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

Use of metrological principles in FIDUCEO

Chris Merchant
Emma Woolliams
Jon Mittaz

FIDUCEO

- **Key idea**: develop a widely applicable basis for the **metrology of Earth observation** including historical satellite missions
- The **motivation** is to establish “uncertainty-quantified” evidence base for long-term climate and environmental change from EO systems
- Project runs March 2015 to February 2019

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WHY?

Why metrology?

To maximize the value of data from EO space assets for climate science and policy

- Trustworthiness and transparency
  - Uncertainty information needs to be believed
- Scientific integrity
  - Not fooling ourselves
  - Consistent uncertainty information across scales
- Better data
  - Can reduce (not only quantify) uncertainty through insight gained
  - Use of disciplinary analysis tools, harmonisation

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WHAT?

www.fiduceo.eu

Satellite-era archives

- AVHRR
- HIRS
- AMSUB
- MVIRI

Metrological methods to:

- **Calculate uncertainty**
- **Harmonise across series**

New L1 FCDRs

Fundamental Climate Data Record (FCDR) : harmonised radiance record from which CDRs for one or more ECVs can be derived

- BTs
- Reflectances
- Components of uncertainty

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Satellite-era archives

- AVHRR
- HIRS
- AMSUB
- MVIRI

New L1 FCDRs

- BTs
- Reflectances
- Components of uncertainty

CDRs L2, L3

- Surface T
- Water Vapour
- Aerosol
- Albedo

Rigorous propagation of L1 uncertainty

- **Scale of effect**
- **Correlation of errors**

Validate uncertainty with GAIA-CLIM

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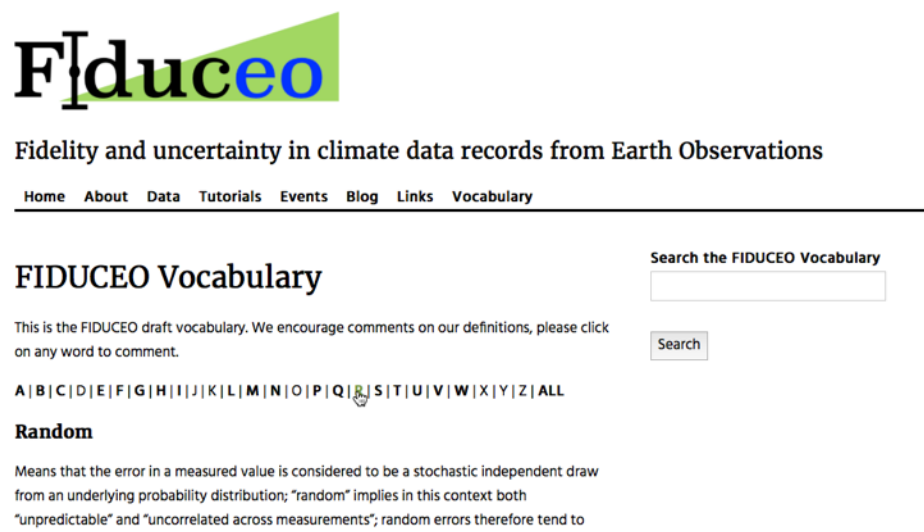
What metrology?

- Conceptual clarity
- Traceability
- Rigorous methods

Conceptual clarity

- Adopt metrological conventions for the expression of uncertainty in measurement
- In moving from lab to EO imagery, some concepts need to be extended/adapted
  - e.g. structured random effects

http://www.fiduceo.eu/vocabulary



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Traceability

- Classic metrological traceability consists of a chain of calibration that ties a measured value to an SI reference, to a stated, defensible uncertainty
- No SI reference in space, but we adopt
  - the traceability of uncertainty estimates
    - ultimately, at all satellite processing levels and all scales
  - tied mutual calibration between sensors
    - Earth observations harmonised by re-calibration

http://www.fiduceo.eu/content/harmonisation-and-recalibration

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Rigorous methods

- Gaining access to disciplinary expertise honed within the metrology community
  - robust methods for estimating variance
  - unbiased methods for line and curve fitting
  - sanctioned approaches to uncertainty estimation
- Have to develop/extend some methods for EO
  - multi-sensor series harmonisation (not pair-wise)

HOW?

How?

- Understand the **measurement equation**
- Quantify the **sources of error** (effects)
- Quantify their **error structures**
- Propagate to get radiance **uncertainty**
- **Harmonise** radiances by **re-calibration**
- Propagate radiance uncertainty to achieve
  - uncertainty quantified **climate data records**
  - across all spatio-temporal **scales**

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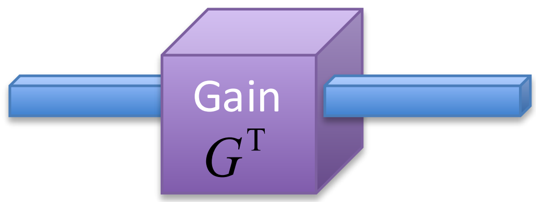
Measurement equation

The equation used to calculated "calibrated radiance" in the FCDR

True signal $C_{\mathrm{E}}^{\mathrm{T}}$



Should respect
the laws of physics
Should reflect
the instrument
Understand sources
of error in each term

Measured Signal

$$C_{\mathrm{E}}^{\mathrm{M}} = G^{\mathrm{T}} R_{\mathrm{E}}^{\mathrm{T}} + \delta C_{\mathrm{E}}$$

Measured gain

$$G^{\mathrm{M}} = G^{T} + \delta G^{T}$$

Measured Earth Radiance

TOA Earth Radiance $R_{\mathrm{E}}^{\mathrm{T}}$

$$R_{\mathrm{E}}^{\mathrm{M}} = \frac{C_{\mathrm{E}}^{\mathrm{M}}}{G^{M}}$$

$$R_E = a_0 + \frac{a_1 R_T - a_2 \dot{C}_T^2}{\dot{C}_T} C_E + a_2 C_E^2 + O$$

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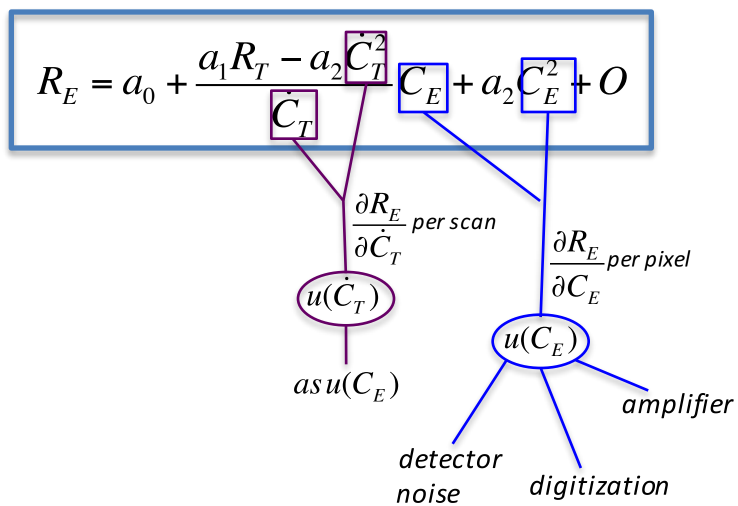
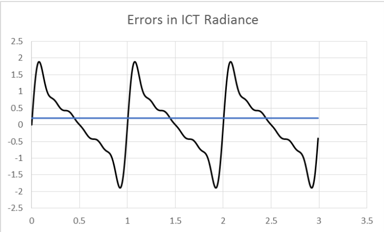

