Uncertainty Estimations

Postgraduate course

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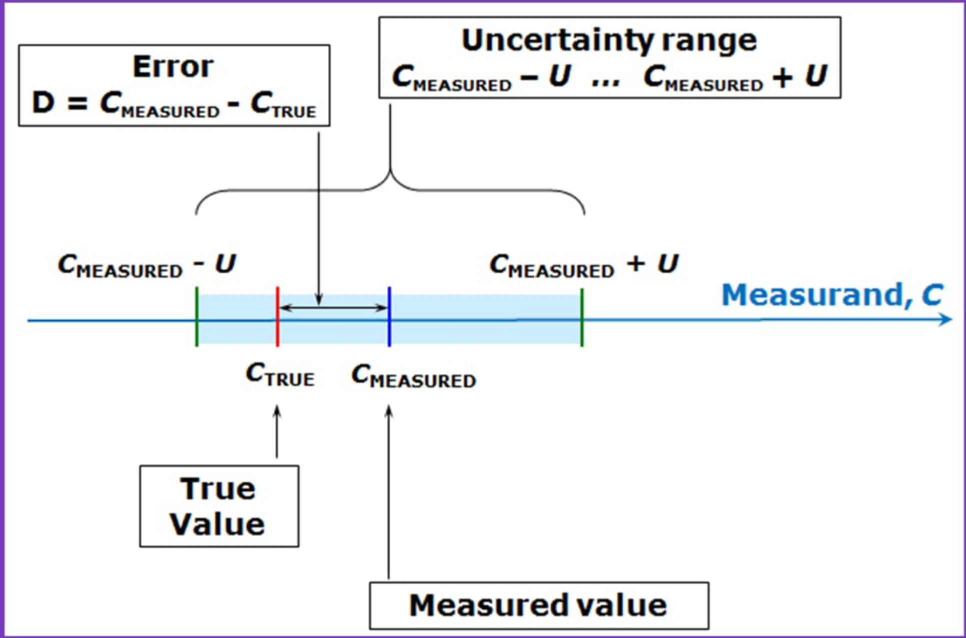

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Measurement quality

Scientific data should contain some estimate on its quality

- Important to compare measurements
- For commercial data legal requirement

Estimating the quality of the measurement is the essence of metrology

Improving the quality of the measurement is the main purpose of metrology

Quality

- **Minimal number of errors and nonconformities**
- **Accuracy, precision, credibility,…**
- **Uncertainty**
- **Or certainty?**

Literature

GUM: Guide to the Expression of Uncertainty in Measurement

- http://www.bipm.org/en/publications/guides/gum.html
- JCGM 100:2008 (GUM 1995 with minor corrections)
- The official standard of uncertainty estimation
- Complete, detailed and widely accepted
- Somewhat hard to read

VIM: Vocabulary of Metrology

EA-4/02 - Evaluation of the Uncertainty of Measurement in Calibration

- http://www.european-accreditation.org/publication/ea-4-02-m
- European Co-operation for Calibration EA-4/02 M: 2013
- Simplified guide for accredited calibration laboratories
- Compatible with GUM
- Easier for beginners

Measurement

- process of experimentally obtaining one or more quantity values that can reasonably be attributed to a quantity (VIM)
- the quantification of attributes of an object or event, which can be used to compare with other objects or events
- process of determining how large or small a physical quantity is as compared to a basic reference quantity of the same kind

Notes

- Measurement does not apply to nominal properties (in science and engineering)
- Mere counting is not a measurement
- In social sciences and statistics more general concept
- In quantum mechanics any process determining the quantum state

Other nomenclature

- **Measurand**
  - Quantity intended to be measured
- **Measurement principle**
  - Phenomenon serving as a basis of a measurement
- **Measurement method**
  - Generic description of a logical organization used in a measurement
- **Measurement procedure**
  - Detailed description of a measurement…
- **Metrology**
  - Science of measurement and its application
  - Includes all theoretical and practical aspects of measurement, whatever the measurement uncertainty and field of application
  - Physical science, often associated with engineering science
- **Measurement science and technology**
  - metrology

Uncertain history

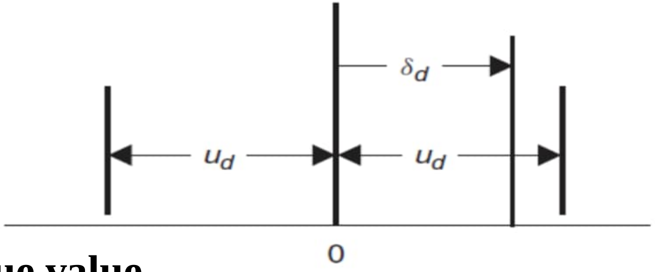
- **Error and error analysis have long been part of practice of science and metrology**
- **Incoherent analysis and nomenclature have made comparisons hard**
- **Renewal of terminology discussed extensively in 1980's**

- **new standards and definitions**
  - ISO: GUM (1993)
  - JCGM 1995
    - Joint Committee for Guides in Measurement
    - BIPM, ISO, IEC, IFCC, IUPAC, IUPAPm IOML, ILAC
  - GUM revised 1995 and 2008
- **Uncertainty**
  - Universal
  - Internally consistent
  - Transferable
  - Easily understood
  - Generally accepted

Definition of uncertainty

- Uncertainty represents the lack of exact knowledge of the value of the measurand
- Definition in GUM:
    - **Uncertainty (of measurement)**: parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand
- VIM (2008): non-negative parameter characterizing the dispersion of the quantity values being attributed to the measurand, based on the information used
- Other consistent though outdated definitions
    - a measure of the possible error in the estimated value of the measurand as provided by the result of a measurement;
    - an estimate characterizing the range of values within which the true value of a measurand lies (VIM:1984, definition 3.09).

Error



- **Uncertainty should not** be mixed with **error**.
  - **Error is the deviation of the measured value from the true value**
  - Errors are never exactly known! Neither are true values.
  - Old scientists use error or error bar as a synonym to uncertainty
  - Error is really relevant only in student exercises where the “true value” is “known”
- Considering error δ, uncertainty u is an estimate of an interval $\pm u$ that should contain δ at certain probability
- Error should be corrected
  - **Systematic errors** are **corrected** to the extent known. After correction, the **expectation value** of a systematic error is 0.
  - **Random errors** arise from unpredictable or stochastic temporal and spatial variations of influence quantities. **Expectation value** of a random error is 0.

Sources of uncertainty

a) incomplete definition of the measurand

b) imperfect realization of the definition of the measurand

c) nonrepresentative sampling — the sample measured may not represent the defined measurand

d) inadequate knowledge of the effects of environmental conditions on the measurement or imperfect measurement of environmental conditions

e) personal bias in reading analogue instruments

f) finite instrument resolution or discrimination threshold;

g) inexact values of measurement standards and reference materials;

h) inexact values of constants and other parameters obtained from external sources and used in the data-reduction algorithm

i) approximations and assumptions incorporated in the measurement method and procedure

j) variations in repeated observations of the measurand under apparently identical conditions.

