Welcome to Agilent’s Metrology Basics module!

In this self-paced module, you will get a summary of measurement processes, measurement terms, **how results** (what is meant here?) and an introduction to causes of uncertainty. Finally, we will have a quick glance at the different kind of units.

This module is intended to provide a foundation for measurement technology. You will frequently run into many of the terms explained here, either when you use an instrument, or when you study other materials on this site.

This module should take 20-30 minutes to study.
Metrology Basics

1 — Introduction
Metrology Basics

• Outline - This course will teach the various aspects of the measurement process, like instrument performance, decomposition of measurement variations and different ways of displaying the results.
• Course Goals/Objectives: Upon completion of this module, you will understand:
  • The measurement process
  • Instrument Performance
  • Measurement Variation
Significance of Metrology

• The effect of measurement can be seen everywhere, allowing people to plan their lives and make commercial exchanges with confidence.
• Measurements are critical for us to know what kind of qualities and quantities we deal with.
  • Measurements define safety limits. For example, the speedometer in a car tells us if the speed we are driving at is safe.
  • Measurements give us confidence in a transaction. For example, we know exactly how much of gold we're getting when we pay per gram.
  • It also determines quality of service. We can choose to negotiate prices with service providers if we can accurately (and without dispute) measure the quality of service we are getting today.

Relate measurements in real life, like when you purchase a merchandise from a grocery shop (e.g. 1 Kg of sugar, A4 size paper, 10g of Gold).

King John signed the Magna Charta in 1215; One (long) paragraph had words to this effect “Throughout the Kingdom there shall be standard measures .wine,.ale,.cloth,. and also weights”.

However, international standards took a few centuries more to come about.
Control of Metrology

• Governments have regulations or laws which cover the practices for commerce and industry. This ensures consistency
• Commerce and industry regulate metrology by contract
• Some companies and governments require that measurement policies conform to:
  • MIL-STD-45662A
  • ISO 9000
  • EN 45000
  • QS 9000
  • ANSI/NCSL Z540-1

The governments have national standard bodies in their respective countries and have regulations to ensure good practices.

The rood in 16 century Europe was once defined as the total length of the feet of twelve men standing heel to toe taken as they left church. The "foot" was one twelfth of a rood.

Newton used the "Paris foot" (12.785in) for his calculations about the moon's orbit and gravity because the French surveyors handmade the most accurate determination of the earth's dimensions at that time.

The commerce in the world is looking at markets everywhere and physical boundaries do not restrict trade. Standards come into play to make sure a product manufactured in one country can work well in any other country (QS 9000 for example is a standard for the automobile industry).
So what does metrology involve?

- Metrology is the science of measurement.
- Everything that has to do with measurement exists within the realm of metrology.
- Metrology involves the process of measurements and comparisons of a measurement standard to either another measurement standard or to a device of unknown accuracy (unit under test). We call this as calibration.
  - It involves the design of tests and methods.
  - It also involves the analysis of test results.
  - All technical, engineering and scientific disciplines use metrology technology in their field of their interest.
This is a key topic as this affects all of us being engineers. Through a discussion we shall explain what all constitute a measurement and what is a good measurement.
Objectives: The Measurement Process

The definition and understanding of measurement processes and their requirements will raise the following questions:

- What is a measurement? What characterizes it?
- Why is the measurement being made?
- What decisions will be made from the measurement?
- What performance requirement do the measurements seek to validate?
- Is the measurement good enough?
- Risk and confidence

We need to understand that the process we use to measure something impacts the accuracy, in other words, the usefulness of the results, as much as the accuracy of the measuring device. For example, a highly accurate thermometer is useless, if we try to measure ambient temp while it’s in the sun! This is an obvious example, but the principle applies very well to test and measurement, for example, using degraded or poor quality connectors or cables with highly accurate instruments will still yield poor measurement results.
Measurements

• What is a measurement?
• What characterizes it?
• Why is the measurement made?
  • Measurement is the set of operations to assign a value to a physical quantity.
  • Measurements are subjected to varying degrees of uncertainty. The uncertainties need to be estimated and from the estimate.
    – The validity of the measurements can be assessed.
    – The risks associated with the decisions based on these measurements can be quantified and corrective actions can be taken to control the growth in measurement uncertainty.
Measurement Terms

• Physical property or condition to be measured: measurand.
• Converts energy of one form to another, typically to an electrical signal: transducer.
• Tool to measure with: instrument.

