Establishing a Common Vocabulary

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Metrology for Earth Observation and Climate

EMRP
European Metrology Research Programme
Programme of EURAMET

The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

Metrology

Worldwide trade/manufacturing
Public health and safety
Scientific Research

Requires data that is:

Stable over time

- so that 'scales' and references aren't changing

Insensitive to the method of measurement

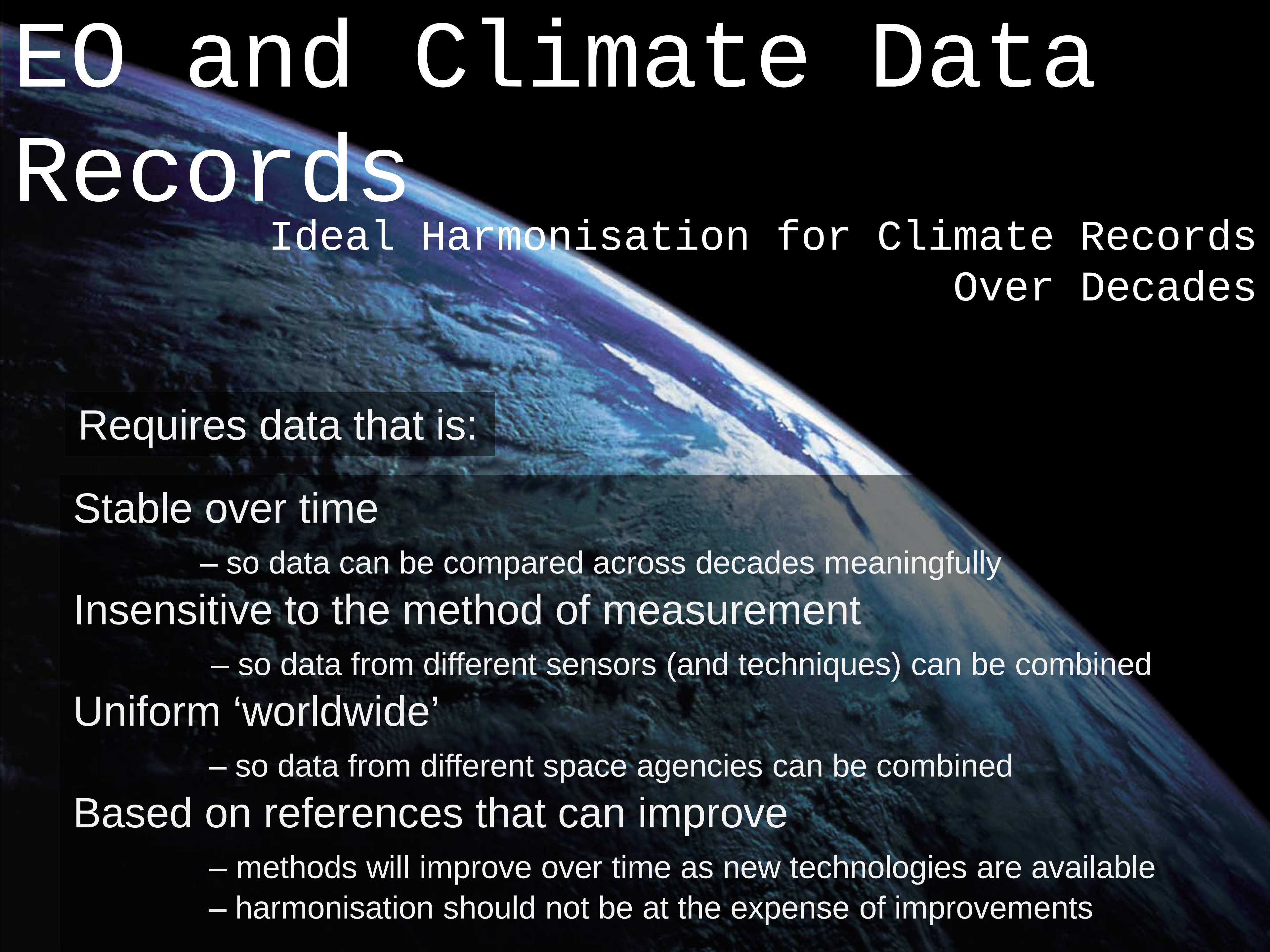
- so the result doesn't depend on how you make the measurement

Uniform worldwide

- so you can build the wings in France and the fuselage in Spain

Based on references that can improve

- methods will improve over time as new technologies are available
- harmonisation should not be at the expense of improvements



EO and Climate Data Records

Ideal Harmonisation for Climate Records Over Decades

Requires data that is:

Stable over time

– so data can be compared across decades meaningfully

Insensitive to the method of measurement

– so data from different sensors (and techniques) can be combined

Uniform ‘worldwide’

– so data from different space agencies can be combined

Based on references that can improve

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Presentation

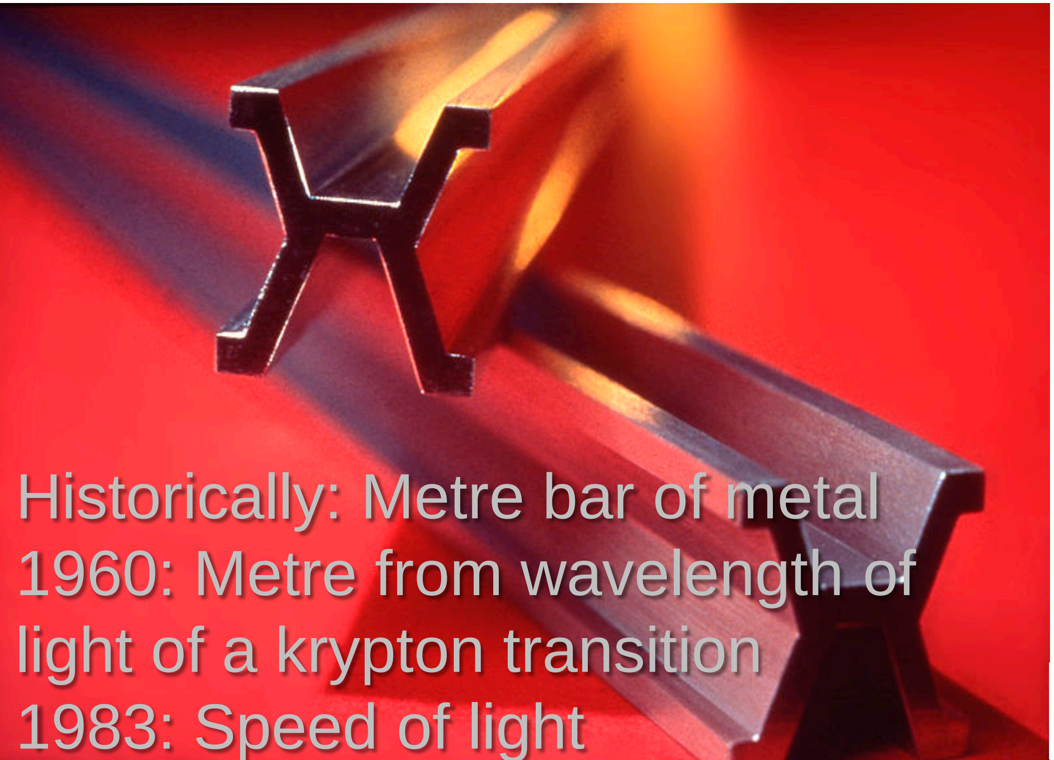
- What is metrology, its history and how does it achieve harmonisation and long-term consistency?
- The vocabulary of metrology – uncertainty and traceability
- Propagating Uncertainties (short version)

