

# 48: Common Sources of Errors in Measurement Systems

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1 Definition of Errors in Measurement Systems	1
2 How Errors Arise in Measurement Systems	2
3 Terms Used to Describe Errors	2
4 Types of Errors in Defined Classes	2
5 List of Error Sources in Measurements	4
6 Standards on Error Description	4
7 Uncertainties of Measurements	5
8 Glossary of Terms for Errors and Uncertainties	6
Reference	6

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## 1 DEFINITION OF ERRORS IN MEASUREMENT SYSTEMS

A number of crucial definitions are first needed to ensure clarity of discussion. These are as follows.

*Measurement error* is defined as the difference between the distorted information and the undistorted information about a measured product, expressed in its measurands. In short, an error is defined as real (untrue, wrong, false, no go) value at the output of a measurement system minus ideal (true, good, right, go) value at the input of a measurement system according to (1):

$$\Delta x = x_r - x_i \quad (1)$$

where  $\Delta x$  is the error of measurement,  $x_r$  is the real untrue measurement value, and  $x_i$  is the ideal true measurement value.

A *measurement* is an experimental process to acquire new knowledge about a product.

A measurement is the realization of planned actions for the quantitative comparison of a measurand with a unit.

A *measurand* is the physical quantity that is to be measured. Generally, a measurand is the input of a measurement system.

*Measuring* is a process for ascertaining or determining the quantity of a product by application of some object of known size or capacity, or by comparison with some fixed unit – see [www.iso.ch/9000e/2000rev\\_8e.htm](http://www.iso.ch/9000e/2000rev_8e.htm).

A *product* is the result of a process after ISO 9000:2000, point 3.4.2 – see <http://www.iso.ch>.

Four generic product categories exist as follows: service, software, hardware, processed material.

Many products comprise elements belonging to different generic product categories. Whether the product is then called service, software, hardware, or processed material depends on the dominant element. A *process* is a set of interrelated or interacting activities that transform inputs into outputs (ISO 9000:2000, point 3.4.1) – see <http://www.iso.ch>. Inputs to a process are generally outputs to other processes.

A *measurement process* is a set of operations used to determine the value of a quantity (ISO 9000:2000, point 3.10.2) – see <http://www.iso.ch>.

Measuring equipment is the measuring instrument, software, measurement standard, reference material or auxiliary apparatus, or a combination, necessary to realize a measurement process (ISO 9000:2000, point 3.10.4) – see <http://www.iso.ch>.

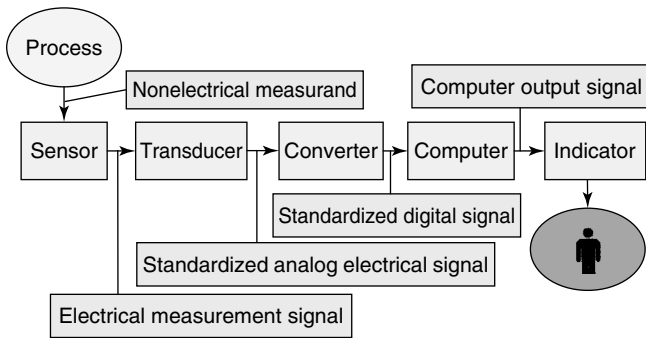


Figure 1. Measurement chain.

A *measurement system* or measuring system is the totality of all measuring equipments and auxiliary means to obtain a measuring result.

A *measurement signal* is the quantity in a measuring instrument or measuring equipment, which is unequivocally related to the measurand.

A *measuring chain* (Figure 1) is the structure of elements of a measuring equipment or measuring system, which channels the transfer of a measurement signal from the input of the measurand to the output of the measured value.

A *measured value* is a value that is unequivocally related to the measurand at the output of a measuring chain.

## 2 HOW ERRORS ARISE IN MEASUREMENT SYSTEMS

A measurement under ideal conditions has no errors. Real measurement results, however, will always contain measurement errors of varying magnitudes. A systematic (clearly defined process) and systemic (all encompassing) approach is needed to identify every source of error that can arise in a given measuring system. It is then necessary to decide their magnitude and impact on the prevailing operational conditions.

Measurement system errors can only be defined in relation to the solution of a real specific measurement task.

If the errors of measurement systems given in technical documentation are specified, then one has to decide how that information relates to which

- measurand
- input
- elements of the measurement system
- auxiliary means
- measurement method
- output
- kind of reading
- environmental conditions.

If the measurement system has the general structure given in Figure 1, the following errors may appear for a general measurement task:

- input error
- sensor error
- signal transmission error 1
- transducer error
- signal transmission error 2
- converter error
- signal transmission error 3
- computer error
- signal transmission error 4
- indication error.

