WORLD METEOROLOGICAL ORGANIZATION

INSTRUMENTS AND OBSERVING METHODS

REPORT No. 86

TRAINING MATERIAL ON METROLOGY AND CALIBRATION

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NOTE

FOREWORD

The Thirteenth Session of the Commission for Instruments and Methods of Observation (CIMO) recognized the need for training to include topical areas such as Metrology, with a target audience being Regional Instrument Centers (RICs). I wish to express my appreciation to Mr Duvernoy and his colleague Mr Dubois on their ongoing contributions in conducting training for RICs as well as evaluating RIC performance with the goal of strengthening their capabilities and performance.

This excellent training document provides the basic instruction and reference materials for operators to improve their understanding of how operational instruments function, are monitored and calibrated. The various modules address primary sensor principles of operation, instrument characteristics, strengths and weaknesses of the various instruments used to measure meteorological parameters, as well as each instrument's range of operation.

In addition, users of this training material will have access to documents addressing:

- Exploratory Data Analysis – an approach as to how data analysis should be carried out.
- Measurement Process Characterization - lays the groundwork for understanding the measurement process in terms of errors that affect the process.
- Production Process Characterization – describes how to analyze data collected in characterization studies and studies how interpret and report the results.
- Process Modeling – provided the background and specific analysis techniques needed to construct a statistical model that describes a particular engineering or scientific process.
- Process Improvement – introduces the basic concepts, terminology, goals and procedures underlying the proper statistical design of experiments.
- Process or Product Monitoring and Control – provides the basic concepts of statistical process control, quality control and process capability.
- Product and Process Comparison – provides the background and specific analysis techniques needed to compare the performance of one or more processes against known standards or one another.

I wish to affirm my sincere gratitude to Mr Duvernoy and Mr Dubois for their efforts in the preparation of these training documents.

(Dr. R.P. Canterford)

Acting President
Commission for Instruments and
Methods of Observation

TRAINING MATERIAL ON METROLOGY AND CALIBRATION

SYLLABUS

1. Vocabulary used in Metrology
2. Measurement Statistics
3. Theoretical Guide to Measurement Uncertainty
4. Metrology of Temperature
5. Metrology of Humidity
6. Metrology of Pressure
7. Metrology organization in Météo-France

1. Vocabulary used in Metrology

WORKSHOP ON METROLOGY

INTERNATIONAL VOCABULARY OF BASIC AND GENERAL TERMS IN METROLOGY

October 2005

Following definitions are extracted from:

International vocabulary of basic and general terms in metrology
Vocabulaire International des termes fondamentaux et généraux de Métrologie
Deuxième édition, 1993.

International Organization for Standardization
Case Postale 56
CH 1211 GENEVE 20 - SWITZERLAND

1 – QUANTITIES AND UNITS

1.1. **(measurable) QUANTITY,**

attribute of a phenomenon, body or substance that may be distinguished qualitively and determined quantitatively.

NOTES:

1 The term quantity may refer to a quantity in general sense or to a **particular quantity**.

2 Quantities that can be placed in order of magnitude relative to one another are called **quantities of the same kind.**

3 Quantities of the same kind may grouped together into **categories of quantities,** for example:
- work, heat, energy;
- thickness, circumference, wavelength.

4 **Symbols of quantities** are given in ISO 31

1.3. **BASE QUANTITY,**

One of the quantity that, in a system of quantities are conventionally accepted as functionally independent of one another.

EXAMPLE: the quantities length, mass and time are generally taken to the base quantities in field of mechanics.

NOTE: The base quantities corresponding to the base units of the International System of Units (SI) are given in note 1.12.

1.4. **DERIVED QUANTITY,**

quantity defined, in a system of quantities, as a function of base quantities of that system.

EXAMPLE: in a system having base quantities length, mass and time, velocity is a derived quantity defined as: length divided by time.

1.7. **UNIT (of measurement),**

particular quantity, defined and adopted by convention, with which other quantities of the same king are compared in order to express their magnitudes relatives to that quantity.

NOTES:

1 Units of measurement have conventionally assigned names and symbols.

2 Units of quantities of the same dimension may have the same names and symbols even when the quantities are not of the same kind.

1.12. International System of Units, SI

the coherent system of units adopted and recommended by the General Conference on Weights and Measure (CGPM).

NOTE: The SI is based at present on the following seven base units:

Quantity	SI base unit	
	Name	Symbol
length	metre	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd

1.13. BASE UNIT (of measurement),

unit of measurement of a base quantity in a given system of quantities.

NOTE: In any given coherent system of units there is only one base unit for each base quantity.

1.14. DERIVED UNIT (OF MESUREMENT),

unit of measurement of a derived quantity in a given system of quantities.

NOTE: some derived units have special names and symbols; for example, in the SI:

Grandeur	SI derived unit	
	Name	Symbol
force	newton	N
energy	joule	J
pressure	pascal	Pa

1.18. VALUE (OF A QUANTITY),

magnitude of a particular quantity generally expressed as a unit of measurement multiplied by a number.

EXAMPLES:

a)	length of a rod:	5.34 m	or	534 cm;
b)	mass of a body:	0.152 kg	or	152 g;
c)	amount of substance of a sample of water (H_2O):	0.012 mol	or	12 mmol.

NOTES:

1 The value of a quantity may be positive, negative or zero.

2 The value of a quantity may be expressed in more than one way.

3 The values of a quantity of dimension one are generally expressed as pure numbers.

4 A quantity that cannot be expressed as a unit of measurement multiplied by a number may be expressed by reference to a conventional reference scale or to a measurement procedure or to both.

1.19. **TRUE VALUE (OF A QUANTITY),**

value consistent with the definition of a given particular quantity.

NOTES:

1 This is a value that would be obtained by a perfect measurement.

2 True values are by nature indeterminate.

3 The indefinite article "a" rather than the definite article "the", is used in conjunction with "true value" because there may be many values consistent with the definition of a given particular quantity.

1.20. **CONVENTIONAL TRUE VALUE (OF QUANTITY),**

value attributed to a particular quantity and accepted, sometimes by convention, as having an uncertainty appropriate for a given purpose

EXAMPLES:

a) At a given location, the value assigned to the quantity realized by a reference standard may be taken as a conventional true value;

b) The CODATA (1986) recommended value for the Avogadro constant, N_A: 6,022 136 7 x 10^{23} mol^{-1}.

NOTES:

1 "conventional true value" is sometimes called **assigned value, best estimate** of the value, **conventional value** or **reference value**."Reference value", in this sense, should not be confused with "reference value" in the sense used in the NOTE to 5.7.

2 Frequently, a number of results of measurements of a quantity is used to establish a conventional true value.

2 - MEASUREMENTS

2.1. MEASUREMENT,

set of operations having the object of determining a value of a quantity.

NOTE: The operations may be performed automatically.

2.2. METROLOGY,

science of measurement.

NOTE: Metrology includes all aspects both theoretical and practical with reference to measurements, whatever their uncertainty, and in whatever fields of science or technology they occur.

2.3. PRINCIPLE OF MEASUREMENT,

scientific basis of a measurement

EXAMPLES:

a) The thermoelectric effect applied to the measurement of temperature;

b) The Josephson effect applied to the measurement of electric potential difference;

c) The Doppler effect applied to the measurement of velocity;

d) The Raman effect applied to the measurement of the wave number of molecular vibrations.

2.4. METHOD OF MEASUREMENT,

logical sequence of operations, described generically, used in the performance of measurement.

NOTE: Methods of measurement may be qualified in various ways such as:
- substitution method
- differential method
- null method.

2.5. MEASUREMENT PROCEDURE,

set of operations, described specifically, used in the performance of particular measurements according to a given method.

NOTE: A measurement procedure is usually recorded in a document that is sometimes itself called a "measurement procedure" (or a **measurement method**) and is usually in sufficient detail to enable an operator to carry out a measurement without additional information.

2.6. MEASURAND,

particular quantity subject to measurement.

EXAMPLE: Vapour pressure of a given sample of water at 20°C.

NOTE: The specification of a measurand may require statements about quantities such as time, temperature and pressure.

2.7. INFLUENCE QUANTITY,

quantity that is not the measurement but that affects the result of the measurement.

EXAMPLES:

a) Temperature of a micrometer used to measure length.

b) Frequency in the measurement of the amplitude of an alternating electric potential difference.

2.8. MEASUREMENT SIGNAL,

quantity that represents the measurand and which is functionally related to it.

EXAMPLE:

a) The electrical output signal of a pressure transducer.

3- MEASUREMENT RESULTS

3.1. RESULT OF A MEASUREMENT,

value attributed to a measurand, obtained by measurement.

NOTES:

1. When a result is given, it should be made clear whether it refers to:
   - the indication
   - the uncorrected resultat
   - the corrected result

and whether several values are averaged.

2. A complete statement of the result of a measurement includes information about the uncertainty of measurement.

3.3. UNCORRECTED RESULT,

result of a measurement before correction for systematic error.

3.4. CORRECTED RESULT,

result of a measurement after correction for systematic error.

3.5. ACCURACY OF MESUREMENT,

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

NOTES:

1. "Accuracy" is a qualitive concept.

2. The term **precision** should not be used for "accuracy".

3.6. REPEATABILITY (OF RESULTS OF MEASUREMENTS),

closeness of the agreement between the result 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,
   - the same observer,
   - the same measuring instrument, used under the same conditions,
   - the same location,
   - repetition over a short period of time.

3. Repetability may be expressed quantitatively in terms of the dispersion characteristics of the results.

3.7. 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,
   - measuring instrument,
   - reference standard,
   - location,
   - conditions of use,
   - 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.

3.8. EXPERIMENTAL STANDARD DEVIATION,

for a series of *n* measurements of the same measurand, the quantity *s* characterizing the dispersion of the results and given by the formula:

$$s = \sqrt{\frac{\sum_{i=1}^{n} \left(x_i - \bar{x} \right)^2}{n-1}}$$

x_i being the results of the i^{th} measurement and $\bar{x}$ being the arithmetic mean of the n results considered

NOTES:

1. Considering the series of n values as a sample of a distribution, $\overline{x}$ is an unbiased estimate of the mean μ, and s^2 is an unbiased estimate of the variance σ^2, of that distribution.

2. The expression $s/\sqrt{n}$ is an estimate of the standard deviation of the distribution of $\overline{x}$ and is called the **experimental standard deviation of the mean**.

3. "Experimental standard deviation of the mean" is sometimes incorrectly called **standard error of the mean**.

3.9. UNCERTAINTY OF MEASUREMENT

parameter, associated with the result of a measurement, that 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, in particular, 2.2.4 and annex D [10]).

3.10. ERROR (OF MEASUREMENT)

result of measurement minus a true value of the measurand.

NOTES:

1. Since a true value cannot be determined, in practice a conventional true value is used (see 1.19 and 1.20).

2. When it is necessary to distinguish "error" from "relative error", the former is sometimes called **absolute error of measurement**. This should not be confused with **absolute value of error**, which is the modulus of the error.

3.11. DEVIATION,

value minus its reference value.

3.13. RAMDOM 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 possible to determine only an estimate of random error.

3.14. 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.

3. For a measuring instrument, see "bias" (5.25).

3.15. CORRECTION,

value added algebraically to the uncorrected result of a measurement 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.

4- MEASURING INSTRUMENTS

4.1. MEASURING INSTRUMENT,

device intended to be used to make measurements, alone or in conjunction with supplementary device(s).

4.2. MATERIAL MEASURE,

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

EXAMPLES:

a) A weight;

c) A standard electrical resistor;

e) A standard signal generator.

4.3. MEASURING TRANSDUCER,

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

EXAMPLES:

a) Thermocouple;

b) Current transformer;

c) Strain gauge;

d) pH electrode.

4.4. MEASURING CHAIN,

series of elements of a measuring instrument or system that constitues the path of the measurement signal from the input to the output.

4.5. MEASURING SYSTEM,

complete set of measuring instruments and other equipment assembled to carry out specified measurements.

EXAMPLE:

a) Apparatus for measuring the conductivity of semiconductor materials;

b) Apparatus for the calibration of clinical thermometers.

4.14. **SENSOR,**

element of a measuring instrument or measuring chain that is directly affected by the measurand.

EXEAMPLES:

a) Measuring junction of a thermoelectric thermometer;

b) Rotor of a turbine flow meter;

c) Bourdon tube of a pressure gauge;

d) Float of a level-measuring instrument;

e) Photocell of a spectrophotometer.

4.15. **DETECTOR,**

device or substance that indicates the presence of a phenomenon without necessarily providing a value of an associated quantity.

EXAMPLES:

a) Halogen leak detector;

b) Litmus paper.

NOTES:

1 An indication may be produced only when the value of the quantity reaches a threshold, sometimes called the **detection limit** of the detector.

2 In some fields the term "detector" is used for the concept of "sensor".

4.29. **GAUGING (OF A MEASURING INSTRUMENT),**

operation of fixing the positions of the scale marks of a measuring instrument (in some cases of certain principal marks only), in relation to the corresponding values of the measurands.

NOTE: (Applicable only to the French text.)

4.30. ADJUSTMENT (OF A MEASURING INSTRUMENT)

operation of bringing a measuring instrument into a state of performance suitable for its use.

NOTE: Adjustement may be automatic, semiautomatic or manual.

4.31. USER ADJUSTEMENT (OF A MEASURING INSTRUMENT),

adjustment employing only the means at the disposal of the user.

5- CHARACTERISTICS OF MEASURING INSTRUMENTS

5.2. SPAN,

modulus of the difference between the two limits of a nominal range.

EXAMPLE: For a nominal of -10 V to +10 V, the span is 20 V.

NOTE: In some fields of knowledge, the difference between the greatest and smallest values is called **range**.

5.4. MEASURING RANGE WORKING RANGE,

set of values of measurands for which the error of a measuring instrument id intended to lie within specified limits.

NOTES:

1 "error" r is determined in relation to a conventional true value.

2 See 5.2 Note.

5.5. RATED OPERATING CONDITIONS,

conditions of use for which specified metrological characteristics of a measuring instrument are intended to lie within given limits.

NOTE: The rated operating conditions generally specify ranges or **rated values** of the measurand and of the influence quantities.

5.6. LIMITING CONDITIONS,

extreme conditions that a measuring instrument is required to withstand without damage, and without degradation of specified metrological characteristics when it is subsequently operated under its rated operating conditions.

NOTES:

1 The limiting conditions for storage, transport and operation may be different.

2 The limiting conditions may be include limiting values of the measurand and of the influence quantities.

5.7. REFERENCE CONDITIONS,

conditions of use prescribe for testing the performance of a measuring instrument or for intercomparison of results of measurements.

NOTE: The reference conditions generally include **reference values** or **reference ranges** for the influence quantities affecting the measuring instrument.

5.9. RESPONSE CHARACTERISTIC,

relationship between a stimulus and the corresponding response, for defined conditions.

EXAMPLE: The e.m.f (electromotive force) of a thermocouple as a function of temperature.

NOTES:

1 The relationship may be expressed in the form of a mathematical equation, a numerical table, or a graph.

2 When the stimulus varies as a function of time, one form of the response characteristic is the transfer function (the Laplace transform of the response divided by that of stimulus).

5.10. SENSITIVITY,

change in the response of a measuring instrument divided by the corresponding change in the stimulus.

NOTE: The sensitivity may be depending on the value of the stimulus.

5.14. STABILITY,

ability of a measuring instrument to maintain constant its metrological characteristics with time.

NOTES:

1 Where stability with respect to a quantity other than time is considered, this should be stated explicitly.

2 Stability may be quantified in several ways, for example:
  - in terms of the time over which a metrological characteristic changes by a stated amount,
  - in terms of the change in a characteristic over a stated time.

5.15. TRANSPARENCY,

ability of a measuring instrument not to after the measurand.

EXAMPLES:

a) A mass balance is transparent;

b) A resistance thermometer that heats the medium whose temperature it is intended to measure is not transparent.

5.16. DRIFT,

slow change of a metrological characteristic of a measuring instrument.

5.17. 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.

5.18. ACCURACY OF A MEASURING INSTRUMENT,

ability of a measuring instrument to give responses close to a true value.

NOTE: "Accuracy" is a qualitative concept.

5.20. ERROR (OF INDICATION) OF A MEASURING INSTRUMENT,

indication of a measuring instrument minus a true value of the corresponding input quantity.

NOTES:

1 Since a true value cannot be determined, in practice a conventional true value is used (see 1.19 and 1.20).

2 This concept applies mainly where the instrument is compared to a reference standard.

3 For a material measure, the indication is the value assigned to it.

5.21. MAXIMUM PERMISSIBLE ERRORS (OF A MEASURING INSTRUMENT) LIMITS OF PERMISSIBLE ERROR (OF A MEASURING INSTRUMENT)

Extreme values of an error permitted by specifications, regulations, etc. for a given measuring instrument.

5.24. INTRINSIC ERROR (OF A MEASURING INSTRUMENT),

error of a measuring instrument, determined under reference conditions.

5.25. BIAS (OF A MEASURING INSTRUMENT)

systematic error of the indication of a measuring instrument.

NOTE: The bias of a measuring instrument is normally estimated by averaging the error of indication over an appropriate number of repeated measurements.

5.26. FREEDOM FROM BIAS (OF A MEASURING INSTRUMENT),

ability of a measuring instrument to give indications free from systematic error.

5.27. REPEATABILITY (OF A MEASURING INSTRUMENT),

ability of a measuring instrument to provide closely similar indications for repeated applications of the same measurand under the same conditions of meaurement.

NOTES:

1 These conditions include:
  - reduction to a minimum of the variations due to the observer,
  - the same measurement procedure,
  - the same observer,
  - the same measuring equipment, used under the same conditions,
  - the same location,
  - repetition over a short period of time.

2 Repeatability may be expressed quantitatively in terms of the dispersion characteristics of the indications.

6- MEASUREMENT STANDARDS, ETALONS

6.1. (MEASUREMENT) STANDARD ETALON,

material measure, measuring instrument, reference material or measuring system intended to define, realize, conserve or reproduce a unit or one or more values of quantity to serve as a reference.

EXAMPLES:

a) 1 kg mass standard;
b) 100 Ω standard resistor;
c) standard ammeter;
d) caesium frequency standard.

6.3. 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 concerned.

6.4. 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.

6.6. REFERENCE STANDARD,

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

6.7. WORKING STANDARD,

standard that is used routinely to calibrate or check material measures, measuring instruments or reference materials.

NOTES:

1 A working standard is usually calibrated against a reference standard.

2 A working standard used routinely to ensure that measurements are being carried out correctly is called a **check standard**.

6.8. TRANSFER STANDARD,

standard used as an intermediary to compare standards.

NOTE: The term **transfer device** should be used when the intermediary is not a standard.

6.10. TRACEABILITY,

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**.

3 (Applicable only to the French text.)

6.11. CALIBRATION,

set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring instrument or measuring 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 **calibration report**.

TRAINING MATERIAL ON METROLOGY AND CALIBRATION

2. Measurement Statistics

PowerPoint presentation

(Bureau of Meteorology, Australia)

Measurement Theory

- Intro to measurement
- Discussion of standards & traceability
- Prac example
- Uncertainty
- Examples of measurement
- Exercises
- Cautions

Measurement

**The process of
determining
the value of
some quantity in
terms of a
standard unit.**

Standards

- There is a hierarchy of standards – that is agreed units
- Some of these are artifacts ie the kg
- Some are “realised” eg temperature
- At the top of the hierarchy are Primary standards
- RIC currently hold Primary standards for P, T and Radiation

True Temperature Scale

Agreed international scale of temperature – ITS-90

Comprised of points on the scale that are realized – that is made up temporarily using physical systems

Interpolation between the points is via Pt resistance thermometers

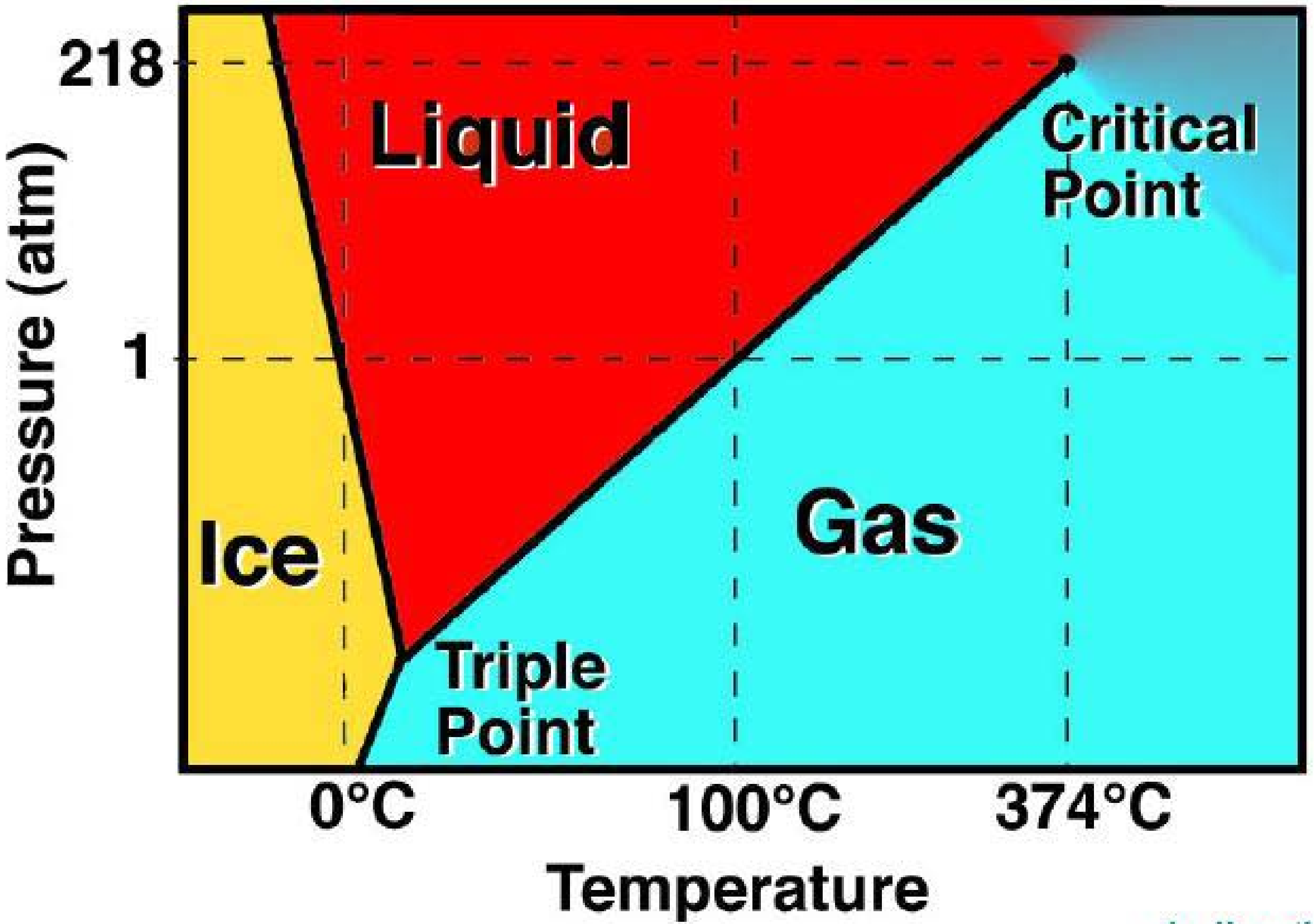
Pt resistance thermometers are approximately linear between points on the true temperature scale

Substance	**Temperature K**	**Temperature °C**	**State**
Mercury, Hg	234.3156	-38.8344	Triple Point
Water, H_20	273.16	0.01	Triple Point
Gallium, Ga	302.9146	29.7646	Melting Point
Indium, In	429.7485	156.5985	Freezing Point
Tin, Sn	505.078	231.928	Freezing Point
Zinc, Zn	629.677	419.527	Freezing Point
Aluminium, Al	933.473	660.323	Freezing Point
Silver, Ag	1234.93	961.78	Freezing

Water Triple Point Cell

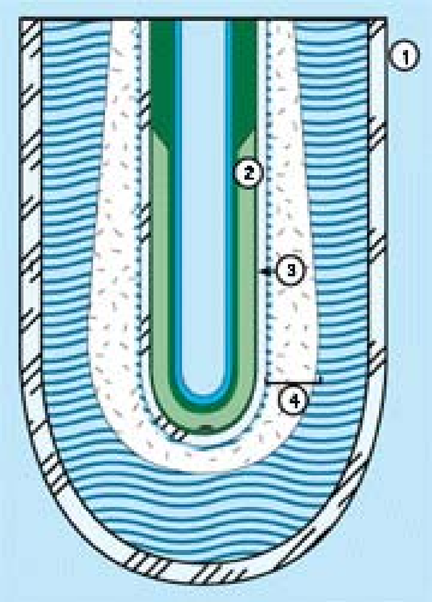
- Ultra pure water is sealed under vacuum into a glass vessel
- The apparent air gap above the liquid is entirely composed of water vapour whose pressure is determined by the temperature
- It forms a sealed system at equilibrium

Phase Diagram - Water



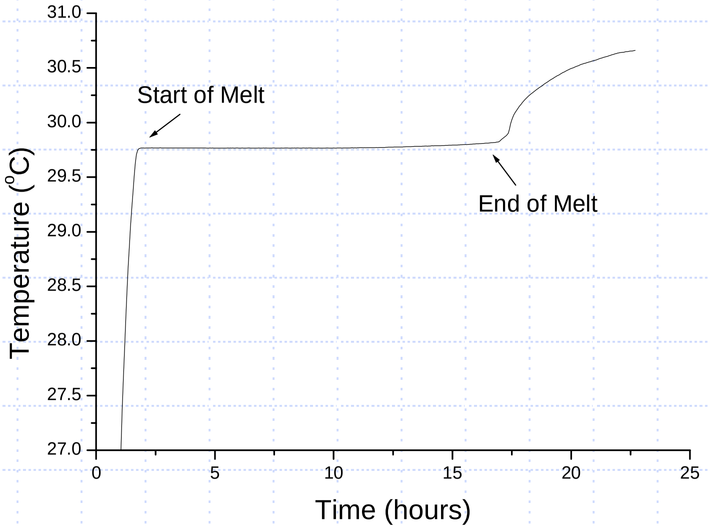
Contd.

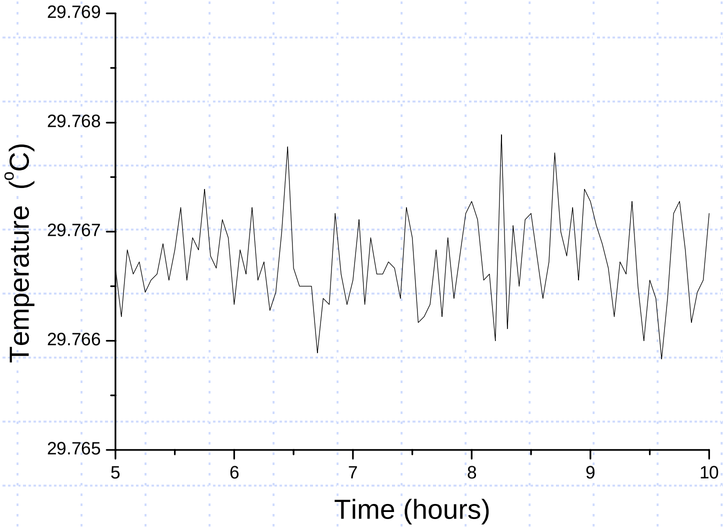
- WTP defined to be at 0.01°C
- The ice must be as a moveable mush ie. It must freely rotate in the cell
- The WTP maintenance bath can keep the cell at this temperature for days
- **The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.**



Gallium Melting Point

- Defined to be at 29.7646 degrees C
- As can be seen in the graph it is a plateau
- Energy is going into breaking bonds – hence no temperature rise until all of the Ga has melted
- Can be drawn out for about 30 hours

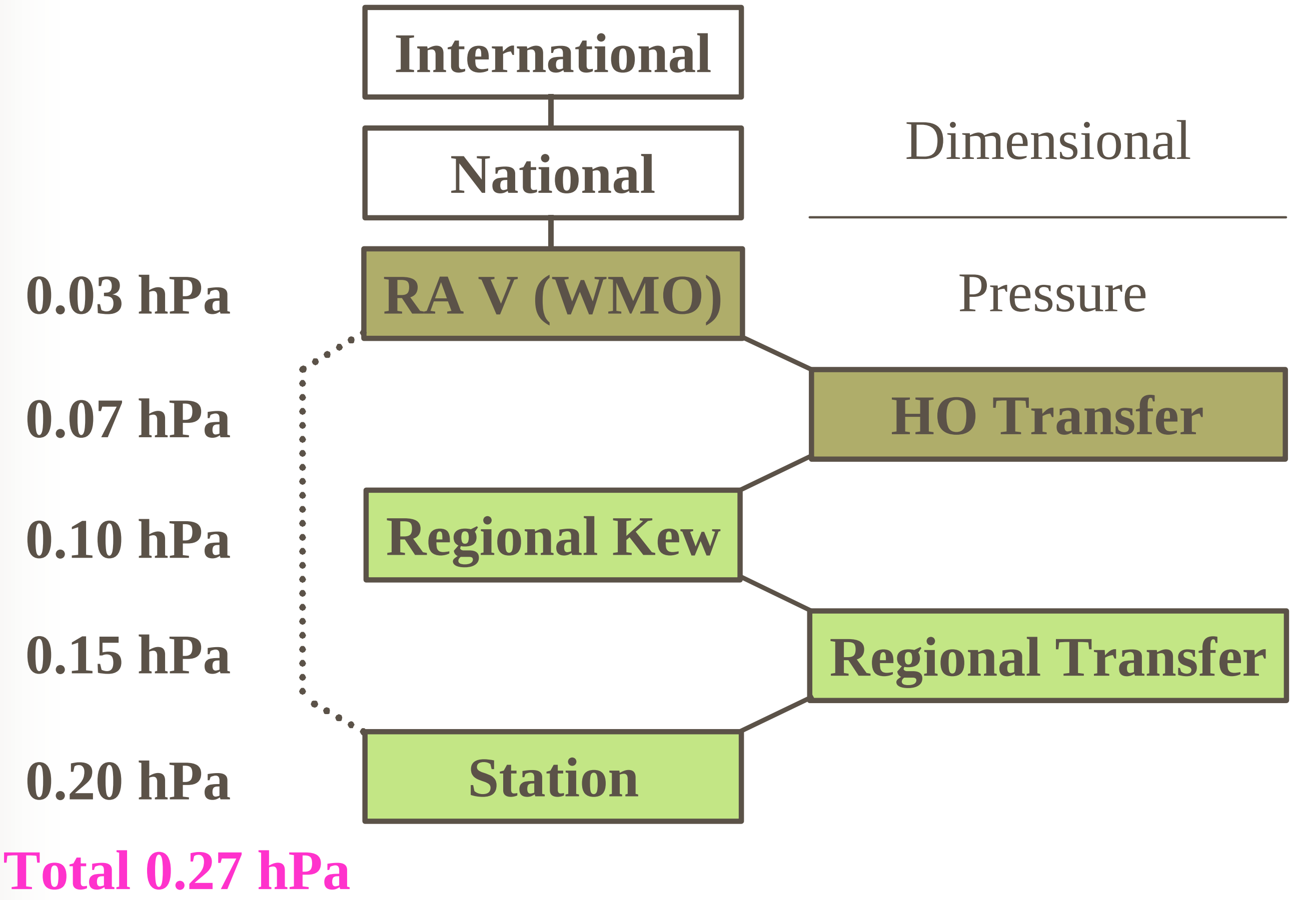




Traceability

- Traceability is the unbroken chain of calibration/verification from a primary standard to the device in question
- This chain may have one link or several depending on the device
- At each stage of must be fully documented

Pressure Traceability



International

National

Dimensional

Pressure

0.03 hPa RA V (WMO)

0.07 hPa HO Transfer

0.10 hPa Regional Kew

0.15 hPa Regional Transfer

0.20 hPa Station

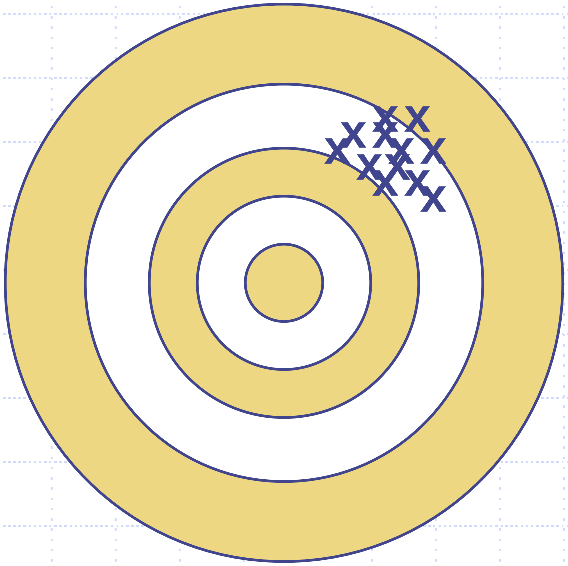
Total 0.27 hPa

Uncertainty

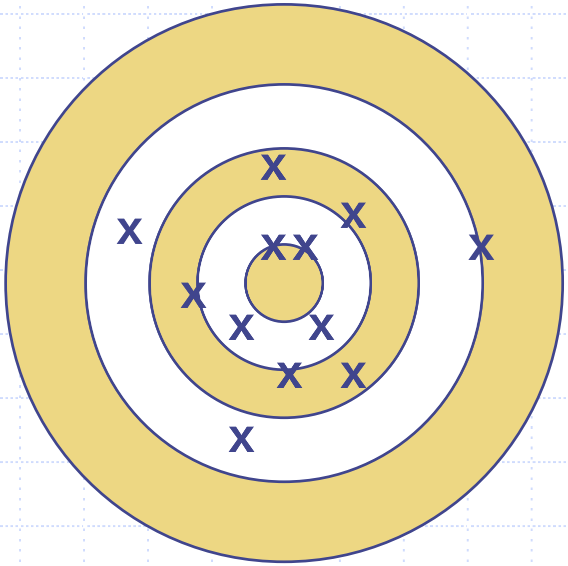
- The degree of doubt about a measurement!
- Parameter, associated with the result of a measurement, that characterises the dispersion of the values that could reasonably be attributed to the measurand.
  (International Vocabulary of Basic and General Terms of Metrology)

Uncertainty

Low Accuracy
High Precision



Medium Accuracy
Low Precision



Accuracy

The closeness of the experimental mean value to the true value.