Metrology

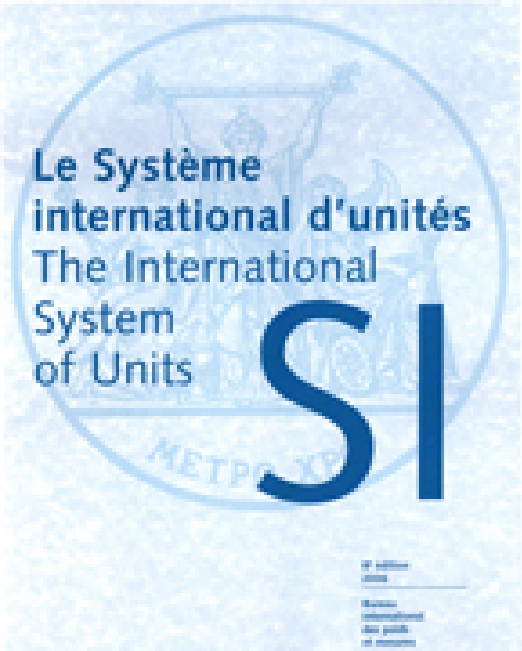
1875: Metre Convention

Established:

- BIPM as a scientific organisation (defining new science of metrology)
- CGPM/CIPM as intergovernmental committees to agree standards for metrology



Historically: Metre bar of metal
1960: Metre from wavelength of light of a krypton transition
1983: Speed of light



Le Système international d'unités
The International System of Units
SI

1960: CIPM set up the SI

Metrology Principles

Documentation

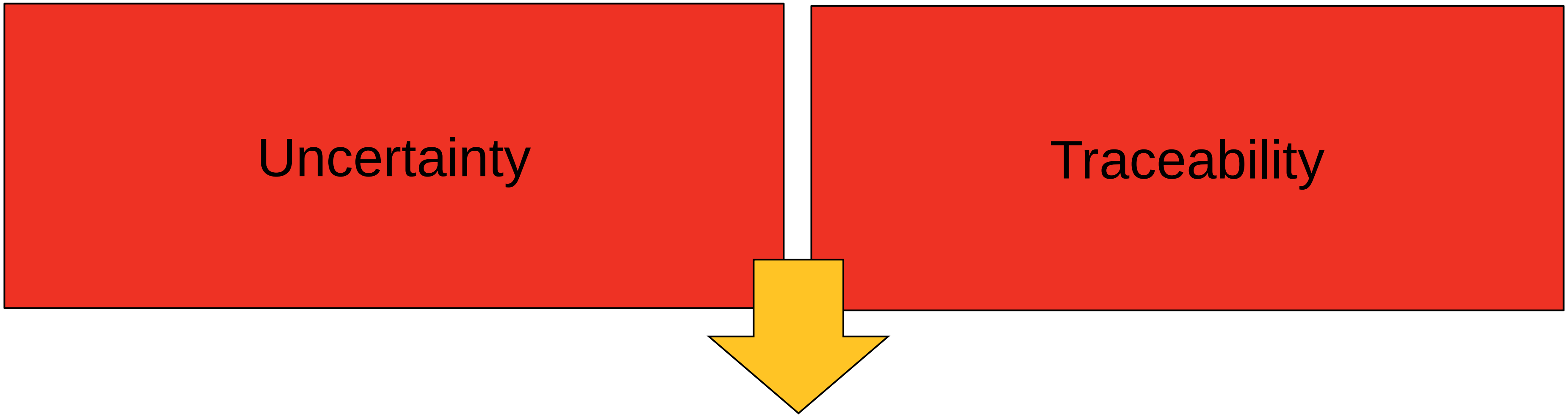
Comparisons

Peer review

Auditing

Community defined references (SI)

Changes made cautiously – consistent to old definitions

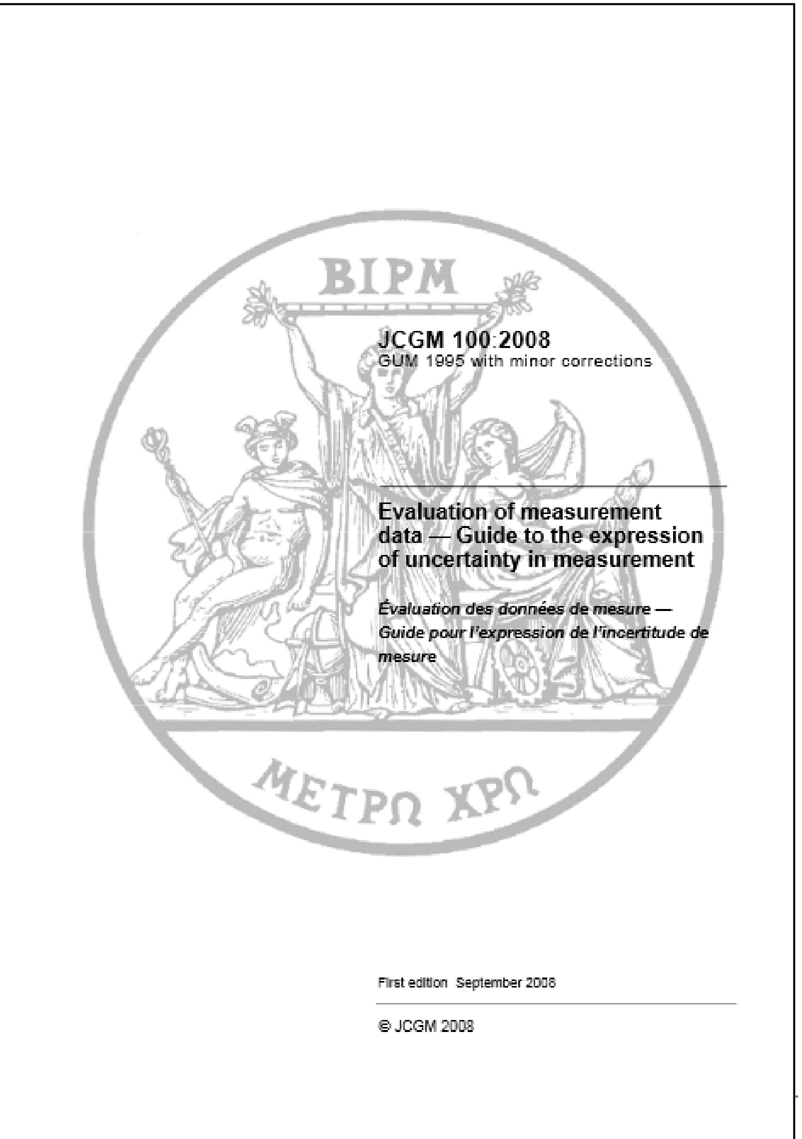


Uncertainty

Traceability

Stable measurements, worldwide consistency, insensitive to methodology

Uncertainty and how to deal with it
The GUM



JCGM 100:2008
GUM 1995 with minor corrections

Evaluation of measurement data — Guide to the expression of uncertainty in measurement

Évaluation des données de mesure — Guide pour l'expression de l'incertitude de mesure

