=2)

$$u_{\text{Trc}} = \frac{0.020^\circ\text{C}}{2} = 0.010^\circ\text{C} \quad (\text{eq. 31})$$

- u_{Trd} : standard uncertainty u_{Trd} is estimated from the maximum drift over all the drift values between successive calibrations. If instrument is new one, the manufacturer's data for stability is taken into account for uncertainty budget calculation. If no manufacturer's data is available the drift is estimated as standard uncertainty in the calibration of reference standard.

Example: drift between calibrations is 0.010 °C (k=2)

$$u_{\text{Trd}} = \frac{0.01^\circ\text{C}}{\sqrt{3}} = 0.0058^\circ\text{C} \quad (\text{eq. 32})$$

- u_{Tra} : repeatability of measurements during a calibration. We assume at least 50 measurements of reference standard was made at each calibration point. Standard deviation of mean is calculated.

Example: $u_{\text{Tra}} = 0.002^\circ\text{C}$

- u_{Trcon} : uncertainty contribution due to a possible heat conduction by the reference standard. Tests should be made at different immersion depths.

Example: pulling the reference standard 20 mm out of the bath led to a temperature change of 2 mK (which due to the temperature variations of the bath could be estimated only inaccurately).

$$u_{\text{Trcon}} = \frac{0.002^\circ\text{C}}{\sqrt{3}} = 0.0012^\circ\text{C} \quad (\text{eq. 33})$$

- u_{Trsh} : uncertainty component due for self-heating of the reference standard. The measurement of resistance involves passing a current through the resistor and, therefore, heating of the resistor. For the highest accuracy measurements, corrections are applied by measuring at two currents, I1 and I2, and extrapolating to zero current. For the determination of the electrical resistance, an electrical measurement must be carried out for which a measurement current must be fed through the sensor. The measurement current leads to the sensor being heated (self-heating) and thus to the measurement result being falsified. This effect is dependent not only on the magnitude of the measurement current but also on the measurement conditions themselves. In the calibration, the self-heating mechanism is to be investigated or a measurement current is to be chosen at which this effect is negligible.

Example: The calibration certificate states that a measurement current of 1 mA in a water triple point cell has led to a heating of 2.1 mK. This contribution is neglected in the following as the thermometer is both calibrated and used now at a measurement current of 1 mA.

- u_{Trint} : uncertainty component due to interpolation of reference function. The reference thermometer is calibrated in several calibration points. Interpolation function defines thermometer characteristics in the operational interval.

5.3 Uncertainties linked to Unit Under Calibration - Tc

- u_{Tca} : repeatability of measurements during a calibration. We assume at least 50 measurements of instrument under calibration was made at each calibration point. Standard deviation of mean is calculated.

Example: $u_{Tca} = 0.002^{\circ}\text{C}$

- u_{Tch} : uncertainty component due to hysteresis. In general, hysteresis is a phenomena that results in a difference in an items behavior when approached from a different path. In PRTs, thermal hysteresis results in a difference in resistance at a given temperature based on the thermal history to which the PRT was exposed. More specifically, the resistance of the PRT will be different when the temperature is approached from an increasing direction vs a decreasing direction, and the magnitude of the difference will depend on the magnitude of the temperature excursion and the design of the PRT.

Example: $u_{Tch} = 0.002^{\circ}\text{C}$

- u_{Tcon} : uncertainty contribution due to a possible heat conduction by the instrument under calibration. Tests should be made at different immersion depths.

Example: pulling the instrument 20 mm out of the bath led to a temperature change of 2 mK (which due to the temperature variations of the bath could be estimated only inaccurately).

$$u_{Tcon} = \frac{0.002^{\circ}\text{C}}{\sqrt{3}} = 0.0012^{\circ}\text{C} \quad (\text{eq. 34})$$

5.4 Uncertainties linked to data acquisition

Two multimeters are used for data acquisition for the reference thermometer and the instrument under calibration, so the uncertainty contribution must be accounted for the reference thermometer and the unit under calibration (UUC):

- u_{Rohm} : uncertainty contribution due to measurement uncertainty in the calibration of the ohmmeter:

Example: According to the calibration certificate, the measurement uncertainty of the multimeter is 0.020Ω ($k = 2$) and the standard uncertainty thus is $10 \text{ m}\Omega$.

