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MeteoMet Training Course

Metrology Principles

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Why worry about uncertainty?

- Every measurement is subject to some level of uncertainty.
- A measurement result is incomplete without a statement of the uncertainty.
- Knowing the uncertainty in a measurement helps you judge it’s fitness for purpose.
- Understanding measurement uncertainty is the first step to reducing it.
- Good measurement practise can help reduce uncertainties.

What is uncertainty?

Definition in the International Vocabulary of Basic and General Terms in Metrology (VIM) — Third edition (2006)

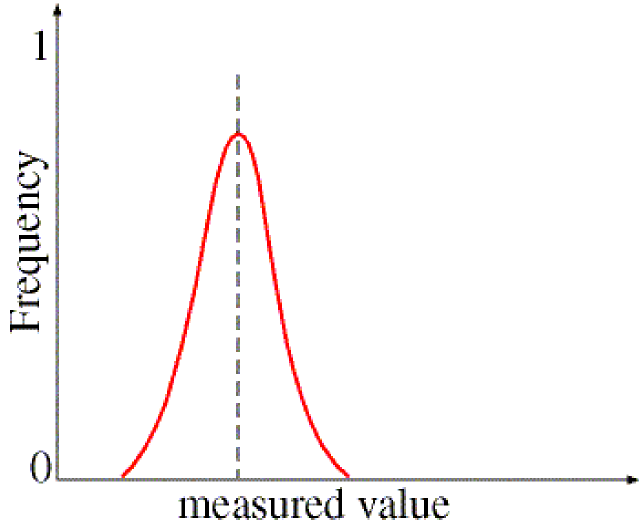
‘Parameter, associated with the result of a measurement, that characterises the dispersion of the values that could reasonably be attributed to the measurand’

From which we can conclude:

- Uncertainty is a topic which seems to attract the most obscure and convoluted definitions;
- Uncertainty is a **property of a result;**
- Indicates the likely range within which we think the ‘true’ value of a measured quantity lies, **given all the information we have;**
- Measurement uncertainty is a single value, expressed in terms of the measurand, either as a percentage or in units or the measurement.

$x \pm U$

(with a given confidence interval defined by a coverage factor, k)



What isn’t it

- Mistakes
  - Uncertainty doesn’t (can’t) cover mistakes.
- The error in the result
  - An error is the difference between a result and the true answer – we don’t know what the ‘true’ answer is.
  - Better to think of measurement uncertainty as a figure of merit, an indication of what range of values the true answer might have.
- An absolute fact
  - It is an estimate, at best we are saying that 95 times out of a 100 the true result is (probably) within our uncertainty bounds.
  - Of course, this also means that 5 times out of a 100 a result will be outside these bounds.

Why evaluate uncertainty

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- Allows us to assess methods and results against data quality requirements.
- Fitness for purpose of a measurement method.
- Interpretation and application of results.
- Equivalency of different results.
- Provides an understanding of the measurement and which parameters should be given most consideration.
- Informs method optimisation and improvement.

As usual the trouble's in the small print

The uncertainty (on a 95 % confidence interval) of the assessment methods will be evaluated in accordance with the principles of the ISO Guide to the Expression of Uncertainty in Measurement (1993) or the methodology of ISO 5725:1994 or equivalent. The percentages for uncertainty in the above table are given for individual measurements averaged over the period considered by the limit value, for a 95 % confidence interval. The uncertainty for the fixed measurements should be interpreted as being applicable in the region of the appropriate limit value. (CEN CR 14377 Approach to uncertainty estimation for ambient air reference measurement results).

Uncertainty of a method

- Measurement uncertainty is a property of a result.
- Ideally this would be evaluated for every result.
- There is general acceptance that it is possible to evaluate the uncertainty of a standardised method – and assume this uncertainty applies to future measurements made with that method.
- Need to be sure the uncertainty evaluation is appropriate for all applications of the method – i.e. conditions and scope of the evaluation (and validation) cover the ongoing use.
- QA/QC requirements within method become important.
- Ideally a method would provide a procedure for a user to evaluate the measurement uncertainty of results they have obtained, and the results of validation of the method uncertainty.