$R_E = a_0 + \frac{a_1 R_T - a_2 \dot{C}_T^2}{\dot{C}_T} C_E + a_2 C_E^2 + O$
$\frac{\partial R_E}{\partial \dot{C}_T}$ per scan
$u(\dot{C}_T)$
as $u(C_E)$
$\frac{\partial R_E}{\partial C_E}$ per pixel
$u(C_E)$
amplifier
detector noise
digitization

Quantify each error source

- Magnitude of uncertainty at parameter level
- Correlation structure of errors
  - between elements
  - between lines (over time)
  - between measurement equation parameters
  - between spectral bands
- Propagate parameter-uncertainty to radiance uncertainty



Nature of each effect captured in a standardised effects table

Example for noise affecting counts measured from cold and hot calibration targets

Information / data	Type / value / equation	Notes / description
Name of effect	**Structured random effect per scan line**	
Measurement equation parameter(s) subject to effect	ICT counts and space counts	
Channels / bands subject to effect	All of them	
a. Scan correlation form	Constant	Top hat, whole scan
b. Time correlation form	Triangular	
c. Units scan correlation	Pixel	
d. Units time correlation	Scan lines	
e. Scales scan corr.	[-∞,∞]	See below
f. Scales time corr.	[-25, 25]	See below
g. Uncertainty PDF shape	Averaged digitised Gaussian	
h. Uncertainty	Allan deviation of the 10 values (of space or ICT view) calculated for each scan line	These values will be provided per scan line
i. Uncertainty units	Counts	
j. Sensitivity coefficient	Partial derivative	
k. Correlation(s) between affected parameters	no	
l. Cross-channel correlation(s)	no	

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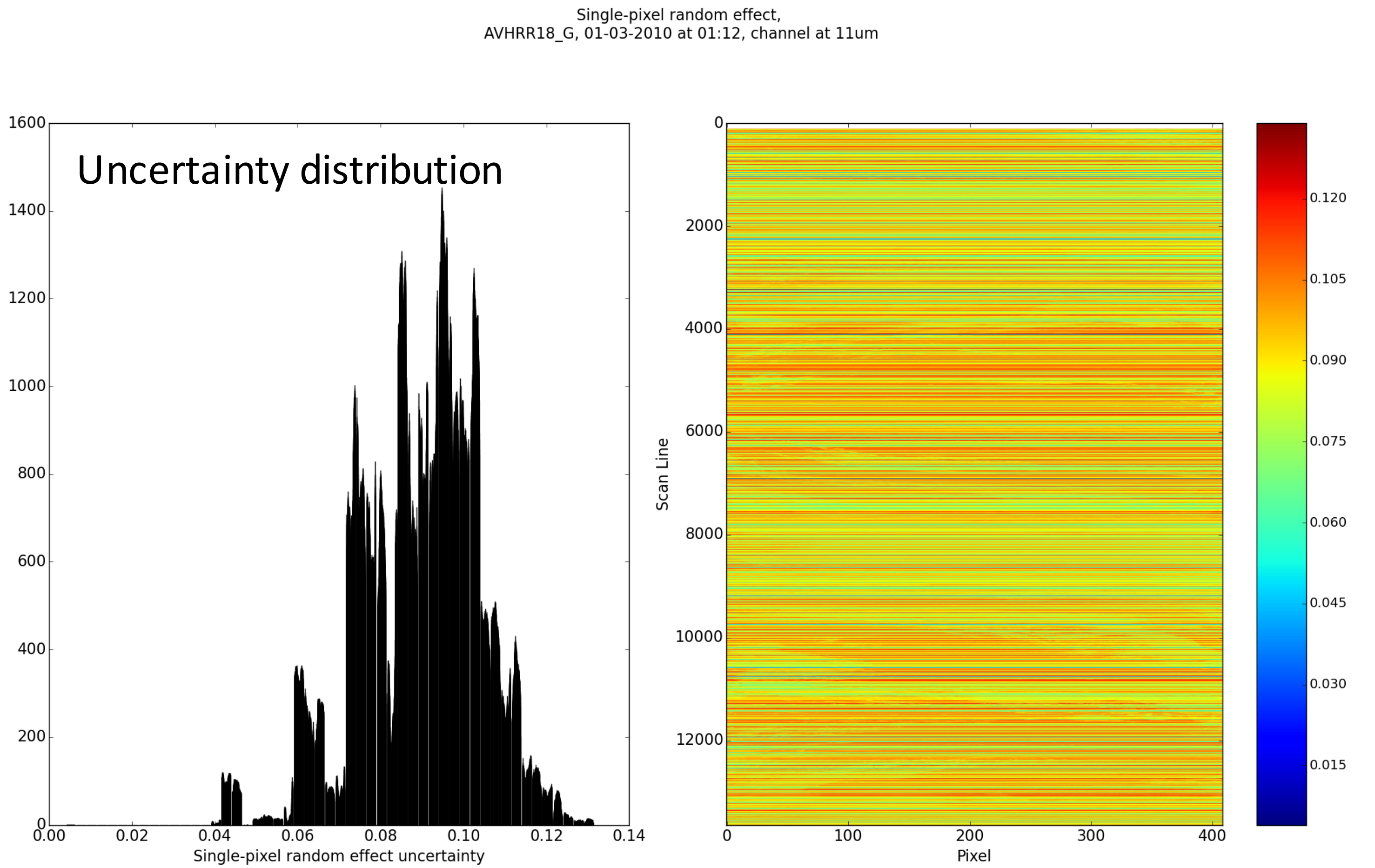
Uncertainty in 11 µm radiance



