METROLOGICAL TRACEABILITY FOR METEOROLOGICAL SENSORS ILLUSTRATED THROUGH EXAMPLES

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Abstract

In the framework of EMRP (European Metrology Research Program) the project “MeteoMet - Metrology for Meteorology” aspires to respond to the questions and needs of meteorological community for traceable measurement and comprehensive in-field uncertainty measurement budgets. The metrological traceability is a property of a measurement result whereby the result can be related to the International System of Units (SI) through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty. To bring this definition into practice the first chain link is the primary reference standard usually maintained in each country by its National Institute of Metrology. The second step in traceability is to compare the instruments to these standards either directly to obtain low calibration uncertainties, or through intermediate secondary standards. This paper explains the primary standards in temperature, humidity and pressure with examples of typical calibration uncertainties at each step in traceability chain, in order to allow instrument’s final users to select an optimal route in accordance with in-situ requested measurement uncertainty.

1. Introduction

Measurements are fundamental to every human activity from trade to science but only have an useful meaning if there is everyone is convinced that the results will not vary with a change of instrument, or operator or any other parameter of the measuring action. This confidence is well established in fields like trade and manufacturing. We all expect to fill our car tanks with the same number of litres of fuel whatever the fuel pump. A manufacturer expects that parts made by different factories in different countries will assemble because their dimensions are in the stated tolerances. This confidence is not based on some invariability of good measurement instruments but on both regulations and international agreements and quality assurance in the measurement process.

It has become a common practice to assess the quality of a measurement by a quantitative statement, the measurement uncertainty associated with the result. The confidence in the value and the stated uncertainty relies on the traceability of measurement involving an unbroken and documented chain linking an internationally agreed measurement standard to the current result. Establishing traceability of measurement for trade, industry and science is the aim of metrology. In practice, a network of national metrology institutes (NMI) maintain and deliver locally the first link in the chain. International equivalence is coordinated by the Bureau International des Poids et mesures (BIPM, www.bipm.org). European NMIs associated inside Euramet organisation (www.euramet.org) have started a global research program (European Metrology Research program – EMRP) co-funded by EU and participant states. EMRP aims at bringing metrological answers to society grand challenges, among them environment; in this frame a consortium of 18 NMIs started the MeteoMet project (www.meteomet.org) to support meteorological community in providing fully trustable measurements, i.e. metrologicaly traceable.

2. What is metrological traceability?

The definition of traceability (as well as other terms in metrology) can be found in the International Vocabulary for Metrology (VIM) [1] : "property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty"

The first step to obtain traceability (figure 1) is to define a reference, internationally accepted. Since 1875 when the Meter Convention was signed, units definitions and their practical realizations are approved by the General Conference on Weights and Measures (CGPM). All members and associates to the Meter Convention (93 states) then agree to implement nationally these references. The practical realization of these definitions is the main task of national metrology institutes. NMis maintain primary standards either by keeping an artifact (as for the kilogram) compared regularly to an international prototype, or reproduce an experiment, following a procedure which will produce a quantity (as for the second realized through cesium transition frequency). To maintain confidence in the international equivalence of the standards, metrology institutes inter-compare them periodically and issue quantitative equivalence statements published on the BIPM key comparisons database (kcdb.bipm.org).

The next chain link(s) aim(s) at transferring the reference from its primary realization to the end users.