Illustration of the concept of uncertainty

Repeated measurements
(of the same thing)

Average

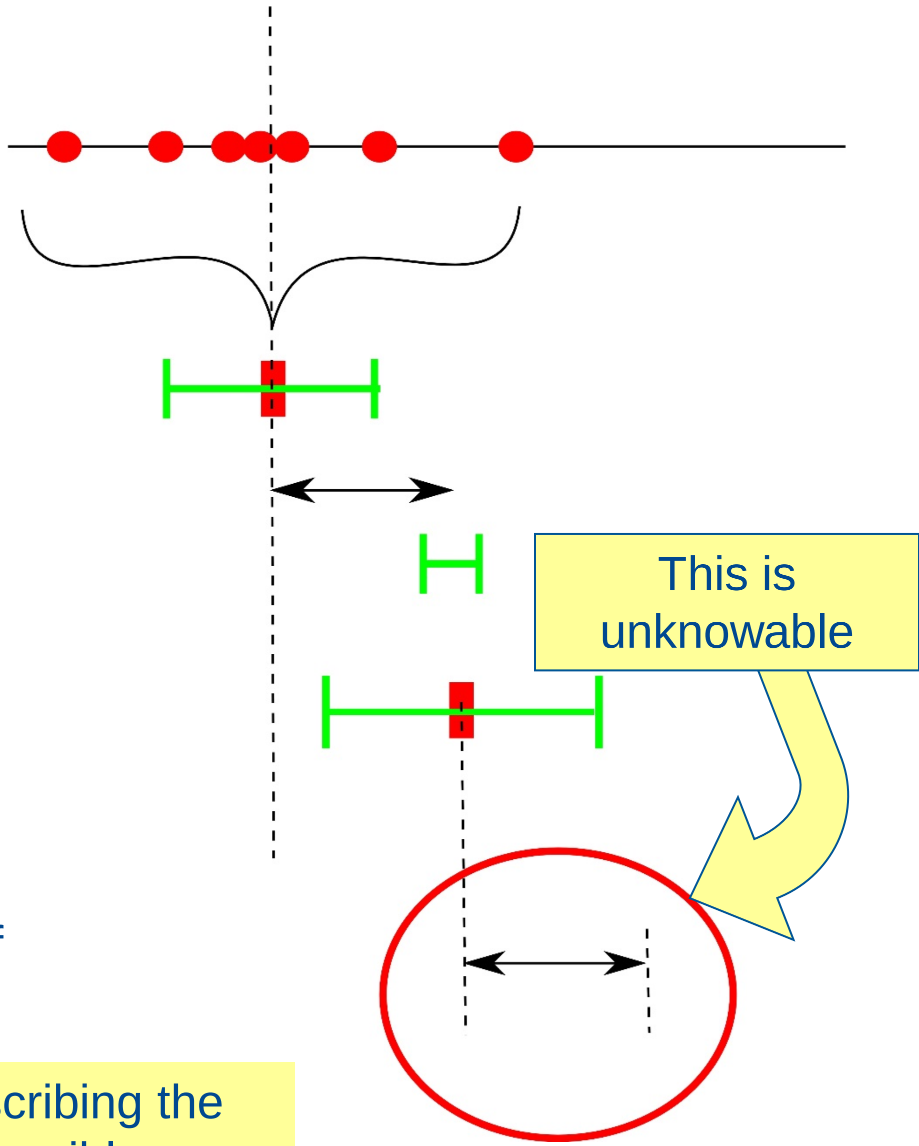
Uncertainty due to repeatability

Correction for external conditions

Uncertainty due to correction

Measurement result and
estimate of uncertainty

However, ‘true’ result may be
outside the uncertainty because of
unknown effects



We minimise this by describing the
method as fully as possible

Level of confidence

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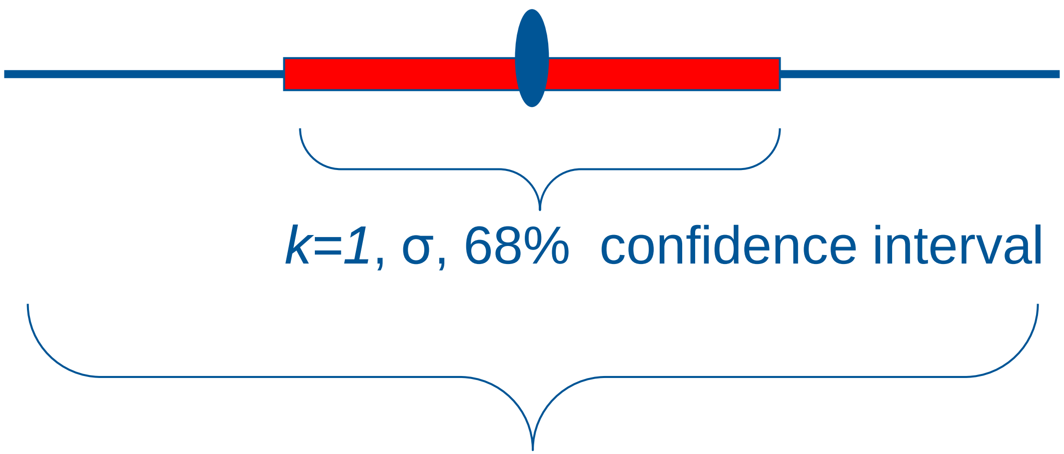
- Measurement uncertainty is a fact of life.
- Our aim is to quantify the uncertainty to allow the measurement result to be interpreted.
- To do this we must calculate uncertainty in a defined way with a known level of confidence (i.e. the uncertainty of our uncertainty).
- Normally this is 95% (*k=2*).