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We have to have something to measure and a way to measure it. The something to measure is called the measurand. It is that quantity, condition or parameter that we want to find out and put a number to. The box in the slide shows several common kinds of measurands. The measurand tells us an easy way to understand a property or condition. 35 degrees Celsius is a precise way to tell us it’s a warm day, instead of “cooler than yesterday but still too warm for a long walk”. Here, the measurand is temperature. Similarly, we estimate car’s “zoom factor” from the measurand acceleration, we decide to inflate the tires based on the measurand pressure. If we can’t put numbers to these measurands, we will have very different understandings of the conditions – for example, what’s pleasant weather to me may be warm to you.

The tool we use to assign an intelligible number to a measurand is the instrument. This is the device that connects up with the measurand and tells us the number.

Instruments can be different for different measurands. We all use instruments sometime or the other. We all use rulers (distance or length), weighing scales (weight), thermometers (temperature). In some cases the process of measurement may not be as simple as dipping a thermometer into a cup of coffee. The measurand may not be directly measurable, or unsafe to touch (like the amount of current coming out of the mains). So we need something to convert the measurand to something manageable (to the instrument). This is the transducer. The transducer is basically a converter. Precise instruments make electrical measurements, so transducer also convert physical (like light, sound) parameters to electrical quantities that instruments can make sense of.
Error and Uncertainty

Error (of measurement) is the result of a measurement minus a true value of the measurand.

Uncertainty is a parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand.

Measurand is the particular quantity subject to measurement.

No measurement is perfect, just as there are no perfect measuring instruments. For any reading that an instruments gives out, there is a finite difference between the displayed value and actual value. This is the measurement error.

The errors should be ideally removed. However, this is impossible beyond a point, so it is important to know what the quantum of error is to factor that into the measurement.

At the same time, we do need to keep in mind that like the measurands we are trying to quantify, our instruments too are fabricated devices and are therefore subject to their own uncertainties. These could be because of internal variations, externally induced variations (like temperature, magnetic fields, etc.) and overall difference from the “real” standards.
So we know about measurands – that’s the stuff we are trying to characterize or put a number to. The transducer does the conversion to an electrical signal, and the instrument does the actual measuring.

Why do we need a transducer? The transducer is a device that converts the quantity we want to measure to something that’s understood by the instrument. For example, the mercury in the thermometer is really a transducer. The heat of the DUT cause the mercury, on contact, to expand and rise through the fine capillary tube.

The mercury bulb just makes it convenient for us to measure by presenting the temperature in a form we can understand and relate to. In other cases, it could be to convert a physical quantity, such as displacement, to an electrical quantity, so that our electronic instruments can measure the displacement. Strain gauges, piezo-electric crystals, LVDTs, thermistors are all examples of transducers.

We have seen some examples of instruments that measure physical quantities – like thermometers for temperature. Examples of instruments that measure an electrical signal are a voltmeter, ammeter, ohmmeter, oscilloscope for the time domain, and a spectrum analyzer for the frequency domain.

The instrument displays the measurements in different ways, though ultimately we are interested in getting a number. In some cases, it could just be a needle moving across a graded scale, as in bathroom scales. Newer ones would display numbers directly, like the electronic thermometers.
A Basic Measurement

- Instrument is calibrated to a standard.
- A measured value is compared against a standard value.

Analog Thermometer

How do we know what the instrument is measuring is right? All instruments are “calibrated” to a standard. Let’s take the example of a thermometer. We take two standard points of reference – when water freezes and when water boils. We look at the mercury level at freezing point and mark that as “zero degrees” and then dip the thermometer in boiling water, mark the mercury position as “100 degrees”. This is the case with the Celsius scale. This is the process of calibration – setting the measurements according to known standards. We then divide up the distance between the zero and 100 marks into as many sublevels as make sense. This gives us the scale, to measure points in between.

Typically, the manufacturer does the calibration. Some instruments require recalibration over time and the user may or may not perform it.
Metrology Basics

2 — Definition of Terms

Now let’s take a look at some common terms,
Instrument Performance – Range

- Range is the amount of the measurand the instrument can detect and display.
- Can the thermometer be used to measure the temperature of cold and hot liquids? Or is it restricted to body temperature ranges?

Range is the “band” of measurements an instrument can make, the space between the lowest and highest values that can be represented.