- u_{Rts} : uncertainty contribution due to time stability of multimeter (user manual)

Example: $u_{Rts} = 0.5 \text{ m}\Omega$

- u_{Rt} : uncertainty contribution due to ambient temperature influence (user manual). Outside certain ambient temperature interval, the component is significant and can be accessed using the user manual. Within a prescribed temperature interval this component is negligible.
- u_{Res} : uncertainty component due to multimeter resolution – least significant bit LSB. Example: The limited resolution of the ohmmeter of $0,001 \Omega$ allows a reading within $\pm 0,0005 \Omega$. From this a standard uncertainty of $0.5 \text{ m}\Omega / \sqrt{3} = 0,29 \text{ m}\Omega$.
- Multimeter additional noise if multiplexer is used.

- Uncertainty linked to the connection: The reference probe is four wires connected to multimeter and the uncertainty associated with this connection type is taken to be negligible.

5.5 Uncertainties components linked to temperature bath - T_{bath}

The spatial and temporal temperature distribution in the working space of temperature stabilized bath must be quantitatively determined and taken into account for uncertainty budget evaluation. Method for the determination of the temporal and spatial distribution involves calibrated thermometers of identical type, positioned on the boundaries of the working space (horizontal, vertical) of the temperature bath. After thermal stabilization, the temperatures measured with the thermometers are continuously recorded (typically over a period longer than 30 min). The maximum temperature difference between the thermometers is used for as uncertainty component in the uncertainty budget (rectangular distribution).

Temperature gradients in temperature-stabilized baths or furnaces can be reduced by providing a metallic stabilizing block with holes to accommodate the standards and calibration items. The thermometer calibration may begin after both the temperature is stabilized in the bath and the thermometers have reached thermal equilibrium.

Uncertainty contribution of an axial gradient is determined as maximum temperature difference between two different positions in axial direction. The radial gradient is a maximum temperature difference between two different positions in a radial direction.

- u_{bath_h} : Spatial homogeneity is a gradient is observed as a change of a temperature reading of a thermometer according to a change of its position inside a calibration bath.
 - ⇒ Basic gradients that can be observed are vertical and horizontal gradient but
 - ⇒ Sometimes it is more appropriate to define an axial and a radial gradient. Uncertainty contribution of an axial gradient is determined as the maximum temperature difference between two different positions in an axial direction. The radial gradient is a maximum temperature difference between two different positions in a radial direction.

Example: $u_{\text{bath}_h} = 0.0184^\circ\text{C}$

- u_{bath_s} : Temporal stability: important characteristic of a bath is also short-term stability of a medium temperature. It strongly depends on type of regulation and flow of medium inside the bath. Since the calibration measurements are taken within a short time interval, the short-time stability is relevant. For the time stability of a bath, temperature deviations of a reference thermometer are observed.

Example: $u_{\text{bath}_s} = 0.0032^\circ\text{C}$

5.6 Expanded measurement uncertainty

The example relates to the calibration of a thermometer at one temperature only. Usually, a thermometer is calibrated at several temperatures (calibration points) for which, as a rule, different measurement uncertainties result. As the user also employs the thermometer to carry out temperature measurements between the calibration points, it is, however, helpful if the calibration certificate also contains statements on the use of the thermometer in the whole temperature range.

