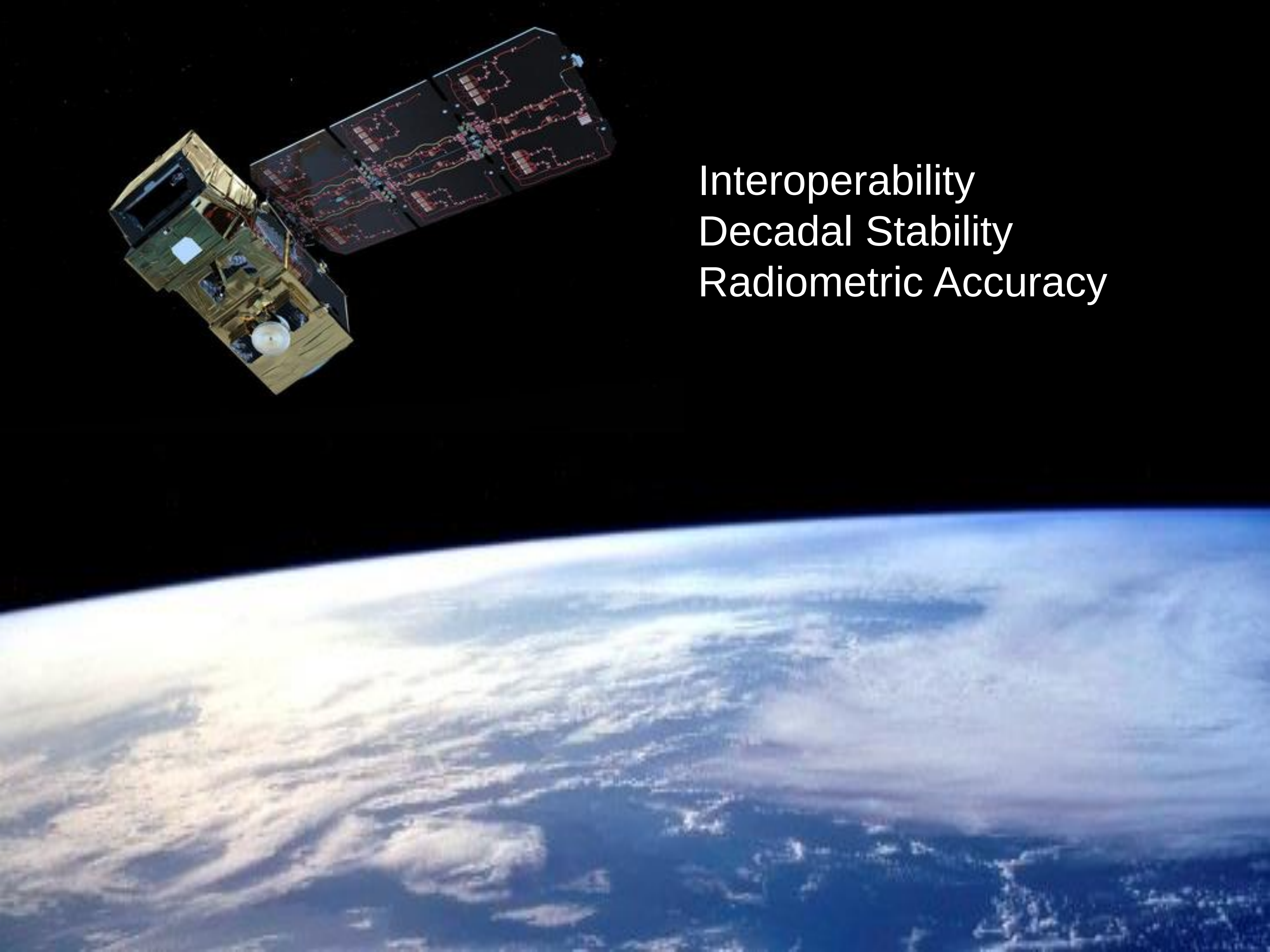
Metrology Principles for Earth Observation: the NMI view

Emma Woolliams

17th October 2017


Interoperability
Decadal Stability
Radiometric Accuracy

NPL
National Physical Laboratory

- Identical worldwide
- Century-long stability
- Absolute accuracy

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Organisation of World Metrology

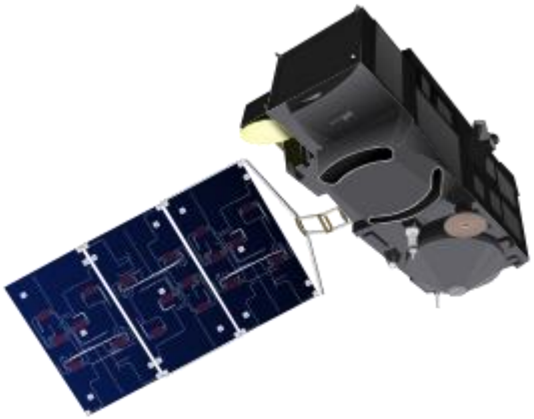
- The Convention of the Metre (*Convention du Mètre*) 1875

- International System of Units (SI) (*Système International d'Unités)* 1960
- Mutual Recognition Arrangement (CIPM-MRA) 1999

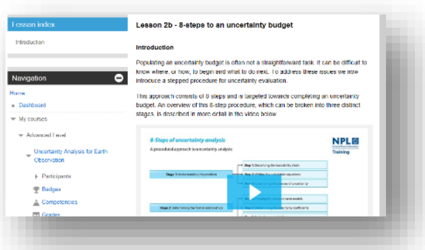
Bureau International des Poids et Mesures

This presentation

1. How world metrology achieves interoperability, stability and accuracy



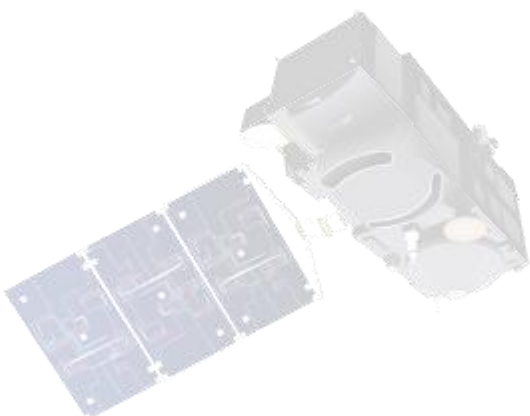
2. How these principles can be applied to Earth Observation



3. Resources to help

This presentation

1. How world metrology achieves interoperability, stability and accuracy



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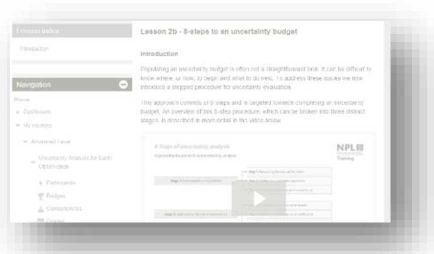

3. Resources to help

- How do we make sure a wing built in one country fits a fuselage built in another?
- How do we make sure the SI units are stable over centuries?
- How do we improve SI over time without losing interoperability and stability?

History of the metre

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1795

1 ten millionth of the distance from the North Pole to the Equator through Paris

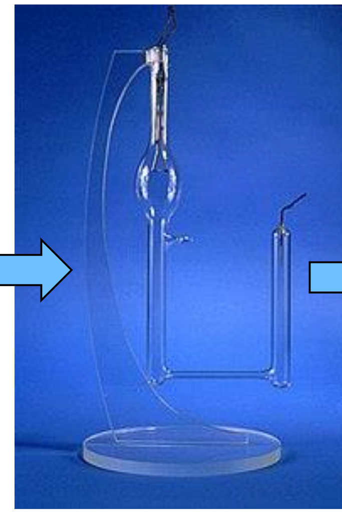
1799

Metre des Archives

1889

International Prototype

1960

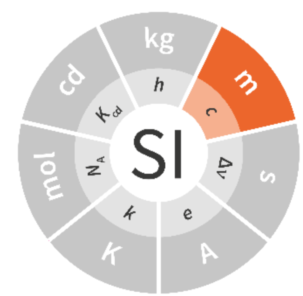


1 650 763.73 wavelengths of a krypton-86 transition

1983

Distance light travels in 1/299 792 458th of a second

2018



Distance that makes the speed of light 299 792 458 m s^{-1}

- Stable
- Improves over time
- Reference to physical process

Three principles

Traceability

Uncertainty Analysis

Comparison

Traceability

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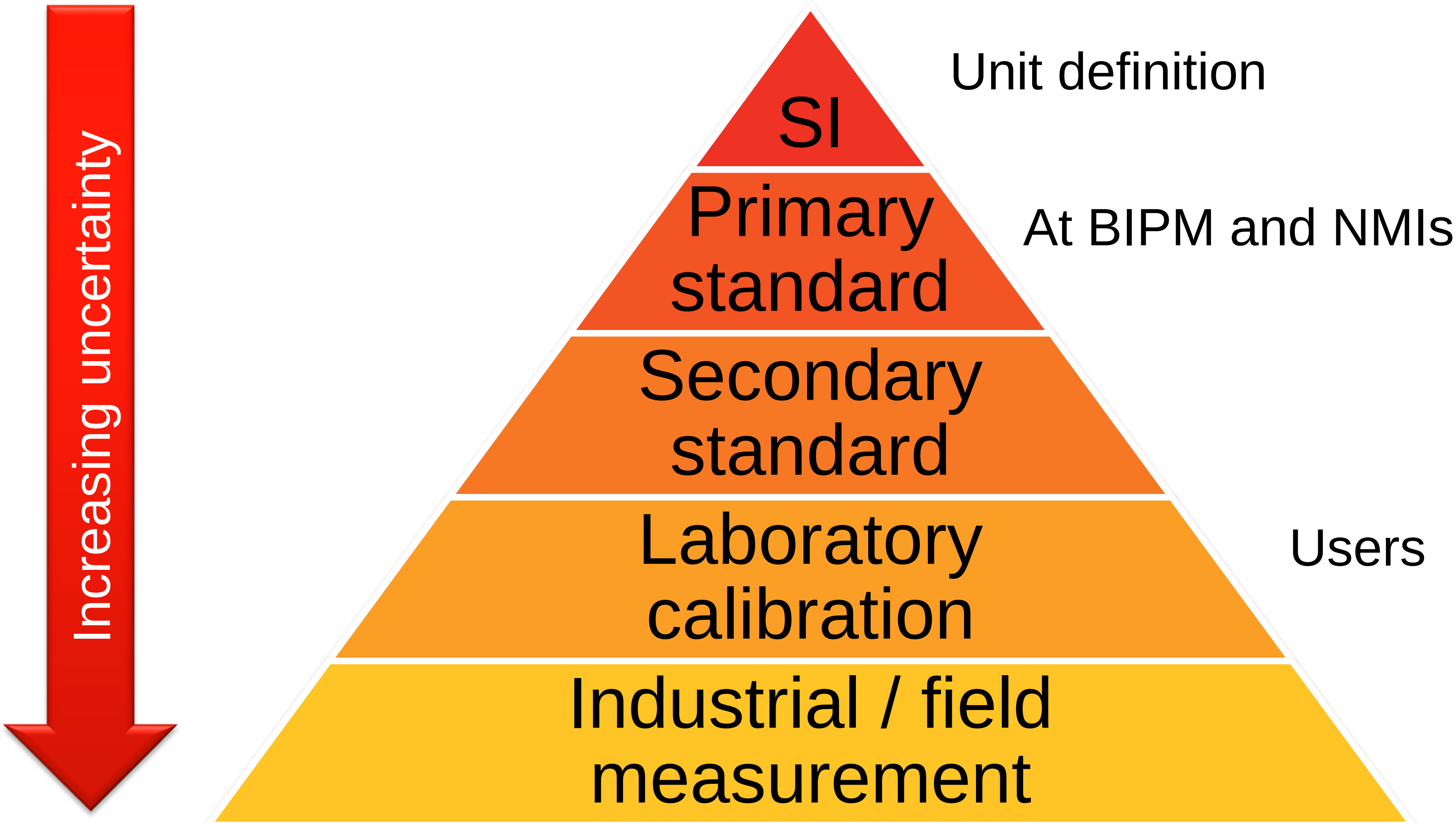
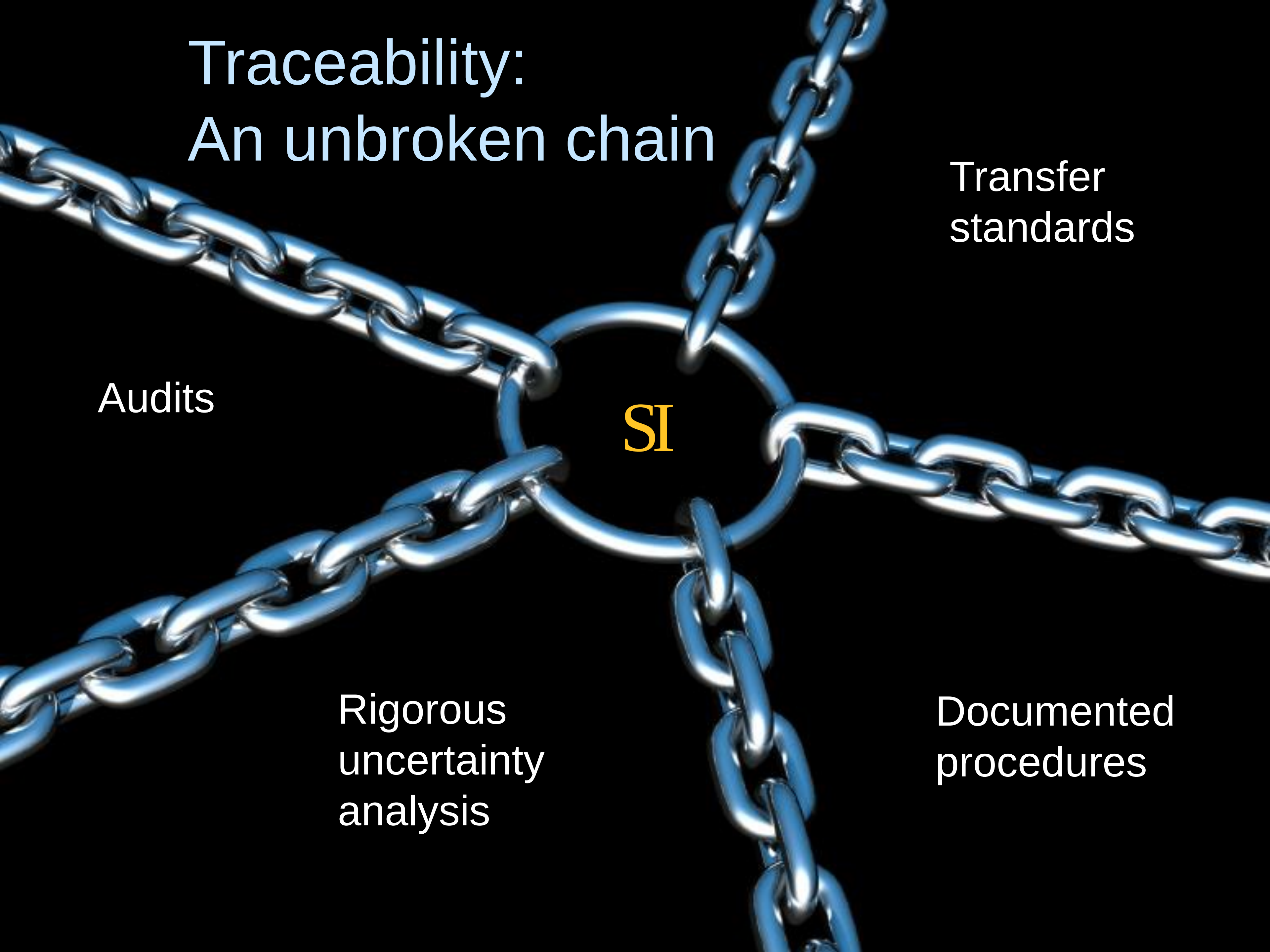