A thermometer for example can have a range of 100 degrees Celsius meaning that it can measure from very cold to boiling hot. However, another may be restricted to, say, body temperature ranges. Another example, a typical desk ruler has a measurement range of 30 cm, while meter stick as the name suggest, will have a range of 100 cm. A surveyor's chain may be several meters long. In the electronic world, a voltmeter may measure just a few 100 volts or go up to kilo volts.
Instrument Performance – Resolution

- Resolution is the smallest change in the property being measured that an instrument can detect.
- If the actual temperature rose 0.1°F, but the thermometer still read 51°F, then that thermometer could not resolve a 0.1°F change.
- The user might be able to resolve 0.5°F, depending on how long the thermometer was and what range of temperature it could measure.

Resolution is the smallest change in a physical property that an instrument can sense. For example, a bathroom scale normally senses weight variations in pounds while a laboratory scale can detect weight in grams. The laboratory scale has better resolution than the bathroom scale.

Do not confuse resolution with accuracy.
Instrument Performance – Accuracy

- Accuracy is how close to the “real” value the instrument measures.
- Instruments are calibrated against established standards, and accuracy is a measure of how close to the standard the instrument measures.
- If the thermometer shows 10°C at freezing point of water, then it’s accuracy is poor.

**Accuracy** is how close the instrument’s measurement is to standards. Standards for measurands ensure consistency of measures across the world. For example, an instrument can have an excellent range and fine resolution, but all this would be wasted if the measurements are not “real”.

From the previous examples of absolute vs relative accuracy, e.g. using a scale, we can not accurately measure large masses in small units with good accuracy, that’s why we put calibrated weights on a scale that can measure the difference very accurately, these weights are transfer standards!

Calibrating instruments to standards is key to achieving higher accuracy.
**Instrument Performance – Linearity**

- An instrument is linear if it responds uniformly to equal changes in the measured property.

The linear region is where the signal amplitude changes in a constant manner. Any non-linearity distorts a signal, so linearity is an important consideration in electrical measurements.

At this point, we should point out that there is nothing in the world that is absolutely linear. There is always some variance from the constant, no matter how small. When making measurements, we therefore pick a range where the linearity is close enough for our purposes.

The noise region of the curve is where the input signal level is affected by spurious signals that are about the same level. The compression region of the curve is where any further increase in the input signal does not cause any change in the output signal.

An example of non-linear behaviour would be the fuel gauges in many cars. The needle points to “full” after the fuel tank has been filled. For a very significant distance initially, the gauge continues to show that the tank is still near full. However, after some big distances have been travelled, the gauge appear to rush to an empty tank. This happens because the gauge is not linear.
Instrument Performance – Sensitivity

• Sensitivity is the smallest value of the physical property that is detectable.
• For example, humans can smell sulfur if its concentration in air is a few parts per million. However, even a few parts per billion are sufficient to corrode electronic circuits.

Sensitivity is the smallest value of the physical property that is detectable. Sensitivity defines the ability of the instrument to respond to small changes in the input level. For example, a kitchen weighing scale will not detect a grain of rice, whereas a laboratory scale would.
Instrument Performance – Stability

• An instrument’s ability to make repeatable measurements of an exact value of the measured property over time.
• What if the thermometer read 51°F one time, and 52°F the next time. It would not be very stable, not very accurate (in-spec, then out-of-spec), and you wouldn’t trust its reading.

Stability
The stability of an instrument refers to its ability to make repeatable measurements under exactly the same physical stimuli over time. High stability will change less over time than low stability.

Calibration
Calibration is the process of comparing a measurement device which has a known accuracy against one that has an unknown accuracy. The purpose of calibration is to make sure an instrument has the accuracy required to perform its intended task, and it is performing as designed. The process of calibration uses standards, as described above.

Traceability
How do we ensure that the accuracy of measurements can be traced to an accepted measurement reference source, or standard? This is accomplished through a process called traceability. A traceable measurement result can be related to a chain of calibrations that conform to the hierarchy of standards as described above.
Instrument Performance – Standards

- An acknowledged measure of comparison.
- An instrument’s variation from a standard during calibration defines its accuracy.

Standards must have traceability

Why don’t we just build the most accurate instrument, with the widest range, the finest resolution and extreme linearity and repeatability? The simple answer is cost. Like cars, higher the performance, higher the complexity and therefore higher the cost. Therefore, we build instruments with optimal performance. The ultimate end use determines the performance needs. For example, a bathroom scale need be accurate to only 0.5 kg and doesn’t require a lot of sensitivity or resolution. It is a course indicator. However, a scale to weigh gold will have to be much more sensitive and accurate. An inaccuracy of just 10 grams can be expensive for gold.

So we build instruments with optimal performance. But they still need to be related to standards.