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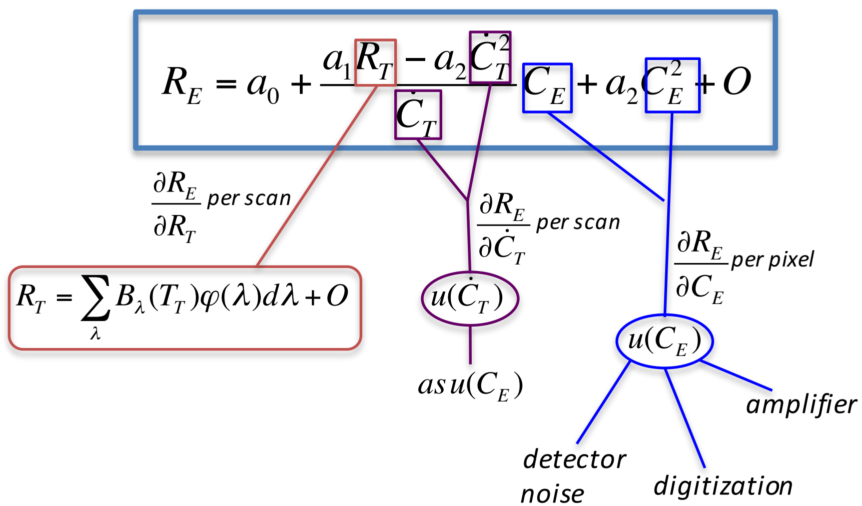
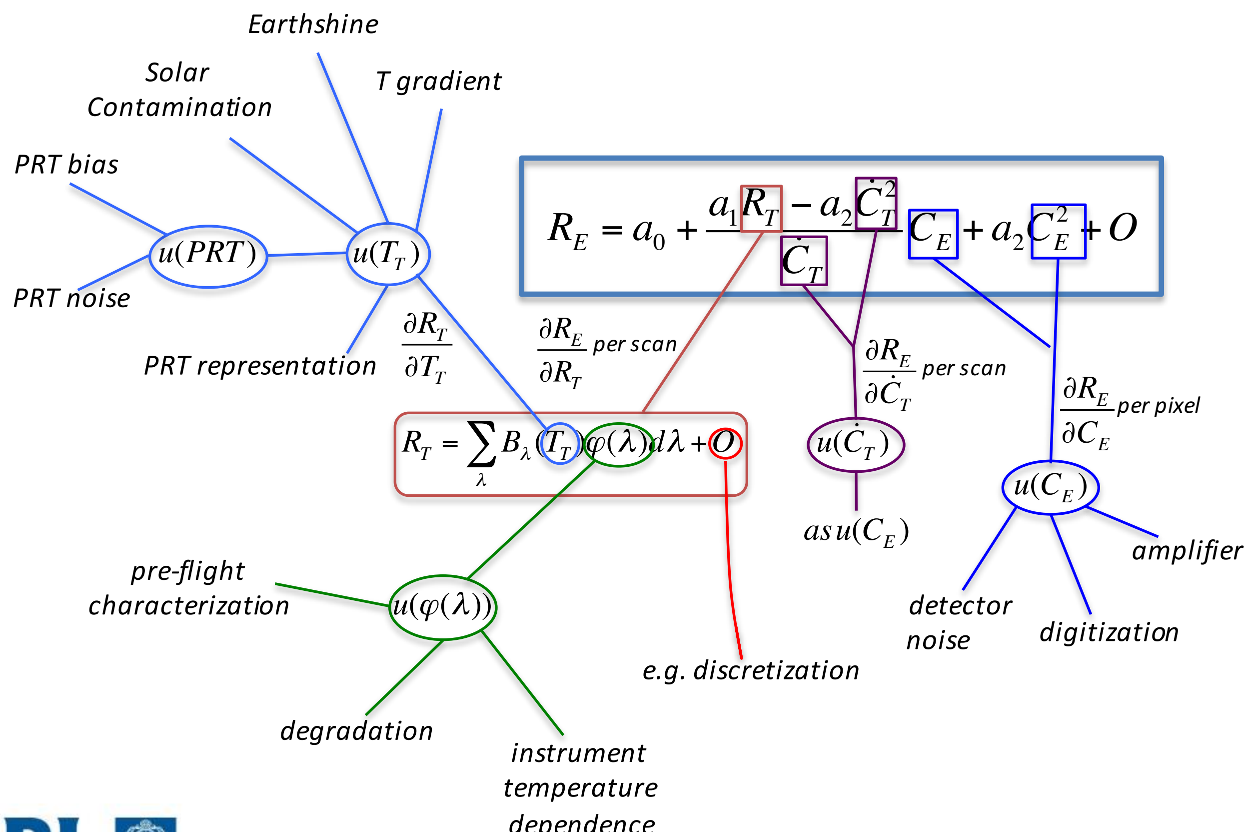
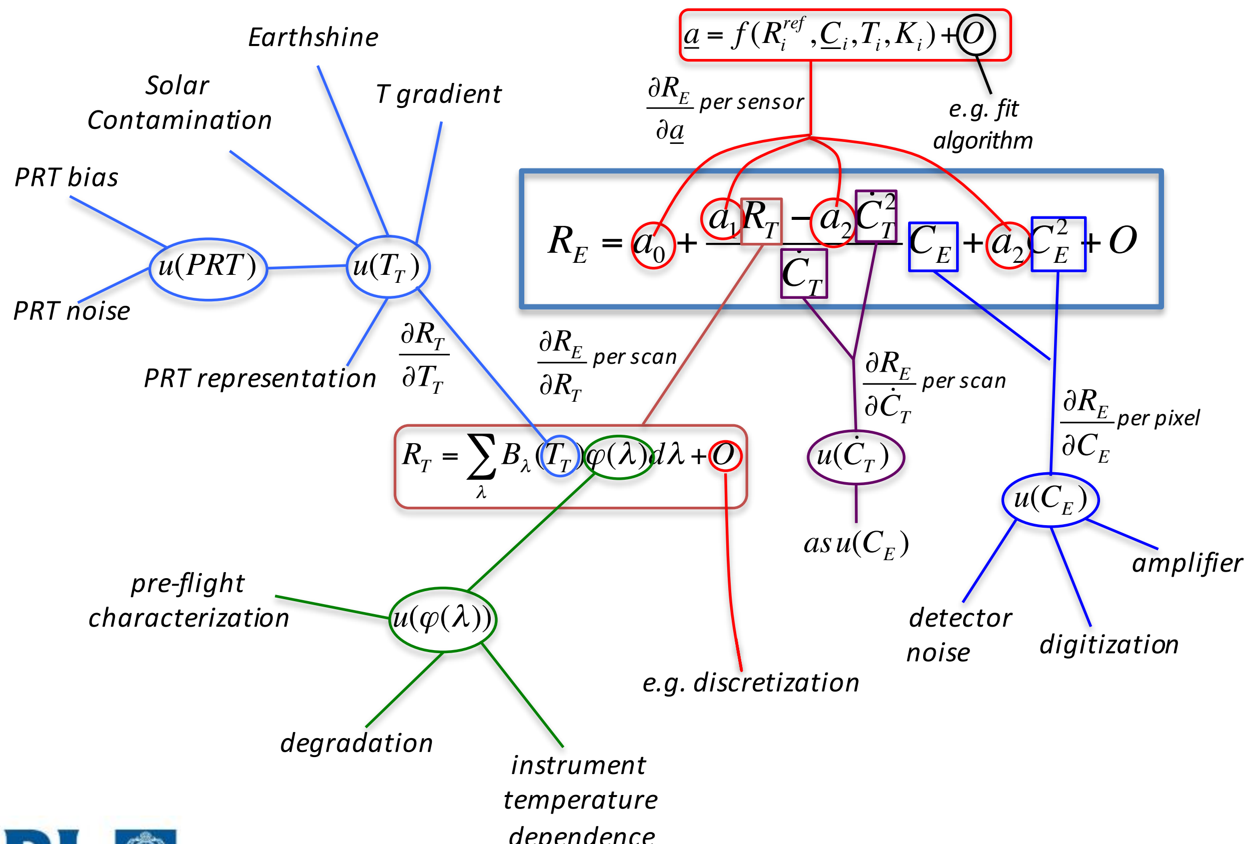

$R_E = a_0 + \frac{a_1 R_T - a_2 \dot{C}_T^2}{\dot{C}_T} C_E + a_2 C_E^2 + O$
$\frac{\partial R_E}{\partial R_T}$ per scan
$R_T = \sum_\lambda B_\lambda(T_T)\varphi(\lambda)d\lambda + O$
$\frac{\partial R_E}{\partial \dot{C}_T}$ per scan
$u(\dot{C}_T)$
as $u(C_E)$
$\frac{\partial R_E}{\partial C_E}$ per pixel
$u(C_E)$
amplifier
detector noise
digitization



Earthshine
Solar Contamination
T gradient
PRT bias
PRT noise
PRT representation
$u(PRT)$
$u(T_T)$
$$R_E = a_0 + \frac{a_1 R_T - a_2 \dot{C}_T^2}{\dot{C}_T} C_E + a_2 C_E^2 + O$$
$\frac{\partial R_T}{\partial T_T}$
$\frac{\partial R_E}{\partial R_T}$ per scan
$\frac{\partial R_E}{\partial \dot{C}_T}$ per scan
$\frac{\partial R_E}{\partial C_E}$ per pixel
$$R_T = \sum_\lambda B_\lambda (T_T) \varphi(\lambda) d\lambda + O$$
$u(\dot{C}_T)$
as $u(C_E)$
$u(C_E)$
amplifier
detector noise
digitization
pre-flight characterization
$u(\varphi(\lambda))$
e.g. discretization
degradation
instrument temperature dependence