Components of uncertainty

- **Uncertainty consists of several components**
- **Can be grouped to**
  - A: those which are evaluated by statistical methods
  - B: Those which are evaluated by other means
- **Any detailed report should include a complete list of components of uncertainty**
  - specifying for each the methods used to obtain its numerical value
- **Previous classification**
  - Random uncertainties
  - Systematic uncertainties
- **Not always a simple correspondence between old and new terms**
  - The term “systematic uncertainty” may be misleading
  - should be avoided
- **New terminology focuses on method instead of origin**
- **BIPM proposal 1980, GUM 1993, NIST 1994, …**

Characterizing uncertainties

- **Components in category A characterized by**
  - Estimated variances s_i^2
  - Estimated standard deviations s_i
  - Number of degrees of freedom v_i
  - Covariances where appropriate
- **Obtained from measured distribution**

- **Components in category B characterized by**
  - Approximations to variances u_i^2
  - Approximations to standard deviations u_i
  - Covariances where appropriate
- **Obtained from assumed probability density function**

One's A may become other's B

Evaluating type A uncertainties

- With *n* statistically independent observations, the arithmetic mean (average) is

$$\bar{q} = \frac{1}{n}\sum_{j=1}^{n} q_j$$

- The experimental variance of the probability distribution

$$s^2(q) = \frac{1}{n-1}\sum_{j=1}^{n}(q_j - \bar{q})^2$$

- Experimental standard deviation

$$s(q) = \sqrt{s^2(q)}$$

If the quantity to be reported is the arithmetic mean (as usual)

- The experimental variance of the mean is given by

$$s^2(\bar{q}) = \frac{s^2(q)}{n}$$

- The experimental standard deviation of the mean

$$s(\bar{q}) = \sqrt{s^2(\bar{q})}$$

- The standard uncertainty for $\bar{q}$ is

$$u(\bar{q}) = s(\bar{q})$$

Some notes for type A evaluation

- **Are random influences really random?**
  - Any drift during the measurement?
  - If you have enough data, compare the results of the first half with the second half of measurements

- **Degrees of freedom should be given when type A evaluations are documented**
  - Usually N-1
  - Generally N-M
    - Number of measurements minus number of measurands
- **For a well-characterized measurement under statistical control, a combined or pooled estimate of variance s_p^2 can be used**
  - Small number of observations vs large number of previous (or reference) measurements under similar conditions

$$s^2(\bar{q}) = \frac{s_p^2}{n}$$

Some notes for type B evaluation

- **May use for the evaluation:**
  - Previous measurement data
  - Experience or general knowledge
  - Manufacturer's specification
  - Data provided in calibration and other certificates
  - Uncertainties assigned to reference data taken from handbooks
- **Evaluating the uncertainty is a skill to be learned in practice**
- **External sources should quote the uncertainty as given multiples of standard deviations**
  - Unless otherwise indicated, assume a normal distribution for uncertainties
- **Degrees of freedom may be estimated to be**

$$\boldsymbol{v = \frac{1}{2}\left(\frac{u}{\Delta u}\right)^2}$$

- **Sometimes ∞**

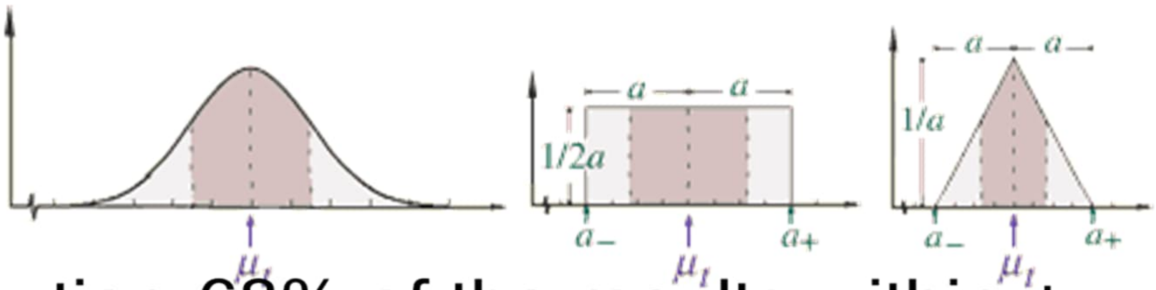
Combining uncertainties

- **Type A and type B uncertainties are treated equally when combining uncertainties**
  - Classification not to indicate any difference in nature of the components
  - Both types of evaluations are based on probability distributions
- **Do not double count**
  - Same component not A+B
- **Combined standard uncertainty**
  - In order to combine uncertainty components, distribution and standard deviation have to be known (or assumed)
  - For normal distribution of uncorrelated components, the square sum of variances

$$u^2\,(y) = \sum_{i=1}^{N} u_i^2(y)$$

  - Include covariances for correlated components

Probability distributions



- Normal distribution 68% of the results within $\pm\sigma$, 95% within $\pm 2\sigma$
- Rectangular (uniform) distribution, $\sigma=(a_{+}-a_{-})/2\sqrt{3}$ (58% propability)
- When various components are added up, the resulting distribution approaches normal.

Normal distribution (Gaussian)

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$$

Most uncertainties naturally follow the normal distribution

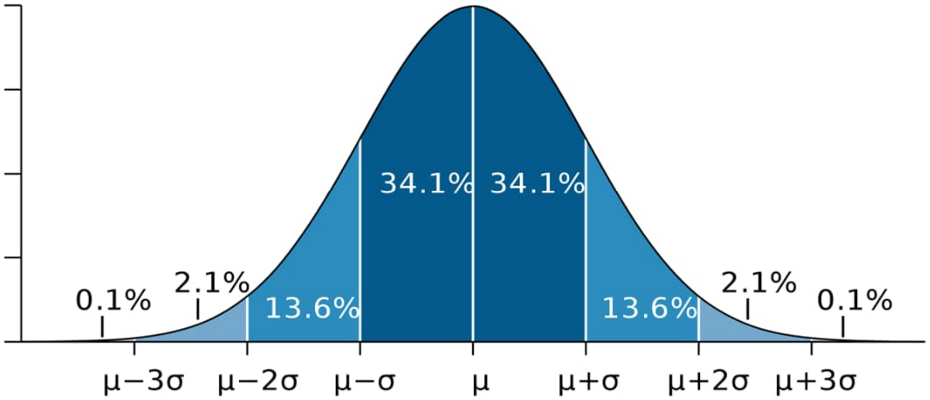
- diffusion
- Independent additive effects

It is also easiest to calculate

Hence distributions are often assumed normal even when it is not exactly justified