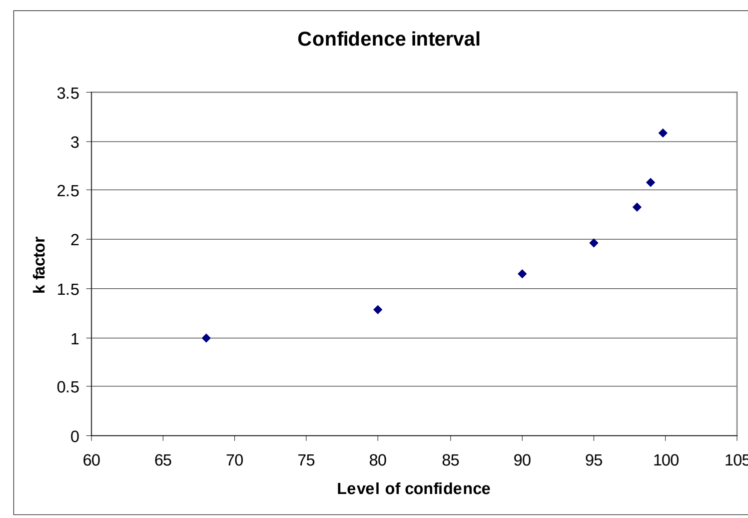
result



k=1, σ, 68% confidence interval

k=2, 2σ, 95% confident

More confident, but within a wider interval



Random uncertainties – average out

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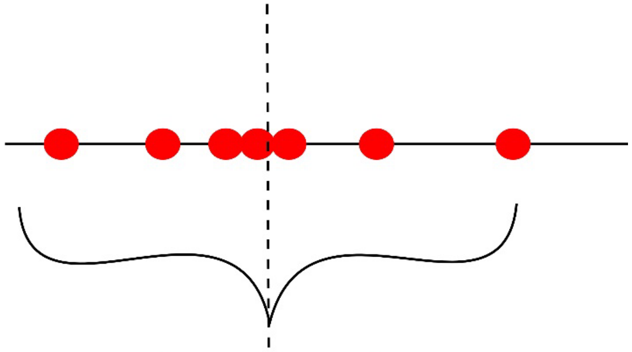
- If we have random terms then averaging multiple measurements will improve the uncertainty.
- So for a normally distributed system, if we have:
  - N measurements
  - with a random uncertainty, Um – which can be estimated as the standard deviation of a series of measurements of an unchanging quantity – then
  - the uncertainty of the mean =

$$\frac{Um}{\sqrt{N}}$$

Repeatability in atmospheric measurements



- One key issue in atmospheric measurements is that in general we can’t make repeated measurements of the measurand.
- For example, if what we are measuring is an annual mean, then we can’t just take the scatter of results as a measure of the random uncertainty in the measurement, as there are many sources and scales of natural variability.
- Need to characterise the repeatability from validation measurements – usually by repeated measurements of a calibration artefact or validation source.