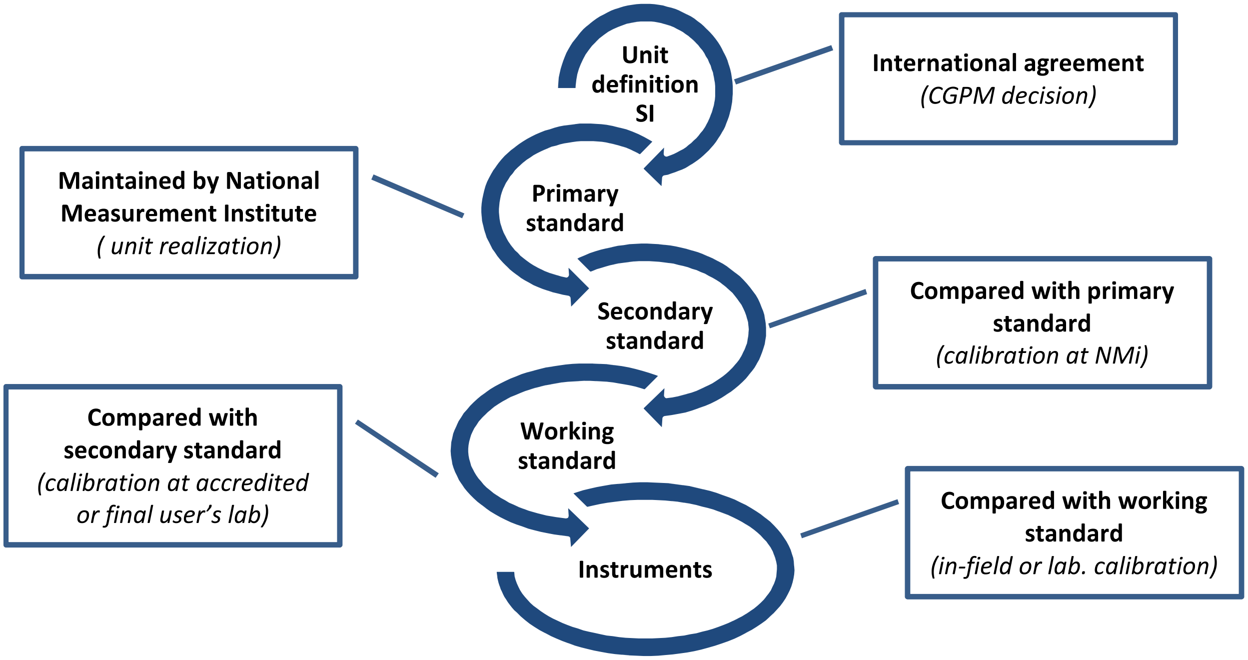

Figure 1. Relating a measurement to a reference through a chain of calibrations.

Till it reaches the final instrument (a mass balance in a shop, a caliper in a factory or the temperature sensor of a weather station) several links might occur. The NMi calibrates a secondary standard which is transferred to a local laboratory. The local laboratory compares it directly to instruments or to working standards.

The second step for traceability foreseen in VIM's definition is to document the unbroken chain of comparisons. Confidence in measurement is achieved only if traceability is proven. The importance of trust in trade and manufacturing uses of measurements has raised the need for a second type of international agreement: mutual recognition of calibration capabilities. The basis of this recognition is the implementation of a quality system in calibration laboratories and the independent verification of the implementation through accreditation. Quality systems accredited under the ISO 17025 standard [2] ensures not only that calibration procedures and methods are appropriate and well executed but also that the documentation requirement is fulfilled.
Therefore the easiest but not mandatory way for the final user to achieve the second requirement for traceability is to have its instruments calibrated by an NMI or an accredited laboratory, depending on their accuracy needs.

Third requirement for traceability is the quantification of the contributions to measurement uncertainty of every link in the chain. As we descend in the traceability chain (figure 1) the measurement uncertainty increases. Each time a comparison with a higher standard takes place, some confidence in the value of the quantity transferred is lost. For example, if we consider a traceability scheme for a temperature sensor as shown in figure 2, to perform a traceable temperature measurement with an associated uncertainty of 0.1 K, the primary standards (fixed points) have to be realized with an uncertainty of 0.1 to 0.6 mK . This level of uncertainty for primary references is available only on very limited temperature ranges.

An important thing that VIM definition recalls is that the traceability and uncertainty refers to a measurement result, not to an instrument. Therefore, the use of a calibrated instrument, related through an unbroken and documented chain of comparisons to a primary reference, is not enough to achieve metrological traceability. Users of the calibrated instrument should finally demonstrate their capability to operate the instrument in order to maintain on long term the confidence in its calibrated indications within the associated uncertainty, i.e. the existence of appropriate validation, intermediate checks and maintenance procedures.

Last but not least it is the instrument user's responsibility to estimate the total measurement uncertainty. Factors that affect the measured value in use, such as environmental changes with regard to the stable laboratory conditions where the instrument has been calibrated, drift in time, operator influence, etc., have to be quantified (and documented) for each measurement. The estimated influences will add to the last calibration chain link value.

To summarize, a measurement has metrological traceability if:

- An unbroken and documented chain of calibrations links the instrument to an internationally agreed reference;
- Each chain link has documented uncertainty estimations;
- The final user has procedures to ensure that the instrument maintains its calibration with associated uncertainties over time;
- The influence factors affecting the measurement are quantified and a total measurement uncertainty is calculated, documented and reported with the result.