Traceability: An unbroken chain



Rigorous Uncertainty Analysis

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BIPM

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

ΜΕΤΡΩ ΧΡΩ

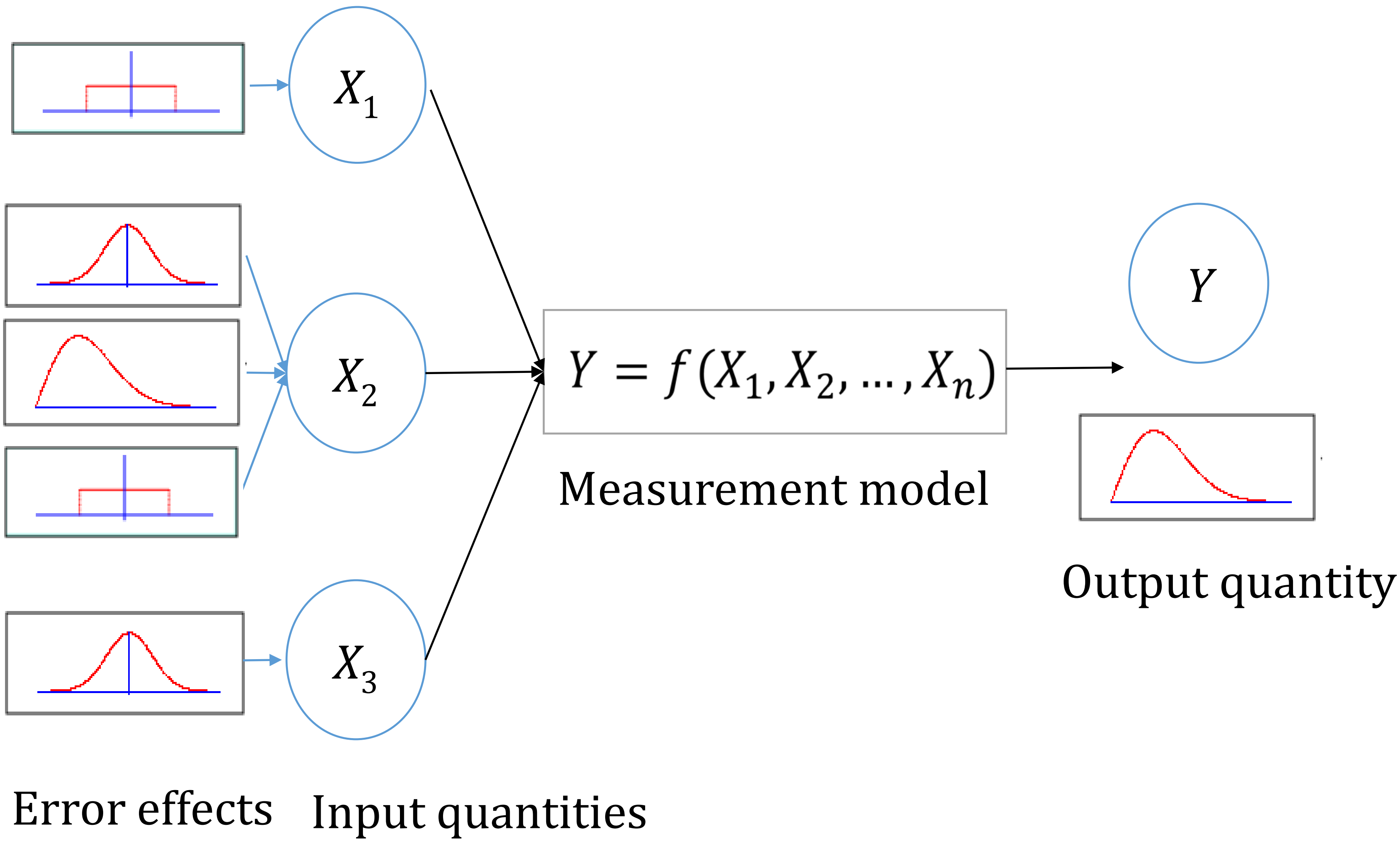
First edition September 2008

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 BIPM, ISO, etc.
- Covers a wide number of applications
- Also a set of supplements

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

Principle of Uncertainty Analysis



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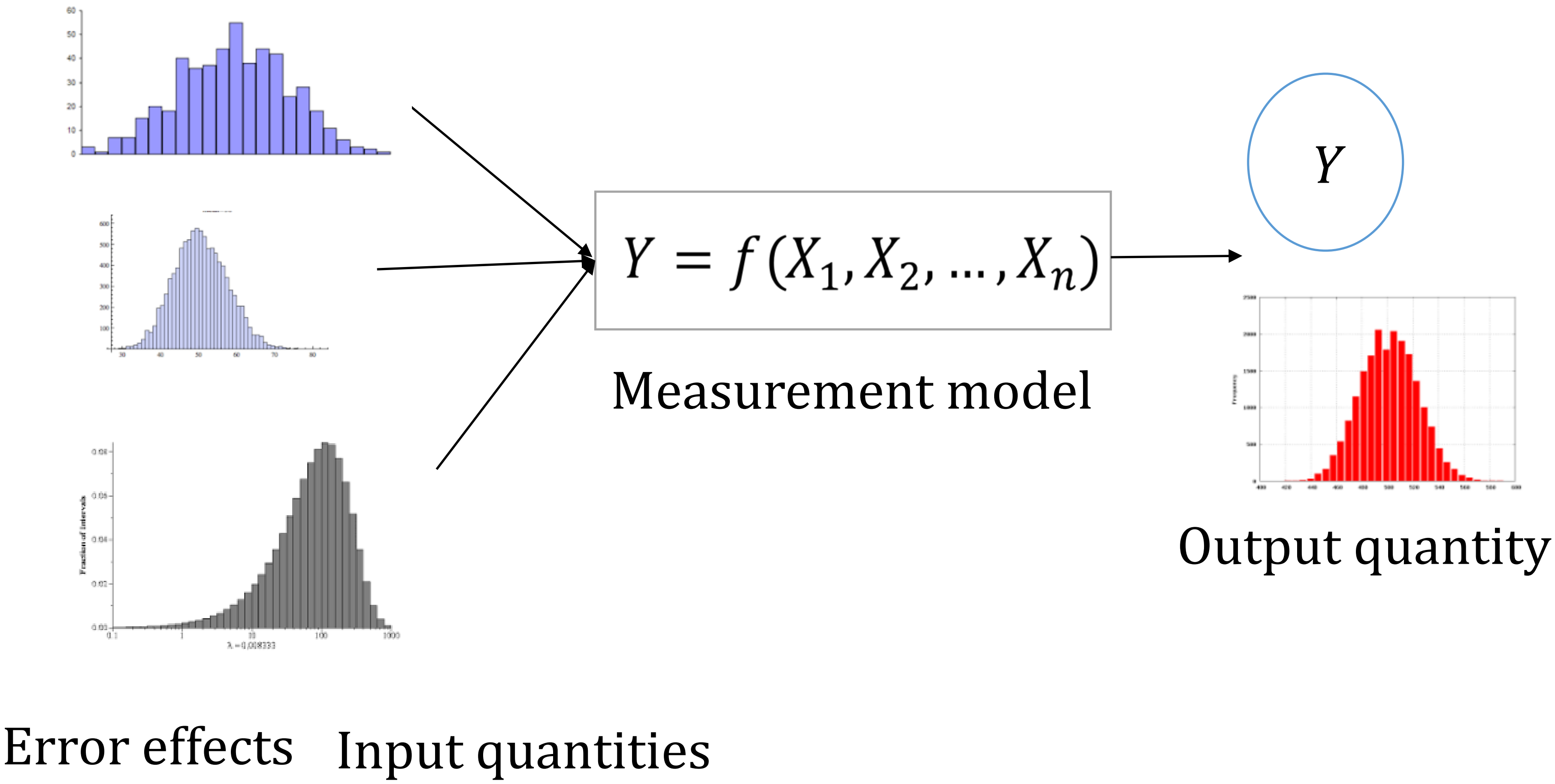
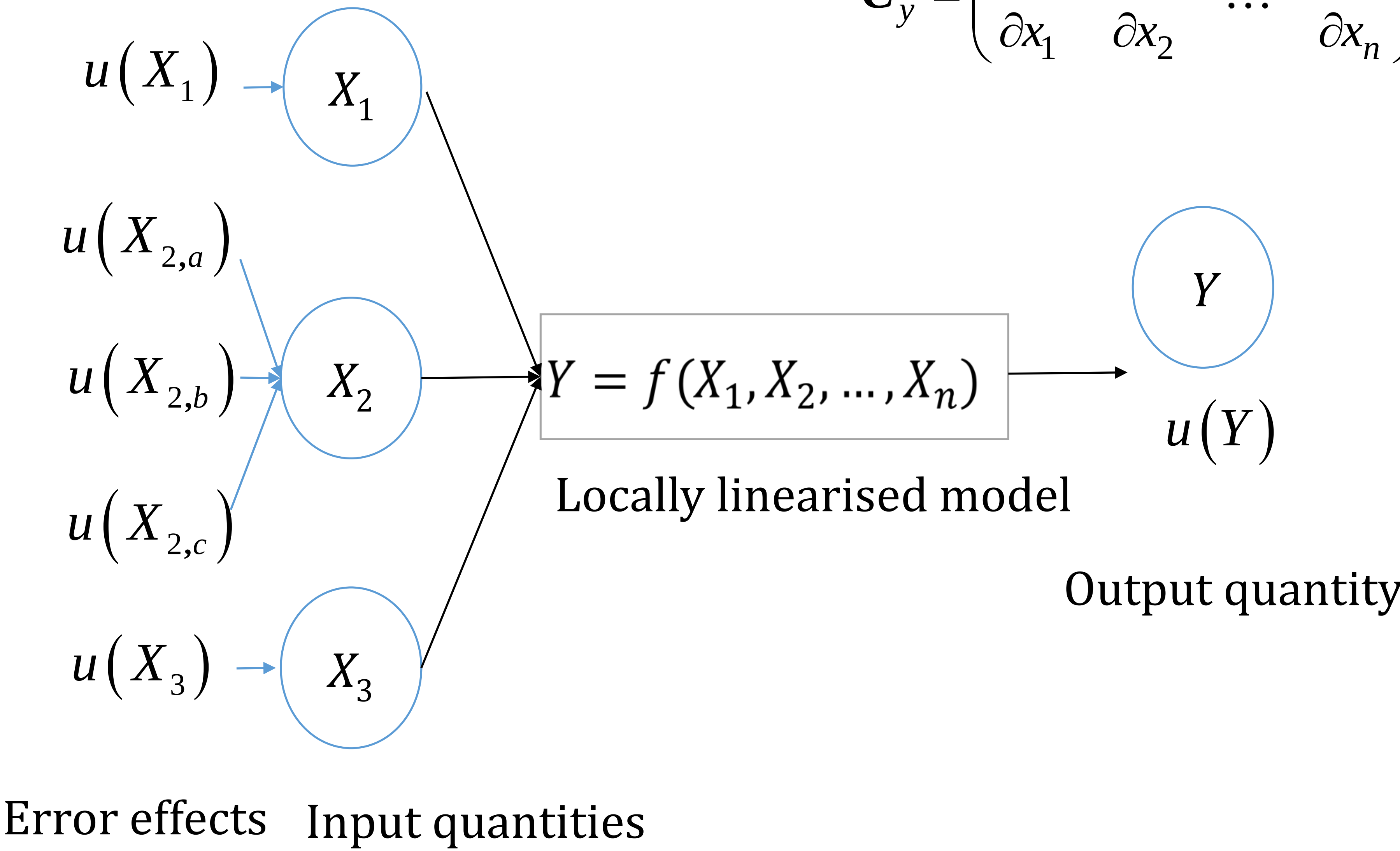
Monte Carlo Approach