- often most conservative

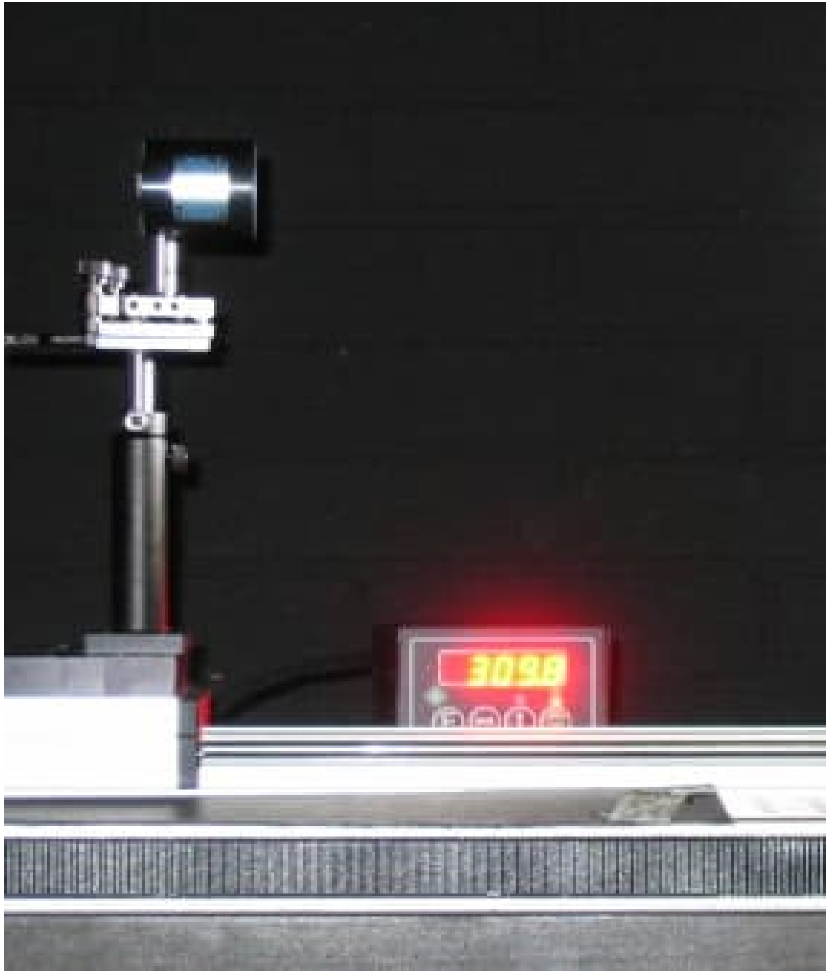
Beware of asymmetries



Resolution

- Often a dominating component
- Depends on signal level
- In analog devices, the reading accuracy
- In digital meters defined by the last digit (±1 digit)
- Rectangular probability distribution

$$u = \frac{1\,\text{digit}}{2\sqrt{3}}$$



Resolution (example)

Measuring power levels in the range **1999,9**

Reading	**Resolution**	**Abs. Uncertainty**	**Relative uncertainty (*k* =1)**
1000.0	0.1	0.03	0.003 %
500.0	0.1	0.03	0.006 %
100.0	0.1	0.03	0.03%
50.0	0.1	0.03	0.06%
10.0	0.1	0.03	0.3 %
5.0	0.1	0.03	0.6 %
1.0	0.1	0.03	3%
0.5	0.1	0.03	6%
0.1	0.1	0.03	29%

→Avoid measurements and calibrations at the low end of ranges

→Ensure before calibrations, that a suitable power level is available (Problematic e.g. with UV-meters and high-power lasers)

Tolerance of a manufacturer

Vendor’s promise that the product is within the specification

- **often quite strict limit**
- **legal consequences**

What is the probability distribution of the resistance for this resistor whose characteristics are read from colour codes?

2.2 kΩ

5 % tolerance

Modelling the measurement

- **Usually, the measurand Y**
  - Not measured directly
  - Determined from *n* other quantities $X_1, X_2, \ldots, X_n$
- **Functional relationship**
  - $Y = f(X_1, X_2, \ldots X_n)$
  - Usually defined theoretically
  - Not always explicitly writeable
  - May be an algorithm to be evaluated numerically
  - Or determined experimentally
  - Y is called output quantity
- **Input quantities X_i**
  - May be viewed as measurands
  - May depend on other quantities
- **Input quantities categorized as quantities whose values and uncertainties are**
  a) directly determined in the current experiment
  b) brought from external sources (handbooks, references, standards…)

Analyzing the results

- **Sometimes the desired output quantity is not directly calculated by a plain formula**
- **May have to perform a thorough analysis of the data**
  - Curve fitting
  - Least squares method
  - Maximum likelihood
  - Simulations, sometimes extensive
- **Within scope of metrology?**
  - Statistics and theory
  - Analyzand vs measurand?
- **A complicated analysis is a tremendous source of potential errors**
  - Misconceptions and maldefinitions
  - Numerical errors
  - Logical errors and bugs in code
  - Cumulative rounding errors
  - Errors in uncertainty estimations
- **Often non-experimentalists analyze the results of others**
  - Gross misunderstandings possible

Law of propagation of uncertainty

- **Consider independent, uncorrelated input quantities x_i with uncertainties $u(x_i)$**
- **The combined variance for the output quantity $Y = f(X_1, \ldots X_n)$ is**

$$\boldsymbol{u_c^2(y) = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i)}$$

- **Standard deviation**

$$\boldsymbol{u_c(y) = \sqrt{u_c^2(y)}}$$

- **If the function f is very non-linear, higher-order corrections may have to be taken into account**

$$\sum_{i=1}^{N}\sum_{j=1}^{N}\left[\frac{1}{2}\left(\frac{\partial f}{\partial x_i \partial x_j}\right)^2 + \frac{\partial f}{\partial x_j}\frac{\partial^3 f}{\partial x_i \partial x_j^2}\right] u^2(x_j) u^2(x_j)$$

  - Rarely necessary for small uncertainties
- **Sometimes the sensitivity coefficients $\frac{\partial f}{\partial x_i} = c_i$ are determined experimentally**

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Correlated input quantities

Significant correlations must be taken into account

$$u_c^2(y) = \sum_{i=1}^{N} c_i^2\, u^2(x_i) + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} c_i c_j u(x_i) u(x_j) r(x_i, x_j)$$

Where $r(x_i, x_j)$ is the correlation coefficient, a number between -1 and 1

Correlations often determined experimentally

Correlations may be avoided by introducing an additional input quantity (often additional measurement) with its own uncertainty

For fully correlated input quantities the combined uncertainty is linear sum

Expanded uncertainty

- $U = ku_c(y)$
- **Quantity defining an interval about the results of a measurement that may be expected to encompass a large fraction of the distribution of values that could be reasonably attributed to the measurand**

- **Often viewed as the coverage probability or level of confidence for an interval**
  - e.g. 95 %
- **Associating a specific level of confidence requires explicit of implicit assumptions regarding the probability distribution**
- **Coverage factor *k***
  - A multiplier of the combined standard uncertainty