High *accuracy* = Small *systematic* error.

Precision

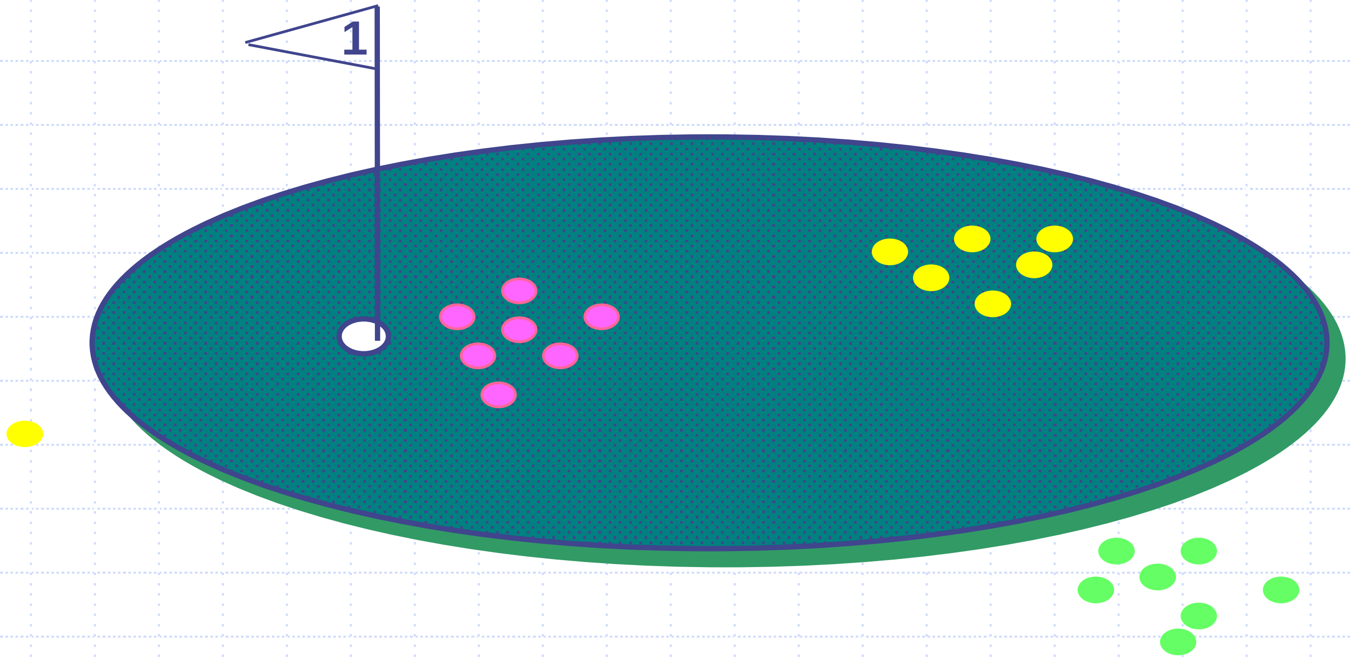
The degree of scatter in the results.

High *precision* = Small *random* error.

Golfer One

High Repeatability / Low Reproducibility

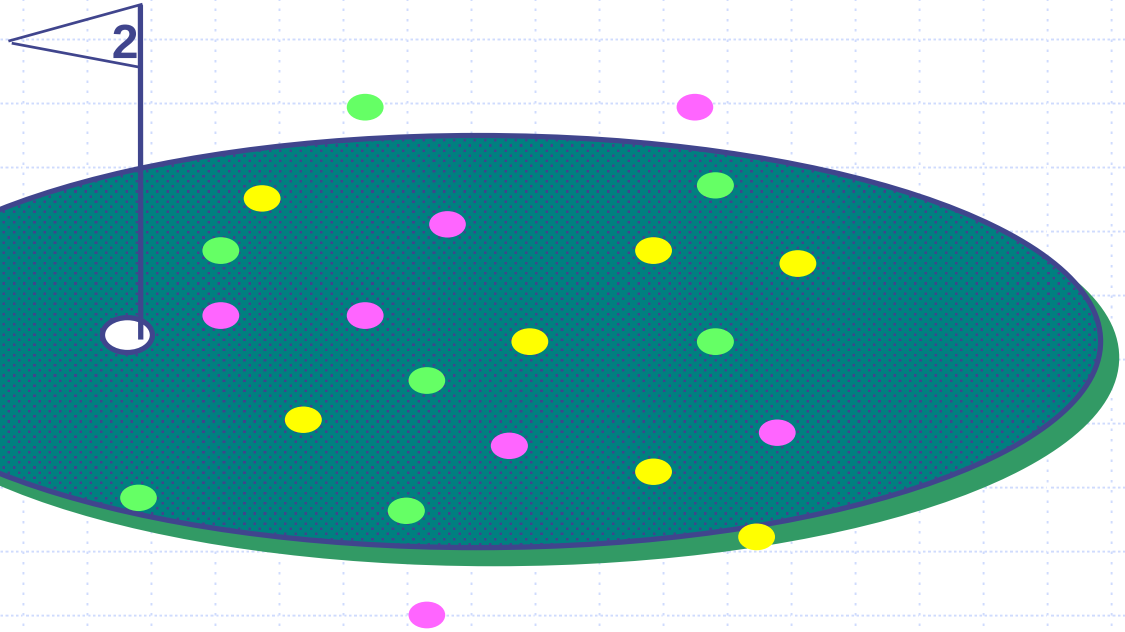
Drift in an instrument



Golfer Two

Low Repeatability / Low Reproducibility

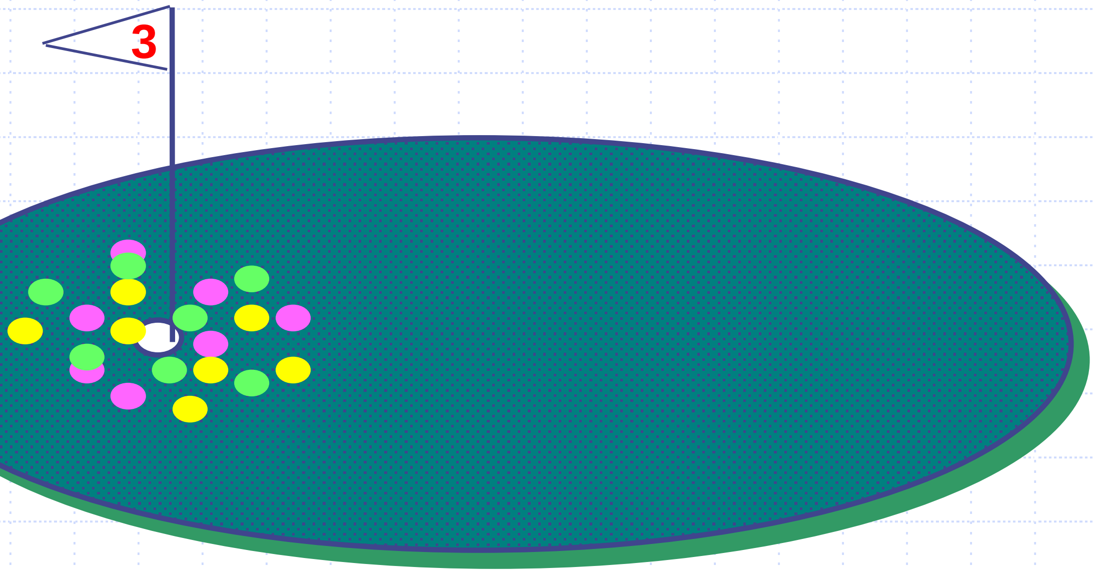
Low Precision



Golfer Three

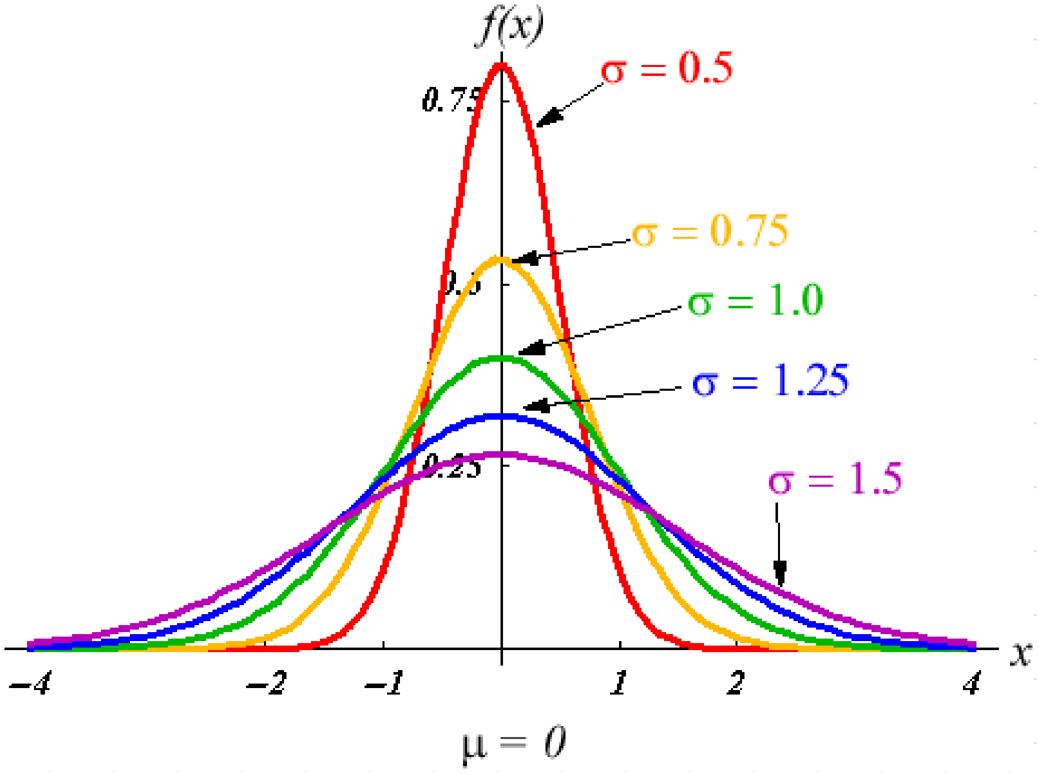
High Repeatability / High Reproducibility

Low Uncertainty

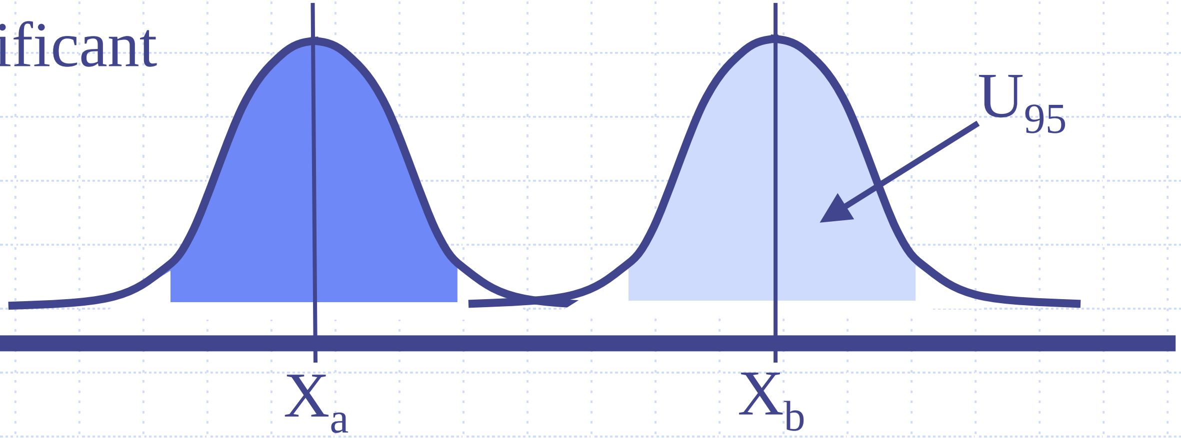


What’s Normal?

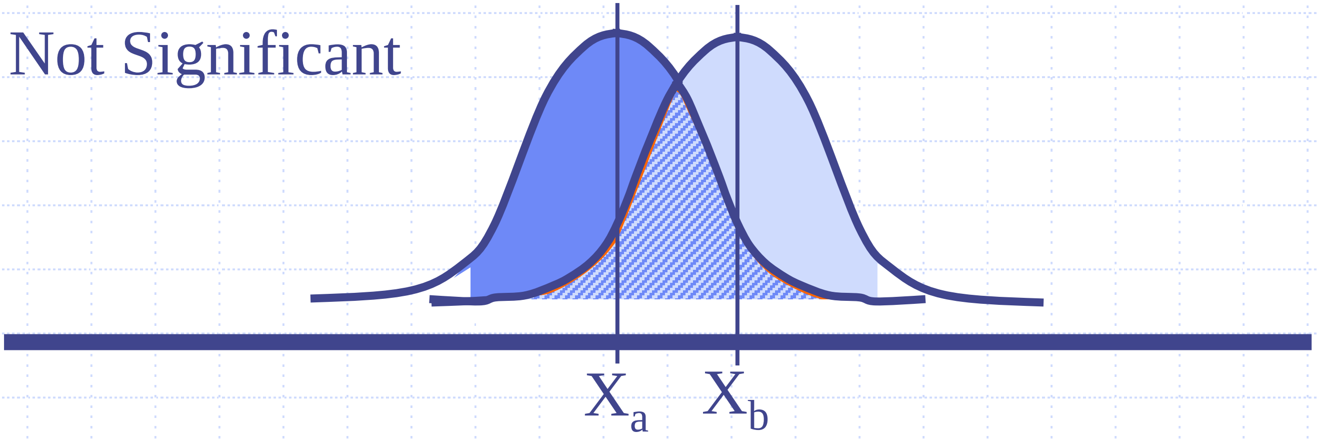
- The outcome of most natural processes is normally distributed
- This results from the central limit theorem



Significance of Differences



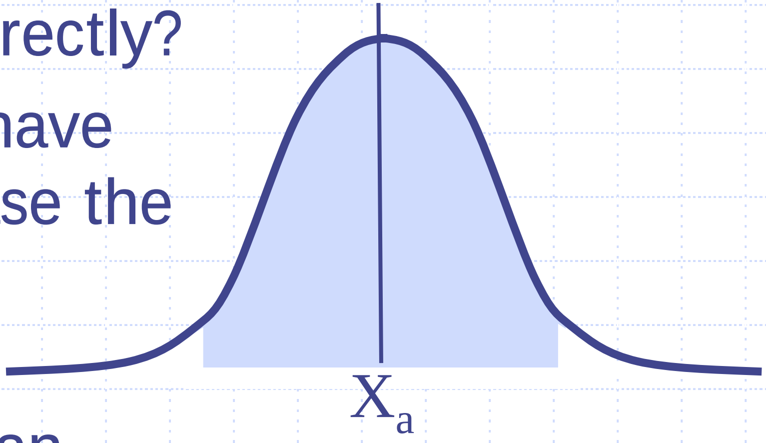
Significant



Not Significant

Confidence

- How many samples do you have to take to be “confident” you have estimated the mean value correctly?
- The mean we determine will have an expected value – in this case the mean of the population and a variance
- How well we estimate the mean depends on how many samples we take.



Temperature Prac

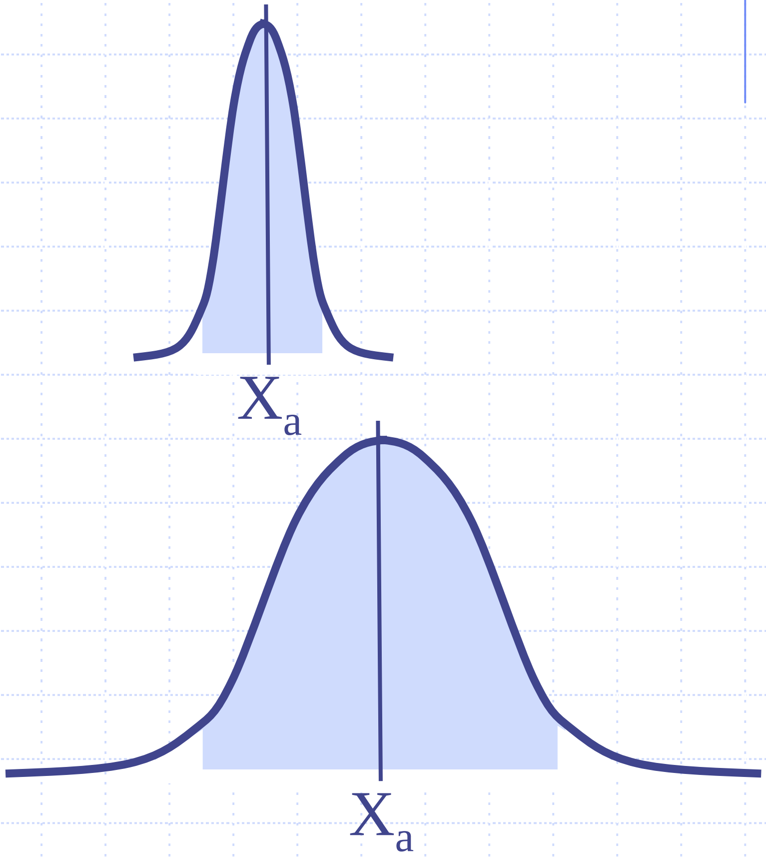
- Use the two IR thermometers to take the victims temp.
- Take 7 measurements with each device
- Form an average
- Max and Min

Making a measurement

- Any single measurement is a “selection” from a distribution of possible values
- More measurements give you greater “confidence” in estimating population parameters
- Can’t make an infinite amount of measurements because the system being tested may not be stable

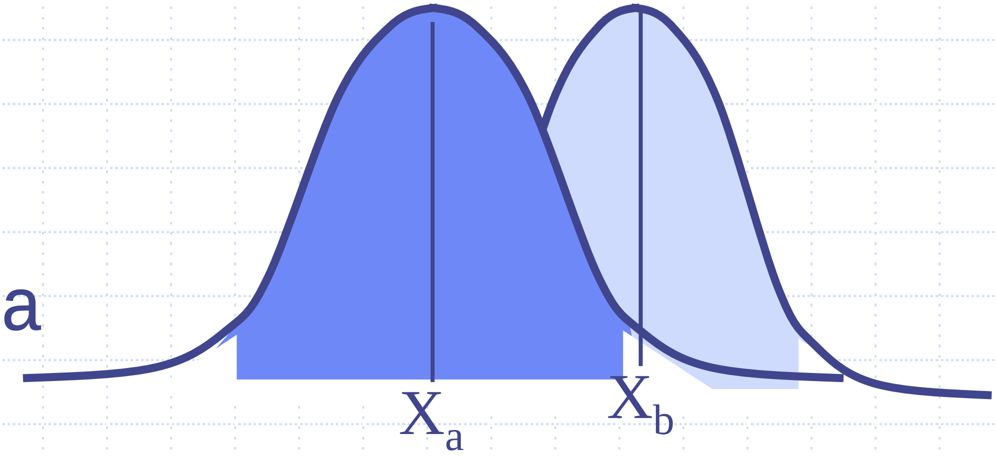
Test Uncertainty Ratio (TUR)

- It is intuitive that in order to measure something you need to measure it with something more accurate
- This is the TUR – the ratio of the uncertainty in your reference to the uncertainty of the device under test
- Usually a TUR value of 4 or better is used



Contd.

- You can work with TURs less than 4
- The barometers are calibrated with a TUR of approximately 1!
- You need to take a lot of samples!

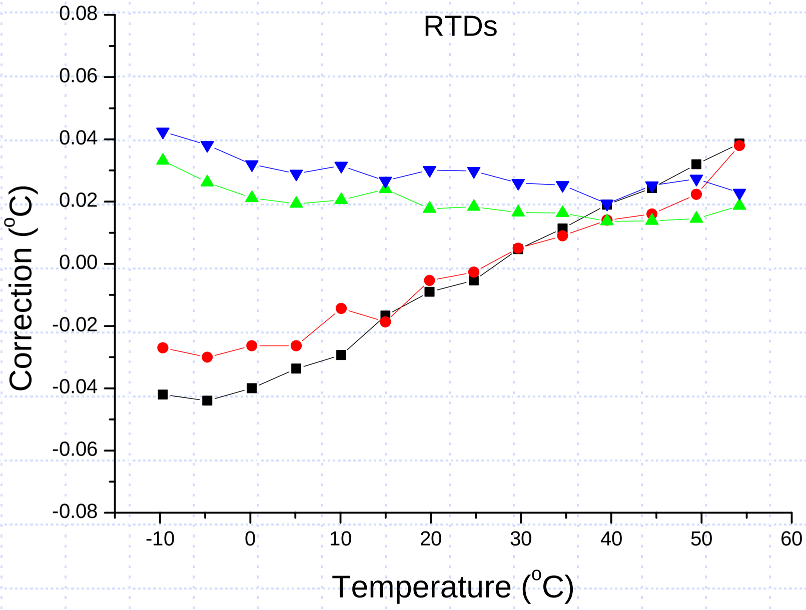


Instrument Properties

- Linearity – Accuracy of response over measurement range
- Stability – short and long term (drift)
- Response time – how fast it responds
- Precision
- Hysteresis

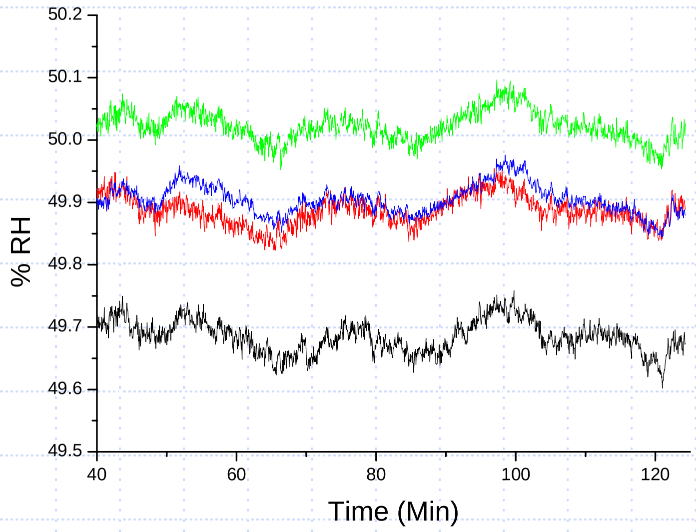
Linearity

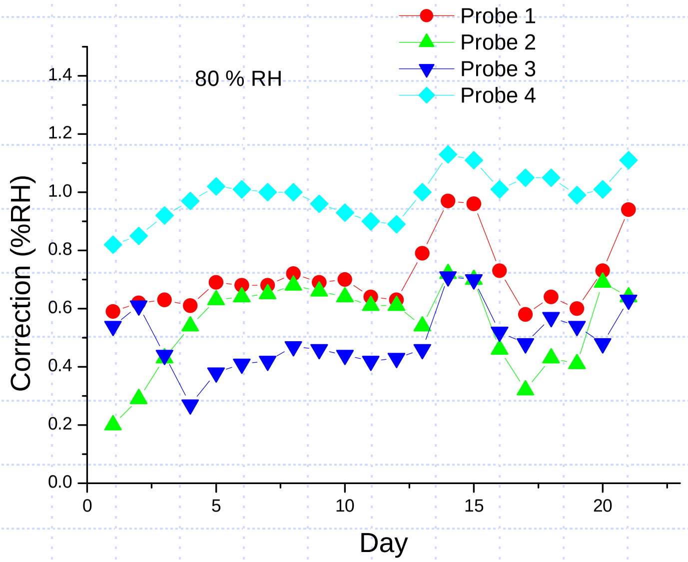
- Opposite are plots of True versus probe temperature for AWS Temp probes
- Note they are all approximately linear in response
- They each have a slightly different line



Stability

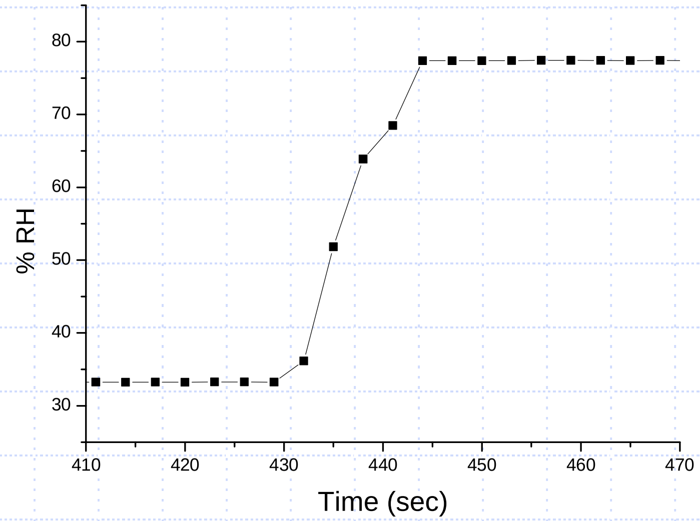
- Humidity probe short term drift (2 hrs)
- Humidity Probe medium term drift (20 days)

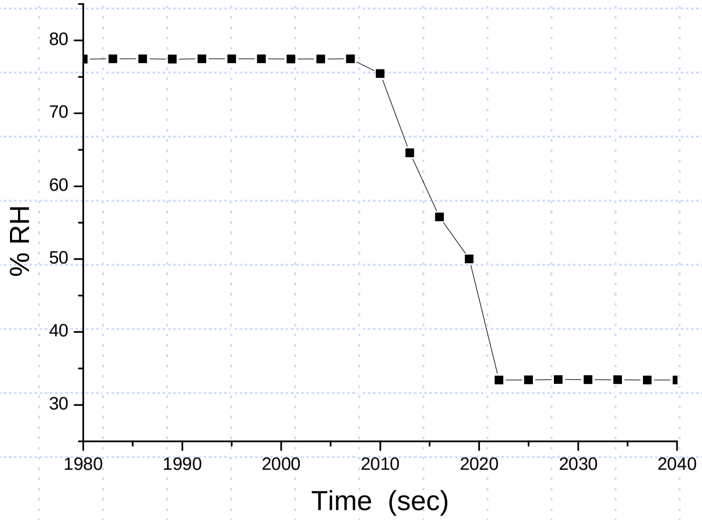




Response Time

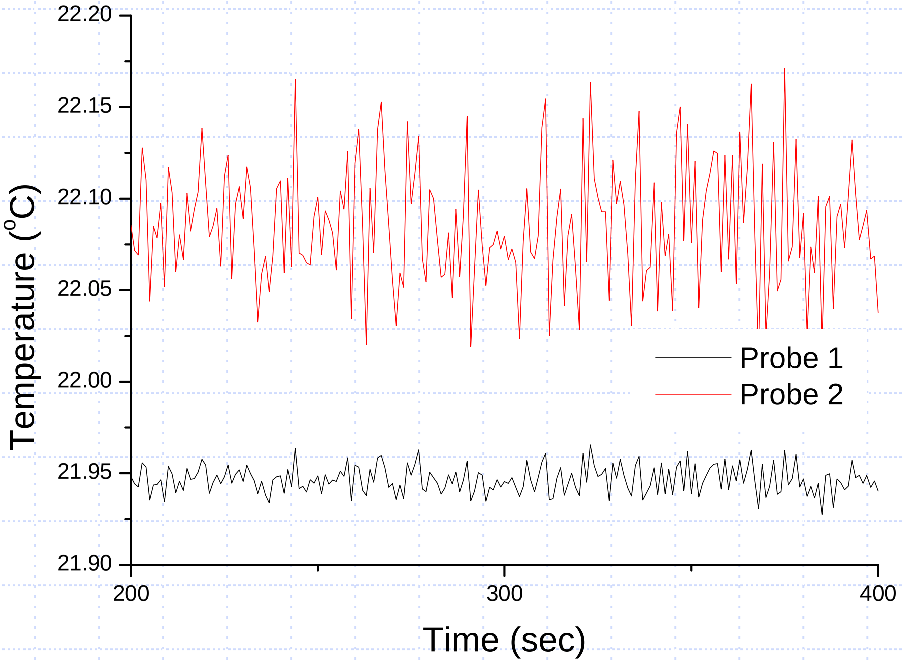
- Opposite are plots of RH versus time for a humidity probe.
- RH was changed “instantaneously”
- “Response time” is defined as the time taken for the instrument to read 63% of the step change





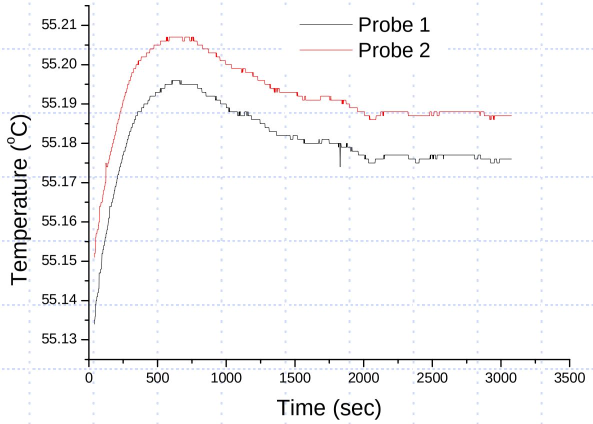
Precision

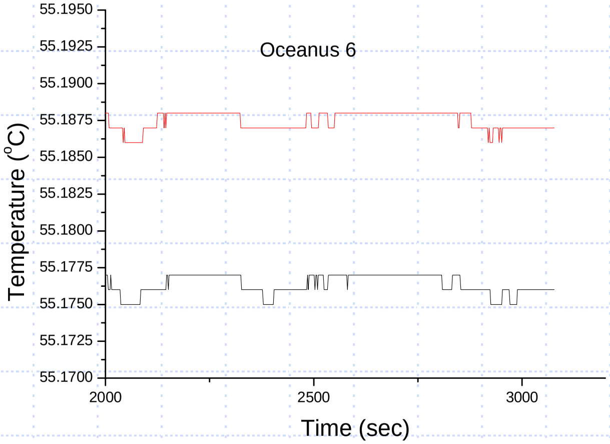
- Opposite are the plots Temp versus time for two probes
- The two probes have differing systematic errors (y axis shift)
- The two probes have different precisions (y axis spread)



Contd.