Quantity	Brief description	Standard uncertainty	Distribution	Sensitivity coefficient	Uncertainty contribution
u_{Trc}	Calibration PRT	10 mK	normal	1	10 mK
u_{Trd}	Drift - reference thermometer	5.8 mK	rectangular	1	5.8 mK
u_{Tra}	Standard deviation	2 mK	normal	1	2 mK
u_{Trcon}	Conduction - reference thermometer	1.2 mK	rectangular	1	1.2 mK
u_{Tca}	Standard deviation	2 mK	normal	1	2 mK
u_{Tch}	DUC Hysteresis	2 mK	rectangular	1	2 mK
u_{Tccon}	DUC Conduction	1.2 mK	rectangular	1	1.2 mK
$u_{RohmRef}$	Calibration multimeter for reference	10m Ω	normal	2.5	25 mK
u_{RtsRef}	Time stability multimeter for reference	0.5m Ω	rectangular	2.5	1.25 mK
u_{ResRef}	Multimeter resolution for reference	0.29m Ω	rectangular	2.5	0.73 mK
$u_{RohmUUC}$	Calibration multimeter	10m Ω	normal	2.5	25 mK
u_{RtsUUC}	Time stability multimeter	0.5m Ω	rectangular	2.5	1.25 mK
u_{ResUUC}	Multimeter resolution	0.29m Ω	rectangular	2.5	0.73 mK
u_{bath_h}	Bath homogeneity	18.4mK	normal	1	18.4mK
u_{bath_s}	Bath stability	3.2mK	normal	1	3.2mK
Expanded measurement uncertainty U (k=2)					83.7mK

Table 2: Temperature calibration uncertainty

In the field, the thermometer is possibly used under conditions which are different from those under which the calibration was carried out. So contributions to the measurement uncertainty might dominate which could remain unaccounted for in the calibration. The measurement uncertainty in use can therefore considerably exceed the measurement uncertainty in calibration.

6 HUMIDITY CALIBRATION

6.1 Introduction

The humidity generator uses saturated salt solutions to calibrate RH probes. A wide range of salt solutions are available (Table 3).

Salt/Temperature (°C)	5.0	10.0	15.0	20.0	25.0
Lithium chloride	11.3	11.3	11.3	11.3	11.3
Magnesium chloride	33.6	33.5	33.3	33.1	32.8
Potassium carbonate	43.1	43.1	43.1	43.2	43.2
Sodium bromide	63.5	62.2	60.7	59.1	57.6
Sodium chloride	75.7	75.7	75.6	75.7	75.3
Potassium chloride	87.7	86.8	85.9	85.1	84.3
Potassium sulphate	98.5	98.2	97.9	97.6	97.3

Table 3: Nominal RH produced by various salt solutions at various temperatures

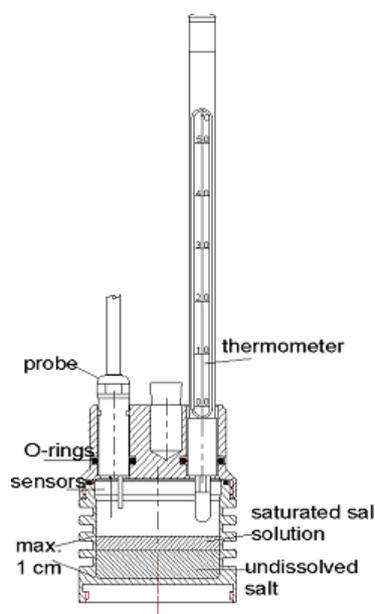


Figure 3: Hygrometer calibration with saturated salt solution as humidity generator and with a reference hygrometer

The salt solution is used only as a generator and the Unit Under Calibration is compared with the reference hygrometer (Figure 3). This method decreases the uncertainty of the calibration. The salt consumables must be changed regularly to maintain low uncertainties. It should be noted that non saturated salt solution based on Lithium chloride is also available giving similar results.

This document derives the expanded 95% confidence interval uncertainties for relative humidity capacitive sensors calibrated by the system.