A standard is an acknowledged measure of comparison. In order to determine that we have an instrument of a certain level of accuracy, we can determine the absolute accuracy by mathematical method, yet this is not a practicable method in day-to-day operations. Not only is it a lot of effort, but it would only apply to a certain instance. Much more practicable, and by far most commonly used method, is to compare its measurement against another measurement of a higher accuracy – we compare it to a standard. These standards are typically an order of magnitude more accurate (or to be precise, have an order of magnitude smaller inaccuracy). The variation of an instrument from the standard quantifies its accuracy. One important role of government is to set and maintain standards for the community.

Governments typically define standards. Standards are very important to electronic instruments because they are used to calibrate instruments for accuracy (calibration is discussed below). Just as there are different levels of accuracy in instruments, there are also different levels of standards to compare the instruments against.

Working standards are the everyday standards that a manufacturer of measuring instruments uses to calibrate the instruments that they produce. They are widely available, and less expensive than higher orders of standards.

Secondary standards are of a somewhat higher level of accuracy. A manufacturer of measuring instruments might periodically need to compare their calibration instruments against this standard.

Primary standards are the ultimate authority against which all other standards are measured. These are often national standards—sometimes physical objects that are stored in a government vault. They have been very carefully determined in the laboratory. They are normally carefully stored to minimize environmental alteration.
Definition of Terms

Measurement
• The value obtained from measuring the DUT a single time.
• Measurement = True Value + Bias + Measurement Error

True Value
• The accepted correct value of the parameter being measured.

Bias
• The difference between the average of repeated measurements of a parameter on a single DUT, and the true value.

Water boils exactly at 100°C at sea-level, that’s the true value. Whatever the thermometer displays, minus the True Value is the measurement error.

As the equation states, the false reading comprises Bias and Measurement Error, bias e.g. would be if the thermometer is in the sun while measuring the boiling water.
Definition of Terms

Measurement Error
- The deviation between an individual measurement of a parameter on a DUT, and the average of many repeated measurements of the same DUT. The standard deviation of measurement error is often called precision.

Measurement System Variation
- Variation arising from all sources in the measurement system. For example, variation among test systems, among fixtures, among repeated measurements.

Test System Variation
- Variation among test systems.

Reproducibility
- The variation in measurements due to all sources of measurement variation except repeatability.

Measurement errors can come from many sources, including the instrument itself. In many cases there would be instance to instance variation in measured results so a statistical average of measurements are chosen to represent the average.
Definition of Terms

Repeatability (Replication Variation)
- The variation of repeated measurements using a single test system and an individual DUT.
  - Static: Measurements taken in succession without changing the setup.
  - Dynamic: The DUT is removed from the measurement device and repeated measurements are separated in time.

DUT Variation
- Variation among DUTs. Excludes any measurement system variation.
  - If present, included in repeatability.
  - To resolve, substitute a standard for the DUT and isolate the pure repeatability of the measurement system.

While it’s great to have instruments with great range, resolution, accuracy and linearity, it is also important to have repeatability. This is essentially the consistency of measurements or measurement system. It is important that the measurement or system present similar results over different measurement instances.

Why? Because measurements need to be repeated and/or compared to other measurements and/or target values, over time, otherwise we don’t need to measure? Example: Implications of poor measurement repeatability on a manufacturing line…means that at least the measurement tolerances have to be narrower by the margin of replication variation, resulting in unnecessary narrow design tolerances for the product.
Random and Systematic Errors - Target Analogy

- Both these marksmen have about the same systematic error but different random errors.

Take the example of marksmen. Both cases above have the same systemic error (the are off-target and veering to left). However, there is no pattern – the bullet holes are random.

We usually focus on removing systematic errors from our Measurements because we can do something about them. They are predictable and repeatable. Why? And what does it imply, a systematic error: An error or inaccuracy in the measurement process.
Error and Uncertainty

- Error (of measurement) is the result of a measurement minus a true value of the measurand.
- Uncertainty is a parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand.
- Measurand is the particular quantity subject to measurement.
The performance of a measurement instrument is related to several important measurement attributes that are important for you to know. Similarly, the operation of instruments is described by the specific measurement parameters within which they operate. Let's introduce you to some of the important terms that relate to these concepts.
Instrument Performance – Accuracy

• Accuracy is the ability of an instrument to measure the actual value within a stated error specification.
• Actual true temperature might be 50°F
• Thermometer might read 51°F
  • If accuracy of thermometer is stated to ±1%, is thermometer in spec?
  • If ±1°F, is it in spec?
• So, we know we are within ±1% or ±1°F of the actual true temperature.
• Stated accuracy can be relative to the value measured (±1%) or absolute based on full-scale limit of instrument (±1°F).