Coverage factor k

Level of confidence p (%)	Coverage factor k_p
68,27	1
90	1,645
95	1,960
95,45	2
99	2,576
99,73	3

- **Corresponding *k* typically from Student's t-distribution**
  - William Sealy Gosset (1908)
  - approaches normal distribution
- **With "suitable" degrees of freedom, *k* = 2 gives confidence level close enough to 95%**
- **Obtaining justifiable intervals with levels of confidence of 99 % or higher is especially difficult because little information is available on the tails of the probability distributions**

Degrees of freedom

- **Should be always given**
  - Even though seldom used
- **Describe the uncertainty of uncertainty**

$$\Delta u = \frac{u}{\sqrt{2v}}$$

- **Effective degrees of freedom given by the formula**

$$v = \frac{u^4(y)}{\sum_{i=1}^{n} \frac{c_i^4 u^4(x_i)}{v_i}}$$

- **May be a real number**
- **Relevant when calculating Student's t-distribution**
  - Get coverage factors

Challenging cases

- **Particular difficulties:**
  - Non-linear dependency on input quantities
  - Strong correlations between input quantities
  - Large uncertainties
  - Non-Gaussian distributions
  - Hard asymmetries
- **These make it hard to estimate reliably particularly expanded uncertainties with high (>90 %) levels of confidence**

- **May compute uncertainties and confidence levels numerically**
  - Loops over all uncertainty components and input quantities
  - or use Monte Carlo
    - Random numbers
  - Statistical analysis for final distribution of the output quantity y
  - Be careful with probability distributions
- **The better you do your measurements, the less you need mathematics!**
  - Small, independent and well-understood uncertainties make it simpler

Err on the safe side?

- **Yes, but**
- **Do not overestimate the uncertainty within the evaluation**
- **Use an appropriate coverage factor only for the combined uncertainty**
  - Never for particular components or input quantities
  - Transform expanded uncertainties of input variables to standard deviations
- **Do not double count**
  - A or B but not both

- **Bad advice:**
  - “Multiply the errors by pi”
  - “Add systematic and statistical uncertainties linearly”
- **Overestimate of uncertainty may be costly and dangerous**
- **Evaluation of uncertainty should not be confused with assigning a safety limit**
  - That is done afterwards using coverage factor or more detailed analysis

Expressing uncertainties (GUM)

- **$m = 100.023$ g with (a combined uncertainty) $u_c = 0.012$ g**
- **$m = 100.023(12)$ g where the number in parenthesis is the numerical value of (the combined uncertainty) u_c referred to the corresponding last digits of the quoted results**
- **$m = 100.023(0.012)$ g where the number in parenthesis is the numerical value of (the combined uncertainty) u_c expressed in the unit of quoted result**
- **$m = (100.032 \pm 0.012)$ g where the number following the symbol $\pm$ is the numerical value of (the combined uncertainty) u_c and not a confidence interval**
  - GUM recommends to avoided this as it has been traditionally used to indicate an interval corresponding to a high level of confidence and thus may be confused with expanded uncertainty

Expanded uncertainties

When reporting an expanded uncertainty $U = ku_c(y)$ one should

a) Describe how the measurand Y is defined

b) State the result of the measurement as $Y = y \pm U$ and give units of y and U

c) Include the relative expanded uncertainty $\frac{U}{|y|}, |y| \neq 0$ when appropriate

d) Give the value of k used to obtain U

e) Give the approximate level of confidence associated with the interval $y \pm U$ and state how it was determined (e.g. 95 % …)

f) Give other relevant information

$m = (100.03 \pm 0.03)$ g where the number following the symbol $\pm$ is the numerical value of (an expanded combined uncertainty) $U = ku_c$, with U defined from a combined uncertainty $u_c = 0.012$ g and (a coverage factor) $k = 2.26$ based on a t-distribution for 9 degrees of freedom, and defines on interval estimated to have a level of confidence 95 %.

Asymmetric distributions

- **The probability distributions above and below the value may be different**
  - More care with analysis
- **Often the output quantity given symmetric interval (y may be off)**
  - $\boldsymbol{Y = y \pm U}$
- **May give two intervals:**
  - $\boldsymbol{y - U_-}$ and $\boldsymbol{y + U_+}$
  - Particularly if one side is more sensitive, costly or dangerous
- **In some occasions all possible values of a quantity lie to one side of a single limiting value**
- **E.g. cosine error**
  - Measure the length of an object
  - A sloppy measurer may inadvert incline the gauge to measure too large values
- **Upper limit for "zero" quantities (negative values being unphysical)**
  - m_v < 0.7 eV (95 % C.L.)
  - Rather than m_v = 0 + 0.7 eV (95 % C.L.)

Additional notes for reporting

If the measurement determines simultaneously more than one measurand, in addition to giving y and u, the covariance or correlation coefficient matrix should be given

Use appropriate number of digits for the uncertainty

- **Usually only one digit**
- **Often two digits for 10-19**
- **You may round the uncertainty upwards**
- **Round only in the final result (expanded uncertainty), never intermediate to avoid cumulative rounding errors**
- **More digits may be used if you particularly study how to analyze and reduce the uncertainty**
    - That is what the real metrologists do…