## 3 TERMS USED TO DESCRIBE ERRORS

Globalization of the economy is strongly driving international standardization and accreditation programs, for example, ISO 9000 and ISO 17025, are the means of assuring quality control of components fabricated throughout the world.

Accrediting organizations such as American Association for Laboratory Accreditation (A2LA) experienced double digit annual growth in the past decade, particularly in the dimensional metrology field (classified under mechanical).

Most of these standards and accreditation programs require traceable measurements and hence measurement uncertainty statements – see [www.mel.nist.gov/proj/sfmi.htm](http://www.mel.nist.gov/proj/sfmi.htm).

Recent developments in metrology use

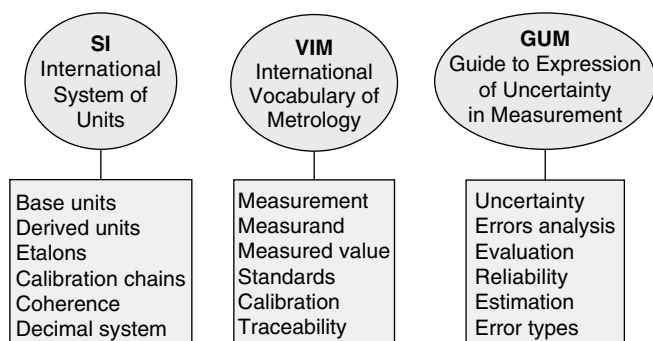
- the International System of Units (SI),
- the Guide to the Expression of Uncertainty in Measurement (GUM), and
- the International Vocabulary of Basic and General Terms in Metrology (VIM),

as a starting point for the application of terms to describe errors in the frame of uncertainties (see Figure 2).

## 4 TYPES OF ERRORS IN DEFINED CLASSES

*Systematic error* (bias) is a permanent deflection in the same direction from the true value. It can be corrected. Bias and long-term variability are controlled by monitoring measurements against a check standard over time.

*Random error* is a short-term scattering of values around a mean value. It cannot be corrected on an individual measurement basis. Random errors are expressed by statistical methods.



**Figure 2.** Main tasks of SI (<http://physics.nist.gov/cuu/units>), VIM ([http://www.abnt.org.br/ISO\\_DGuide\\_99999\(E\).pdf](http://www.abnt.org.br/ISO_DGuide_99999(E).pdf)), and GUM (<http://www.gum.dk/home.html>).

A fundamental source for theory and application of statistical methods is the NIST/SEMATECH Engineering Statistics Handbook (*NIST/SEMATECH e-Handbook of Statistical Method* – see <http://www.itl.nist.gov/div898/handbook/>, 26.03.2003).

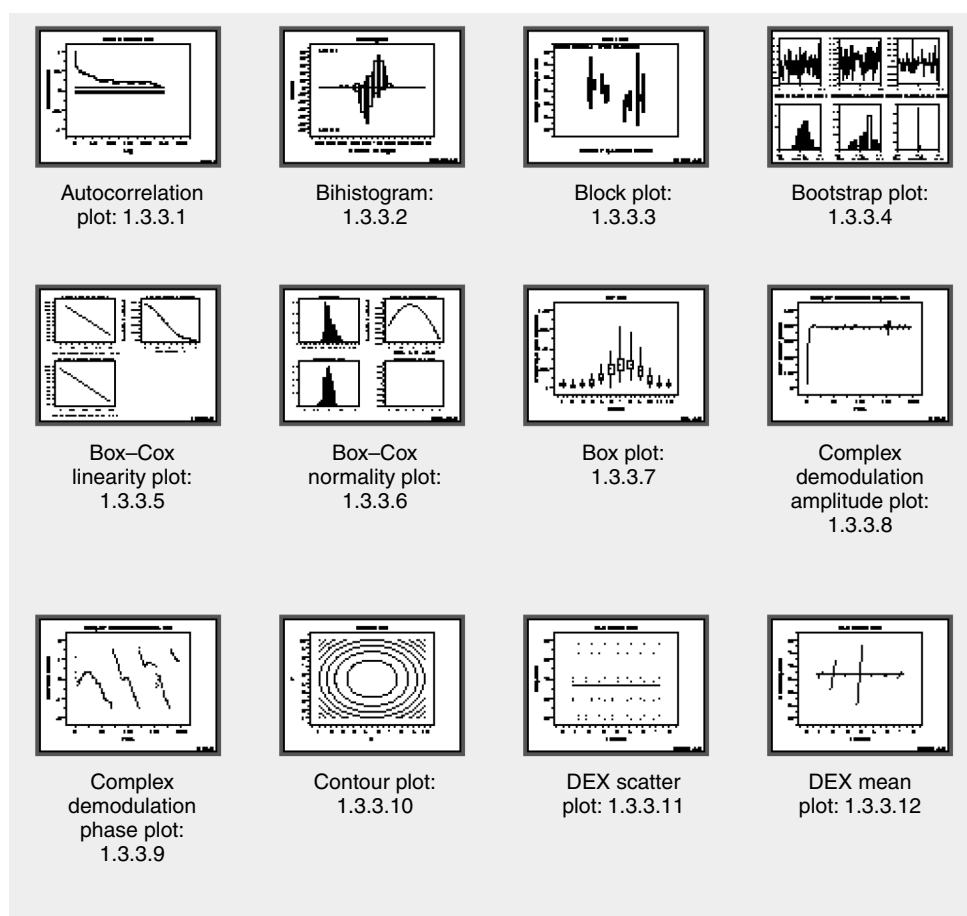
It describes, and uses in detail, the so-called EDA method. Exploratory data analysis (EDA) is an approach for

