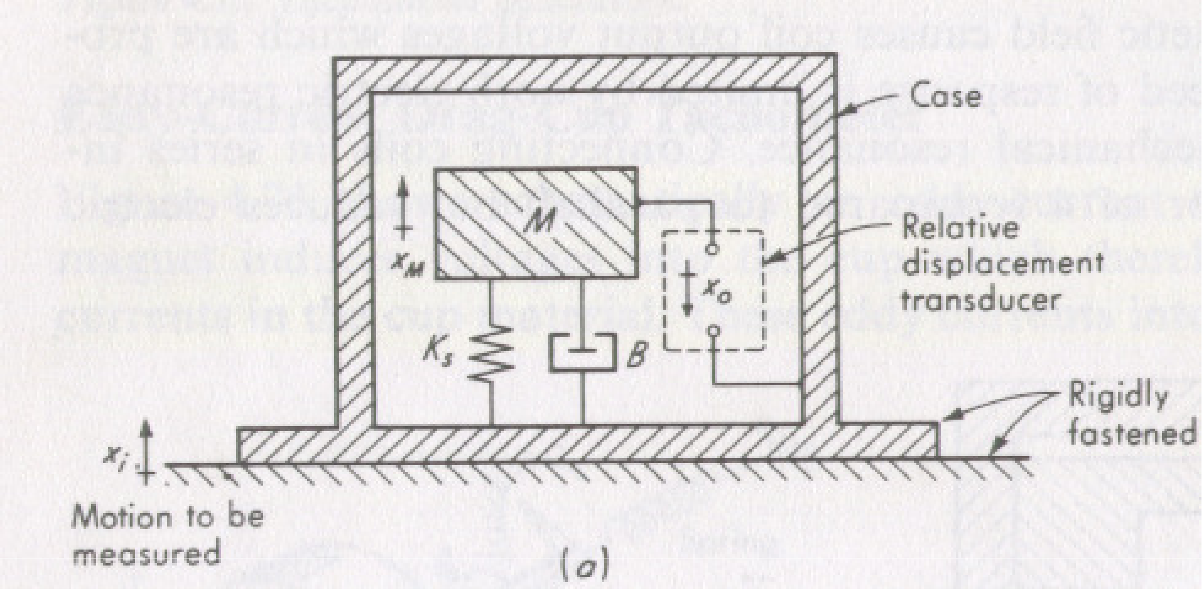
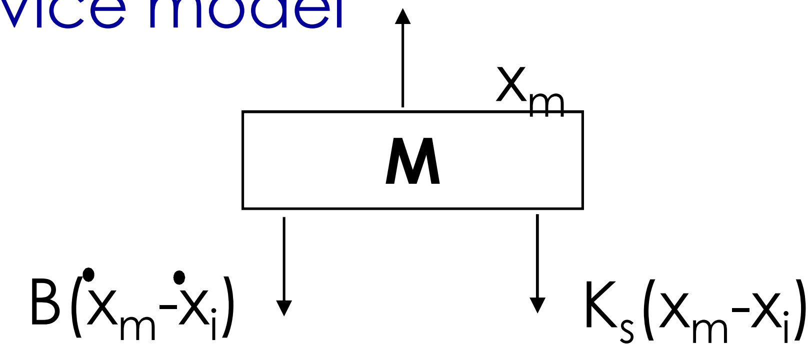
Class:	**Sensors and advanced measurement systems**
Prof:	**Bruno Ando’**
Objectives:	***Basics for design and synthesis of measurement systems***
Contents	• Resistive sensors: potentiometers, Strain Gauges and RTD sensors. • Conditioning electronics for resistive sensors • Reactive sensors: capacitive, Inductive, LVDT • Conditioning electronics for reactive sensors • Active sensors: Thermocouples, Piezoelectric and Ferroelectric sensors • Charge amplifier and measurement amplifier • Absolute sensors (displacement, velocity, acceleration) • Other sensors (Force, pressure, flux, etc.) • Digital sensors and ultrasound sensor • Multi-sensor systems and sensor networks • Innovative materials for sensors • Basics on technologies for sensors
Examination	Colloquium and laboratory report
Teaching materials	– Slides (to be considered only as a route for contents), available from: http://www2.diees.unict.it/users/bando/ando/didattica.html – Books: – *E. Doebelin:* Mesurement systems, Mc Graw Hill; – *Pallas-Areny J.G. Webster:* Sensors and Signal Conditioning;

Transducers

- Transducers convert a physical quantity in a electrical quantity, with obvious adavntages…



The device model


x_m

M

$B(\dot{x}_m-\dot{x}_i)$

$K_s(x_m-x_i)$

$$M\ddot{x}_m = -B(\dot{x}_m-\dot{x}_i)-k_s(x_m-x_i)$$

$$x_m - x_i = -x_o$$

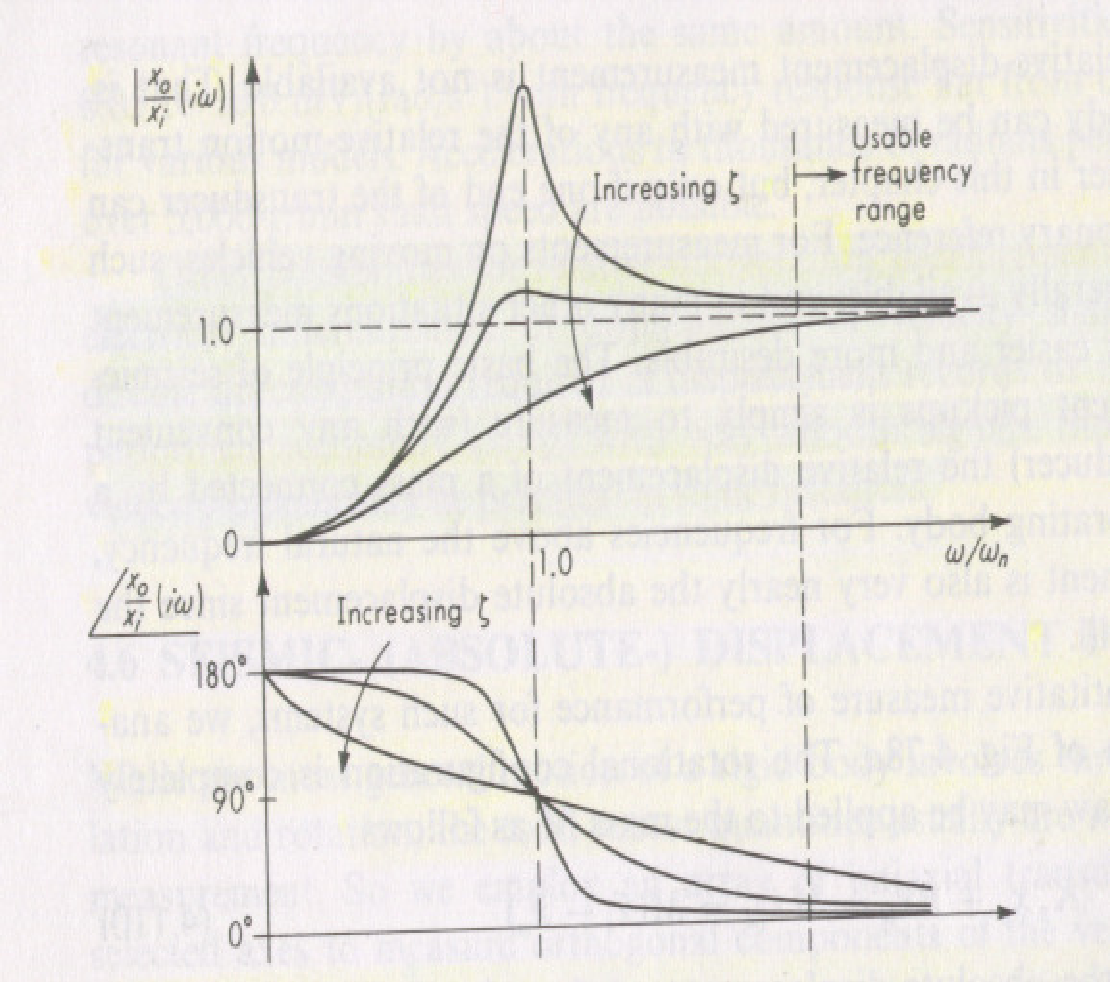
$$M(\ddot{x}_i-\ddot{x}_o) = B(\dot{x}_o)+k_s(x_o)$$

Seismic sensors

The device model (displacement)

$$\frac{x_o}{x_i}(s)=\frac{s^2}{s^2+2\zeta\omega_n s+\omega_n^2}$$

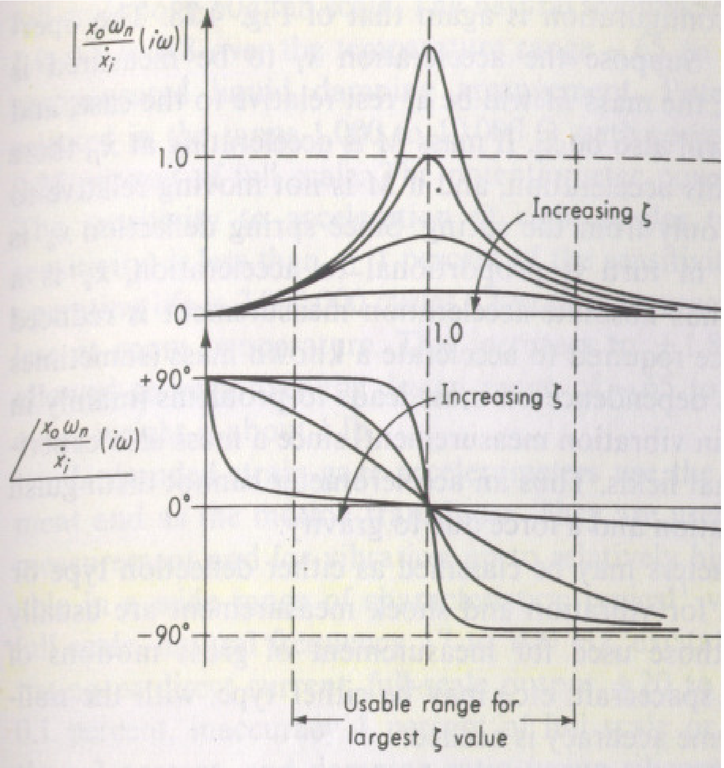
$$\omega_n=\sqrt{\frac{K_s}{M}}\,,\zeta=\frac{B}{2\sqrt{K_s M}}$$



Seismic sensors

The device model (velocity)

$$\frac{x_o}{\dot{x}_i}(s)=\frac{x_o}{s x_i}(s)=\frac{s}{s^2+2\zeta\omega_n s+\omega_n^2}$$

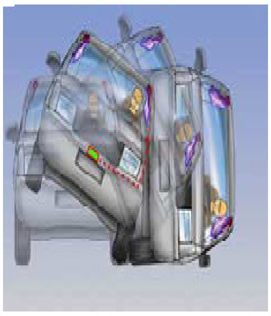


The device model (acceleration)

$$\frac{x_o}{\ddot{x}_i}(s)=\frac{x_o}{s^2 x_i}(s)=\frac{1}{s^2+2\zeta\omega_n s+\omega_n^2}$$

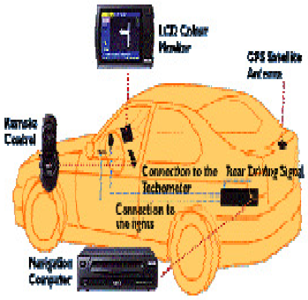
MEMS - Micromachined Inertial Sensors

Micromachined gyroscopes



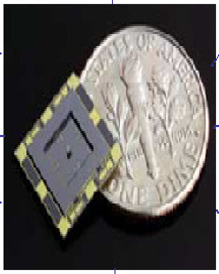
- Rollover detection

- GPS assisted inertial navigation for autos



- Tracking in virtual reality systems

- Camcorder stabilization



- Navigation in micro-robotics

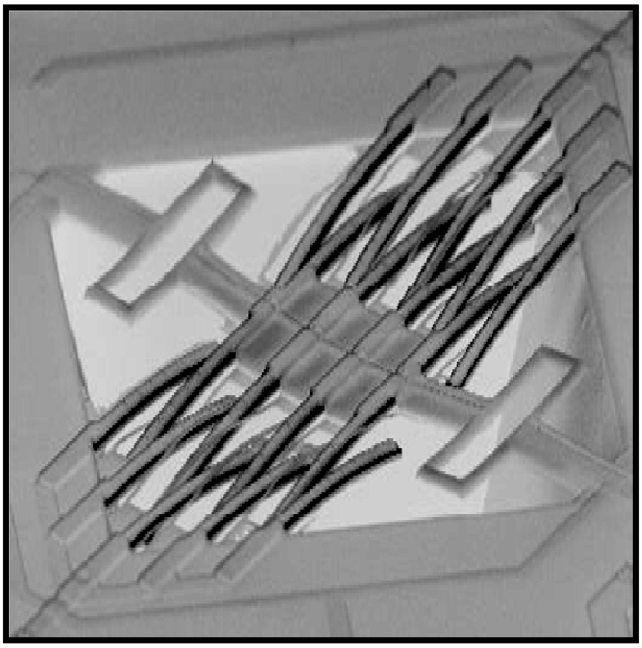
- Interactive pointing devices

- Implantable devices for inner-ear balance disorders

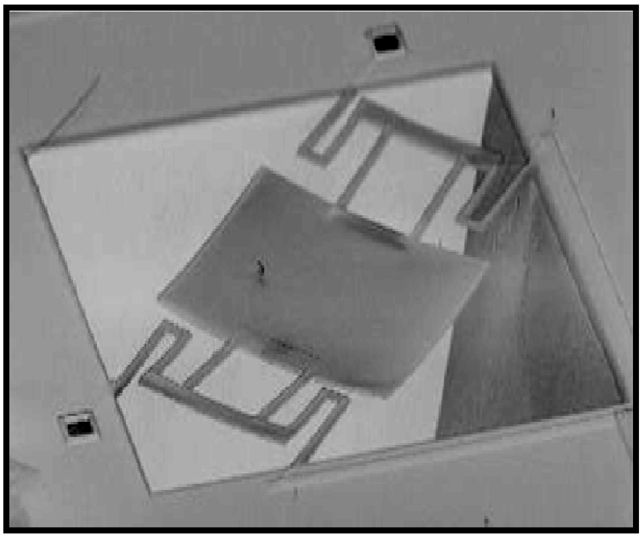
- 3-axis attitude sensing on micro satellites