First edition September 2008

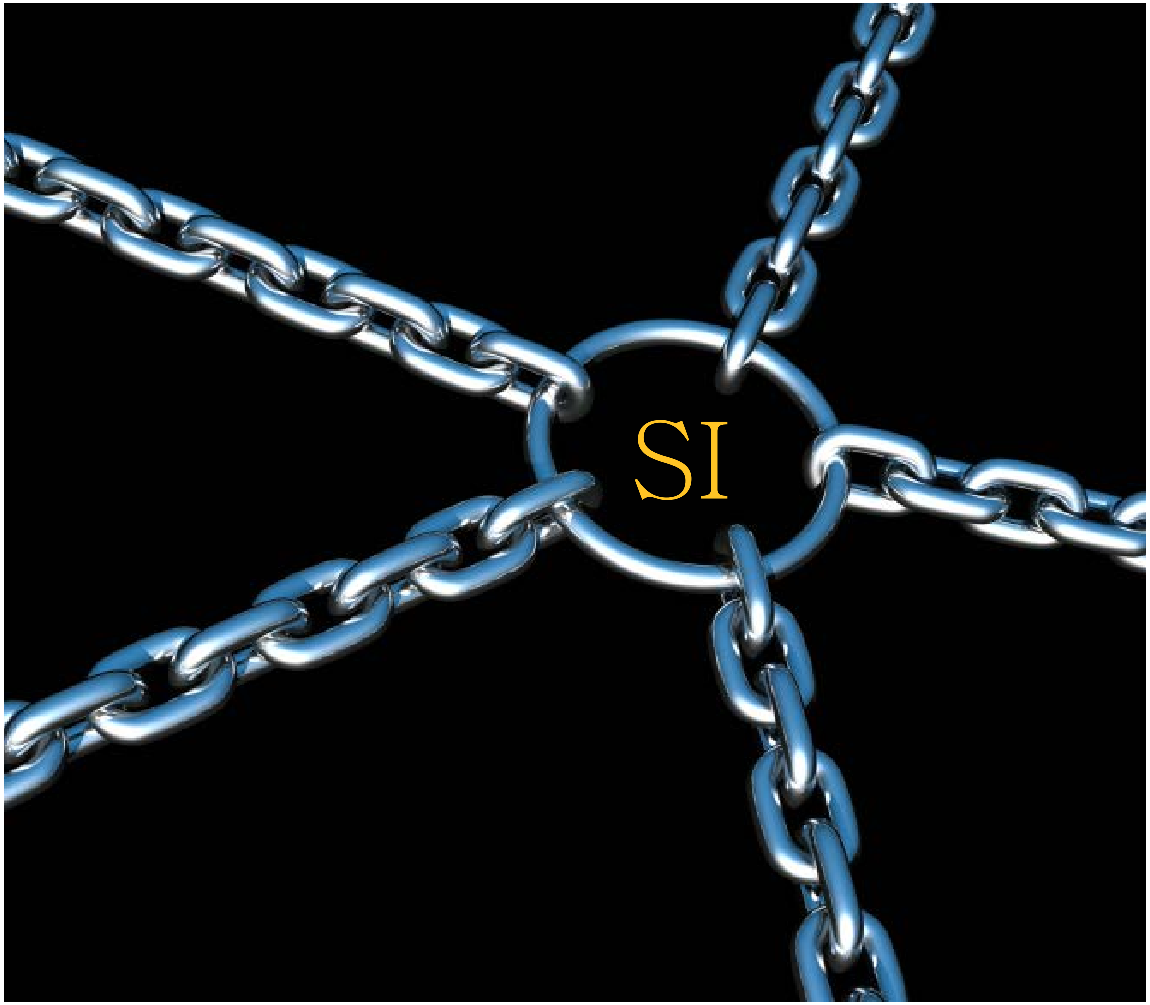
© JCGM 2008

The Guide to the expression of Uncertainty in Measurement (GUM)

- The foremost authority and guide to the expression and calculation of uncertainty in measurement science
- Written by the JCGM and BIPM between 1977 and 1995 (updated 2008)
- Covers a wide number of applications
- Technical with formal mathematics

http://www.bipm.org/en/publications/guides/gum.html

Ensuring long-term stability: Traceability



Traceability is about achieving an unbroken chain back to the SI reference.

The reference is stable

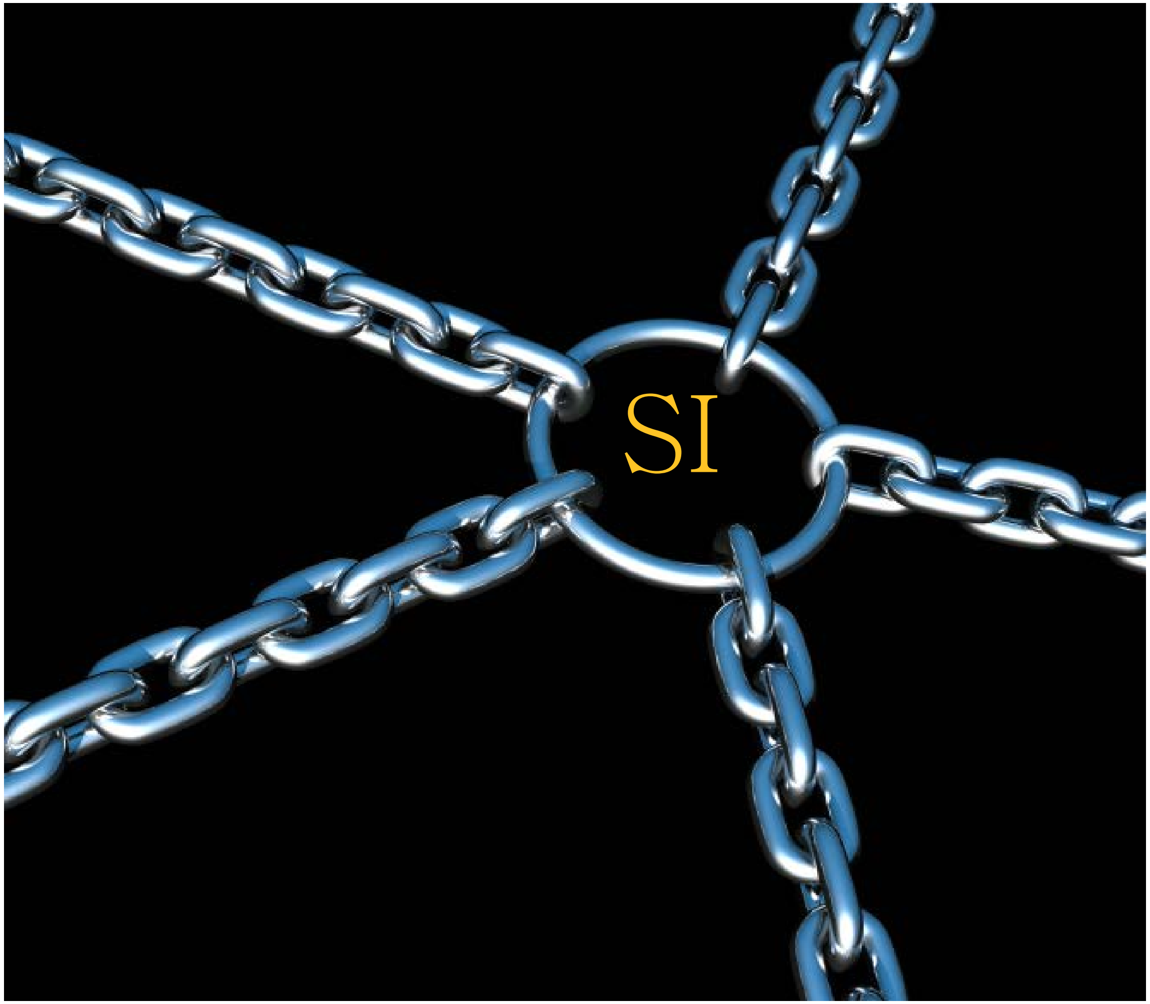
All measurement has this unbroken chain to a stable reference