Only then, a measurement result can be compared with any other traceable result measured in another place and/or time.

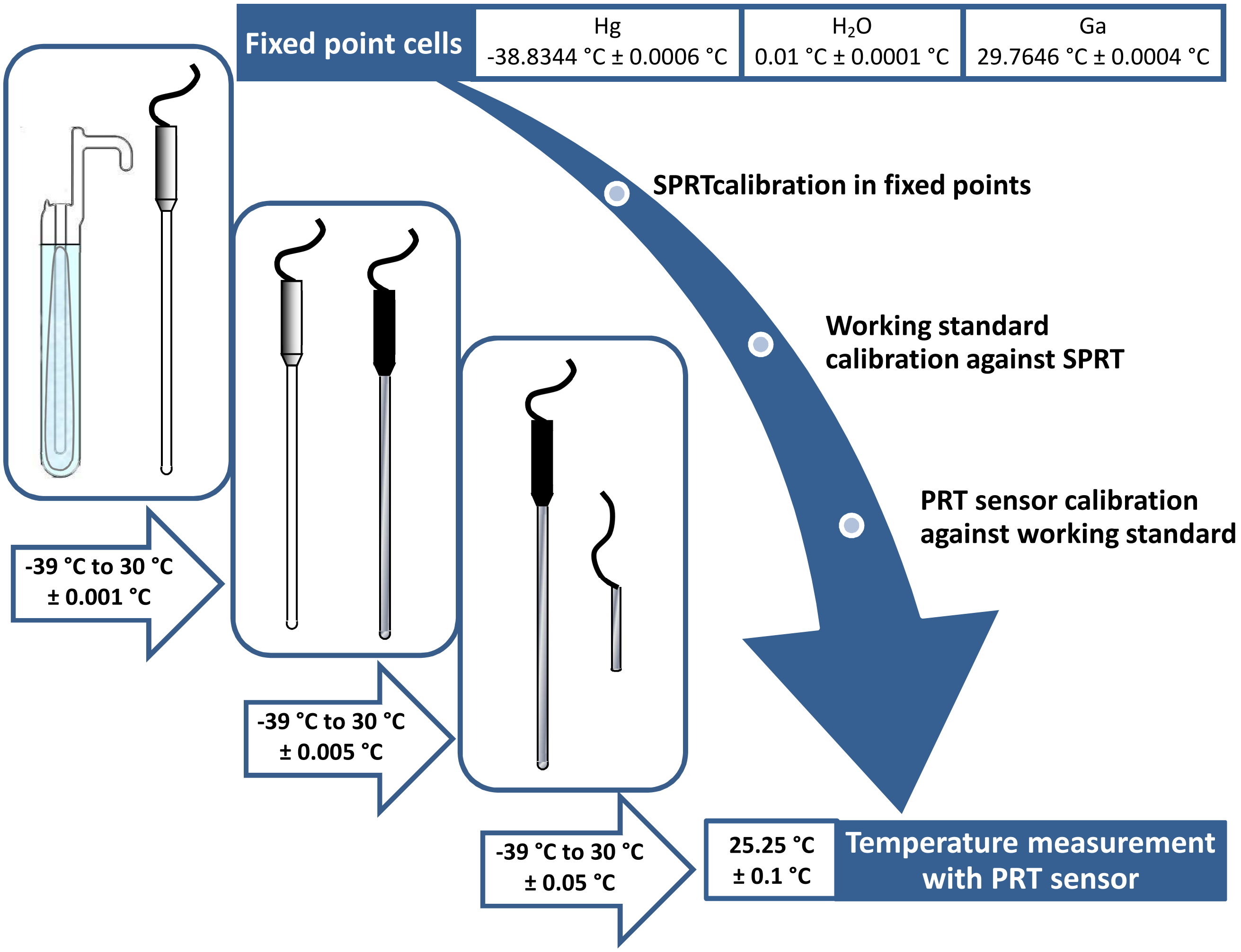

Figure 2. Example of traceability chain for temperature measurement

3. Traceable temperature measurements

The internationally agreed reference for temperature measurements is the International Temperature Scale of 1990 (ITS90) [3]. The physical principle for this reference is phase transition of pure materials. For a given pressure, a pure material undergoes phase transitions (for example melting) at fixed and reproductible temperatures. Primary reference standards for realizing the scale are fixed points cells – carefully manufactured containers of very pure materials, pressure controlled.