Don’t confuse variability of the measurand with uncertainty of the measurement

Random vs Systematic Terms

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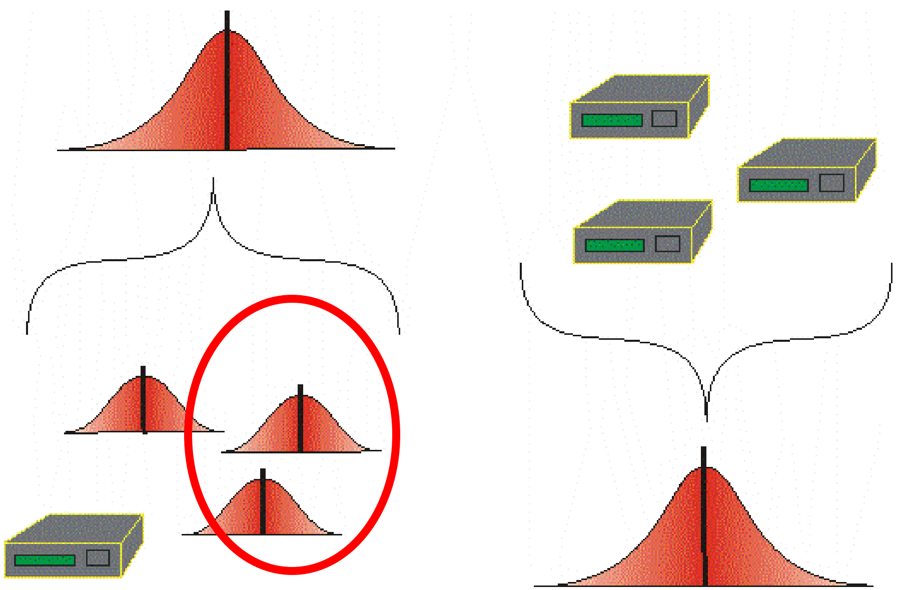
- Always define the scope of the measurement result that you are determining the uncertainty of.
- What may appear as a systematic term (bias) in one context may be a random term (noise) in another (and vice versa).
- For example over a year the use of different calibrations will randomise some uncertainties.
- If you can randomise a systematic (bias) term then it can be reduced (e.g. use multiple independent calibration artefacts) through multiple measurements.

Approaches to calculate uncertainty

- There are two broad approaches to determining uncertainty:

  Top Down - Method comparison – EN ISO 20988

  Bottom Up - Uncertainty combination – GUM



EN ISO 20988

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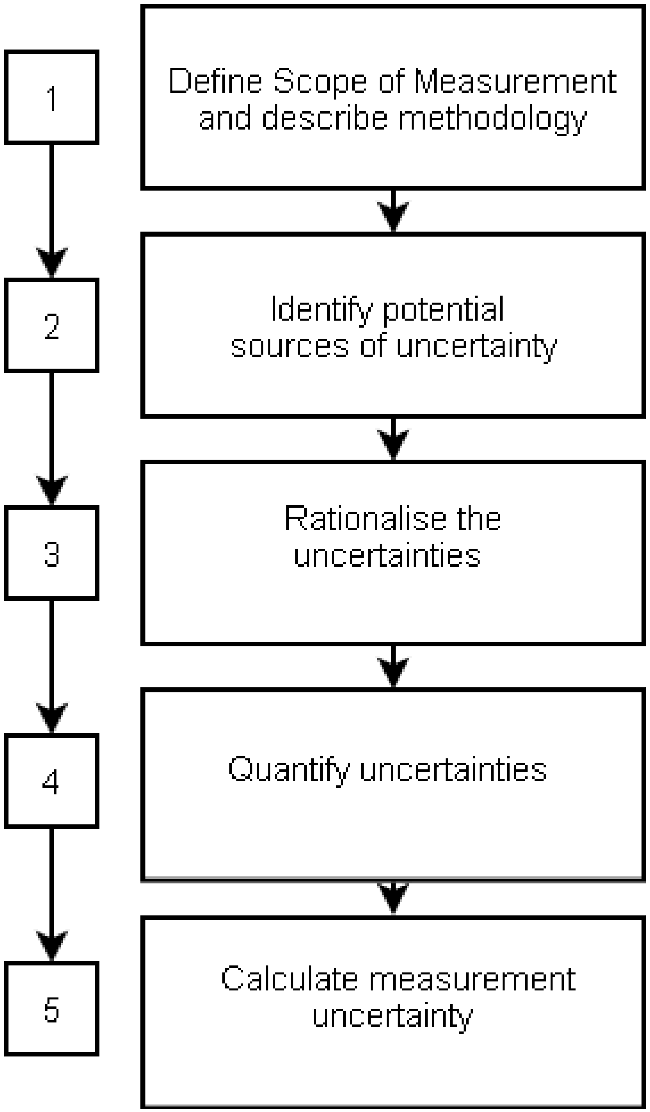
- Guidelines for measuring measurement uncertainty
- Provides eight models of ‘experiment’ which may provide input data to an uncertainty evaluation, and statistical approaches to assess these.
  - A1: simple random sampling;
  - A2: repeated observation of a reference material by a measuring system;
  - A3: observation of different reference materials in a calibration procedure;
  - A4: repeated observation of different reference materials by identical measuring systems;
  - A5: parallel measurements with a reference method of measurement;
  - A6: paired measurements of two identical measuring systems;
  - A7: inter-laboratory comparison of identical measuring systems;
  - A8: parallel measurement of identical measuring systems.
- **Not the easiest standard to apply.**