Traceability

"Property of a measurement result relating the result to a stated metrological reference (free definition and not necessarily SI) through an unbroken chain of calibrations of a measuring system or comparisons, each contributing to the stated measurement uncertainty"

Committee on Earth Observation Satellites (CEOS)

Ensuring long-term stability: Traceability: 2



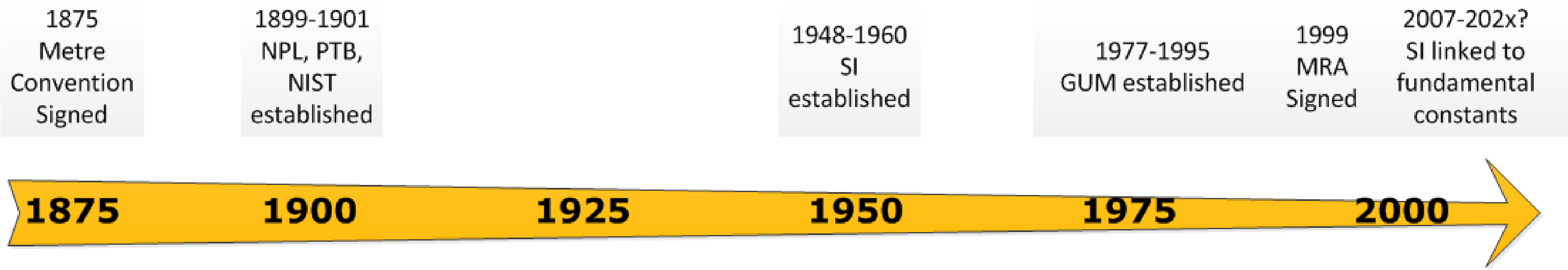
Traceability requires:

- Documented procedures for each stage
- Uncertainty budget for each stage
    - Forces a review of all processes
- Audit / peer review of the calibration process
- Demonstration of traceability chains during/after poster session

Metrology Timescales

A lot of effort has gone into Metrology.

- The GUM was the result of 18 years of discussion
- SI was the result of 12 years of discussion
  - They started discussing linking SI to fundamental constants in 2007 maybe available 2020.
- The 1999 Mutual Recognition Arrangement formalised the need for comparisons
  - Many problems identified with the process and procedures now documented



1875 Metre Convention Signed

1899-1901 NPL, PTB, NIST established

1948-1960 SI established

1977-1995 GUM established

1999 MRA Signed

2007-202x? SI linked to fundamental constants

What Metrology can do for us?

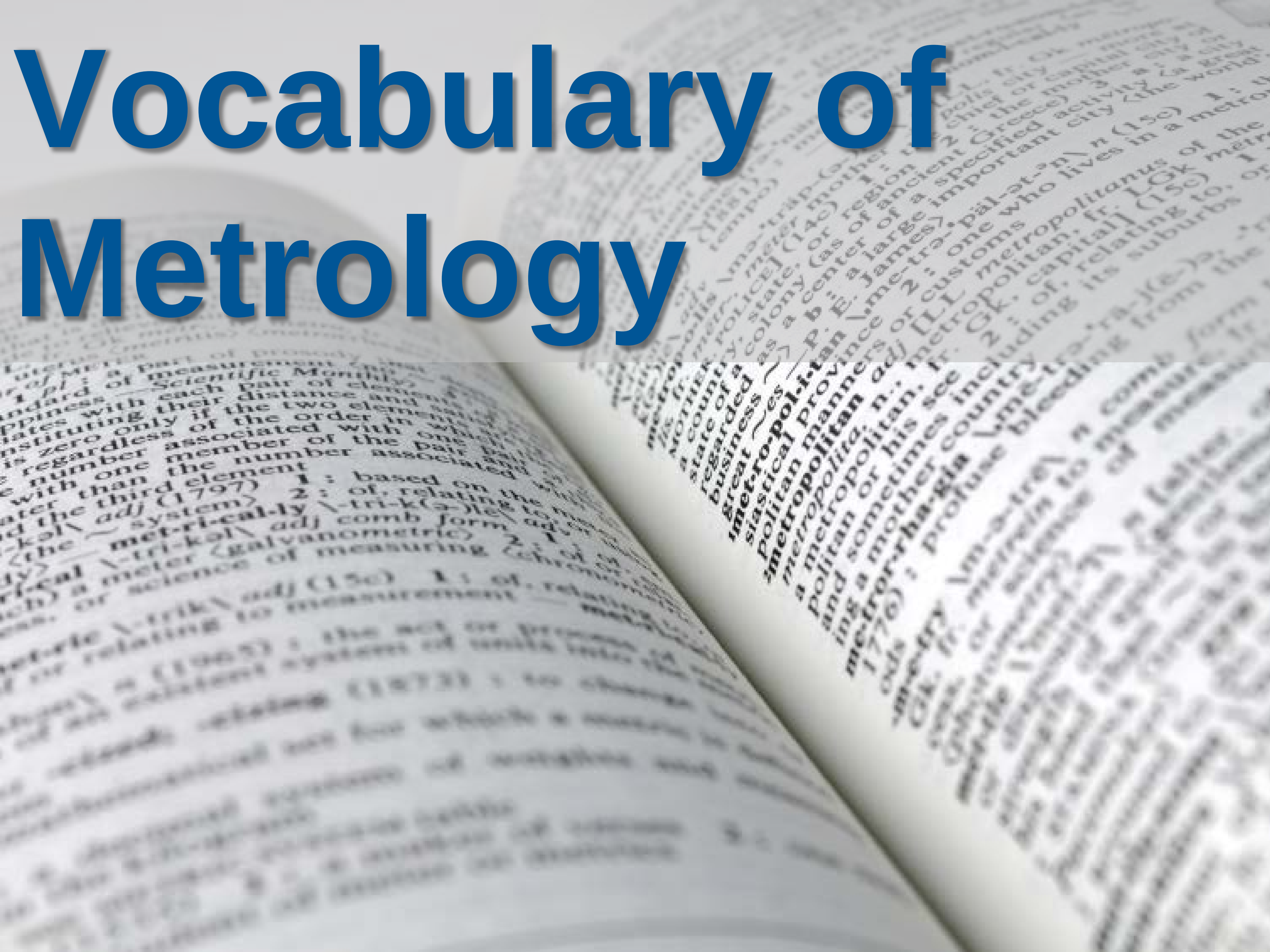
Metrologists have thought long and hard about measurement and uncertainty and have over 100 years experience

Now have processes to ensure international agreement for measurements

- Best practice for comparing data
- How to document traceability
- Dealing with uncertainties in a rigorous manner

This is experience we can use in EO

Vocabulary of Metrology



Error

is NOT the same as

Uncertainty

Uncertainty vs. error

Uncertainty:

- Describes the spread of a probability distribution i.e. standard deviation

Uncertainty is the doubt you have on the value

Error:

- Difference from truth

Result of measurement imperfections

From random and systematic effects

Correction

- Where an error is known, it can be corrected by applying a correction

There will always be an unknown residual error which adds to the uncertainty

Consistency in terminology is important!

