Electronic Metrology

dr hab. inż. Łukasz Śliwczyński
Electronics Department
Faculty of Computer Science,
Electronics and Telecommunications

sliwczyn@agh.edu.pl
C3 – 515

Module characteristics

- lecturer

  dr hab. inż. Łukasz Śliwczyński
  e-mail: sliwczyn@agh.edu.pl
  phone: (617) 27-40
  C3 – 515
- lecture
  - 18 h (01.03 – 14.04)
    9 lectures, twice a week (Mondays & Wednesdays)
- laboratory exercises
  - 14 h, schedule will be available soon (this week)
    a catch up meeting to be decided by the laboratory instructor
    laboratory instructor
    dr inż. Witold Skowroński, room: C1-309, skowron@agh.edu.pl, phone: 44-74
- webpage:
  http://galaxy.uci.agh.edu.pl/~lab515/dzienne/metrology/lecture.html

Obtaining a course credit

- you need to pass the laboratory exercises and pass tests covering the material presented at the lectures
- the final mark is calculated as:

  $MF = 0.7*M_{Lab} + 0.3*M_{Test}$

  ($MF > 50\%$ is required for positive final mark)

Lack of the preparation will prevent from the participation in the lab.
One term to catch-up will be provided at the end of the semester.

Your activity during the exercises can increase you overall laboratory mark.

You are welcome to stop the lecture and ask questions
or request additional explanation

Please use this deliberately to allow the lecturer doing his job...

What do we want to learn?

metrology

theoretical

quantities and units

systems of quantities

measurement scales

uncertainty analysis

legal

homogenity and legality of measuring devices

- law acts
- norms
- technical conditions

applied

construction and usage of measuring devices

measuring quantities necessary for human activity

electronic metrology

- measurement of electrical quantities
- measurement of non electrical quantities using electronic methods
- electronic measuring instruments

measurement → comparison → reference

BIPM
Bureau international des poids et mesures
NMI
National Metrology Institution
GUM
Główny Urząd Miar

ISO
International Organization for Standardization
IEC
International Electrotechnical Commission
PKN
Polski Komitet Normalizacyjny

Program of our lecture

1) introduction: measurement, units, standards, etc.
2) signals and their parameters; principles of basic measurements
3) digital measurements
4) measurement of non-electrical quantities: force, mass, pressure
5) oscilloscope and oscilloscope measurements (two lectures)
6) impedance measurements: indirect and bridge methods
7) measurement uncertainty

Laboratory exercises are closely connected with the lectures so it is generally recommended to attend the lectures...

Why do we need to measure?

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

measurement:

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

International vocabulary of metrology — Basic and general concepts and associated terms (VIM)

analysis:	monitoring:	control:
- theories verification - building empirical models - characterising materials, devices and components	- measuring the value of the quantity, eg.: temperature, voltage, power ... - constructing/testing equipment, systems	- measuring the value of the quantity to use it in an automatic control system (feedback or feedforward)

some remarks:

- measurement → comparison with a reference, determining relations
- comparison → direct or indirect
- one assumes that the comparison is repeatable and reproducible
- one uses proper equipment and procedures
- one knows how to use/operate the equipment
- the measurement is done under proper conditions
- one is aware of measurement uncertainty
- one knows how to interpret the result

a measurement is much more than just reading some number from an instrument display

Measurement result

$Q = |Q|[Q]$

Q - quantity value
|Q| - numerical value
[Q] - unit

International System of Units – SI (1960)

base units

quantity	**symbol**	**quantity unit**	**quantity symbol**
length	l, h, r, x	metre	m
mass	m	kilogram	kg
time	t	second	s
electric current	I, i	amper	A
temperature	T	kelvin	K
amount of substance	n	mole	mol
luminous intensity	I_v	candela	cd

derived units

$$[Q] = \left[kA^{a}B^{X}C^{Y}\right] \qquad \text{eg: } [N] = \left[kg \cdot m \cdot s^{-2}\right]$$