MEMS - Micromachined Inertial Sensors

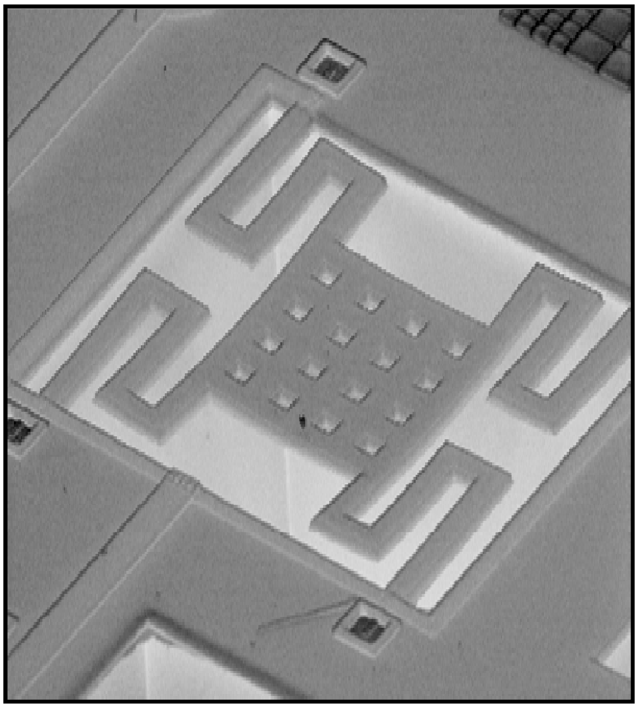
DEES IC1…TMAH etching procedures



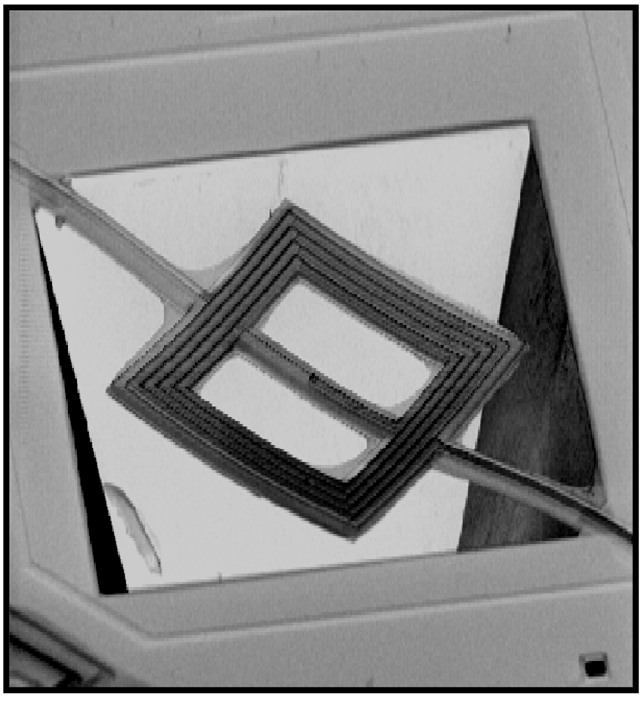
SEM image: interdigitated comb



SEM image: vertical resonator

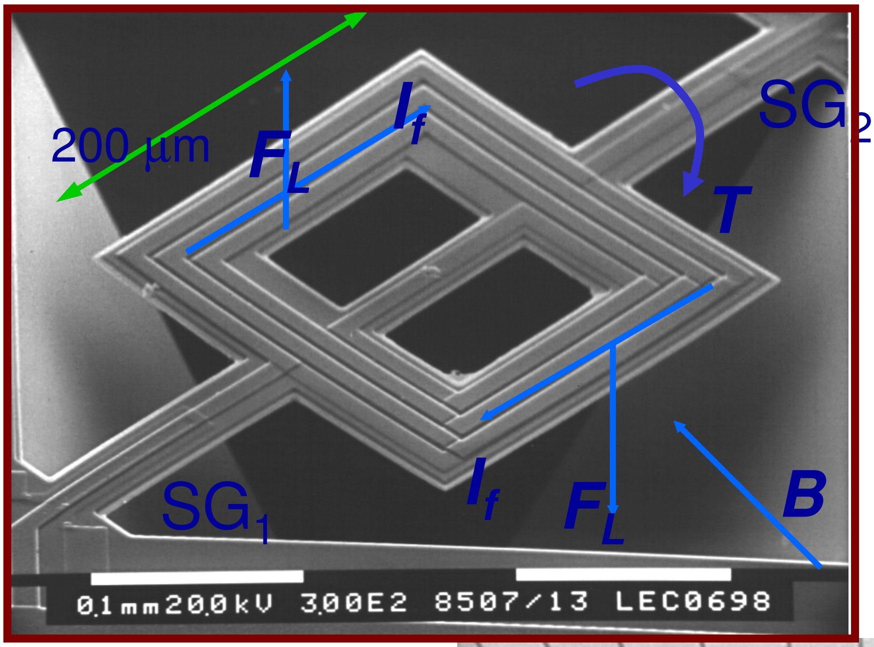


SEM image: vertical resonator

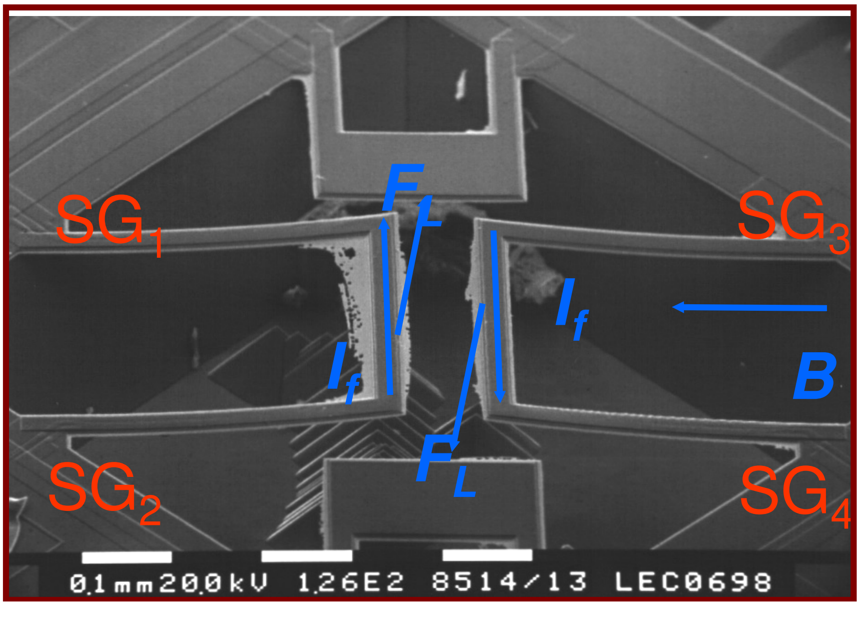


SEM image: magnetic torsional coils

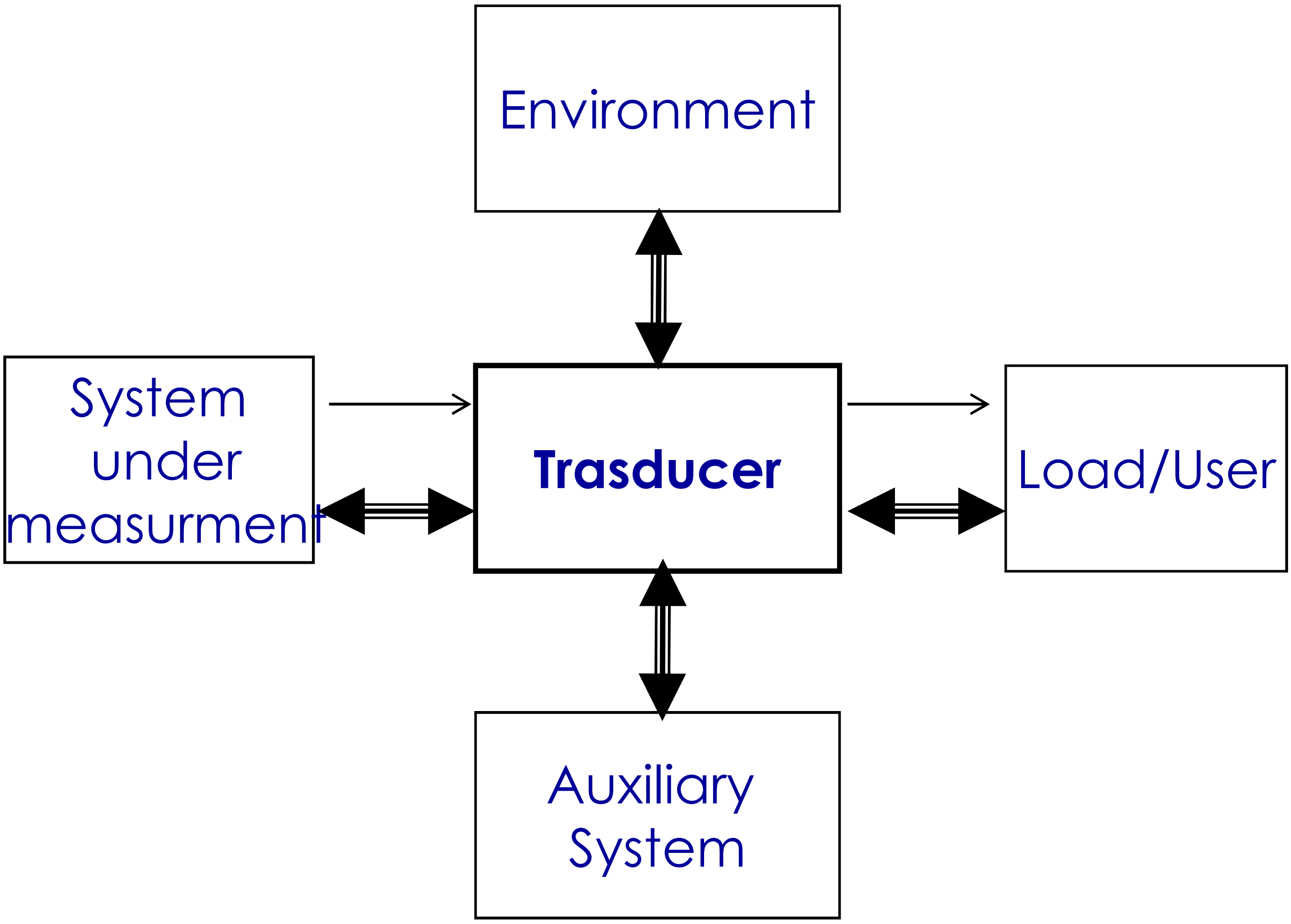
MEMS


200 µm
F_L
I_f
SG$_2$
T
SG$_1$
I_f
F_L
B
0.1mm20.0kV 300E2 8507/13 LEC0698


1mm20.0kV 374E1 8511/13 LEC0698


F_L
SG$_1$
SG$_3$
I_f
I_f
B
SG$_2$
F_L
SG$_4$
0.1mm20.0kV 126E2 8514/13 LEC0698

Introduction on sensors



Environment

System under measurment

Trasducer

Load/User

Auxiliary System

Classificazione di un trasduttore

- ***Formato dell'uscita(Output)***
  - *Specie*
  - *Campo di normale funzionamento (output range)*
  - *Valori di sovraccarico(output overload range)*
  - *Potenza erogabile (output power)*
  - *Impedenza d'uscita (output impedance)*
  - *Incertezza intrinseca dell'uscita*

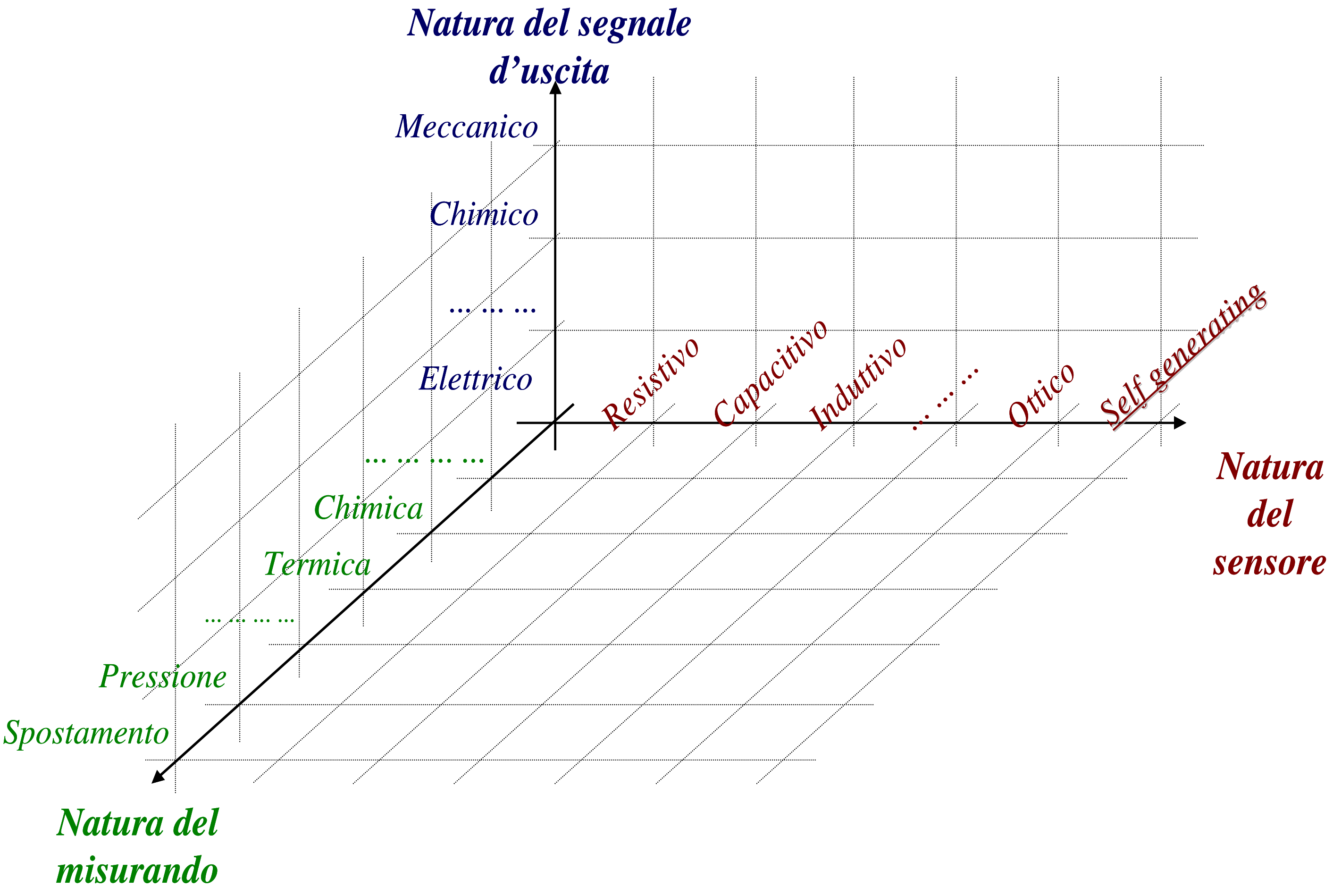
- *Il **comportamento energetico**:*
  - *trasduttori attivi*
  - *trasduttori passivi (adattamento di impedenza)*

- ***Alimentazione ausiliaria (Auxiliary supply)***

Introduction on sensors

Classification

- Output format
- Type of Measurand
- Readout strategy



Natura del segnale d’uscita

Meccanico

Chimico

… … …

Elettrico

Resistivo

Capacitivo

Induttivo

… … …

Ottico

Self generating

Natura del sensore

… … … …

Chimica

Termica

… … … …

Pressione

Spostamento

Natura del misurando

International Vocabulary of Metrology Basic and General Concepts and Associated Terms (VIM)

3rd Edition

Vocabulaire international de métrologie Concepts fondamentaux et généraux et termes associés (VIM)

3ème Édition

Prof. B. Andò

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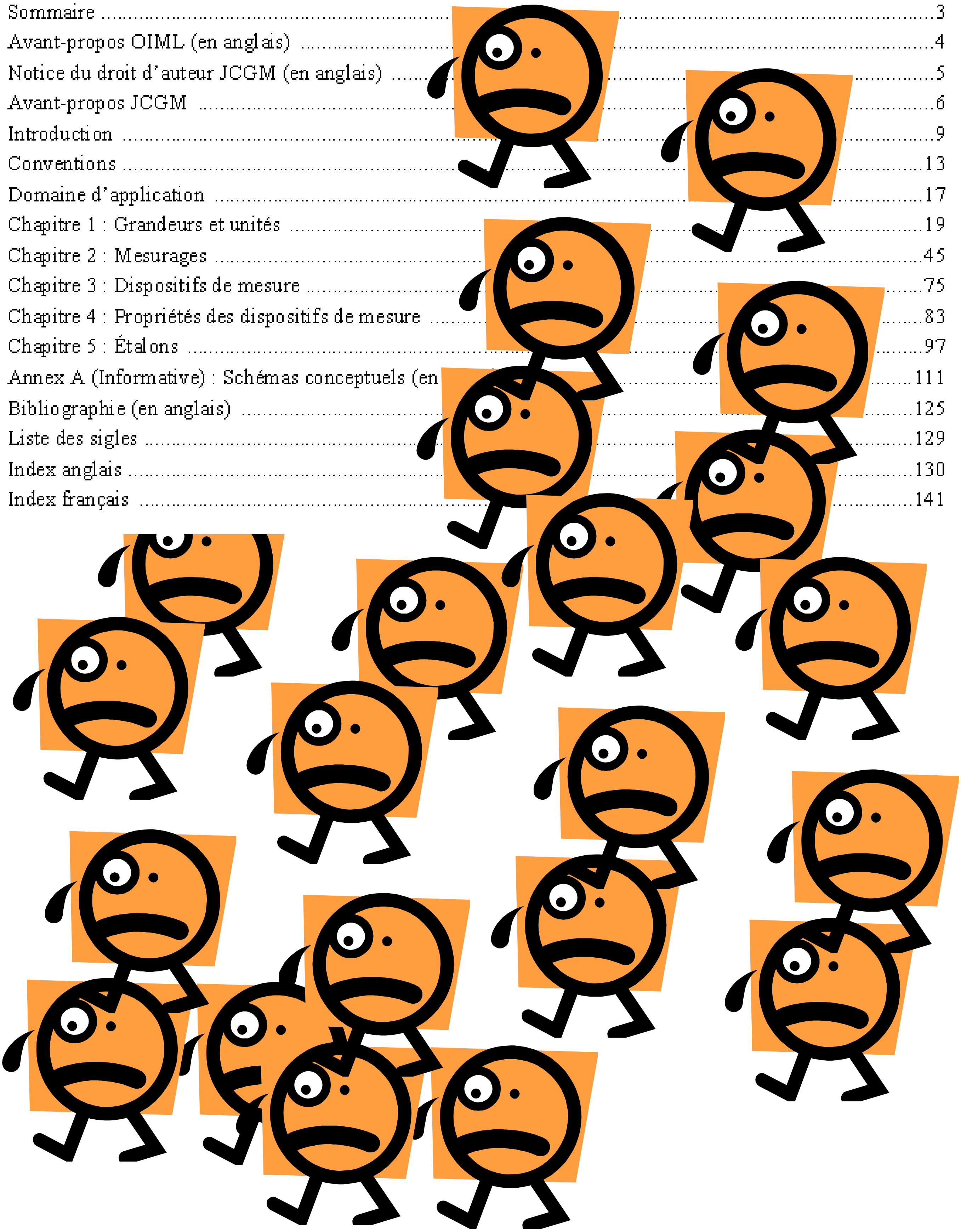

VIM

JCGM Foreword

In 1997 the Joint Committee for Guides in Metrology (JCGM), chaired by the Director of the BIPM, was formed by the seven International Organizations that had prepared the original versions of the Guide to the Expression of Uncertainty in Measurement (GUM) and the International Vocabulary of Basic and General Terms in Metrology (VIM).

The **Joint Committee** was originally made up of representatives from the

- International Bureau of Weights and Measures (BIPM), the
- International Electrotechnical Commission (IEC),
- the International Federation of Clinical Chemistry and
- Laboratory Medicine (IFCC),
- the International Organization for Standardization (ISO),
- the InternationalUnion of Pure and Applied Chemistry (IUPAC),
- the International Union of Pure and Applied Physics (IUPAP),
- the International Organization of Legal Metrology (OIML).

In 2005, the International Laboratory Accreditation Cooperation (ILAC) officially joined the seven founding international organizations.

VIM

Chapter 1: Quantities and units

1.1 (1.1)

quantity

property of a phenomenon, body, or substance, where the property has a magnitude that can be expressed as a number and a reference

Note 1 The generic concept ‘quantity’ can be divided into several levels of specific concepts, as shown in the following table. The left hand side of the table shows specific concepts under ‘quantity’. These are generic concepts for the individual quantities in the right hand column.

length, l	radius, r	radius of circle A, r_A or $r(A)$
	wavelength, λ	wavelength of the sodium D radiation, λ_D or $\lambda(D; Na)$
energy, E	kinetic energy, T	kinetic energy of particle i in a given system, T_i
	heat, Q	heat of vaporization of sample i of water, Q_i
electric charge, Q		electric charge of the proton, e
electric resistance, R		electric resistance of resistor i in a given circuit, R_i
amount-of-substance concentration of entity B, c_B		amount-of-substance concentration of ethanol in wine sample i, $c_i(C_2H_5OH)$
number concentration of entity B, C_B		number concentration of erythrocytes in blood sample i, $C(\text{Erys}; B_i)$
Rockwell C hardness (150 kg load), HRC(150 kg)		Rockwell C hardness of steel sample i, $\text{HRC}_i(150\text{ kg})$

VIM

1.2 kind of quantity

Kind: aspect common to mutually comparable **quantities**

EXAMPLE
The quantities diameter, circumference, and wavelength are generally considered to be quantities of the same kind, namely, of the kind of quantity called length.

Note 2 Quantities of the same kind within a given ***system of quantities have the same quantity dimension.***

1.3 system of quantities

set of **quantities together with a set of non-contradictory equations relating those quantities**

1.4 base quantity

quantity in a conventionally chosen subset of a given system of quantities, where no subset quantity can be expressed in terms of the others

Note 1 The subset mentioned in the definition is termed the “set of base quantities”.

1.5 derived quantity

quantity, in a system of quantities, defined in terms of the base quantities of that system
EXAMPLE
In a system of quantities having the base quantities length and mass, mass density is a derived quantity defined as the quotient of mass and volume (length to the third power).

1.6 International System of Quantities ISQ
system of quantities based on the **seven base quantities** ***length, mass, time, electric current, thermodynamic temperature, amount of substance, and luminous intensity***

Note 1 This system of quantities is published in the ISO 80000 and IEC 80000 series Quantities and units.
*Note 2 The **International System of Units (SI), see item 1.16, is based on the ISQ.***

……

1.9 measurement unit (unit of measurement)
real scalar **quantity, defined and adopted by convention, with which any other quantity of the same kind can** be compared to express the ratio of the two quantities as a number

1.10 base unit
measurement unit that is adopted by convention for a base quantity

EXAMPLE
In the **SI, the metre is the base unit of length. In the CGS systems the centimetre is the base unit of** length.

1.11 derived unit
measurement unit for a derived quantity

EXAMPLES
The metre per second, symbol m/s, and the centimetre per second, symbol cm/s, are derived units of speed in the **SI. The kilometre per hour, symbol km/h, is a measurement unit of speed outside the SI but accepted for** use with the SI.