Guide to Uncertainty in Measurement (GUM)

- The GUM has been adopted as an overarching methodology
- Approach can be summarised as:
  - Describe measurement steps.
  - Identify uncertainties associated with these and all inputs.
  - Combine them.
  - Assign known level of confidence to this uncertainty.



GUM approach to determining uncertainty

- Define the measurement process

  In principle we should know the 'measurement equation'

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

- Quantify uncertainties of each X_i these as standard uncertainties (in units of measurand)
  - by repeated measurement - Type A
  - by estimation - Type B
  - Insignificant contributions may be ignored.
- Combine these as square root of the sum of the variances – for random uncorrelated sources.
- Expand the combined uncertainty to give an estimate of the uncertainty with a required level of confidence by multiplying be a coverage factor.

Controlling uncertainty - calibration

- Calibration ties down the uncertainties *at the conditions present during calibration*.
- Influence quantities which don't change from the conditions of calibration won't contribute to the uncertainty.
- Only things which are either uncontrolled by calibration or that change during measurements should be included in uncertainty.
- Of course the calibration itself introduces an uncertainty.
- Calibration therefore needs to be considered as one (important) part of the overall measurement process.

Traceability

- VIM definition of metrological traceability:

"property of a measurement result whereby the result can be related to a stated reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty."

- Traceability is a crucial element in establishing comparability between different measurement methods.
- However, this definition focusses on measurements made under controlled (laboratory) conditions
- It doesn't reflect the impact changing external conditions could have on the measurements.
- Discussions are underway to revise the definition to make it more applicable to field measurements.

Validation

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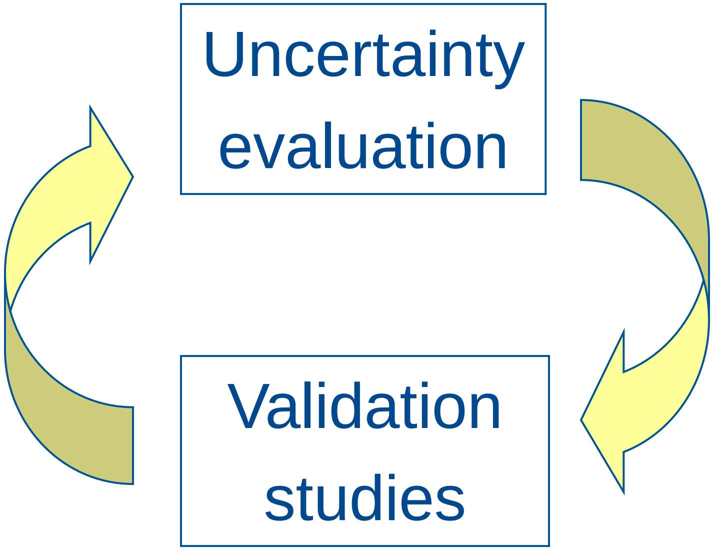
- Validation provides evidence that a method is fit for purpose.
- Often takes the form of inter-comparison studies of different methods supported by laboratory method assessment.
- Should include all QA/QC and other procedures used to control the method.
- Note that validation needs to cover the complete measurement method, rather than just calibration of a sensor.
- The uncertainties of both methods need to be considered.



Validation studies can be used to check uncertainty evaluations or to provide input into them.