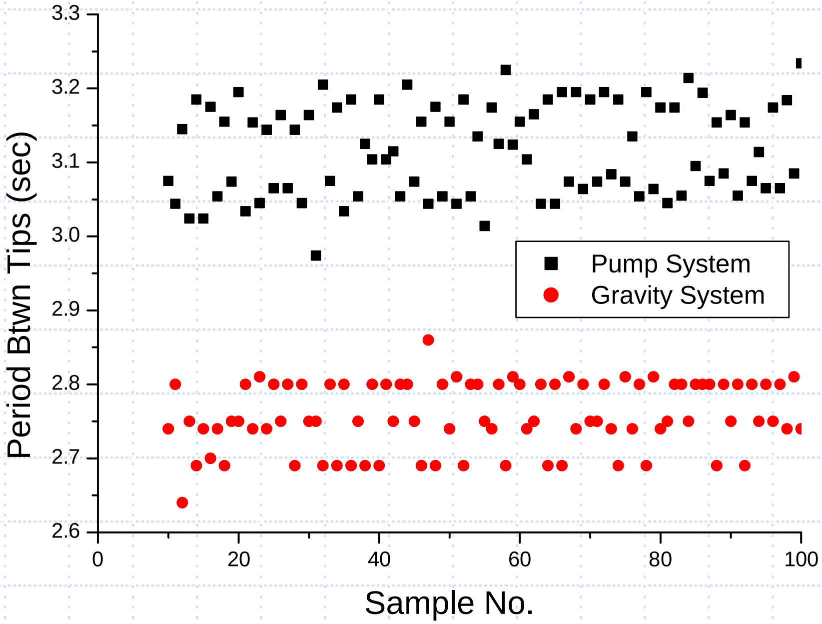
- The probes exhibit a systematic error – offset or bias
- Both probes have approximately the same precision



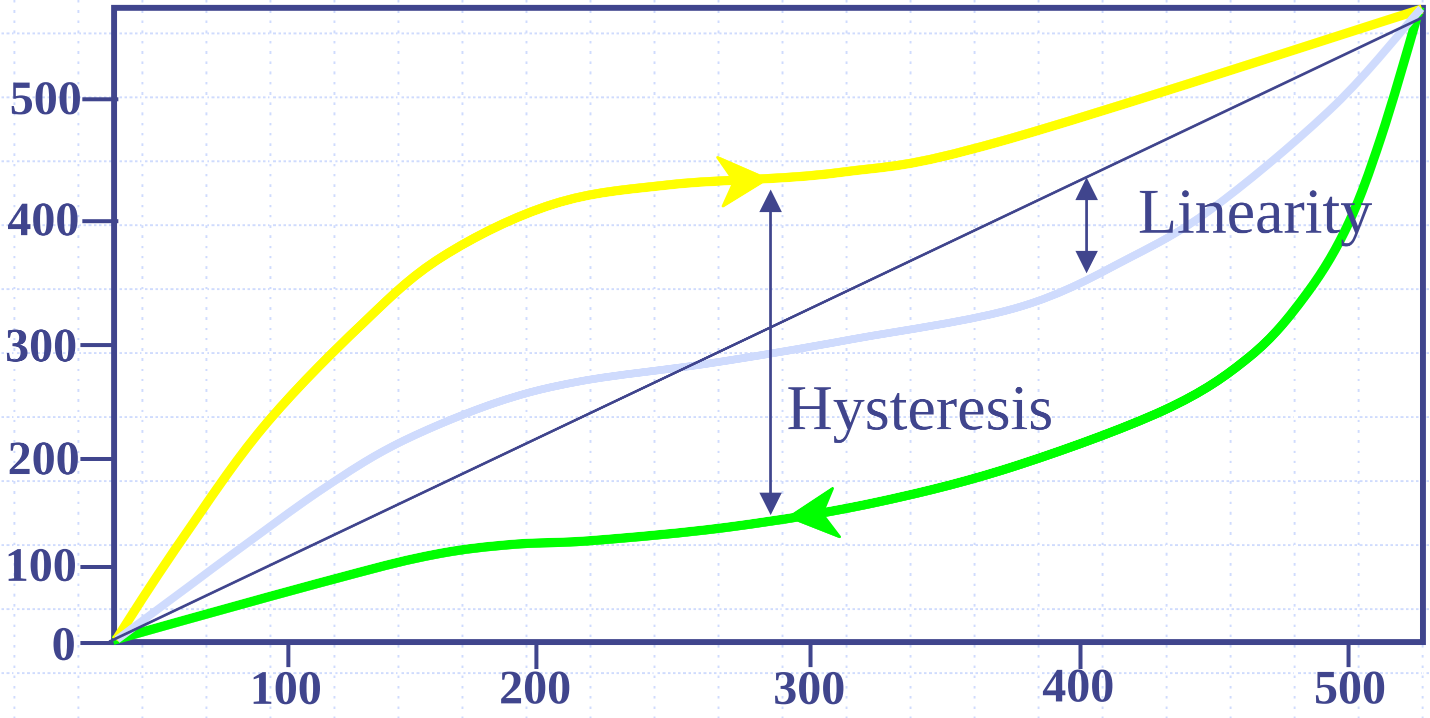


Quantization

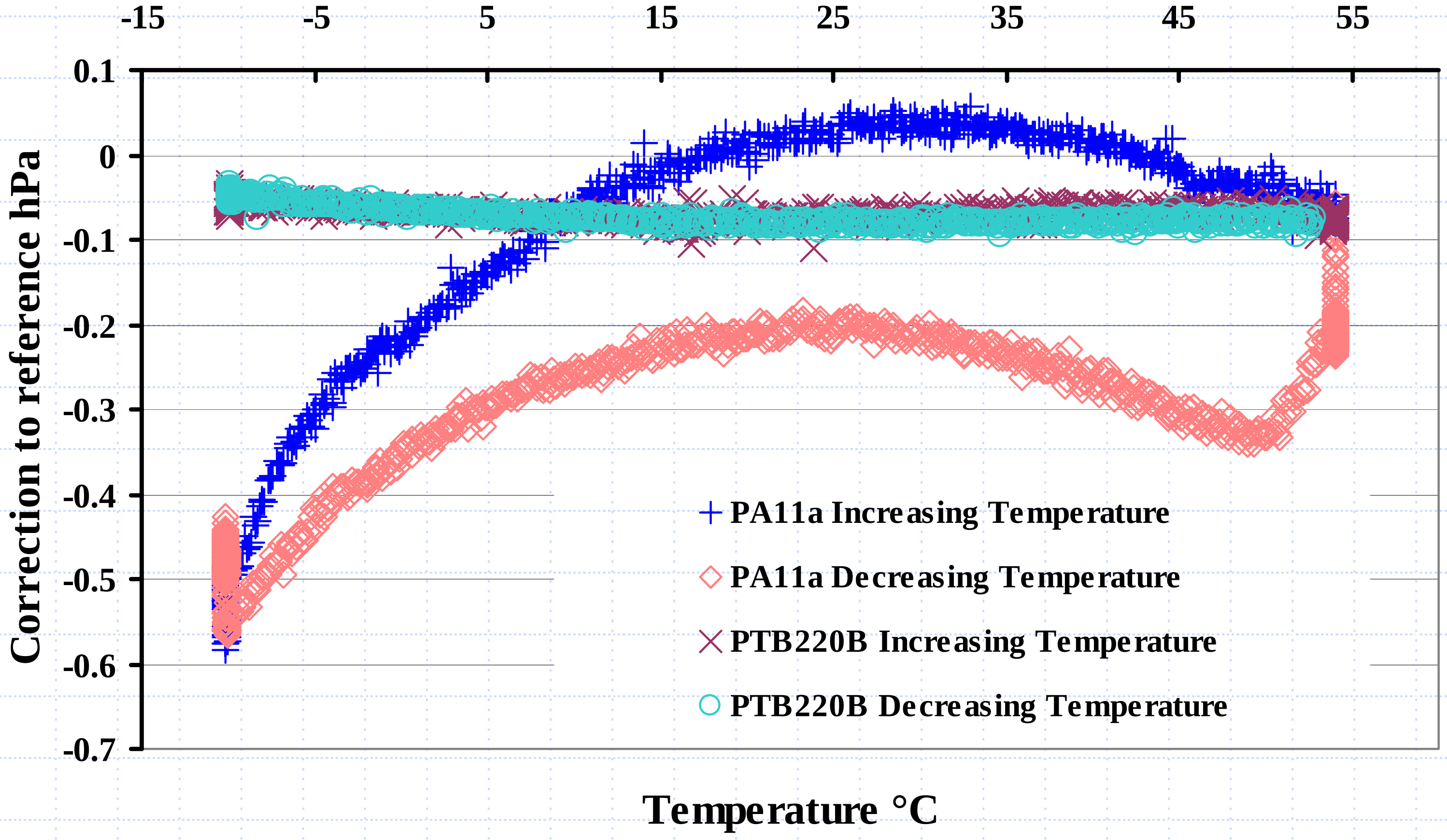
- Quantized measurements take discrete levels
- Important to know how they were quantized
- Were they rounded or truncated?
- No necessarily less accurate than analogue data



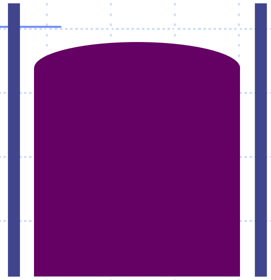
Hysteresis & Linearity



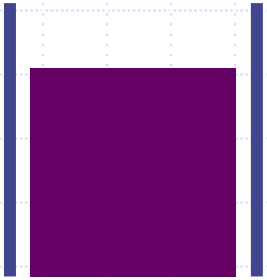
PA11a & PTB220B Hysterisis



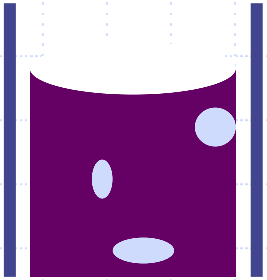
Mercury Barometers



Good
Clean Mercury
Rising Pressure



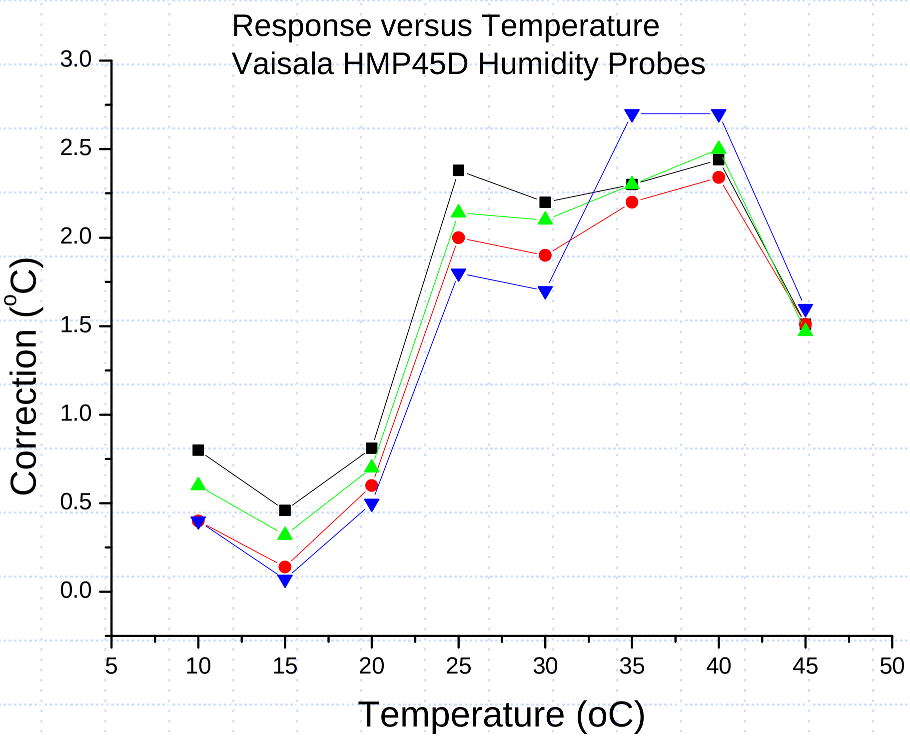
Bad
Possibly Dirty Mercury
Falling Pressure



Very Bad
Dirty Mercury
Falling Pressure

Response Versus Temperature

- Opposite is a plot of the corrections required for HMP45D probes versus Temp
- Note – response is quite consistent – but not linear



Repeatability

Variability on an occasion

With-in run precision.

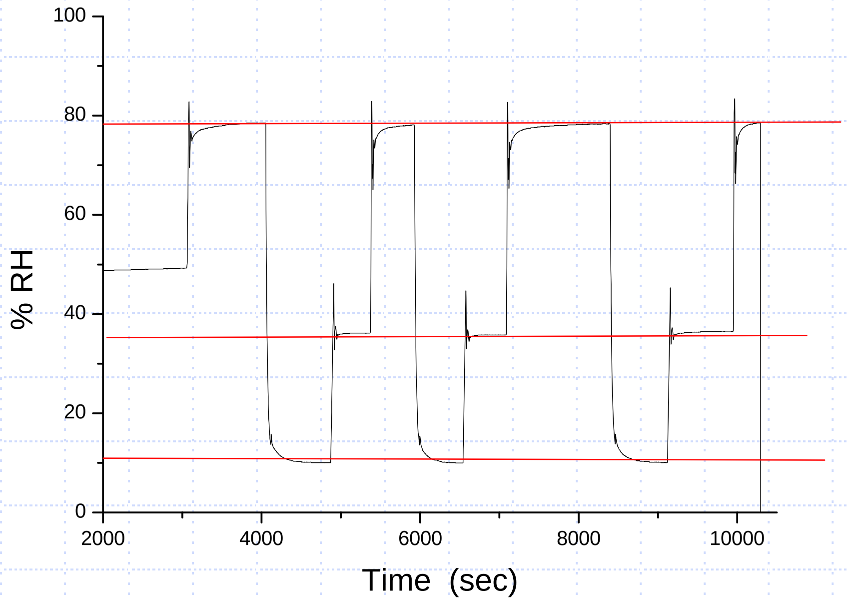
Reproducibility

Variability on different occasions

Between-run precision

Contd.

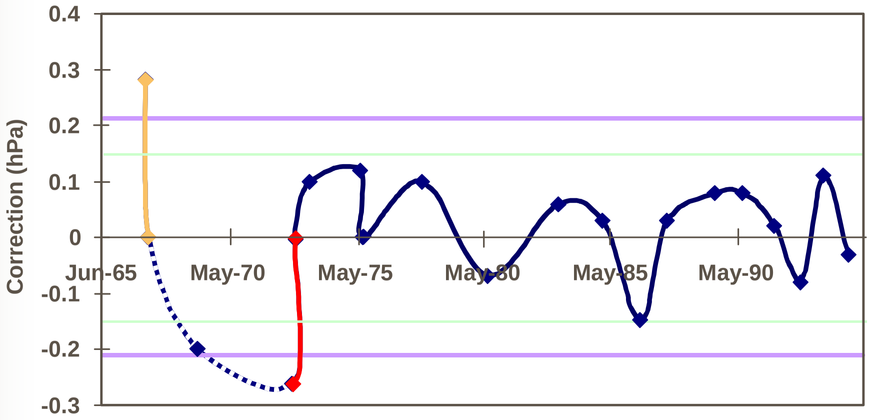
- Opposite is a plot of the RH reached by the humidity generator versus time
- System was cycled between 3 RH levels
- Repeatability is the closeness of the match in RH achieved



Reproducibility

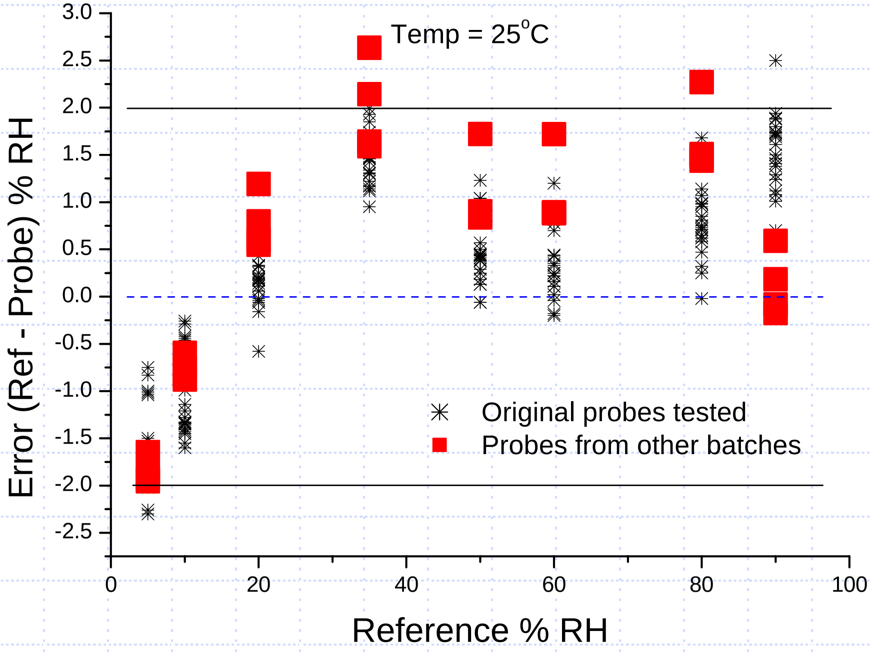
- Reproducibility is the “between trial” variability
- Opposite is a plot of the long term error for a barometer

Calibration Errors



Populations

- ➢Opposite is a plot of the offset errors for a batch of humidity probes.
- ➢The error for any particular probe for any measurement will be approximately normally distributed
- ➢The offset or bias of the all probes is also expected to be normally distributed!



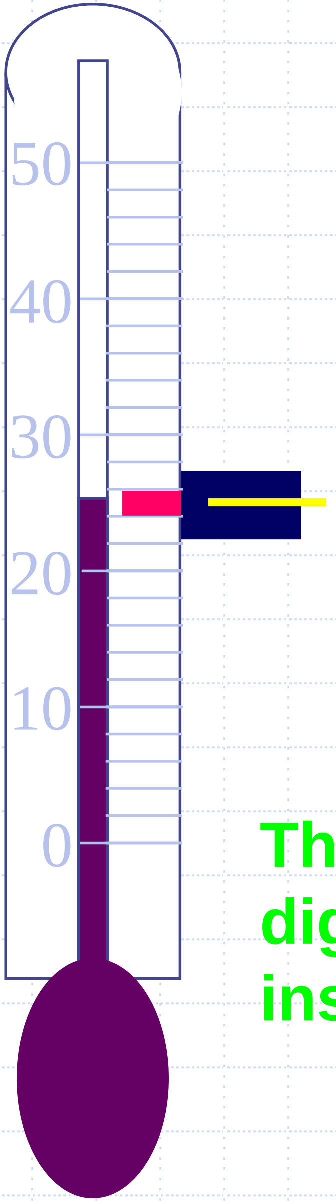
Resolution

- Resolution is the smallest increment in value the instrument can return
- Resolution will affect the precision of the instrument
- Resolution will not ordinarily affect the accuracy of an instrument

Resolution ≠ Uncertainty

The uncertainty of this thermometer is ± 2°C.

Half of the least significant digit on an analogue instrument



If the scale has 10°C divisions

The resolution is 5°C

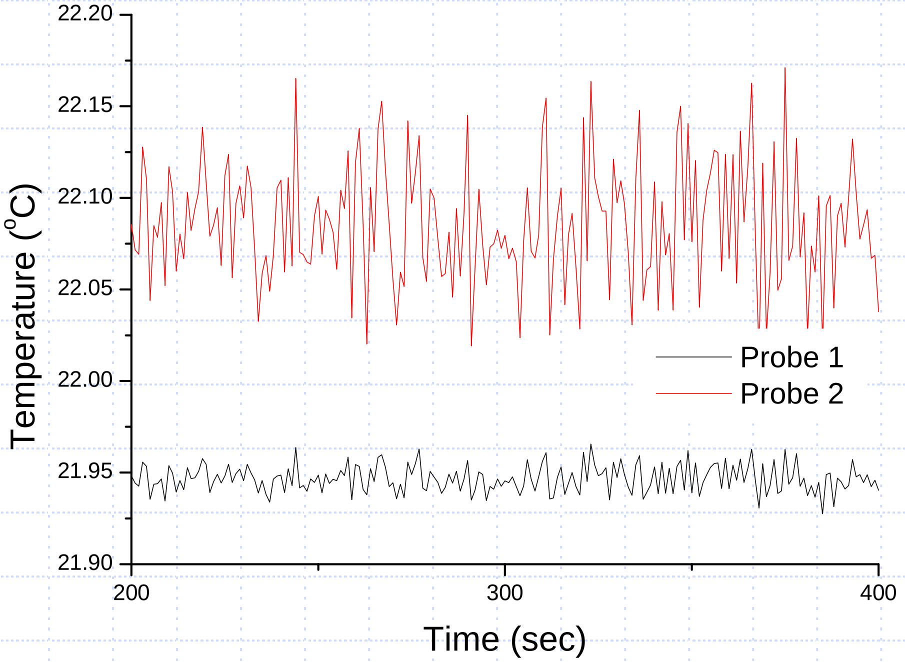
If the scale has 2°C divisions

The resolution is 1°C

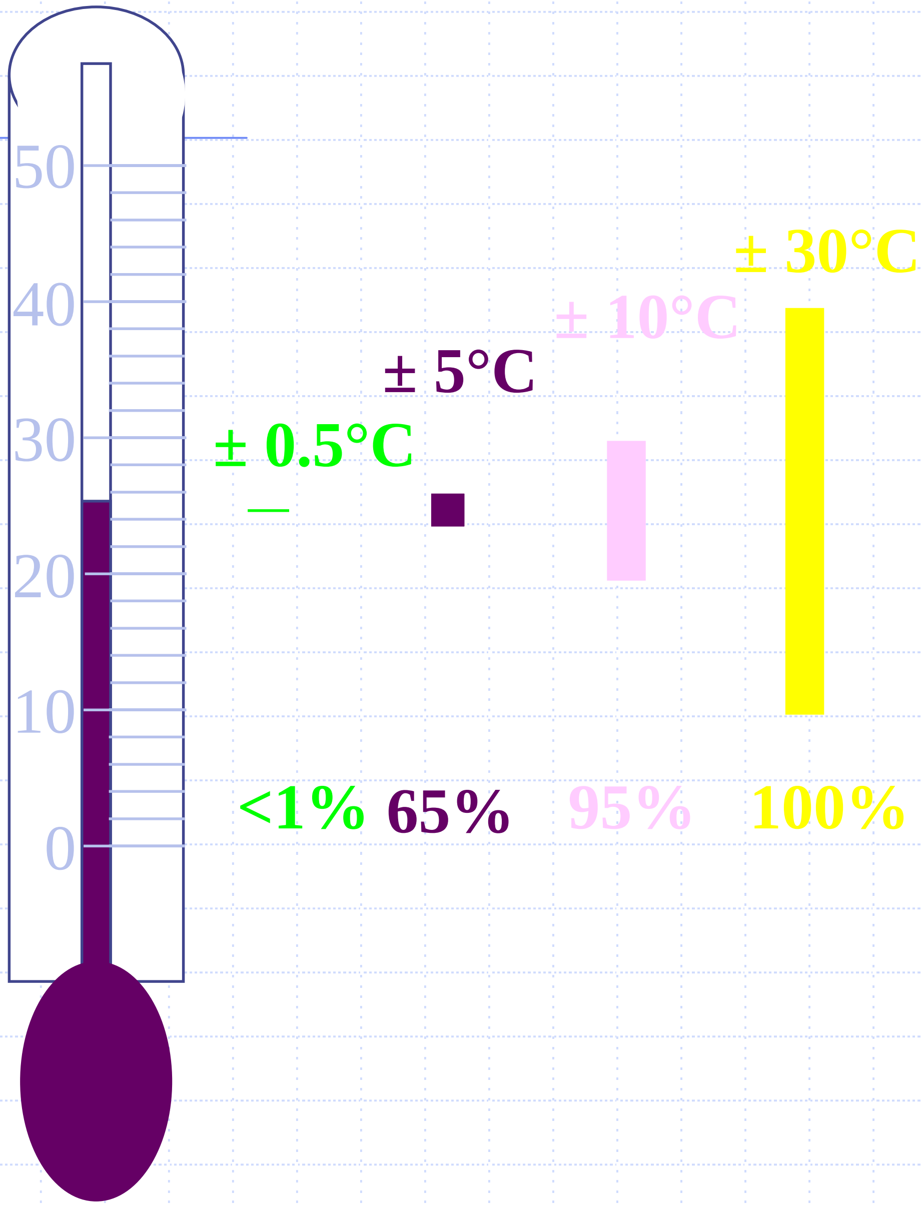
The least significant digit on a digital instrument.