The fixed point cells materialize a discrete scale, for a continuous reference a convenient interpolating instrument is used for the major part of the range (from argon triple point, -189.34 ℃ to the silver freezing point 961.78 ℃). It is the long stem standard platinum resistance thermometer (SPRT). The interpolation functions for this type of thermometer are part of ITS-90. Figure 3 shows the lower part of a triple point of water (TPW) cell with a SPRT inserted in the inner

Figure 3. Triple point of water cell and SPRT

well. The last international comparison on triple point of water cells organized by BIPM and published in its database showed that the best uncertainty in a TPW realization is about 60 µK [4].

The first step in the traceability chain is a calibration of a SPRT in selected fixed points according to the user's range.

For measurements of meteorological temperatures, the most useful fixed points are, mercury triple point (-38.83 ℃), water triple point (0.01 ℃) and gallium melting point (2 9.76 ℃).

Establishing traceability routes and unceratinty analysis start both from a mathematical model $Y = f\left(x_1, x_{2,} ..., x_n\right)$ relating the output quantity Y to be measured to the n input quantities x_i. Traceability to reference standards is acheved if x_i are all traceable or constants. The use of the model for uncertainty analysis is detailed in the Guide to the expression of Uncertainty in Measurement [5] published by BIPM.

For example in modelling the temperature measurement with an SPRT there are several steps:

- The physical principle that undepins tempeature measurements with an SPRT is the almost linear positive change in electrical resistance of pure metals with temperature changes. Therefore, the measured value is an electrical resistance. The thermometer resistance is measured by passing a current through it and measuring the correspondent voltage change. Accurate resistance measurements make use of a resistance bridge which compares the value of the unknown resistance R to a known reference resistance Rs. If the bridge reading is X, the measured resistance is $R = R_s \cdot X$.

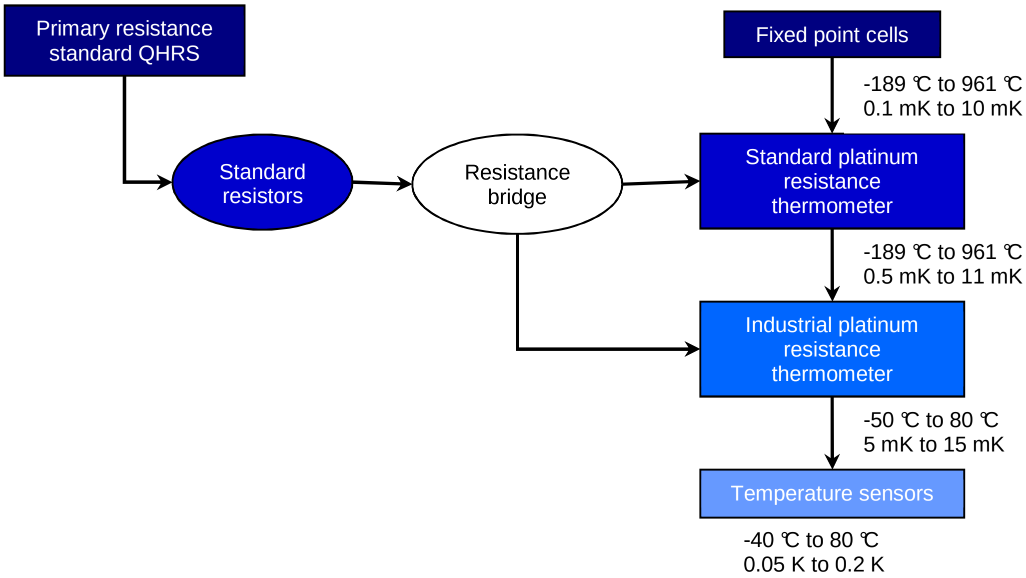

Figure 4. Example of traceability scheme for temperature measurement

- ITS 90 gives a reference function, Wr for an "ideal" thermometer. This reference function is expressed as a ratio $W = R(T90)/R(0.01\,^{\circ}C)$, where $R(T90)$ is the measured SPRT resistance at the specified temperature and $R(0.01\,^{\circ}C)$ is the measured SPRT resistance at the triple point of water.The measured temperature is calculated from the deviation of measured ratio to the reference one, $T = f(W - W_r)$.

When an SPRT is calibrated in fixed points, there are in fact two references to be taken into account for the traceability, one is the group of fixed points to which it is compared in the given range, the other comes from the electrical measurement: the reference resistance, as shown in the traceability chart from figure 4.