Law of Propagation of Uncertainty

$$u^2(y) = \boldsymbol{C}_y \boldsymbol{U}_x \boldsymbol{C}_y^\top$$

$$\boldsymbol{C}_y = \begin{pmatrix} \frac{\partial f}{\partial x_1} & \frac{\partial f}{\partial x_2} & \cdots & \frac{\partial f}{\partial x_n} \end{pmatrix}$$

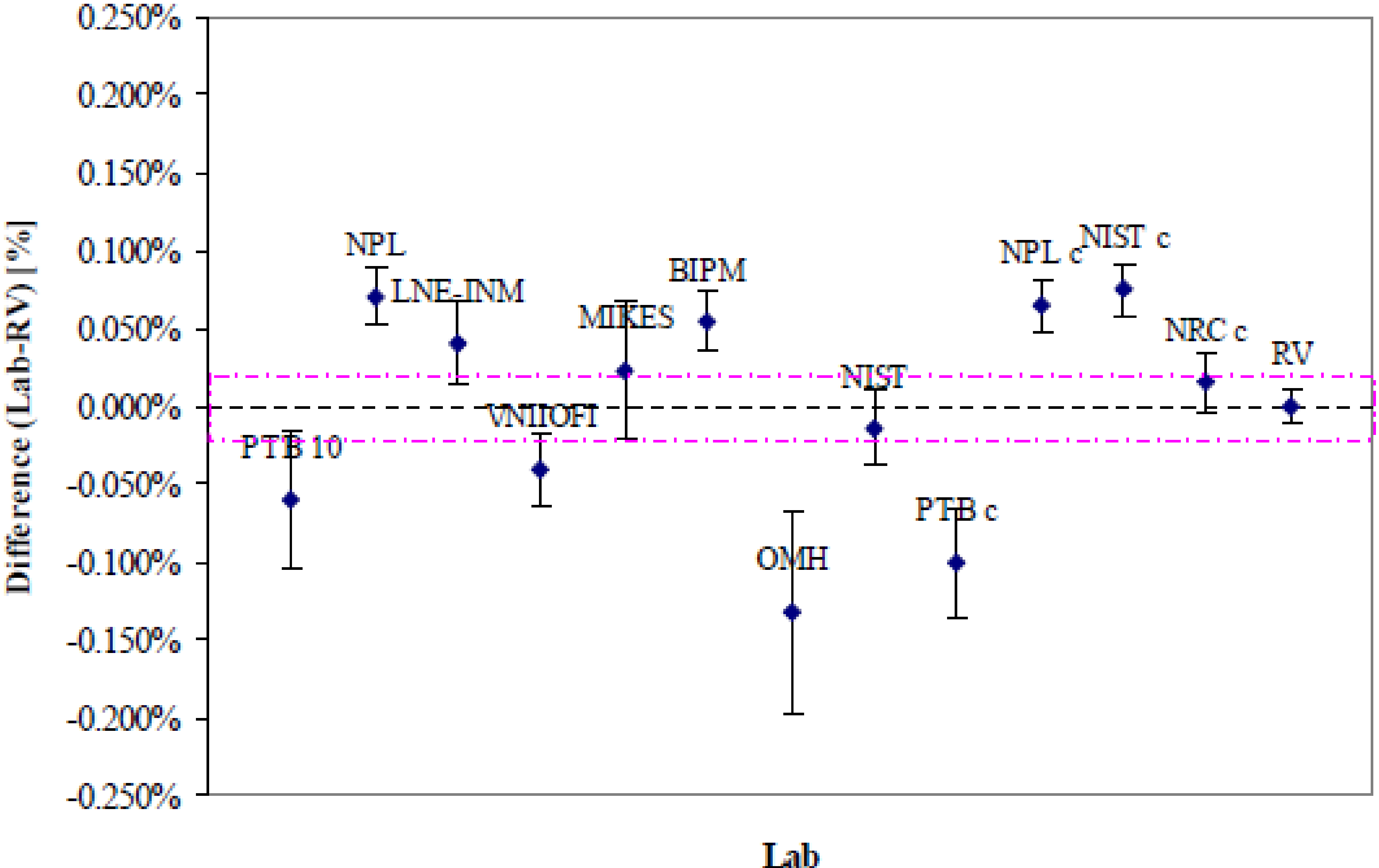


Comparisons

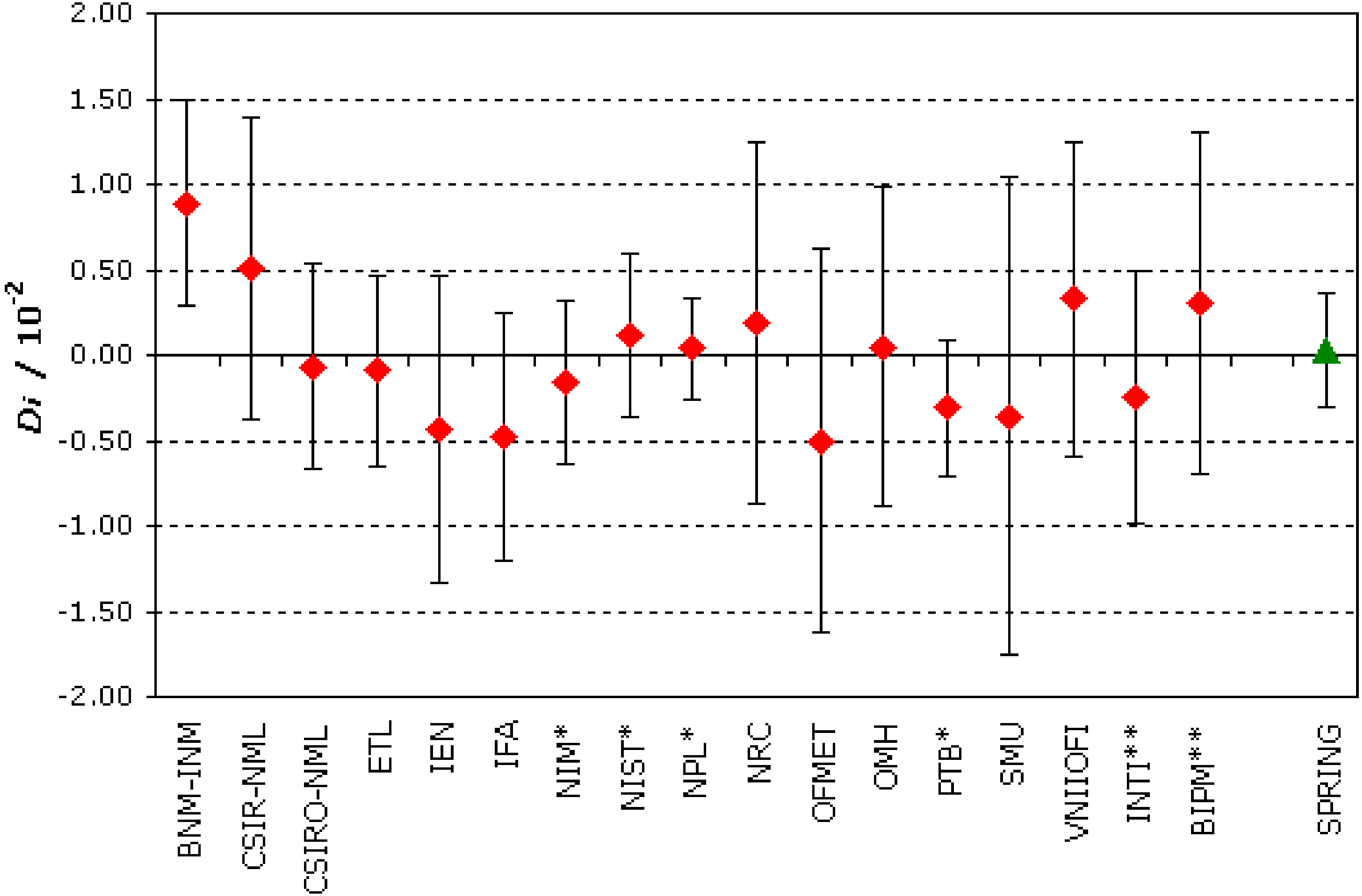
Scientific comparisons:
Immature field – learning what we don't know

Formal MRA comparisons:
Mature field – to check world metrology still works!