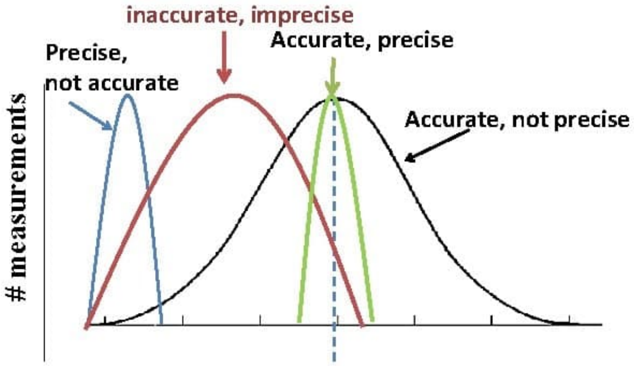
Redoing the measurement

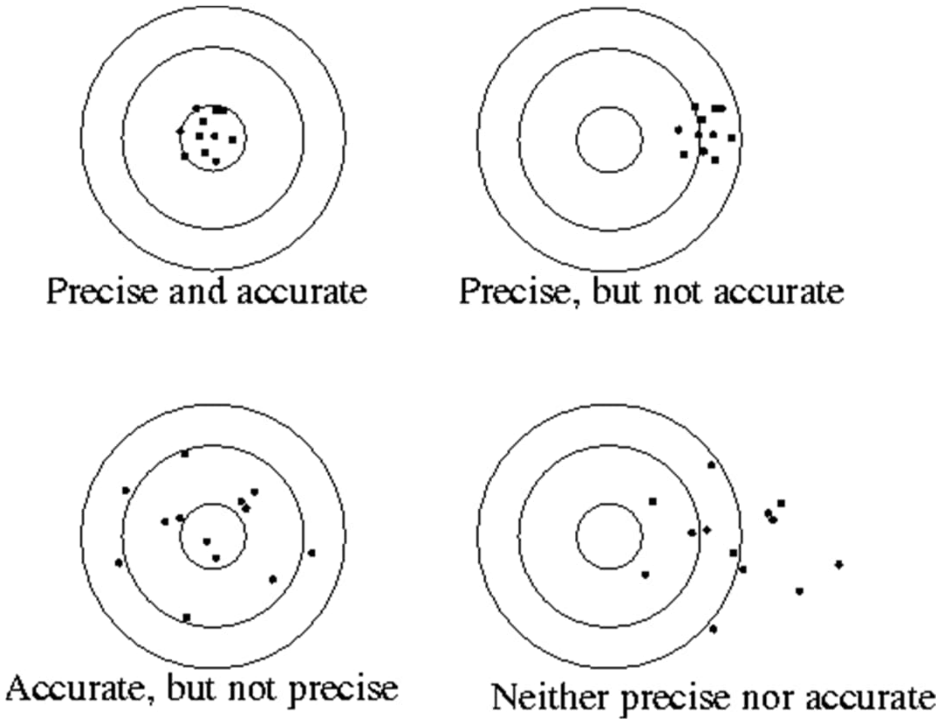
- **Repeatability**
  - Closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurements
    - Same observer
    - Same procedure
    - Same location
    - Same instrument …

- **Reproducibility**
  - Closeness of the agreement between the results of the measurements of the same measurand carried out under changed conditions
    - Other scientist
    - Other place
    - Other instrument
    - Etc
  - Typically, another group redoes similar experiment in their lab following your report

Precision and accuracy

Graph Accuracy Precision





"It is better to be roughly right than precisely wrong." — Alan Greenspan

Anomalies

In successive measurement one result may be an outlier

- clearly off the trend

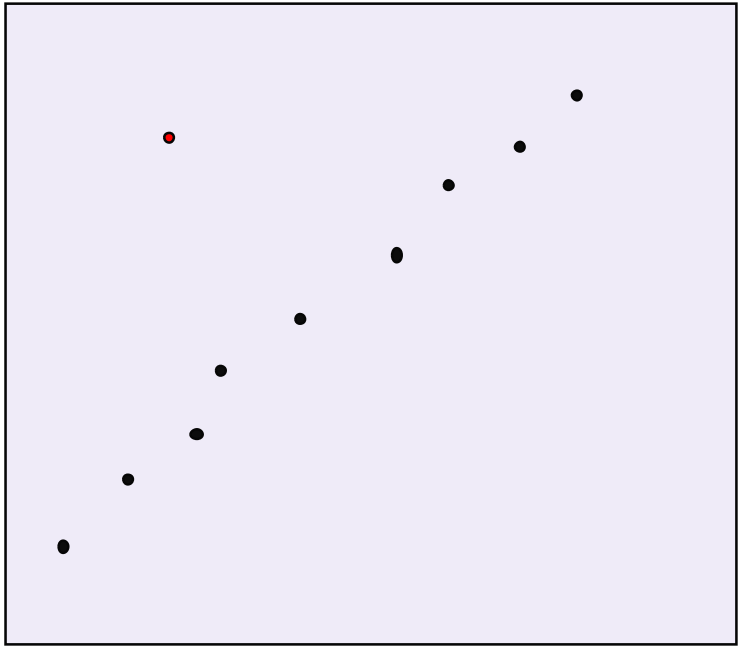
May be due to a specific error or malfunction

Should be investigated thoroughly

May be thrown out of data if its cause is found

Should not be dropped without reason

Gather more data if possible



8 steps evaluating uncertainty (GUM)

1. Express the mathematical relationship between measurand Y and the input quantities X_i
2. Determine the estimates x_i of the input quantities by measurement(s) or by other means
3. Evaluate the standard uncertainties $u(y)$ of each input quantity estimate x_i, by statistical methods (type A) or by other means (type B). Take into account distribution.
4. Find and estimate correlation coefficients between pairs of input quantities. (Typically negligible, not always)

5. Calculate the result of the measurand according to the equation from Step 1: $y = f(x_1, \ldots, x_n)$.

6. Calculate the combined standard uncertainty $u_c(y)$ of the measurand result y by applying the law of propagation of uncertainties with the individual standard uncertainties and estimates*)

7. Calculate an expanded uncertainty U by multiplying the standard uncertainty $u_c(y)$ with a coverage factor k: $U = ku_c(y)$. For confidence level of 95 % with normal distribution, $k = 2$.

8. Report the measurement result y together with its expanded uncertainty.

*) NOTE: Very often this is really simple if you use relative uncertainties in %.

Reducing uncertainty

- **Type A uncertainty**
  - Get more data
    - Uncertainty proportional to $\frac{1}{\sqrt{N}}$
  - Reduce noise
    - When signal-to-noise is bottleneck

- **Type B uncertainty**
  - Know your experiment better
    - General recipes often too general
  - Test it several ways
  - Measure critical components or materials instead of relying on manufacturer's specifications
  - Use better components
  - Remove sources of background
  - Calibrate

Reducing uncertainty always costs time and money
Is it worth it? Or is it obligatory? What is cost effective?

Most accurate quantities and measurements

- **Very few measurement reach 10^{-10} relative uncertainty**
- **Time can be measured with >15 digits**
  - Finnish time VTT MIKES 10 ns
  - relative uncertainty up to 10^{-20}
- **Change of distance**
  - relative uncertainty 10^{-21}
  - by laser interferometry (LIGO)
- **Magnetic moment of electron**
  - Relative accuracy of 1.7×10^{-13}

- **SI base quantities, exact values by definition**
  - ground-state hyperfine transition frequency of the cesium-133 atom -> s
  - Speed of light *c* -> m (1983)
  - Elementary charge *e* -> A (2019)
  - Boltzmann constant *k* –> K (2019)
  - Planck constant *h* -> kg (2019)

Ultimate limit: Quantum uncertainty

$$\Delta x \Delta p \geq \frac{h}{4\pi}$$

- **Heisenberg principle**
- **One cannot measure the position and momentum (velocity) simultaneously**
- **Neither time and energy**

- **In most practical, macroscopic measurements this limit is irrelevant**
  - Except some fundamental scientific measurements and quantum metrology
- **They are playing with uncertainty at Department of Applied Physics at Aalto University**
  - Most important scientific discovery of 2021
  - Sillanpää & Mercier de Lépinay

Optical calibrations in Mikes-Aalto

- Photometry
  - Luminous intensity (0.3%)
  - Illuminance (0.2%-0.5%)
  - Luminance (0.8%)
  - Luminous flux (1%)
- Radiometry
  - Spectral irradiance(0.6%-3%)
  - Spectral radiance (1%)
  - Colour coordinates *x*, *y* (0.1%)
  - Colour temperature (0.15%)
  - Optical power (0.05% - 10%)
- Spectrophotometry
  - Transmittance (0.05%-1%)
  - Reflectance (0.5%-5%)
  - Diffuse reflectance (0.4%-1%)
  - Fluoresence