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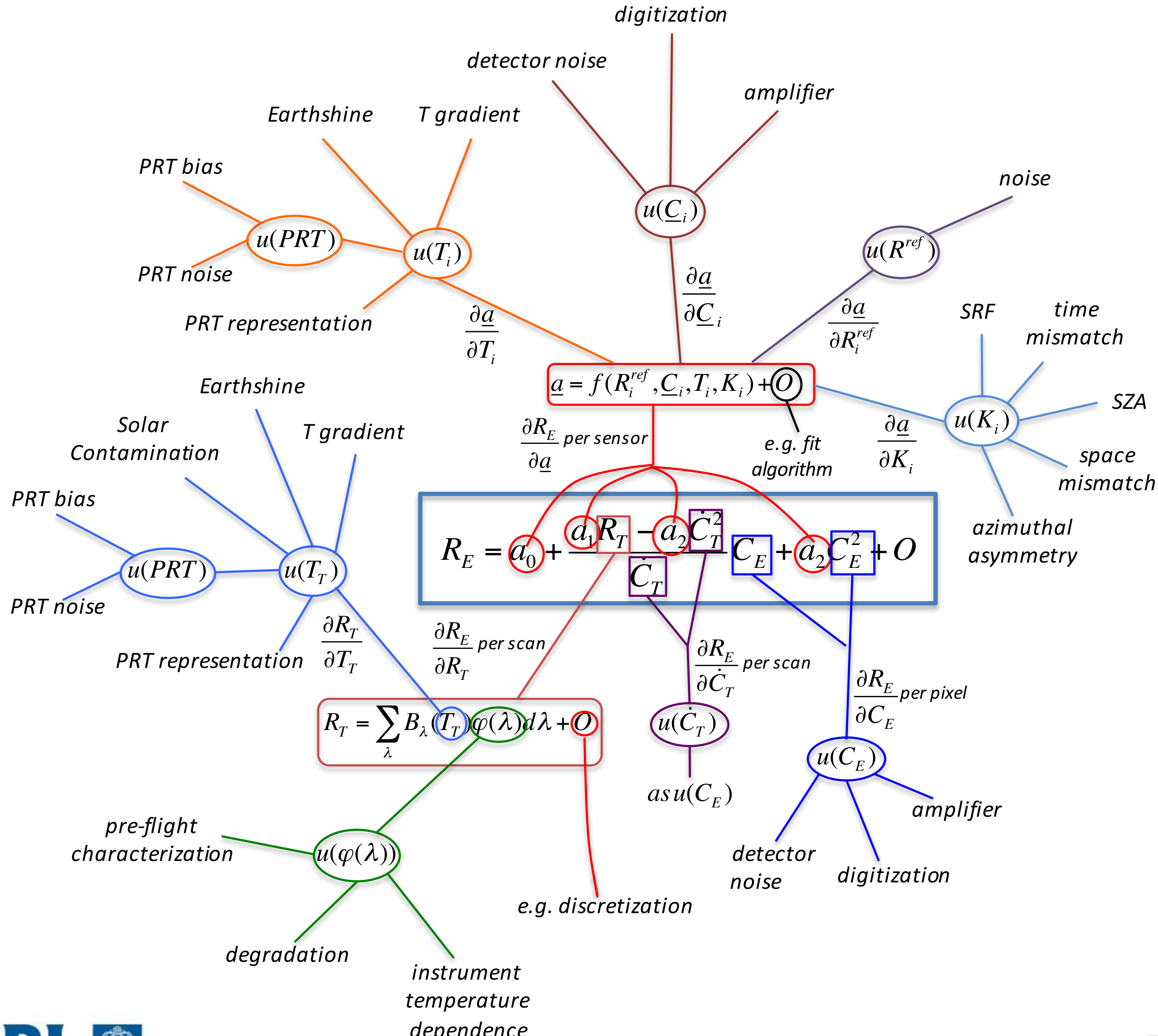

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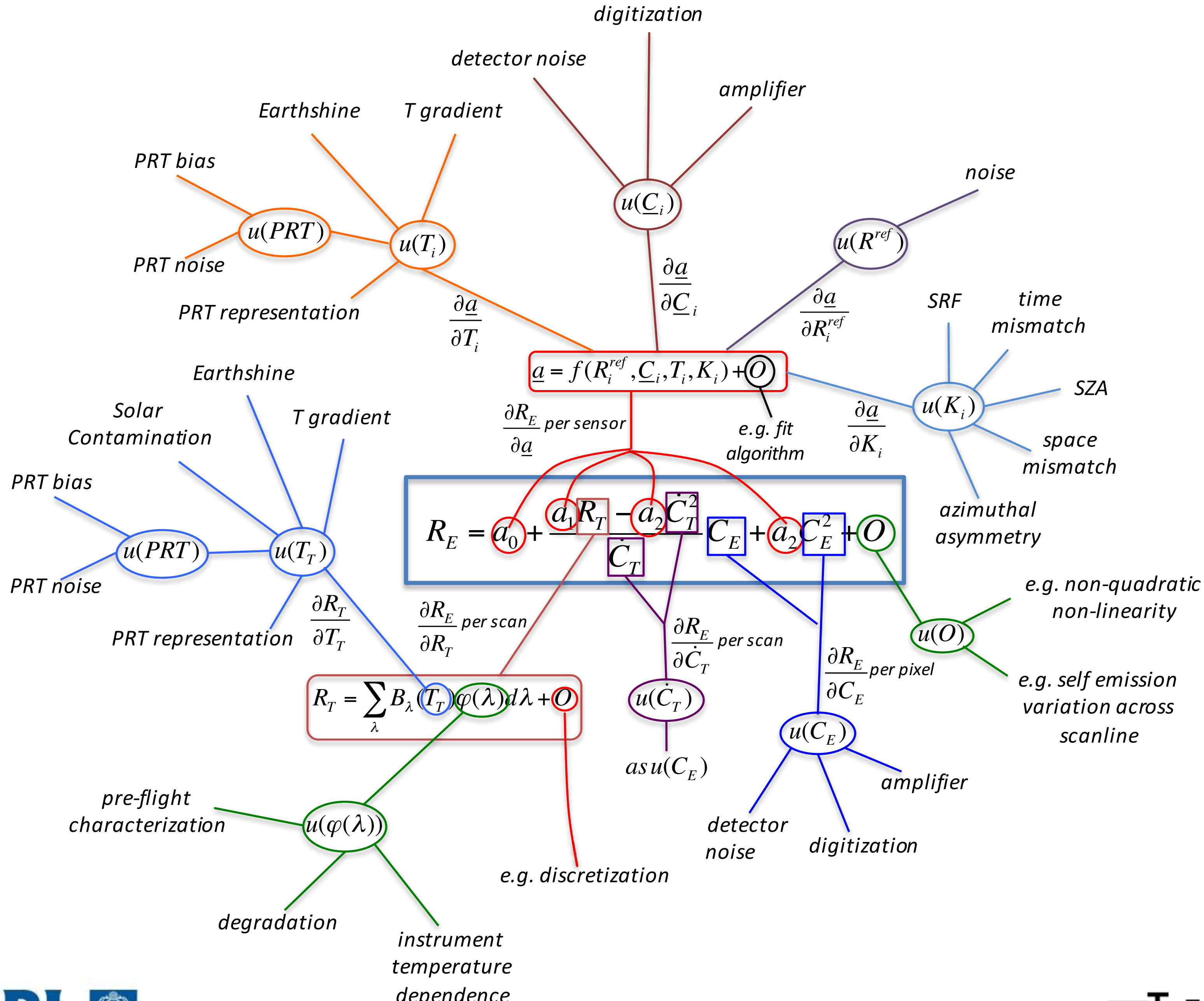