Lab-to-lab
(results of a scientific comparison)



MRA Formal comparison
Luminous Intensity key comparison



CMC Database

- https://kcdb.bipm.org/
- Evidence: Formal peer review or audit of procedures, participation in a relevant key comparison (within 10 years) with declared uncertainties defended, review within region and between regions

Irradiance, spectral. Tungsten lamp, **6E-03 (W/m^2)/nm to 0.27 (W/m^2)/nm**
Relative expanded uncertainty (*k* = 2, level of confidence 95%) in %: **0.9 to 0.8 (with wavelength)**
Spectroradiometer
Wavelength: 500 nm to 800 nm
Bandwidth: < 20 nm
Other types of source can also be measured
Approved on 20 April 2017

Irradiance, spectral. Tungsten lamp, **1.5E-03 (W/m^2)/nm to 0.29 (W/m^2)/nm**
Relative expanded uncertainty (*k* = 2, level of confidence 95%) in %: **0.5**
Spectroradiometer
Wavelength: 801 nm to 1600 nm
Bandwidth: < 20 nm
Other types of source can also be measured
Approved on 20 April 2017

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Protocol
- Written by working group
- Approved by participants
- Reviewed then approved by CCPR

Measurements
- Results sent to pilot only
- Often star-form

Pre-Draft A
- Relative results (intra-lab consistency)
- Review of uncertainty statements
- No results shown
- Discussion on dealing with outliers (blind)

Draft A
- First time participants see results
- Review by participants

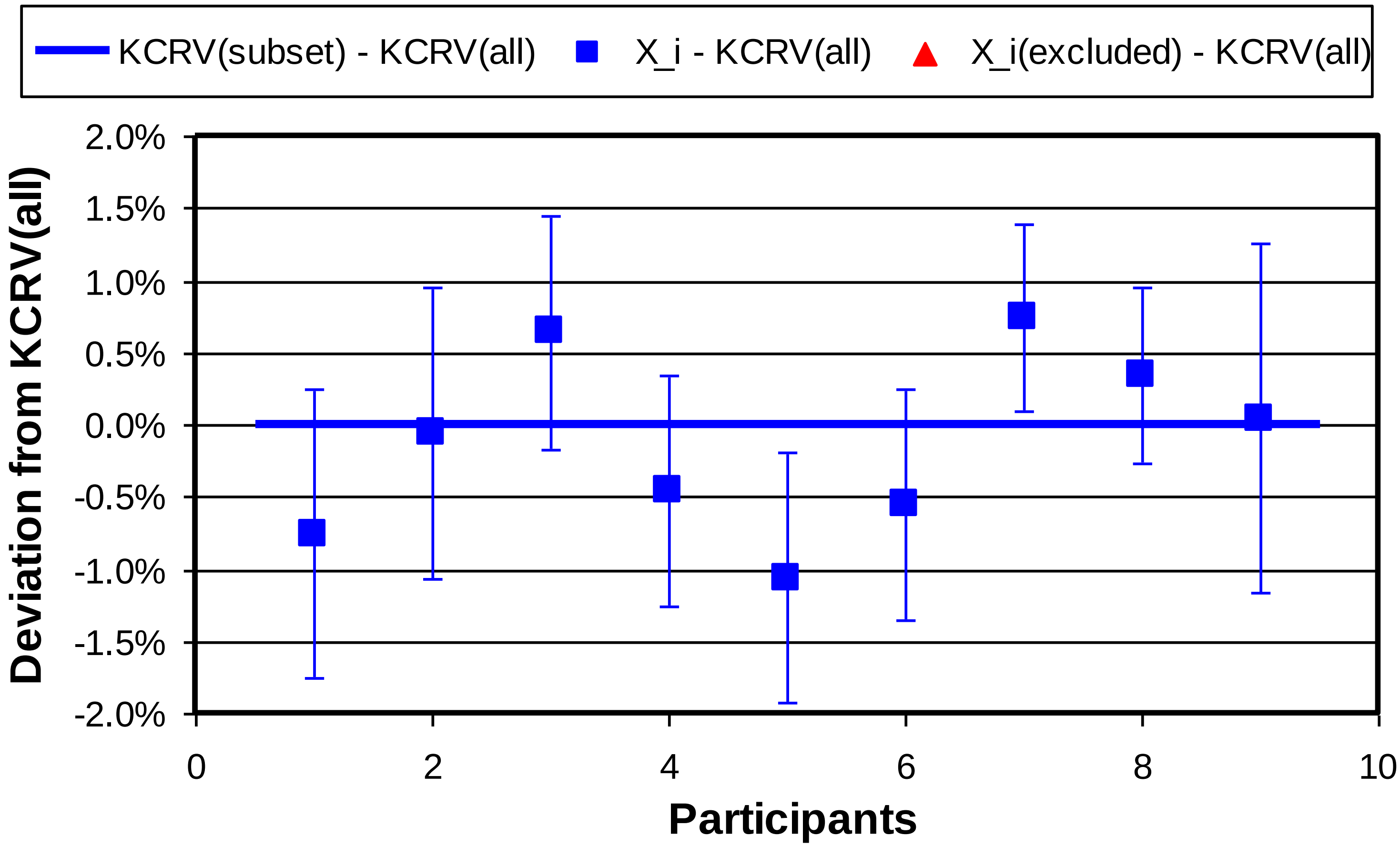
Draft B
- Review by experts
- Approval by CCPR

Final report
- Published

Used to:
- Validate CMCs
- Inform customers

Ongoing research: Outliers

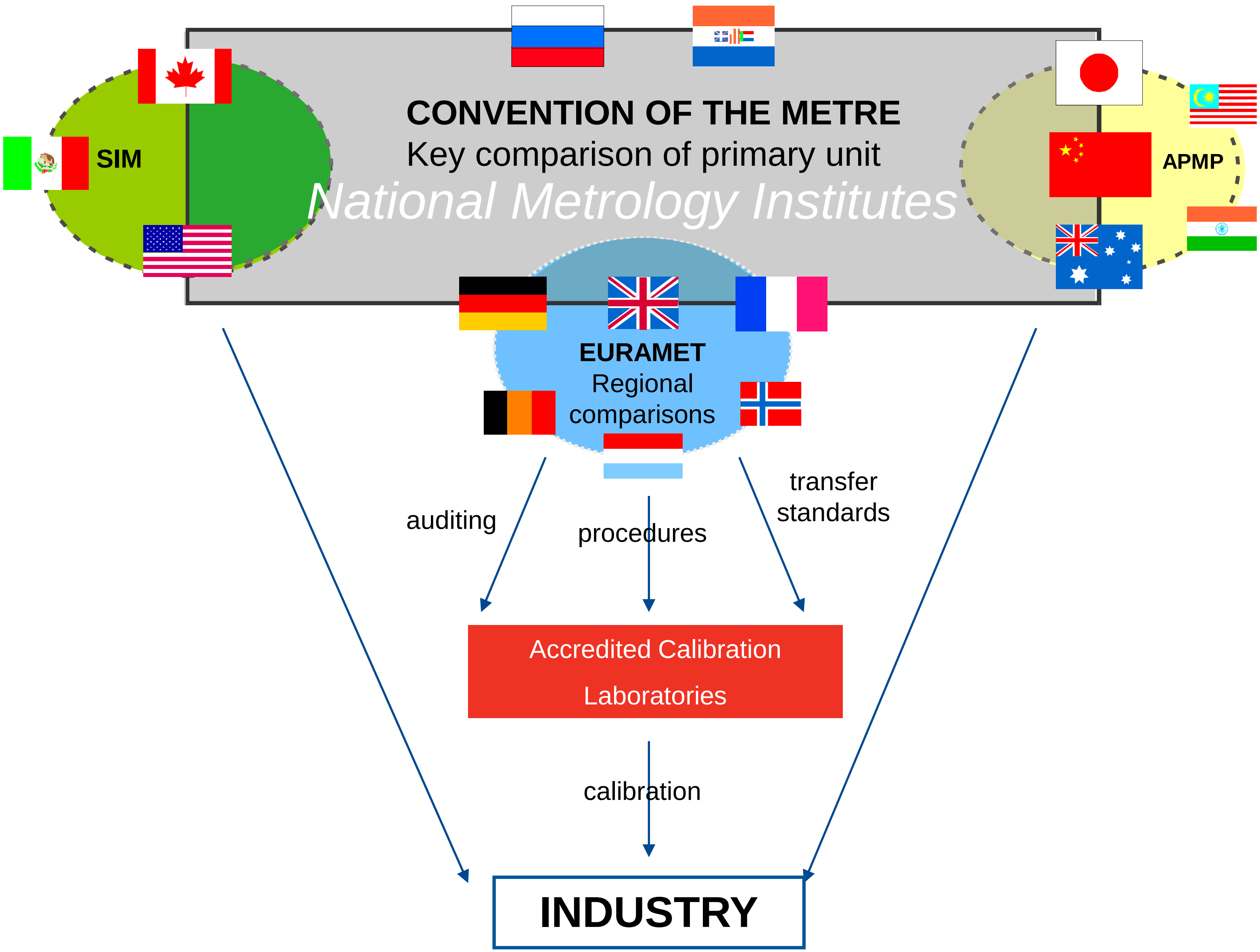
Error bars: expanded unc.(*k* = 2)



χ^2_{obs}	20.5
$\chi^2_{0.05}(\nu)$	15.507

If you exclude 5 or 7 the others (including 7 or 5) become consistent

Mutual Recognition Arrangement



National Physical Laboratory

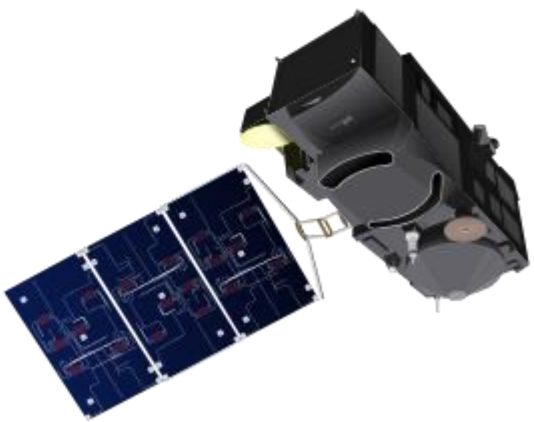
- Identical worldwide
- Century-long stability
- Absolute accuracy

Achieved through:

- Traceability
- Uncertainty Analysis
- Comparison

This presentation

1. How world metrology achieves interoperability, stability and accuracy



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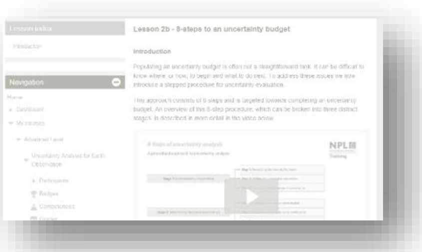
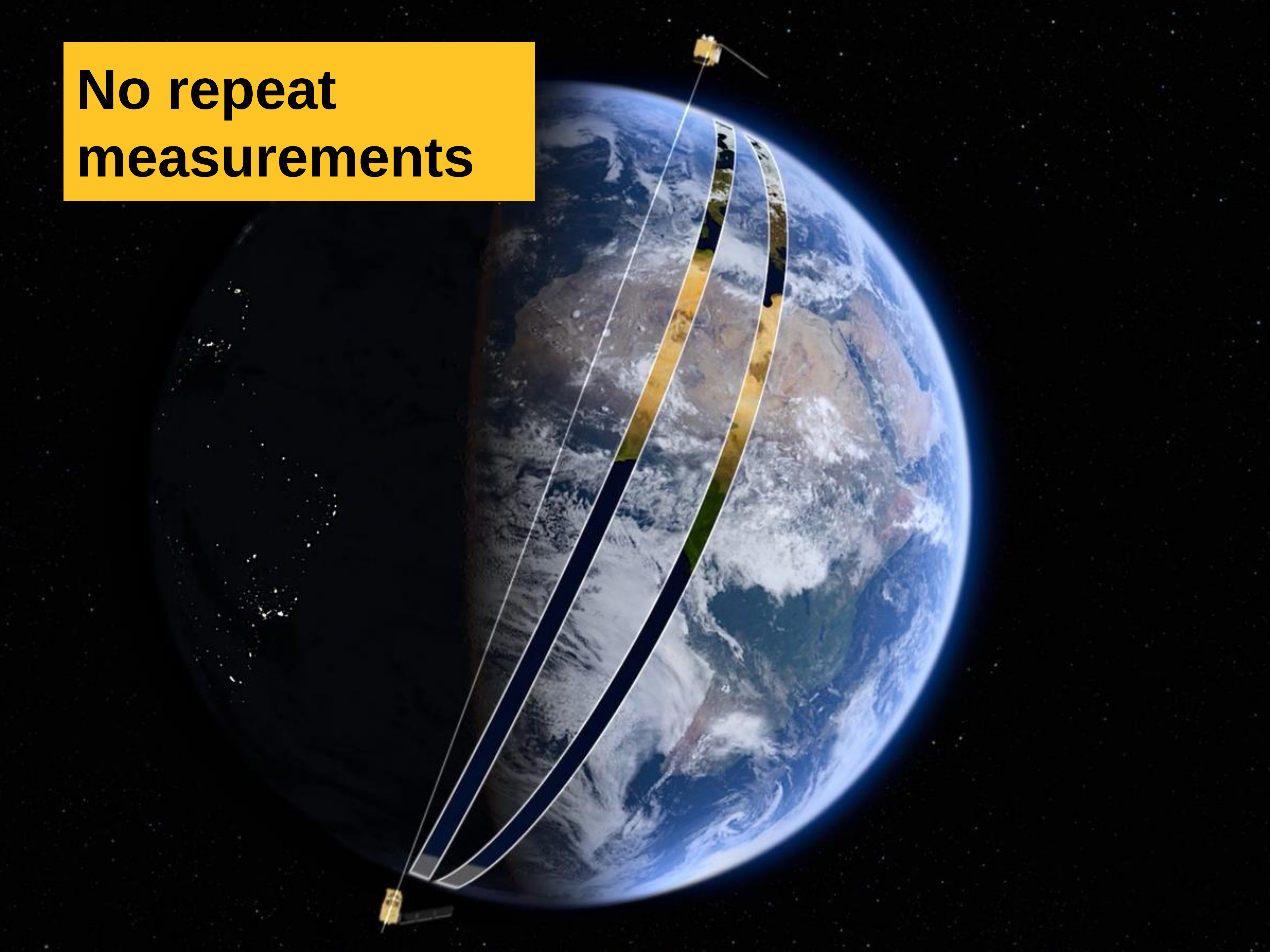