Contd

- Both probes have the same resolution
- Red probes has approx four times the uncertainty

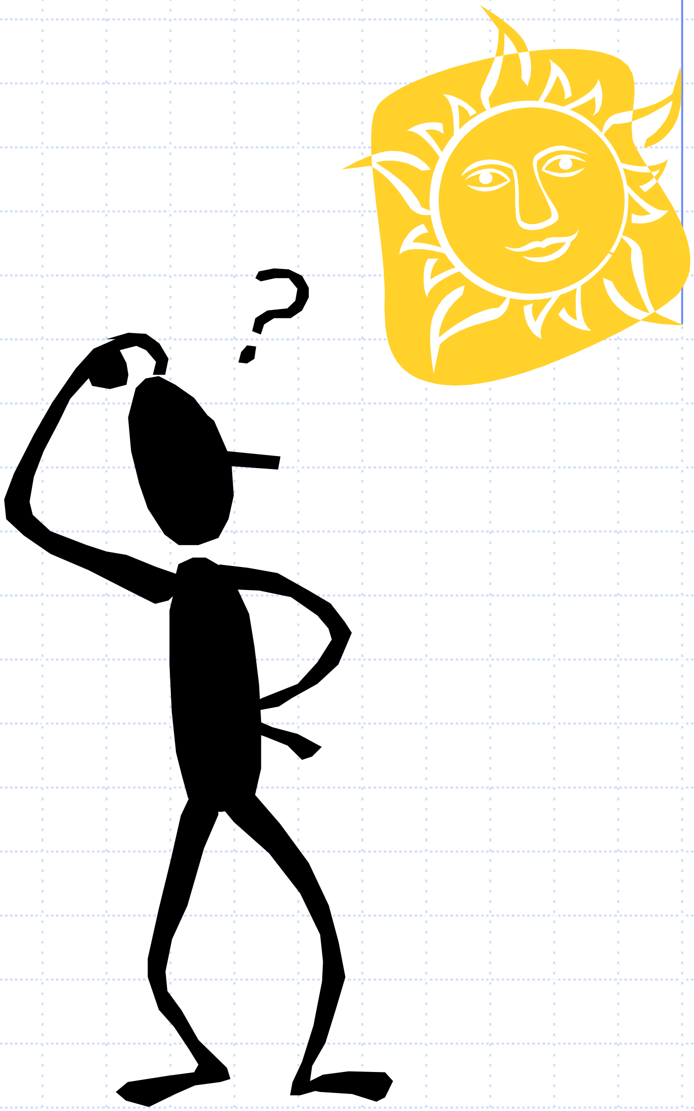


Confidence



± 0.5°C
± 5°C
± 10°C
± 30°C

<1% 65% 95% 100%



Errors Vs Blunders

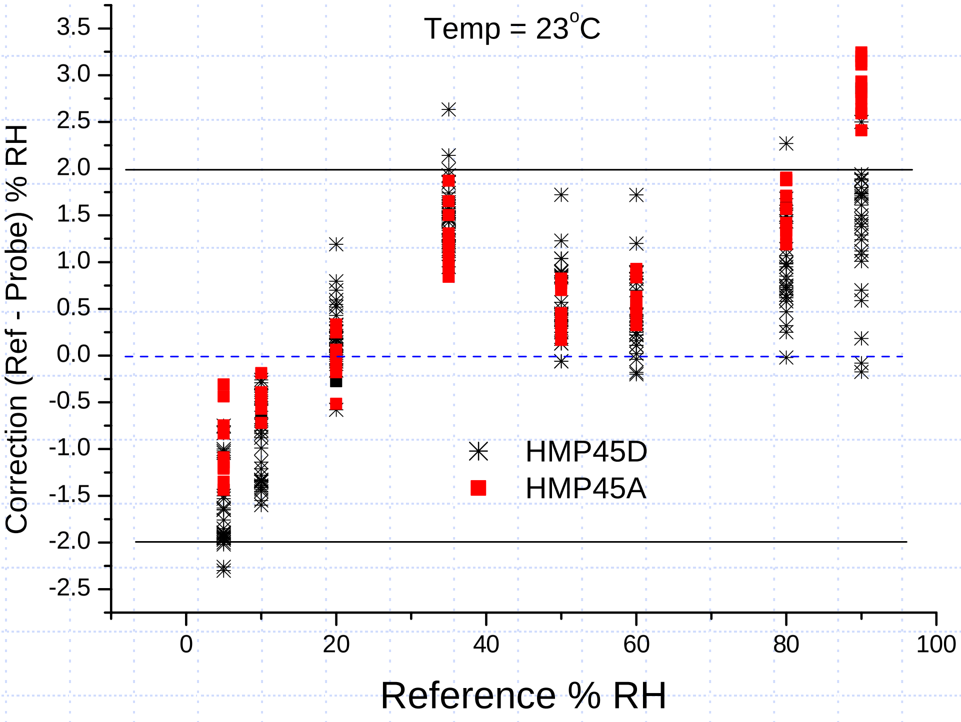
- By definition most measurements will not be exactly “right” they will be in error to some degree
- A blunder is when a human is in the loop and produces a mistake
- Ie. Misreads a thermometer as 35.25°C instead of 25.25°C

Calibration

- Comparing the reading of an instrument when it is exposed to a known artifact or condition
- Either the instrument is adjusted to read “correctly” or
- A table of corrections is produced so that the operator can “correct” the instrument reading to the true reading
- May need to interpolate

Verification

- Most of the work of the RIC involves verifying that an instrument/probe etc is in specification
- This is not a calibration since corrections etc are not supplied
- Hence equipment sent to the field is within spec but may lie anywhere within the specification - two humidity probes could differ in readings by 4% RH and both could still be in spec

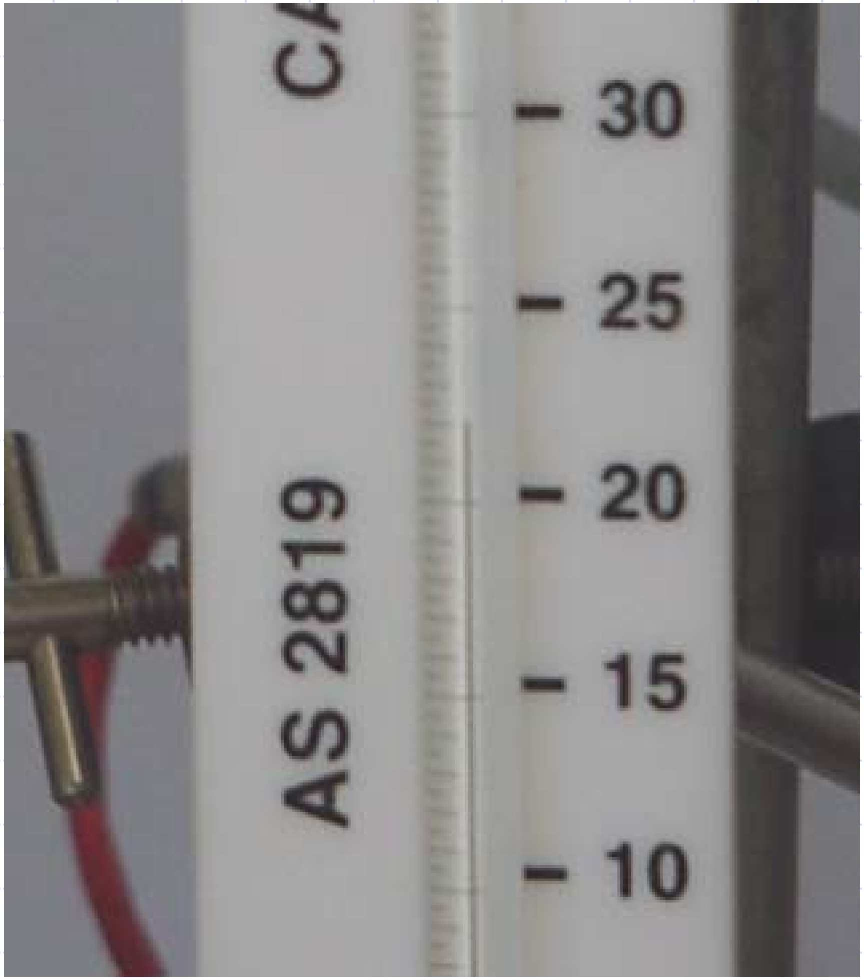


Field Tolerances

Sensor	**Comparison Method**	**Uncertainty**	**Field Tolerance**
Pressure	Standard	0.3hPa	0.5hPa
Temperature	Within Screen Psychrometer	0.3°C 0.4°C	0.5°C 0.6°C
Relative Humidity	Within Screen Psychrometer	4%	5% 6%
Wind Speed	?	10%	N/A
Wind Direction	Compass	5%	10%
Rainfall	With Syphon Without Syphon	3% (<250mm/h) 4% (250 – 350mm/h) 8%	8%

Exercise 1

- Currently the inspection handbook “checks” an AWS RTD with an Inspection grade Mercury in glass thermometer
- RTD accurate to 0.2°C – MIG accurate to?
- Single measurement after 1 hour of stabilisation
- What is are the flaws in this procedure?
- Come up with some alternatives alternatives

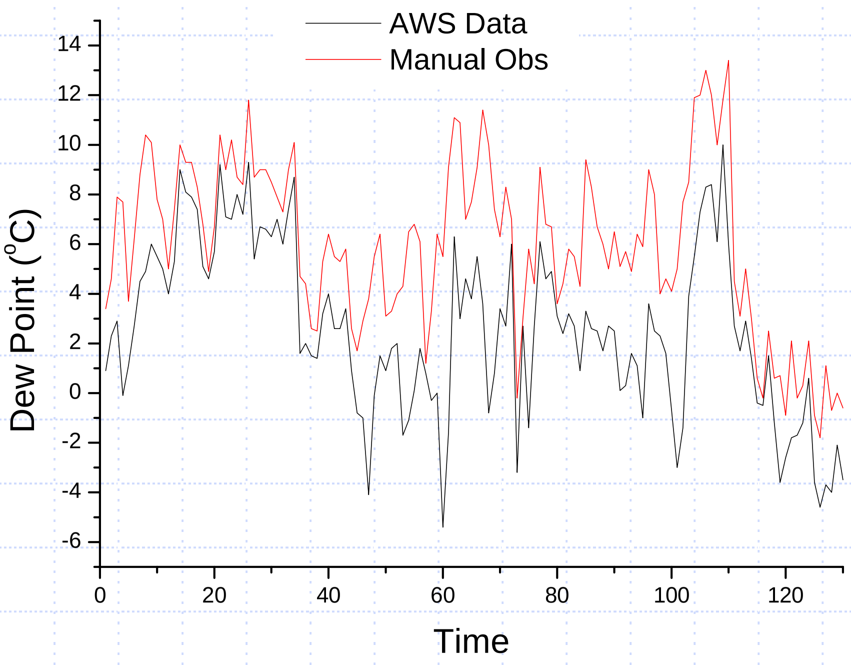


Exercise 2

- Currently the inspectors check an AWS humidity probe with an wet/dry bulb thermometers
- One wet/dry measurement after 1 hour of stabilisation
- What is are the flaws in this procedure
- Suggest alternatives

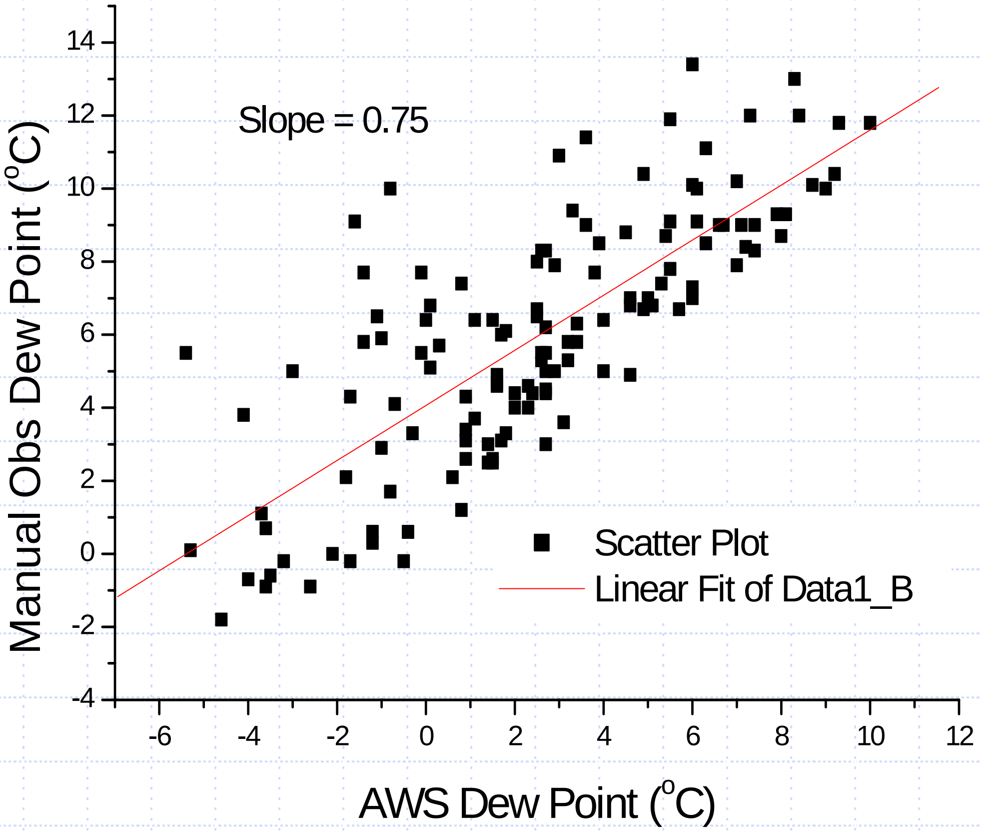
Exercise 3

- NCC alerted RIC to anomalous readings from manual sites (red) and AWS humidity probes (black)
- The manual obs (wet/dry bulb) appear to over-estimate the dew point



Contd.

- Plotted opposite is the DP from manual obs (x-axis) versus the AWS derived DP (y-axis)
- In a perfect world the data would lie along the line y = x
- Postulate a model as to what has gone wrong
- Assume humidity probe was checked and found to be in-spec within previous 6 months.



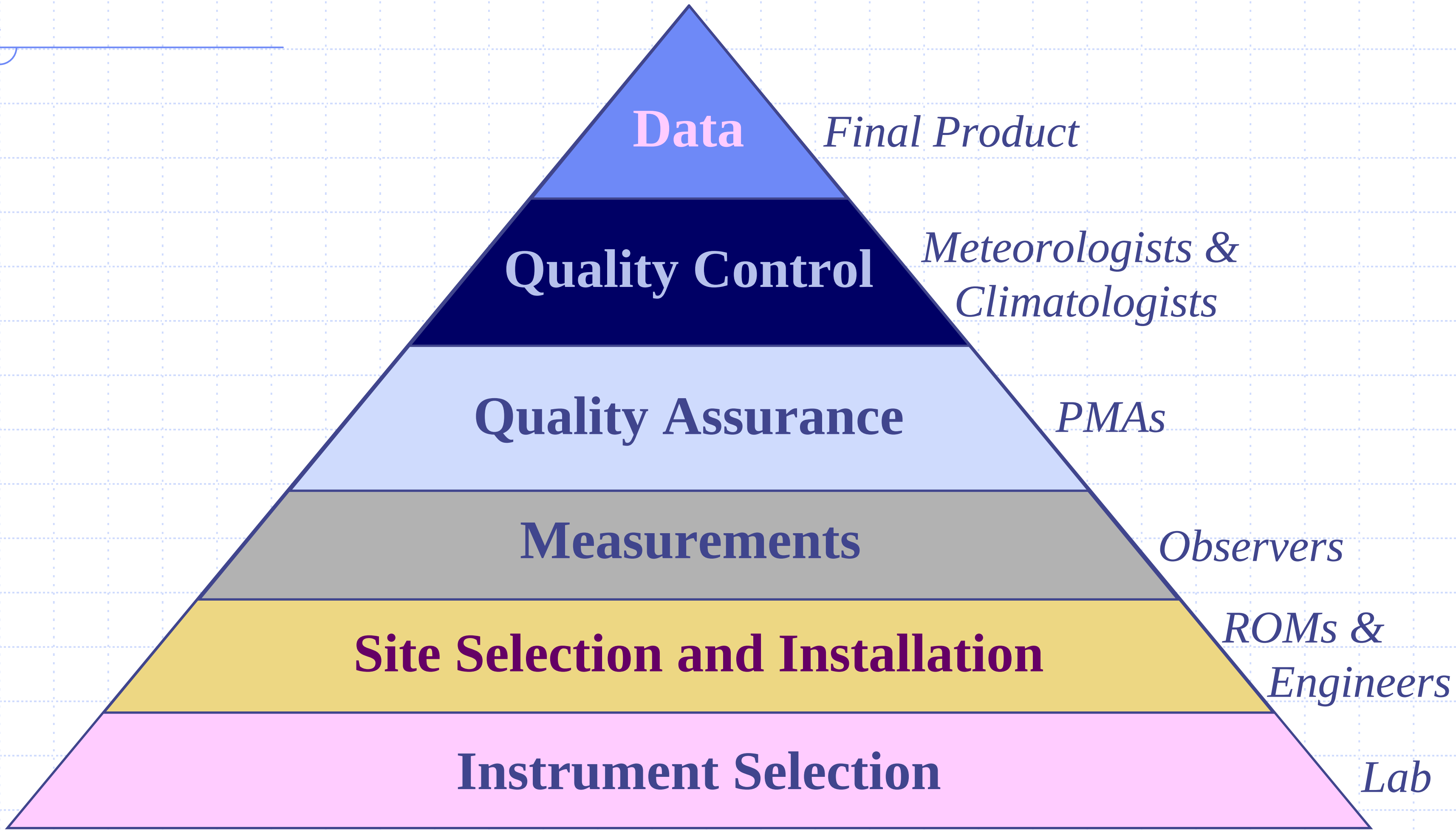
Hypotheses

- 1 – The humidity probe is stuft!
- 2 – The manual observers were drunk!
- 3 – Both 1 & 2
- 4 – Both sets of data are correct!
- Come up with some others –
- *Also assume all measurements made were correct!*

Best Guess

- It is troubling that the line of best fit does not have a slope of 1 and this suggests there may be a problem with the algorithms used to calculate DP.
- Having said that, it is most likely that both sets of data are essentially “correct”.
- RH probes (currently in use) measure RH
- Wet/dry bulb measurements really measure evaporation rate – not really the same thing
- Wet/dry measurements over-estimate humidity by up to 20% in still air conditions.
- A useful comparison would be RH from each technique after selecting data obtained when the wind speed was greater than 2 m/s

Data Quality



Data — *Final Product*

Quality Control — *Meteorologists & Climatologists*

Quality Assurance — *PMAs*

Measurements — *Observers*

Site Selection and Installation — *ROMs & Engineers*

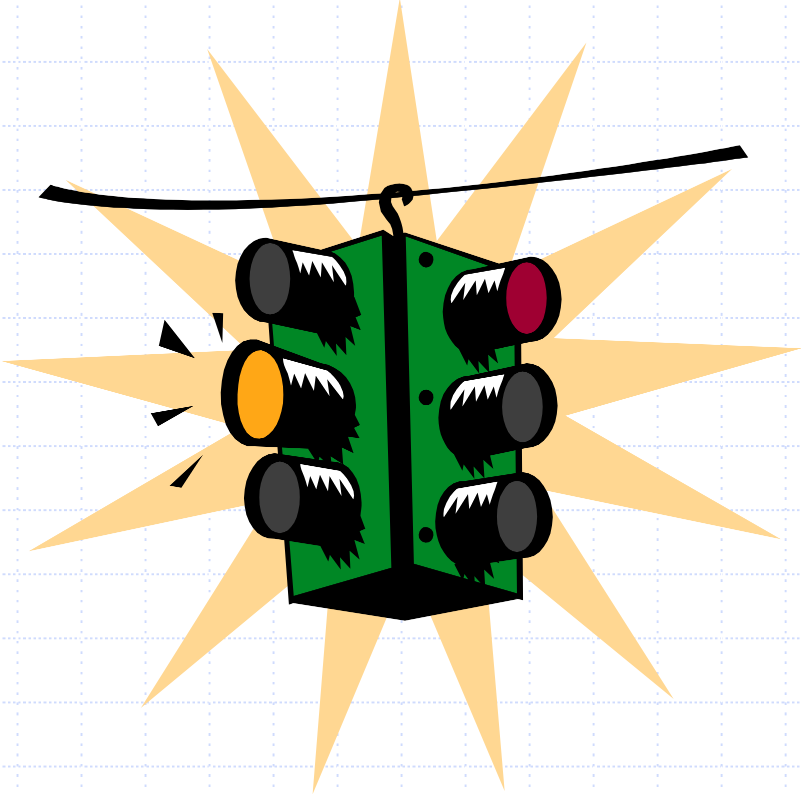
Instrument Selection — *Lab*

How to improve the Data Quality

- Training
- Double check
- Use Calibrated instruments
- Minimize the number of variables
- Use standard test procedures
- “If it is not broken don’t fix it”
- Document, document, document

Field Adjustment

- Don’t
- Just DON’T!
- An adjustment in the field will remove all traceability
- If it is out of spec – remove and return



Questions?

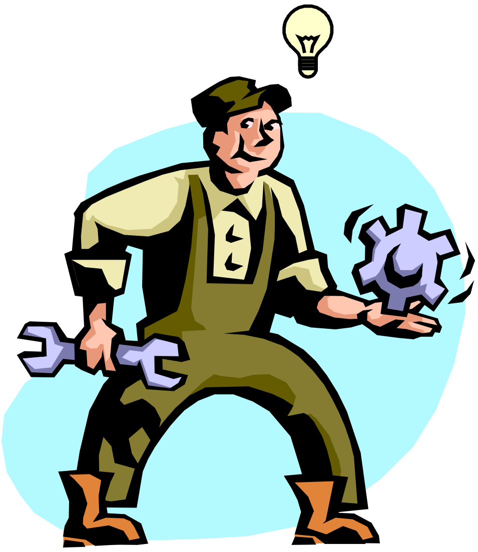
TRAINING MATERIAL ON METROLOGY AND CALIBRATION

1. Vocabulary used in Metrology
2. Measurement Statistics

3. Theoretical Guide to Measurement Uncertainty

4. Metrology of Temperature
5. Metrology of Humidity
6. Metrology of Pressure
7. Metrology organization in Météo-France

Theoritical guide to measurement uncertainty



1. What's uncertainty ?

1.1. Definition

A measurement aims at determining the measurand value, the *particular quantity subject to measurement ([2])*. The result of a measurement is just an estimation of the measurand value ([1]).
A quantitative indication has to be given with a result to inform about its reliability: the uncertainty of measurement. Without uncertainty, we are unable to compare the results between themselves or against standards, limits...

Uncertainty ([2]): *parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand*

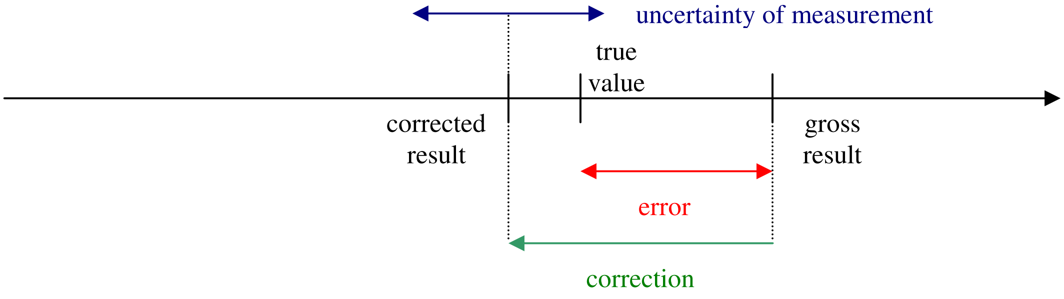


Diagram. 1 : Uncertainty

A full result of a measurement has to be given with its uncertainty.

1.2. Error

A measurement incorporates some errors, that can be neglected since the true value is unknown.

Error ([2]): *result of a measurement minus a true value of the measurand*

Error

- random: due to unexpectable variations, *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 ([2])*
- systematic: *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 ([2])*

result = true value + random error + systematic error

To increase the number of observations and to take the mean enable to decrease the random error. Corrections should be applied to avoid the systematic error.

2. Guide to determine uncertainty

The estimation of the uncertainty of measurement is based on 4 steps:

- the calculation of the result by defining the measurand, by analysing the measurement process and by establishing the mathematical model;
- the calculation of the type-uncertainties;
- the determination of the composed uncertainty;
- the calculation of the enlarged uncertainty.

2.1. To calculate the result of measurement

<u>Mesurand ([2]) :</u> *particular quantity subject to measurement*

The definition of the measurand has to be as precise as possible.

<u>Example :</u> air temperature in a screen located 1 meter above the ground.

The analysis of the measurement process takes an interest in the way the results are obtained: operators, sensors, references, method, modus operandi, surroundings…This analysis enables to list the factors that could influence the result. The causes of error will be also controlled by applying corrections or by repeating measurements.
The analysis can be made according the following diagram called "5 M diagram":

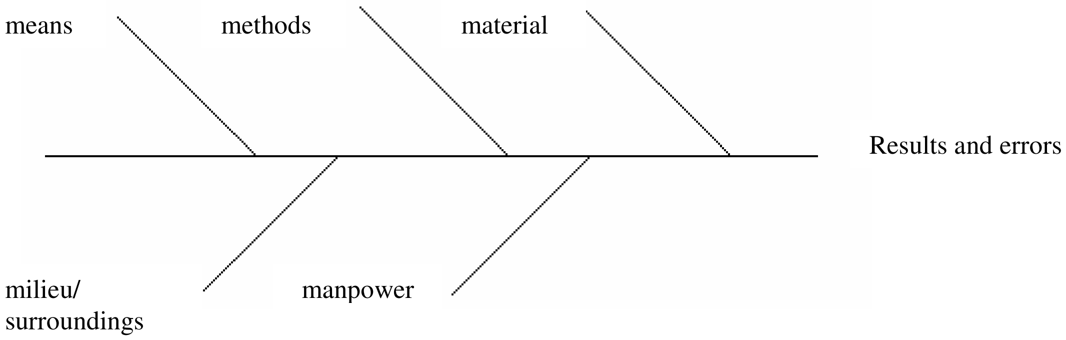


Diagram. 2 : 5 M

The formulation of the mathematical model is based on the modus operandi or how the informations are used to calculate the result of measurement.

$$Y = f(X_1, X_2 ....X_N)$$

measurand Y

measurement process

input data : corrections, sensors…

$$y = f(x_1, x_2 ....x_N)$$

best estimation of the measurand Y, result of measurement

measurement process

estimation of the input data

2.2. How to determine the type-uncertainties

2.2.1. Estimation method of type A or type B

The errors made on the input data compose the uncertainty of the final result. 2 methods to estimate a component of the uncertainty, based on the theory of probability:

- called type A, with the statistical analysis of measurements,
- called type B, for the others methods.

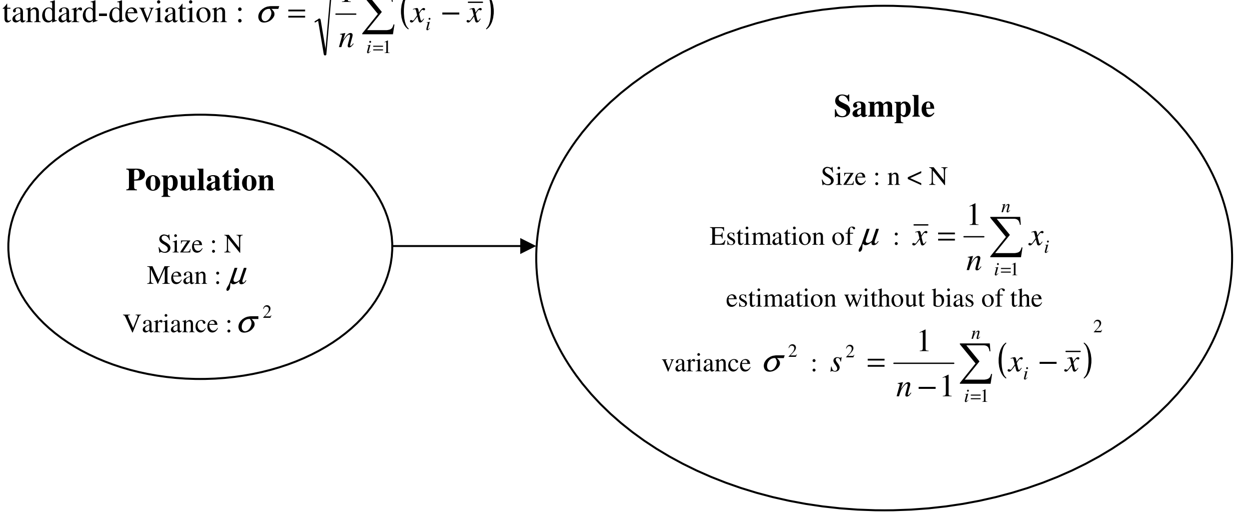
In any case, a component of the uncertainty is given by a standard deviation or a variance, hence type-uncertainty.

2.2.2. Some statistics formula

Mean : $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$

Variance : $\sigma^2 = \frac{1}{n}\sum_{i=1}^{n} \left(x_i - \bar{x}\right)^2$

Standard-deviation : $\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n} \left(x_i - \bar{x}\right)^2}$



2.2.3. Some precisions about type A and type B methods

To estimate a component of the uncertainty according a type A method, we can calculate the repeatibility of the measurement process.

<u>Example:</u>
10 observations of temperature(°C):
19,9 ; 20,0 ; 20,0 ; 20,1 ; 20,0 ; 19,9 ; 19,9 ; 19,8 , 19,9 ; 20,0
mean: 19,95 °C

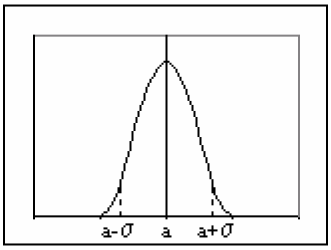
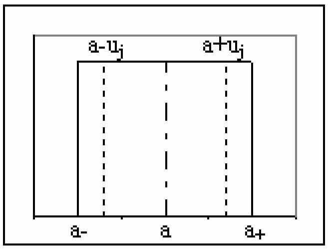
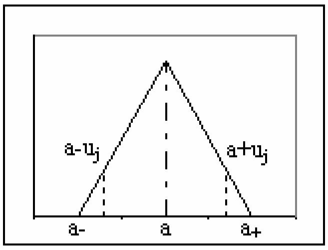
standard deviation: $s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n} \left(x_i - \bar{x}\right)^2}$ =0.085 °C

A type A method demands generally time and ressources to be applied.

A type B method is based on a scientific judgement, thanks to the available informations (experience and experiments, calibrations…). It demands time and a good knowledge of the process.

According to the parameter, 2 points to verify:

- the distribution of observations according to the theory of probability;
- the variation extent.

DISTRIBUTION	HYPOTHESIS	TYPE UNCERTAINTY
Normal	Extremes a_+ and a_- Normal distribution around the mean $a = \frac{a_+ + a_-}{2}$  	$u_j = \frac{a}{coef}$ coef = 1,64 ; 1,96 or 2,58 respectively for a truth level of 90 %, 95% or 99%
Rectangular	Extremes a_+ and a_- Uniform distribution around the mean $a = \frac{a_+ + a_-}{2}$  	$u_j = \frac{a}{\sqrt{3}}$
Triangular	Extremes a_+ et a_- Triangular distribution around the mean $a = \frac{a_+ + a_-}{2}$  	$u_j = \frac{a}{\sqrt{6}}$

2.3. How to determine the composed uncertainty

The type-uncertainty of the measurand estimation y, $u_c(y)$, is the composition of the different type-uncertainties associated with each input data $x_1, x_2, \ldots x_N$.

According to the relationship of uncertainties propagation ([1]):

If $\quad y=f(x_1,x_2,...x_N)$

so
$$u_c^2(y)=\sum_{i=1}^{N}\Bigg(\underbrace{\frac{\partial f}{\partial x_i}}_{\text{sensitivity coefficient}}\Bigg)^2\underbrace{u^2(x_i)}_{\text{variance associated with each input data}}+2\underbrace{\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\frac{\partial f}{\partial x_i}\frac{\partial f}{\partial x_j}u(x_i,x_j)}_{\text{Covariance terms in case of dependence between parameters}}$$

If all the input data are independent:
$$u_c^2(y)=\sum_{i=1}^{N}\left(\frac{\partial f}{\partial x_i}\right)^2u^2(x_i)$$

More, if $y=x_1+x_2+...x_N$ so:
$$u_c^2(y)=u^2(x_1)+u^2(x_2)+...u^2(x_N)$$

If 2 parameters are dependent, we can:

- estimate the coefficient of correlation and $u(x_i,x_j)=u(x_i)u(x_j)r(x_i,x_j)$;
- directly calculate the covariance if we have n sets of observations x_i et xj, so:
$$u(x_i,x_j)=\frac{1}{n(n-1)}\sum_{k=1}^{n}\left(x_{i,k}-\bar{x}_i\right)\left(x_{j,k}-\bar{x}_j\right).$$

The parameter are often supposed to be independent, anyway the terms of correlation are most of the time not significative compared to the others. Statistic tests could ensure of independance.

2.4. How to determine the enlarged uncertainty

The enlarged uncertainty U is obtained by multiplying the composed type-uncertainty $u_c(y)$ by a coefficient k so $U=k\cdot u_c(y)$.

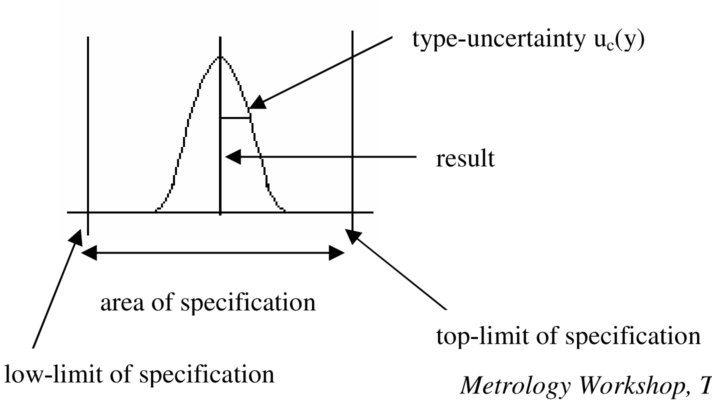
k is chosen according to the requirements, generally k=2.