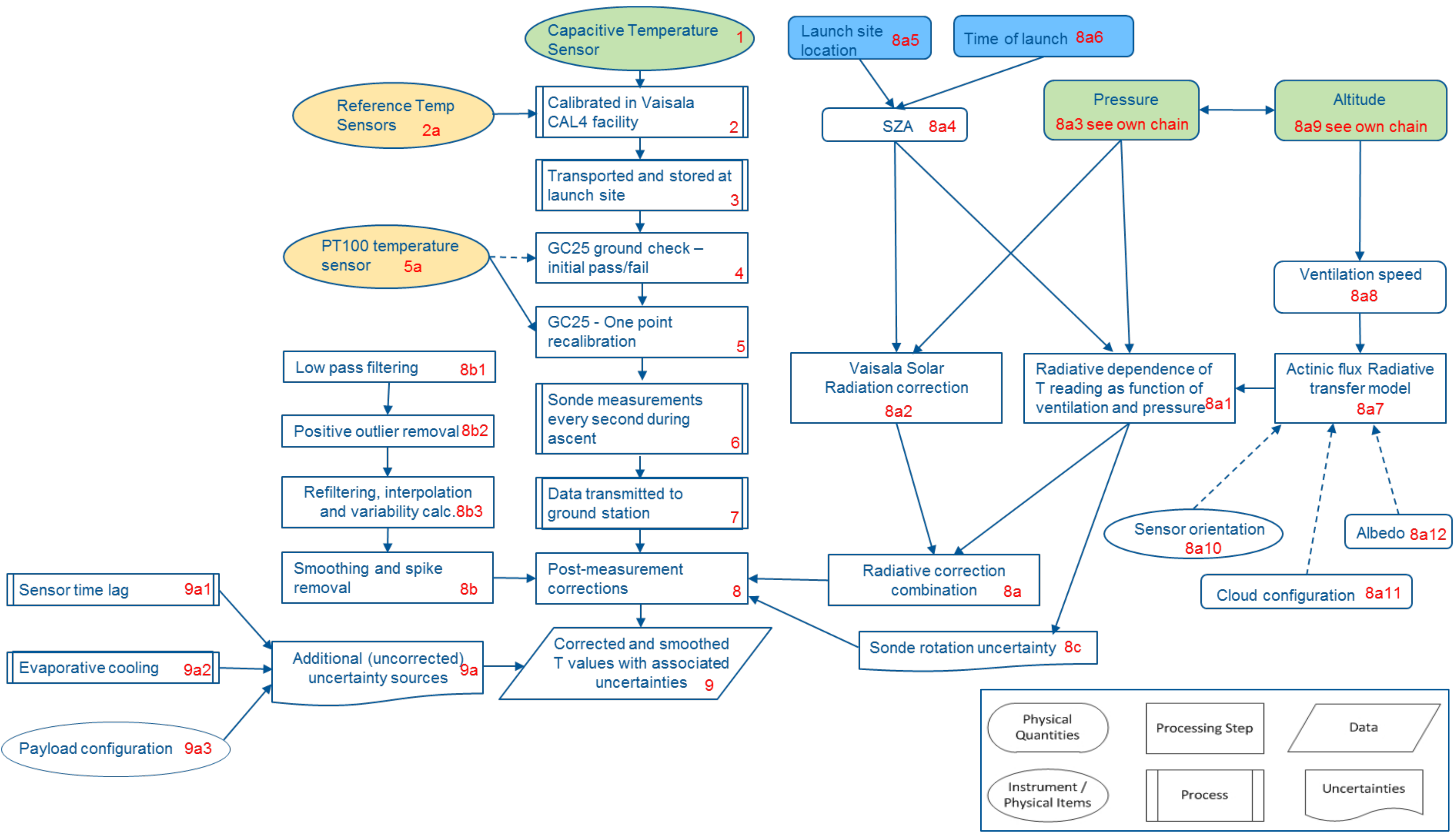
Uncertainty evaluation can be used to help plan validation studies.

Ideally the two processes should be iterated.

GAIA-CLIM traceability and uncertainty assessment

- Traceability and uncertainty assessments are being carried out for a range of ECV measurements, a number of which are relevant to GRUAN.
- All steps in the process of generating the measurement product are considered in terms of:
  - The uncertainty related to that step.
  - The temporal and spatial correlation of the uncertainty.
  - The influence of the step on the final result.
  - Any correlations with other steps in the process.
  - The traceability and validation relevant to that step.
- Provides current best estimate of overall uncertainties, in addition to information on key uncertainty components and their correlations, and identify gaps in current knowledge of uncertainties.

Traceability and uncertainty assessment – RS-92 example (draft)



Summary

- Uncertainty is present in any measurement process.
- Knowledge of the uncertainty is crucial in understanding if a measurement is ‘fit for purpose’.
- Use of a common terminology brings clarity and consistency to uncertainty discussions.
- Traceability and validation are key elements in confirming uncertainties and establishing comparability between different measurements.
- Both of these are challenging for atmospheric measurements.
- Consideration of the complete measurement process is required to derive a robust total uncertainty, and to identify and separate random and systematic components.