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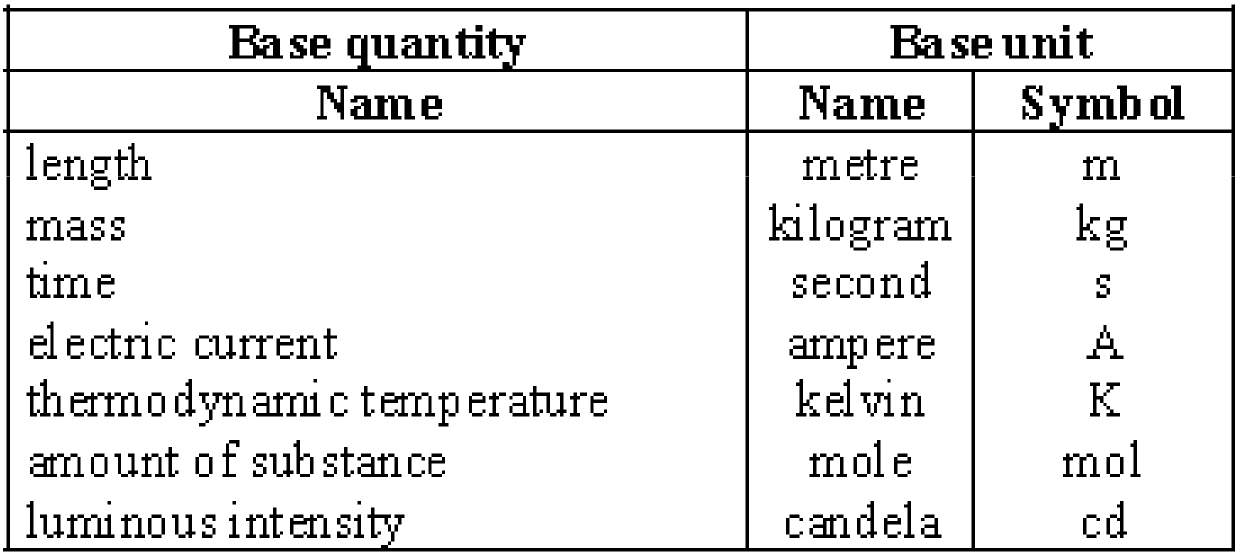
1.16 International System of Units (SI)

system of units based on the International System of Quantities, their names and symbols, including a series of prefixes and their names and symbols, together with rules for their use, adopted by the General Conference on Weights and Measures (CGPM)

Note 1 The SI is founded on the seven ***base quantities of the ISQ and the names and symbols of the*** corresponding **base units that are contained in the following table.**



Base quantity	Base unit	
Name	Name	Symbol
length	metre	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd

1.19 quantity value

value of a quantity

number and reference together expressing magnitude of a **quantity**

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2.1 measurement

process of experimentally obtaining one or more **quantity values that can reasonably be attributed to a quantity**

Note 3 Measurement presupposes a description of the quantity commensurate with the intended use of a **measurement result, a measurement procedure, and a calibrated measuring system operating** according to the specified measurement procedure, including the measurement conditions.

2.2 metrology

science of **measurement and its application**

Note Metrology includes all theoretical and practical aspects of measurement, whatever the ***measurement*** **uncertainty and field of application.**

2.3 measurand

quantity intended to be measured

Note 1 The specification of a measurand requires knowledge of the ***kind of quantity, description of the state of the phenomenon***, body, or substance carrying the quantity, including any relevant component, and the chemical entities involved.

Note 3 The ***measurement,*** including the measuring system and the conditions under which the measurement is carried out, **might change the phenomenon, body, or substance such that the quantity being measured may differ from the measurand as defined.** In this case adequate correction is necessary.

EXAMPLES

a) The potential difference between the terminals of a battery may decrease when using a voltmeter with a significant internal conductance to perform the measurement. The opencircuit potential difference can be calculated from the internal resistances of the battery and the voltmeter.

VIM

2.4 measurement principle
phenomenon serving as the basis of a **measurement**

EXAMPLES
a) Thermoelectric effect applied to the measurement of temperature.

2.5 measurement method
generic description of a logical organization of operations used in a **measurement**

Note Measurement methods may be qualified in various ways such as:

- substitution measurement method,
- differential measurement method, and
- null measurement method;

or

- direct measurement method, and
- indirect measurement method.

2.6 measurement procedure
detailed description of a **measurement according to one or more measurement principles and to a given measurement method, based on a measurement model and including any calculation to obtain a measurement result**

*Note 2 A measurement procedure can include a statement concerning a **target measurement uncertainty.***

2.7 reference measurement procedure
measurement procedure accepted as providing measurement results fit for their intended use in assessing measurement trueness of measured quantity values obtained from other measurement procedures for quantities of the same kind, in calibration, or in characterizing reference materials.

VIM

2.9 measurement result

set of **quantity values being attributed to a measurand together with any other available relevant** information

Note 1 A measurement result generally contains “relevant information” about the set of quantity values, such that some may be more representative of the measurand than others. This may be expressed in the form of a probability density function (PDF).

Note 2 A measurement result is generally expressed as a single ***measured quantity value and a*** **measurement uncertainty. If the measurement uncertainty is considered to be negligible for some** purpose, the measurement result may be expressed as a single measured quantity value. In many fields, this is the common way of expressing a measurement result.

2.10 measured quantity value

quantity value representing a measurement result

Note 1 For a ***measurement involving replicate indications, each indication can be used to provide a*** corresponding measured quantity value. This set of individual measured quantity values can be used to calculate a resulting measured quantity value, such as an average or median, usually with a decreased associated **measurement uncertainty.**

Note 4 In the GUM, the terms “result of measurement” and “estimate of the value of the measurand” or just “estimate of the measurand” are used for ‘measured quantity value’.

2.11 true quantity value (true value)
quantity value consistent with the definition of a quantity

Note 1 *In the Error Approach to describing* ***measurement, a true quantity value is considered unique and, in*** practice, unknowable. The Uncertainty Approach is to recognize that, owing to the **inherently incomplete amount of detail in the definition of a quantity**, there is not a single true quantity value but rather a set of true quantity values consistent with the definition.
However, this set of values is, in principle and in practice, unknowable.

Note 2 In the special case of a fundamental constant, the quantity is considered to have a single true quantity value.

Note 3 When the ***definitional uncertainty associated with the measurand is considered to be negligible*** compared to the other components of the **measurement uncertainty, the measurand may be** considered to have an "essentially unique" true quantity value. This is the approach taken by the GUM and associated documents, where the word "true" is considered to be redundant.

2.13 measurement accuracy

closeness of agreement between a **measured quantity value and a true quantity value of a measurand**

Note 1 The concept 'measurement accuracy' is not a ***quantity and is not given a numerical quantity value.***
A **measurement is said to be more accurate when it offers a smaller measurement error.**

Note 3 'Measurement accuracy' is sometimes understood as closeness of agreement between measured quantity values that are being attributed to the measurand.

2.15 measurement precision (precision)

closeness of agreement between **indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions**

Note 1 Measurement precision is usually expressed numerically by measures of imprecision, such as standard deviation, variance, or coefficient of variation under the specified conditions of measurement.

Note 2 The 'specified conditions' can be, for example, ***repeatability conditions of measurement,*** **intermediate precision conditions of measurement, or reproducibility conditions of measurement**

Note 3 Measurement precision is used to define ***measurement repeatability, intermediate measurement*** **precision, and measurement reproducibility.**

Note 4 Sometimes 'measurement precision' is erroneously used to mean ***measurement accuracy.***

VIM

2.16 measurement error

measured quantity value minus a reference quantity value

Note 1 The concept of 'measurement error' can be used both

a) when there is a single reference quantity value to refer to, which occurs if a **calibration is** made by means of a **measurement standard with a measured quantity value having a** negligible **measurement uncertainty or if a conventional quantity value is given, in** which case the measurement error is known, and

b) if a **measurand is supposed to be represented by a unique true quantity value or a set of** true quantity values of negligible range, in which case the measurement error is not known.

2.17 systematic measurement error

component of **measurement error that in replicate measurements remains constant or varies in a** predictable manner

Note 2 Systematic measurement error, and its causes, can be known or unknown. A ***correction can be*** applied to compensate for a known systematic measurement error.

Note 3 Systematic measurement error equals measurement error minus ***random measurement error.***

2.18 measurement bias

estimate of a **systematic measurement error**

2.19 random measurement error

component of **measurement error that in replicate measurements varies in an unpredictable manner**

Note 1 A ***reference quantity value for a random measurement error is the average that would ensue from*** an infinite number of replicate measurements of the same **measurand.**

VIM

2.20 repeatability condition of measurement
condition of measurement, out of a set of conditions that includes the same measurement procedure, same operators, same measuring system, same operating conditions and same location, and replicate measurements on the same or similar objects over a **short period of time**

2.24 reproducibility condition of measurement
condition of measurement, out of a set of conditions that includes different locations, operators, measuring systems, and replicate measurements on the same or similar objects

2.26 measurement uncertainty

non-negative parameter characterizing the dispersion of the **quantity values being attributed to a measurand, based on the information used**

Note 1 Measurement uncertainty includes components arising from systematic effects, such as components associated with ***corrections and the assigned quantity values of measurement standards, as well as*** *the* ***definitional uncertainty. Sometimes estimated systematic effects are not corrected for but,*** *instead, associated measurement uncertainty components are incorporated.*

Note 2 The parameter may be, for example, a standard deviation called ***standard measurement uncertainty (or a specified multiple of it), or the half-width of an interval, having a stated coverage probability.***

Note 3 Measurement uncertainty comprises, in general, many components. Some of these may be evaluated by ***Type A evaluation of measurement uncertainty from the statistical distribution of the quantity*** *values from series of* ***measurements and can be characterized by standard deviations. The other*** *components, which may be evaluated by* ***Type B evaluation of measurement uncertainty, can also*** *be characterized by standard deviations, evaluated from probability density functions based on experience or other information.*

Note 4 In general, for a given set of information, it is understood that the measurement uncertainty is associated with a stated quantity value attributed to the measurand. A modification of this value results in a modification of the associated uncertainty.

2.27 definitional uncertainty

component of **measurement uncertainty resulting from the finite amount of detail in the definition of a measurand**

Note 1 Definitional uncertainty is the practical minimum measurement uncertainty achievable in any **measurement of a given measurand.**

Note 2 Any change in the descriptive detail leads to another definitional uncertainty.

Note 3 In the GUM:1995, D.3.4, and in IEC 60359 the concept 'definitional uncertainty' is termed "intrinsic uncertainty". .

VIM

2.28 Type A evaluation of measurement uncertainty

evaluation of a component of **measurement uncertainty by a statistical analysis of measured quantity values obtained under defined measurement conditions**

*Note 1 For various types of measurement conditions, see **repeatability condition of measurement,*** **intermediate precision condition of measurement, and reproducibility condition of measurement.**

Note 2 For information about statistical analysis, see e.g. the GUM:1995.

2.29 Type B evaluation of measurement uncertainty

evaluation of a component of **measurement uncertainty determined by means other than a Type A evaluation of measurement uncertainty**

EXAMPLES
Evaluation based on information

- associated with authoritative published **quantity values,**
- associated with the quantity value of a **certified reference material,**
- obtained from a **calibration certificate,**
- about drift,
- obtained from the **accuracy class of a verified measuring instrument,**
- obtained from limits deduced through personal experience.

2.30 standard measurement uncertainty

measurement uncertainty expressed as a standard deviation

2.31 combined standard measurement uncertainty

standard measurement uncertainty that is obtained using the individual standard measurement uncertainties associated with the input quantities in a measurement model

2.32 relative standard measurement uncertainty

standard measurement uncertainty divided by the absolute value of the measured quantity value.

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2.36 coverage interval

interval containing the set of **true quantity values of a measurand with a stated probability, based on the** information available

2.37 coverage probability

probability that the set of **true quantity values of a measurand is contained within a specified coverage interval**

2.39 calibration

operation that, under specified conditions, in a first step ìestablishes a relation between the **quantity values** with **measurement uncertainties provided by measurement standards and corresponding indications with** associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a **measurement result from an indication**

Note 1 A calibration may be expressed by a statement, calibration function, ***calibration diagram,*** **calibration curve, or calibration table. In some cases it may consist of an additive or multiplicative correction of the indication with associated measurement uncertainty.**

Note 2 Calibration should not be confused with ***adjustment of a measuring system, often mistakenly*** called “self-calibration”, nor with **verification of calibration.**

Note 3 Often, the first step alone in the above definition is perceived as being calibration.

2.44 verification

provision of objective evidence that a given item fulfils specified requirements

2.45 validation

verification, where the specified requirements are adequate for an intended use

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2.47 metrological compatibility of measurement results
metrological compatibility property of a set of measurement results for a specified measurand, such that the absolute value of the difference of any pair of measured quantity values from two different measurement results is smaller than some chosen multiple of the standard measurement uncertainty of that difference

2.48 measurement model
mathematical relation among all quantities known to be involved in a measurement

2.49 measurement function
function of quantities, the value of which, when calculated using known quantity values for the input quantities in a measurement model, is a measured quantity value of the output quantity in the measurement model

2.52 influence quantity
quantity that, in a direct measurement, does not affect the quantity that is actually measured, but affects the relation between the indication and the measurement result

Chapter 3: Devices for measurement

3.1 measuring instrument

device used for making measurements, alone or in conjunction with one or more supplementary devices

3.2 measuring system

set of one or more measuring instruments and often other devices, including any reagent and supply, assembled and adapted to give information used to generate measured quantity values within specified intervals for quantities of specified kinds

3.3 indicating measuring instrument

measuring instrument providing an output signal carrying information about the value of the quantity being measured

EXAMPLES
a) Voltmeter,
b) micrometer,
c) thermometer,
d) electronic balance.

Note 2 An output signal may be presented in visual or acoustic form. It may also be transmitted to one or more other devices.

3.4 displaying measuring instrument

indicating measuring instrument where the output signal is presented in visual form

3.5 scale of a displaying measuring instrument

part of a displaying measuring instrument, consisting of an ordered set of marks together with any associated quantity values

3.8 sensor

element of a measuring system that is directly affected by a phenomenon, body, or substance carrying a quantity to be measured

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3.11 adjustment of a measuring system

set of operations carried out on a measuring system so that it provides prescribed indications corresponding to given values of a quantity to be measured

Note 1 Types of adjustment of a measuring system include ***zero adjustment of a measuring system, offset*** adjustment, and span adjustment (sometimes called gain adjustment).

Note 2 Adjustment of a measuring system should not be confused with ***calibration, which is a prerequisite*** for adjustment.

Note 3 After an adjustment of a measuring system, the measuring system usually must be recalibrated.

3.12 zero adjustment of a measuring system

adjustment of a measuring system so that it provides a null indication corresponding to a zero value of a quantity to be measured

Chapter 4: Properties of measuring devices

4.1 indication

quantity value provided by a measuring instrument or a measuring system

Note 1 An indication may be presented in visual or acoustic form or may be transferred to another device.
An indication is often given by the position of a pointer on the display for analog outputs, a displayed or printed number for digital outputs, a code pattern for code outputs, or an assigned quantity value for **material measures.**

*Note 2 An indication and a corresponding value of the **quantity being measured are not necessarily values*** of quantities of the same **kind.**

4.3 indication interval

set of quantity values bounded by extreme possible indications

Note 1 An indication interval is usually stated in terms of its smallest and greatest quantity values, for example, “99 V to 201 V”.

Note 2 In some fields the term is “range of indications”.

4.7 measuring interval (working interval)

set of values of quantities of the same kind that can be measured by a given measuring instrument or measuring system with specified instrumental uncertainty, under defined conditions

Note 1 In some fields the term is “measuring range” or “measurement range”.

Note 2 The lower limit of a measuring interval should not be confused with ***detection limit.***

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4.9 rated operating condition

operating condition that must be fulfilled during measurement in order that a measuring instrument or measuring system perform as designed

Note Rated operating conditions generally specify intervals of ***values for a quantity being measured and*** for any **influence quantity.**

4.10 limiting operating condition

extreme operating condition that a measuring instrument or measuring system is required to withstand without damage, and without degradation of specified metrological properties, when it is subsequently operated under its rated operating conditions

Note 1 Limiting conditions for storage, transport or operation can differ.
Note 2 Limiting conditions can include limiting ***values of a quantity being measured and of any influence*** **quantity**

4.12 sensitivity of a measuring system

quotient of the change in an indication of a measuring system and the corresponding change in a value of a quantity being measured

4.14 resolution

smallest change in a quantity being measured that causes a perceptible change in the corresponding indication

Note The resolution can depend on, for example, noise (internal or external) or friction. It may also depend on the **value of a quantity being measured.**

VIM

4.24 instrumental measurement uncertainty

component of measurement uncertainty arising from a measuring instrument or measuring system in use

Note 1 *Instrumental measurement uncertainty is obtained through calibration of a measuring instrument or* measuring system, except for a primary measurement standard for which other means are used.

Note 2 *Instrumental uncertainty is used in a Type B evaluation of measurement uncertainty.*

Note 3 *Information relevant to instrumental measurement uncertainty may be given in the instrument* specifications.

4.30 calibration diagram

graphical expression of the relation between indication and corresponding measurement result

Note 1 *A calibration diagram is the strip of the plane defined by the axis of the indication and the axis of the* measurement result, that represents the relation between an indication and a set of measured quantity values. A one-to-many relation is given, and the width of the strip for a given indication provides the instrumental measurement uncertainty.

Note 2 *Alternative expressions of the relation include a* ***calibration curve and associated measurement*** **uncertainty, a calibration table, or a set of functions.**

Note 3 *This concept pertains to a* ***calibration when the instrumental measurement uncertainty is large in*** comparison with the measurement uncertainties associated with the **quantity values of measurement standards.**

4.31 calibration curve

expression of the relation between indication and corresponding measured quantity value

Note A calibration curve expresses a one-to-one relation that does not supply a ***measurement result as it*** bears no information about the **measurement uncertainty.**

Chapter 5: Measurement standards (Etalons)

5.1 measurement standard

etalon

realization of the definition of a given quantity, with stated quantity value and associated measurement uncertainty, used as a reference

5.3 national measurement standard

measurement standard recognized by national authority to serve in a state or economy as the basis for assigning quantity values to other measurement standards for the kind of quantity concerned

5.4 primary measurement standard

measurement standard established using a primary reference measurement procedure, or created as an artifact, chosen by convention

5.5 secondary measurement standard

secondary standard

measurement standard established through calibration with respect to a primary measurement standard for a quantity of the same kind

5.6 reference measurement standard

measurement standard designated for the calibration of other measurement standards for quantities of a given kind in a given organization or at a given location

VIM

5.7 working measurement standard

measurement standard that is used routinely to calibrate or verify measuring instruments or measuring Systems

Note 1 A working measurement standard is usually calibrated with respect to a ***reference measurement*** **standard.**

Note 2 In relation to ***verification, the terms "check standard" or "control standard" are also sometimes used.***

5.8 travelling measurement standard

travelling standard

measurement standard, sometimes of special construction, intended for transport between different locations

EXAMPLE

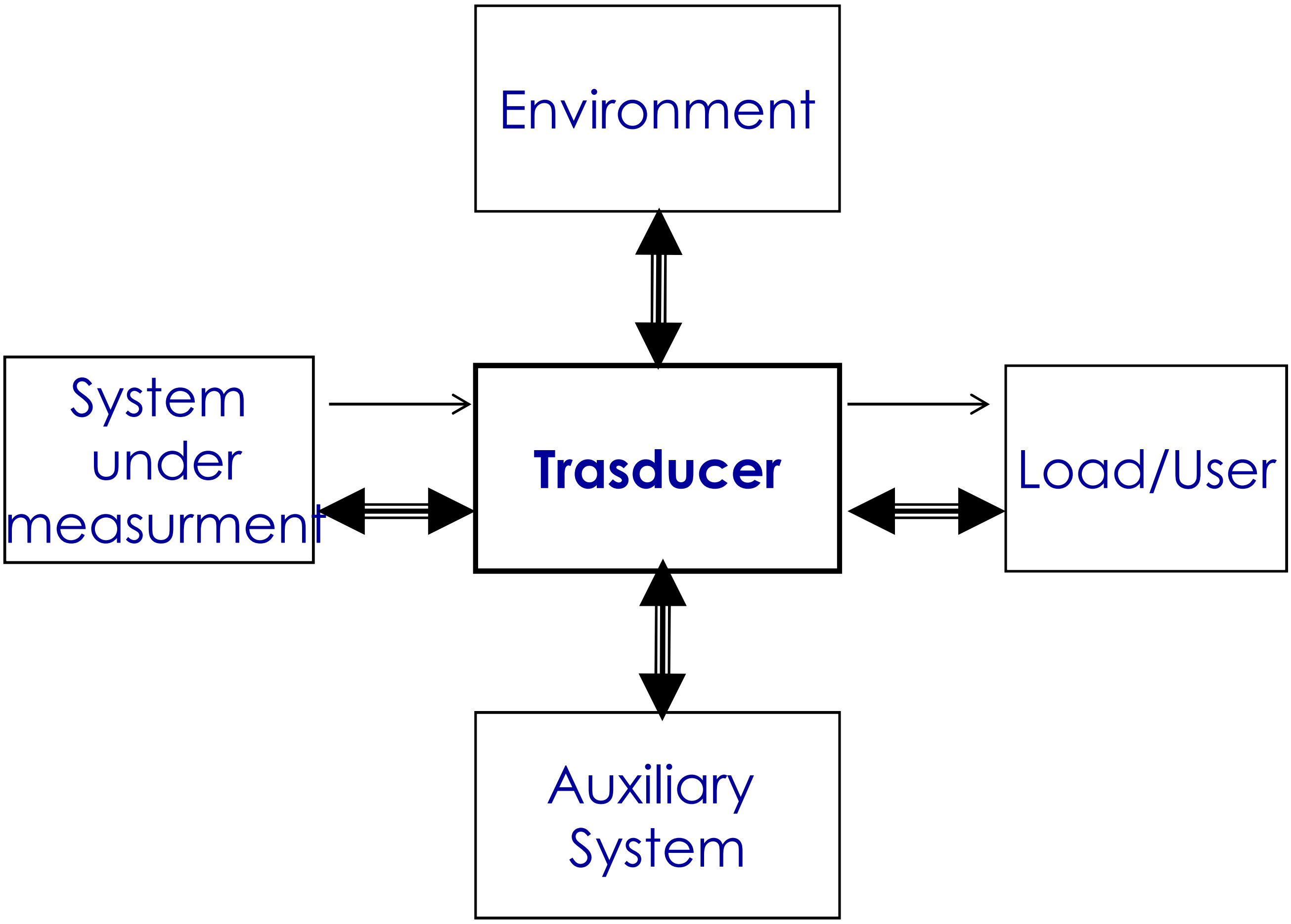
Portable battery-operated caesium-133 frequency measurement standard.