data analysis that employs a variety of techniques (mostly graphical) to

1. maximize insight into a data set,
2. uncover underlying structure,
3. extract important variables,
4. detect outliers and anomalies,
5. test underlying assumptions,
6. develop parsimonious models, and
7. determine optimal factor settings.

Most EDA techniques are graphical in nature with a few quantitative techniques included. The reason for the heavy reliance on graphics is that graphics gives the analysts unparalleled power to reveal the structural secrets of data and to be always ready to gain some new, often unsuspected, insight into the measured data in combination with the inherent pattern-recognition capabilities of man – see <http://www.itl.nist.gov/div898/handbook/eda/section1/eda11.htm>.

Most of the graphical techniques outlined in Figure 3 are demonstrated in the case studies given in the above-mentioned Web site.



**Figure 3.** Graphical techniques in alphabetical order see (excerpt) (<http://www.itl.nist.gov/div898/handbook/eda/section3/eda33.htm>).

## 5 LIST OF ERROR SOURCES IN MEASUREMENTS

*Systematic errors* or bias are repeatable errors existing with the specified source; these can be adjusted out or compensated for.

The terms ‘bias’ and ‘systematic error’ have the same meaning. Bias is defined in the International Vocabulary of Metrology, VIM, as the difference between the measurement result and its unknown ‘true value’. It can often be estimated and/or eliminated by calibration to a reference standard – see <http://www.itl.nist.gov/div898/handbook/mpc/section7/mpc7.htm#VIM>.

To investigate sources of systematic errors, a general checklist of error sources in measurement should be used, which has been collected by specialists working in the field concerned. The main sources are

### 5.1 Lack of gauge resolution

Resolution better called (but rarely done so) *discrimination* is the ability of the measurement system to detect and faithfully indicate small enough changes in the characteristic of the measurement result – see <http://www.itl.nist.gov/div898/handbook/mpc/section4/mpc451.htm>.

### 5.2 Lack of linearity

A test of linearity starts by establishing a plot of the measured values versus corresponding values of the reference standards. This obtains an indication of whether or not the points fall on a straight line with slope equal to 1, which indicates linearity (proportional variation) – see <http://www.itl.nist.gov/div898/handbook/mpc/section4/mpc452.htm>.

Nonlinearities of gauges can be caused by the following facts:

- gauge is not properly calibrated at the lower and upper ends of the operating range,
- errors in the values at the maximum or minimum range,
- worn gauge,
- internal design problems (in, say the electronic units of the gauge).

### 5.3 Drift

Drift is defined as a slow change in the response of a gauge.

Short-term drift is frequently caused by heat buildup in the instrument during the time of measurement. Long-term

drift is usually not a problem for measurements with short calibration cycles – see <http://www.itl.nist.gov/div898/handbook/mpc/section4/mpc453.htm>.

### 5.4 Hysteresis

Hysteresis is a retardation of the effect when the forces acting upon a body are changed (as in viscosity or internal friction); for example, a lagging in the values of resulting magnetization in a magnetic material (as iron) because of a changing magnetizing force. Hysteresis represents the history dependence of a physical system under real environmental conditions – see <http://www.lasp.cornell.edu/sethna/hysteresis/WhatIsHysteresis.html>.

Specific devices will possess their own set of additional error sources. A checklist needs to be developed and matured. The following is an example of such a list.

*Hall Effect measurement* error checklist – see <http://www.eeel.nist.gov/812/errs.htm>.