Once a SPRT is calibrated in fixed points, it can be used as a primary standard to calibrate other thermometers by comparison. To do that, additional equipment is used namely adequate isothermal enclosures that provide the necessary stable thermal conditions to perform the calibration. When estimating the uncertainties in the calibration by comparison method, not only the ones corresponding to the standards calibration have to be considered but also other influence factors like their drifts between calibrations and the influence of the isothermal enclosures used. When other steps are required, additional uncertainties are added in each one in a similar way.

4. Traceable humidity measurements

For humidity measurements [5], a standard is either a system that can produce a gas stream of known humidity or is an instrument that can measure humidity in a gas in a fundamental way (chilled mirror hygrometer, electrolytic hygrometer, psychrometer,…). There are primary standards for humidity in many countries, operating on various principles, such as gravimetric systems and two-pressure generators. An example of traceability scheme for humidity measurements is shown in figure 5.

The humidity (absolute) is defined as the mass of water vapor in a unit volume of moist air at a given temperature and pressure. This definition implies the need for traceability to mass, temperature and pressure reference standards and can be exemplified through the measurement model for a humidity generator.

- To generate a gas with known moisture content, the first step is to saturate the gas with water at a known temperature and pressure. The mole fraction x of water vapor in the gas is therefore calculated using the equation $x = e(T_s) \cdot f(T_s, P_s)/P_s$. T_s and P_s are the temperature and pressure of the gas and water in the saturator, and $e(T_s)$ is the water vapor pressure at T_s calculated from saturation properties of water tables. There is also an enhancement factor $f(T_s, P_s)$ to account for non-ideal gas and solution. Vapor pressure and enhancement factors are determined by calculations, when estimating the uncertainty budget, the uncertainty due to formulae calculations should also be considered.
- The second step in generating a given humidity can be done by two techniques: two-pressure and divided flow. For the two-pressure generator the gas is saturated at high pressure and then expanded till atmosphere, in divided flow technique, the saturated gas is mixed with known amounts of dry gas. Therefore flow meters measurements used to determine these amounts have also to be traceable.
- If dew point or relative humidity is the measured quantity, additional temperature and pressure measurements are requested, each traceable and with stated uncertainty

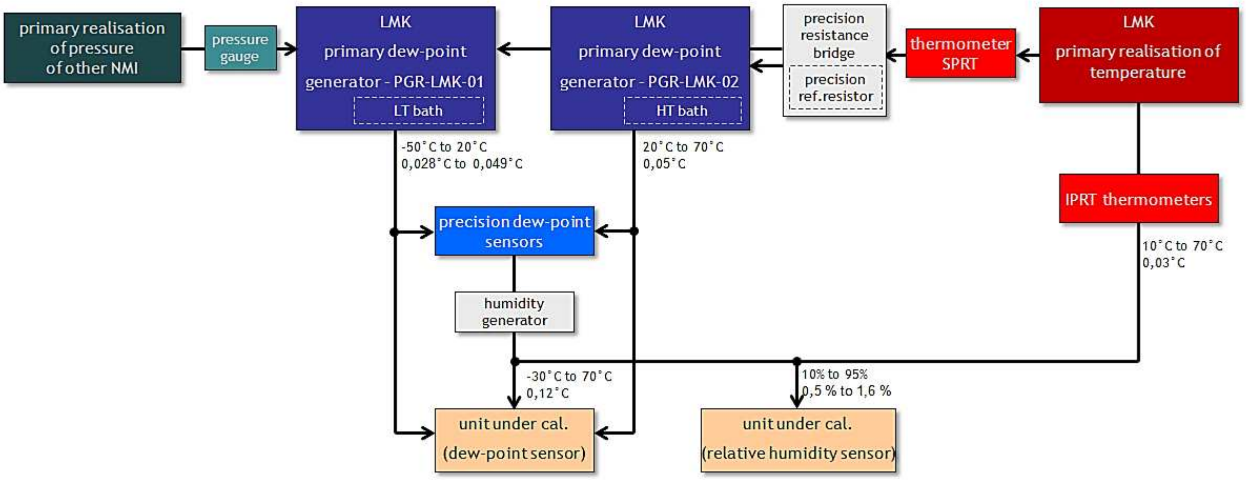

Figure 5. Exemple of traceability scheme for humidity measurements

5. Traceable pressure measurements

As for humidity, pressure measurement traceability is indirect, involving a combination of references. The primary standards in pressure are piston gauges and laser interferometric manometers (figure 6).