Measurement uncertainty can not be lower than calibration uncertainty

Detailed uncertainties listed in the CMC database http://kcdb.bipm.org/appendixc/

Measuring the smallest masses

Neutrinos

- **Tiny elementary particles**
- **Have no electric charge**
- **only weak interactions**
- **they penetrate all objects easily**
- **they are all around**
- **No mass measured**
- **Theory allows neutrinos to be massless or massive**

Direct weighing of neutrinos impossible

Indirect measurement by beta decay

$$3H \rightarrow 3He + e + \nu_e$$

Cannot see neutrinos:

- **too invisible**

Cannot measure the impulse to Helium atom

- **too weak**

Can measure the energy of electrons

Statistical analysis of beta decay

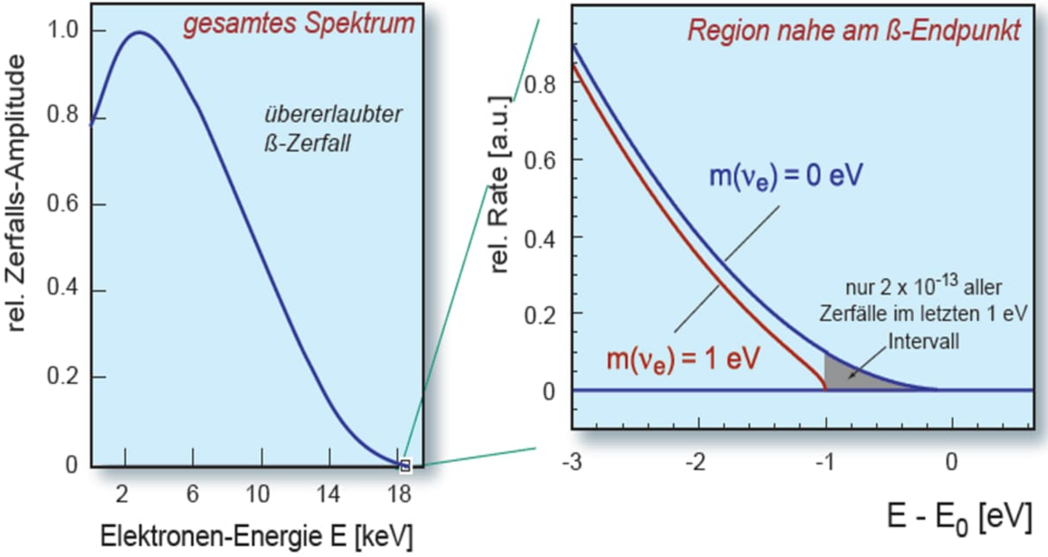
Energy spectrum of emitted electrons proportional to

$$\sqrt{(E-E_0)\sqrt{(E-E_0)^2-m_v^2}}$$

Where E is the electron energy and E_0 is the released nuclear energy

Endpoint depends on neutrino mass m_v

Need huge amount of data (ca 10^{13} decays) and very low background



Katrin experiment

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Results

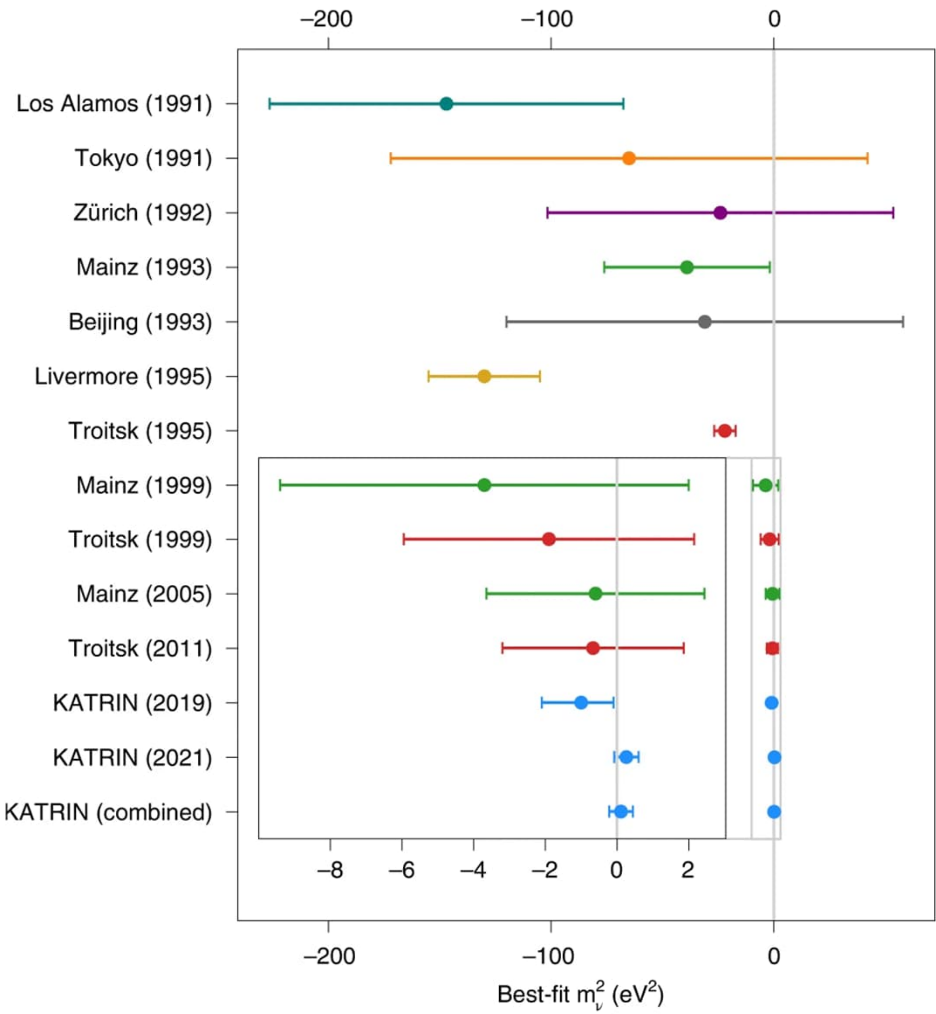
So far no positive results

Upper limit $m_\nu < 0.8\ \mathrm{eV/c^2}$ (90 % C.L.)