The enlarged uncertainty is often expressed with the same number of significative figures as the result of measurement.

<u>Example :</u>

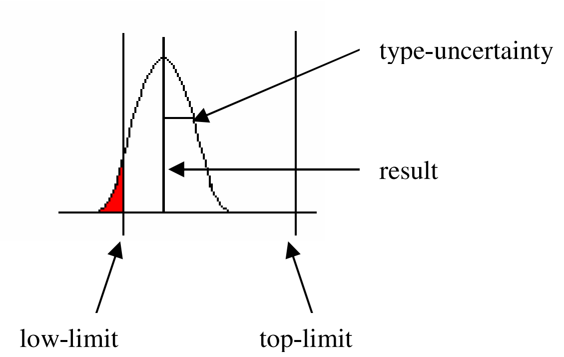
P=1013.15 hPa ± 0.11 hPa

2.5. How to compare a result of measurement with a specification



The following diagram shows a result of measurement with its uncertainty comparing to a specification. Here, the compliance is easy to assess and report.

But when the result with its uncertainty is bigger than the limits, neither the compliance or the contrary can be assess.



The following diagram shows a result of measurement with its uncertainty comparing to a specification. In this case, as the result associated with its uncertainty exceeds the limit, there is a risk to assess compliance.

The risk depends on the probability of the event (metrological aspect) and its cost (commercial aspect).
There is no law to assess or not the compliance, only guideline.

However there is an international guideline ILAC-G8 :1996 Guidelines on assessment and reporting of compliance with a specification to help to decide how to assess compliance.

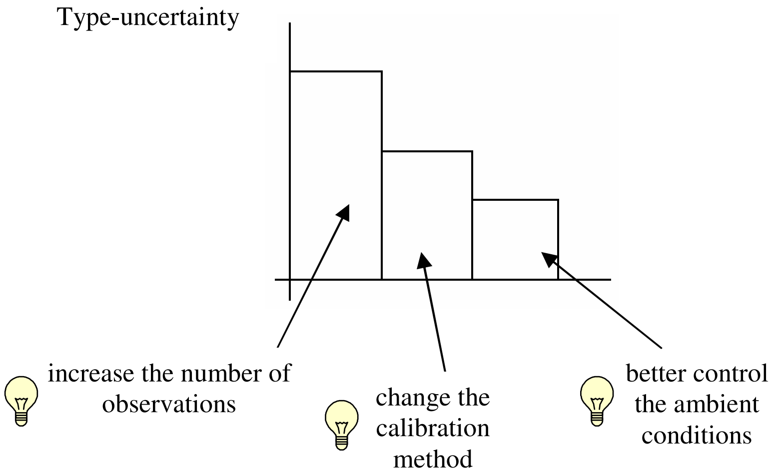
3. To sum up

The uncertainty of measurement is also a tool to better control and improve the measurement process. By calculating the different type-uncertainties, the influence of each data input in the final uncertainty is estimated. It can be represented in a Pareto diagram. The uncertainty becomes a tool to decide at what step the process has to be improved.

Example :

If $\frac{s^2}{n}$ is the type-uncertainty linked to repeatibility, $\left(\frac{u}{k}\right)^2$ the one linked to calibration and $u^2(c_a)$ linked to the surroundings:

$$u_c^2(y)=\frac{s^2}{n}+\left(\frac{u}{k}\right)^2+u^2(c_a)$$



To sum up, the different steps to determine the uncertainty of measurement are:

- to define the measurand, analyse the measurement process and to establish the mathematical model;
- to calculate the type-uncertainty of each input data;
- to spread the uncertainties;
- to express the enlarged uncertainty.

If it is impossible to apply this guideline to express the uncertainty of measurement (that is sometimes the case in chemistry for example) the performance of the method has to be estimated. The standard NF ISO 5725 enables to determine the fidelity of a method of test, it is an estimation of the accuracy and the dispersion thanks to interlabs tests.

BIBLIOGRAPHY :

[1], Guide to the expression of uncertainty in measurement (Guide pour l'expression de l'incertitude de mesure), NF ENV 13005, August 1999, AFNOR
[2], International vocabulary of fundamental and general terms of metrology (Vocabulaire international des termes fondamentaux et généraux de métrologie), 2nd edition, 1993, International Organisation of Standardization (Geneva-Switzerland)

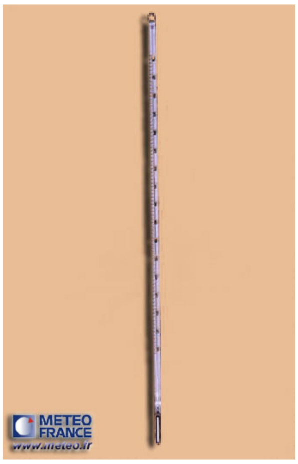
TRAINING MATERIAL ON METROLOGY AND CALIBRATION

1. Vocabulary used in Metrology
2. Measurement Statistics
3. Theoretical Guide to Measurement Uncertainty

4. Metrology of Temperature

5. Metrology of Humidity
6. Metrology of Pressure
7. Metrology organization in Météo-France

Metrology of temperature



1. The temperature parameter

1.1. Generalities

As pressure and humidity, temperature is one of the atmosphere's state parameters.
Meteorological requirements for temperature measurements primarily relate to:

- the surface;
- the upper air;
- the surface levels of the sea and lakes.

These measurements are required for input to numerical weather forecast models, for agriculture, hydrology or climatology.
Temperature is an intensive parameter : the temperature of 2 different bodies which are put together is not the sum of the two temperatures of the different bodies. Temperature is also not directly measurable.
The primary thermometer is a sensor that links temperature to others physical parameters with a law like the ideal gases law (PV=nRT), it is a thermodynamical temperature of which unit is Kelvin (K). But such primary thermometers are quite difficult to use and expensive. Even, they cannot cover all the different experimental cases. But we need sensitive, reproductible, consistent and easy to use, sensors.

1.2. The International Temperature Scale

To link physical laws with reality, an international scale of temperature has been defined.
A scale of temperature is made up of:

- a thermometer, a sensor with an output depending on temperature;
- an interpolation function that links the sensor's output with temperature;
- fixed points of temperature to define the interpolation function.

The International Temperature Scale, first defined in 1927, has been reviewed to reduce the difference between absolute temperature and temperature in the scale. The last scale was defined in 1990 hence ITS 90. The triple point of water is the major point of definition (t=0.01 °C).
ITS 90 consists of different areas and sub-areas with their own definition of T_{90}. For the common parts, the definitions coexist.

$$t(°C)=T(K)-273.15$$

$$t_{90}(°C)=T_{90}(K)-273.15$$

ITS 90 enables easy and reproductible measurements of temperature.
ITS 90 is defined with a thermometer with platinum resistance, the interpolation functions are expressed with reduced resistance W(T), against the resistance at the triple point of water R(273.16K): $W(T)=\frac{R(T)}{R(273.16K)}$ and against the reference function: $W(T)=Wr(T)+\Delta W(T)$.
ITS 90 is defined by some fixed points.

1.3. The fixed points of ITS 90

The following spreadsheet sums up the different fixed points that define the ITS 90, at the atmospheric pressure (except for the triple point) :

NUMBER	TEMPERATURE		BODY[1]	POINT
	T_{90} (K)	T_{90} (°C)		
1	3 à 5	-270,15 à –268,15	He	V
2	13,8033	-259,3467	e-H_2	T
3	~17	~-256,15	e-H_2 ou He	V ou G
4	~20,3	~-252,85	e-H_2 ou He	V ou G
5	24,5561	-248,5939	Ne	T
6	54,3584	-218,7916	O_2	T
7	83,8058	-189,3442	Ar	T
8	***234,3156***	***-38,8344***	***Hg***	***T***
9	***273,16***	***0,01***	***H_2O***	***T***
10	***302,9146***	***29,7646***	***Ga***	***M***
11	429,7485	156,5985	In	F
12	505,078	231,928	Sn	F
13	692,677	419,527	Zn	F
14	933,473	660,323	Al	F
15	1234,93	961,78	Ag	F
16	1337,33	1064,18	Au	F
17	1357,77	1084,62	Cu	F

[1] e-H_2: according to molecular composition

[2] V: saturated vapour pressure

T: triple point between fluid, vapour and gas

G: thermometer with gas

F,M: freezing or melting point

Spreadsheet. 1: Fixed points of the ITS 90

Our range is between the triple point of mercury and the melting point of gallium. Between the triple point of hydrogen (13,8033K) and the freezing point of silver (961.78 °C) temperature according ITS 90, T_{90}, is defined with a platinum resistance thermometer, calibrated against specific fixed points and using the interpolation functions.

The interpolation is made with this reference function, defined in the standard EN 60751: 1995, with t in °C:

- from –200 to 0 °C:

$$R_t = R_0\left[1 + A \cdot t + B \cdot t^2 + C(t - 100) \cdot t^3\right]$$

- from 0 to 850 °C:

$$R_t = R_0\left(1 + A \cdot t + B \cdot t^2\right)$$

A	$3.90802.10^{-3}$ °C^{-1}
B	$-5.802.10^{-7}$ °C^{-2}
C	$-4.27350.10^{-12}$ °C^{-4}

2. The different types of sensor

As the thermometer only gives its own temperature, it should not upset the surroundings.

The following spreadsheet sums up the usual thermometers:

METHOD	MARK	RANGE
Fluid expansion	Volume	-200 °C to 650 °C
Platinum resistance	Resistance	13 K to 961 °C
Rhodium-iron resistance	Resistance	0.6K to 273 K
Thermoelectric couple	Electromotive force	-180 °C to 2500 °C
Thermistor	Resistance	0 °C to 100 °C

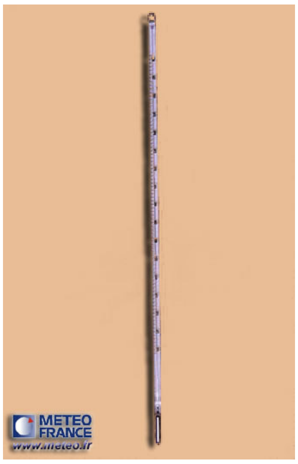
Spreadsheet 2: Examples of types of sensors

Bimetallic thermometers or with gas expansion are also used.

Extract from [1]:

All temperature measuring instruments should be issued with a certificate confirming compliance with the appropriate accuracy or performance specification, or a calibration certificate which gives the corrections that must be applied to meet the required accuracy.

2.1. Liquid-in-glass thermometer



Diag.1 : Liquid-in-glass thermometer

These devices use the thermal expansion and contraction of a liquid to indicate temperature.
By calibration with a standard thermometer, a scale of temperature can be marked on the stem.

The sensititvity depends on :

- the volume of the bulb;
- the difference between the expansion of the liquid and the one of the glass.

This sensitivity is inversely proportional to the capillary section.

The following spreadsheet sums up the usual liquids :

RANGE	LIQUID	DIFFERENTIAL EXPANSION COEFFICIENT IN THE THERMOMETER (IN °C)
-200 to 20 °C	Pentane	0.001
-110 to 100 °C	Alcohol	0.001
-38 to 650 °C	Mercury	0.00016
-56 to 650 °C	Mercury-thalium	0.00016

Spreadsheet 3: Usual liquids

The following spreadsheet sums up the characteristics of mercury and alcohol :

	MERCURY	ALCOHOL
Melting point (°C)	-38.9	-117.3
Boiling point (°C)	336.9	78.5
Thermal expansion coefficient	182.10^{-6}	1100.10^{-6}
Heat capacity ($J.K^{-1}$)	0.12	2.43
Thermal conductivity ($W.K^{-1}.m^{-1}$)	8.361	0.180
Wetting ?	no	yes
Stable	yes	no
Linear expansion	yes	no
Transparency	no	yes
Condensation	no	yes
Liquid breaking up	no	yes

Spreadsheet 4: Characteristics of mercury versus alcohol

Mercury has a lot of advantages but it is hazardous.
The glasses are refired to obtain a good stability, like the pyrex. The thermometers are usually nitrogen filled to retard vaporization or separation.

Attention must be paid with liquid-in-glass thermometers because of:

- parallax error: when the meniscus is not viewed from a perpendicular position;
- interpolation error : the scale is bigger than the required decimal reading;
- due to differential expansion between liquid and glass;
- changes in the volume of the bulb produced by external or internal pressure;
- breaking up of the liquid column;
- adhesion to the glass;
- interferences: pollution, breathing…the measurement must be as quick as possible, the liquid has to be as pure as possible;
- emergent stem: with a partial immersion, the effective temperature of the stem is different from that of the bulb, an error will result.

The use of a liquid-in-glass thermometer assumes:

- the expansion law is known;
- the glass doesn't expand;
- no interaction between glass and liquid.

The ordinary mercury thermometer registers the actual temperature at the time of reading. The maximum thermometer has a constriction in the bore near the bulb. When the temperature increases, the mercury expands past the constriction into the bore. However, it cannot move back into the bulb when the temperature decreases. The minimum thermometer contains a tiny metal dumbbell (index) in the liquid. This is forced toward the bulb by the retreating surface of the alcohol as the temperature falls. When the temperature rises the dumbbell remains in place and registers the minimum temperature. It is reset by tilting the thermometer so that the dumbbell rests against the alcohol-gas surface. These two types of thermometers should be mounted at an angle of about 2° from the horizontal.

2.2. The resistance thermometer

Diag. 2: Platinum resistance thermometer

It is a device measuring temperature by the reversible change of the electrical resistance of a metal wire.
According to the metal, sheath, there is a lot of different types of sensors.

The metal's choice depends on sensitivity, reproductibility, linearity…The platinum sensing resistor is prevailing in Europe and in the world. Its advantages include chemical stability, relative ease of manufacture, availability of platinum in a highly pure form and excellent reproductibility of its electrical characteristics.
Physical law of a resistance thermometer :

$$R(T) = \rho(T) \cdot \frac{L}{A}$$ avec L : length of the wire

A : section
ρ : resistivity

According to an empiric law : ρ(T) = ρ'(T) + ρ'(Z) with Z for impurities.

The use of a resistance thermometer assumes :

- stability of the sensing element;
- the law R(T) is known;
- the sensing element is kept free of contamination.

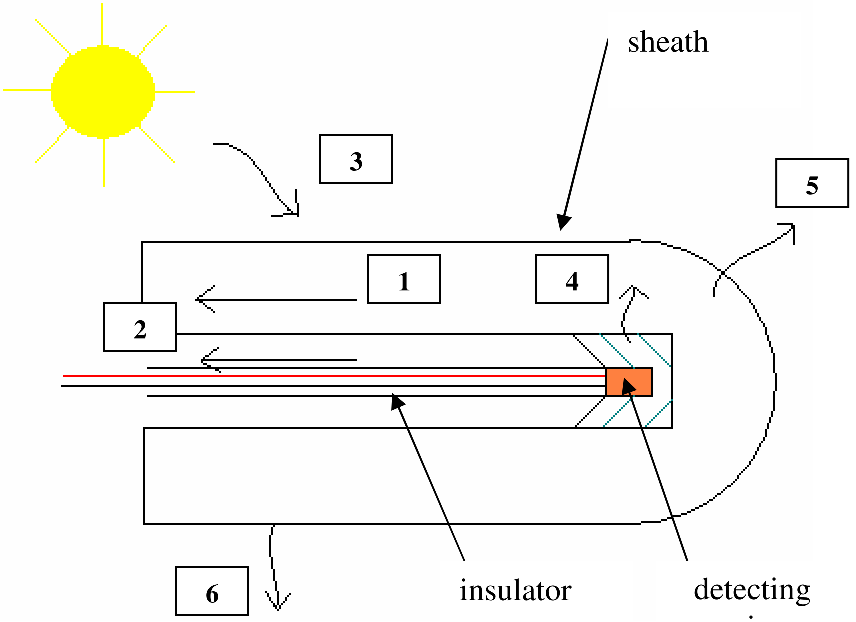
The standard DIN 43760 gives the value of the resistance 100 Ω (nominal resistance), the law R(T) and the margins for interchangeability, according to 2 classes :

- class A : $\Delta T < 0{,}15 + 0{,}002|T|$
- class B : $\Delta T < 0{,}3 + 0{,}005|T|$

Major errors come from :

- stability because of impurities, mechanical and thermal stress, that can be estimated with annealing or testing at 0 °C. For pollution, it is a problem only for very hot temperature (>550 °C);
- hysteresis, linked to the metal of the sheath;

- thermal leaks:



- Permanent static leak:
  - **1** due to conduction, increase immersion
  - **2** due to conduction, decrease the section
  - **3** due to radiation, avoid or protect from light source
- Sealf-heating error, due to the current:
  - **4** due to conduction
  - **5** due to convection
  - **6** due to radiation

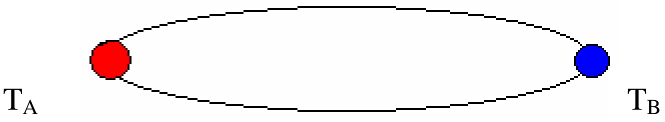
Diag.3: Diagram of thermal leaks

So it implies, a weak or alternative current and correction of self-heating.

- Dynamic error because of response time;
- Electrical error with 2 or 3 wires setting.

2.3. The thermocouple

The thermocouple is a thermoelectric temperature sensor which consists of two dissimilar metallic wires. These two wires are connected at two different junctions, one for temperature measurement and the other for reference.



Diag. 4: Diagram of a thermocouple

The temperature difference between the two junctions is detected by measuring the change of voltage (electromotive force, EMF) accross the dissimilar metals at the temperature measurement junction, according to the Seebeck effect :

$$E = \int_{T_A}^{T_B} \sigma(T)dT \text{ with } \sigma \text{ Seebeck coefficient.}$$

The following spreadsheet sums up the different types of thermocouples :

NAME	COUPLE	SENSITIVITY	RANGE	!
S	Pt with Rhodium 10 % / Platinum	10 µV/°C	0 à 1600 °C	Reducing atmosphere
B	Platinum with Rhodium 30 % / platinum with Rhodium 6%	9 µV/°C	50 à 1750 °C	Reducing atmosphere
R	Platinum with Rhodium 13 % / Platinum	12 µV/°C	0 à 1700 °C	Reducing atmosphere
K	Nickel Chromium / Nickel Aluminium	40 µV/°C	-180 à 1350 °C	Reducing atmosphere
N	Nickel Chromium Silica / Nickel Silica	40 µV/°C	-270 à 1300 °C	More stable than K
E	Nickel Chromium / Copper Nickel	80 µV/°C	0 à 800 °C	Neutral atmosphere
J	Iron / Copper Nickel	56 µV/°C	-180 à 750 °C	Reducing atmosphere
T	Copper / Copper Nickel	46 µV/°C	-250 à 400 °C	Oxydizing atmosphere

Spreadsheet. 5: types of thermocouples

The use of a thermocouple assumes:

- stability of metallic wires;
- EMF generated according to the temperature;
- point measurement.

It is important to appreciate that thermocouples measure the temperature difference between two points, not absolute temperature. In most applications, one of the junctions — the "cold junction" — is maintained at a known (reference) temperature, whilst the other end is attached to a probe. The relationship between the temperature difference and the output voltage of a thermocouple is nonlinear and is given by a complex polynomial equation (which is fifth to ninth order depending on thermocouple type). To achieve accurate measurements, some type of linearisation must be carried out, either by a microprocessor or by analogue means.

Major errors come from :

- the dependence of the Seebeck coefficient on type of metal;
- homogeneity;
- stability.

2.4. The bimetallic strip thermometer


Diag. 5: Bimetallic strip thermometer

In bimetallic thermometer, the movement of the recording pen is controlled by the change in curvature of a bimetallic strip or helix, one end of which is rigidly fixed to an arm attached to the frame.
Major errors come from :

- oxydizing;
- thermal inertia;
- problem of linearity if elasticity is exceeded;
- influence of links between the strips.

2.5. Types of shields ([1])

A radiation shield or screen should be designed to provide an enclosure to exclude radian heat and precipitation. Best results are obtained with forced ventilation but most of the numerous varieties of the louvred screen rely on natural ventilation. The walls of such a screen should preferably be double-louvred and the flour, made of staggered boards. The roof should be double-layered. In cold climates, the screen should also have a double floor. The screen also allows ample space between the instruments and the walls to exclude all possibility of direct contact of the thermometer sensing elements with the walls. The screen should be painted both inside and outside with white, non-hygroscopic paint.

3. Means of calibration

3.1. Definition ([2])

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

For temperature, calibrations are achieved thanks to generators, that create the comparing surroundings.
There are 4 types of generators:

- generators using cryogenics, with nitrogen baths, for the very cold temperatures;
- baths, from –80 to 180 °C ;
- kilns for high temperatures ;
- climatic chamber.

3.2. Baths

Diag. 6: Bath with mixing

To obtain the best stability, both special fluid and thermal block of equalization are used in a bath.
Alcohol, water or oil are used according to the wanted range of temperature.

There are 2 types of baths : bath with overflow, especially for the liquid-in-glass thermometers or with mixing.

3.3. Kilns

There are 3 types of kilns:

- classical, that requires a thermal block of equalization;
- heat pipe kiln that is like a climatic chamber with a fluid in gas balance, condensation in the kiln determines the level of temperature;
- special, with alumina powders.

3.4. Climatic chambers

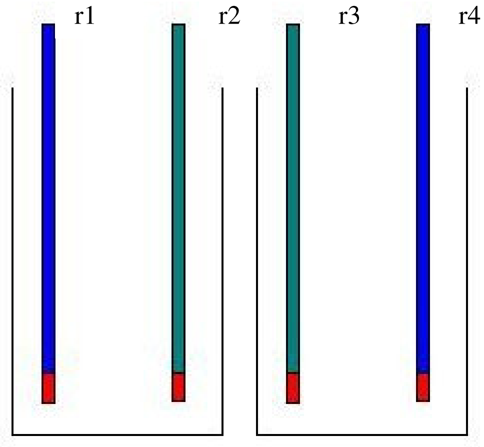
Diag. 7: Climatic chamber

Used when it is impossible to immerge the sensors in a fluid (thermohygrometer…), the calibration is made in the air.

3.5. Generator's use

The use of a generator implies that homogeneity and stability should be determined. Some procedures shoulb be written to define the methods of characterization.

Example of a characterization of a block in a bath :



Diag. 8: double weighing of Gauss

To calculate the uncertainty due to homogeneity between 2 thermometers number 1 et number 2 :

- given r1 the resistance of the thermometer 1 in L1 ;
- given r2 the resistance of the thermometer 2 in L2 ;
- given r3 the resistance of 2 in L1 ;
- given r4 the resistance of 1 in L2.

So :

- r1=R1(T) and r2=R2(T+ε)
- r3=R2(T) and r4=R1(T+ε) with Ri(T) the output of the thermometer i for the level of temperature T.

ε is the difference between the thermometer 1 and 2 for the same level of temperature but not at the same place.

Given $\rho_1 = \frac{r_1}{r_2}$ and $\rho_2 = \frac{r_3}{r_4}$. So $\varepsilon = \frac{R(1-\rho_1\rho_2)}{2s}$ with s the sensitivity ($s = 0.390744\Omega/°C$ for a resistance thermometer Pt 100 Ω).

The enlarged uncertainty is given by the following formula : $U(\varepsilon) = \pm 2 \times \frac{1}{s} u_c(\varepsilon)$ with $u_c(\varepsilon)$ the uncertainty over a resistance measurement.

So the uncertainty becomes : $U(\varepsilon) = 2 \times \frac{\frac{\Delta\rho}{4} \cdot R(T)}{s}$ with $\Delta\rho$ the range of the ratio between the resistances for a level of temperature (10 measurements at a level) and R(T) the average resistance.

The differences ε with their uncertainty are calculated over all the couples of thermometers, for all the levels. The more important value gives the homogeneity of the bath.

Example of a characterization of a climatic chamber

See the standard NF X 15-140.

4. Calibration methods

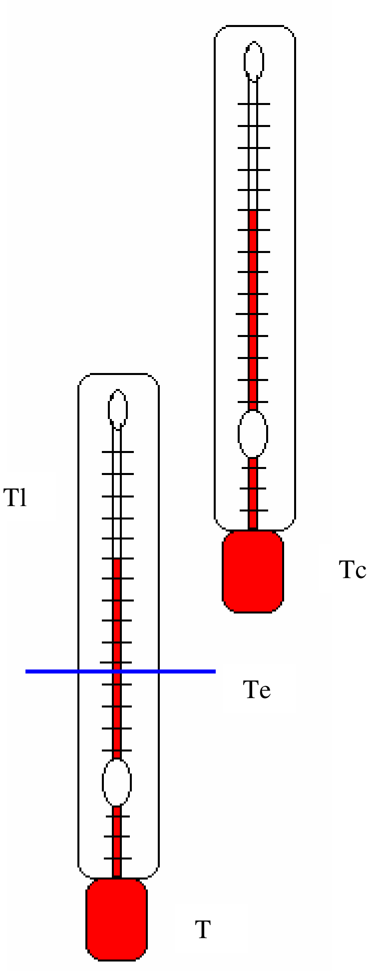
Calibration is performed by comparison to a standard with a generator.

4.1. Calibration of a liquid-in-glass thermometer

The generator is typically a bath with overflow.

- Immersion

If the thermometer is totally immerged or at the reading, the liquid is at the surroundings temperature, there is no correction due to emergent stem. If it is not the case, if the thermometer is immerged with a specified depth, a correction has to be made because a part of the liquid is not balanced with the environnement.

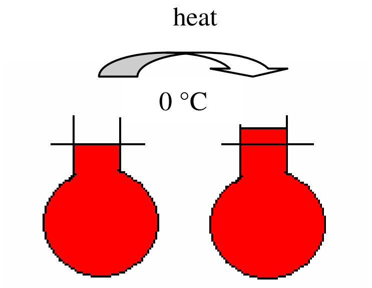


Tl: temperature reading
Tc: average temperature of the emergent stem
Te: temperature between liquid and air
T: bulb temperature
K: sensitivity

$$T = Tl + K\,(Tl - Te)\,(Tl - Tc)$$

Diag. 9: Correction of the emergent stem

- Changes in the volume of the bulb



Diag. 10: Rise of the zero

The bulb of the thermometer tends to contract slowly over a period of years and thus, causes the zero to rise. The greatest change will take place in the first year and then the rate of change will gradually decrease. This alteration can be reduced by heat treatment of the bulb. For accurate work, the zero should be redetermined periodically.

- Capillarity

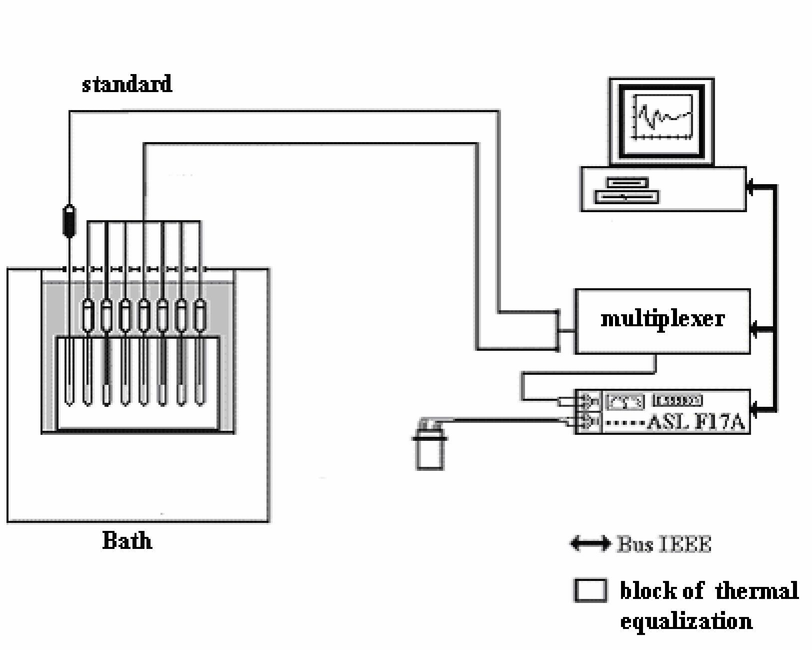
For the mercury thermometer with a very fine capillarity, the variations of the meniscus curvature cause variations of pressure and the liquid advances by leaps. To relax the internal stresses, tapping the thermometer with a pen for example is enough.

Unlike mercury, organic liquids generally wet the glass and therefore, when the temperature falls rapidly, a certain amount of the liquid may remain on the walls of the bore, causing the thermometer to give lower temperature.

4.2. Calibration of the resistance thermometers

Calibration is typically made in a bath.

Example: calibration in Météo france



Diag. 11: Diagram of calibration

For routine calibrations of 4-wires resistance thermometers, a bath with a block of thermal equalization is commonly used. The calibration is made by comparing to the standard from –20 °C to 40 °C. At a level of temperature, 10 measurements every 5 secondes are made with a bridge and multiplexer. The common measurement current is 1 mA. An other measurement is made at $\sqrt{2}$ mA to estimate the self-heating. Before and after the calibration, our standard is controlled thanks to the fixed point of Gallium.

- Stability

The stresses and impurities modify the electrical resistance of the sensing element. Stability has to be estimated. Practical thermometers are artificially aged before use. The CEI 751 standard establishes the maximum drifts into 2 classes A and B.

- Law R(T)

Self-heating occurs because the passage of a current through the resistance element produces heat ($P=Ri^2$) and thus the temperature of the thermometer element becomes higher than that of the surrounding medium. This typical error depends on the surroundings and thermal exchanges.

If it is possible, the better is to make 2 measurements at 2 differents currents to estimate the resistance with no current or the current has to be as weak as possible. For practical use,
10 mA maximum is tolerated (hence an error from 0.05 to 1.5 °C).

- Number of wires

Links with 2 or 3 wires form a resistance which alters depending on the temperature. 4 wires is better.

- Thermal leaks

To prevent measurement from thermal leaks, due to the thermometer geometry and surroundings, the thermometer has to be totally immerged.

4.3. Calibration of the thermocouples

- Stability

The method will begin with the higher temperature to determine the influence of oxydization.

- Heterogeneity

Several immersions during the calibration allow to determine the homogeneity of the couple.

The choice of a sensor and its method of calibration depend on the use but some characteristics have an influence too over the steps of the calibration.
In meteorology, 2 types are commonly used:

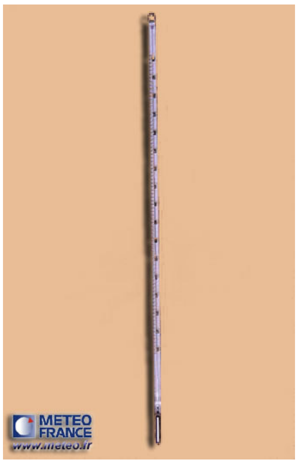
- liquid-in-glass thermometer;
- resistance thermometer (Pt 100).