A calibration for a hygrometer consists of testing it across the range 11% to 97% against a capacitive relative humidity standard. This process generates only one sets of results for each point across the range. These results are processed to derive both the corrections and an uncertainty for the hygrometer.

Unfortunately, this simplified method shown in this example does not allow for calculation of hysteresis for the UUC.

For each pass at each test point 5 measurements are collected. The operator checks if all measurements are inside 0.1%. So the spread of these measurements around the readings are then used to verify that the sensors repeatability is lower than 0.1%. The same method is also used to check the reproducibility for the hygrometer at that point.

The uncertainty model used is:

$$C = RH_{ref} - RH_{UUC} \quad (\text{eq. 35})$$

where:

- RH_{Ref} The reading from the reference hygrometer including potential corrections deriving from its certificate.
- RH_{UUC} The reading from the unit under calibration.
- C The correction for the unit under calibration.

C is the correction obtained at each point from the corrected reading of the reference and the instrument being calibrated.

If the covariance is neglected, the uncertainty is estimated as:

$$u^2(C) = u^2(\bar{R}H_{Ref}) + u^2(\bar{R}H_{UUC}) \quad (\text{eq. 36})$$

6.2 Uncertainties components linked to reference standard

- Reference calibration

The uncertainty due to the reference standard calibration is part of the calibration report. ($U_{\text{calibration report}}$ expanded uncertainty (k=2)). It is expressed as:

$$u_{\text{cal}} = 1/2 * U_{\text{calibration report}} \quad (\text{eq. 37})$$

Example: $u_{\text{cal}} = 1.2 / 2 = 0.6\%$

- Drift: standard uncertainty u_{Trd} is estimated from the maximum drift $\delta D = \mathbf{Max}(\delta d)$ over all the drift values between successive calibrations (δd) at the same point. If instrument is new one, the manufacturer's data for stability is taken into account for uncertainty budget calculation. If no manufacturer's data is available the drift is estimated as standard uncertainty in the calibration of reference standard.

$$u_{\text{drift}} = \delta D / \sqrt{3} \quad \text{with } \delta D = \mathbf{Max}(\delta d)$$

- Temperature: the internal calibration done at different temperature (20; 23; and 26°C) before the external traceable calibration leads to the temperature component. This uncertainty is calculated from the maximum calibration extent expressed at all different humidity points (from 11 to 95%).

$$u_{\text{temp}} = \max(|C_{26} - C_{23}|, |C_{20} - C_{23}|) / \sqrt{3} \quad (\text{eq. 38})$$

- Repeatability and reproducibility: These components are estimated from the reference calibration reports. The standard deviation at each humidity point should not be more than:

$$u_{\text{repeat}} = 0.1 \%$$

$$u_{\text{repro}} = 0.1 \%$$

- Resolution: The resolution of the working references is $r = 0.1$, the derived uncertainty is:

$$u_{\text{res}} = \frac{r}{2 \cdot \sqrt{3}} \quad (\text{eq. 39})$$

- Hysteresis; the reference calibration reports contains the up (C_{up}) and down (C_{down}) corrections for each calibration point. The hysteresis uncertainty component (u_{hys}) is expressed from the biggest range of corrections ($\delta_{\text{var}} = |C_{\text{up}} - C_{\text{down}}|$) as follows:

$$u_{\text{hys}} = \delta_{\text{var}} / (2 * \sqrt{3}) \quad (\text{eq. 40})$$

Example $u_{\text{hys}} = 0.03\%$

6.3 Uncertainties linked to the measurand generator

The spatial and temporal humidity distribution in the working area of the humidity generator must be quantitatively determined and taken into account for uncertainty budget evaluation. Method for the determination of the temporal and spatial distribution involves calibrated hygrometers of identical type, positioned in the working area of the humidity generator. After thermal stabilization, the humidity measured with the hygrometers are continuously recorded

(typically over a period longer than 30 min). The maximum humidity difference between the hygrometers is used for as stability uncertainty component u_{stab} in the uncertainty budget (rectangular distribution). Then the hygrometers are exchanged one by one. Finally, the homogeneity u_{hom} uncertainty component is calculated using the double substitution method.