Cf electron mass 510 000 eV

Note

- **electron volt eV is a nass unit of particle physicists**
- **off at SI system**



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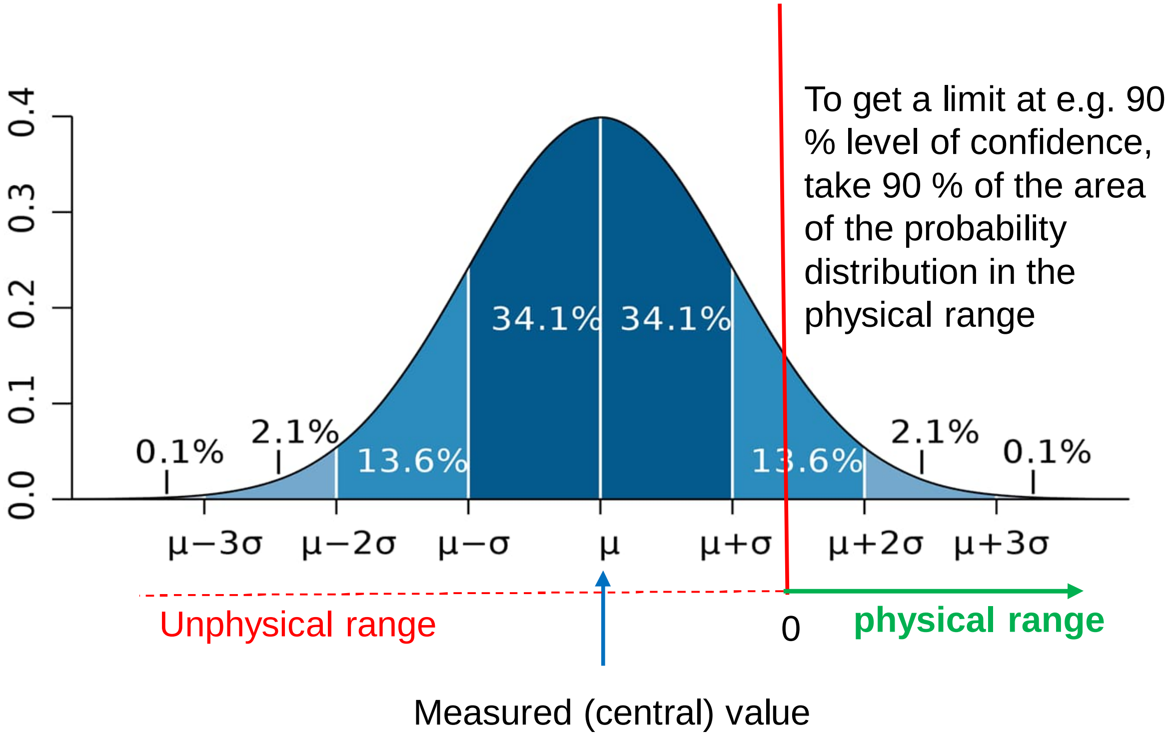
Non-physical values

How to interpret and analyze if the measured value for the quantity lies at unphysical range

- less than zero or a known lower limit

Warning: if the central value is too far off, there may be something wrong with the measurement

- Some ancient cosmological …



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Detector noise and dark current

Fake signals from the detector, source or other electronics (amplifiers)

- **Thermal effects**
- **Chemical effects**
- **Malfunctions**
- **Unstabilities**
- **Quantum effects**

May appear as

- **Random effects**
- **Continuous leak current or streams**
- **Gradual change of measurements**

Typically type A uncertainty

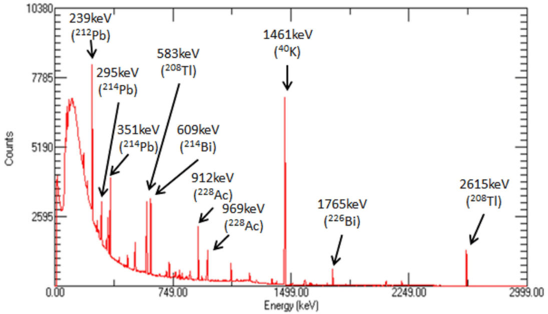
Background radiation

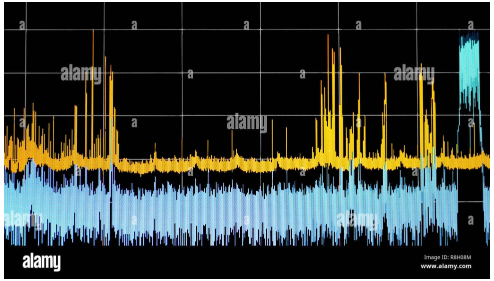
When measuring radiation, other non-desired radiation sources or other true physical events affect the measurement

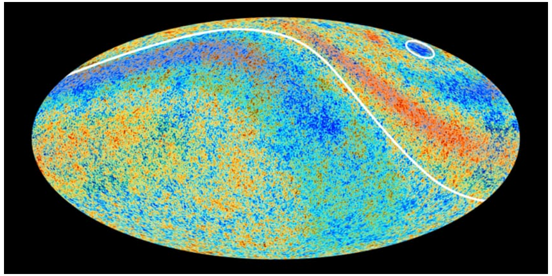
- **Stray light**
- **Thermal radiation**
- **Natural radioactivity**
- **Cosmic rays**
- **Relic radiation from early universe**

One's background is another's signal

Typically type A uncertainty, sometimes type B







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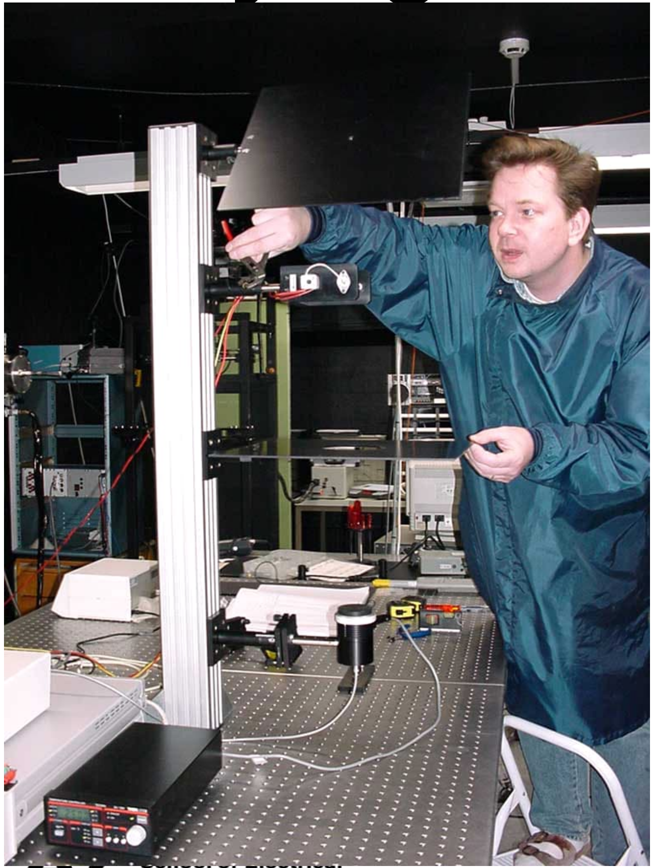
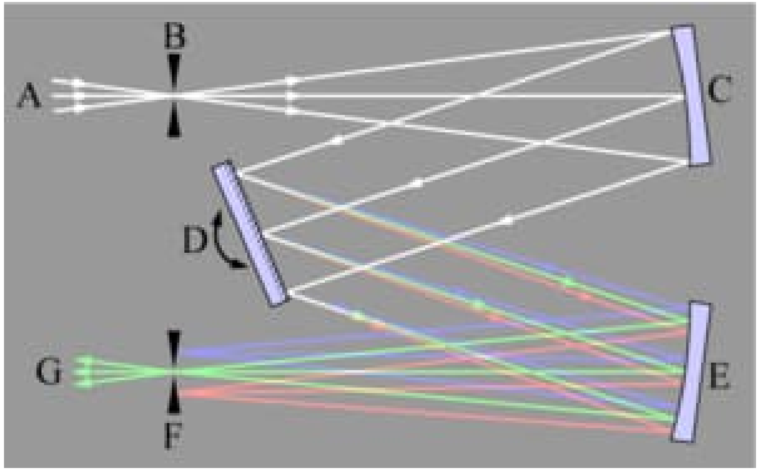
Stray light