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Traceable uncertainty

- Measurement-equation centred approach
- Traceability diagram
  - to organise
  - to document
- Branching structure reflects the nature of the problem
- Standardised “effects table” per “twig”
  - systematic documentation
  - ongoing – how this is codified into FCDR format
- Same for deriving higher-order products (CDRs)
  - uncertainty from L1 is simply one of the effects in L2

Uncertainty cascade

detector, amplifier, digitisation, non-linearity …

L0

↓

calibration (targets and model), geolocation …

L1b

↓

ambiguity of inversion, definitional uncertainty …

L2

↓

spatio-temporal sampling…

L3

↓

extra-/interpolation, smoothing

L4

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Same measurement-centred approach applies at each transformation

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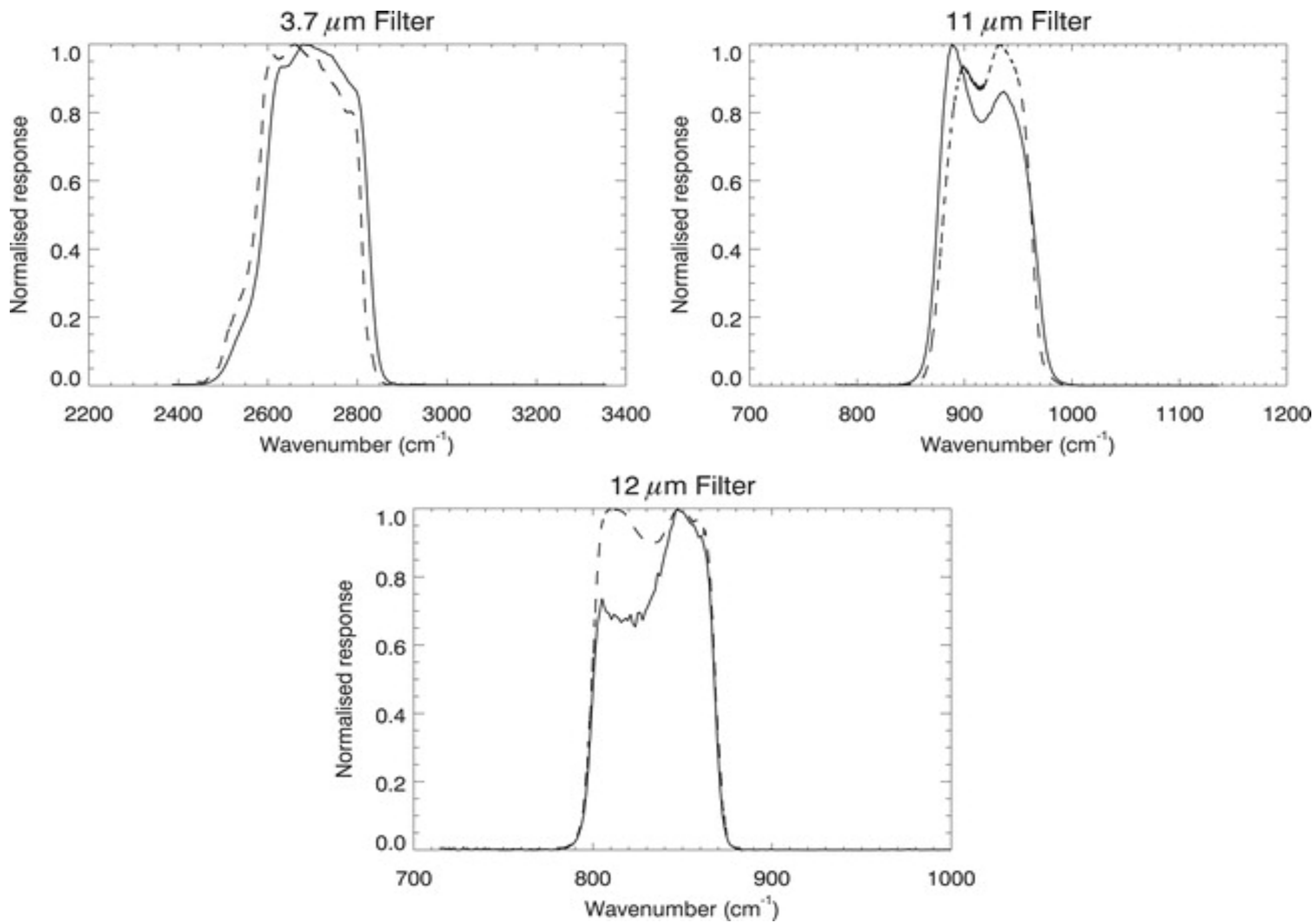
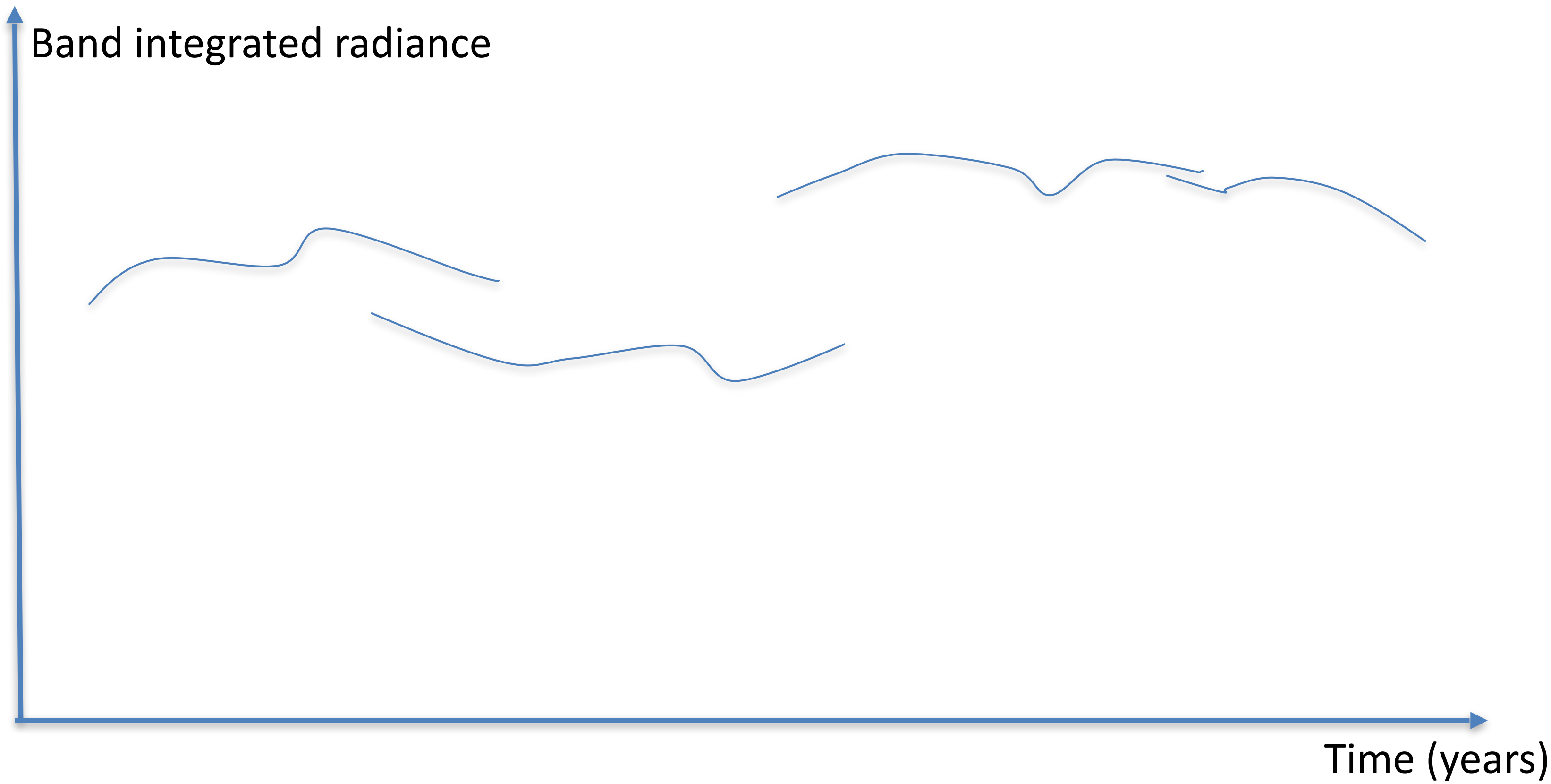
Families of sensors