Notation of measurement results

SI prefixes

value	name	symbol	value	name	symbol
10^{1}	deca	da	10^{-1}	deci	d
10^{2}	hecto	h	10^{-2}	centi	c
10^{3}	kilo	k	10^{-3}	mili	m
10^{6}	mega	M	10^{-6}	micro	µ
10^{9}	giga	G	10^{-9}	nano	n
10^{12}	tera	T	10^{-12}	pico	p
10^{15}	peta	P	10^{-15}	femto	f
10^{18}	exa	E	10^{-18}	atto	a
10^{21}	zetta	Z	10^{-21}	zepto	z
10^{24}	jotta	Y	10^{-24}	yokto	y

exponential (scientific) notation

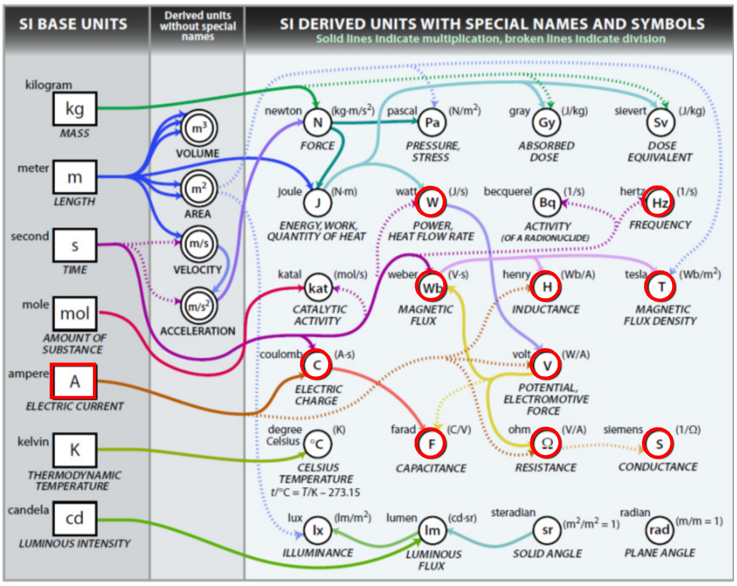
$X = \pm M \cdot 10^{E}; \quad M \in [1,10); \quad E \in Z$

eg: Is 10 kΩ equal to 10 000 Ω ???

$$\pm 1\% \Rightarrow U = 100\ \Omega \Rightarrow \underbrace{1.00}_{\text{significant figures}} \cdot 10^{4}\ \Omega$$

Notation „R = 10 kΩ" may suggest that 9.5 kΩ < R < 10.5 kΩ, so uncertainty of, say, 5%.

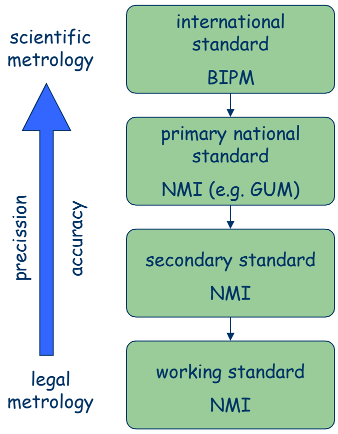
Derived units



source: http://physics.nist.gov/cuu/Units/SIdiagram.html

Measurement standards (etalons)

realisation of the definition of a given quantity, with stated quantity value and associated uncertainty, used as a reference (VIM)



scientific metrology

international standard

BIPM

primary national standard

NMI (e.g. GUM)

precission

accuracy

secondary standard

NMI

legal metrology

working standard

NMI

primary measurement standard – measurement standard established without referring to other standards of the same kind

secondary measurement standard - measurement standard established through calibration with respect to a primary standard

working measurement standard - measurement standard established through calibration with respect to a primary standard, used routinely for calibration

Kilogram – a short story...

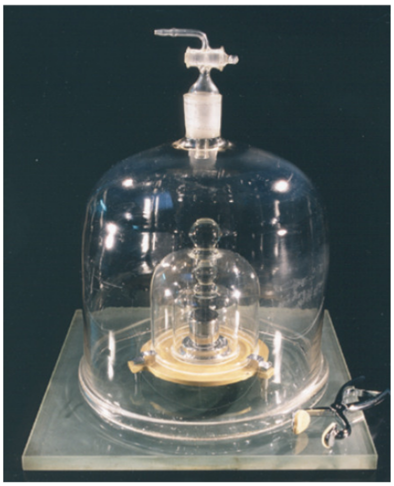
Ancient Greece, 560-550 BC
weighting silphium under king's supervision


source: hellenicaworld.com

China, Quin empire, 221 - 207 p.n.e.
weighting scale approved by
emperor Shi Huangdi


source: ajaonline.org

BIPM, the present
in principle not much has changed...
but...