Simple explanation for those who like programming …

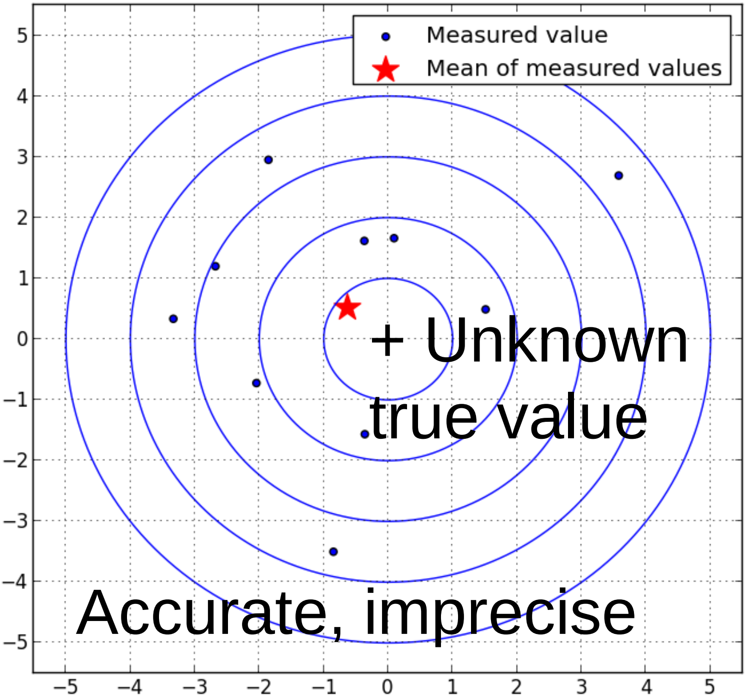
Modelling a measurement process – what is the result of the measurement?

Define a true value → In the real world you never know this!

Define a probability distribution → The standard deviation is the uncertainty.

Get a random value from the distribution → This is the error. In the real world you never know this.

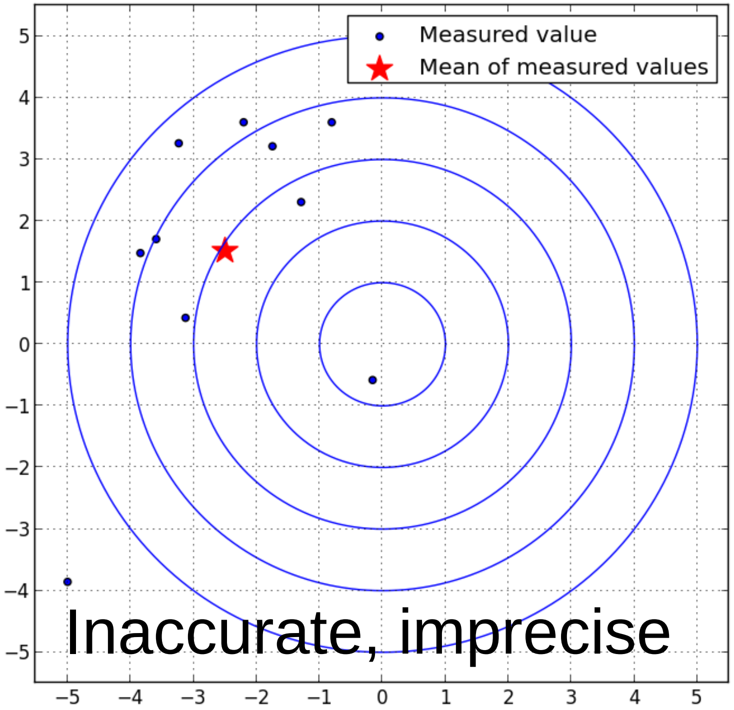
Add the value to the true value → This simulates the measured value.



+ Unknown true value

Accurate, imprecise

High random



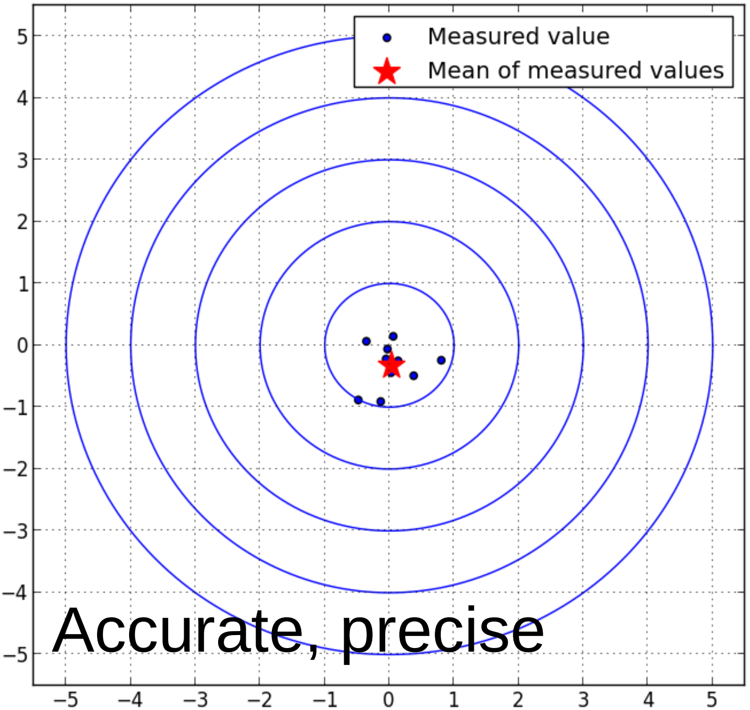
Inaccurate, imprecise

Random

and

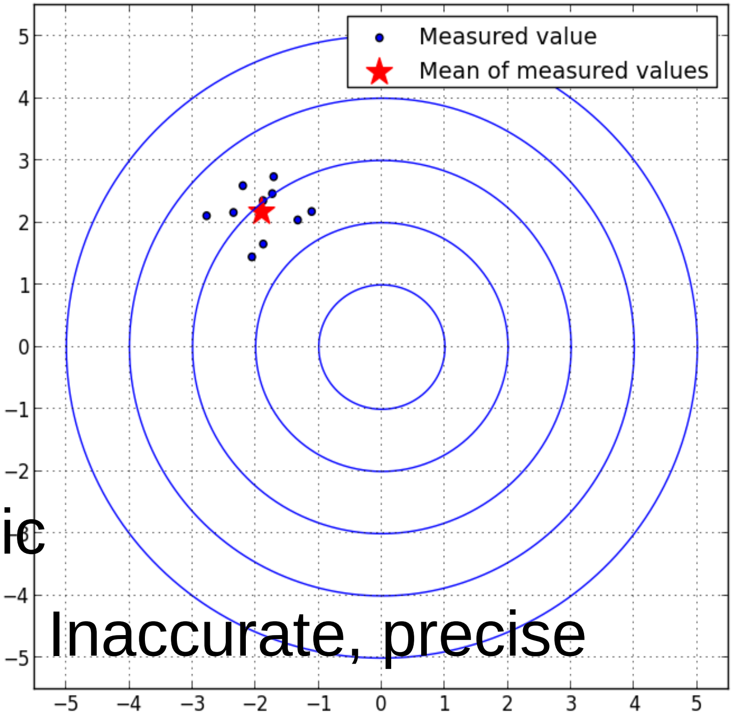
systematic

effects



Accurate, precise

High Systematic



Inaccurate, precise

Random Effects

- Random effects

  Different error for every measurement (different random number)

  Cannot be corrected for even if the measurement is dully understood

  Can have same associated uncertainty (drawn from same probability distribution)

  - e.g. Detector noise etc.