- Single-sensor methods are now being applied
- Ongoing development of metrology methods at the “sensor family” level
  - i.e., within series and across series of sensors with comparable mission specifications and target ECVs
  - a sensor family will be **harmonised** with respect to calibration
- **Method: mutual recalibration across the family**
- New areas of metrological application
  - spectral response function uncertainty
  - satellite-to-satellite matching

Two members of a sensor family compared



Harmonisation is not …



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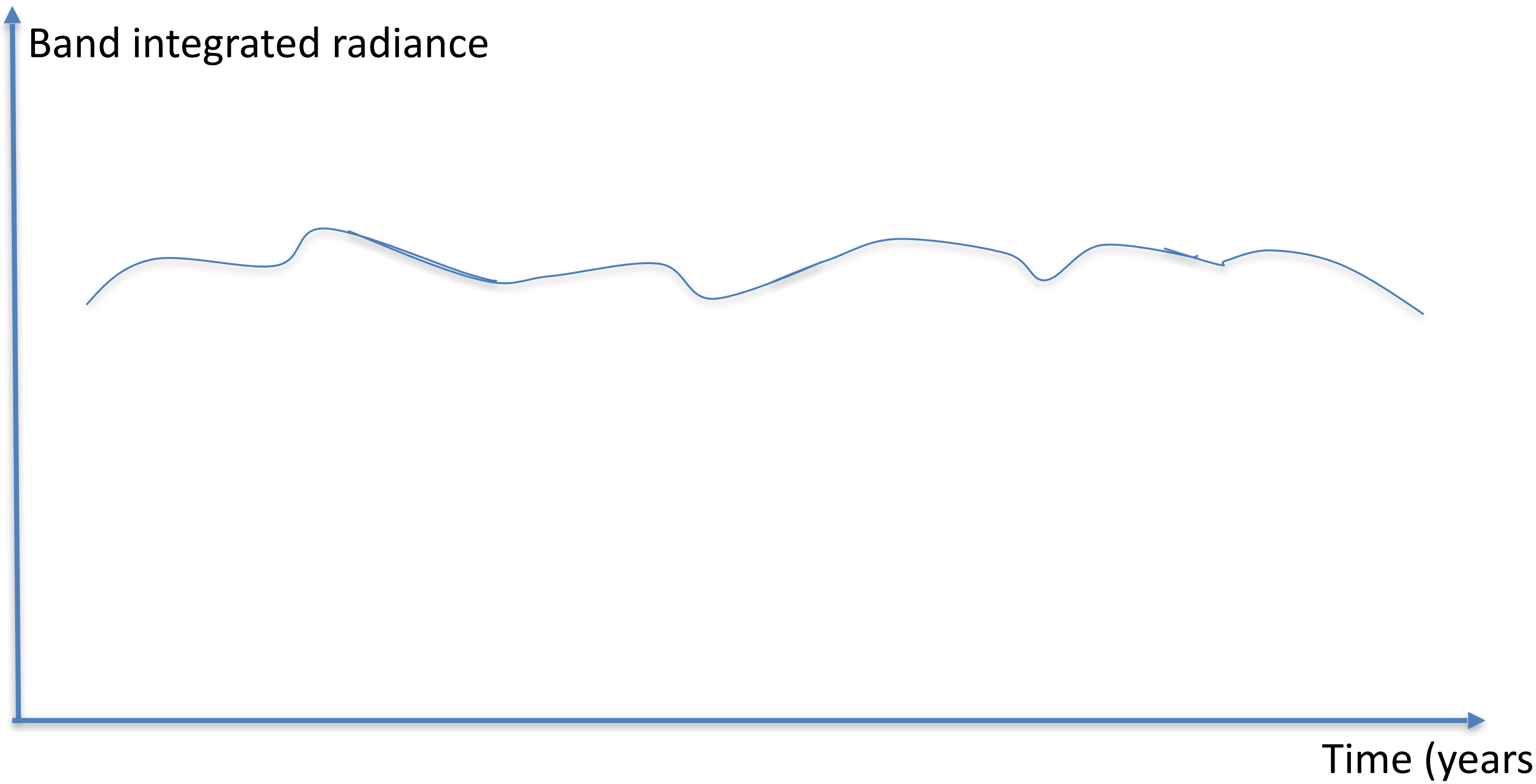
Harmonisation is not …