How well does the results of the measurement agree with the actual value of the property that is being measured? This is known as accuracy. It is the ability of the instrument to measure the actual value to within a stated error specification. So, accuracy is the difference between an individual measurement and the true value. For a measurement to be accurate, both the bias and the measurement error must be small.

The accuracy is often defined as a percentage of the reading of the meter. For example, a meter might have a reading of 10 V and an accuracy of +2%. This means that the actual voltage could be between 10.2 and 9.8 volts.
Precision versus Accuracy

Bias
True Value
Average
Single Measurement

Accuracy
Instrument Performance – Measurement Uncertainty

- The uncertainty of the result of a measurement reflects the lack of exact knowledge of the value of the measurand (true value).
  - Remember, the result of measurement even after correction is an estimate of the value of the measurand.
- The result of a measurement is complete only when accompanied by a statement of uncertainty.

These statements were paraphrased from “Guide to the Expression of Uncertainty in Measurement” ISO 1995

Uncertainty (of measurement)

A parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand. Because of the lack of different words for this general concept of uncertainty and the specific quantities that provide quantitative measures of the concept, for example, the standard deviation, it is necessary to use the word "uncertainty" in these two different senses.
Uncertainty Growth

- M&TE and standards need to be calibrated at periodic interval to limit the growth of measurement uncertainty to acceptable limits.
- The knowledge of the value of a calibrated parameter becomes less certain as time elapses since calibration.

Because of the inherent random processes and diversity of usage and environment stresses, parameter values tends to vary randomly. Thus the uncertainty surrounding the value of a calibrated parameter grows as time elapses since calibration.

M&TE: Measurement and Test Equipment
4 — Decomposition of a Measurement Variation
Variance in measurements have several components and cases. The total variance occurs because of changes from device to device and because of the measurement system. Each interaction with the measurement system (because of, say, the connections) can be slightly different. There could also be system to system variation – caused for example, but different calibration periods. And finally, there’s the instrument’s own precision to consider.
Each variance has a statistical distribution, as can be seen from the chart above.
Measurement Process Fundamentals

5 — Measurement Results
Measurement Results – Types

- Analog display
- Numeric (meter reading)
- Alphanumeric (ASCII data)
- Binary (computer data)
- Graphical (formatted to user)

The 1/2 Digit

999 3-digit
1999 3-1/2 digit

The simplest display is an analog meter – a sweeping hand indicates the value. The amount of sweep is proportional to the magnitude of the measurand. Analog displays are convenient for trends or relative values.

A numeric display is much more convenient to get a number. Many numeric displays are often specified by the number of digits they display. The extra 1/2 digit gives an instrument the ability to measure 100% above the normal full-scale range.

Binary data is usually provided by an instrument in the form of an interface circuit that can communicate to other electronic devices.

Graphical data is normally formatted by the instrument for displaying to the user.
Measurement Results – Graphical

One piece of information per plot.
Independent variable, usually time or frequency.

Graphical display are ideal for trends or comparing values relative to another – such as variation of voltage over time (time domain), or variation of amplitude over frequency (frequency domain).
Measurement Results – Graphical Polar

Two pieces of information per plot.
Independent variable, usually time or frequency.

You can easily convert between polar and Cartesian coordinates.

\[ X = \text{magnitude} \times \cos (\theta) \]
\[ Y = \text{magnitude} \times \sin (\theta) \]

\[ \text{magnitude} = \sqrt{X^2 + Y^2} \]
\[ \text{angle} = \arctan (Y/X) \]
Measurement Process Fundamentals

6 — Measurement Units
Here are some common measurements that we may run into. Some are more common than others (on an average day, few of us ever specify things in Newton-meters or hogsheads). Barring furlongs and hogsheads, all the units above are used frequently in the engineering world.

One other comment on measurement units – some of them are basic and many are derived. For example, time is a basic measurand, while phase and frequency are derived from time. Similarly, current, resistance, etc. can all be derived from volts.
Finally, this chart explains all those scaling factors. Most of us are familiar with the range from pico to giga. This chart explains the rest as well.
Thank you.

Questions, more information? Please email tm_ap@agilent.com
Want to learn this in greater detail? Please try
www.agilent.com/find/training and look for course availability at a
location near you.