Pressure gauges materialize the definition of pressure (force applied per unit of surface). A reference pressure p is generated and its value determined by balancing it against a known force applied on a known area. A piston of area A moves freely inside a cylinder and on top of it known masses m are loaded. When the force generated by the masses and the force applied by the reference pressure are equal, the piston floats and the pressure can be calculated from the forces equilibrium for a given g (constant local gravitational acceleration), $p \cdot A = m \cdot g$.

This simple model equation reflects the traceability routes, to meter definition through accurate measurement of piston area, and to kilogram through precise determination of loaded masses. But there are several other effects and factors affecting the measurement result as dilatation of piston and cylinder due to temperature and pressure, surface tension effects around piston, air buoyancy over masses, liquid column head. The final equation becomes much more complicate [6] and involves accurate and traceable determination of temperature, liquid and air properties, etc.

In the classical U tube manometer the measured pressure is equilibrated by the weight of a mercury column. If the column height h is measured with a laser interferometer, the measurement can directly be traceable to the meter definition. Here also the first assumption equation is simple: $p = \rho \cdot g \cdot h$ but there are multiple effects to consider. Once again temperature has an important influence through thermal expansion phenomena and adds one more branch to traceability scheme.

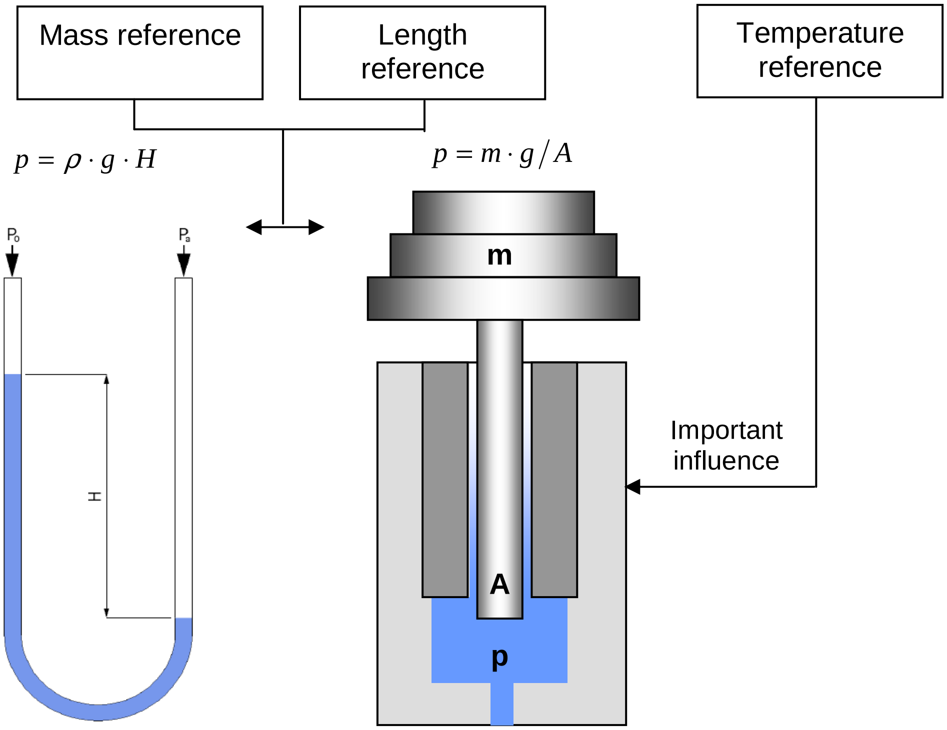

Figure 6. Primary standards in pressure measurement

6. Conclusion

This paper shows the hidden aspects of metrological traceability concept. Traceability is the corner stone of trust in a measurement result and for meaningful comparisons with other similar measurements performed in other places or times. The visible part of the traceability iceberg is that physical quantities have internationally defined and agreed references and that any measurement in trade industry and science should prove its equivalence (within an uncertainty) with the assigned reference. Most of the physical principles put into practice in measurement instruments involve more than one physical quantity thus requiring more than one traceability route. Moreover, important influencing factors which could affect the measurement results also need traceable quantification. Last but not least, documentation is mandatory to support both claimed traceability and uncertainty of a measurement.

7. Acknowledgements

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