source: BIPM

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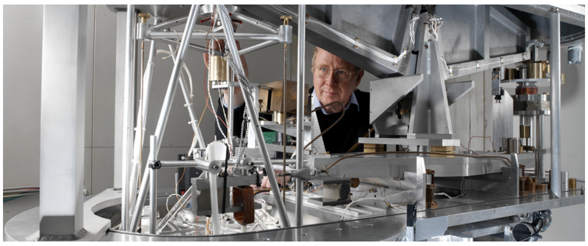
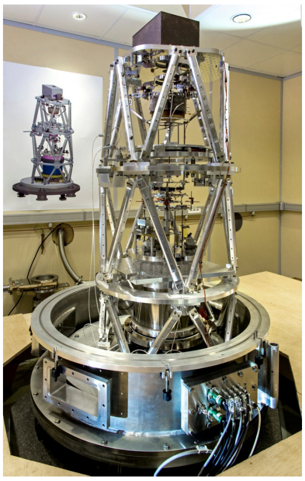
20 May 2019 – redefinition of base SI units

kilogram:

1 kilogram [kg] is a mass at which the Plancka constant equals exactly to $6.62607015 \cdot 10^{-34}$ J·s (kg·m²·s⁻¹, metr [m] and second [s] are defined by speed of light and hyperfine transition is Cs^{133} atoms)

The „old" kilogram weight is changing into the Kibble balance (formerly known as a watt balance)


source: NPL, GB


source: BIPM

https://www.kwantowo.pl/2018/11/16/nowy-kilogram-lepszy-bo-kwantowy/
https://www.bipm.org/en/bipm/mass/watt-balance/
https://www.bipm.org/utils/common/pdf/.../Michael_Stock.pdf
https://en.wikipedia.org/wiki/2019_redefinition_of_SI_base_units

Units – definition, realisation, uncertainty

time:

1 second [s] is the duration of 9 192 631 770 periods of radiation corresponding to the transition between two hyperfine levels of the ground state of Cs^{133} atom

commercial cesium reference standard 5071A
(Symmetricom, formerly HP)
uncertainty 5×10^{-13} - 1×10^{-12}

caesium clocks at PTB
Physikalish-Technische
Bundesanstalt
Braunschweig , Germany

uncertainty 1.2×10^{-14}
1×10^{-9} s/day
1 s/2.7×10^{6} years

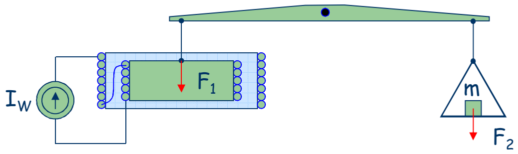
cesium fountain 1×10^{-15}

Units – definition, realisation, uncertainty

electric current:

1 amper [A] is the electric current, that if maintained in two stright and paralel conductors with infinite length… separated by 1 meter in vacuum would produce between these conductors a force of 2×10^{-7} N per each meter of length (technically impossible….)

Rayleigh current balance

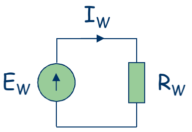


$$F_1 = K\cdot I_W^2;\ F_2 = m\cdot g$$
$$F_1 = F_2$$
$$\downarrow$$
$$I_W = \sqrt{\frac{m\cdot g}{K}}$$

uncertainty 6ppm → 6×10^{-6}

realisation based on Ohm's law

1ppm → 1×10^{-6}



$$I_W = U_W / R_W$$

substantial change: 20 May 2019

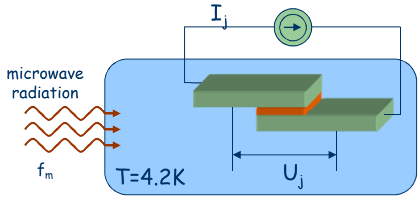
1 amper [A] is the electric current at which the elementary charge equals exactly to $1.602176634\cdot10^{-19}$ C (A·s, second is defined by the hyperfine transition in cesium atoms Cs^{133})

Units – definition, realisation, uncertainty

electric potential difference (valtage):

1 volt [V] is the difference of potentials between two points of a conductor carrying a constant current of 1 A when the power dissipated between these points equals 1 W. (1948)

realisation based on (inverse) Josephson effect (90' XX century)



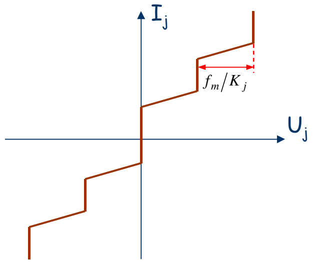
$$U_j = n \cdot f_m \frac{h}{2e} = \frac{n \cdot f_m}{K_j}$$