5.9 transfer measurement device

transfer device

device used as an intermediary to compare measurement standards

Introduction on sensors



Environment

System under measurment

Trasducer

Load/User

Auxiliary System

Classificazione di un trasduttore

- ***Formato dell'uscita(Output)***
  - *Specie*
  - *Campo di normale funzionamento (output range)*
  - *Valori di sovraccarico(output overload range)*
  - *Potenza erogabile (output power)*
  - *Impedenza d'uscita (output impedance)*
  - *Incertezza intrinseca dell'uscita*

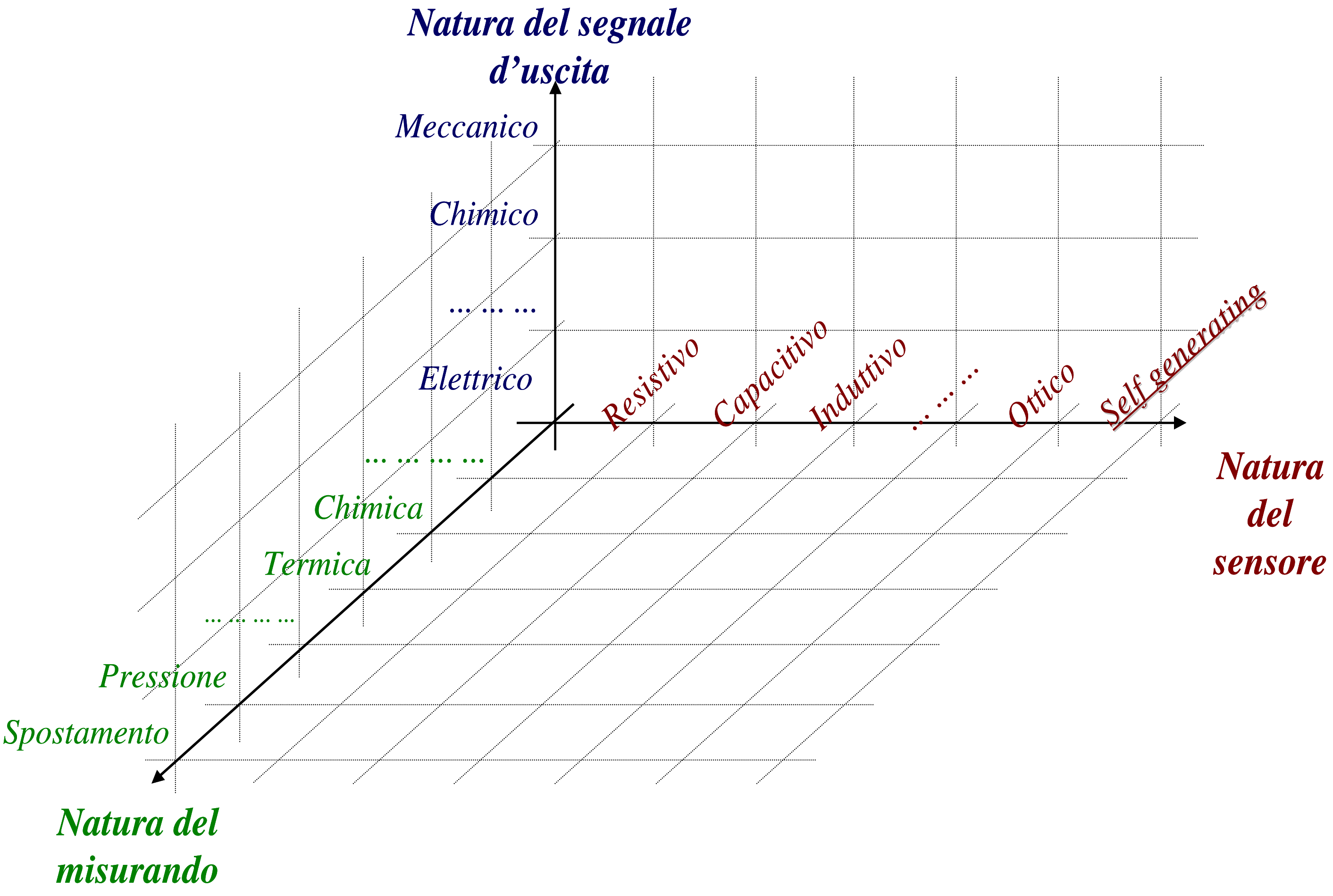
- Il ***comportamento energetico***:
  - *trasduttori attivi*
  - *trasduttori passivi (adattamento di impedenza)*

- ***Alimentazione ausiliaria (Auxiliary supply)***

Introduction on sensors

Classification

- Output format
- Type of Measurand
- Readout strategy



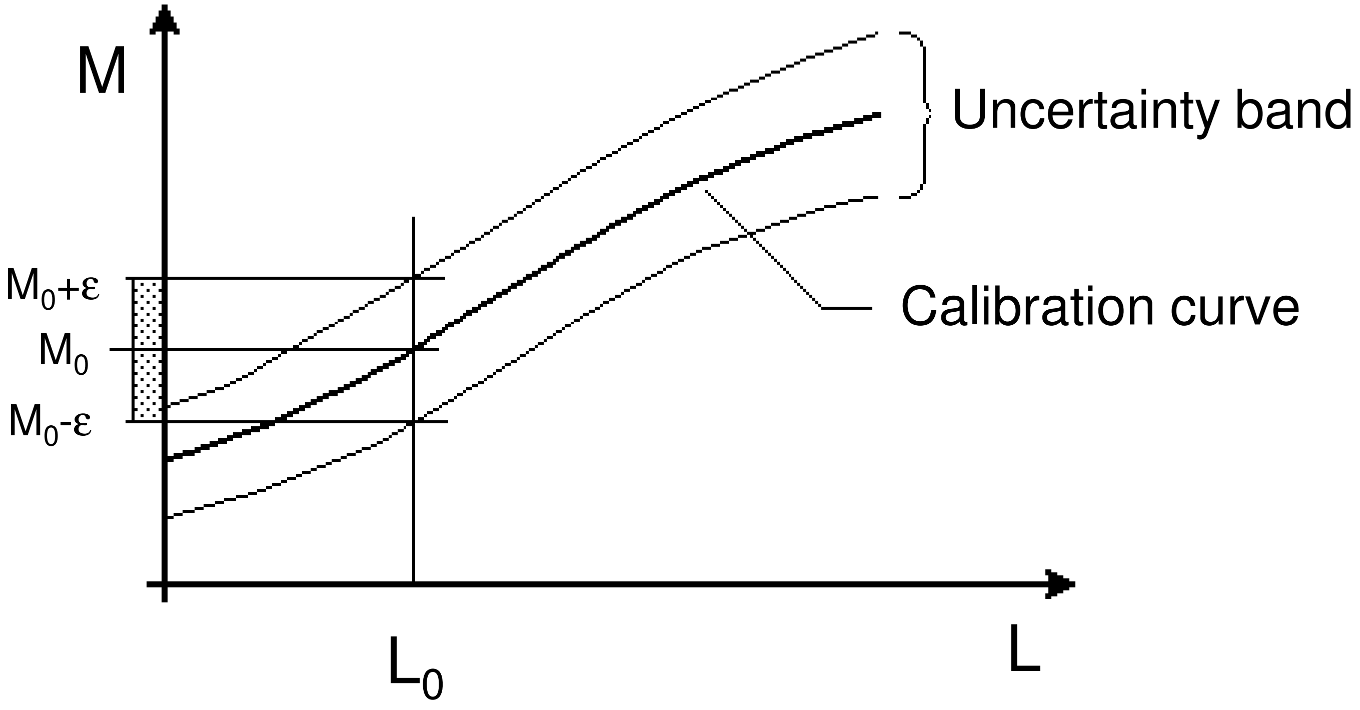
Introduction on sensors

Metrological Characteristics

Static metrological characteristics

Calibration diagram

- *Calibration curve*
- *Cal. Uncertainty*
- *Sensitivity*
- *Linearity*
- *Resolution*
- *Repeatibility*
- *Hysteresis*
- *Stability*



Basics on sensors

- Transduction fucntion

$$y(t)=f[x(t)]$$

- *Calibration function*

$$x(t)=f^{-1}[y(t)]$$

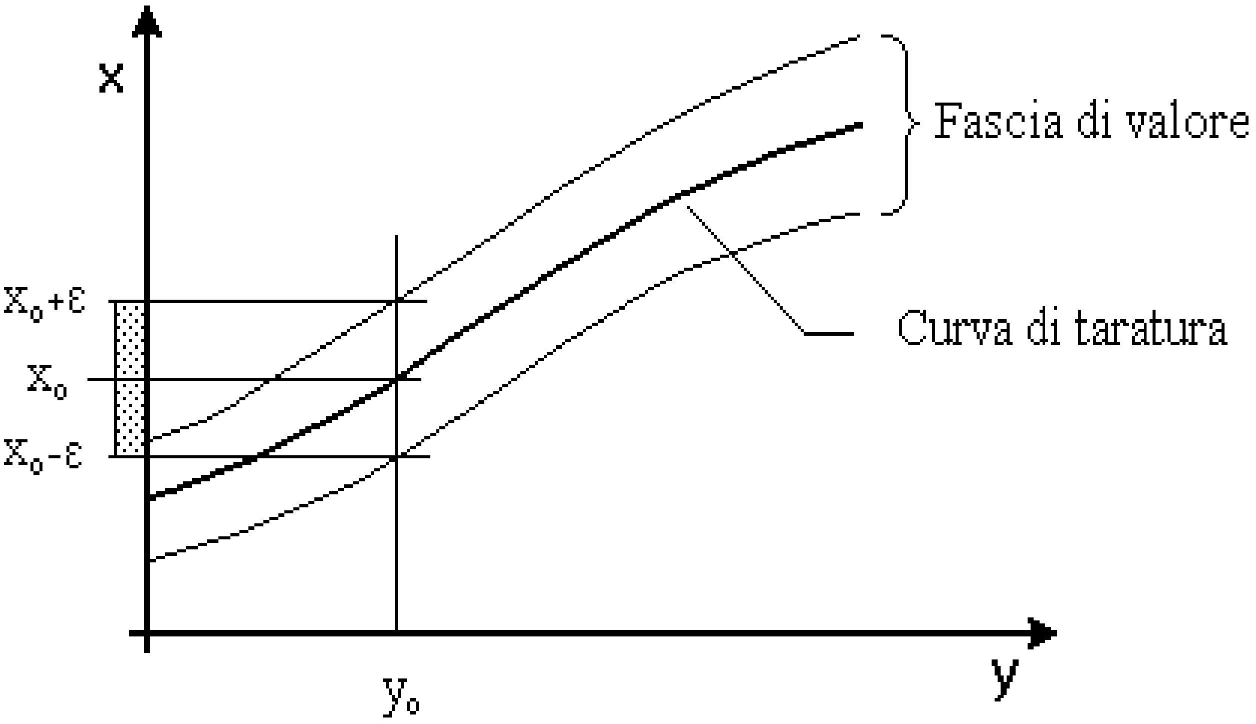
- Influencing quantities:

$$x(t)=f[y(t),\bullet]$$

- The time:

$$x(t)=f[y(t),\bullet,t]$$

Basics on sensors



- The **sensitivity** is ratio between output variation due and the input variation

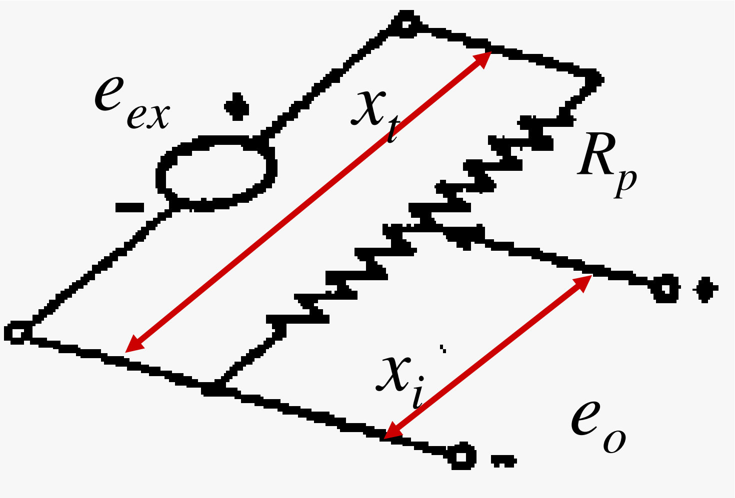
- Its value is the inverse of the slope of the tangent in one point of the curve

- In case of a linear fuinction it coincides with the inverse of the function slope

Basics on sensors

Sensitivity

Example: *the potentiometer*



$$R_0 = R_p \frac{x_i}{x_t}$$

$$S = \frac{DR_0}{Dx_i} = \frac{R_p}{x_t}$$

$$S = \frac{e_{ex}}{x_t} = \frac{\sqrt{PR_p}}{x_t}$$

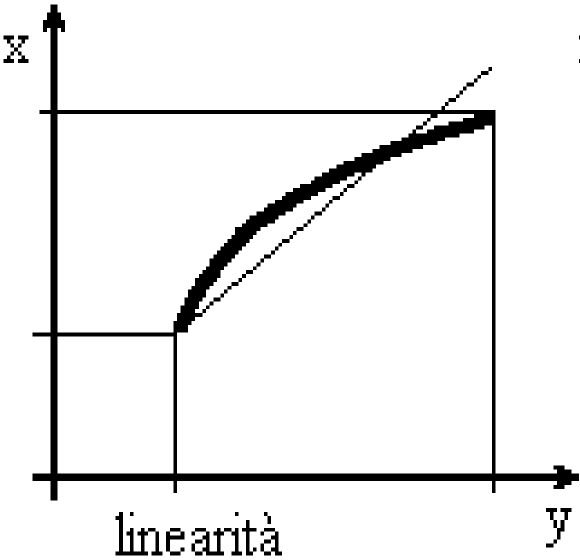
Basics on sensors

……. Other metrological characteristics

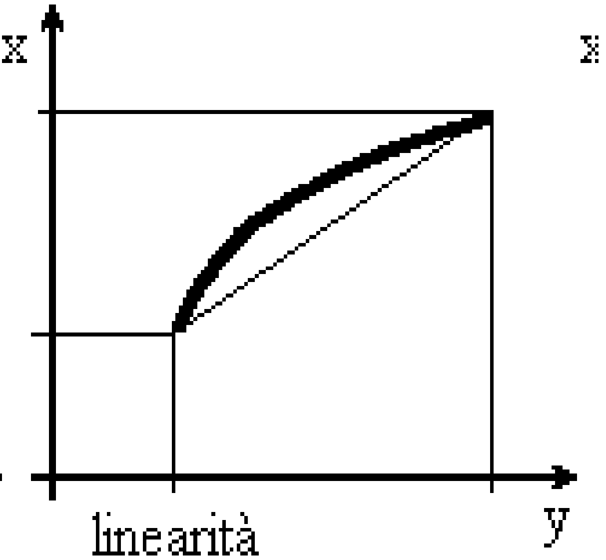
- Resolution
- Repeatibility
- Reproducibility
- Linearity

Basics on sensors

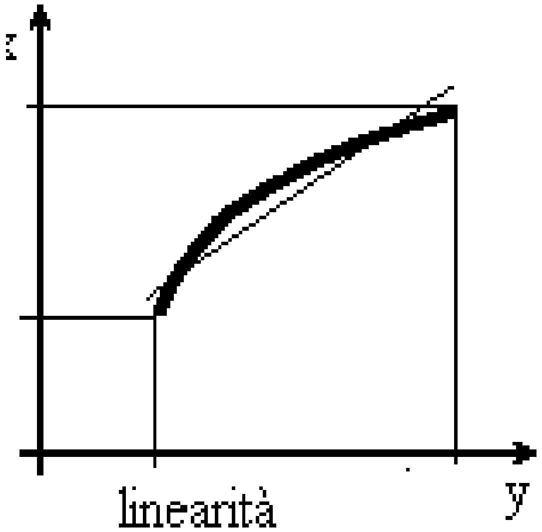
- Linearity: disclosure between the calibration curve and a linear model



linearità
riferita allo zero



linearità
riferita agli estremi

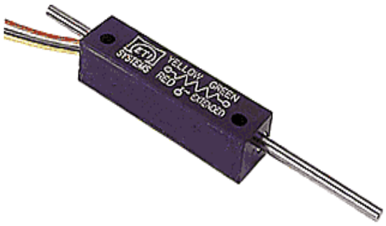


linearità
indipendente

Basics on sensors

Non linearity can be included in the uncertainty band!!!