1. Are the probes or wires making good contact to the sample?
2. Are the contact *I-V* characteristics linear?
3. Is any contact much higher in the resistance than the others?
4. Do the voltages reach equilibrium quickly after current reversal?
5. Is there visible damage (cracks, especially around the contacts)?
6. Is the sample being used in the dark?
7. Is the sample temperature uniform?
8. Are dissimilar wiring materials used resulting in large temperature gradients across the wiring?

## 6 STANDARDS ON ERROR DESCRIPTION

Standards, when they are part of a single and coherent set of standards, promote market efficiency and expansion, foster international trade, encourage competition and lower barriers to market entry, diffuse new technologies, protect consumers against unsafe or substandard products, and provide trust and reliability – see <http://www.iso.ch/iso/en/commcentre/events/2002/standardsforservices.html>.

On the other hand, people talk about raising standards when they perceive slackness in the ropes of control, when they see a sloppiness infiltrating the verities of life, when they begin to be fearful about life-diminishing certainties. Talk of standards is to talk about conservation, about protecting the past in its imagined superiority and security, and defending the future through strong leadership – see <http://epaa.asu.edu/epaa/v6n10/c6.htm>.

Comprehensive and precise terminologies have an extraordinary importance to the industry. The following are examples:

ISO/TR 7178:1983

Liquid flow measurement in open channels – velocity-area methods – investigation of total error.

ISO 8655-6:2002

Piston-operated volumetric apparatus – Part 6: Gravimetric methods for the determination of measurement error.

ISO/IEC 10021-7:1997/Amd 1:1998

Security error diagnostic codes.

ISO/IEC 10166-2:1991/Amd 1:1995

Minor enhancement for additional error.

ISO 12142:2001

Electronic imaging – media error monitoring and reporting techniques for verification of stored data on optical digital data disks.

ISO 7509:2000

Plastic piping systems – glass-reinforced thermosetting plastic (GRP) pipes – determination of time for failure under sustained internal pressure.

ISO 10365:1992

Adhesives – designation of main failure pattern.

ISO 11782-1:1998

Corrosion of metals and alloys – corrosion fatigue testing – Part 1: Cycles to failure testing.

ISO 13953:2001

Polyethylene (PE) pipes and fittings – determination of the tensile strength and failure mode of test pieces from a butt-fused joint.

## 7 UNCERTAINTIES OF MEASUREMENTS

*Uncertainty* is a measure of the ‘goodness’ of a result. Without such a measure, it is impossible to judge the fitness of the value as a basis for making decisions relating to health, safety, commerce, or scientific excellence – see <http://www.itl.nist.gov/div898/handbook/mpc/section5/mpc5.htm>.

Uncertainty of measurement is a parameter associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be expected – see <http://physics.nist.gov/cuu/Uncertainty/glossary.html>.

In this model, 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, contribute to the dispersion. Typical examples for systematic effects are uncertainties of

- systematic errors that generally can be corrected either numerically or technically,

- measurement standards that generally are negligibly small in comparison with the uncertainty of the measurement system in total.

*Standard deviation* is the generally used parameter for expressing the value of uncertainty. It is defined as the point of inflection in the Gaussian normal distribution – see Figure 4 – of randomly scattering values.

*Evaluation of uncertainty* is an ongoing process that can consume time and resources. It can also require the services of someone who is familiar with statistical data analysis techniques – see <http://www.itl.nist.gov/div898/handbook/mpc/section5/mpc51.htm>.

*Measurement result* is the best estimate of the value of the measurand.

*Standard uncertainty* in the measurement result is expressed with a standard deviation – see <http://physics.nist.gov/cuu/Uncertainty/glossary.html>.

*Combined standard uncertainty* in the measurement result has to be calculated by the error propagation law for statistical characteristics.

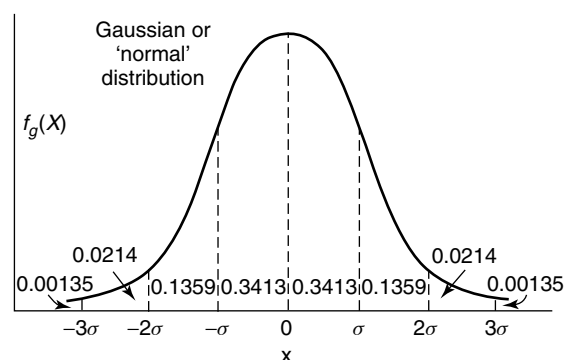
*Type A uncertainty* in the measurement result is expressed as a deviation evaluated by the method of statistical analysis from a series of observations.