- Light propagates from source to detector via all possible (and impossible) routes

→ Baffles are used to reduce stray light in e.g. lamp measurements and monochromators to as low as possible

- Black surfaces absorb stray light



Use of baffles in lamp measurement

Preferred light propagation in Czerny-Turner monochromator

Accounting for background in optical measurements

- It is impossible to remove all stray light. Also, the detectors and electronics typically give a small signal even in dark (dark signal)
- Before measurement, light path is blocked using shutter

→ Effect of background and dark signal

- Dark reading subtracted from result
- Uncertainty evaluated “using other means.” Reading not added to uncertainty!
- Can also be made manually in simple measurements

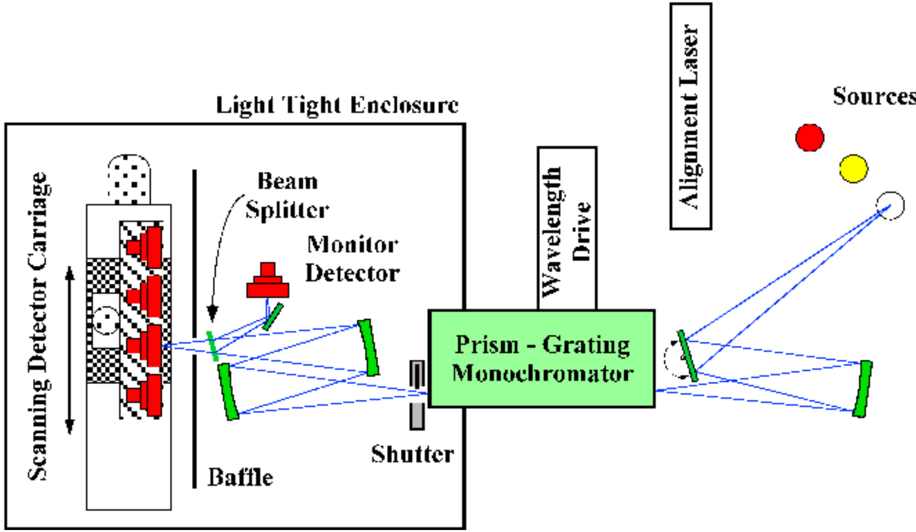


Figure courtesy of NIST

Using chopper to reduce background

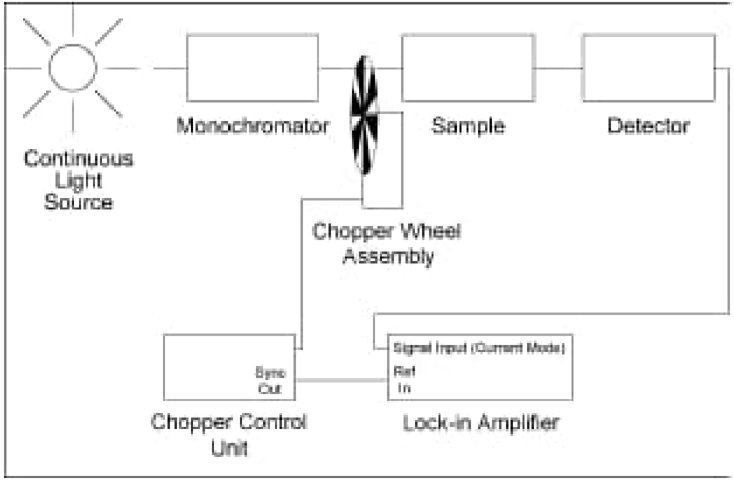


Figure 3, AC Measurement System using a Lock-in Amplifier and Mechanical Chopper

Figure courtesy of Ametek Signal Recovery

- A small signal can be recoved under large background using a chopper and a lock-in amp
- Signal chopped, background not

→ Lock-in amp only responds to chopped radiation

- As a bonus, $1/f$ noise improves
- It is possible to extend measurement range by ~3 decades
- Pyroelectric radiometers chopped always

Reducing background and noise

- **Isolate your device from spurious sources**
  - Opaque walls
  - Faraday cage
  - Thick walls (Pb)
  - Water
  - Deep underground
- **Use radiopure materials**
  - Avoid all radioactivity
  - Let it decay
- **Use high quality components**
- **Do not expose components to external radiation or contamination sources**
- **Cool the detector**
  - Sometimes close to absolute zero
- **Statistical analysis**
  - Big device, long measurement
- **Necessary actions depend on what you measure and what quality you aim at**

Detector ageing

- Detector ageing depends on
  - Technique, type, manufacturer
  - Use of the detector (used lot/kept in closet, UV)
  - Conditions of use (dirt, dust, user)
- The only way to determine is frequent calibrations!
  - Keep log book about behavior of the device
  - As a starting point, manufacturer recommendations
  - After obtaining knowledge on behaviour, calibration interval can be shortened or extended!
  - 1 year calibration interval is not a rule or law

Example: Customer calibration

Component	Standard uncertainty	
	1,4 mW	9,0 mW
Calibration of the pyro	0,4 %	0,5 %
Wavelength dependence of pyro	0,3 %	0,3 %
Resolution of calibrated device	0,2 %	0,03 %
Repeatability	0,54 %	0,18 %
Alignment	0,4 %	0,4 %
Combined standard uncertainty u_c	**0,86 %**	**0,70 %**
Expanded uncertainty U (k=2)	**1,72 %**	**1,39 %**

Typically, calibrations have a couple of major uncertainty components and minor components can be neglected!

- Customer calibration with pyroelectric radiometer
- Dominating components in addition to calibration
  - Wavelength dependence (calibrated in VIS, meas in IR)
  - Resolution
  - Repeatability at small signal levels
  - Alignment
- Best measurement capability with traps is 0,05 %. After two calibration steps, we are almost 2 decades higher!

Details of the setup

- Infrared laser beam within a tube. Customer meter is compared with a calibrated pyroelectric radiometer