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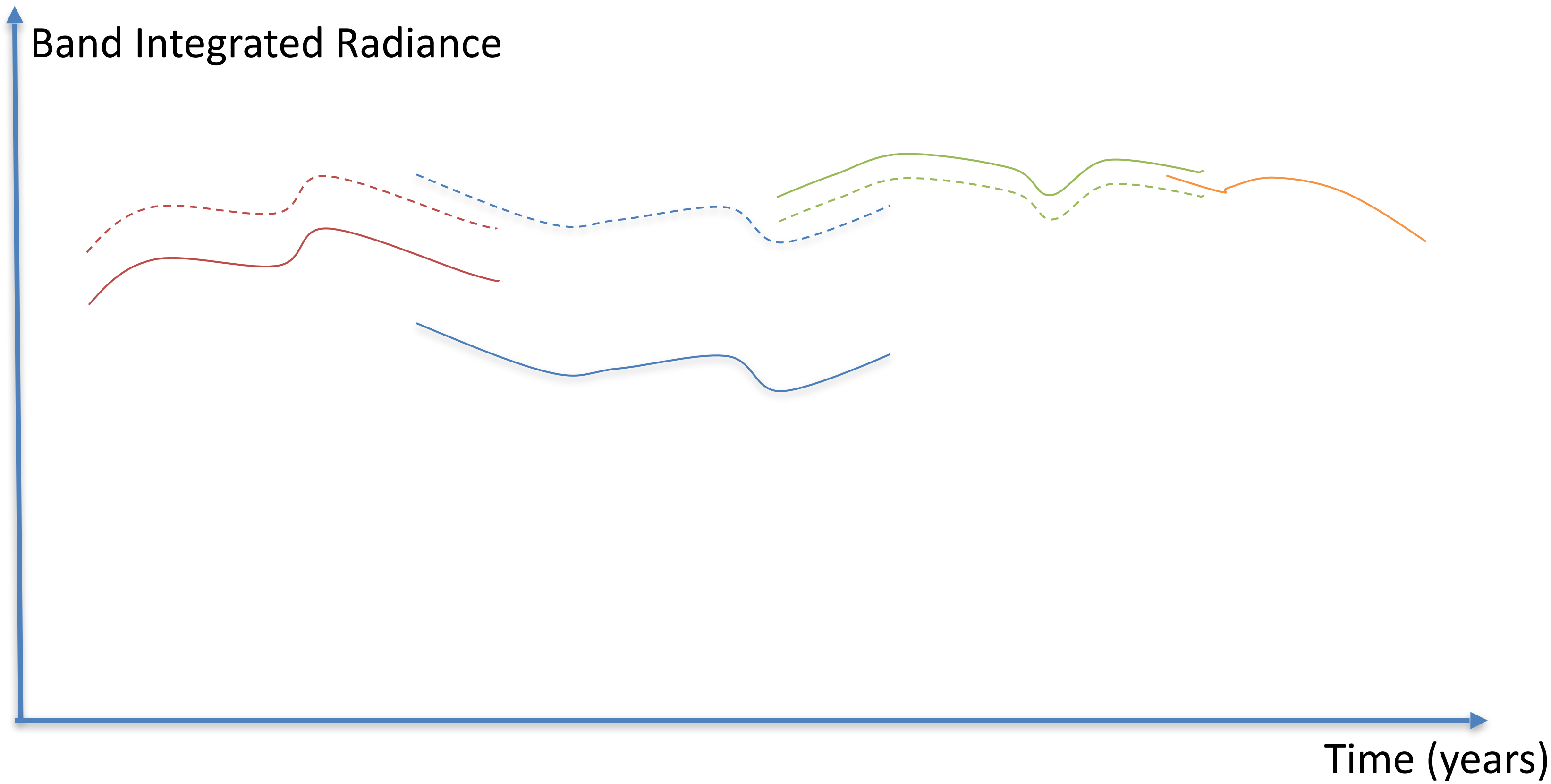
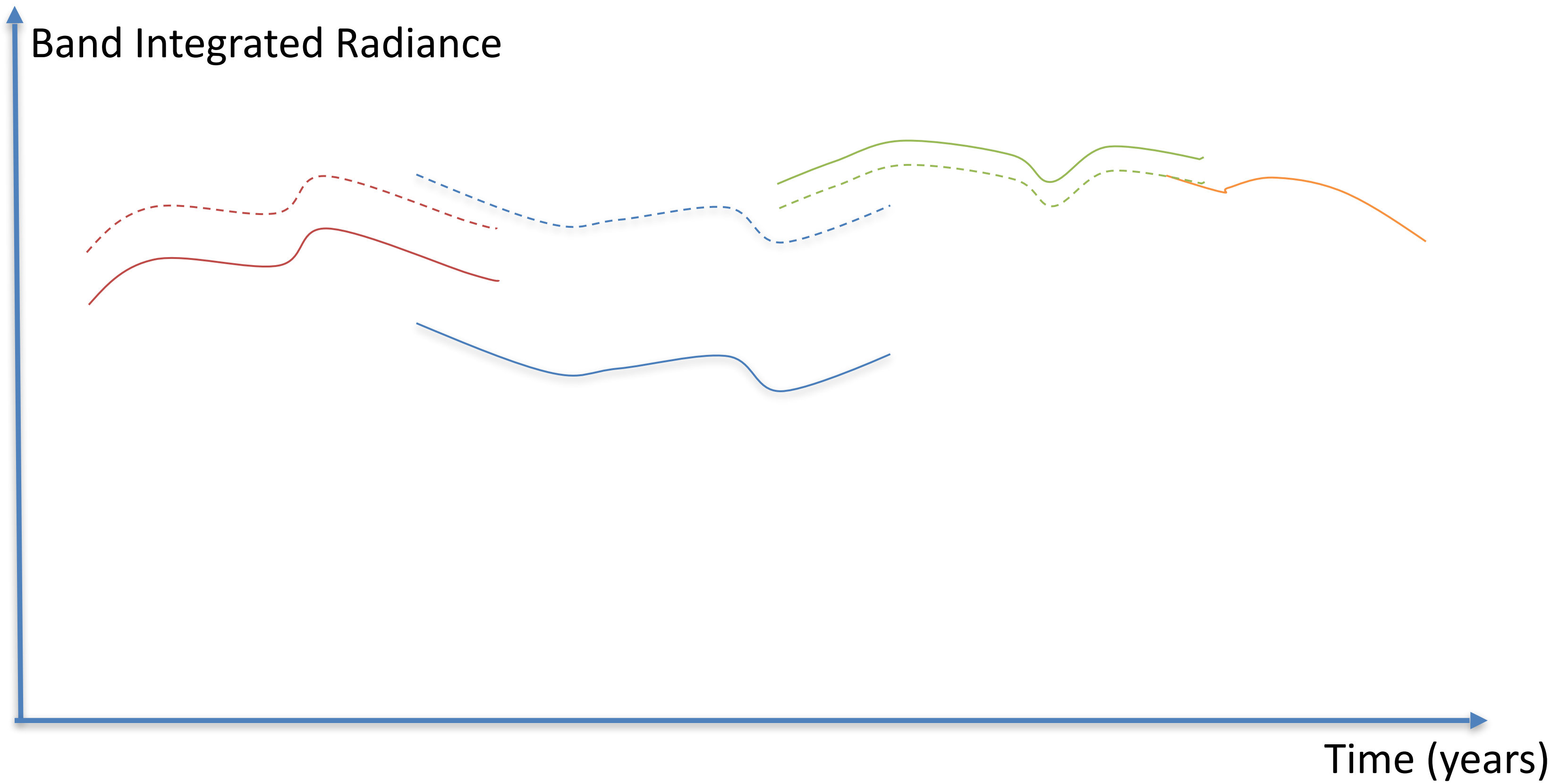
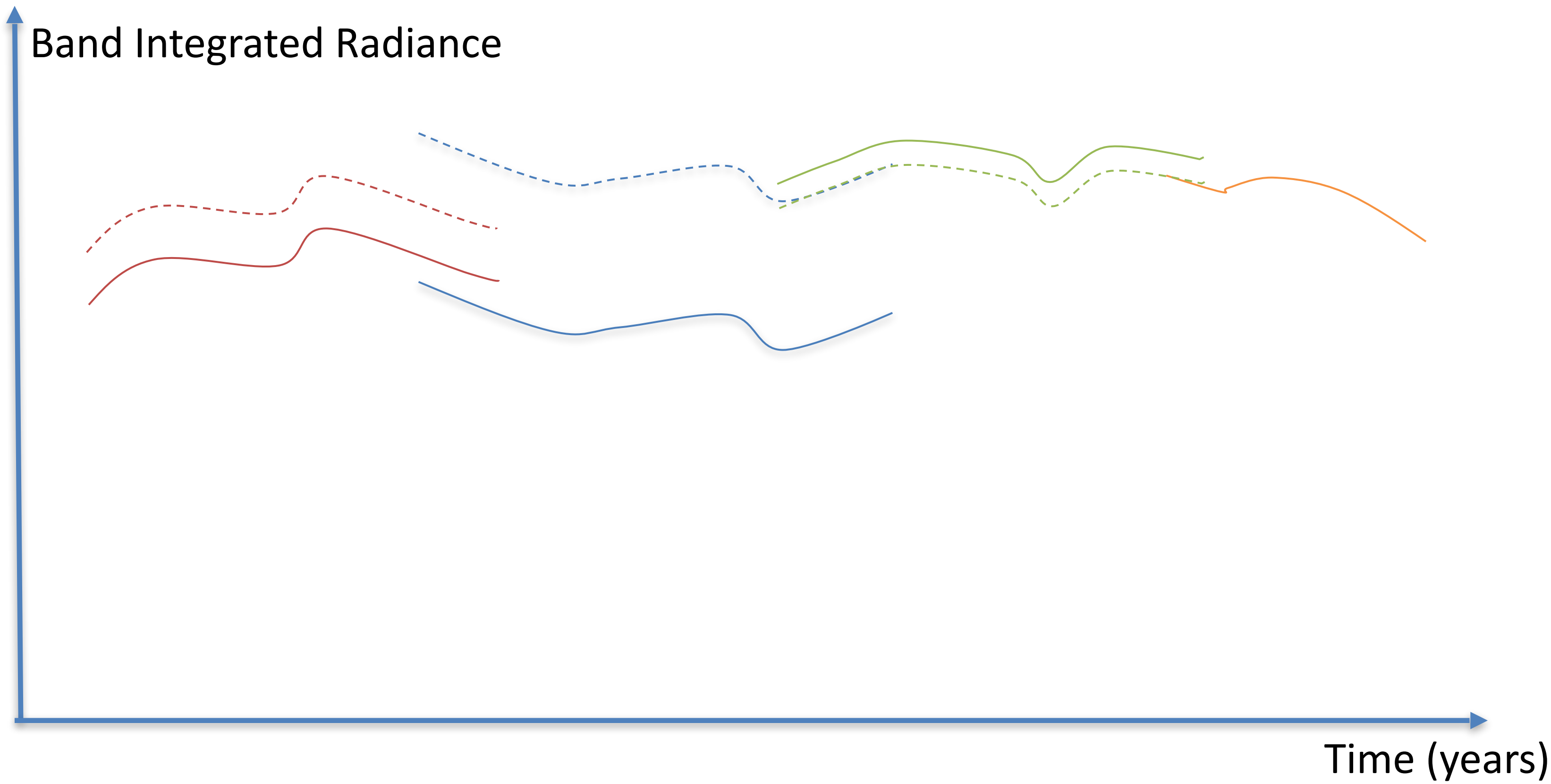
Harmonisation is …