3. Resources to help

The traceability chain is broken


No repeat measurements

No reference in space …

No reference in space … yet

www.npl.co.uk/truths

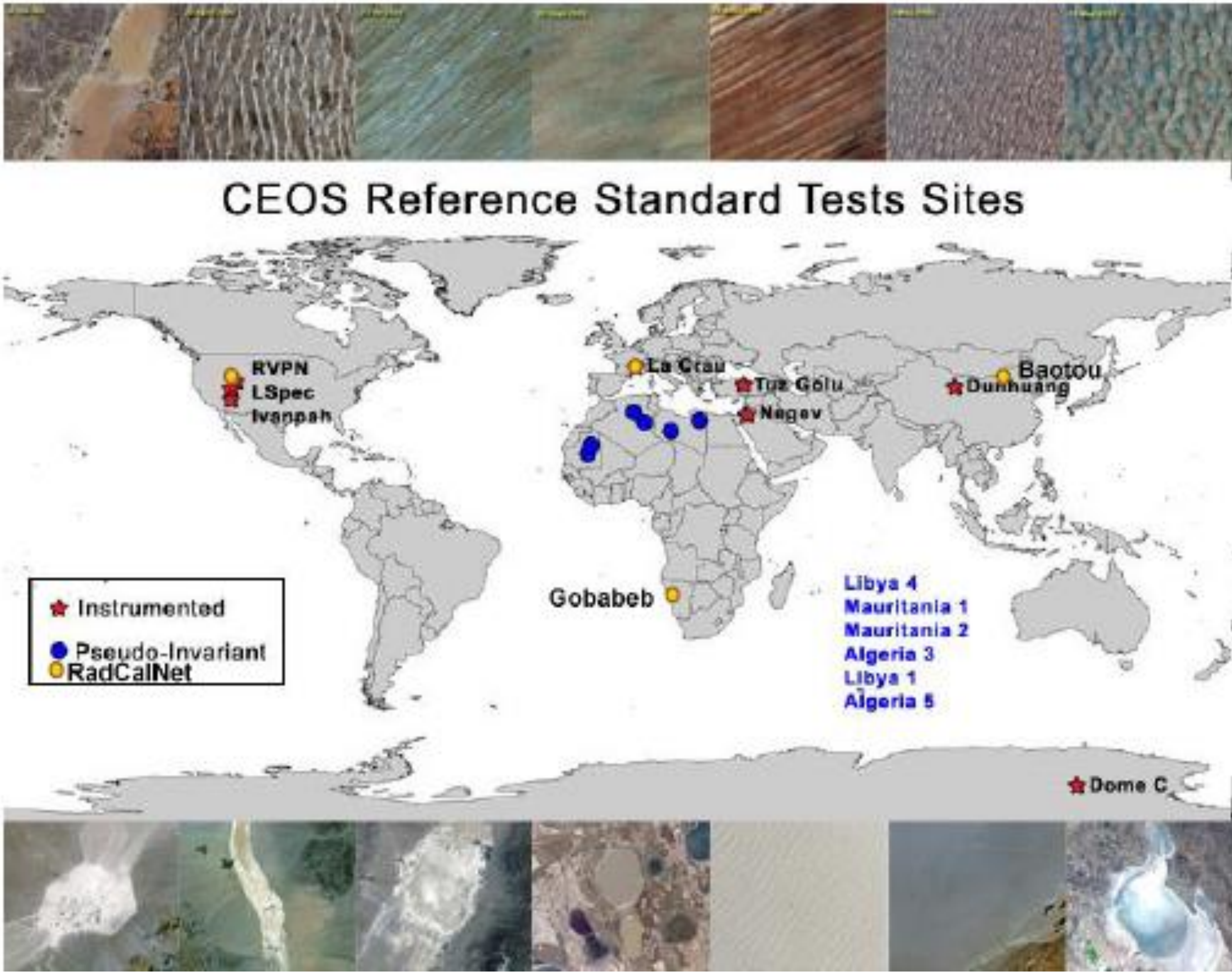
Three principles

Traceability

Uncertainty Analysis

Comparison

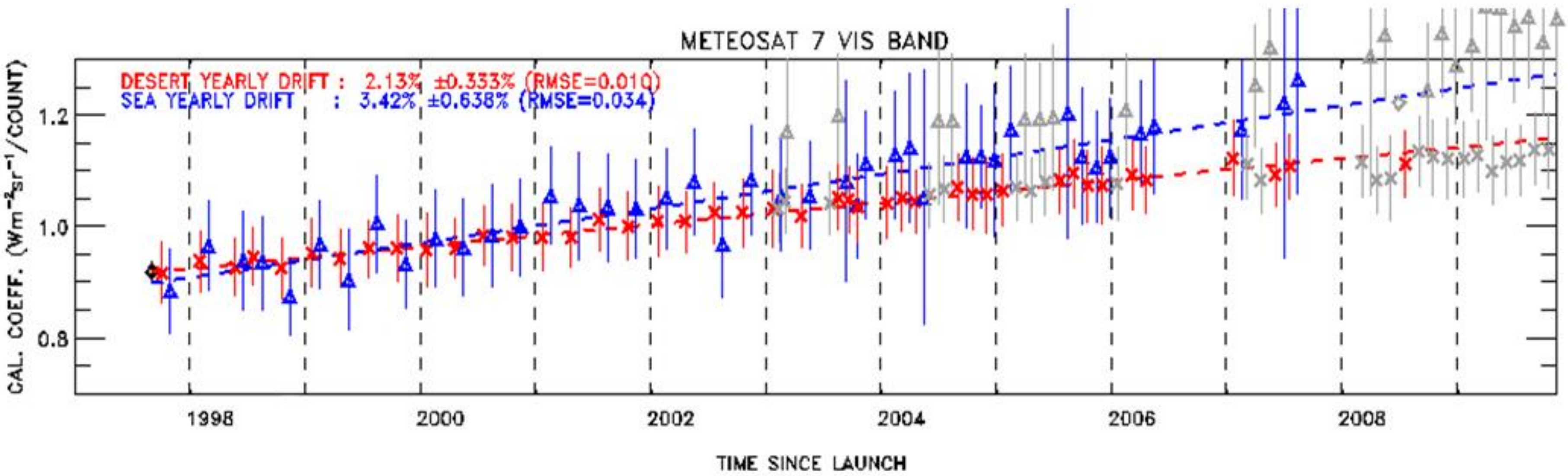
Traceability



RadCalNet

CEOS

Traceability: Using reference sites



Drift of MVIRI Vis band since launch as determined from desert (red) and ocean (blue) test sites.
Figure from:
https://scienceblog.eumetsat.int/2016/11/improving-climate-data-records-with-fiduceo/