$K_j = 483597.9$ GHz/V

$f_m = 9.9546537$ GHz $\rightarrow$ U $\cong 20\mu$V...

matrix of ~8192-69632 Josephson's junctions

range –10 ÷ +10V, uncertainty ~10^{-10}

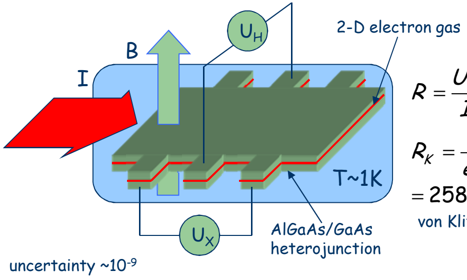


Units – definition, realisation, uncertainty

electric resistance:

1 ohm [Ω] is the resistance between two points of a conductor when the current of 1A causes difference of 1V between these two points

realisation based on quantum Hall effect



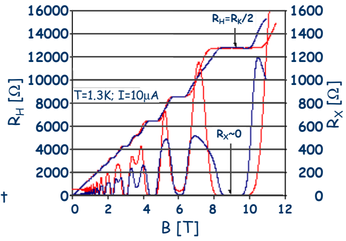
$$R = \frac{U_H}{I} = \frac{R_K}{n}$$

$$R_K = \frac{h}{e^2} =$$

$= 25812.807$ Ω

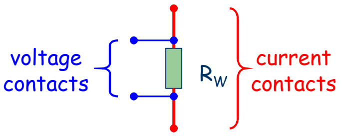
von Klitzing constant

uncertainty ~10^{-9}



source: LNE-SYRTE

four-terminal (Kelvin) reference resistors



resistance range:
1 Ω ÷ 20M Ω

uncertainty
~1 ÷ 20 ppm

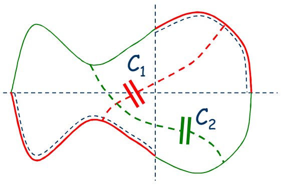
stability
2 ÷ 10 ppm/year

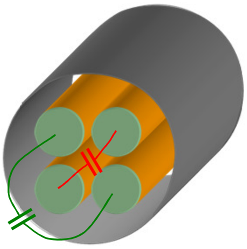
Units – definition, realisation, uncertainty

electric capacity:

1 farad [F] is a capacity of a capacitor between the plates of which a potential difference of 1 V appears when charged with a charge of 1 C.

Thompson-Lampard calculable capacitor





$$C_1 = C_2 = C_0 = \frac{\varepsilon_0}{\pi}\ln 2 = 2.818376\ \text{pF/m}$$

uncertainty ~0.02 ppm

source: PTB

working capacitance standards

<10pF - air
<1μF - mica
>1μF - polipropylene

uncertainty – 0.02 ÷ 2%

source: IET-LABS

Units outsite the SI

units for expressing a ratio

neper [Np]

$$L = \ln\frac{q_1}{q_2}\ [\text{Np}]$$

bel [B], decibel [dB]

$$L = \log\frac{P_1}{P_2}\ [\text{B}] \qquad L = 10\cdot\log\frac{P_1}{P_2}\ [\text{dB}]$$ for power

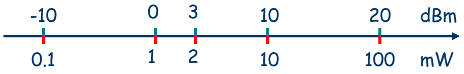
$$20\cdot\log\frac{X_1}{X_2}\ [\text{dB}]$$ for other quantities eg. I, U, R etc.

$$L_{dB} = 10\cdot\log\left(e^{L_{Np}}\right) = L_{Np}\cdot 10\cdot\log e \cong 4.34\cdot L_{Np}$$

$$L_{Np} = \ln 10^{L_{dB}/10} = L_{dB}\cdot\frac{\ln 10}{10} \cong 0.23\cdot L_{dB}$$

logarithmic unit of power - dBm

$$P_{dBm} = 10\cdot\log\frac{P}{1\ \text{mW}}$$



other logarithmic units (used, eg in acoustics)

dBV – referenced to 1 V
dBu – referenced to 0.7746 V

Some remarks about dBm-s

dB and dBm addition – BE CAREFUL!

result in general will depend on the types of added signals and their phase relations