Example $u_{Stab} = 0.3\%$,
 $u_{Hom} = 0.35\%$

6.4 Uncertainties linked to unit under calibration

- Repeatability

These two components are estimated at the same time. The component are estimated by the operator with the maximum extend of the readings during the humidity calibration. Example $u_{repeatUUC} = 0.03$ if the extend is equal to the resolution. Example $u_{Stab} = 0.3$

- Data acquisition

A multimeter is used for data acquisition for instrument under calibration, so the uncertainty contribution must be accounted for unit under calibration (UUC). The multimeter measurements are not corrected but controlled as the bias is not more than 0.1%.

$$u_{acquisUUC} = 0.1 \%$$

- Resolution

Resolution: The resolution of the working references is $r = 0.1$, the derived uncertainty is:

$$u_{resUUC} = \frac{0.1}{2 \cdot \sqrt{3}} = 0.03 \%$$

6.5 Expanded measurement uncertainty

Best capabilities

$$U_{means} = 2 * \sqrt{u_{cal}^2 + u_{drift}^2 + u_{temp}^2 + u_{res}^2 + u_{hys}^2 + u_{repro}^2 + u_{repeat}^2 + u_{Stab}^2 + u_{Hom}^2} \quad (\text{eq. 41})$$

Expanded uncertainty:

$$U_{expanded} = 2 * \sqrt{(U_{means}/2)^2 + u_{resUUC}^2 + u_{repeatUUC}^2 + u_{acquisUUC}^2} \quad (\text{eq. 42})$$

All uncertainty components are expressed in the following table (see Table 4):

Quantity	Brief description	Standard uncertainty	Distribution	Sensitivity coefficient	Uncertainty contribution
u_{cal}	Calibration uncertainty	0.6%	Rectangular	1	0.6%
u_{drift}	Drift reference hygrometer	0.25%	rectangular	1	0.25%
u_{temp}	Temperature dependency	0.2%	Arcsine	1	0.2%
u_{res}	resolution	0.03%	Rectangular	1	0.03%
u_{hyst}	hysteresis	0.03%	Rectangular	1	0.03%
u_{repeat}	repeatability	0.1%	Normal	1	0.1%
u_{repro}	reproducibility	0.1%	Normal	1	0.1%
u_{Stab}	Generator stability	0.3%	Rectangular	1	0.3%
u_{Hom}	Generator homogeneity	0.35%	Normal	1	0.35%
u_{resUUC}	UUC resolution	0.03%	Rectangular	1	0.03%
$u_{repeatUUC}$	UCC repeatability	0.03%	Normal	1	0.03%
$u_{acquisUUC}$	Calibration multimeter	0.1%	Normal	1	0.1%
$u_{combined}$					0.84%
Expanded measurement uncertainty U (k=2)					1.7%

Table 4: Humidity calibration uncertainty

7 CONCLUSIONS

This report sets down the principles of the evaluation of the uncertainty of measurement in calibration and shows three main examples in the meteorological area. The method presented is part of an EA document which has to be taken as reference. To make the information more easily applicable, various examples coming from different Calibration Laboratory or Regional Instrument Centre present how to ensure harmonisation between the different fields and methods.

However, it is recalled that these examples should be considered only as examples for some components and not as the absolute truth. The uncertainty must be evaluated for each calibration process.

8 ACKNOWLEDGEMENTS

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9 REFERENCES

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- 2 International Vocabulary of Metrology – Basic and General Concepts and Associated Terms JCGM 200:2012 The abbreviation of the title of this vocabulary is VIM.
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ANNEX

1 Pressure calibration

It should be noted that the BOM RIC uses a degree of freedom to estimate the coverage factor. This method is explained in the Appendix G of the GUM. A harmonized calculation for pressure calibration has been presented in section 4, resulting from BMKG calibration laboratory. The full study of BOM RIC is available in this annex. It should be noted that even there, based on the same calibration parameter, these two examples remain different.