The means are most of the time baths or climatic chambers.
As thermometers cannot be adjusted, the calibration drives the user to accept or reject the sensor according the requirements. In Météo France, the requirement is to have class A thermometers.

BIBLIOGRAPHY :

[1] Guide to meteorological instruments and methods of observation, sixth edition, WMO N°8, 1996
[2] International vocabulary of basic and general terms in metrology, BIPM and al., second edition, 1993

An example of uncertainties budget:
Calibration of a liquid-in-glass thermometer



1. Method, means and mathematical model

1.1. Principle of the calibration

The following example deals with the calibration of a liquid-in-glass thermometer, 0.1 °C graduated, by comparison with a reference, at a temperature T (20 °C).
We aims at finding the correction.

1.2. Method

The thermometers are read by an operator, able to interpolate to the fifth division. The thermometers are immerged to the degree to be read.
A cycle is composed on 10 readings of the reference, 10 of the thermometer to calibrate and finally 10 readings of the reference again. Between each reading, the operator taps the thermometer with a pen to relax the internal stresses.
Before and after the calibration, the thermometer is controlled towards the point of melting ice, to check the zero.

1.3. Means

Reference : reference liquid-in-glass thermometer
Liquid-in-glass thermometer graduated to within 0.1 °C and calibrated against the national references. The thermometer was totally immerged and the readings were performed by an operator able to interpolate to the fifth division.

Surroundings : a bath with characterized homogeneity and stability.

1.4. Mathematical model

$$C = Tr - Tc + \delta T_{\mathrm{int}er\_ref} + \delta T_{calib\_ref} + \delta T_{drift\_ref} + \delta T_{emer\_stem} + \delta T_{stab} + \delta T_{\mathrm{hom}} + \delta T_{zero} + \delta T_{\mathrm{int}er\_thermo}$$

C : correction to determine
Tr : temperature of the reference thermometer
Tc : temperature of the thermometer to calibrate
$\delta T_{\mathrm{int}er\_ref}$: correction due to the interpolation to read the temperature of the reference
δT_{calib_ref} : correction due to the calibration of the reference
δT_{drift_ref} : correction due to the drift of the reference (between 2 calibrations)
δT_{emer_stem} : correction due to the influence of the surroundings on the emergent stem
δT_{stab} : correction due to the stability of the bath
δT_{hom} : correction due to the homogeneity of the bath
δT_{zero} : correction due to the rise of the zero of the thermometer to calibrate
$\delta T_{\mathrm{int}er\_thermo}$: correction due to the interpolation to read the temperature of the thermometer

2. How to determine the type-uncertainty

2.1. Details about corrections

Tr : the operator read 20.02 °C (mean of the 10 readings) with a range of 0.02 °C.

With a rectangular statistical law, the type-uncertainty is $\frac{0.02}{2\sqrt{3}} = 0.006°C$.

Tc : the operator read 20.10 °C (mean of the 10 readings) with a range of 0.02 °C.

With a rectangular statistical law, the type-uncertainty is $\frac{0.02}{2\sqrt{3}} = 0.006°C$.

$\delta T_{\mathrm{int}\,er\_ref}$: the operator reads to the fifth division. The correction is considered as null.

With a rectangular statistical law, the type-uncertainty is $\frac{0.1/5}{2\sqrt{3}} = 0.006°C$.

δT_{calib_ref} : in the certificate, the correction is 0.01 °C with an enlarged uncertainty (k=2) equal to 0.2 °C.

δT_{drift_ref} : the chronological account of the calibrations doesn't show a drift, considered as null.

The type-uncertainty is : 0.006 °C as the interpolation uncertainty.

δT_{emer_stem} : there is no correction as the thermometers are totally immerged.

The type-uncertainty is : 0.006 °C as the interpolation uncertainty.

δT_{stab} : no correction but the experimental standard deviation during the tests to characterize the bath gives the type-uncertainty : 0.01 °C.

δT_{hom} : no correction but the experimental maximum limit during the tests to characterize the bath gives the type-uncertainty: 0.04 °C.

With a rectangular statistical law, the type-uncertainty is $\frac{0.04}{2\sqrt{3}} = 0.012°C$.

δT_{zero} : the measurements before and after the calibration with melting ice don't show a problem with the zero.

The type-uncertainty is : 0.006 °C as the interpolation uncertainty.

$\delta T_{\mathrm{int}\,er\_thermo}$: the operator reads to the fifth division. The correction is considered as null.

With a rectangular statistical law, the type-uncertainty is $\frac{0.1/5}{2\sqrt{3}} = 0.006°C$.

2.2. Budget of the type-uncertainties

TYPE	ESTIMATION	TYPE-UNCERTAINTY	LAW	SENSITIVITY COEFFICIENT	TYPE-UNCERTAINTY
Tr	20.02	0.006	rectangular	1	0.006
Tc	20.10	0.006	rectangular	1	0.006
$\delta T_{\mathrm{int}\,er\_r\acute{e}f}$	0	0.006	rectangular	1	0.006
δT_{calib_ref}	-0.02	0.1	normal	1	0.1
δT_{drift_ref}	0	0.006	rectangular	1	0.006
δT_{emer_stem}	0	0.006	rectangular	1	0.006
δT_{stab}	0	0.01	normal	1	0.01
δT_{hom}	0	0.012	rectangular	1	0.012
δT_{zero}	0	0.006	rectangular	1	0.006
$\delta T_{\mathrm{int}\,erp\_thermo}$	0	0.006	rectangular	1	0.006

3. Global uncertainty

$$C = Tr - Tc + \delta T_{\mathrm{int}\,er\_ref} + \delta T_{calib\_ref} + \delta T_{drift\_ref} + \delta T_{emer\_stem} + \delta T_{stab} + \delta T_{\mathrm{hom}} + \delta T_{zero} + \delta T_{\mathrm{int}\,er\_thermo}$$

$$C = 20.02 - 20.10 + 0 - 0.02 + 0 + 0 + 0 + 0 + 0 + 0$$

$$C = -0.10°C$$

The parameters are considered as independent.
According the mathematical model, the final type-uncertainty is the quadratic sum of the different type-uncertainties:

$$u_c^2(y) = 0.006^2 + 0.006^2 + 0.006^2 + 0.1^2 + 0.006^2 + 0.006^2 + 0.01^2 + 0.012^2 + 0.006^2 + 0.006^2$$

$$u_c(y) = 0.103°C$$

The correction is (–0.10 ± 0.21) °C.

BIBLIOGRAPHY :

[1], Technical guideline for an accreditation in temperature, COFRAC, December, 10th,1999

An example of uncertainties budget:
Calibration of a platinum resistance

1. Method, means and mathematical model

1.1. Method of the calibration

This example deals with the calibration of a platinum resistance Pt-100 Ω of the Météo France network. The calibration is made by comparison with our working reference.
The parameter to determine is whether the Pt-100 Ω is a class A thermometer or not.

1.2. Method

The calibration is performed under the requirements of an internal modus operandi, hence 4 levels of temperature: 40 °C, 20 °C, 0 °C et –20 °C, by comparison with our working reference. The temperatures are generated with a bath and the measurements are made with 2 electric currents (1 and $\sqrt{2}$ mA) to estimate self-heating.
Before and after the calibration, the reference is controlled with a gallium cell.

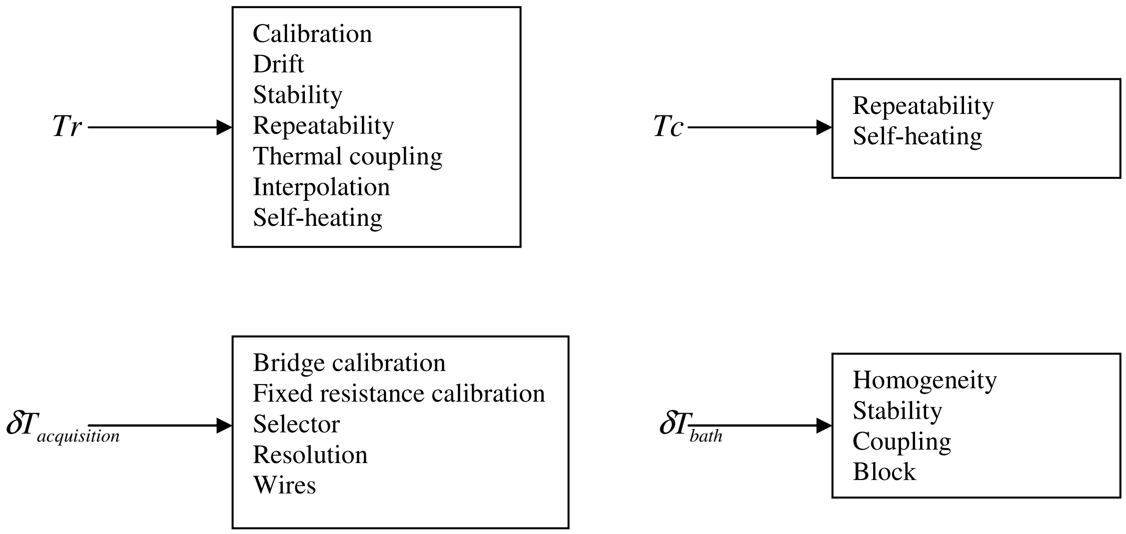
1.3. Means

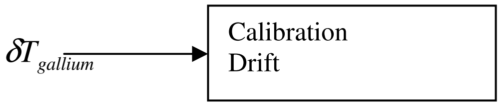
Reference : working reference
Pt-100 Ω thermometer calibrated in the laboratory of metrology.
Surroundings : bath
Both the bath and the thermal equalizing block were characterized in the laboratory for homogeneity and stability.
Electrical means : bridge ASL F 17

1.4. Mathematical model

$$Tc = Tr + \delta T_{acquisition} + \delta T_{bath} + \delta T_{gallium}$$

Tr : temperature of the reference
Tc : temperature of the thermometer to calibrate
$\delta T_{acquisition}$: correction linked with the acquisition
δT_{bath} : correction linked with the influence of the surroundings
$\delta T_{gallium}$: correction due to the use of the gallium cell to control the stability of the reference





2. Type-uncertainties

2.1. Type-uncertainties of the reference

The corrections found during the last calibration are used in the acquisition software (polynomial interpolation). As the correction due to the interpolation is not made, it is added to the final uncertainties, as well for self-heating.

u_{calib} : the reference is calibrated each two years. The corrections are applied, the enlarged uncertainty is 0.029 °C (k=2).

u_{drift} : the drift is calculated with all the former calibrations, it is the maximal difference between two successive calibrations and with a rectangular law: $\frac{0.01}{\sqrt{3}} = 0.0058°C$.

u_{stab} : a control with a gallium cell before and after the calibration enables to check the reference stability, the criteria is a maximum difference of 0.0005 °C.

u_{repeat} : the maximum standard deviation during the calibration gives the repeatability of the reference.

$u_{coupling}$: the influence of the surroundings over the reference was characterized (with testing the calibration at different heights in the bath) and the type-uncertainty is : $\frac{0.011}{2\sqrt{3}} = 0.0032°C$ with a rectangular law.

c_{heat} : the correction due to self-heating is calculated during the last calibration. As the correction is not applied, it will be added at the final uncertainty: 0.009 °C.

c_{inter} : the correction due to interpolation is not applied, but added at the final uncertainty: 0.0002 °C.

2.2. Type-uncertainties of the thermometer to calibrate

s_{heat} : the type-uncertainty due to self-heating is estimated during the calibration, by making measurements at 2 electric currents in order to extrapolate the results for 0 mA.

s_{repeat} : the type-uncertainty is the maximum standard deviation of the calibration.

2.3. Uncertainties due to acquisition δT_{acquis}

The bridge is used 3 times, for the reference, the thermometer to calibrate and for the control with the gallium cell.

u_{bridge} : type-uncertainty linked with the calibration and use of the bridge ASL: 0.0013 °C.

u_{fixR} : type-uncertainty linked with the calibration and use of the fixed resistance: 0.0009°C.

u_{select} : type-uncertainty linked with the use of the selector, characterized by control card: 0.0002 °C.

u_{resol} : type-uncertainty due to the resolution of the bridge, calculated with the smaller digit and a rectangular law: 0.0001 °C.

u_{wire} : type-uncertainty due to the wires, considered as negligible.

2.4. Uncertainties due to the bath δT_{bath}

The use of the bath implies homogeneity and stability uncertainties.

u_{hom} : type-uncertainty due to the horizontal homogeneity of the bath, calculated during the characterization: 0.0184 °C.

u_{stab_bath} : type-uncertainty due to stability of the bath, calculated during the characterization: 0.0032 °C.

u_{therm} : type-uncertainty due to the vertical homogeneity or the influence of the surroundings over the bath, calculated during the characterization: 0.0040 °C.

u_{block} : type-uncertainty due to the thermal equalizing block : 0.0015 °C.

2.5. Uncertainties due to the use of gallium cell $\delta T_{gallium}$

u_{calib_ga} : type-uncertainty due to the calibration of the cell, in a accredited laboratory: 0.0013°C (k=2).

u_{drift_ga} : type-uncertainty due to the drift of the cell between 2 calibrations and with a rectugular law: $\frac{0.0001}{\sqrt{3}} = 0.0001°C.$

2.6. Type-uncertainties summary

TYPE	LAW	TYPE-UNCERTAINTY (°C)
u_{calib}	normal	0.0145
u_{drift}	rectangular	0.0058
u_{stab}	normal	0.0005
u_{repeat}	normal	0.002 for the best each time
$u_{coupling}$	rectangular	0.0032
c_{heat}	/	0.009
c_{inter}	normal	0.0002
u_{bridge}	normal and rectangular	0.0013
u_{fixR}	normal and rectangular	0.0009
u_{select}	rectangular	0.0002
u_{resol}	rectangular	0.0001
u_{wire}	/	negligible
u_{hom}	rectangular	0.0184
u_{stab_bath}	normal	0.0032
u_{therm}	rectangular	0.0040
u_{block}	rectangular	0.0015
u_{calib_ga}	normal	0.0007
u_{drift_ga}	rectangular	0.0001
s_{heat}	rectangular	each time
s_{repeat}	normal	each time

3. Global uncertainty

$$U_c = \sqrt{u_{calib}^2 + u_{drift}^2 + u_{stab}^2 + u_{icoupling}^2 + u_{repeat}^2 + 3 \cdot \left(u_{resol}^2 + u_{bridge}^2 + u_{fixR}^2 + u_{select}^2\right) + u_{\mathrm{hom}}^2 + u_{stab\_bath}^2 + u_{therm}^2 + u_{block}^2 + u_{calib\_ga}^2 + u_{drift\_ga}^2 + s_{het}^2 + s_{repeat}^2}$$

$$U = \pm 2 \cdot U_c + c_{\mathrm{heat}} + c_{\mathrm{inter}} \text{ with } k = 2$$

4. Compliance with the class A

The compliance with class A thermometers is prononced if the results of the calibration respect the maximal tolerated error (EMT) in fact $0.15 + 0.002 \cdot |T|$ (°C).
For Météo-France, the calibrated thermometer is a class A thermometer if at each level of temperature : $|correction| + U < EMT$.

BIBLIOGRAPHY :
DT 202 et LT 202: internal documents on temperature uncertainties of the laboratory of metrology.

TRAINING MATERIAL ON METROLOGY AND CALIBRATION

1. Vocabulary used in Metrology
2. Measurement Statistics
3. Theoretical Guide to Measurement Uncertainty
4. Metrology of Temperature

5. Metrology of Humidity

6. Metrology of Pressure
7. Metrology organization in Météo-France

METROLOGICAL WORKSHOP

HUMIDITY MEASUREMENT

October 2005

SOMMAIRE

1. OBJECT

The object of this document is to define the main terms used in moisture measurement. The term moisture refers to the water content of any material; solid, liquid or gas. However, in this paper, the word "moisture" will refer to the water content of solids or liquids, reserving the term "humidity" for the water content of gases.

Main utilizations of humidity measurement are:

- Weather observation, (meteorological service)
- Air conditioning and climatization,
- Climatic chambers, climatized rooms, drying equipments
- Water vapor detection (gas, micro-electronic, metal factories…),
- etc....

This paper also defines quantity value used in different calculation.

2. DEFINITIONS

2.1. DRY AIR

Dry air is a mixture of atmospheric gases, mainly nitrogen, oxygen, argon, carbon dioxide gas and, in few quantities, a lot of others gases, such as neon, helium, krypton, hydrogen… The rate of these gases is variable depending on time and area, but this rate could be considered as constant in a first approximation (standard air).

Gas	Proportion by volume
Nitrogen	78
Oxygen	21
Argon	0.94
Carbon dioxide	0.03

2.2. MOIST AIR

The moist air is a mixture in variable proportion of dry air and water vapor. Water vapor is, in fact, the third largest component of the atmosphere after nitrogen and oxygen. At room temperature, as much as 2.5% by volume of the air may be water vapor.
The pressure in this mixture can be estimated by using Daltons Law:
This Law states that the total pressure of a mixture of gases is equal to the sum of the partial pressures of the constituent gases. The partial pressure is the pressure each gas would exert if it alone occupied the whole volume of the mixture.

Daltons Law for moist air can be expressed as:

$$p = p_a + p_w$$

where

p = total pressure of air (Pa, N/m2)

p_a = partial pressure (Pa, N/m2)

p_w = partial pressure water vapor (Pa, N/m2)

2.3. CONCENTRATION

The proportion of water vapor in a gas mixture can be expressed in the usual concentration terms; mass of water vapor per unit volume or mass of water vapor per unit mass of dry gas. The former is called "absolute humidity" and the latter "mixing ratio".
Mixing ratio is expressed in term of ratio of mass or volume of water vapor to mass or volume of dry gas (excluding the water vapor), rather than to the mass or volume of the total gas mixture (including the water vapor); the latter is termed "specific humidity".

2.3.1. MIXING RATIO (r)

The mixing ration is the proportion of water vapor expressed in term of mass per unit of mass of dry gas as:

$$r = \frac{m_v}{m_a}$$

where r is the mixing ratio,

m_v = water vapor mass,

m_a= dry air mass.

This ratio is without unit.

2.3.2. SPECIFIC HUMIDITY (q)

The specific humidity is the proportion of water vapor expressed in term of mass per mass of the total gas mixture, as:

$$q = \frac{m_v}{m_v + m_a}$$

where m_v = mass of water vapor,
m_a = mass of dry air.

This ratio is without unit.

2.3.3. ABSOLUTE HUMIDITY (ρv)

The absolute humidity is the proportion of water vapor expressed in terms of mass of water vapor per unit volume.

$$\rho_v = \frac{m_v}{V}$$

where m_v = mass of water vapor,
V = mixture volume (expressed in m3),

ρ_v is expressed in kg/m^3.

2.3.4. VOLUME RATION (x)

In industrial applications the most commonly used units to express humidity as a concentration are parts per million on a volume basis (ppmv) or the ratio of the volume of water vapor to the volume of dry gas.

$$x = \frac{v}{V}$$

where v = water vapor volume (expressed in m3),
V total volume of mixture (expressed in m3),

This ratio is expressed without unit in parts per million on a volume basis (ppmv).

2.3.5. MOLE FRACTION (xv)

The mole fraction x_v of the water vapor of a sample of moist air is defined by the ration of the number of moles of water vapor to the total number of moles of the sample:

$$x_v = \frac{n_v}{n_a + n_v}$$

n_v number of moles of the water vapor,
n_a number of moles of dry air,

This relationship can be expressed in terms of mass and mole as:

$$x_v = \frac{m_v / M_v}{m_v / M_v + m_a / M_a} = \frac{r}{r + \frac{M_v}{M_a}}$$

where M_v is the mole mass of water vapor (18,01528 × 10-3 kg / mole),
M_a is the mole mass of dry air (28,96455 × 10-3 kg / mole).
m_v is the water vapor mass,
m_a is the dry air mass

Then,

$$x_v = \frac{r}{r + 0{,}62198}$$

2.4. HYPOTHESIS: IDEAL GAS LAW

Under the hypothesis of the ideal gas law, the previous relationships and definitions could be expressed differently.

Applying the Ideal Gas Law, the Dalton Law can be modified to:

$p = p_a + e$
where p is the total pressure of moist air,
p_a is the partial pressure of dry air $pa = x_a \times p$
e is the partial pressure of water vapor $e = x_v \times p$

2.4.1. ABSOLUTE HUMIDITY (under Ideal Gas Law)

The definition

$$\rho_v = \frac{m_v}{V}$$

can be expressed as:

$$v = \frac{e \times M_v}{R \times T}$$

where e is the partial pressure of water vapor
M_v is the mole mass of water vapor
R is the ideal gas constant
T the thermodynamic temperature of the mixture.

2.4.2. MIXING RATIO (under Ideal Gas Law)

The definition

$$r = \frac{m_v}{m_a}$$

can be expressed as:

$$r = \frac{0.62198 \times e}{P - e}$$

where P is the total pressure
e is the partial pressure of water vapor

2.4.3. SPECIFIC HUMIDITY (under Ideal Gas Law)

The definition

$$q = \frac{m_v}{m_v + m_a}$$

can be expressed as:

$$q = \frac{0{,}62198 \times e}{P - 0{,}37802 \times e}$$

where P is the total pressure
e is the partial pressure of water vapor

2.4.4. VOLUME MASS OF MOIST AIR (under Ideal Gas Law)

Considering a moist air sample at p pressure and T thermodynamic temperature, which volume is V and total mass is m, the volume mass is defined as:

$$\rho = \frac{m}{V}$$

This relationship can be expressed as:

$$\rho = \frac{M_a}{R} \times \frac{(P - 0{,}37802 \times e)}{T}$$

And the virtual temperature can be defined by the following relationship:

$$T_v = \frac{T}{1 - 0{,}37802 \times \frac{e}{P}}$$

The virtual temperature T_v is then defined as the temperature which may be the temperature of an equivalent mass of dry air at the same pressure p when the volume mass is the same as a moist air characterized by a pressure p, a temperature T and a mixing ratio r.

2.4.5. MOLE FRACTION (under Ideal Gas Law)

The definition of water vapor mole fraction:

$$x_e = \frac{v_e}{V}$$

can be expressed as:

$$x_e = \frac{e}{P} = \frac{r}{0.62198 + r}$$

In the same way, the definition of mole fraction of dry air:

$$x_a = \frac{v_a}{V}$$

can be expressed as:

$$x_a = \frac{P - e}{P} = \frac{0,62198}{0,62198 + r}$$

where P is the total pressure
e is the partial pressure of water vapor

2.5. SATURATION

Moist air at a given temperature and pressure is said to be saturated if its mixing ratio is such that the moist can co-exit in neutral equilibrium with an associated condensed phase (liquid or solid) at the same temperature and pressure, the surface of separation being plane.

In other terms, this means that the quantity of water vapor inside air at a given pressure and temperature can not exceed a certain value after which every quantity of water will ever appears in condensed phase (liquid or solid). When this value is reached, air is said to be saturated.

2.5.1. SATURATION MIXING RATIO (under Ideal Gas Law)

The symbol r_w denotes the saturation mixing ratio of moist air with respect to a plane surface of associated liquid phase.
The symbol r_i denotes the saturation mixing ratio of moist air with respect to a plane surface of associated solid phase.

Remark: the associated liquid and solid phases referred to consist of almost pure water and almost pure ice, respectively, there being some dissolved air in each.

$$r_w = \frac{0{,}62198 \times e_w}{p - e_w} \qquad r_i = \frac{0{,}62198 \times e_i}{p - e_i}$$

where $p > e_w$ and $p > e_i$ at a given temperature T.

2.5.2. MOLE FRACTION OF WATER IN MOIST AIR SATURATED WITH RESPECT TO WATER OR ICE

The mole fraction of water vapor in moist air saturated with respect to water (similarly ice) at pressure p and temperature T, is the mole fraction x_{vw} (similarly x_{vi}) of the water vapor sample of moist air, at the same pressure p and the same temperature T, that is in stable equilibrium in the presence of a plane surface of water (similarly ice) containing the amount of dissolved air corresponding to equilibrium.

$$x_{vw} = \frac{r_w}{\frac{M_v}{M_a} + r_w} = \frac{r_w}{0{,}62198 + r_w} \qquad x_{vi} = \frac{r_i}{\frac{M_v}{M_a} + r_i} = \frac{r_i}{0{,}62198 + r_i}$$

These relationships are always true and do not need the hypothesis of Ideal Gas Law.

2.5.3. SATURATION VAPOUR PRESSURE OF MOIST AIR

In reality, moist air is not completely an ideal gas, so the product $x_v \times p$ is not truly equal to the vapor pressure e.

A new coefficient is then defined. The saturation vapor pressure with respect to water e_w' (similarly ice e_i') of moist air at pressure p and temperature T is defined by:

$$e_w' = x_{vw} \times p = \frac{r_w}{0{,}62198 + r_w} \times p$$

Similarly:

$$e_i' = x_{vi} \,.\, p = \frac{r_i}{0{,}62198 + r_i} \times p$$

2.5.4. SATURATION VAPOR PRESSURE IN THE PURE PHASE

The saturation vapor pressure e_w of pure water vapor with respect to water (similarly ice) is defined as the vapor pressure when in a state of neutral equilibrium with a plane surface of pure water (similarly ice) at the same temperature and pressure.
e_w is only dependent on temperature:

$$e_w = e_w\,(T)$$

Similarly

$$e_i = e_i\,(T)$$

Tables are generally used to calculate the saturation vapor pressure in pure phase with respect to water or ice.
These tables are computed with Sonntags relationship:

- Saturation vapor pressure in pure phase in respect to water

  $\ln(e_w) = -6096{,}9385\times T^{-1} + 16{,}635794 - 2{,}711193\times 10^{-2}\times T + 1{,}673952\times 10^{-5}\times T^2 + 2{,}433502\ \ln(T).$

  $173{,}15 \leq T \leq 373{,}15$

- Saturation vapor pressure in pure phase in respect to ice

  $\ln(e_i) = -6024{,}5282\times T^{-1} + 24{,}7219 + 1{,}0613868\ 10^{-2}\times T - 1{,}3198825\times 10^{-5}\times T^2 - 0{,}49382577\ \ln(T).$

  $173{,}15 \leq T \leq 273{,}16$

T is expressed in respect to EIT 90 scale, e_w (T) and e_i (T) are expressed in hPa.

2.5.5. RELATIONS BETWEEN SATURATION VAPOR PRESSURE OF THE PURE PHASE AND OF MOIST AIR

e_w' is a weak function of *p* and *T*, e_w is only dependent on *T*.
Similarly, e_w' is dependant on p and *T*, e_w is only dependent on *T*.

The ratio f_w (p,T) is defined as:

$$f_w(p,T) = \frac{e_w'}{e_w}$$

Similarly

$$f_i(p,T) = \frac{e_i'}{e_i}$$

f_w (p,T) and f_i (p,T) are called ″enhancement factor of saturation vapor pressure″.

These ratio are expressed without unit.

For the current use in meteorological condition of pressure and temperature, the enhancement factors f_w and f_i are about 1 and are omitted. For meteorological use, error is less than 0.5 % more or less.

$e_w' = e_w$
$e_i' = e_i$

Tables are generally used to calculate the enhancement factor of saturation vapor pressure.

But at high pressure, the correction due to the enhancement factor becomes quickly very important (about 4 % at 1 MPa and 10 % at 3 MPa).

2.6. THERMODYNAMIC DEW-POINT TEMPERATURE (T_d)

T_d of moist air at pressure p and with mixing ratio r is the temperature at which moist air, saturated with respect to water at the given pressure, has a saturation mixing ratio r_w equal to the given mixing ratio r.
So, the dew-point temperature is given by the relationship:

$r = r_w (p,Td)$

2.7. THERMODYNAMIC FROST-POINT TEMPERATURE (T_f)

T_f of moist air at pressure p and with mixing ratio r is the temperature at which moist air, saturated with respect to water at the given pressure, has a saturation mixing ratio r_w equal to the given mixing ratio r.
So, the frost-point temperature is given by the relationship:

$r = r_i (p,T_f)$

2.8. RELATIONSHIPS BETWEEN DEW- AND FROST-POINT TEMPERATURE AND MIXING RATIO

Taking into account the previous definitions, the dew-and frost-point temperature can be expressed in respect to the mixing ratio and the total pressure as:

$$e'_w(p,Td) = \frac{r_w}{0{,}62198 + r_w} \times p = x_{vw} \times p$$

$$e'_w(p,Td) = f_w(p,Td) \times e_w(Td)$$

Similarly,

$$e_i'(p,Tf)=\frac{r_i}{0.62198+r_i}\times p=x_{vi}\times p$$

$$e_i'(p,Tf)=f_i(p,Tf)\times e_i(Tf)$$

2.9. RELATIVE HUMIDITY U_w (with respect to water)

The relative humidity U_w with respect to water of moist air at pressure p and temperature *T* is the ratio in per cent of the vapor mole fraction x_v to the vapor mole fraction x_{vw} which the air would have if it were saturated with respect to water at the same pressure p and temperature *T*. Accordingly:

$$U_w=100\times\left(\frac{x_v}{x_{vw}}\right)_{p,T}=100\times\left(\frac{e'}{e_w'}\right)_{p,T}=100\times\left(\frac{e'}{f_w\times e_w}\right)_{p,T}$$

$$U_w=100\times\frac{f_w(p,Td)\times e_w(Td)}{f_w(p,T)\times e_w(T)}$$

U_w is also related to the mixing ratio *r* by :

$$U_w=100\times\frac{r}{r_w}\times\frac{0,62198+r_w}{0,62198+r}$$

where r_w is the saturation mixing ratio at the pressure and temperature of the moist air.

2.10. RELATIVE HUMIDITY U_i (with respect to ice)

The relative humidity U_i with respect to ice of moist air at pressure p and temperature *T* is the ratio in per cent of the vapor mole fraction x_v to the vapor mole fraction x_{vi} which the air would have if it were saturated with respect to water at the same pressure p and temperature *T*. Similarly:

$$U_i=100\times\left(\frac{x_v}{x_{vi}}\right)_{p,T}=100\times\left(\frac{e'}{e_i'}\right)_{p,T}=100\times\left(\frac{e'}{f_i\times e_i}\right)_{p,T}$$

$$U_i=100\times\frac{f_i(p,Tf)\times e_i(Tf)}{fi(p,T)\times e_i(T)}$$

For meteorological use, most hygrometers, which are essentially responsive to the relative humidity, indicate relative humidity with respect to water at all temperatures.

2.11. THE THERMODYNAMIC WET-BULB TEMPERATURE

The thermodynamic wet-bulb temperature of moist air at pressure *p*, temperature *T* and mixing ratio *r* is the temperature T_w attained by the moist air when brought adiabatically to saturation at pressure *p* by the evaporation into the moist air of liquid water at pressure *p* and temperature T_w and containing the amount of dissolved air corresponding to equilibrium with saturated air of the same pressure and temperature.