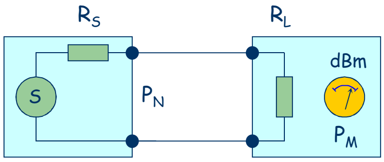
converting to voltage/current

$$U_{RMS} = \sqrt{1[\text{mW}] \cdot R_L \cdot 10^{P_{dBm}/10}} = \sqrt{R_L[\text{k}\Omega] \cdot 10^{P_{dBm}/10}}$$

R_L = 50 Ω: 0 dBm ⇒ U_{RMS} = 223,6 mV

R_L = 600 Ω: 0 dBm ⇒ U_{RMS} = 774,6 mV

source/load impedance mismatch

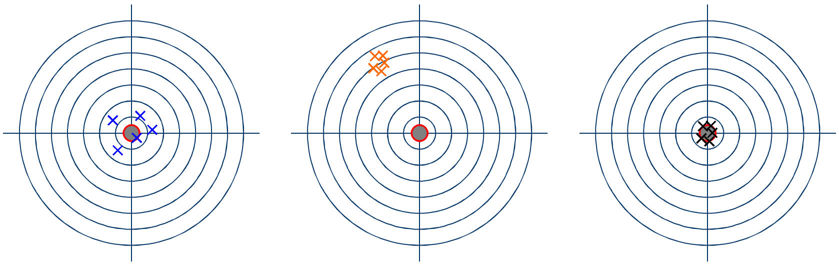


if $R_S \neq R_L \Rightarrow P_M \neq P_N$; $P_M = P_N + K$

correction $K = 10 \cdot \log \frac{4 R_S R_L}{(R_S + R_L)^2}$ [dB]

R_S = 50 Ω; R_L = 600 Ω ⇒ -5.47 dB
R_S = 600 Ω; R_L = 50 Ω ⇒ -5.47 dB

Accuracy, precision



accurate precise precise and accurate

measurement accuracy – closeness of agreement between measured quantity value and true quantity value

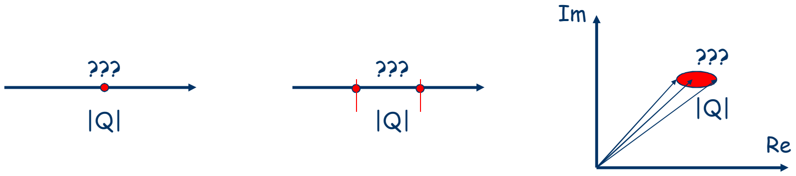
measurement precision – closeness af agreement between measured quantity values obtained by replicate measurements of the same quantity

measurement trueness – closeness of agreement between the average of an infinite number of replicate measured quantity values and a reference quantity value

Quantity value, measurement result

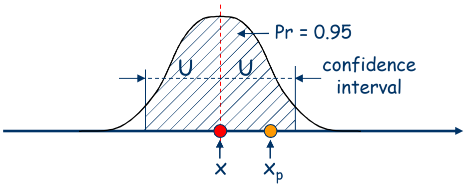
$Q = |Q|[Q]$

Q – quantity value
$|Q|$ - numerical value
$[Q]$ – unit



measurement uncertainty (measure of accuracy)

an interval around a measured result, in which a true value of measured quantity may be found with significant (eg. 95%) probability



$\Pr\{x_p \in (-U+x, x+U)\} = 0.95$
$\Pr\{x_p \notin (-U+x, x+U)\} = 0.05$

result of measurement:

x ± U

Measurement methods and results (VIM)

direct method

value of a quantity is obtained without the need of performing any calculations, eg measuring a voltage using a voltmeter;

indirect method

value of a quantity is obtained from direct measurement of other quantities, related to the measured quantity through known mathematical equation and performing necessary calculations, eg: determining the resistance using voltmeter and ammeter or determinig the circumference of a cirle using its diameter;

$A = \pi \cdot d$

```
    ππππ.........
  x  ddd
    rrrr.........
   rrrr.........
 +rrrr.........
  zzzzzz.........
```