Example:



Potentiometer

R= *20* Ω;

P=*0.1* W;

Range: *2* cm;

Linearity error: *0.05* FSO

$$S = \frac{R}{X} = \frac{20}{2} = 10\,\Omega/\mathrm{cm}$$

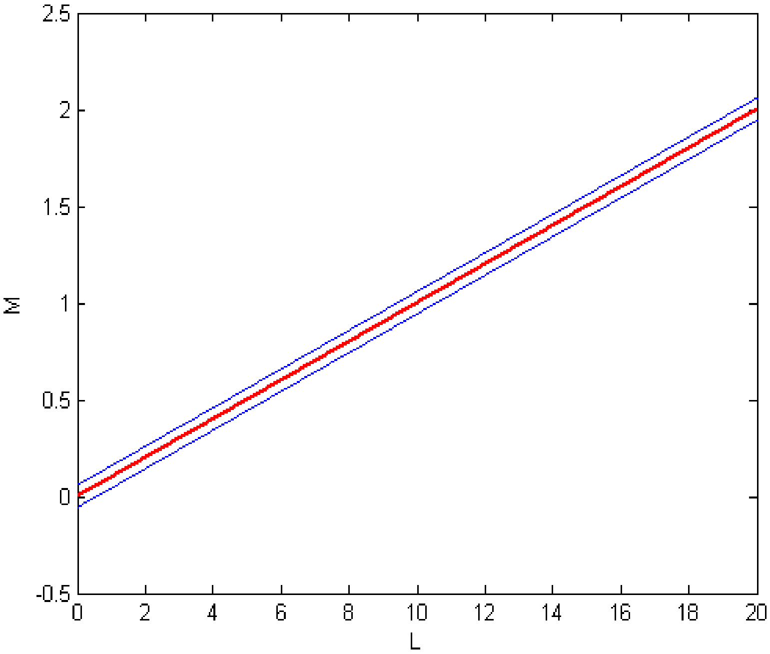
The uncertainty given by the linearity error is:

$$\frac{0.05 * FSO}{\sqrt{3}} = \frac{0.05 * 2}{\sqrt{3}} = 0.06\,\mathrm{cm}$$

Basics on sensors

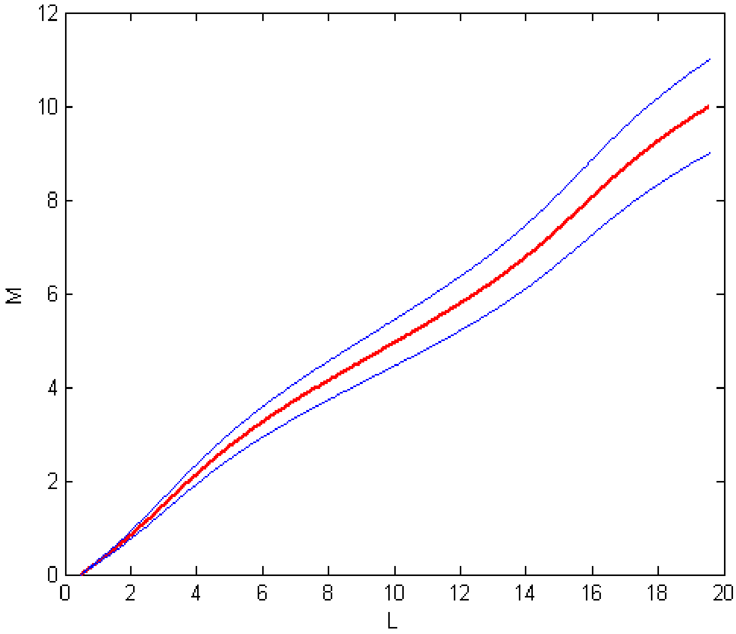
Non linearity uncertainty

Absolute constant value model



The above model compromise low values of the operating range

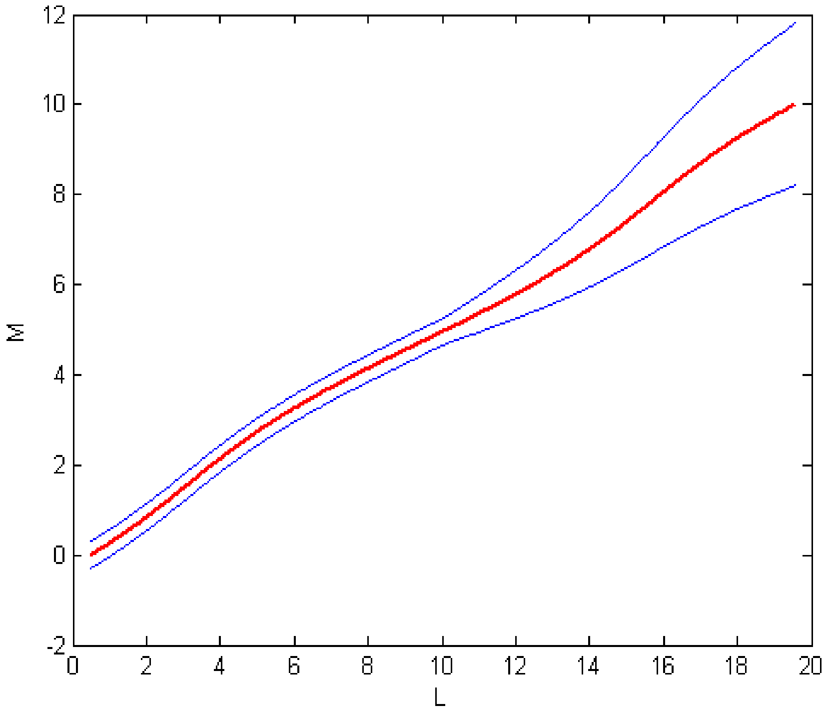
Relative Value Model



The above model produces problems for low values of the operating range

Basics on sensors

Mixed model



Type	Tolerance class 1 (°C)	Tolerance class 2 (°C)	Tolerance class 3 (°C)
Type T			
Temperature	-40≤t≤125	-40≤t≤133	-67≤t≤40
Tolerance	±0,5	±1	±1
Temperature	125≤t≤350	133≤t≤350	-200≤t-67
Tolerance	±0,004•|t|	±0,0075•|t|	±0,015•|t|
Type E			
Temperature	-40<t≤375	-40≤t≤333	-167≤t≤40
Tolerance	±1,5	±2,5	±2,5
Temperature	375≤t≤800	333≤t≤900	-200≤t≤-167
Tolerance	±0,004•|t|	±0,0075•|t|	±0,015•|t|
Type J			
Temperature	-40<t≤375	-40≤t≤333	-
Tolerance	±1,5	±2,5	-
Temperature	375≤t≤750	333≤t≤750	-
Tolerance	±0,004•|t|	±0,0075•|t|	-

Basics on sensors

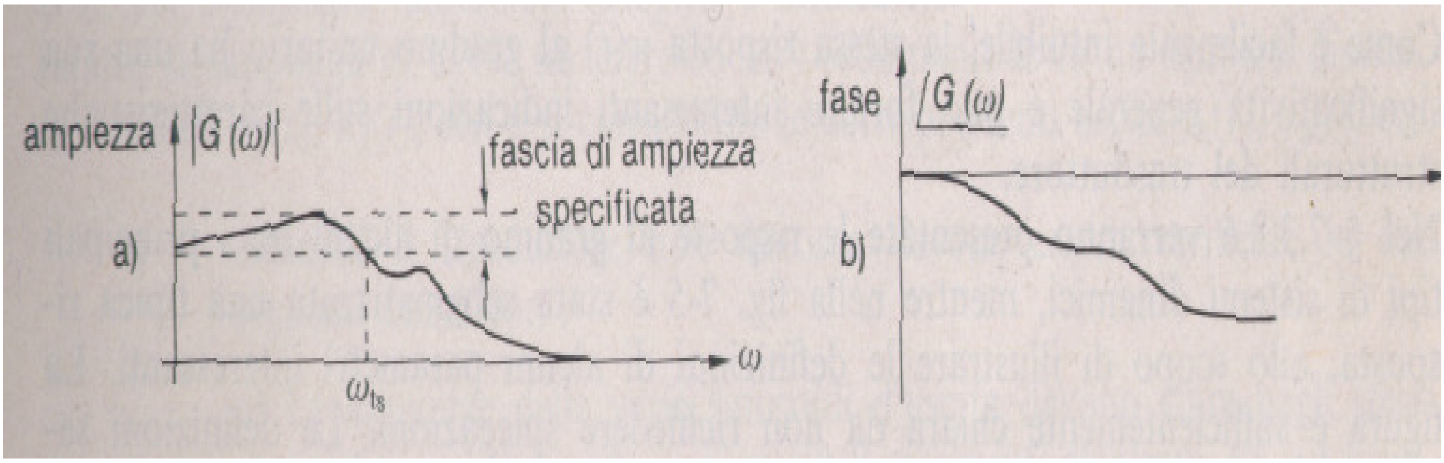
- ***Caratteristiche metrologiche in regime dinamico (Dynamic characteristics)***

  - *Risposta in frequenza (Frequency response)*

Campo di frequenze di non distorsione (Frequency range)

Frequency interval assuring a frequency response which amplitude is within a defined tolerance band.

  - *Frequenza di risonanza (Resonant frequency)*



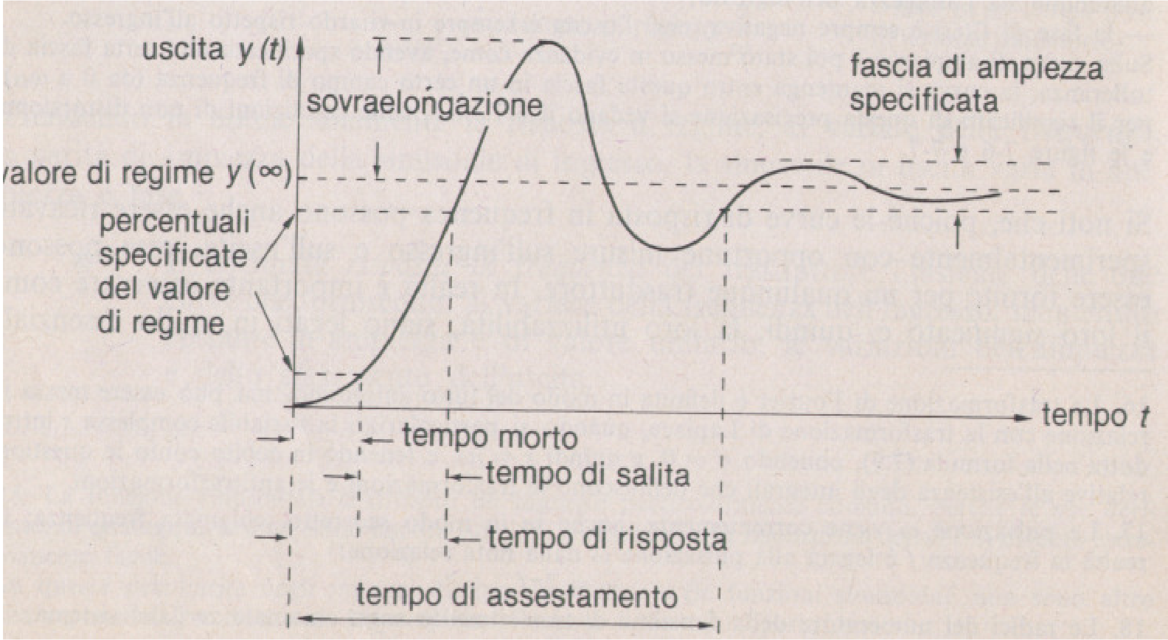
Basics on sensors

- ***Caratteristiche metrologiche in regime dinamico (Dynamic characteristics)***

  Risposta al gradino (Step responce)

  - *Sovraelongazione (Overshoot)*
  - *Tempo morto (Deat time)*
  - *Tempo di salita (Rise time)*
  - *Tempo di risposta (Response time)*
  - *Tempo di assestamento (Settling time)*
  - *Frequenza delle oscillazioni di assestamento (Ringing frequency)*

- *Risposta libera (natural responce)*



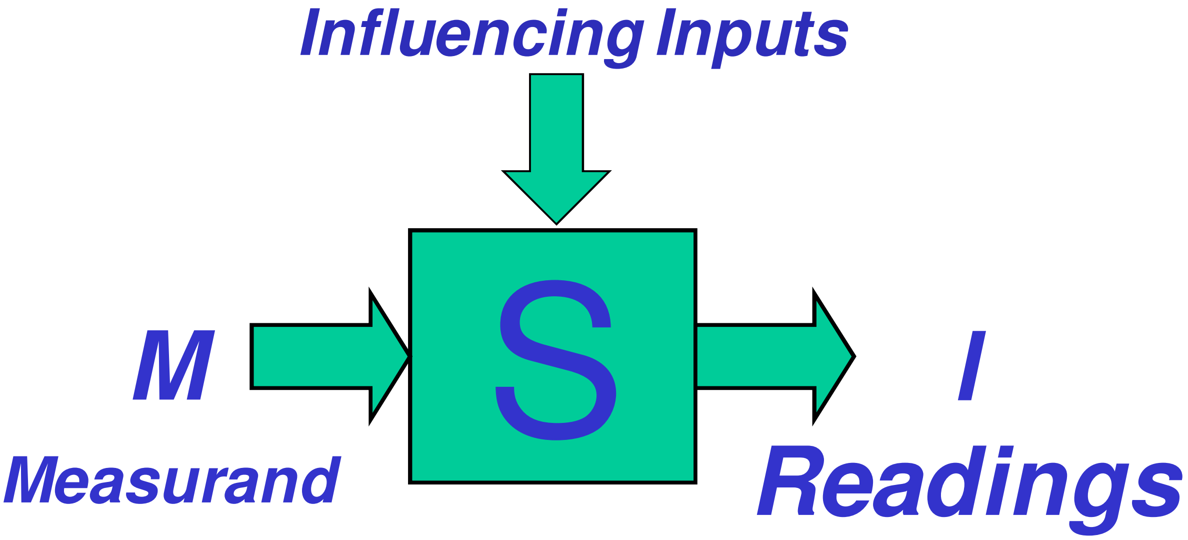
Basics on sensors

- ***Tempo di vita (Life Time)***
  - *Numero di cicli (cicling life)*
  - *Tempo di funzionamento (operating life)*
  - *Tempo di magazzino (storage life)*
  - *Affidabilità: è dovuta a **guasti** o da **debolezza** strutturale del sensore o da funzionamento al di fuori dei limiti di **sicurezza:***
    - **Degradazione:** Variazione graduale delle caratteristiche nel tempo
    - **Rottura:** Improvvisa degradazione delle caratteristiche.

- ***MTBF (Mean time between failure - tempo medio fra guasti)***

MTBF = (N. dispositvi in esame x N. ore di uso) / N. totale di guasti

Calibration



Influencing Inputs

M

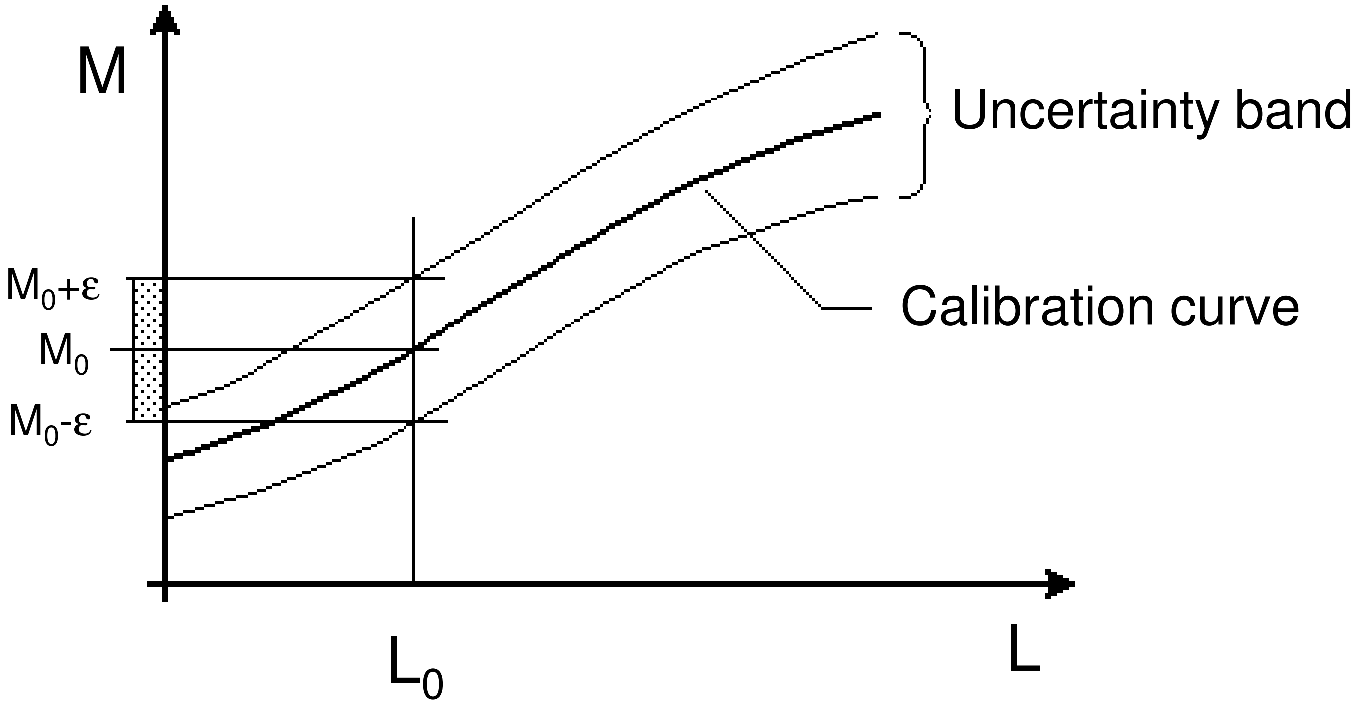
Measurand

S

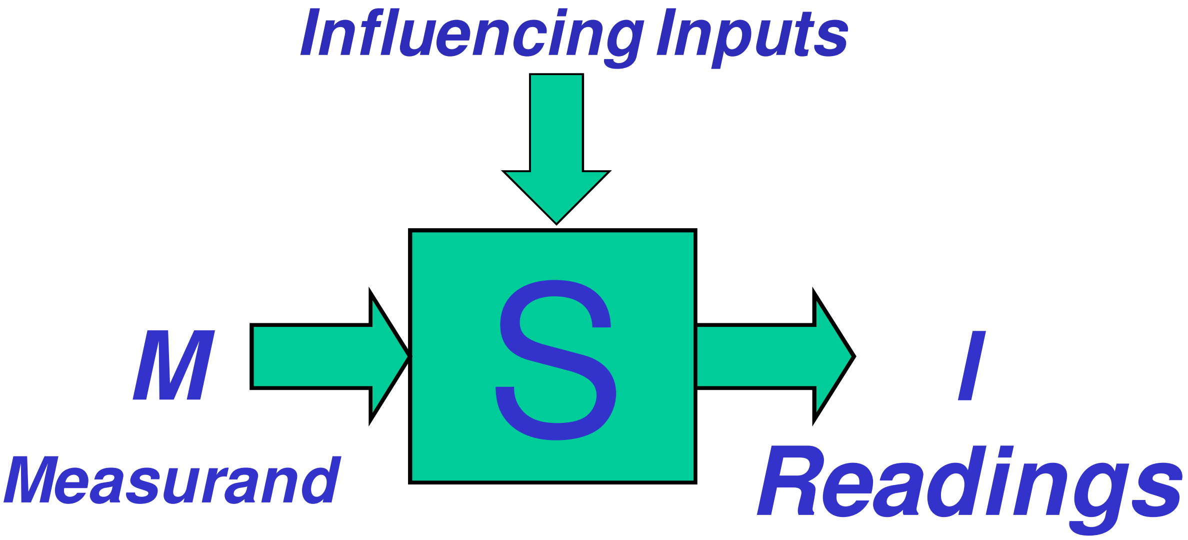
I

Readings

- The calibration is a procedure aimed to estimate the metrological characteristics of a device (sensor, instrument).
- Static calibration and dynamic calibration