Note: don’t use the incorrect phrase “random uncertainties” – “uncertainty” describes the probability distribution.
Strictly: “uncertainties associated with random effects”

Systematic effects

- Errors which in principle can be corrected for if the cause of the error was fully understood

  Of course often you don't know what this correction is so you have an uncertainty associated with such systematic effects

  - E.g. Incorrect instrument parameterisation
- With many systematic effects there is a time and space scale which is applicable
  - E.g. Instrument degradation – changes slowly over time
- Local effects
  - Metrology doesn't yet have a formal way of describing these
  - Effects that are local in time and/or space
    - E.g. Atmospheric effects, calibration (solar contamination) etc.

Type A and Type B methods

- Two methods of assessing uncertainty

  Type A

    Application of statistical methods to a series of repeated determinations.(real or simulated)

  Type B

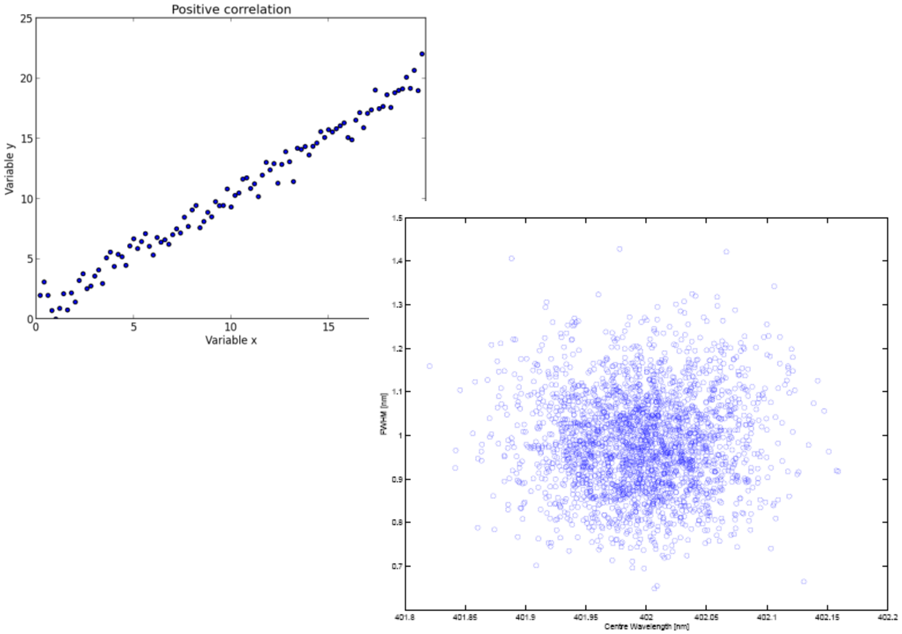
    Based on experience and knowledge of physical processes

    The uncertainty associated with the systematic error is known even though the error itself isn't

How to determine correlation (and covariance)

Type A methods:
From the data (real or simulated)

- Discover correlations



Type B: From knowledge (measurement model)

$$E_i = E_{\text{True}} + \enclose{circle}{S} + R_i$$

This is where the correlation comes from!

$$u(x,y) = u(S)$$

Propagating Uncertainty

The Law of Propagation of Uncertainties (GUM)

National Physical Laboratory

$$u_c^2(y) = \boxed{\sum_{i=1}^{n}\left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i)} + \boxed{2\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\frac{\partial f}{\partial x_i}\frac{\partial f}{\partial x_j}u(x_i, x_j)}$$

Adding in quadrature

Sensitivity coefficient times uncertainty

Correlation term

$$u(x_i, x_j) = u(x_i)u(x_j)r(x_i, x_j)$$

Sensitivity coefficients times covariance

2 because symmetrical:

$$u(a,b) = u(b,a)$$

Law of Propagation of Uncertainties (2)

National Physical Laboratory

- In Matrix form we have

$$C_x = \left(\frac{\partial f}{\partial x_1}, \frac{\partial f}{\partial x_2}, \quad \cdots \quad \frac{\partial f}{\partial x_n} \right)$$

Sensitivity coefficients

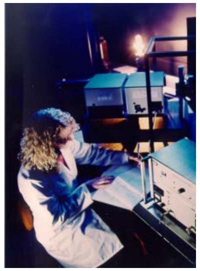
$$U_x = \begin{bmatrix} u^2(x_1) & u(x_1, x_2) & \dots & u(x_1, x_n) \\ u(x_1) & u^2(x_2) & \dots & u(x_1) \\ \vdots & \vdots & \ddots & \vdots \\ u(x_n, x_1) & u(x_n, x_2) & \dots & u^2(x_n) \end{bmatrix}$$