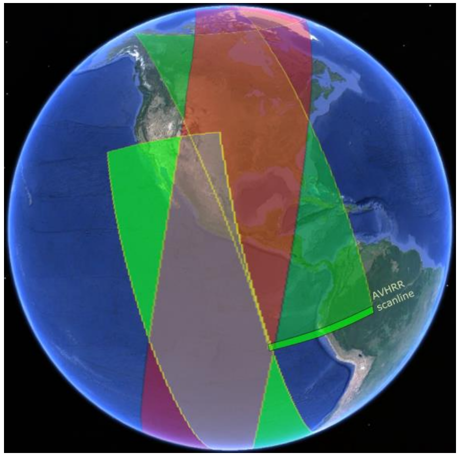
rayference FastOpt EUMETSAT FIduceo

Traceability

Reference to sensors

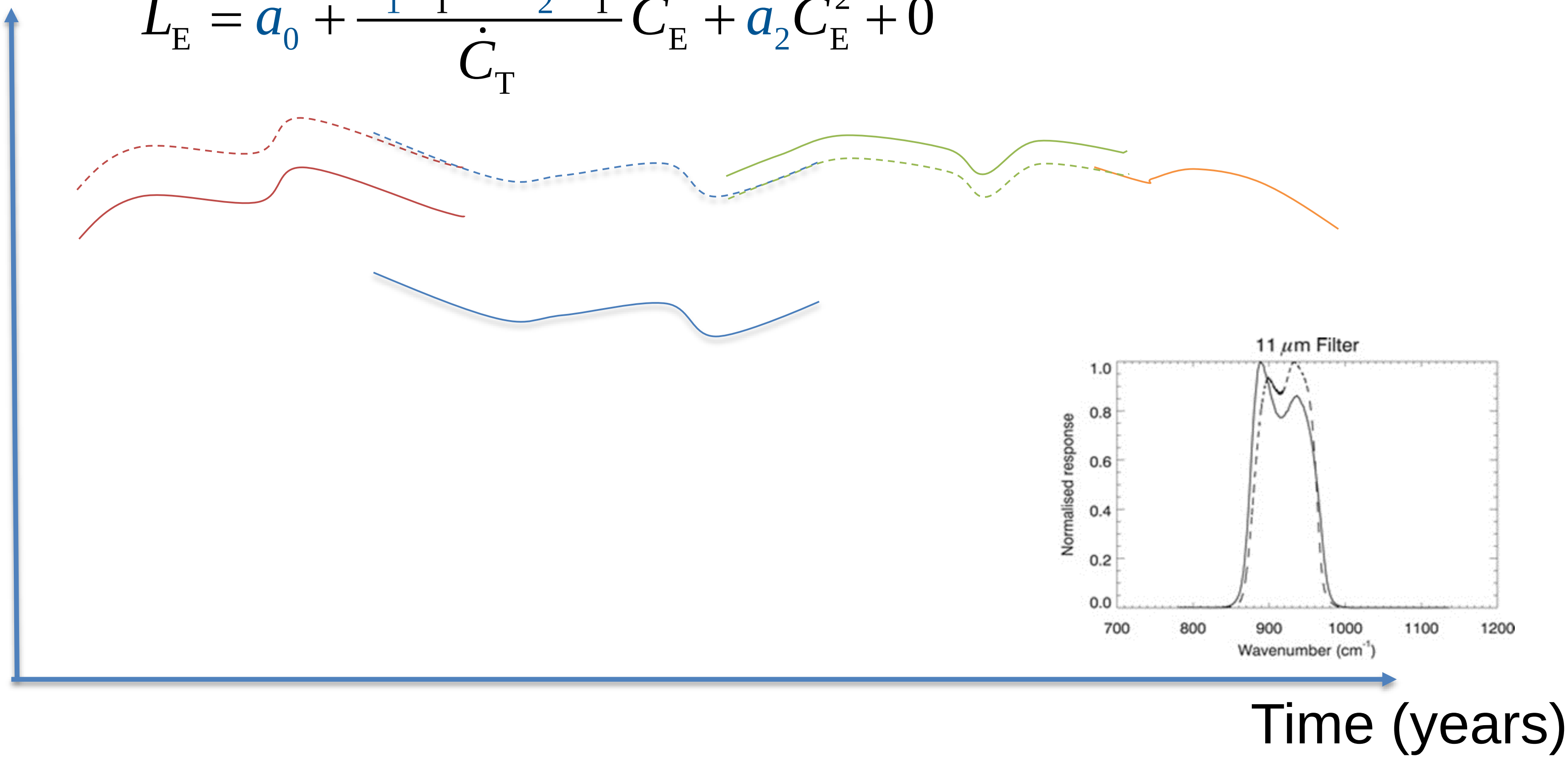
Sensor to sensor

- Reference radiance, or sensor-to-sensor
- Many (150 million +)
- Correlated

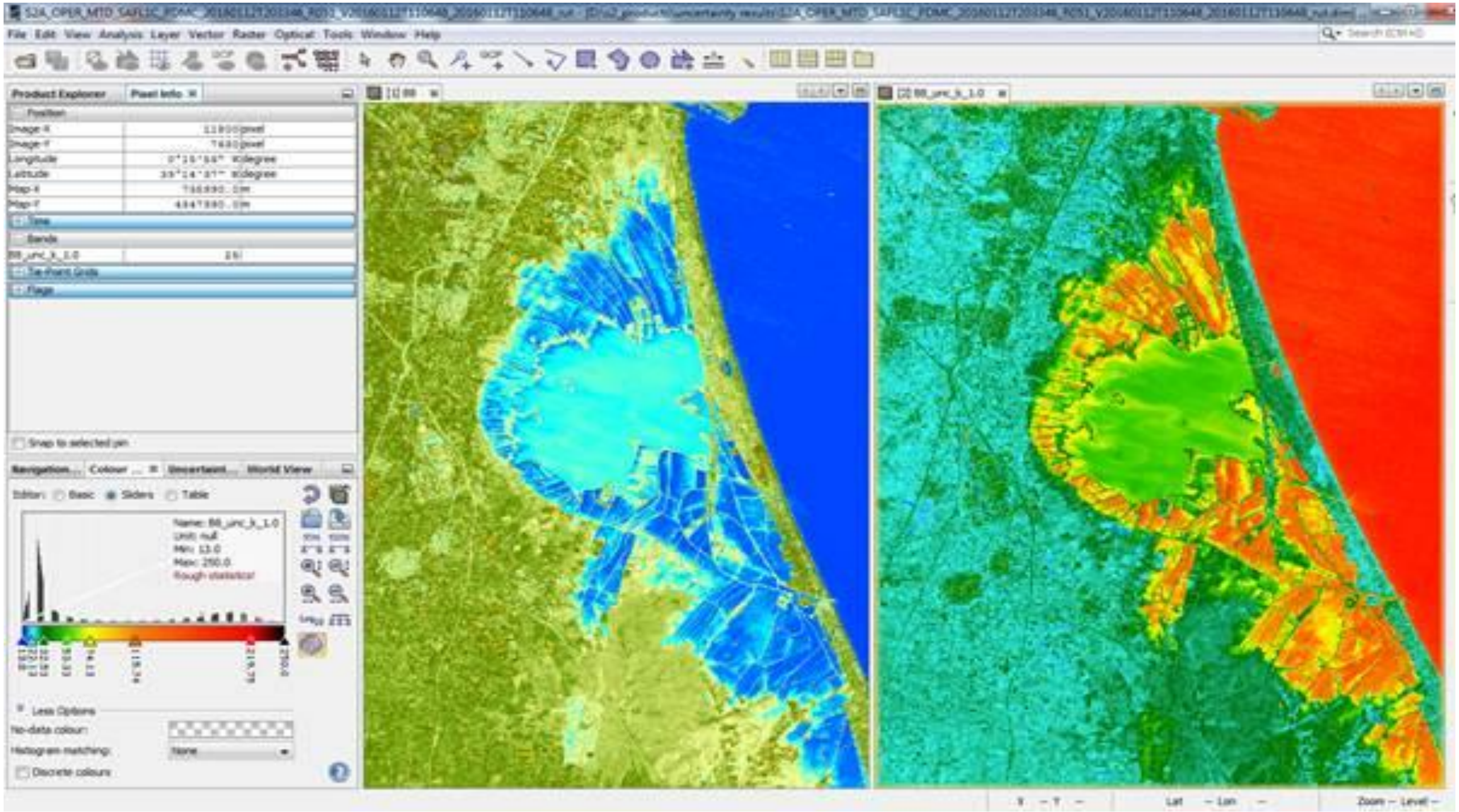


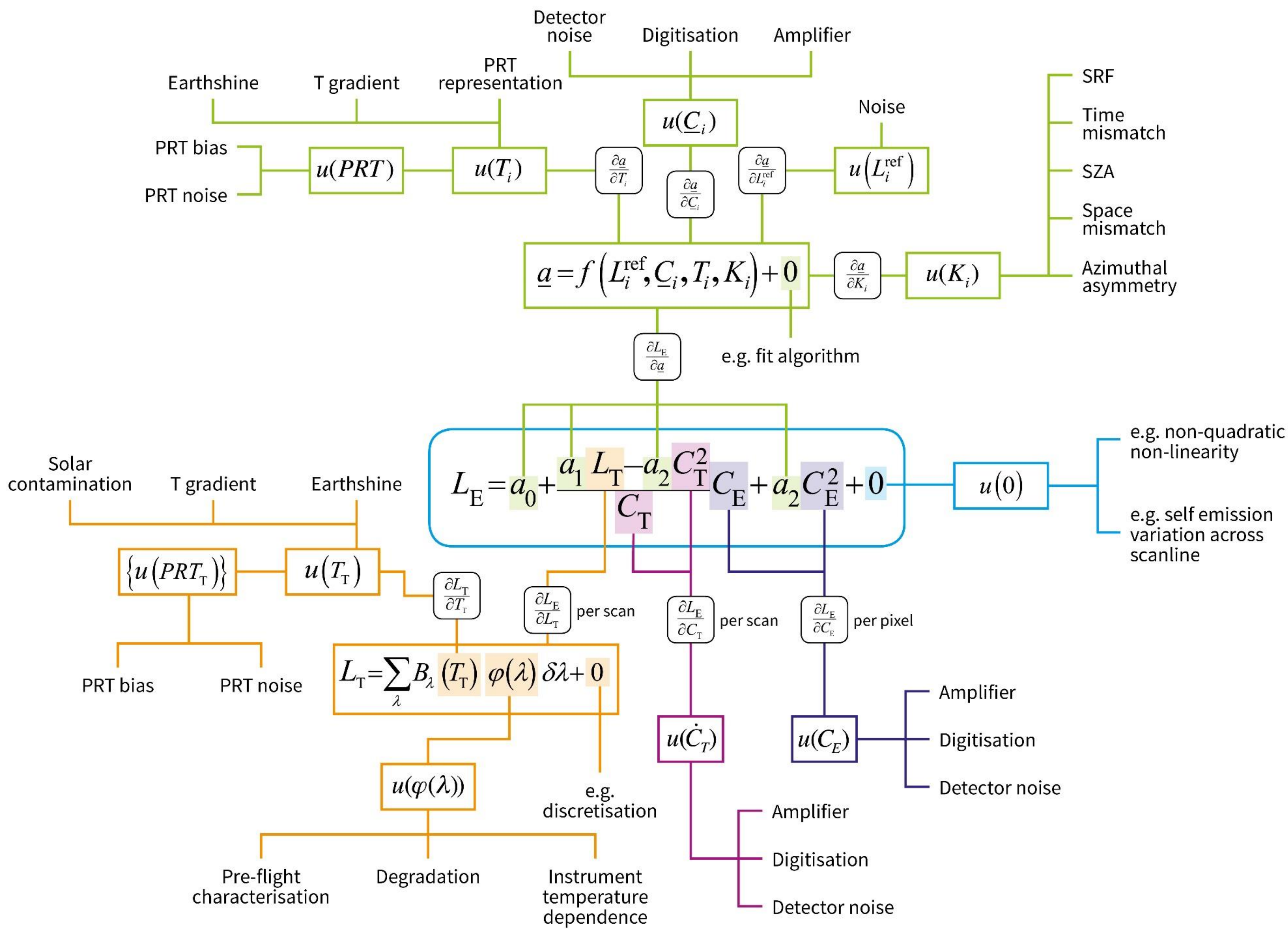
Traceability: Using matchups

$$L_{\mathrm{E}} = a_0 + \frac{a_1 L_{\mathrm{T}} - a_2 \dot{C}_{\mathrm{T}}^2}{\dot{C}_{\mathrm{T}}} C_{\mathrm{E}} + a_2 C_{\mathrm{E}}^2 + 0$$



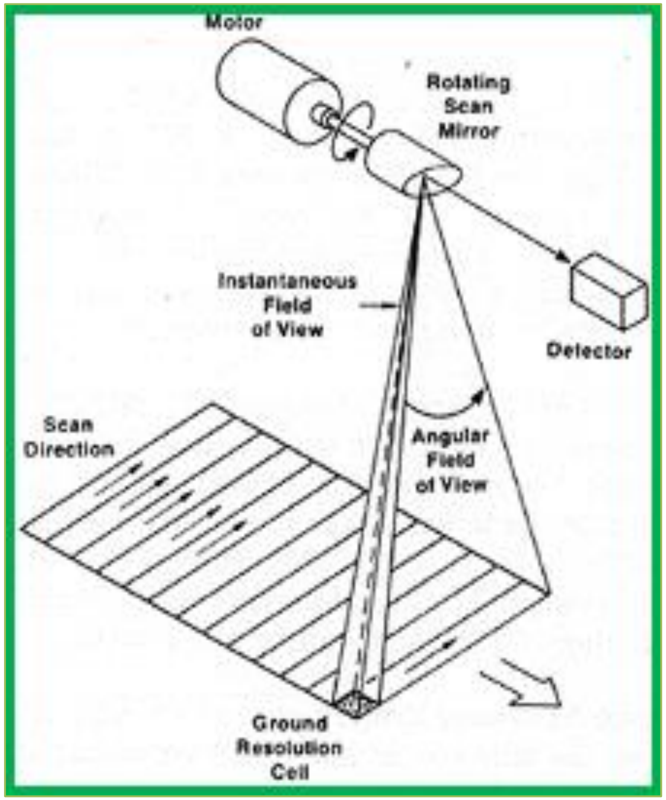
Uncertainty Analysis
S2 Radiometric Uncertainty Tool