1.1 Introduction

This document derives the expanded 95 % confidence interval uncertainties for pressure instruments calibrated by the system. The case of a field instrument (silicon barometer) calibrated against a working reference is presented.

A calibration for a barometer consists of testing it across the range 700 hPa to 1100 hPa in two ascending and two descending passes, at 50 hPa steps against a reference standard. This process generates four sets of results for each point across the range with less at the turning points at the end of each pass. This is due to the difficulty in achieving an increasing pressure point at the lowest turning point pressure or a decreasing pressure at the top turning point of the range. These results are processed to derive both the corrections and an uncertainty for the barometer.

For each pass at each test point 30 measurements are collected. These measurements are used to determine an average correction at the test point during that pass. The spread of these measurements around the average are then used as the measure of the barometers repeatability. The maximum difference between any two averages at the same point, from different passes, is used as the reproducibility for the barometer at that point.

For the uncertainty calculation, the reference uncertainty, maximum repeatability and reproducibility from all test points, is combined with the barometer's resolution and its maximum drift rate between calibrations. The constructed uncertainty will be applicable for use over its operating range during its calibration period. If the determined uncertainty exceeds the required operational uncertainty, it is replaced.

A Ruska model 2465 piston gauge (DWT) is the laboratory primary barometer laboratory standard. The calibration of the piston gauge by the National Measurement Institute provides traceability to national standards.

1.2 Uncertainty model

The uncertainty model used is shown in the following equation:

$$C = P_{\text{ref}} - P_{\text{UUC}}$$

where:

P_{Ref} The corrected reading from the reference.

P_{UUC} The reading from the unit under calibration.

C The correction for the instrument under calibration.

1.3 Uncertainty components

For the calibrations, the operational uncertainty is made up from the combination of:

- the uncertainty of the reference;
- the drift between calibrations;
- the resolution of the instrument;
- the maximum repeatability; and
- the maximum reproducibility for the corrections achieved during the calibration.

1.4 Uncertainties components linked to reference standard

- **Reference uncertainty**

Working references are used as the reference for the field instruments. From the uncertainty calculation of the working references, the maximum uncertainty for a working reference is:

± 0.037 hPa at a 95 % confidence interval with a coverage factor of 2.006 and 53 degrees of freedom.

- **Maximum drift**

The drift rate of the working references (Paroscientifics) is specified in its purchase specification by the manufacturer as < 0.10 hPa per year. This is a very conservative estimate and further work by the manufacturer has reduced this figure.

From regular checks conducted in the laboratory and the manufacturers report, a reasonable worst case estimate for the annual drift is:

± 0.010 hPa/year coverage factor $1/\sqrt{3}$ with 30 degrees of freedom.

- **Resolution**

The resolution of the working references is:

± 0.001 hPa coverage factor $1/\sqrt{3}$ with 30 degrees of freedom;

and is used as the range of a square distribution in the uncertainty calculation.

- **Repeatability**

During each calibration, the standard error of the mean (SEOM) is calculated, for each ascending and descending test point average. The SEOM is calculated according to the method specified in the GUM. The SEOM describes the spread of the corrections around each of the test points recorded. The maximum SEOM at any test point is used in the uncertainty calculation for the repeatability of the working barometer.

The maximum SEOM shown in this calibration is 0.0025 hPa with 55 degrees of freedom.

The worst case SEOM shown by the Paroscientifics used as working references by the laboratory is less than ± 0.006 hPa with 30 degrees of freedom. In expanded uncertainty terms this is: ± 0.012 hPa at a 95% confidence interval, a coverage factor of 2.0 with 30 degrees of freedom

This figure is used for the repeatability in this uncertainty analysis.