*Type B uncertainty* in the measurement result is expressed as a deviation evaluated by methods other than the statistical analyses of series of observations.

*Expanded uncertainty* in the measurement result is expressed as the quantity of an interval that is large enough to include that fraction of the distribution function of the measured values that might be reasonably attributed to the measurand.

A special kind of expanded uncertainty is the confidence interval of a Gaussian normal distribution – see <http://mathworld.wolfram.com/GaussianDistribution.html> – where the factor  $a > 1$ .

Coverage factor is a numerical factor used as a multiplier or the combined standard uncertainty in order to obtain



**Figure 4.** The Gaussian normal distribution (<http://hyperphysics.phy-astr.gsu.edu/hbase/math/gaufcn.html>).

**Table 1.** Selected glossary of terms on error and uncertainty (<http://www.rit.edu/~vwlsp/uncertainties/uncertaintiespart2.html#glossary>).

Term	Brief definition
Absolute error	An error in a quantity, having the same units as the quantity. For $c = (2.95 \pm 0.07) \text{ m s}^{-1}$ , the absolute error is $0.07 \text{ m s}^{-1}$ .
Accuracy	How close a measurement is to being correct. $g = 9.7 \text{ m s}^{-2}$ on earth is more accurate than $g = 9.532706 \text{ m s}^{-2}$ . See <i>precision</i> .
Average	When several measurements of a quantity are made, the sum of the measurements divided by the number of measurements.
Average deviation	The average of the absolute value of the differences between each measurement and the average. See <i>standard deviation</i> .
Confidence level	The fraction of measurements that can be expected to lie within a given range.
Deviation	A measure of range of measurements from the average. Also called <i>error or uncertainty</i> .
Error	A measure of range of measurements from the average. Also called <i>deviation or uncertainty</i> .
Estimated uncertainty	An uncertainty estimated by the observer based on his or her knowledge of the experiment and the equipment.
Gaussian distribution	The familiar bell-shaped distribution, assumed for random errors. Also called <i>normal distribution</i> .
Independent variables	Changing the value of one variable has no effect on other variables. <i>Error propagation</i> assumes this independence.
Instrument limit of Error (ILE)	Smallest reading that an observer can make from an instrument. This is generally smaller than the <i>least count</i> .
Least count	Size of the smallest division on a scale. Typically the <i>ILE</i> equals the least count or 1/2 or 1/5 of the least count.
Precision	The number of significant figures in a measurement. $g = 9.532706 \text{ m s}^{-2}$ is more precise than $g = 9.7 \text{ m s}^{-2}$ .
Propagation of errors	Method of determining an uncertainty in a function of independent variables each with their own uncertainty.
Random error	Deviations from the 'true value' can be equally likely to be higher or lower than the true value. See <i>systematic error</i> .
Relative error	The ratio of absolute error to the average, $Dx/x$ . Also called percentage error or fractional uncertainty. See <i>absolute error</i> .
Standard deviation	The statistical measure of uncertainty. See <i>average deviation</i> .
Systematic error	A situation where all measurements fall above or below the 'true value'. To realize and correct systematic errors is difficult.
Uncertainty	A measure of range of measurements from the average. Also called <i>deviation or error</i> .

an expanded uncertainty of combined measurements – see <http://physics.nist.gov/cuu/Uncertainty/glossary.html>.

Problems of uncertainties and error propagation and their solutions are collected in <http://www.rit.edu/~vwlsp/uncertainties/Uncertaintiespart2.html#problems/>.

The issue of error and uncertainty is covered in more depth in **Article 54, Explanation of Key Error and Uncertainty Concepts and Terms, Volume 1** and other articles of the Subsection 'Errors and Uncertainty'.

## 8 GLOSSARY OF TERMS FOR ERRORS AND UNCERTAINTIES

A glossary of terms for errors and uncertainties is available that can be used as a checklist for error handling – see <http://www.rit.edu/~vwlsp/uncertainties/Uncertaintiespart2.html#glossary>.

Table 1 provides a selected glossary of terms on error and uncertainty from that source.

Terms used in the description of static system performance are also covered in **Article 57, Static Considerations of General Instrumentation, Volume 1** and **Article 58, Description of Accuracy, Linearity, and Drift, Volume 1**. Terms used to cover dynamic performance are dealt with in **Article 59, Introduction to the Dynamic Regime of Measurement Systems, Volume 1**.

## REFERENCE

The Web sites cited above are possibly the best sources of information on the terms and concepts for errors and uncertainty. Generally, texts are not sufficiently standardized – often using terms that are now defunct – to act as definitive sources; their use is, as other expressions of what is not an easy topic to be made crisp and accurate.