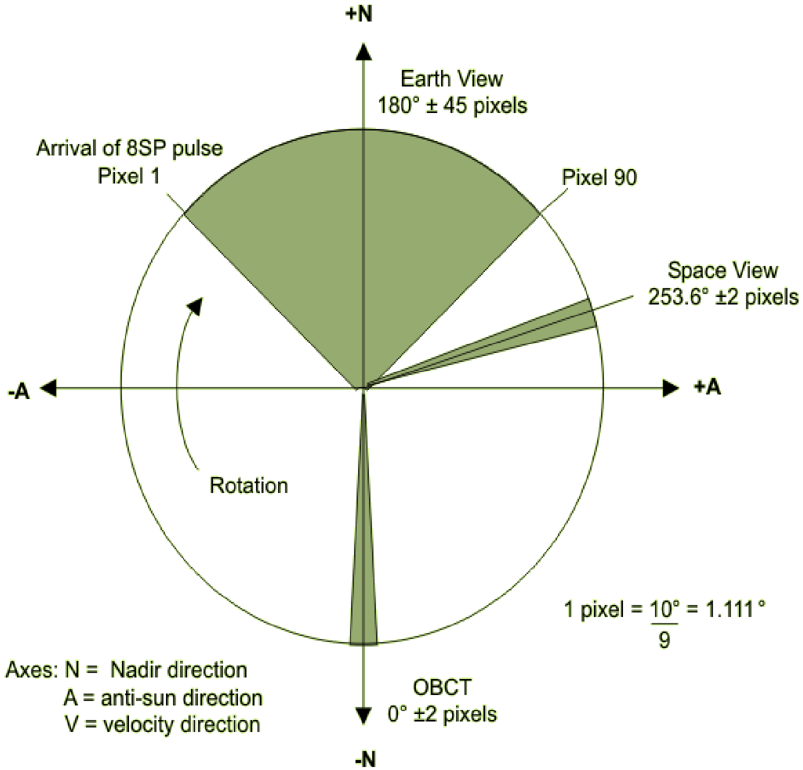



Detector noise
Digitisation
Amplifier
Earthshine
T gradient
PRT representation
$u(\underline{C}_i)$
Noise
SRF
Time mismatch
PRT bias
PRT noise
$u(PRT)$
$u(T_i)$
$\frac{\partial a}{\partial T_i}$
$\frac{\partial a}{\partial \underline{C}_i}$
$\frac{\partial a}{\partial L_i^{ref}}$
$u\left(L_i^{ref}\right)$
SZA
Space mismatch
$\underline{a} = f\left(L_i^{ref}, \underline{C}_i, T_i, K_i\right) + 0$
$\frac{\partial a}{\partial K_i}$
$u(K_i)$
Azimuthal asymmetry
$\frac{\partial L_E}{\partial a}$
e.g. fit algorithm
e.g. non-quadratic non-linearity
$L_E = a_0 + \frac{a_1 L_T - a_2 C_T^2}{C_T} C_E + a_2 C_E^2 + 0$
$u(0)$
Solar contamination
T gradient
Earthshine
e.g. self emission variation across scanline
$\{u(PRT_T)\}$
$u(T_T)$
$\frac{\partial L_T}{\partial T_T}$
$\frac{\partial L_E}{\partial L_T}$
per scan
$\frac{\partial L_E}{\partial C_T}$
per scan
$\frac{\partial L_E}{\partial C_E}$
per pixel
PRT bias
PRT noise
$L_T = \sum_\lambda B_\lambda(T_T)\,\varphi(\lambda)\,\delta\lambda + 0$
Amplifier
$u(\dot{C}_T)$
$u(C_E)$
Digitisation
Detector noise
$u(\varphi(\lambda))$
e.g. discretisation
Amplifier
Digitisation
Detector noise
Pre-flight characterisation
Degradation
Instrument temperature dependence

FIduceo

Error correlation





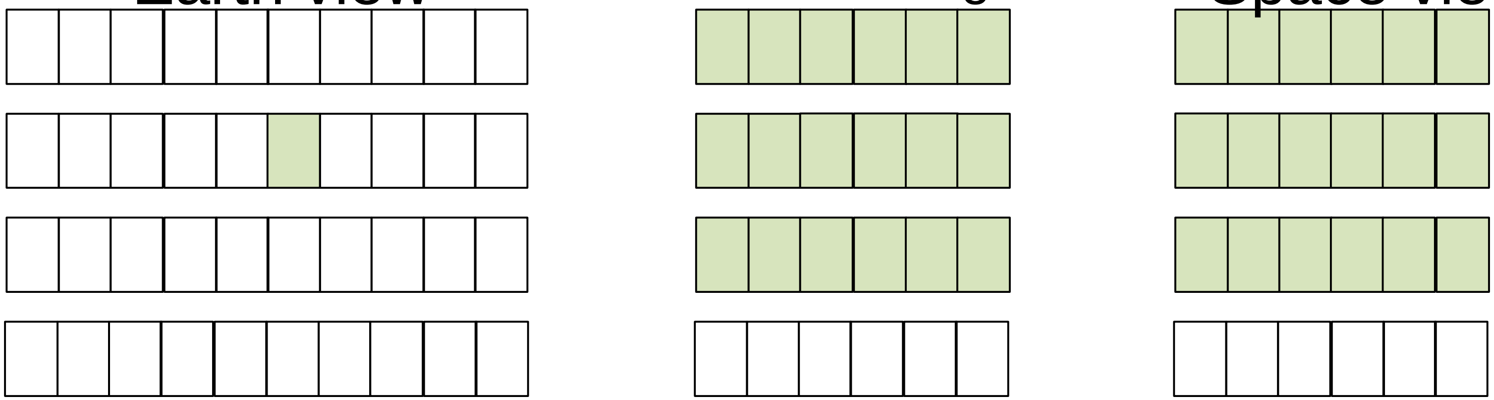
Fiduceo

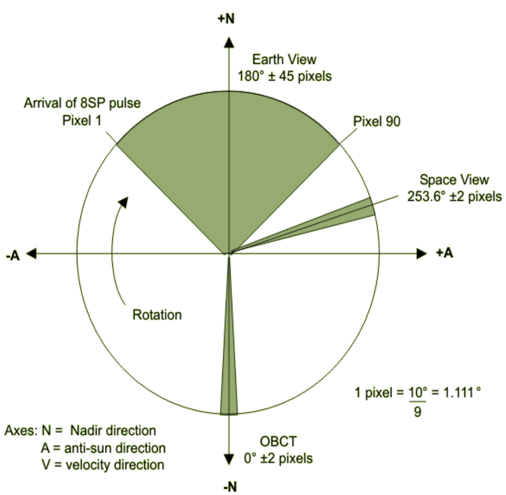
Error correlation between measured values

Earth view

Calibration target view

Space view





FIduceo

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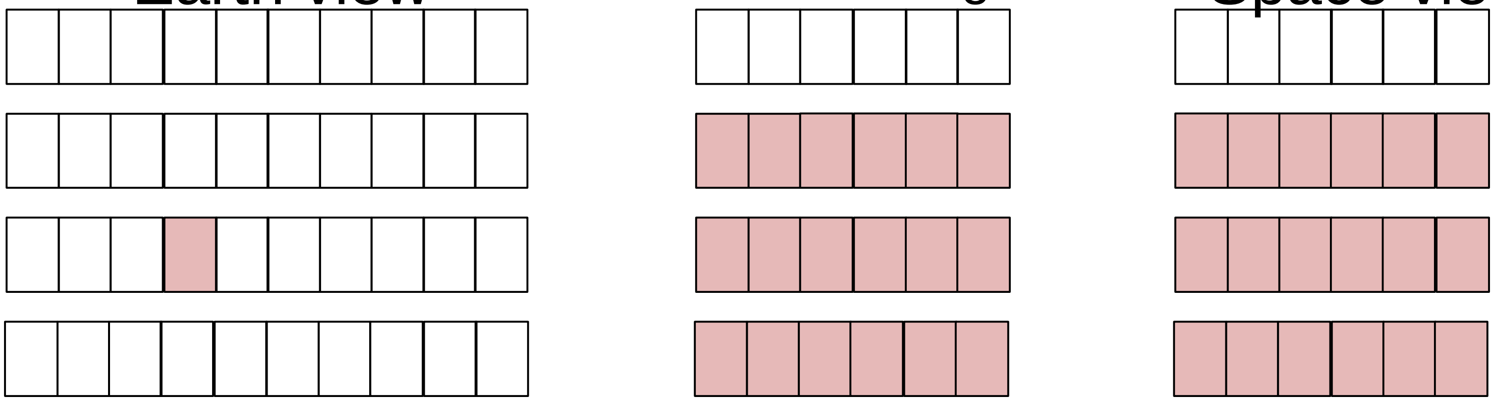

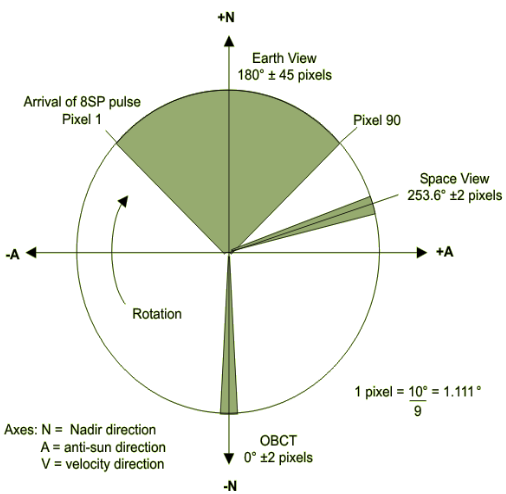

Fiduceo

Error correlation between measured values

Earth view

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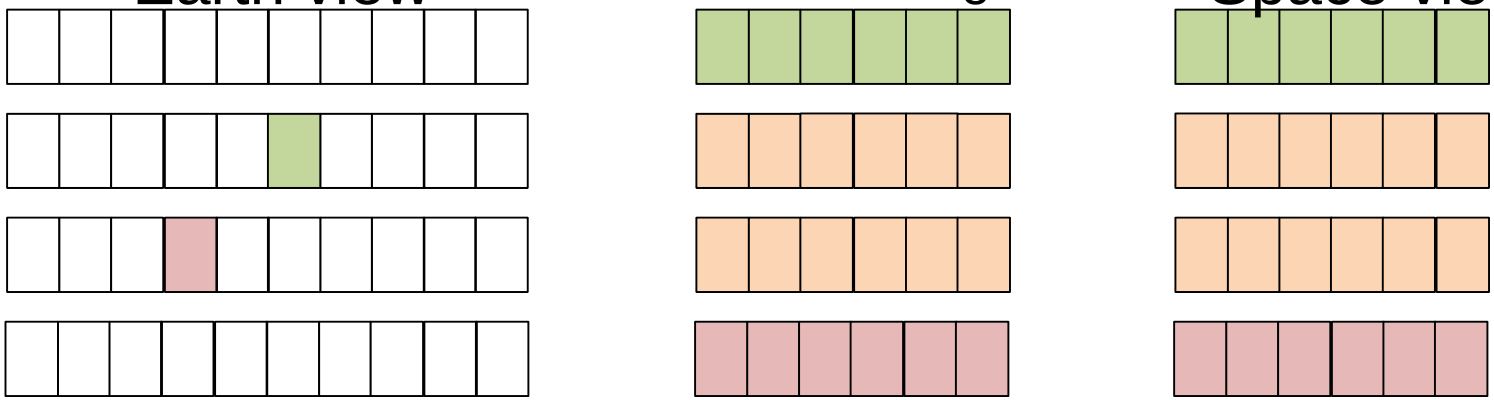
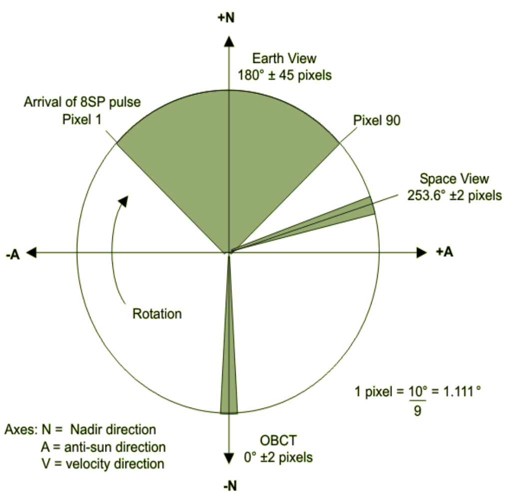
Space view