If dry air and water vapor are regarded as ideal gases with constant specific heats, the relationship between the temperature *T* and the wet-bulb temperature can be expressed as:

$$T - T_w = \frac{[r_w(p,T_w) - r]L_v(T_w)}{c_{pa} + rc_{pv}}$$

where $L_v(T_w)$ is the heat of vaporization of water at temperature T_w

c_{pa} is the specific heat of dry air at constant pressure

c_{pv} is the specific heat of water vapor at constant pressure.

2.12. THE THERMODYNAMIC ICE-BULB TEMPERATURE

Similarly, the thermodynamic ice-bulb temperature of moist air at pressure *p*, temperature *T* and mixing ratio *r* is the temperature T_i attained by the moist air when brought adiabatically to saturation at pressure *p* by the evaporation into the moist air of solid water at pressure *p* and temperature T_i and containing the amount of dissolved air corresponding to equilibrium with saturated air of the same pressure and temperature.

If dry air and water vapor are regarded as ideal gases with constant specific heats, the relationship between the temperature *T* and the wet-bulb temperature can be expressed as:

$$T - T_i = \frac{[r_i(p,T_i) - r] \times L_s(T_i)}{c_p + r \times c_{pv}}$$

where $LS_v(T_i)$ is the heat of vaporization of water at temperature T_w

c_{pa} is the specific heat of dry air at constant pressure

c_{pv} is the specific heat of water vapor at constant pressure,

$r_i\ (p,T_i)$ is the mixing ratio of saturated moist air at pressure *p* and temperature T_w

2.13. RELATIONSHIP BETWEEN THE THERMODYNAMIC WET-BULB TEMPERATURE AND THE DEW-POINT TEMPERATURE

Considering above relationships, the dew-point temperature and the thermodynamic wet-bulb temperature are related to the following relationship:

$$e' = e_w'(p,T_d) = ew'(p,T_w)-A \times p \times (T-T_w)$$

where e' is the partial pressure of water vapor,
e_w' (p,T_w) is the saturation vapor pressure at wet-bulb temperature,
T is the temperature,
T_w is the wet-bulb temperature
A is the psychrometric coefficient.

3. REFERENCES

Mainly, definitions are extracted from these references:

- World Meteorological Organization
  Règlement technique - document de base n° 2 - OMM n° 49
  Appendices A et B - Edition 1984

- Fundamental Concepts and Definitions Relating to Humidity
  L. P. HARRISON
  Humidity and Moisture - ISA

- Vapor Pressure Formulation for Water in Range 0°C to 100°C
  A Revision - Arnold WEXLER
  JOURNAL OF RESEARCH of the National Bureau of Standards - A Physics and Chemistry Vol 80A - Nos 5 and 6 - September-December 1976

- Vapor Pressure Formulation for Ice
  Arnold WEXLER
  JOURNAL OF RESEARCH of the National Bureau of Standards - A Physics and Chemistry - Vol 81A - No 1 - January-February 1977

- A correlation for the Second Interaction Virial Coefficients and Enhancement Factors for Moist Air
  R.W. HYLAND
  JOURNAL OF RESEARCH of the National Bureau of Standards - A Physics and Chemistry - Vol 79A No 4 - July-August 1975

- Mesures des paramètres hygrométriques
  Recommandation RM AERO 808 01
  Bureau de Normalisation de l'Aéronautique et de l'Espace

METROLOGICAL WORKSHOP

HUMIDITY MEASUREMENT

October 2005

SOMMAIRE

1 GENERAL

The measurement of atmospheric humidity is an important requirement of most physic, chemical or biological process. To better deal with this process, the humidity measurement must be adapted to the appropriate application.

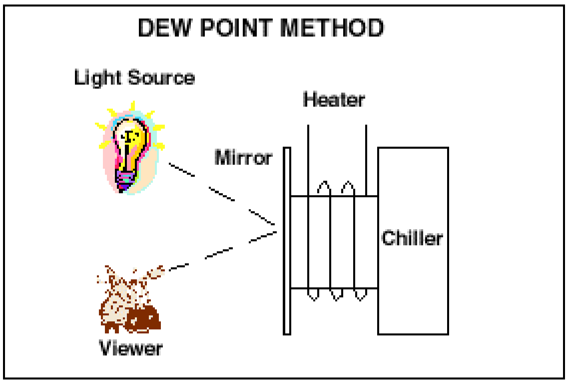
It is important to remember that humidity measurement is complex because it is implying a lot of physic parameters and so a perfect process management is needed.

2 DEW OR FREEZING POINT TEMPERATURE MEASUREMENT

2.1 CONDENSING HYGROMETER

2.1.1 PRINCIPLE

Dew point hygrometers are primary instruments. These hygrometers utilize a cooled area to directly measure that temperature at which the vapour adjacent to a surface of water is in equilibrium with the vapour in the sample gas. This is the dew point temperature of the gas. The surface is maintained at the temperature where the rate of evaporation from the surface water or ice is equal to the rate of condensation. There is a known hysteresis or dead band phenomenon associated with the evaporation or condensation of water, so that any change in surface humidity, however slight, will immediately upset the equilibrium condition and begin to increase or decrease the mass of water present on the surface.



2.1.2 RANGE

Dew point hygrometer are available to measure freezing point or dew point from -90 °C to +100 °C.

2.1.3 TECHNICAL DESCRIPTION

Nowadays, system are composed of:

- A thermoelectrically cooled mirror (Peltier effect),
- A detection unit, typically the detection is optical. A light beam is emitted to the mirror; the reflectance is electronically measured. Other detection unit such as ultra sounding system is now available,
- A temperature control, so when the mirror is exposed to a flow of gas containing some amount of water vapour, it is cooled until enough water is condensed out of the gas stream to achieve the dew point,
- A thermometer to measure the mirror temperature which appears to be the dew point temperature,
- An optical system to the operator.

These instruments are used with some accessories, such as pomp, flow meter…).
Some sensors are available to specifically meteorological measurements.

2.1.4 MAIN METROLOGICAL CARACTERISTICS

- Dew or freezing point temperature measurement uncertainty for laboratory instrument: from ± 0,1 °C to ± 0,5 °C,
- Cooling mirror system (Δt @ 25 °C): 45 °C to 95 °C (4 level unit),
- Fidelity: about ± 0,05 °C,
- Typical use temperature: from - 20 °C to + 60 °C.

2.1.5 STRENGTHS AND WEAKNESSES

- Direct measure of a fundamental parameter,
- Could be used as a standard,
- Reliable,
- But expensive,
- Important response delay,
- Affected by pollution (dust salt…),
- Need a lot of accessories.

2.2 SORPTION HYGROMETER

2.2.1 PRINCIPLE

The principle is based on saturated salt solution property:
At a given temperature, the pressure vapour upon a saturated salt solution is always less than the pressure vapour upon pure water.
The electrical power is going through a saturated salt solution only if the pressure vapour of the environment is higher than its own. At the equality, the conductible state comes to none-conducting state.

2.2.2 TECHNICAL REALISATION

The sensor is composed of:

- A platinum thermometer covered with a woven glass impregnated with saturated salt solution (generally a lithium chloride solution).
- Two electrodes, rolled around the salt solution, are used for heating.

In operation, the electrical power causes the evaporation by a Joule effect. The solution conductivity is decreasing with the water, theoretically until crystallisation. The equilibrium is obtained between three states (crystallisation, salt solution and water vapour) and the temperature measured at this very moment is related to the dew point temperature.

2.2.3 RANGE

For meteorological use from -20 °C to + 50 °C.

2.2.4 MAIN METROLOGICAL CHARACTERISTICS

- Uncertainty from about ± 0,5 °C to ± 1,5 °C,
- Response time about some minutes (because of the special filter),
- Fidelity ± 0,2 °C to ± 0,4 °C.

2.2.5 STRENGTHS AND WEAKNESSES

- Cheap,
- Easy to be changed,
- Need a permanent power supply,
- Frequent regeneration,
- Systematic error due to the gas flow,
- Equilibrium temperature is related to the ambient temperature.

3 RELATIVE HUMIDITY MEASUREMENT

3.1 MECHANICAL HYGROMETER

3.1.1 PRINCIPLE

One of the properties of the atmospheric water vapour is the modification of some organic or synthetic materials. Then, the length of a natural fibber, such as hair, is related to the moisture of ambient air.

One edge of the sensible element is fixed and the other edge is connected to an amplifying lever and gears, which activate a mechanical pointer, by rotation or translation. This system is used on autonomous hygrometers.

Some mechanical hygrographs had a recording part.

3.1.2 RANGE

It allows measurement of relative humidity from 20 % to 100 % hr at ambient temperature between - 10 °C and + 40 °C.
Generally hygrograph uses a weekly record.

3.1.3 STRENGTHS AND WEAKNESSES

- Not expensive,
- Good aspect of the tendency,
- Not reliable,
- Response time is high,
- Very sensible to transportation,
- Not so easy to be calibrated.

3.2 IMPEDANCE HYGROMETER

3.2.1 PRINCIPLE

The sensible sensor is made of some hygroscopic materials, which have the property of being in hygrometric equilibrium with the surroundings. The water content changes the electrical characteristics of the sensible sensor, such as capacitance or resistance.
A measuring transducer changes the electrical quantity into a signal related to the relative humidity. Due to the principle used, it is necessary to know for every sensor the relationship between the capacitance or resistance and the relative humidity measured.
Both resistance and capacitance hygrometers exist.

3.2.2 RANGE OF CAPACITANCE HYGROMETERS

The complete range covers all of a part of the entire domain from 5 % to 95 %. And even up to 100 % at temperature between -40 °C and + 50 °C.
These sensors are limited in use by the absorbing capacity of the used materials. In practice, the using limit is equal to a mixing ratio which value is between 0.1 and 1.4.

3.2.3 METROLOGICAL CHARACTERISTICS

- Typical uncertainty is about ± 2 % (a constant temperature) up to ± 5 %. Generally, those sensors are sensible to temperature and a correction must be applied to the measurement. This could also be implemented in the measuring transducer,
- Response time is about 10 seconds (a little bit more is used with a protection filter),
- Long-term drift is about 1 % to 2 % per year.

3.2.4 STRENGTHS AND WEAKNESSES

- Transparent instrument,

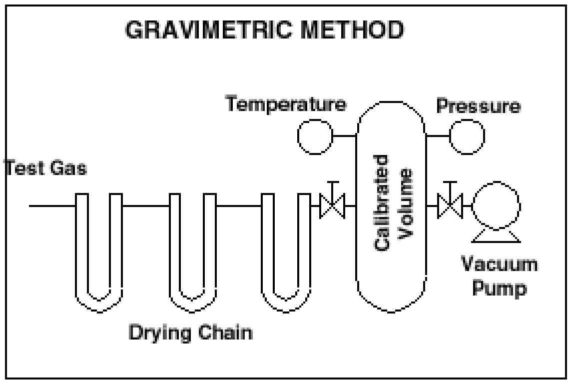
- Display directly the relative humidity,
- Low cost of the hygrometer and the sensible sensor.
- Could be handled,
- Some hygrometers have an important drift if used at or near the saturation point
- Some precautions during the stocking period
    - Drying material,
    - Sometimes a regeneration is needed,
- Sensible to polluted atmosphere.

4 OTHER HYGROMETERS

4.1 GRAVIMETRIC HYGROMETER

4.1.1 PRINCIPLE

The water vapour contained in a moist air sample is absorbed by a drying material, such as $Mg(ClO_4)_2$ and P_2O_5) then the material is weighted. The dry air mass is determined with pressure, temperature and volume measurements.



It is a reference measurement, which allows obtaining the best uncertainties.

The current state-of-the-art in a precision humidity instrument is the gravimetric hygrometer developed and maintained by the National Bureau of Standards. The gravimetric hygrometer yields a determination of absolute water vapor content, since the weight of the water absorbed and the precise measurement of the gas volume associated with the water vapor determines the absolute humidity of the incoming gas.

In this system, a test gas is pumped from a humidity generator through a drying train and a precision gas volume measuring system contained within a temperature-controlled bath. The precise measurements of the weight of water absorbed from the test gas and the associated volume of gas as measured at closely controlled temperature and pressure, accurately define the absolute humidity of the test gas in units of weight per unit volume. When used as a calibration instrument the same test gas is also supplied to an instrument under calibration. This system has been chosen as the primary standard because the required measurements of weight, temperature, pressure and volume can be made with extreme precision. The gravimetric hygrometer is a rather unwieldy instrument to use, and in the low humidity ranges may require up to 30 hours per calibration point. For this reason, the gravimetric hygrometer is not used for normal measurement purposes and would not be useful for industrial measurement or control.

4.1.2 RANGE

At NIST, the system could obtain measurements at freezing or dew point between - 80 °C to + 80 °C, with a dry temperature from - 30 °C to + 50 °C. Uncertainty obtained is lower than ± 0.03 °C.
But in practice it is reserved to very high-level laboratories (NIST…)

4.2 PSYCHROMETER

4.2.1 PRINCIPLE

Psychrometers principle is based on relationship between dry and wet temperatures.
The simplest psychrometer consists of two thermometers mounted together. One thermometer is ordinary. The other has a cloth wick over its bulb and is called a wet-bulb thermometer.
The wick is wet by water (pure water is recommended), so the water evaporates from the wick, cooling the wet-bulb thermometer. Then the temperatures of both thermometers are read.
If the surrounding air is dry, more moisture evaporates from the wick, cooling the wet-bulb thermometer more so there is a greater difference between the temperatures of the two thermometers. If the surrounding air is holding as much moisture as possible - if the relative humidity is 100% - there is no difference between the two temperatures.

4.2.2 RANGE

Psychrometers are used from 0 °C to + 60 °C for meteorological instruments.
Uncertainty on humid temperature is about ± 0,2 °C to ± 1 °C.
A lot of type of psychrometers is also used. But to give satisfying measurements, the wet-bulb thermometer must be ventilated, such as Assmann psychrometer (electrically or mechanically ventilated) or a sling psychrometer

4.2.3 STRENGTHS AND WEAKNESSES

- Simple to use (with some precautions),
- Stable in time,
- Big range of use (but not so easy at low humidity level),
- Need an instrument calibration to determine the thermometers correction but also the psychrometric coefficient,

- Maintenance even neglected but needed,
- Uncertainty related to the used process.

4.3 IR ABSORPTION HYGROMETER

Absorption of infrared light by water molecule in this domain from 1,4 to 1,9 µm.
Some models exist (type COSMA, gaseous filter correlation, two wavelengths beam…).
With some instruments, the beam goes alternatively through a measuring cell and a reference cell, and then both measurements are compared.
The measuring range is variable from vapour trace to 90 % relative humidity.
Generally, these instruments are used in labs.

4.4 LYMAN ALPHA HYGROMETER

The ultraviolet (121.6 nm) light is absorbed by water vapour molecules.
This instrument consists of a light (discharge hydrogen lamp) and a UV detector.
This kind of instrument is built to detect very fast humidity variations. Its response time is measured in milliseconds.
For absolute measurement, it should be calibrated against a reference hygrometer.

5 BIBLIOGRAPHY

- MESURE DES PARAMETRES HYGROMETRIQUES
  Recommandation RM. Aéro 808 01 (1988)
  BUREAU DE NORMALISATION DE L'AERONAUTIQUE ET DE L'ESPACE

- NORME NFX 15 - 111
  MESURE DE L'HUMIDITE DE L'AIR
  GENERALITES SUR LES INSTRUMENTS DE MESURE
  GUIDE DE CHOIX

AFNOR 1993

- NORME NFX 15 - 112
  MESURE DE L'HUMIDITE DE L'AIR
  HYGROMETRES A CONDENSATION
  AFNOR

- NORME NFX 15 - 113
  MESURE DE L'HUMIDITE DE L'AIR
  HYGROMETRES A VARIATION D'IMPEDANCE
  AFNOR

- GUIDE DES INSTRUMENTS ET DES METHODES D'OBSERVATION METEOROLOGIQUES
  SECRETARIAT DE L'ORGANISATION METEOROLOGIQUE MONDIALE
  OMM N°8 - Cinquième édition (1990)
  GENEVE -SUISSE

- CIAME
  ESSAIS D'EVALUATION DES HYGROMETRES
  METHODES ET PROCEDURES
  LA DOCUMENTATION FRANCAISE - PARIS 1980

TRAINING MATERIAL ON METROLOGY AND CALIBRATION

1. Vocabulary used in Metrology
2. Measurement Statistics
3. Theoretical Guide to Measurement Uncertainty
4. Metrology of Temperature
5. Metrology of Humidity

6. Metrology of Pressure

7. Metrology organization in Météo-France

WORKSHOP ON METROLOGY

PRESSURE MEASUREMENT

OCTOBRE 2005

1 CONCEPTS, TERMS AND DEFINITIONS

Pressure is generally the result of molecules impacting on their surroundings. Its magnitude depends on the force of impacts over the defined area.

The relationship between pressure (p), force (F) and area (A) is given by:

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

Atmospheric pressure is the force (F) exerted on a surface of unit area (A) caused by earth's gravitational attraction of the air vertically above that area. It is transmitted equally in all directions within the air and may be measured by a variety of techniques.

Atmospheric pressure decreases with increasing altitude. At the top a mountain, the remaining column of air above us is smaller and the acceleration due to gravity is less, so atmospheric pressure is less.

Pressure unit: **pascal (Symbole Pa)** – which is a 1 N (Newton) force applied to a 1 square meter (1 m^2).area. It is a unit derived from the SI system.

The relationship between the Pascal and some other pressure units are shown in Table 1, but note that not all are or can be expressed exactly.

UNIT	Symbol	Number of pascals
Pascal	Pa	1
Bar	bar	1. 10^5 (exactly)
Millibar	mbar	100 (exactly)
Hectopascal	hPa	100 (exactly)
Millimetre of mercury	mmHg	133.322…
Inch of mercury	inHg	3 386.39…
Inch of water	inH_2O	248.6… to 249.1…
Torr	torr	101 325/760 (exactly)
Kilogram-force per square centimeter	kgf/cm^2	98 066.5 (exactly)
Pound-force per square inch	Lbf/in^2	6 894.76…

Table 1: relationship between Pascal an other used commonly used.

2 PHYSICAL PRINCIPE

A number of quite different principles are utilised in pressure measuring instruments. Some of these are fundamental in character such as measuring height of a liquid column of known density.

2.1 Liquid column instruments

One of the earliest pressure measurement, and still one of the most accurate today, liquid columns are based on the ability of a compressed medium force liquid up a tube.

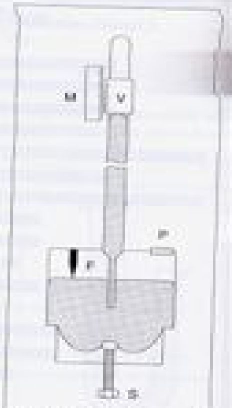


Figure 5-4 Fortin barometer
Key: F, fiducial point;
M, mainscale;
P, porous material;
S, screw; V, vernier

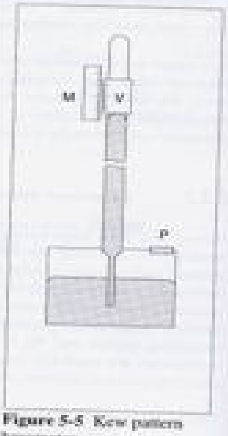


Figure 5-5 Kew pattern barometer
Key: M, mainscale;
P, porous material;
V, vernier

The pressure p, at the lower liquid surface is given by:

$$p = \rho \times g \times h$$

where h is the vertical height of liquid column above the datum level, ρ is the density of the liquid and g is the local value of acceleration due to gravity.

Mercury, water and oil are used in various design of manometer, although for barometric purposes mercury is always used; its density is over 13 times greater than that of water or oil and thus, for a given pressure, it requires a much shorter column –about 0.75 m when measuring atmospheric pressure. Typical mercury density is given by: ρ(0 °C, 101325 Pa) = $1{,}359508\ 10^4$ $kg.m^{-3}$.

Individually built large-bore mercury barometers, using a variety of optical, capacitive, ultrasonic or inductive methods detecting the mercury surface positions, are used around the world by national laboratories as primary and national standards. The most accurate mercury columns use large diameter tubes (several tens of millimetres) to reduce capillarity depression of the meniscus and other surface tension effects. They are however the most expensive pressure measuring instruments.

Fortin barometers

Fortin barometers measure pressure over the normal atmospheric range only. The precise amount of mercury in the Fortin barometer is not critical. Atmospheric air enters through a porous material in the cistern lid. Handled properly, though, they are very reliable. Beyond any calibration corrections, corrections for instrument temperature and the local value of gravitational acceleration have to be applied to their Vernier readings.

Kew pattern

One version of a Kew pattern barometer, known as a station barometer, is similar to a Fortin barometer except it has a fixed cistern and to compensate for the varying height of the mercury surface in the cistern, as atmospheric pressure changes the scale is contracted slightly. They use a pressure port and thus do not need total immersion calibration. The amount of mercury in either design of Kew pattern barometer is critical to its operation.

Accuracy obtained:

- Industrial type (pressure range from 20 to 1000 hPa) : accuracy obtained from 0,02 to 0,3 hPa
- Accuracy of a reference mercury barometer (Schwien)) ± (2 Pa + $1{,}4\ 10^{-5}$ p)
- The best national reference for most elaborate barometers: accuracy near $5\ 10^{-6} \times$ P.

2.2 Pressure balances and dead-weight testers

Consisting essentially of finely machined pistons mounted vertically in very close-fitting cylinders, the internal pressure required to support the weight of the rotating piston and associated masses is calculated from the fundamental relationship between three quantities : mass, length and time:

$$P = \frac{mg}{A_e}$$

where m is the mass of the associated masses, g is the local value of acceleration due to gravity and A_e is the effective area of the piston-cylinder combination, taken to be the area bounded by the neutral surface in the fluid between the piston and the cylinder.

Two main forces are existing inside the system:

- The first one is the up force created by the pressure p applied to the affective area A_e:

$$F_1 = p \times A_e$$

A_e: effective area of the piston-cylinder combination.

- The second down force is generated by the masses m situated on the piston's head and submitted to the gravity:

$$F_2 = m_a \times g$$

g: local value of acceleration due to gravity.
m_a: masses corrected by the Archimed's relation.

$$m_a = m \times (1 - \frac{\rho_a}{\rho_m})$$

Pressure measurement is similar to equalize the two forces F_1 and F_2:

$$p = \frac{m \times g}{A_e} \times (1 - \frac{\rho_a}{\rho_m})$$

There is a small gap between the piston and the cylinder and when the piston rotates in the cylinder it is centralised by lateral forces in the pressure medium, thus avoiding contact between the piston and the cylinder.

Masses are generally loaded directly on top of the piston or via an overhanging weight carrier. Non-magnetic stainless steel is the preferred material for masses and weight carrier as it is more stable than other materials, such as brass or cast iron.

Most conventional styles of pressure balances use pistons and cylinders made of hardened and stabilised tool steels or tungsten carbide, which are relatively wear-resistant, as are some newer ceramic components.

Pressures balances are also know as *piston gauges*. When fitted with a means of pressure control, additional pressure ports and masses, the complete system is sometimes known as *dead-weight tester*.

Accuracy obtained:

For industrial pressure balances: from $\pm 10^{-4} \times p$ to $\pm 5\ 10^{-5} \times p$. (sometimes $\pm 2\ 10^{-5} \times p$)

3 DERIVED SYSTEMS

3.1 MECHANICAL DEFORMATION INSTRUMENTS

3.1.1 Mechanical deformation elements

When pressure is applied to a deforming element it will move. There are several techniques to determine the extend of the deflection. These range from mechanical amplification producing a visible deflection of a pointer or light beam to electronic detection methods.

3.1.2 Diaphragms

A membrane attached to a rigid surround will be subjected to a force if a difference in pressure exists between each side. The pressure difference will produce a deflection of the diaphragm with a maximum deflection at the centre (typically the diaphragm is circular) and this deflection can be measured with a variety of mechanical and electronic sensors. This phenomenon was first employed by Shaffer in the 19th century.
Applications: Beryllium or Inconel X750 diaphragm, silicium diaphragm

3.1.3 CAPSULES

Capsules are made from a pairs of diaphragms joined at their outer edges. Clearly the effect of having two diaphragms acting in series is to double the deflection. More stacks mean more movement but also greater weight and greater instability (especially vibration).

Applications: Vaisala PA11, AIR, NAUDET barometers

3.1.4 Bellows

Bellows have multiple sections, serially stacked, and generally the corrugations are small compared with the diameter. Bellows may be rolled from tube formed under pressure or built up from welded elements. Sometimes there are called capsule stacks.

Application: type 51 Sextant Avionique pressure sensor

3.1.5 BOURDON TUDES

Various design exist but the typical form is a closed tube oval cross-section, curved along is length. When pressurised the tube tends to straighten and the sensor detects this movement. Simple “C”-shape, spiral and helical types are available. Electronic detection of the end movement is commonly used with quartz helix device.

A range of metal, such as iron, steel and brass, and fused quartz are the usual materials of construction.

Application: 6000 Ruska sensor.

3.2 MECHANICAL DEFORMATION SENSING

The nature of the sensing technique and the associated instrumentation will affect the performance of the transducer. There are many combinations of deforming elements and sensing techniques, each will have advantages and disadvantages. The upper pressure limit will generally be determined by the limitations of the moving element, not the sensing technique.

3.2.1 MECANIQUE DISPLAY

These gauges use a direct mechanical display of the movement of a Bourdon tube, a diaphragm or a capsule stack. The movement is transmitted through a connecting rod to an amplifying lever and gears, which activate a mechanical pointer, by rotation or translation. This system is used on autonomous barometers.

The precision aneroid barometer is based on sealed capsule stack. The position is detected by a micrometer, scaled in pressure units, via an amplifying lever. The measurement of the micrometer is obtained by turning the adjusting knob until an electrical circuit indicates the contact.

Applications: aneroid barometer, bourdon tube dial gauge.

3.2.2 CAPACITIVE TECHNIQUES

There are normally used in conjunction with a diaphragm or a capsule, which may form one plate of a capacitor with the pressure containing cover the other plate. That requires that the two parts are electrically isolated and the dielectric properties remain constant. To measure absolute pressures, such as atmospheric pressures, the reference chamber is evacuated. When a pressure is applied to one side, the diaphragm or the capsule deflect, changing the capacitances.

The capacitances may be measured by an AC bridge circuit or a resonant circuit.

Applications: Vaisala PA 11 barometer

3.2.3 LINEAR VARIABLE DIFFERENTIAL TRANSFORMERS (LVDTs)

Linear variable differential transformers (LVDTs) are inductive devices that act position sensors and may be attached to a deflecting component such as diaphragm or bellows. They comprise a cylinder of ferromagnetic material, which is attached to the centre of a diaphragm (capsule) or the end of a bellows. As the magnetic cylinder moves within the tube the magnetic field coupling is changing; with suitable electronics, which may include temperature compensation, a linear relationship between cylinder position and output can be obtained.

3.2.4 STRAIN GAUGES

Strain gauges are essentially devices whose electrical resistance changes when they are strained, by extending or compressing them. The phenomenon of a change in resistivity due to a strain, induced by a mechanical force, is known as piezo-resistivity and is exhibited by most conductors and semi-conductors.

When a metal wire is stretched (strained) it becomes longer and thinner, and its resistance will increase by an amount related to geometry and piezo-resistivity. In this example it can be expressed as:

The gauge factor $k = \dfrac{dR/R}{dl/\ l}$,

dR: resistance variation
dl: length variation due to strain.
R: resistance
L: length.

The gauge factor is very much greater in semi-conductors than in metals –typically 50 much greater- because the piezo-resistive contribution to the gauge factor in semi-conductor is very large. This makes them much more sensitive and suitable for use as strain gauges.

3.2.5 VIBRATING STRUCTURES

Vibrating structures are attached to deflecting elements, such as diaphragms or capsule, in such way that deflection induces a change in their tension/compression thereby changing their resonant frequency. The first type of sensors using this idea employed a thin vibrating wire stretched between, say the end of a bellows or capsule or centre of a diaphragm and a rigid member firmly attached to the base of the bellows or the edges of the capsule or diaphragm.

Application: vibrating ribbon barometer LEEM, PTB 220

3.2.6 PIEZO-ELECTRIC DEVICES

Certain crystal materials when subjected to stress via external pressure develop a voltage across their surfaces. This piezo-electric effect can be used to measure the pressure. Quartz is the main material employed although certain ceramics also exhibit the piezo-electric effect.

Application: Paroscientific sensor.

4 METEO SERVICE AND PRESSURE MEASUREMENT

Each meteorological service has its own selection criteria. They will include many factors, such as metrological, historical and budget terms.

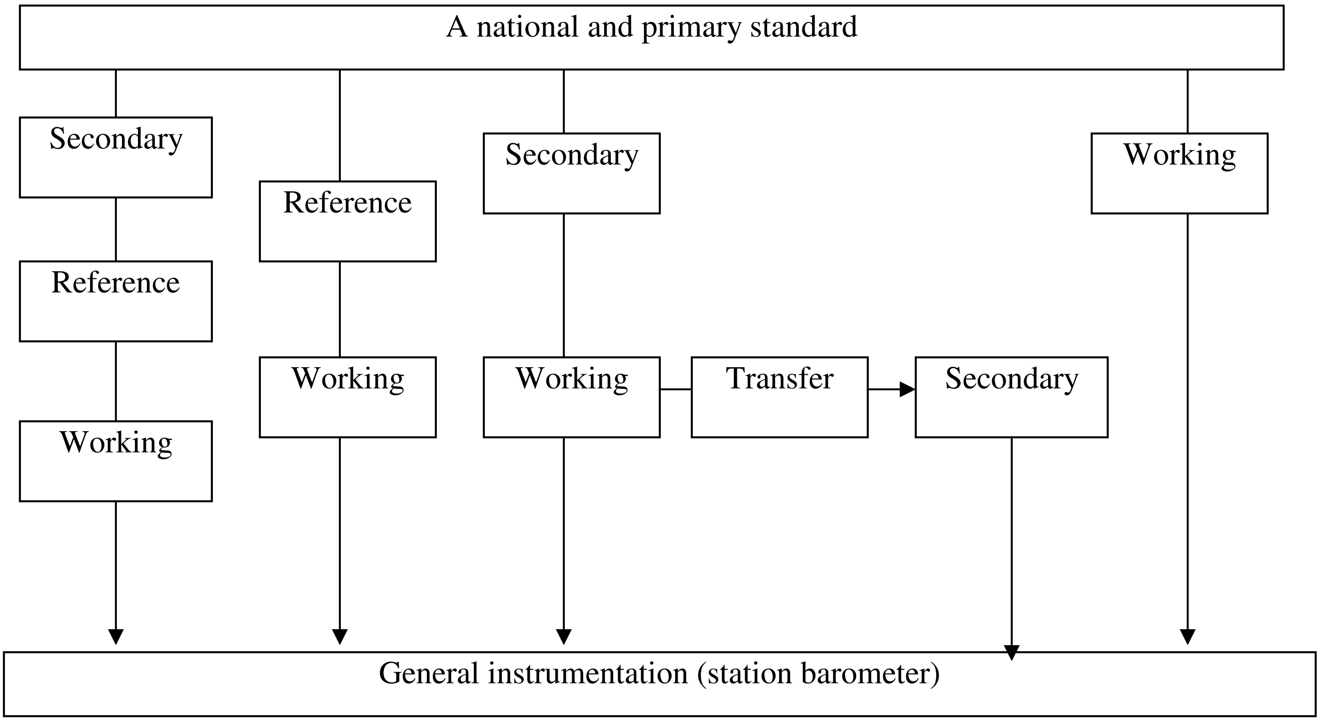
4.1 SENSOR IN USE

Historically, barometric pressure is measured by a mercury barometer or by an aneroid barometer. The reference barometer used is a siphon (U-tube) or a Fortin barometer, the station barometer is Kew-pattern one. Nowadays, electronic devices are required by AWS (Automatic Weather Station).