- **Reproducibility**

The reproducibility of the barometer at each test point is evaluated using the maximum difference between successive passes at the same test point. The maximum reproducibility is determined is then used in the calculation of the uncertainty.

The maximum reproducibility shown by the working references used by the laboratory is less than:

± 0.015 hPa with a coverage factor $1/\sqrt{3}$ with 16 degrees of freedom;

and is considered the range of a square distribution. This is the figure used in the working reference uncertainty analysis.

Unit Under Calibration

- **Calibration periodicity**

Field instruments are calibrated initially, and then verified every 12 months against inspection instruments. Once the correction exceeds ± 0.3 hPa it is returned for adjustment and calibration.

- **Maximum drift**

The maximum drift rate for the PTB220 field instruments has been determined by the laboratory as:

± 0.043 hPa/year with 20 degrees of freedom and a coverage factor of $1/\sqrt{3}$;

and is considered the range of a square distribution.

- **Resolution**

The resolution of the inspection instrument is:

± 0.001 hPa coverage factor $1/\sqrt{3}$ with 30 degrees of freedom;

and is considered the range of a square distribution for the uncertainty calculation.

- **Repeatability**

As was done for the calibration of the working references, the standard error of the mean (SEOM) is calculated for each ascending and descending test point average on each inspection instrument. The maximum SEOM at any test point is used in the uncertainty calculation for the repeatability of the inspection instrument.

As a general case for inspection instruments a worst case SEOM estimate will be used of less than ± 0.010 hPa with 40 degrees of freedom. In expanded uncertainty terms this is:

± 0.020 hPa at a 95% confidence interval, a coverage factor of 2.021 with 40 degrees of freedom.

This figure is used for the repeatability in this uncertainty analysis.

- **Residual Corrections**

Field instruments are used without corrections being applied. For field instruments to be suitable for the use, the average correction at any point cannot exceed ± 0.10 hPa. If a field instrument has a correction at any point which exceeds ± 0.10 hPa it is adjusted to meet the specification or sent for repair, or disposal if repair is not possible.

- **Reproducibility**

The reproducibility of the barometer at each test point is evaluated using the maximum difference between successive passes at a test point.

The maximum reproducibility shown in this calibration is ± 0.007 hPa with 33 degrees of freedom

The worst case SEOM shown by a PTB220A is less than:

± 0.015 hPa with a coverage factor $1/\sqrt{3}$ with 16 degrees of freedom;

For the uncertainty calculation this will be considered as the range of a square distribution.

The maximum reproducibility shown in this calibration is ± 0.007 hPa with 33 degrees of freedom

1.5 Expanded Uncertainty

The table below contains a summary of the uncertainty calculation and the input uncertainty components for a field instrument, presented in section 1.3 of this annexe.

Parameter	Expanded Uncertainty	Coverage Factor	Unit	Sensitivity Coefficient	Standard Uncertainty (hPa)	Degrees of freedom	Type
Uncertainty of Working Reference	0.037	2.0057	hPa	1	1.828×10^{-02}	53	B
Annual Drift	0.010	1.732	hPa	1	2.483×10^{-02}	30	B
Resolution	0.001	1.732	hPa	1	5.774×10^{-04}	30	B
Max Repeatability	0.012	2.004	hPa	1	9.896×10^{-03}	55	A
Max Reproducibility	0.015	1.732	hPa	1	8.661×10^{-03}	16	A
Combined							
Standard Uncertainty					0.034	86.86	
95% Expanded Uncertainty	0.067	1.989					

Table 5: PTB220B Field Instrument uncertainty

The uncertainty of PTB220B as field instruments when they leave the laboratory can be stated as the standard uncertainty ± 0.034 hPa with 86 degrees of freedom, or the expanded uncertainty of ± 0.067 hPa at a 95 % confidence interval with a coverage factor of 1.989.

Annex taken from : FD X 07-021: Aide à la démarche pour l'estimation et l'utilisation de l'incertitude des mesures et des résultats d'essais