Comparison

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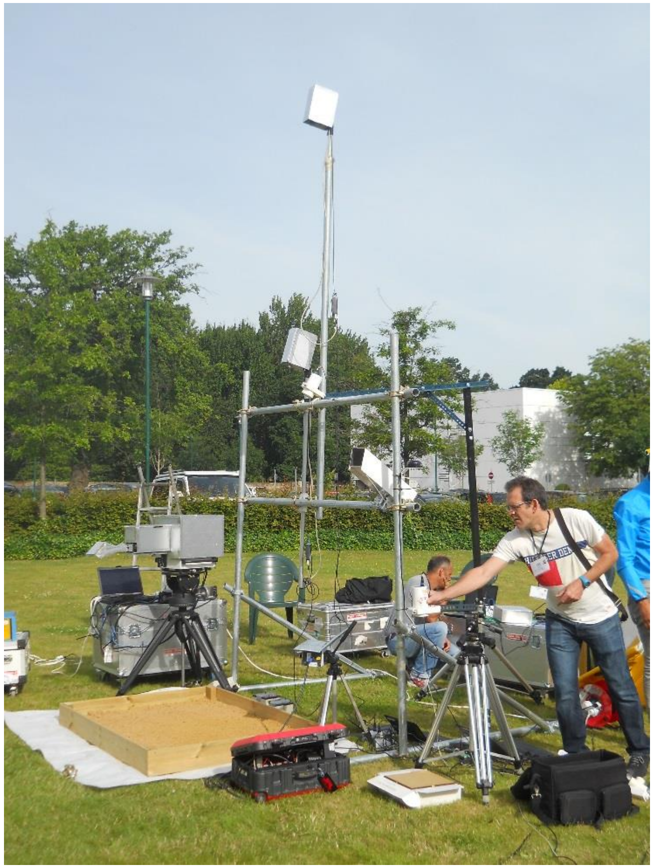

fiducial reference
temperature
measurements

This presentation

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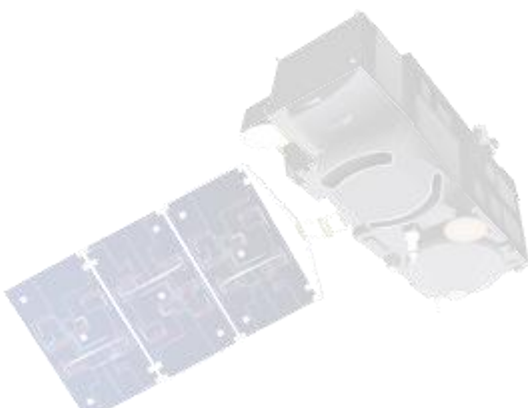

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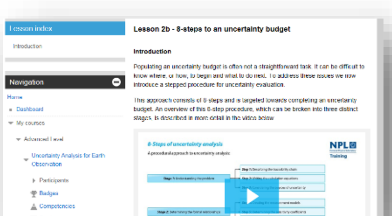

3. Resources to help

Metrology for Earth Observation and Climate

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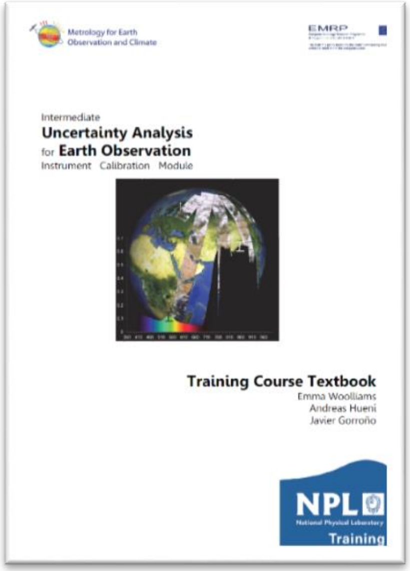
Training materials

- www.meteoc.org/outreach-training.html
  - Text book “uncertainty analysis for EO instrument calibration”
  - Videos of lectures (30-60 minutes each)



- www.npl.co.uk/e-learning
  - Sign up for NPL’s e-learning courses
  - Includes free “introduction to metrology” and “introduction to uncertainty”
  - And (currently free) “Uncertainty Analysis for Earth Observation”

Screen shots from e-Course

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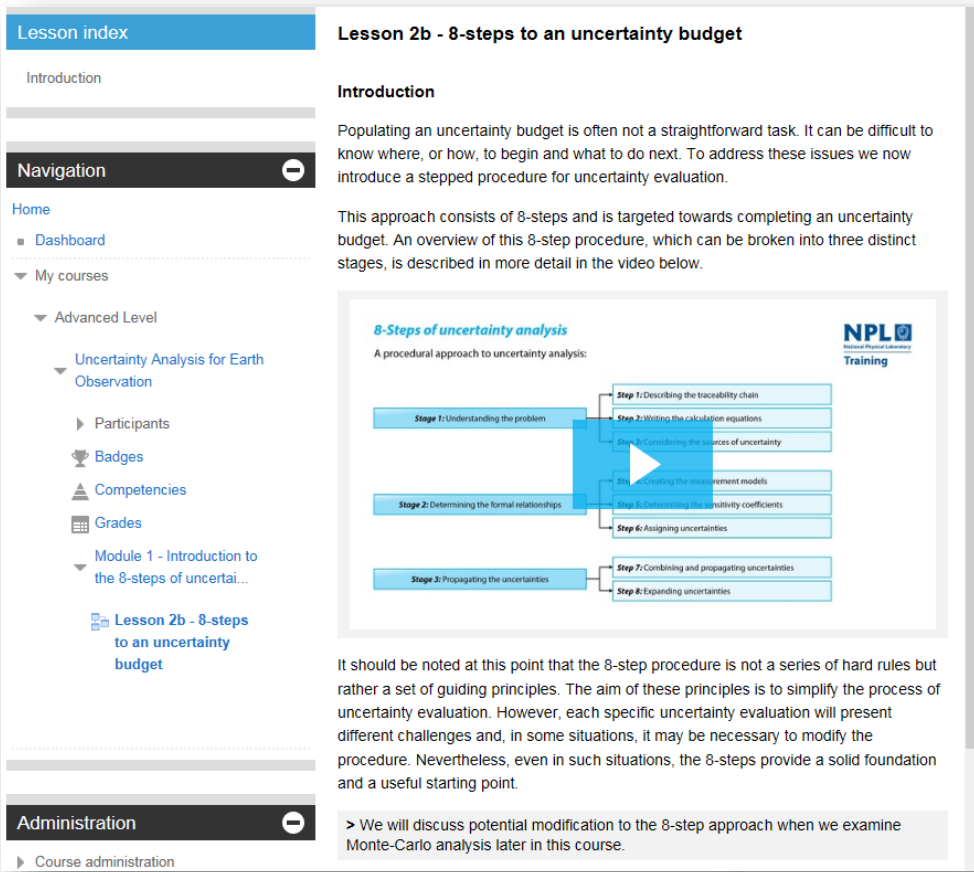

Lesson index

Introduction

Navigation

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My courses

Advanced Level

Uncertainty Analysis for Earth Observation

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Grades

Module 1 - Introduction to the 8-steps of uncertai...

Lesson 2b - 8-steps to an uncertainty budget

Administration

Course administration

Lesson 2b - 8-steps to an uncertainty budget

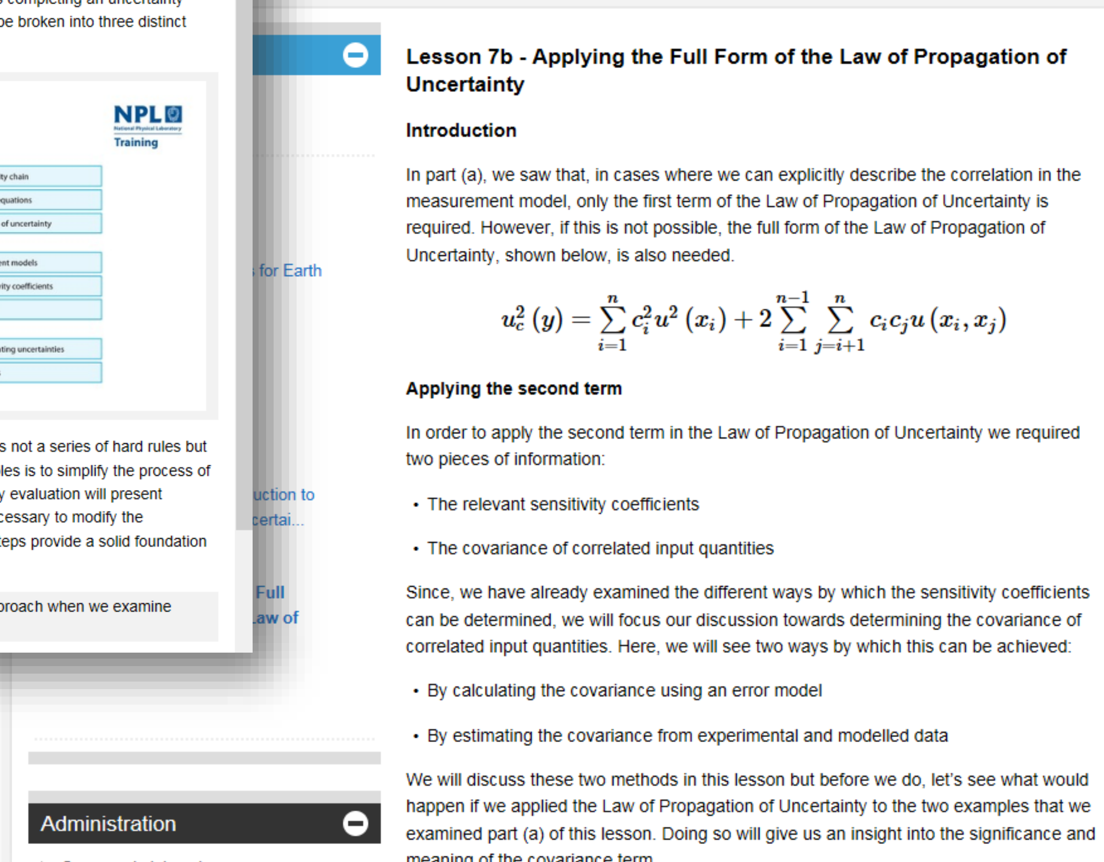
Introduction

Populating an uncertainty budget is often not a straightforward task. It can be difficult to know where, or how, to begin and what to do next. To address these issues we now introduce a stepped procedure for uncertainty evaluation.

This approach consists of 8-steps and is targeted towards completing an uncertainty budget. An overview of this 8-step procedure, which can be broken into three distinct stages, is described in more detail in the video below.

It should be noted at this point that the 8-step procedure is not a series of hard rules but rather a set of guiding principles. The aim of these principles is to simplify the process of uncertainty evaluation. However, each specific uncertainty evaluation will present different challenges and, in some situations, it may be necessary to modify the procedure. Nevertheless, even in such situations, the 8-steps provide a solid foundation and a useful starting point.

> We will discuss potential modification to the 8-step approach when we examine Monte-Carlo analysis later in this course.



Lesson 7b - Applying the Full Form of the Law of Propagation of Uncertainty

Introduction

In part (a), we saw that, in cases where we can explicitly describe the correlation in the measurement model, only the first term of the Law of Propagation of Uncertainty is required. However, if this is not possible, the full form of the Law of Propagation of Uncertainty, shown below, is also needed.

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

Applying the second term

In order to apply the second term in the Law of Propagation of Uncertainty we required two pieces of information:

- The relevant sensitivity coefficients
- The covariance of correlated input quantities

Since, we have already examined the different ways by which the sensitivity coefficients can be determined, we will focus our discussion towards determining the covariance of correlated input quantities. Here, we will see two ways by which this can be achieved:

- By calculating the covariance using an error model
- By estimating the covariance from experimental and modelled data

We will discuss these two methods in this lesson but before we do, let's see what would happen if we applied the Law of Propagation of Uncertainty to the two examples that we examined part (a) of this lesson. Doing so will give us an insight into the significance and meaning of the covariance term.

Administration

Course administration

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New material under development

- Question and answer based "shorts" (2 minute videos/single page texts)
- Focus on satellite Level 1 products

Examples:

- What do I need to know about an effect to propagate uncertainties?
- Can noise ever be correlated?
- How do we calculate the error correlation between measured values in different spectral bands?
- How do I know whether my uncertainties are right?

1 Concepts
- Chains and measurement function diagrams
- Propagating uncertainties
- Sensitivity coefficients
- Generic correlation

2 Practical implementation
- Noise
- Spectral uncertainties
- Calculating correlation
- Fitting

3 Validation and iteration
- Validating uncertainty budgets
- Discovering sensitivities and patterns

FIduceo

Metrology for Earth Observation and Climate

Resources to help…

- NPL
- MetEOC
- FIDUCEO
- FRM programme

Thank you

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Metrology for Earth Observation and Climate

MetEOC and MetEOC-2 were funded by EMRP
MetEOC-3 is funded under EMPIR

EMPIR EURAMET
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Department for Business, Energy & Industrial Strategy

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FIDUCEO

FIDUCEO has received funding from the European Union's Horizon 2020 Programme for Research and Innovation, under Grant Agreement no. 638822

esa
European Space Agency
Agence spatiale européenne

UK SPACE AGENCY

Centre for EO Instrumentation