Covariance matrix

and

$$u^2(y) = C_x U_x C_x^T$$

Sensitivity Coefficients/Correlations



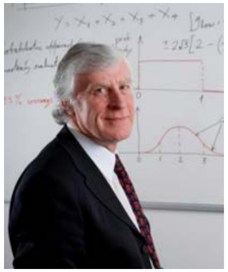
Experimentally

Vary in the lab and see what happens

Difficult (if not impossible) for many EO missions

Numerically

Vary in the model and see what happens



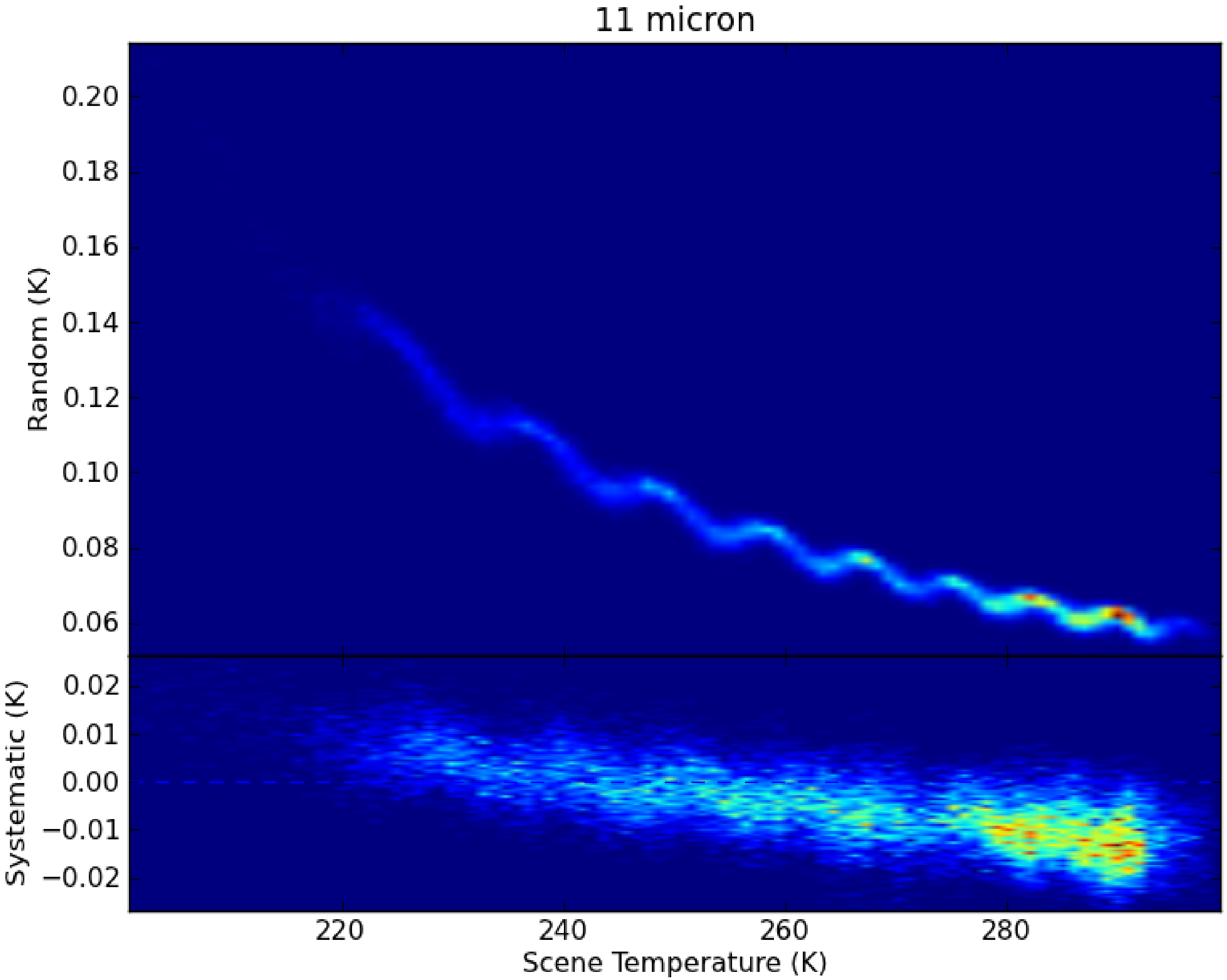
Mathematically

$$c_{x_i} = \frac{\partial f}{\partial x_i}$$

How sensitive is my result to this?

All are acceptable

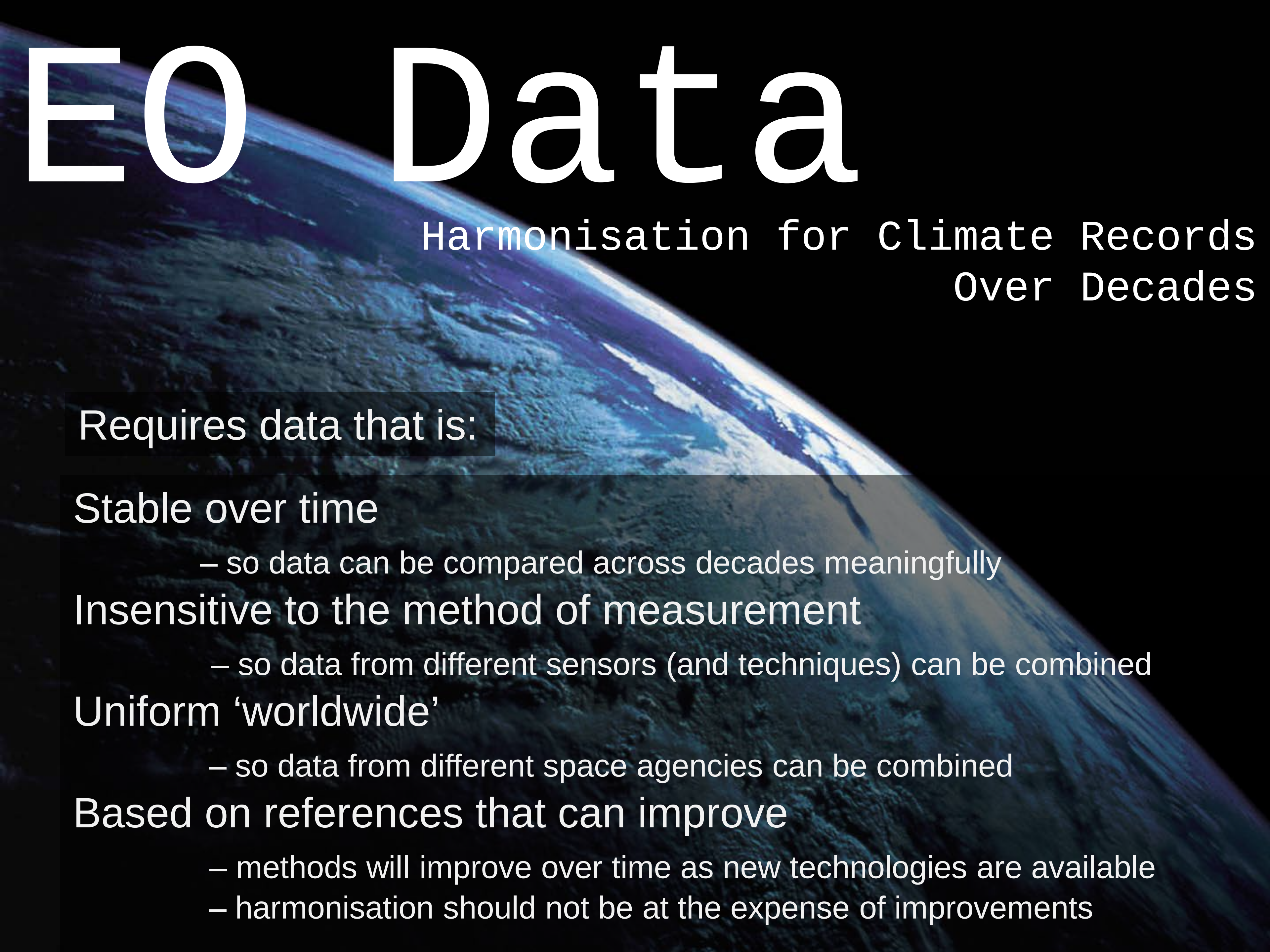
Numerical Approach



- Good at estimating systematic effects
- Systematic error here dominated by error in non-linear calibration term

