

Measurement: From Indication to Value

IDE-014 · Fundamental Ideas

Concept essays for *The Universe and Its Observers*

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Article Abstract

A measurement result is not a number an instrument hands over. It is a value assigned to a defined quantity, together with a statement of the dispersion of values that could reasonably be attributed to it, arrived at through a model connecting the instrument's indication to that quantity.[1,2] Each part of that sentence does work. Defining the measurand comes first, because ambiguity there cannot be repaired by better instruments. Calibration and traceability connect an indication to reference standards through a documented chain, each link of which adds uncertainty rather than removing it. And uncertainty is not the unknown difference between the result and the truth. This article follows a result from indication to decision, and hands the general theory of models to IDE-015.

In 60 Seconds

Metrology starts by defining the measurand, the quantity intended to be measured, and the definition can itself be the limiting factor: asking for the length of a rod is incomplete until the temperature, the supporting conditions and what counts as its ends are stated.[1] Only then does the instrument matter. Calibration relates the instrument's indication to values realized by a standard, and traceability is the documented chain of such comparisons up to a reference, usually an SI realization.[1,3] Traceability does not make a result exact; every link contributes uncertainty, and the chain's value is that the contributions are known and can be added. Uncertainty itself is a parameter characterizing the dispersion of values that could reasonably be attributed to the measurand, evaluated either statistically from repeated observations or by other means, and it is not the unknown deviation from a true value.[2] Between indication and value sits a measurement model, and results depend on it. When a result is used to decide whether something conforms, the uncertainty has to enter the decision rule explicitly rather than being reported and ignored.[4]

Why This Question Matters

Measurement is the point where a theory meets a number, and most disputes about numbers are really disputes about one of four things: what was being measured, what it was compared against, what assumptions turned the reading into a value, and how confident anyone is entitled to be. Treating a result as a bare number hides all four. It also makes two common errors invisible: reading two values as disagreeing when their measurands were never the same intended quantity, and declaring conformity or non-conformity without accounting for the uncertainty, which converts a measurement into a verdict it cannot support.

1. Define the Measurand First

The measurand is the quantity intended to be measured, and specifying it requires more than naming a quantity kind.[1] The specification has to include whatever conditions materially affect the value: the temperature at which a length is defined, the plane in which a diameter is taken, the exact chemical species whose concentration is wanted rather than a family of related ones.

Where the definition is incomplete, the residual variability is not instrument error. Metrology gives it a name, definitional uncertainty, and it sets a floor below which no instrument can take you.[1] This is a genuinely useful idea outside metrology too, because it explains why some disagreements cannot be settled by more precise apparatus.

The consequence is not that results about different quantities cannot be compared: metrology defines comparability for results of the same kind of quantity that are traceable to a common reference, which is why results for an Earth to Moon distance and for a Paris to London distance are comparable when both trace to the metre.[1] What it does require is that before two results are read as disagreeing about the same target, their measurand specifications be aligned well enough that they are results about the same intended quantity. Sea surface temperature measured at intake depth and measured at the skin are different quantities that happen to share a name, and reconciling them is a matter of definition before it is a matter of correction. Apparent disagreement between measurement methods can arise from differing measurands or operational definitions.

Where That Leaves Us

The measurand has to be specified with all the conditions that affect its value, and whatever ambiguity remains sets a floor that no instrument can beat. Traceability to a common reference is what makes results of the same kind comparable; the measurand definition settles whether two results are about the same intended quantity. With the quantity fixed, the next question is what the instrument's reading is being compared against.

2. Traceability Is a Chain, Not a Certificate

Calibration establishes a relation between the indications of an instrument and values provided by measurement standards, under stated conditions, together with the uncertainties of both.[1] It does not adjust the instrument, though adjustment often follows; it documents a relation.

Metrological traceability is the property of a result whereby it can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty.

[1] The reference is usually a realization of an SI unit, and since the 2019 revision all SI units are

defined by fixing the numerical values of a set of constants, so realization is a matter of physics rather than of custody of an artefact.[3]

The phrase each contributing to the uncertainty is the load-bearing part. A traceable result is not a certified-correct result; it is one whose distance from the reference has been accounted for. A calibration certificate that reports no uncertainty is not evidence of accuracy but a missing piece of the chain.

Where That Leaves Us

Calibration documents the relation between indication and standard, and traceability is the unbroken documented chain of such relations back to a reference, with every link adding to the uncertainty. The point of the chain is that the contributions are known, not that they vanish. That makes the meaning of the uncertainty itself the next thing to get right.

3. Uncertainty Is Not Error

The GUM defines measurement uncertainty as a parameter characterizing the dispersion of the values that could reasonably be attributed to the measurand.[2] It is a statement about a set of values consistent with what was done, not an estimate of how far the result is from a true value, because the true value is by construction unknown.