Calibration



Influencing Inputs

M

Measurand

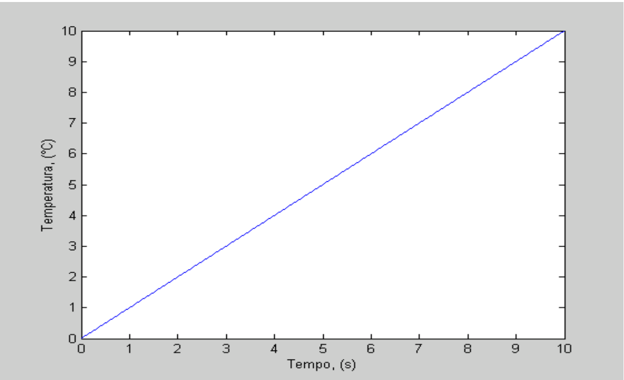
S

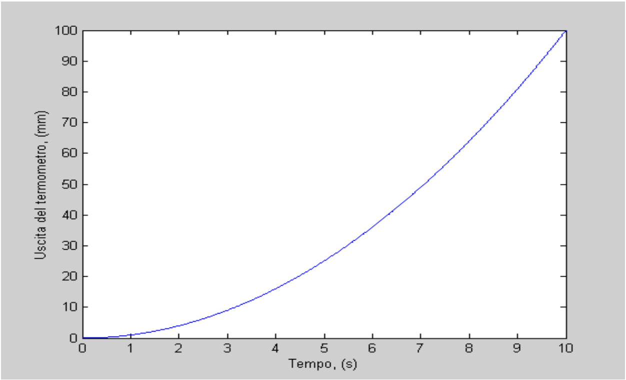
I

Readings

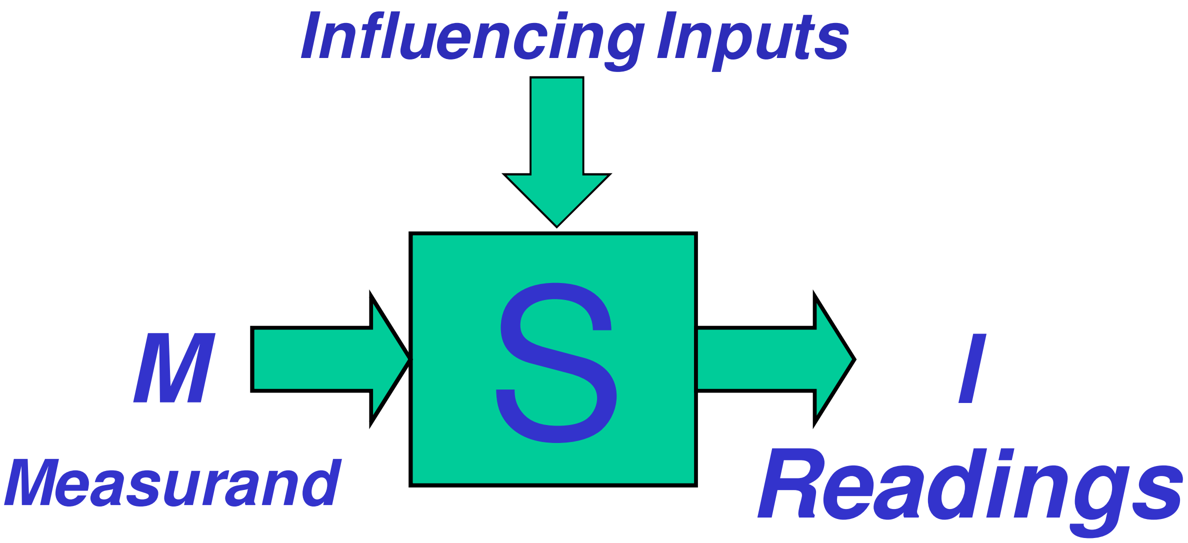
Operatively….

- During the calibratilon procedure all the system inputs must be kept constant except the considered input. The latter must be swept in the considered operating range.
- The obtained IN/OUT relationship is valid in the condition defined by the other inputs.





Calibration



♦What do we have to measure?

♦Which must be the accuracy of the measurement system?

•Each **influencing input** must be measured.

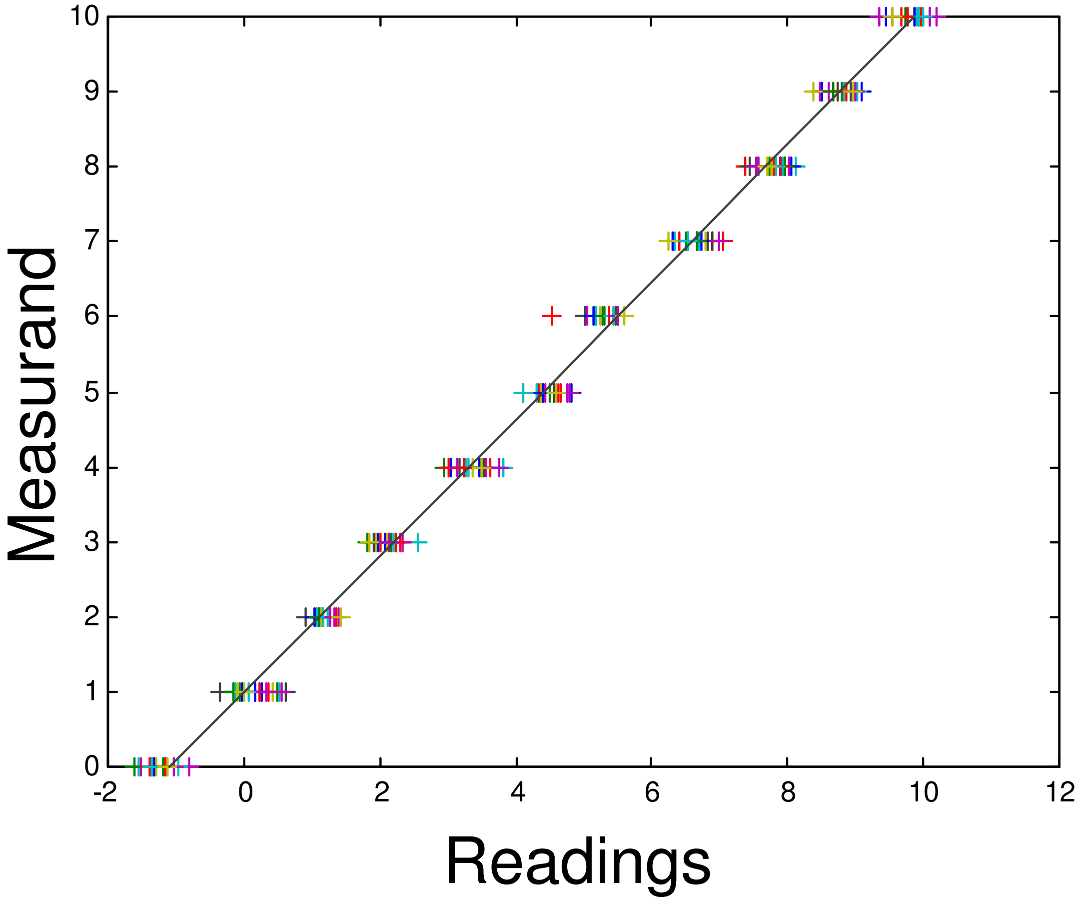
Random and polarizing effects of influencing input and the importance of replicated measurements.

•The considered input must be accurately (10 times better) measured.

Calibration

OPERATIVELY

1. Instrument inspection and investigation on all (meaningfull) system inputs;
2. Maintaining fixed the influencing input
3. Assuring a reliable sweep of the considered input;
4. Build the calibration diagram.



Calibration

Regime of statistic control

- Real influencing inputs
- Other influencing inputs
- We can say that the system under considerationj is in statistic control if:

the effect of other influencing inputs is negligible and they globally act as a random influence.

Calibration

The regime of statistic control must be assesed!

Data coming from an observation in regime of statistic control must have a Random distribution.

- An euristich approach: the ***4-plot Explanatory Data Analysis (EDA).***
- **An analytical method: the** χ^2.

Calibration

Regime of statistic control

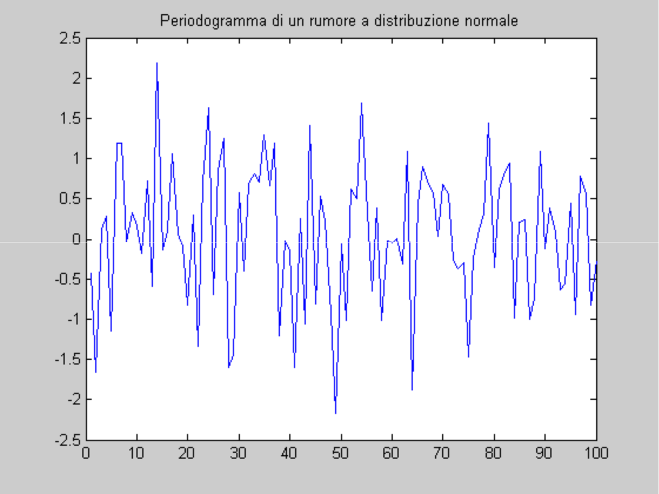
4-plot (Explanatory Data Analysis)

- Run sequence plot
- Lag Plot
- Histogram ;
- Normal Probability Plot.

Calibration

Regime of statistic control

In case of random signal:


Periodogramma di un rumore a distribuzione normale

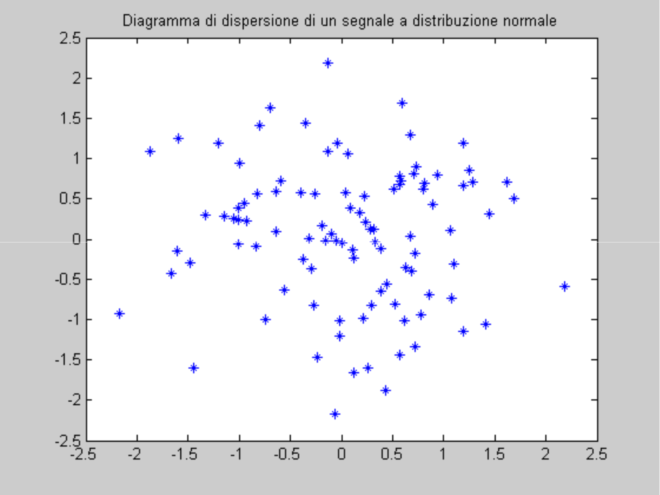
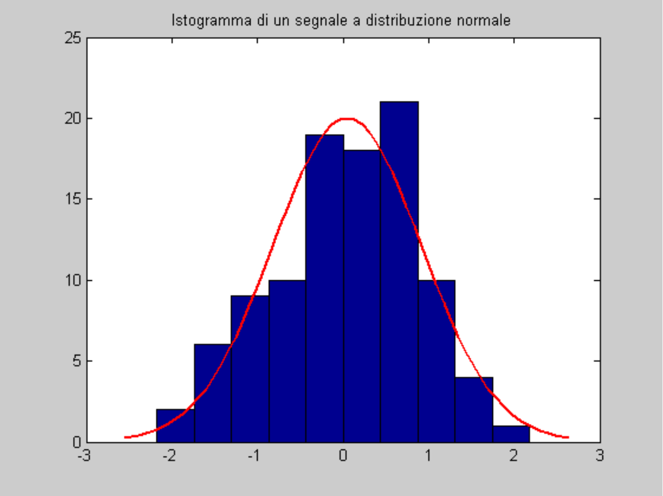
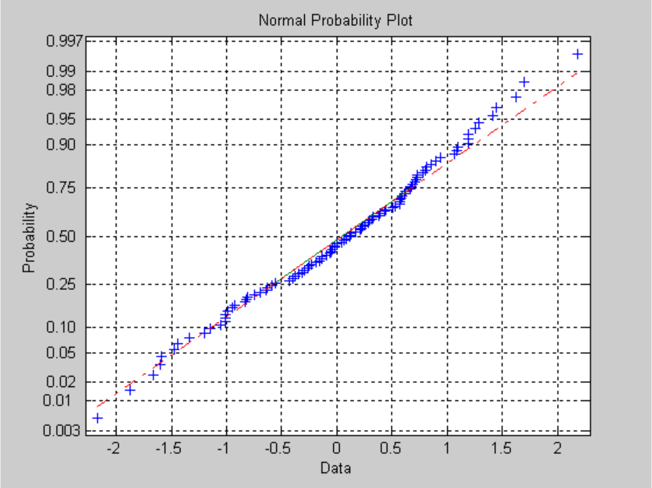


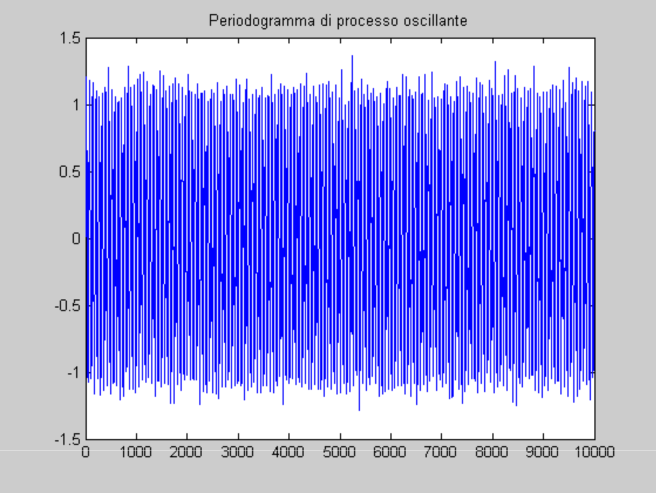
Diagramma di dispersione di un segnale a distribuzione normale

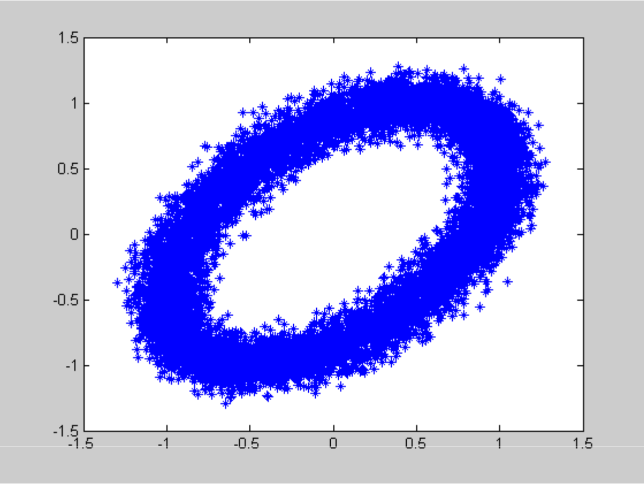

Istogramma di un segnale a distribuzione normale

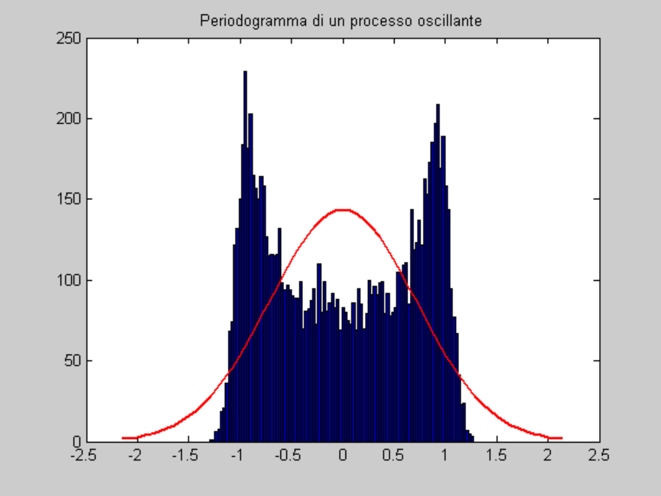

Normal Probability Plot

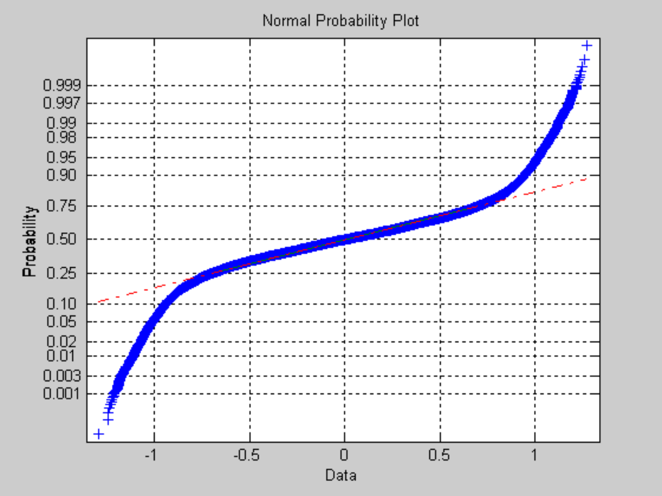
Calibration

Regime of statistic control









Case of a random signal superimposed to a periodic signal.

Calibration

Regime of statistic control

Example

Let's suppose to acquire 20 measures from a pressure sensor, nominally, in the same condition.

N	Pressure, kPa
1	10.02
2	10.20
3	10.26
4	10.20
5	10.22
6	10.13
7	9.97
8	10.12
9	10.09
10	9.90
11	10.05
12	10.17
13	10.42
14	10.21
15	10.23
16	10.21
17	9.98
18	10.10
19	10.04
20	9.81

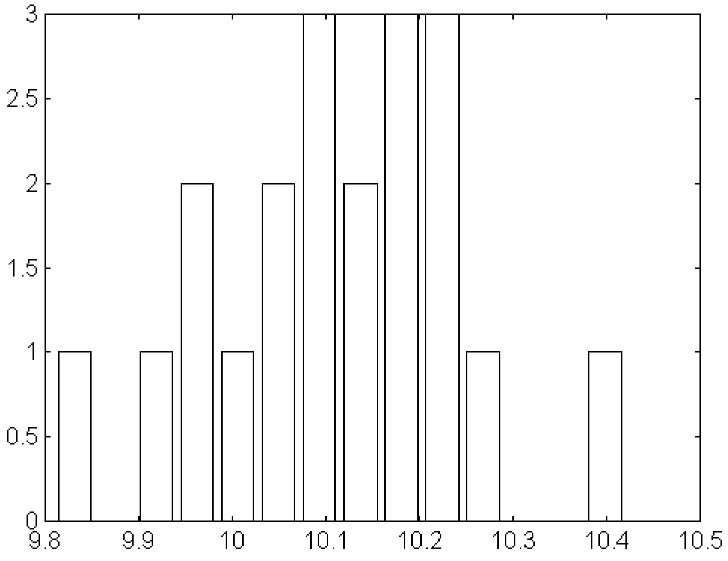
Calibration

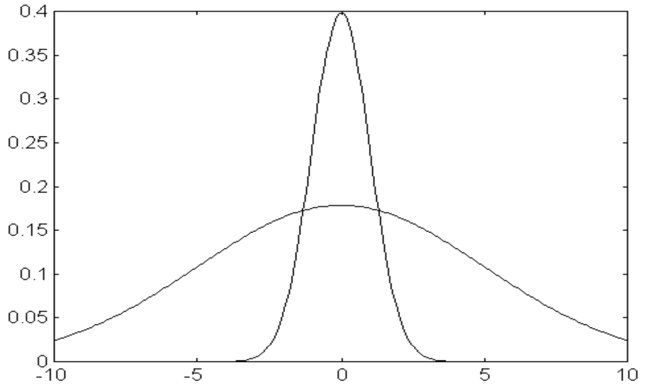
Regime of statistic control

Histogram

Sorting data and defining intervals belonging to the operating range, the following quantity an be defined:

$$Z = \frac{(\text{numero di campioni finestra}) / (\text{numero totale di letture})}{\text{ampiezza della finestra}}$$





Calibration

Regime of statistic control

χ^2 method

- Define GROUPS by sorting data and defining intervals belonging to the operating range.