Measured value well within random uncertainty

Still gives significant systematic effect



EO Data

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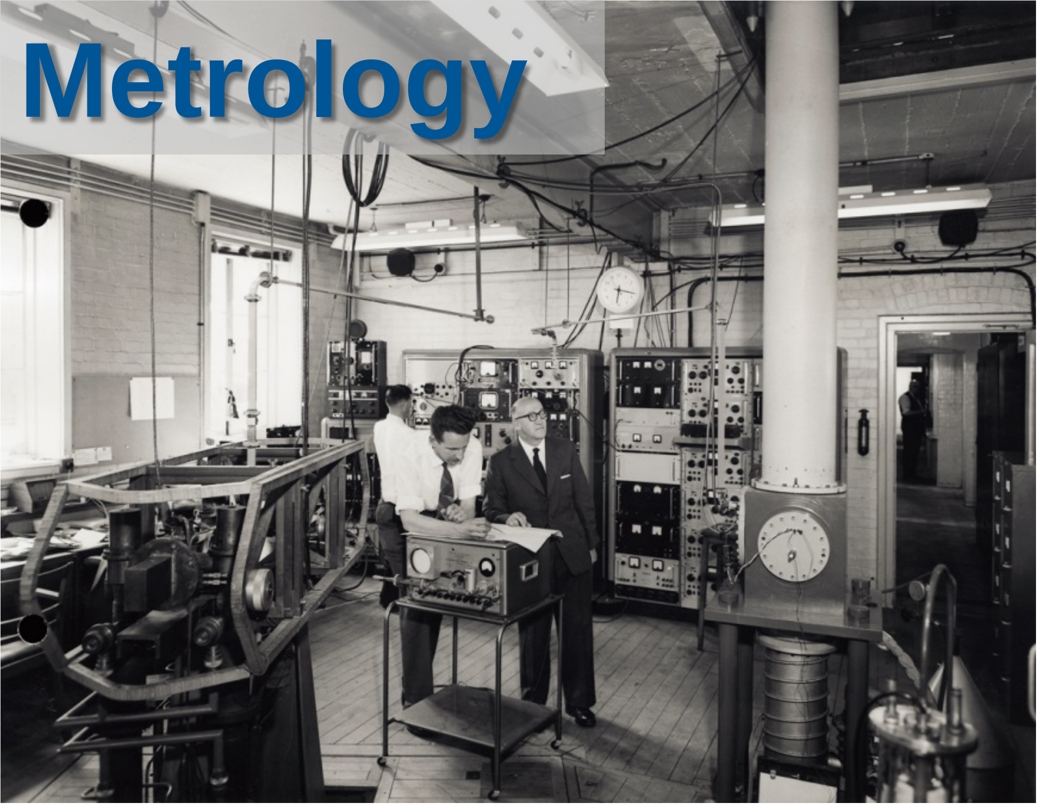
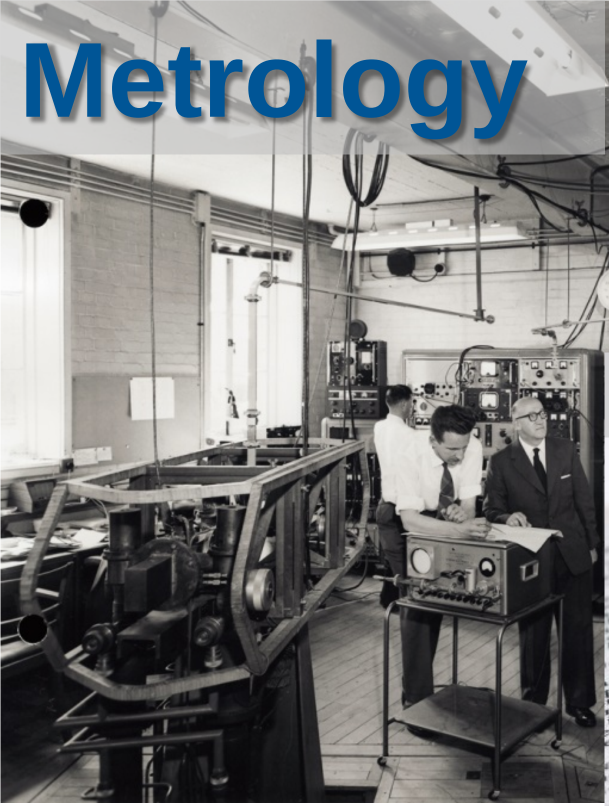


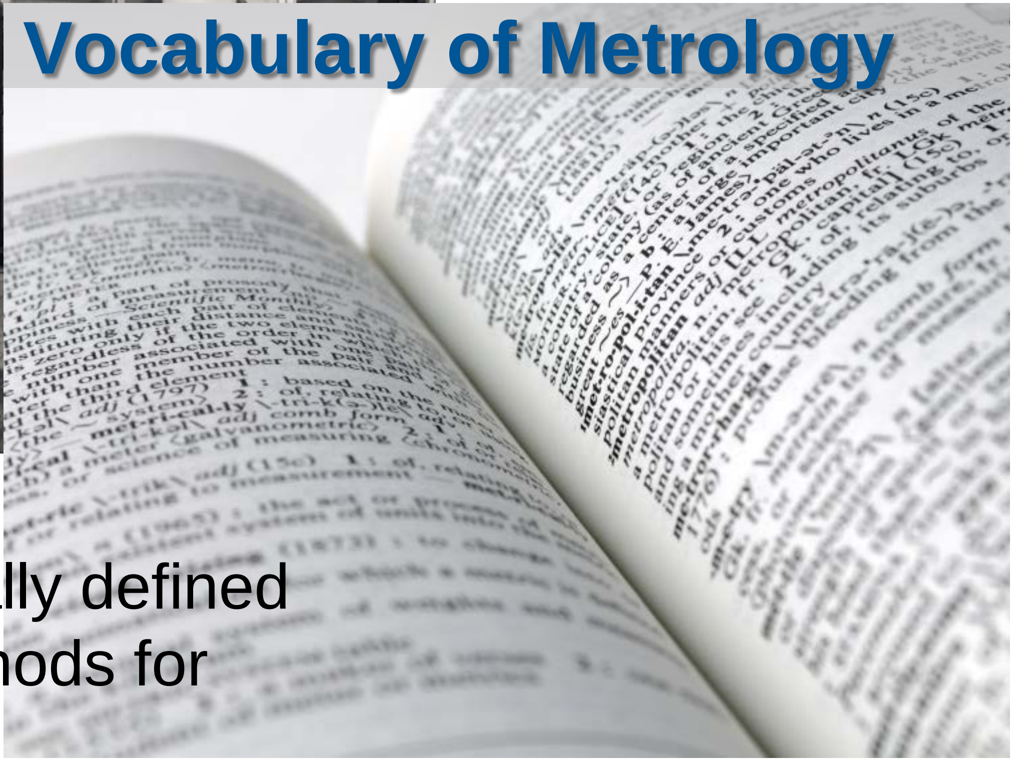
Metrology has established techniques to ensure worldwide consistency and long-term stability :

- Traceability
- Uncertainty analysis
- Peer review and Comparison

Metrology

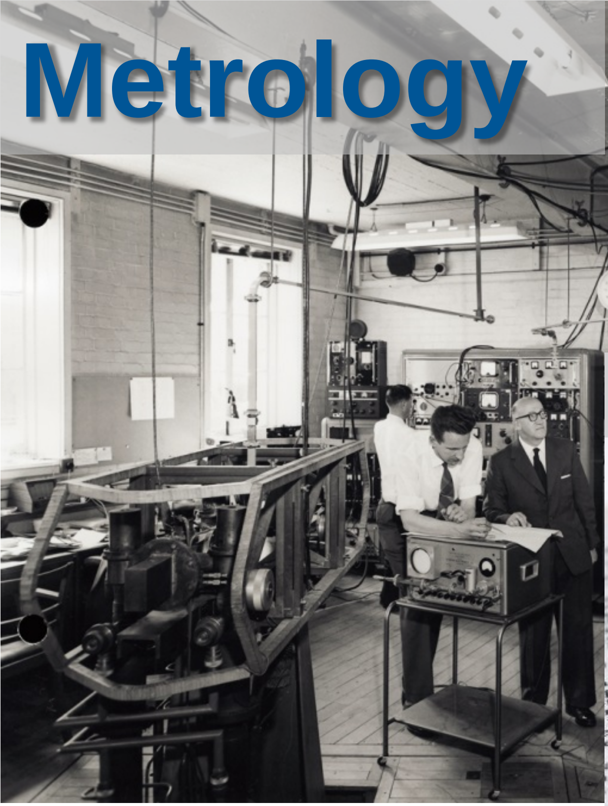


Vocabulary of Metrology



Metrology has formally defined vocabulary and methods for uncertainty analysis:

- Error is not uncertainty
- The GUM is the internationally accepted method for uncertainty analysis



Metrology

NPL
National Physical Laboratory

Vocabulary of Metrology

Propagating Uncertainty

Propagating uncertainty requires the law of propagation of uncertainty:

- Sensitivity coefficients can be determined experimentally, analytically or numerically