4.2 CALIBRATION GENERALITIES

The characteristics of the measurement standard should be compatible with both the instrument being calibrated and the associated systems. It used to say that the accuracy of the measurement standard should be about ten times better than the instrument being calibrated. It was a metrological luxurious rule, though and economic arguments reduced the recommended factor to about four – and sometimes one or two, especially in pressure measurement.

There are a lot of terms used to describe the hierarchical relationship of measurement standards and definitions of *national, primary, secondary, reference, transfer and working* standard can be found in the VIM or into CIMO guide.



There are essentially four routes, but whichever way is chosen, the calibrations will only provide traceability if the results are related to stated references, usually national or international standards, through an unbroken chain of comparisons.

4.3 PRESSURE CALIBRATION REQUIREMENTS

The list of items required to undertake calibrations generally includes:

- A suitable environment
- An appropriate standard
- A set of pressure connection
- A method of generating and regulating the pressure
- A system of recording measurements
- A method for calculating results
- A procedure
- Trained staff

4.3.1 Environment

The environment should normally be stable, with minimal vibration and a stage temperature (remember the perfect gas relationship).

4.3.2 Measurement standard

The standard must be traceable to national reference. All corrections needed must be applied (temperature, instrumental, gravity, height…).

4.3.3 Connecting up

Nowadays, the majority of pressure measuring instruments is calibrated by connecting their pressure port to a pressure standard via suitable pipework.

Some instruments, such as mercury or some aneroid barometer or barograph, are total immersion device and have to be calibrated inside a pressure vessel, where the pressure is measured by a standard, which is either inside the vessel too or connected to it via a pipe.

4.3.4 Generating and regulating pressure

They are many ways of generating the required nominal pressure. In all cases, the generator must be qualified in stability. In all calibration applications it is important to ensure that the pressure is held as stable as possible. Perhaps in the presence of small leaks a regulation is required to hold the pressure steady.

4.3.5 Recording measurements

For much calibration work, measurements can be made adequately by eye and recorded by hand. In many situations, however, some degree of automation is possible. Much pressure measuring instrumentation provides electrical outputs, which can easily be connected to a computer for automatic or semi-automatic data logging. The most important point, however, is to have decided in advance which measurements to take and record.

4.3.6 Calculating results

It is obvious, but it is important that the correct calculation is performed.

4.3.7 Procedures

In the same way, calibration procedure must be known by operator. The best way is to write every procedure, but perhaps it is not always realistic.

4.3.8 Trained staff

Both theoretical and practical training are needed for operator and staff management.

5 BIBLIOGRAPHIE

- La mesure des pressions statiques
  J. C. Legras
  Monographie du Bureau National de Métrologie
  Editions Chiron - 1988

- Les capteurs de mesure
  M. Desjardins
  La Documentation Française - 1975

- Guide de choix des instruments de mesure de pression
  Recommandation RM Aéro 802 01 - Janvier 1989
  Bureau de Normalisation de l'Aéronautique et de l'Espace
  Technopolis 54 - 199 rue J. J. Rousseau
  92138 Issy les Moulineaux CEDEX

- Guide des Instruments et des Méthodes d'Observation Météorologique (guide CIMO)
  OMM n° 8 - 1990
  Secrétariat de l'Organisation Météorologique Mondiale
  Genève - Suisse

- Bulletin d'information du Bureau National de Métrologie
  Spécial « Pressions » n° 28
  22 rue Monge
  75005 Paris

- Essais d'évaluation des capteurs de pression (2ème édition)
  Commission Industrie Administration pour la Mesure
  Méthodes et procédures - octobre 1981
  La Documentation Française
  29 - 31 quai Voltaire
  75340 Paris

- Guide to the Measurement of Pressure and Vacuum
  The Institut of Measurement and Control
  87 Gower Street
  London

THE IN SITU PRESSURE CALIBRATION SYSTEM IN MÉTÉO FRANCE

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ABSTRACT :

Surveying and forecasingt the atmosphere’s behaviour is the first vocation of Météo France. The responsability of the observation in Météo France has been entrusted to the Direction of Observation’s Systems (DSO), which manages, in consequence, a network of 600 automatic weather stations. On these 600 stations, more than 300 barometers are installed.

In order to ensure the accordance of the barometers with metrological specifications, they are calibrated every 2 years in the Laboratory of Metrology of the DSO and are controlled in situ once per year. For that, the DSO developped its own in situ pressure calibration system, which is composed of a portable generator and a special software, called LEON SITE. It enables them to easily garantee the traceability chain.

In a first part, we will describe the generator’s running, which was achieved by EFFA. The running is based on the creation into two gasholders of high and low pressure (compared to the ambient pressure). The barometers to compare are connected with the mixer gasholder. The plateau are generated between 800 and 1060 hPa with a stability of 0.03 hPa.

In a second part, we will study the opportunities of the software LEON for the data acquisition and processing. The system enables us to use as reference either the inner barometer or an other reference standard, on condition that it should be calibrated before and after.

Finally, we will present the operational use of this system for Météo France’s network and the usual uncertainty of measurement. For example, countries such as Cuba, Libya or Madagascar or the Asecna organization require the Meteo-France’s support as Regional Instrumentation Center (RIC) to check their barometers in situ with this system.

Next step will be a LEON Software update to take into account the in-situ accreditation criteria and a Multilanguage interface.

TEXT :

1. Specifications

1.1. Description

The whole generator is embedded in a small suitcase in order to make it easy to use and transport.

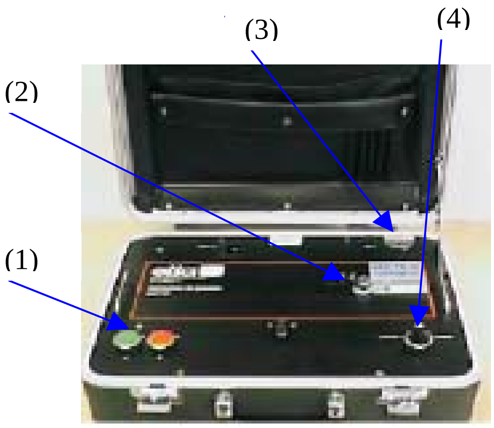


fig.1 : Photo of the generator

- Weight : 8 kG
- Size : 170 x 410 x 300 mm
- Power supply : - 220 V
  - inside lead-acid battery 12V (for an autonomy of 5 hours)

The electrical system and the circuit of gas generation are inside. On the outside, there are impulsive buttons for generation (1), pressure socket (2) and serial interface RS 232 (3) to connect a computer. The switch (4) is used to select the loading, measuring or stop mode.

Every kind of barometers equipped with external pressure fittings can be used.

The generator is also equipped with an internal capacitive barometer, as travelling standard.

1.2. Generation

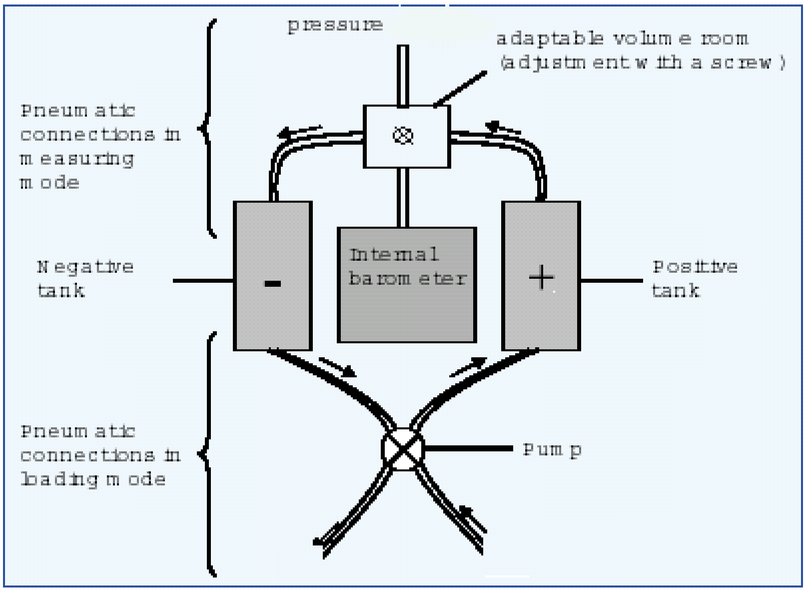


fig.2 : Inside the generator

An electric pump creates in two air tanks high (+400 hpa) and low (-600 hPa) pressure, compared to the ambient pressure. In loading mode, filtered air is pumped to fill the positive tank and some air is expulsed from the negative. In measuring mode, the tanks are driven by electrovalves in order to fill and empty the air circuit. An accurate adjustment of the level of pressure is obtained by changing the volume adjusted by a specific screw. The maximum speed of variation is limited to 4 hPa per second through the pressure range of 600 hPa to 1100 hPa.

2. Calibration principle

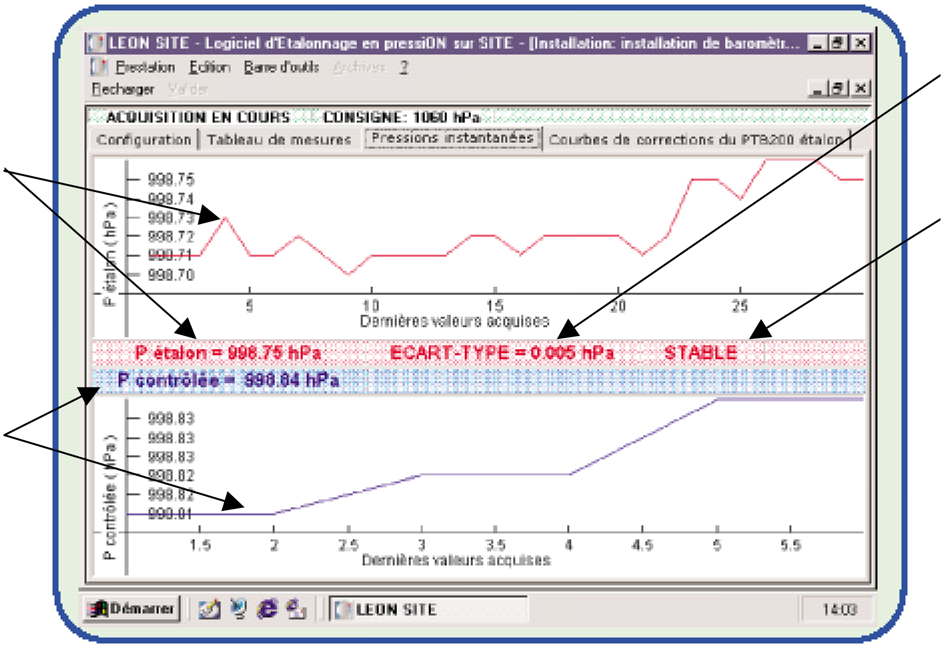
2.1. Operating principle

fig.3 : Complete calibration system

Calibrated barometers are connected with the generator by the pressure socket (fig.1-(2)). The data acquisition and processing is done by a computer, thanks to a calibration software, called LEON.

LEON is a french acronym for Logiciel d'Etalonnage en pressiON. That means Pressure Calibration Software. Figure 3 shows the whole calibration system. The travelling standard is the internal barometer but the software enables the use as standard of either the internal or an other barometer standard.

The operating barometers are checked by a cycle calibration at fourteen pressure values from 1060 hPa down to 800 hPa.



ACQUISITION EN COURS CONSIGNE: 1060 hPa

P étalon = 998.75 hPa ECART-TYPE = 0.005 hPa STABLE

P contrôlée = 998.84 hPa

pressure of the standard

standard deviation

stability under criteria

barometer's pressure

fig.4 : Software LEON

The calibration software, programmed in Delphi® (Pascal), uses serial RS 232 communication but there are manual calibration options too. This software is very useful for the calibration operator. The management of raw and corrected data, reference barometer, working standard and calibrated barometer is simplified.

2.2. Validation of the calibration

This system fulfills the needs of the traceability chain when there is no permanent installations to calibrate automatic weather station network barometers.

To validate in situ measurement, the travelling standard is calibrated before the travel and after the return (The tolerated criteria is 0.03 hPa). That means that the difference between both calibrations must be less than 0.03 hPa This criteria is part of the uncertainty balance.

3. Performance

3.1. Stability

The stability of the generator belonging to the Laboratory of Metrology was studied in July, 2004, to characterize its response time and its range of generation.

The study was led in the laboratory, at the ambient temperature, with an external standard (one of the working standard of the Laboratory of Metrology) at 20 %, 50 % and 80 % of the whole common range (1060 hPa-800 hPa). So the generator was studied from 850 hPa to 1010 hPa down first and from 1010 hpa to 850 hPa up after. Two blank cycles were made before testing.

Once the established working obtained (the standard deviation on the last five measurements is below than 0.01 hPa), one measurement was taken every 5 seconds during one minute.

Here, results are shown:

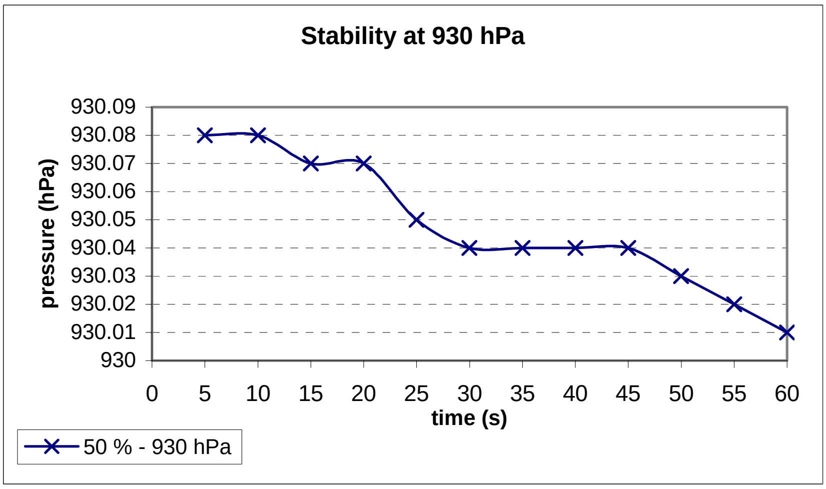


fig.5 : Stability from 1010 hPa to 850 hPa down

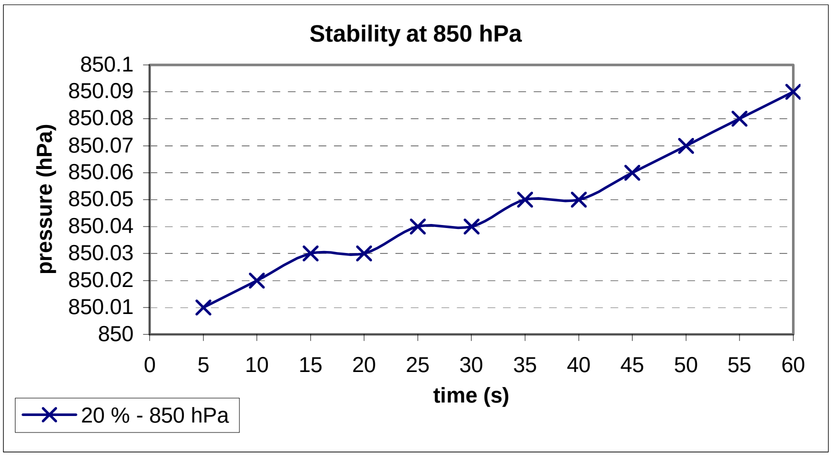


fig.6 : Stability from 1010 hPa to 850 hPa up

During one minute, the generation range is 0.08 hPa in the two cases. The diagrams shows the hysteresis of the generation. It contributes to the uncertainty balance with a component of 2.3 Pa considering a normal distibution law.

3.2. Intercomparison

To study the efficiency of our in situ calibration in pressure, an intercomparison was made with the calibration in laboratory. In our laboratory, we use a PPC 1 generator, with an external standard and special software for data acquisition.

We chose two paroscientific-sensor based barometers among our standards : n°1331, our reference standard, which was considered as the standard, and the n°1332, a working standard, which was considered as the calibrated barometer .

N°1331 was calibrated in October, 2003.
N°1332 was calibrated with LEON in January, 2004, compared to n°1331, in our laboratory. Then, it was calibrated also in our laboratory with our fixed means, in March, 2004, by the same operator and according to the same measurement procedure : two blank cycles, one cycle from 1060 hPa to 800 hPa down, hence fourteen points.

Here the calibration diagram :

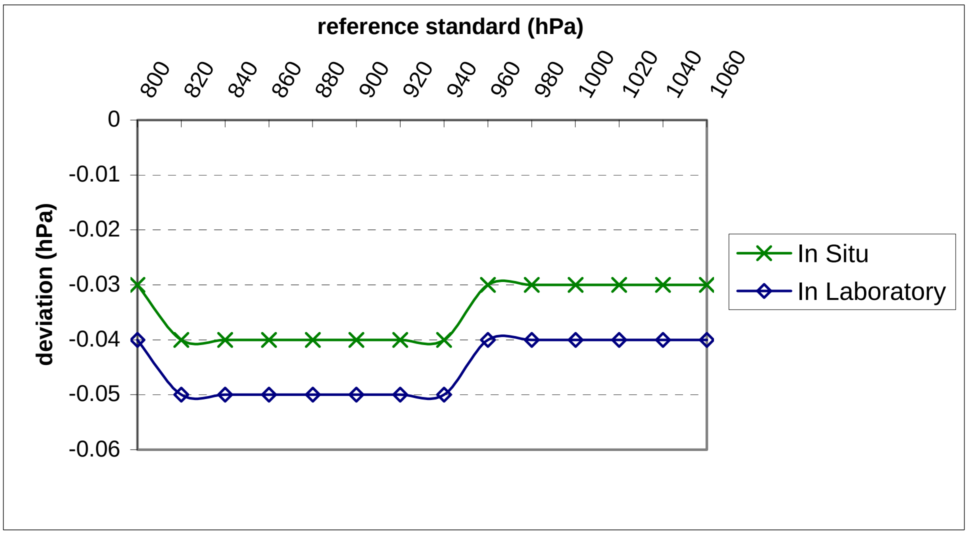


fig.7 : Intercomparison between in situ and in laboratory

The two calibration diagrams are similar on figure 7. The normalised deviation is : 0.08 <<1 so the two calibrations are very coherent.

To conclude, this in situ calibration system is a reliable one, which fulfills the needs of the traceability chain, provided the requirements are satisfied.

It is used by Météo France to check the drift of the french synoptical network operating pressure transmitters in addition to the calibration in the Laboratory of Metrology. This equipment is also used by Asecna, french nuclear plants network or when some countries require Météo France’s support as Regional Instrument Center (RIC) to check their reference barometers (recently Egypt and Algeria).

Next step will be a LEON Software update to take into account the in-situ accreditation criteria.

This step will also include a multiple language setup (French, English, Spanish, Italian and Czech in the first step).

TRAINING MATERIAL ON METROLOGY AND CALIBRATION

7. Metrology organization in Météo-France

Infrastructure and Instruments of a standard laboratory:
Example of the Laboratory of Metrology of Météo France

1. General presentation of the Laboratory of Metrology of Météo France

1.1. Context

The laboratory of metrology is considered as the expert of Météo France for the reference standards in pressure, temperature and humidity. For that, the laboratory defines the methods of calibration.
Part of the Direction of Observing Systems, it is composed of 11 people, whose 9 especially deal with calibration. The laboratory uses 2 rooms with air conditioned to achieve calibrations.

1.2. Infrastructure for temperature

The laboratory uses 2 baths, 2 standards, one used as a reference standard, the other as a working standard (see photo 1), a resistance bridge for data acquisition and a computer dedicated to data processing.
Calibrations are performed from –20 to 40 °c or from –50 to 50 °C.

Photo 1: Baths for temperature calibration

1.3. Infrastructure for pressure

The laboratory uses several standards, one as the reference, the others as working standards, one generator PPC 1, a climatic chamber for temperature tests and a computer dedicated to data processing (see photo 2). Calibrations are performed from 500 to 1060 hPa.

Photo 2: Calibration pressure systems

The laboratory uses an in situ pressure calibration system too. It is composed of a portable generator with its internal transfer standard or it can be used also with an external standard (see photo 3). It works both manually or with a computer for data processing.

Photo 3: In situ pressure calibration system

Calibrations are performed from 800 to 1060 hPa and this system is used in Météo France for the intermediate controls of the network's barometers.

1.4. Infrastructure for humidity

The laboratory has 2 methods to generate humidity, the one at the ambient temperature with satured salt solutions, the other with a bath that generates humidity.

1.4.1. Calibration with satured salt solutions

5 satured salt solutions create 5 levels of humidity according to chemical properties in order to calibrate capacitive hygrometers. The values are read with a multimeter and the calibration is made totally manually. The reference humidity is given by a reference hygrometer.

Photo 4: Satured salt solutions for humidity calibration

1.4.2. Calibration with a generating bath

The bath creates satured air at dew point that a pump makes circulate into a climatic chamber, where the dry temperature is controlled. Relative humidity is also created to calibrate capacitive or dew point hygrometers.

Photo 5: Generating bath of satured air

2. Quality process

Météo France is carrying out a quality process in order to certify all its activities, except research, according to the standard ISO 9001. The laboratory's activities are managed by a quality system, except the training and the in-situ calibration. The traceability chain of our standards meets the requirements of the standard ISO 17025.

2.1. Definitions

In fact, an exchange implies the concept of quality, whose definition is ([1]) :
Ability of internal characteristics to meet requirements.
The objectives are:

- to win the customer's trust (companies, Government...);
- to favour exchanges between laboratories;
- to have a performing management tool.

Quality assurance ([1]):
Part of the quality management system that aims at giving trust in the fact that requirements will be met.

Quality management system ([1]):
Coordinated activities that lead and control an organization for quality, which generally implies to define the quality policy, to formulate the quality objectives, to plan the quality management system and to encourage continual improvement.

2.2. Accreditation ([2])

The international standard ISO/CEI 17025 gives the requirements to meet for the laboratories to prove a work under quality management and technical skills, on the contrary to a certification. The results after a calibration are also more easily exchanged and understood between accredited laboratories or between laboratories that satisfy the ISO/CEI 17025 requirements.
An accreditation means that an institution, taken as the authority, officially recognizes that an organization is competent to achieve specific tasks.
In Europe, accreditation is given by a public utility service, to avoid partial judgment. In France, for example, the accreditation is given by the COFRAC (FRench COmmittee for ACcreditation).
The laboratory of metrology of Météo France has its own quality management system, accredited for humidity, temperature and pressure calibration.

2.2.1. Requirements for accreditation

Requirements of the standard ISO/CEI 17025 deal with both management and technics.

The requirements relative to management are about:

- the general organization of the laboratory;
- the control of documentation;
- the services given to the customers and how they are treated;
- subcontracting;
- purchasing;
- the control of malfunctions;
- the internal audit;
- the review of the laboratory by the direction.

The technical requirements are about:

- the skills of the staff and how to maintain them;
- the facilities and the ambient conditions;
- methods;
- equipment;
- traceability;
- materials handling;
- quality of results.

2.2.2. Details about methods

It is sometimes necessary to describe the methods that have to be validated by giving:

- the application area;
- the parameter to determine;
- the equipment and references;
- the required ambient conditions;
- the process to follow;
- the criteria;
- the data acquisition and processing;
- the uncertainty.

2.2.3. Details about equipment

The equipment that is used should be identified and surveyed thanks to a paper that gives:

- the serial number;
- the manufactory;
- the location;
- the controls that are made or have to be made;
- the care planning;
- the eventual repairs.

2.2.4. Details about certificates

The certificates have:

- a title and a special number;
- the name and address of the laboratory;
- the name and address of the customer;
- the description of the method;
- the description of the object;
- the date;
- the results;
- the conditions;
- the associated uncertainties;

- a sign and seal.

2.3. Certification ([1])

The standard ISO 9001, 2000 versus, specifies the requirements to meet for an organization that:

- must prove its skills to supply product in accordance with laws and with what was agreed with the customer;
- wants to enhance the customer's satisfaction thanks to an effective quality management system.

Certification is given by independent organizations, themselves often accredited. On the contrary to accreditation, there are several organizations in a country.

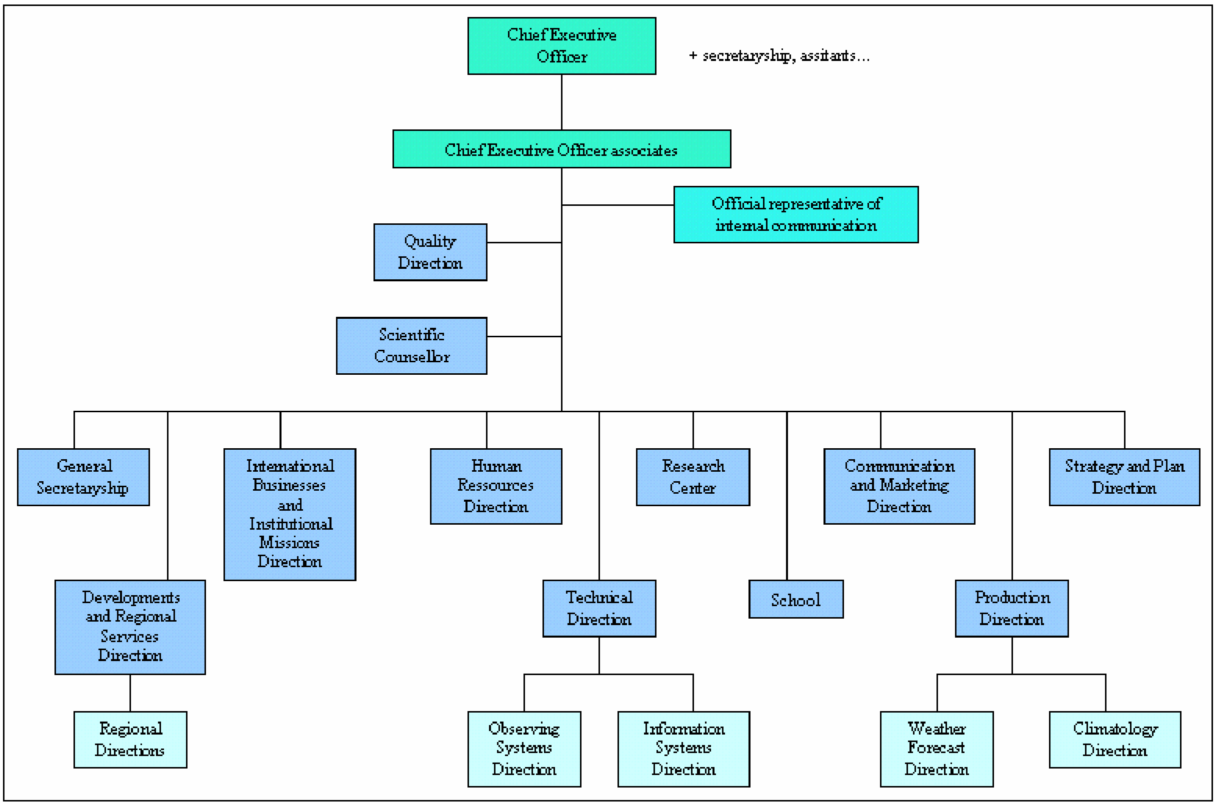
Requirements deal with:

- the quality system;
- the responsibilities of the direction;
- human and material resources management;
- production;
- the improvement process.

3. Metrology's organization in Météo France

3.1. General organization of Météo France

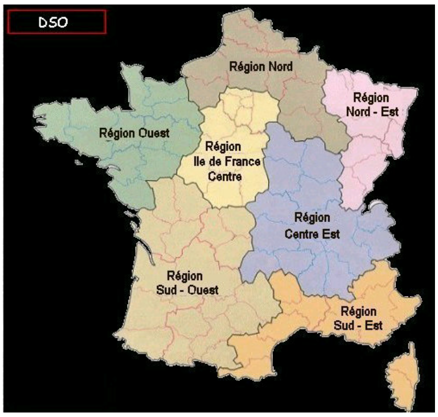
The following diagram sums up the general organization in Météo France, in thematic directions:



Diag. 1: General Organization of Météo France

The Direction of Observing Systems -DSO-, part of the Technical Direction (see Diagram 1), is responsible for weather observation in Météo France, from the design of systems to the supplying in the databasis of the Information Systems Direction -DSI- ([3]).

Some service providers help the DSO to carry out its missions like the DSI or the Regional Directions (see diagram 2).



Diag. 2: Regional Directions

The terms and conditions of services with the Regional Directions are defined in an organization chart and are regularly reviewed thanks to meetings. With the DSI, they are reviewed by the Technical Director, who manages the observation and information policy.

3.2. Metrology in the DSO

A metrology process, according to the certified system ISO 9001, leads the activities of metrology in the DSO.
The objectives of this process are:

- the coherence of the metrology applied to the observing systems;
- the coherence of the metrology applied to the standards or all equipment of control;
- to achieve calibration.

For that, the process gives for each meteorological parameter the periodicity to satisfy to assure the quality of measurement.

Examples of periodicity:
Capacitive hygrometer: from 12 to 15 months
Barometers: from 24 to 30 months
Rain Gauge: 2 controls a year
Anemometer: 1 control a year
These controls or calibrations are both realized in the DSO or in situ when it is possible.

If the sensors have to be calibrated outside the station (in the DSO in the laboratory of metrology for example), the Surface's Observation Department is responsible for the turnover. They give a calibrated sensor in advance and repatriate the former sensor according the diagram 3. They are helped by a specific maintenance software and thanks to their own databasis. The DSO through the department of surface's observation and the laboratory of metrology is managing the survey of the sensors of the Météo France network.

Diag. 3: Exchanges between stations and DSO

BIBLIOGRAPHY:
[1] NF EN ISO 9001, AFNOR, december 2000
[2] NF EN ISO 17025, AFNOR, May 2000
[3] DSO's quality manual, DSO, versus 3, 25th January 2005