- Number of groups:

- In case of sample number ranging between 20 and 40, groups with at least five samples/group must be formed.

- If n>40 the Kendal-Stuart expression can be used to find the optimal number of groups:

$$G = 1.87\left(N - 1\right)^{0.4}$$

Calibration

Regime of statistic control

χ^2 method

The following quantity must be estimated:

$$\chi^2 \equiv \sum_{i=1}^{n} \frac{\left(n_0 - n_e\right)^2}{n_e}$$

where:

n is the group number.

n_0 is the real number of elements in the group

n_e is the expected number of elements in the group in case of a Gaussian distribution.

Calibration

Regime of statistic control

χ^2 method

n_e can be estimated by the following steps:

1) Estimate the normalized boundary of each group

$$W = \frac{x-\mu}{\sigma}$$

2) Estimate for each group the probability

$$P(x \in group)$$

$$Es.\ \ P(-\infty < x < 10{,}03)$$

3) Estimate

$$n_e = P * N$$

4) Estimate the **Degree of freedom**:

Number of groups-3

Calibration

Regime of statistic control

χ^2 method

$$W = \frac{x-\mu}{\sigma}$$

$$P(x \in group)$$

$$Es.\ \ P(-\infty < x < 10{,}03)$$

$$ne = P * N$$

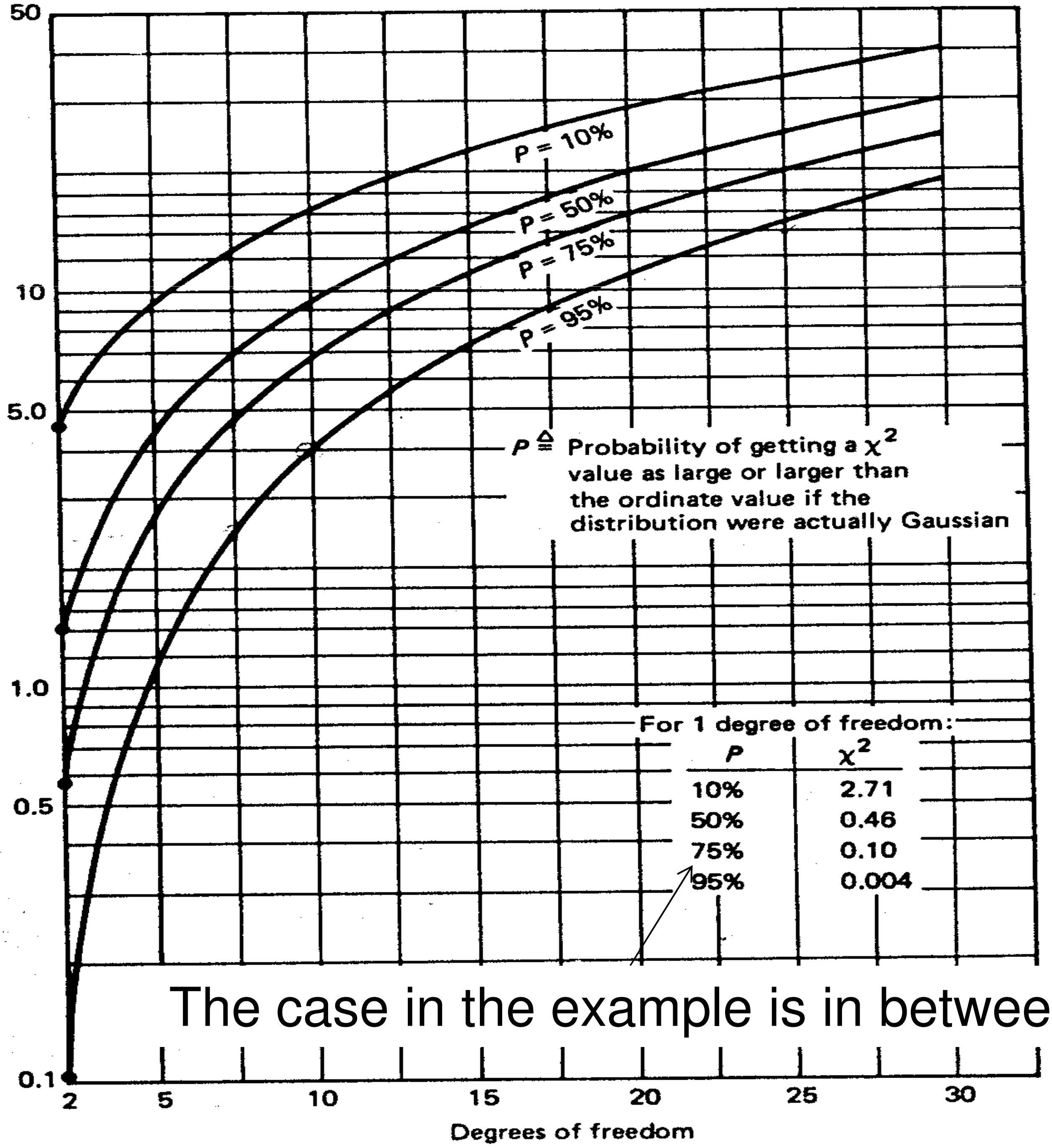
Data	Sorted	Interval	Normalized	F	ne	no	(no-ne)^2/ne
10,02	9,81				0		
10,2	9,9				0		
10,26	9,97				0		
10,2	9,98				0		
10,22	10,02	10,03	-0,58958741	0,2777	5,5547	5	0,055387978
10,13	10,04				0		
9,97	10,05				0		
10,12	10,09				0		
10,09	10,1				0		
9,9	10,11	10,115	0,0253197	0,2324	4,6473	5	0,026763322
10,05	10,12				0		
10,17	10,13				0		
10,42	10,17				0		
10,21	10,2				0		
10,23	10,2	10,205	0,67639782	0,2405	4,8101	5	0,007495648
10,11	10,21				0		
9,98	10,22				0		
10,1	10,23				0		
10,04	10,26				0		
9,81	10,42			0,2494	4,9879	5	2,94454E-05
						X2	0,089676394

Calibration

Regime of statistic control

χ^2 method

Once χ^2 has been estimated the following table will give the probability the distribution could be Gaussian.



$P \triangleq$ Probability of getting a χ^2 value as large or larger than the ordinate value if the distribution were actually Gaussian

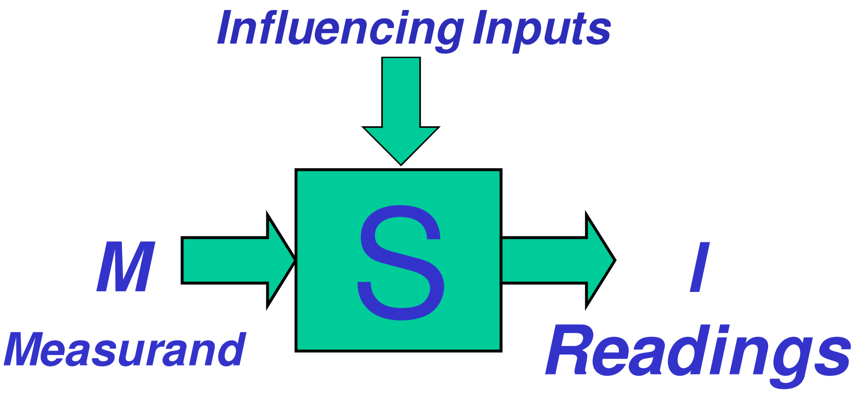
For 1 degree of freedom:

P	χ^2
10%	2.71
50%	0.46
75%	0.10
95%	0.004

The case in the example is in between

Calibration

Estimation of the calibration diagram



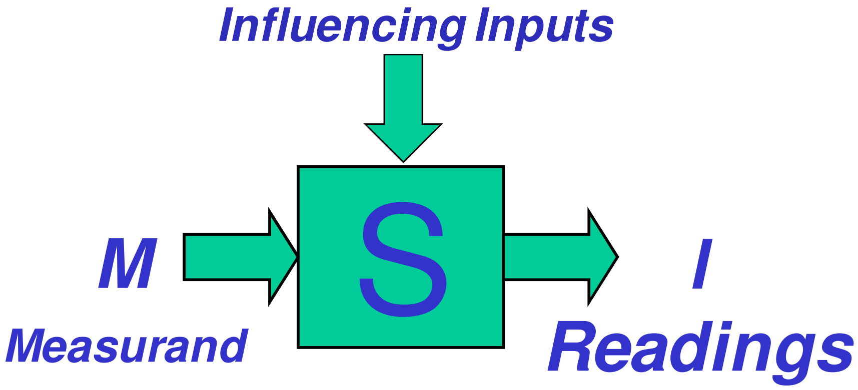
A **model** of the device behaviour must be obtained:

$$I=f(m)\ \text{(transduction function)}$$

$$m=f^{-1}(I)\ \text{(calibration function)}$$

Calibration

Estimation of the calibration diagram



How do we find the transduction function?

I=f(m)

TWO APPROACHES

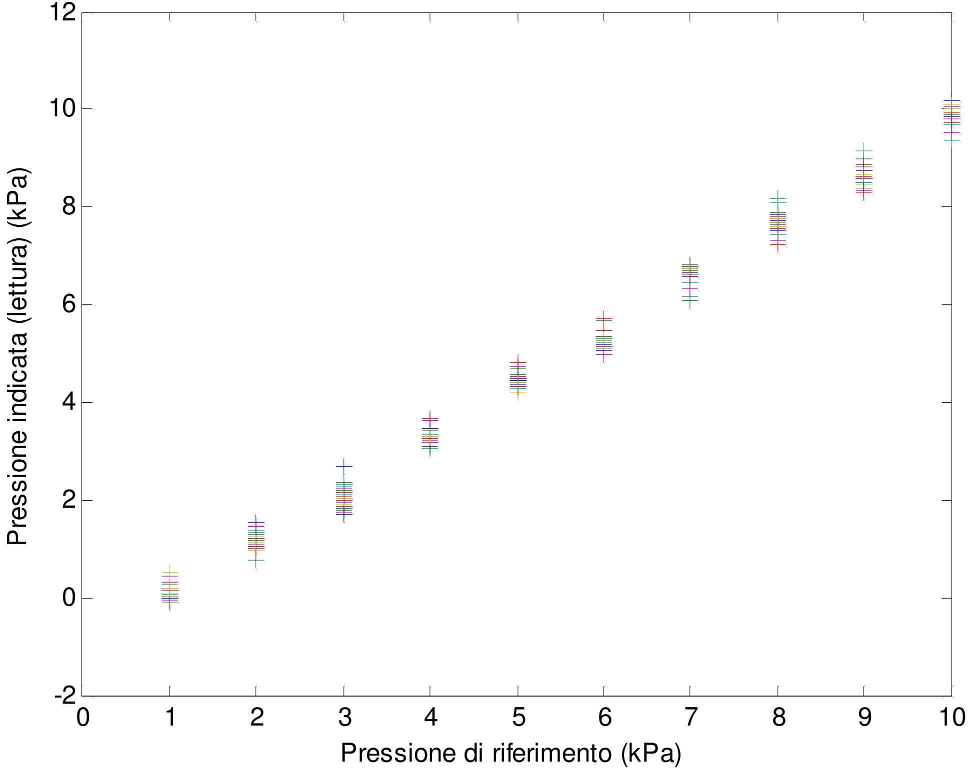
For each value of m

1) several readings are performed
2) A couple of readings are accomplished; one for increasing value of m and one for decreasing value of m, to evidence hysteretic behaviours.

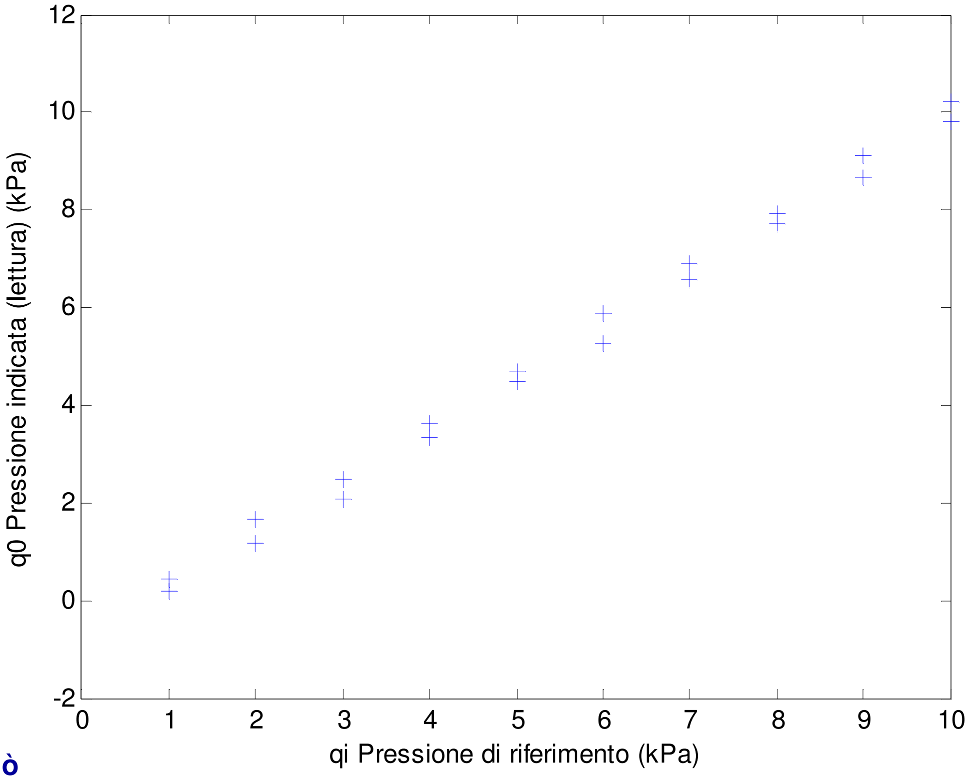
Calibration

Estimation of the calibration diagram

Several readings:



A couple of readings one for increasing value of m and one for decreasing value of m



Calibration

Estimation of the transduction curve

Supposing the following model (transduction function)

$$l = am + b$$

a LMS approach can be used for parameters estimation.

$$a = \frac{N\sum ml - \left(\sum m\right)\left(\sum l\right)}{N\sum m^2 - \left(\sum m\right)^2}$$

$$b = \frac{\left(\sum m^2\right)\left(\sum l\right) - \left(\sum ml\right)\left(\sum m\right)}{N\sum m^2 - \left(\sum m\right)^2}$$

Coefficient variances are:

$$s_a^2 = \frac{N s_l^2}{N\sum m^2 - \left(\sum m\right)^2}$$

$$s_b^2 = \frac{s_l^2 \left(\sum m^2\right)}{N\sum m^2 - \left(\sum m\right)^2}$$

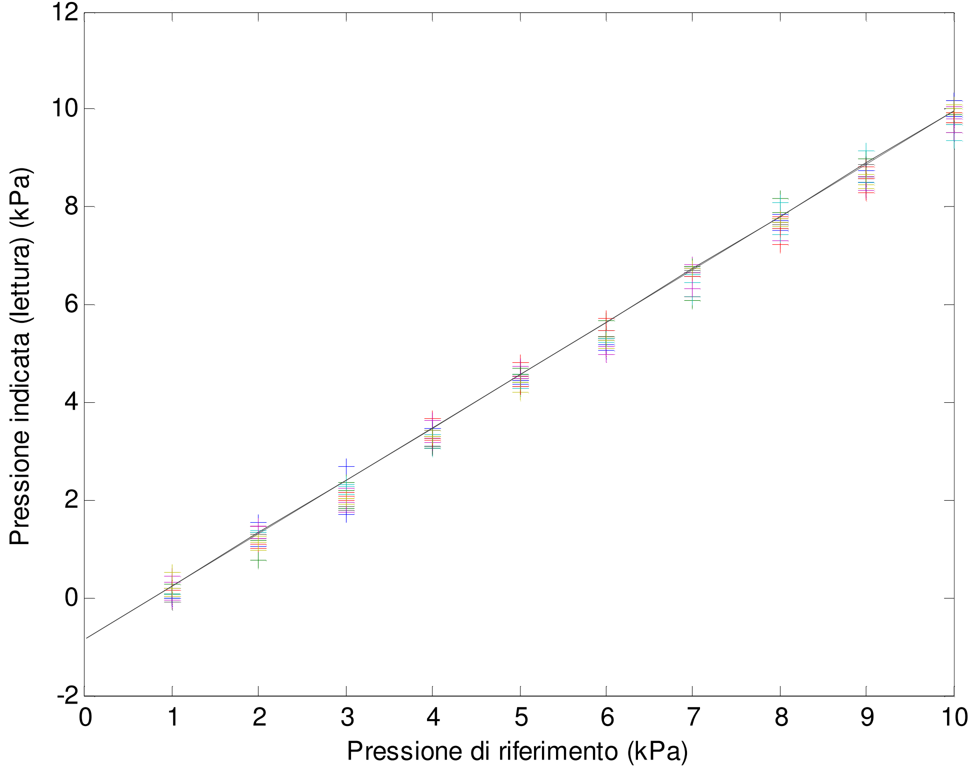
Estimated values of readings can be hence calculated:

$$l_{est} = am + b$$

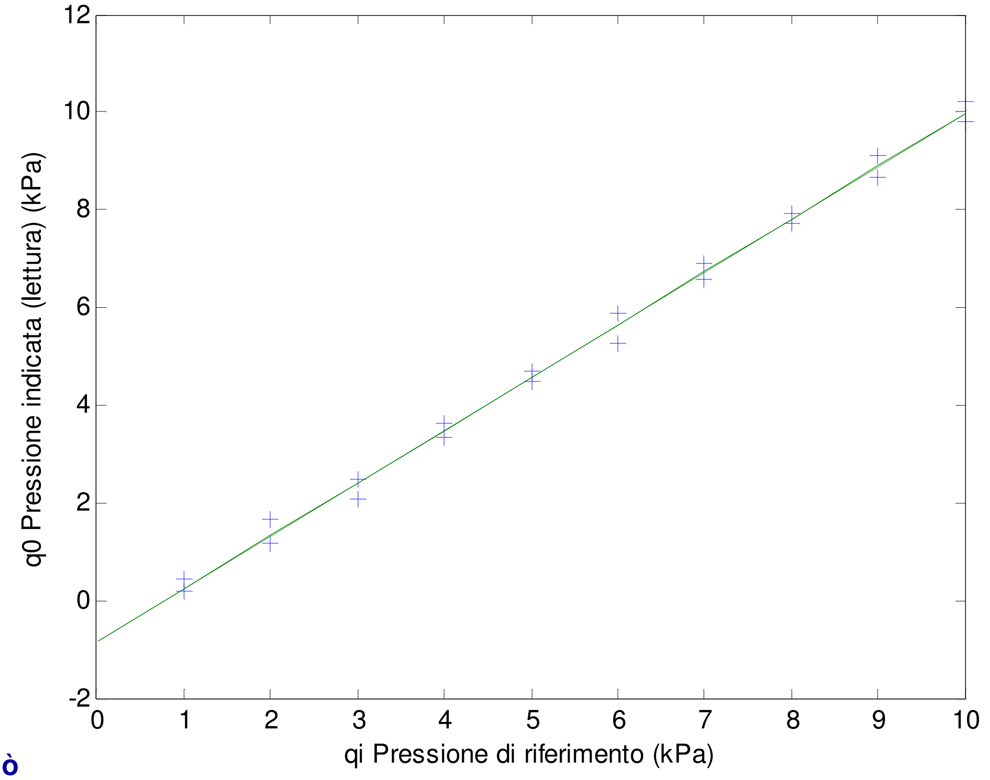
Calibration

Examples of the transduction curve

Several readings:



A couple of readings one for increasing value of m and one for decreasing value of m



Calibration

Estimation of the uncertainty band

In case of several readings, for each value of m the standard deviation, U_l, of reisduals between model estimations and readings can be estimated.