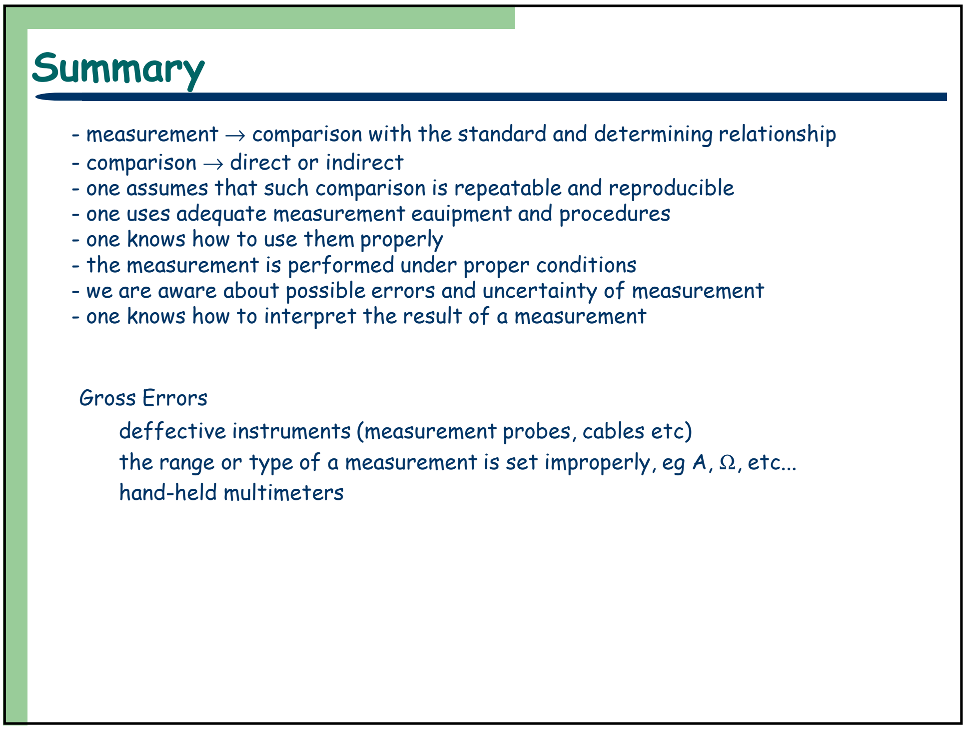
Simplified procedure:

addition/subtraction:
round the result to the same number of decimal places as the least accurate number

multiplication/division
round the result to the same number of significant figures as the least accurate number

rising to a power/finding the root or logarithm
round the result to the same number of digits as is in the number undergoing the operation

These problems will be considered in more detail during the lecture on the uncertainty of the measurement



Summary

- measurement → comparison with the standard and determining relationship
- comparison → direct or indirect
- one assumes that such comparison is repeatable and reproducible
- one uses adequate measurement eauipment and procedures
- one knows how to use them properly
- the measurement is performed under proper conditions
- we are aware about possible errors and uncertainty of measurement
- one knows how to interpret the result of a measurement

Gross Errors

deffective instruments (measurement probes, cables etc)
the range or type of a measurement is set improperly, eg A, Ω, etc...
hand-held multimeters

Recommended literature and other sources

- S. Tumański: Principles of Electrical Measurements, Taylor & Francis, 2005
- R.A. Witte (Agilent Technologies): Electronic Test Instruments: Analog and Digital Measurements, Prentice Hall, 2002
- SI Units Brochure:
  http://www.bipm.org/utils/common/pdf/si_brochure_8_en.pdf
- The NIST Reference on Constants, Units and Uncertainty
  http://physics.nist.gov/cuu/Units/index.html
- International Vocabulary of Metrology (VIM):
  http://www.bipm.org/utils/common/documents/jcgm/JCGM_200_2012.pdf
- R.A. Witte (Agilent Technologies): Spectrum & Network Measurements, Prentice Hall, 1993
- A.K. Ghosh: Introduction to Measurements and Instrumentation, PHI Learning, 2012
- R.B.Northrop: Introduction to Instrumentation and Measurements, Taylor & Francis, 2005

(some books in Polish)
- S. Tumański: Technika Pomiarowa, WNT, 2013
- A. Zięba: Analiza danych w naukach ścisłych i technice, PWN, 2013
- J. Dusza, G. Gortat, A. Leśniewski: Podstawy miernictwa, Oficyna Wydawnicza Politechniki Warszawskiej, 2007
- A. Kamieniecki: Współczesny oscyloskop, btc, 2009
- A. Zatorski, R. Sroka: Podstawy Metrologii Elektrycznej, Wydawnictwa AGH, 2011
- J. Arendarski: Niepweność pomiarów, Oficyna Wydawnicza Politechniki Warszawskiej, 2003
- Niepweność pomiarów w teorii i praktyce – praca zbiorowa, GUM
  http://www.gum.gov.pl/pl/komunikacja/publikacje/niepewnosc-pomiarow-w-teorii-i-praktyce/spis-tresci/