The evaluation is divided by method rather than by nature. Type A evaluation uses the statistical analysis of repeated observations; Type B uses everything else, including calibration certificates, manufacturers' specifications, handbook data and the analyst's knowledge of the process.[2] Both yield standard uncertainties that combine in the same way, which is what allows components of very different origins to be added coherently.

Two habits follow. Reporting a result without an uncertainty is reporting an incomplete result, because nothing has been said about what values are consistent with it. And quoting more digits than the uncertainty supports asserts a precision that the measurement does not have, which is a claim about the world and not a matter of formatting.

Where That Leaves Us

Uncertainty characterizes the values that could reasonably be attributed to the measurand, evaluated either from repeated observations or from other information, and it is not the unknown gap between the result and the truth. A result without one is incomplete. Both the uncertainty and the value depend on something that has so far stayed implicit: the model connecting indication to quantity.

4. Every Result Is Model-Mediated

Between the instrument's indication and the reported value sits a measurement model: the set of relations expressing the measurand in terms of the input quantities actually observed, together with corrections for known effects.[2] A thermocouple gives a voltage; the temperature comes from the voltage plus a reference-junction correction plus a calibration relation plus assumptions about what the sensor is in contact with.

The model-based account of measurement makes the model central rather than incidental: a measurement outcome is an inference from indications, and its accuracy is assessed by robustness

among the consequences of models representing different measurement processes rather than by comparison with an inaccessible true value.[7] This is a description of what standards laboratories actually do when they compare independent realizations of the same unit.

The practical consequence is that model assumptions belong in the uncertainty budget. If a correction was applied, its own uncertainty propagates; if a known effect was neglected because it was judged small, that judgement is itself an input. A result is therefore conditional on a stated model, and changing the model can change both the value and its uncertainty without any new observation.

Where That Leaves Us

A reported value is an inference from indications through a measurement model, and the model's assumptions and corrections belong in the uncertainty budget rather than outside it. Accuracy is assessed by coherence among independent realizations rather than against an inaccessible truth. What remains is what happens when such a result has to support a decision.

5. From a Value to a Decision

Most measurements exist to support a decision: does this part conform, is this concentration below a limit, has this target been met. A measured value near a limit cannot answer that question by itself, because the values consistent with the measurement straddle the limit.[4]

Conformity assessment therefore requires an explicit decision rule. Guard bands narrow the acceptance interval relative to the specification so that the risk of accepting a non-conforming item is controlled, and the width of the guard band follows from the uncertainty and from which error is considered worse.[4] Both the rule and the risk it accepts are choices, and they should be stated.

This is where the whole chain earns its keep. The measurand definition fixes what is being decided about; traceability makes the comparison meaningful beyond one laboratory; the uncertainty gives the decision rule something to work with; and the model records what was assumed. A number quoted without these is not a measurement result but an indication with ambitions.

Where That Leaves Us

A value near a limit cannot decide conformity on its own, so decision rules and guard bands built from the uncertainty are required, and the risk they accept is a stated choice. Measurand, traceability, uncertainty and model each do work in that chain. IDE-015 takes up the models themselves, and what makes one adequate for the inference it is being asked to support.

What We Know, and How

- Defining the measurand precedes instrumentation, and residual ambiguity in the definition sets a floor on uncertainty that no instrument can go below.[1]
- Metrological traceability is a documented unbroken chain of calibrations to a reference in which every link contributes to the uncertainty;[1] the SI references are now realized from fixed constants rather than artefacts.[3]
- Measurement uncertainty characterizes the dispersion of values reasonably attributable to the measurand and is evaluated by statistical analysis of repeated observations or by other means, both combining coherently.[2]

- A reported value is an inference from indications through a measurement model, so model assumptions and applied corrections belong in the uncertainty budget.[2]

What We Still Don't Know

- How best to express measurement uncertainty for quantities defined by complex procedures rather than by physical relations, which is a live question in the biological and social sciences. [6]
- Whether and how the metrological framework transfers to constructs measured through questionnaires and rating scales, where the measurand is defined by the instrument itself.[6]
- How to treat the uncertainty contributed by computational models embedded in a measurement chain, where the propagation is not analytic and the model may be opaque.

What Could Change Our Minds

- A demonstrated case in which two laboratories realizing the same SI unit from the defining constants, with fully declared uncertainty budgets, disagreed by far more than their stated uncertainties and the discrepancy resisted resolution would indicate a defect in the definitions or in the uncertainty framework.[2,3]
- A worked account showing that a measurement result can be complete without a measurement model, so that an indication maps to a value with no inferential step, would overturn the model-mediated account.[5,7]
- Evidence that guard-band decision rules built from stated uncertainties systematically misestimate acceptance risk in a well-characterized production setting would require revision of the conformity assessment framework.[4]

If You Remember Only One Thing

A measurement result is a value plus an uncertainty for a defined quantity, obtained through a model and a traceable comparison; a bare number is none of those things.

Related Articles

- IDE-015 — Model
- IDE-017 — Uncertainty
- IDE-023 — What Is Observation?

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