M	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15	L16	L17	L18	L19	L20		
0	-0.53	-1.22	-0.84	-1.61	-1.38	-1.14	-1.32	-1.35	-1.08	-1.41	-1.24	-0.87	-1.15	-1.22	-1.54	-1.21	-1.14	-1.21	-0.96	-1.37		
1	0.08	0.26	0.35	0.19	0.60	0.14	0.44	0.40	0.49	0.15	0.56	0.41	-0.03	0.22	-0.10	0.30	0.31	0.00	0.09	0.38		
2	1.01	1.38	1.42	0.79	1.41	1.10	1.16	1.41	1.37	1.05	1.15	1.22	1.08	1.01	0.86	1.39	1.05	1.36	1.28	0.82		
3	1.71	2.15	1.74	2.19	2.02	1.95	2.03	2.14	1.92	2.44	1.94	2.19	2.07	2.15	2.14	1.79	1.88	2.10	2.04	2.33		
4	3.18	3.42	3.60	3.52	3.69	3.46	3.24	3.39	3.39	2.98	3.62	3.10	3.58	2.88	3.01	2.95	3.54	3.53	3.17	3.05		
5	4.31	4.51	4.59	4.57	4.17	4.03	4.52	4.30	4.05	4.34	4.18	4.69	4.60	4.63	4.48	4.18	4.86	4.64	4.68	4.27		
6	5.03	5.61	5.35	5.12	5.32	5.38	5.51	5.39	5.03	5.06	5.46	4.92	5.46	5.28	5.16	5.53	5.43	5.53	5.00	5.00		
7	6.59	6.64	6.39	6.51	6.56	6.69	6.47	6.92	6.80	6.45	6.71	6.87	6.58	6.56	6.30	6.10	6.37	6.39	6.45	6.64		
8	7.62	7.90	7.71	7.69	7.83	7.90	7.80	8.04	7.66	7.65	7.61	7.82	7.69	7.55	7.67	7.90	7.34	7.96	7.86	7.54		
9	8.77	8.44	8.96	8.74	8.54	8.85	8.87	8.66	8.95	8.77	8.52	8.76	8.67	8.41	8.85	8.91	8.77	8.74	8.68	8.92		
10	9.79	9.81	9.58	9.51	10.11	9.57	9.59	9.89	9.78	9.89	9.85	9.70	9.82	9.66	9.87	9.80	9.50	9.68	10.00	10.04		
L_Est	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R9**	**R10**	**R11**	**R12**	**R13**	**R14**	**R15**	**R16**	**R17**	**R18**	**R19**	**R20**		**UL**
-1.05	0.52	-0.17	0.22	-0.55	-0.33	-0.09	-0.27	-0.30	-0.03	-0.35	-0.19	0.19	-0.10	-0.16	-0.49	-0.16	-0.09	-0.16	0.10	-0.32		0.25
0.03	0.05	0.23	0.32	0.16	0.56	0.11	0.41	0.37	0.45	0.12	0.52	0.38	-0.06	0.19	-0.13	0.27	0.27	-0.03	0.06	0.35		0.20
1.12	-0.11	0.26	0.30	-0.33	0.29	-0.02	0.03	0.29	0.25	-0.07	0.03	0.10	-0.05	-0.11	-0.26	0.27	-0.07	0.24	0.16	-0.30		0.20
2.21	-0.49	-0.05	-0.47	-0.02	-0.19	-0.26	-0.18	-0.07	-0.28	0.23	-0.26	-0.02	-0.13	-0.05	-0.07	-0.41	-0.33	-0.11	-0.16	0.13		0.18
3.29	-0.12	0.13	0.31	0.23	0.39	0.17	-0.05	0.09	0.09	-0.32	0.33	-0.19	0.29	-0.41	-0.28	-0.34	0.24	0.24	-0.13	-0.24		0.26
4.38	-0.07	0.13	0.21	0.19	-0.21	-0.35	0.14	-0.08	-0.33	-0.04	-0.20	0.31	0.22	0.25	0.09	-0.20	0.48	0.26	0.30	-0.11		0.24
5.47	-0.44	0.14	-0.12	-0.35	-0.15	-0.08	0.04	-0.08	-0.44	-0.40	-0.01	-0.55	-0.01	-0.18	-0.31	0.06	-0.04	0.06	-0.47	-0.47		0.21
6.55	0.03	0.09	-0.16	-0.04	0.01	0.14	-0.08	0.36	0.25	-0.10	0.16	0.31	0.02	0.00	-0.25	-0.46	-0.19	-0.17	-0.10	0.09		0.20
7.64	-0.02	0.26	0.07	0.05	0.19	0.26	0.15	0.40	0.02	0.01	-0.03	0.18	0.05	-0.09	0.03	0.26	-0.30	0.32	0.21	-0.10		0.17
8.73	0.04	-0.28	0.23	0.01	-0.19	0.12	0.14	-0.06	0.23	0.04	-0.21	0.04	-0.05	-0.32	0.13	0.18	0.05	0.01	-0.05	0.19		0.16
9.81	-0.02	-0.01	-0.24	-0.31	0.29	-0.25	-0.22	0.07	-0.03	0.07	0.04	-0.12	0.00	-0.15	0.06	-0.01	-0.32	-0.13	0.19	0.23		0.17
																					max(UL)	0.26
																					UM	0.24

Calibration

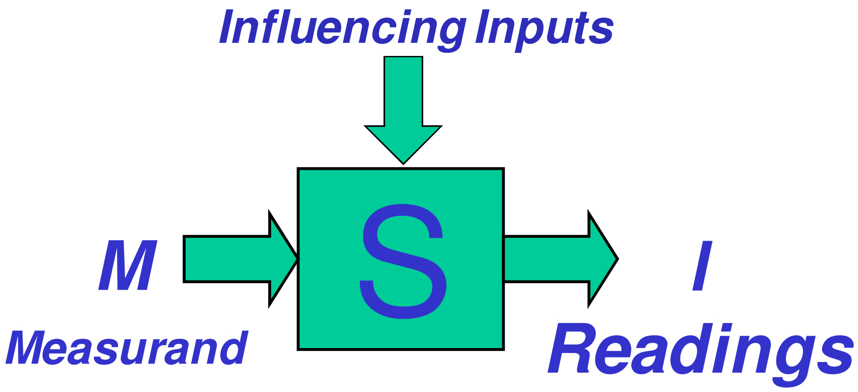
Estimation of the uncertainty band

In case of **two readings**, the standard deviation, σ_l, must be estimated taking into account residuals between readings and model estimation related to all values of m inspected. The hypothesis of a σ_l constant over the whole range of *m* is performed.

M	L	L_Est	Res
0	-1.12	-0.85	0.27
1	0.21	0.24	0.03
2	1.18	1.32	0.14
3	2.09	2.40	0.31
4	3.33	3.48	0.15
5	4.50	4.56	0.06
6	5.26	5.65	0.39
7	6.59	6.73	0.14
8	7.73	7.81	0.08
9	8.68	8.89	0.21
10	9.80	9.98	0.18
0	-0.69	-0.85	-0.16
1	0.42	0.24	-0.18
2	1.65	1.32	-0.33
3	2.48	2.40	-0.08
4	3.62	3.48	-0.14
5	4.71	4.56	-0.15
6	5.87	5.65	-0.22
7	6.89	6.73	-0.16
8	7.92	7.81	-0.11
9	9.10	8.89	-0.21
10	10.20	9.98	-0.22
		UL	**0.20**
		UM	**0.19**
		3UM	**0.56**

Calibration

Estimation of the calibration diagram


Influencing Inputs

M

Measurand

S

I

Readings

The **calibration function** can be easily obtained

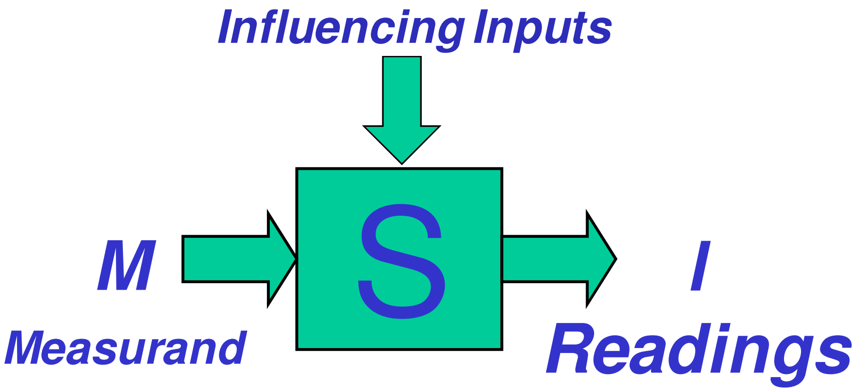
$$m = \frac{l - b}{a}$$

as well as the uncertainty band:

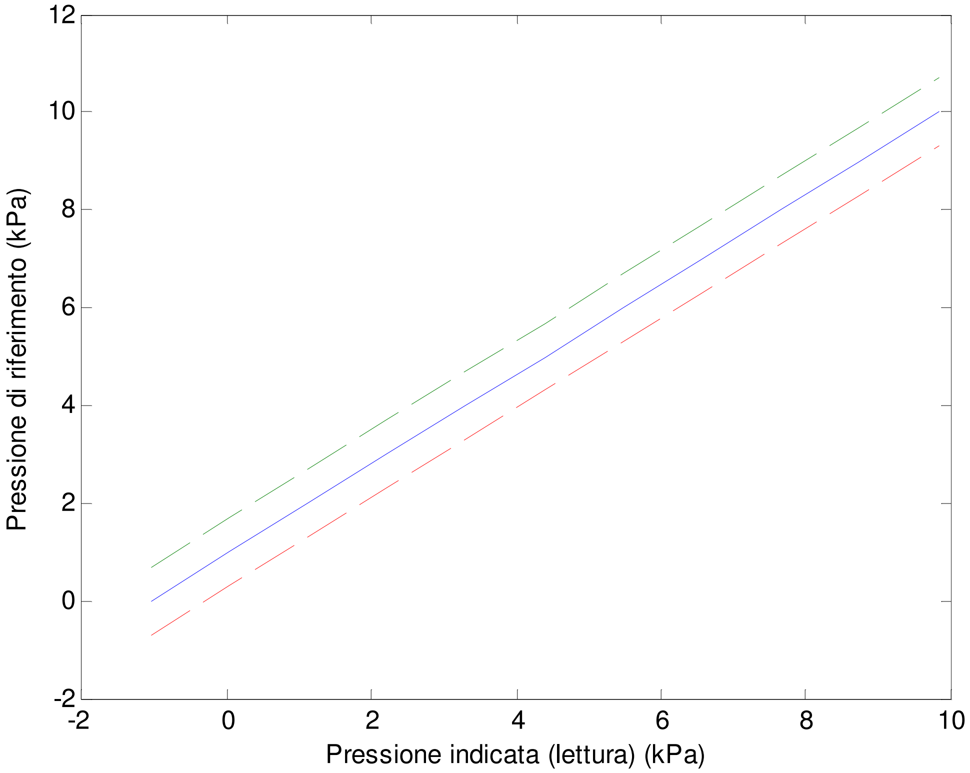
$$U_m = \frac{U_l}{a}$$

Calibration

Estimation of the calibration diagram



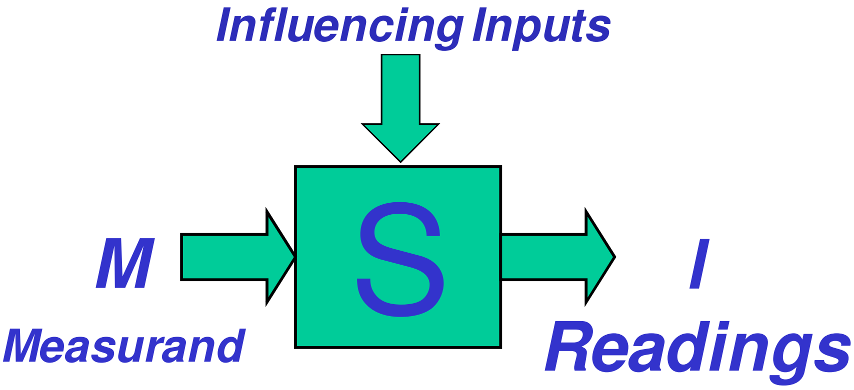
Several readings:



A coverage factor equal to 3 has been used!

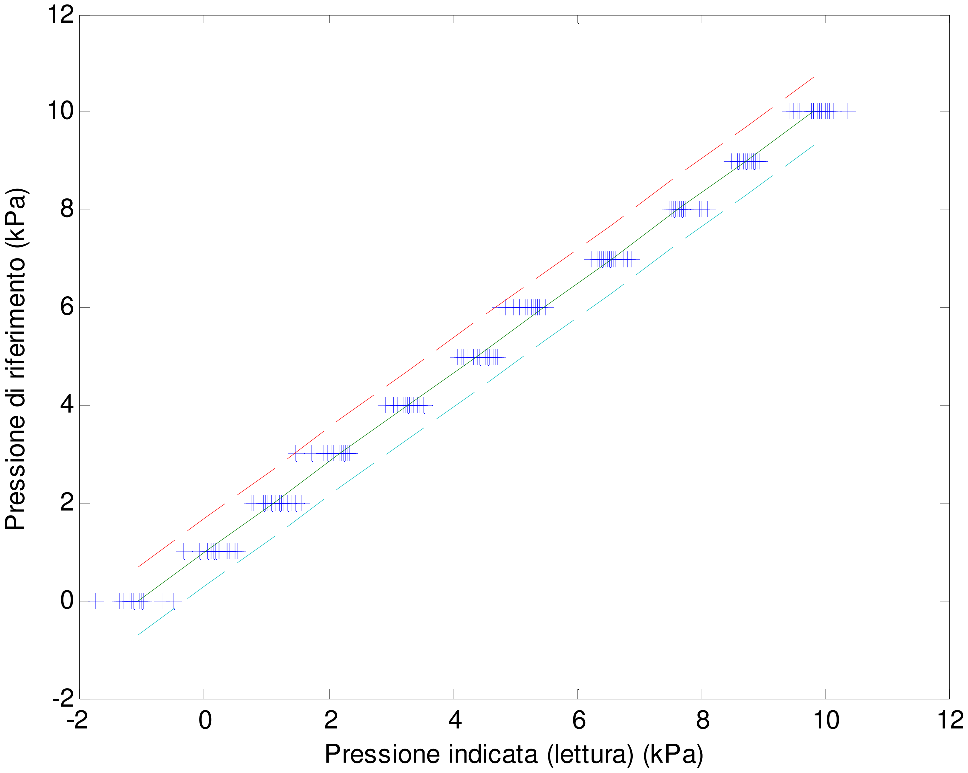
Calibration

Estimation of the calibration diagram



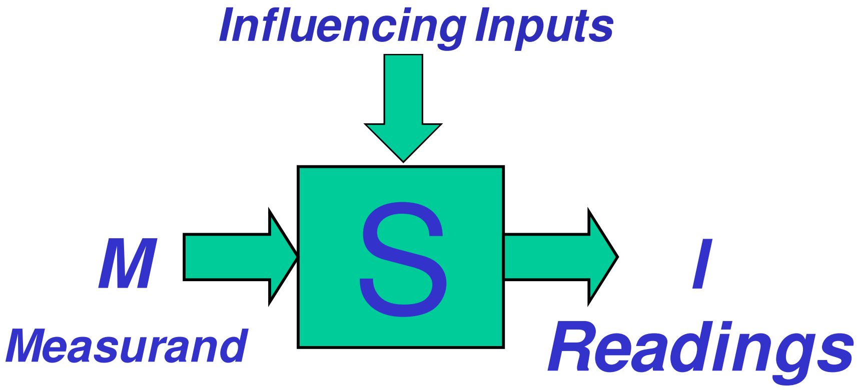
Several readings:

Using a coverage factor equal to 3 means that, practically, the uncertainty band contains all the readings!



Calibration

Estimation of the calibration diagram



Influencing Inputs

M

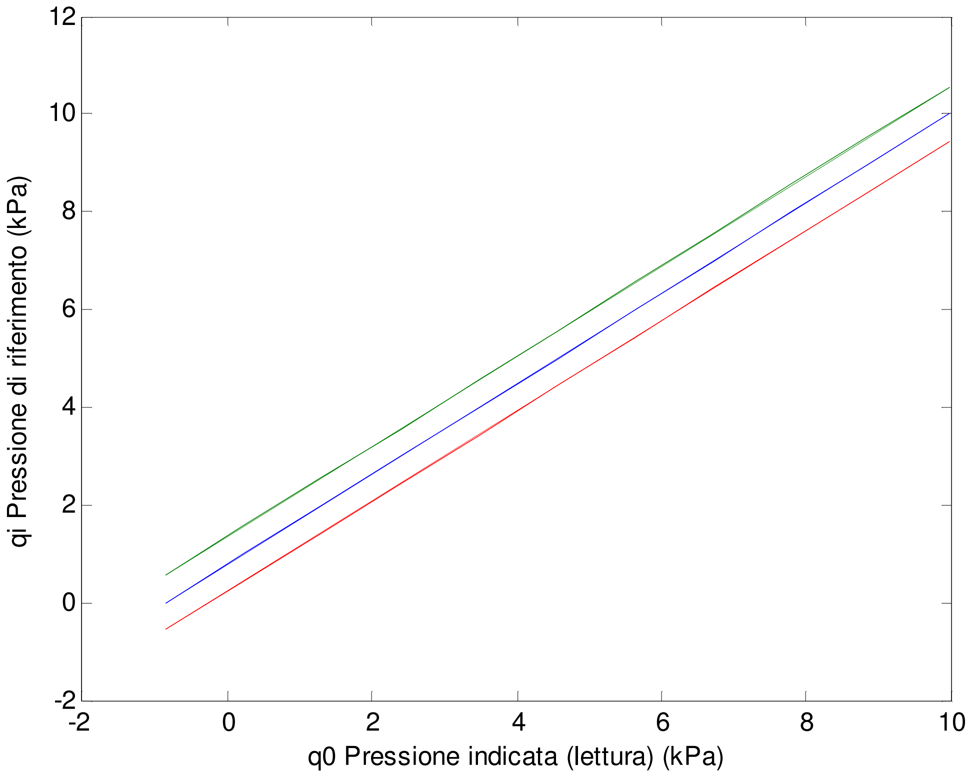
Measurand

S

I

Readings

A couple of readings one for increasing value of m and one for decreasing value of m



A coverage factor equal to 3 has been used!