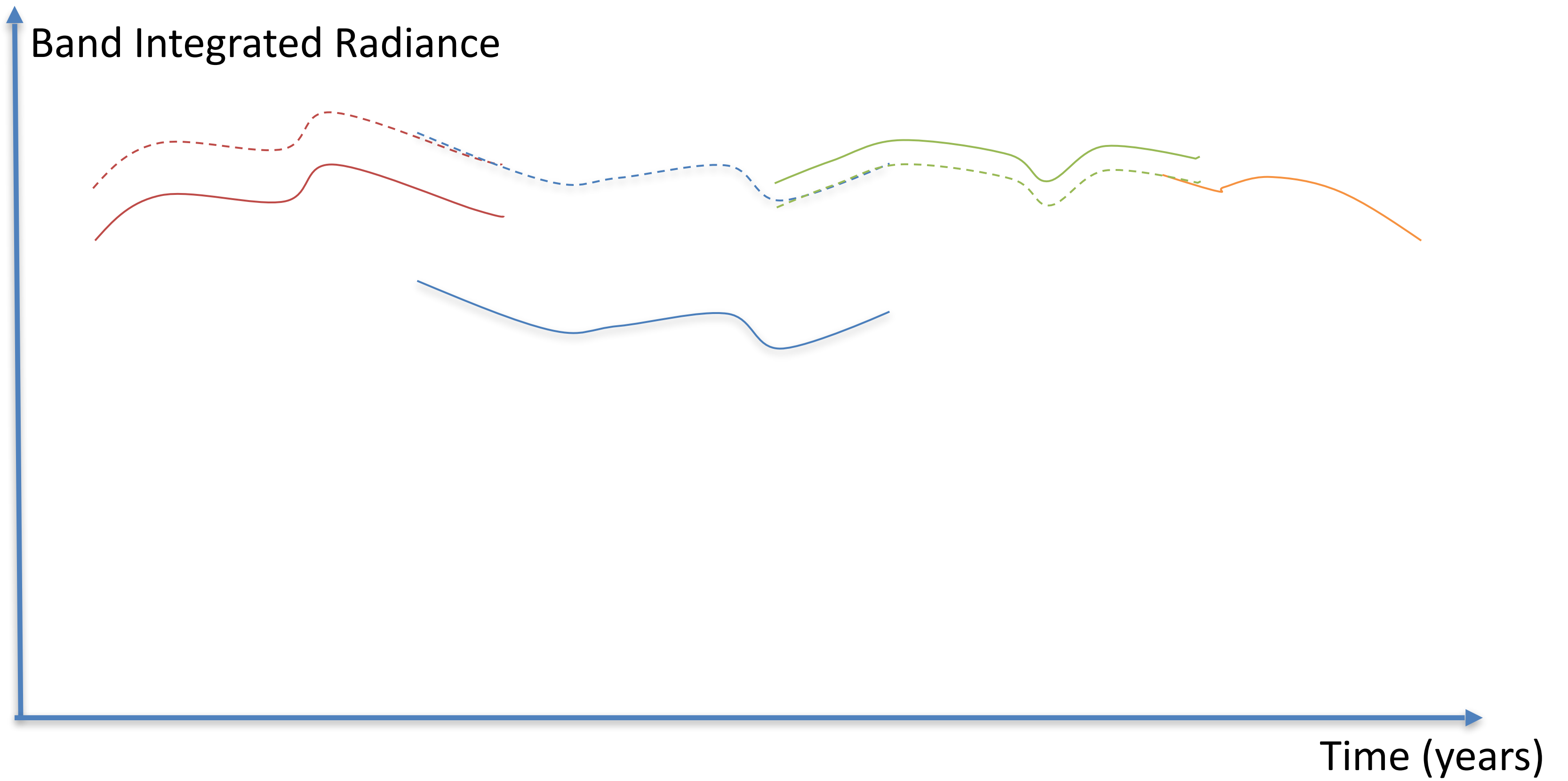
Harmonisation is …



Harmonisation is …



Harmonisation is …



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Interacting with GSICS

Method / Aim	Bias correction	Recalibration
Respecting satellite SRF differences while reconciling calibration	GSICS definition for 'Sensor equivalent calibration'	FIDUCEO definition for 'harmonisation'
Adjusting for SRF differences and calibration differences	GSICS definition for 'Reference sensor normalised calibration'	FIDUCEO definition for 'homogenisation'


GSICS Global Space-based Inter-Calibration System Quarterly
Newsletter– Summer 2016 Issue
Volume 10 Number 2 2016
doi:xxx/xxxx
CMA • CNES • EUMETSAT • IMD • ISRO • JAXA • JMA • KMA • NASA • NIST • NOAA • ROSHYDROMET • USGS • WMO

In This Issue

Articles

Harmonisation and Recalibration: A FIDUCEP perspective
By Emma Woolliams (NPL), Jon Mittaz (NPL, UOR), Chris Merchant (UOR) and Arta Dila (NPL)

How good are GSICS References, IASI-A and AIRS
By Manik Bali (NOAA), Jonathan Mittaz (NPL) and Mitch Goldberg, NOAA

The Moon as a diagnostic tool for microwave sensors
By Martin Burgdorf, T. Lang, S. Michel, S. A. Buehler and I. Hans, Universität Hamburg.

GRUAN in the service of GSICS: Using reference ground-based profile measurements to provide traceable radiance calibration for space-based radiometers
By Jordis Tradowsky, Greg Bodeker (Bodeker Scientific), Peter Thorne (Maynooth University), Fabien Carminati (Met Office) and William Bell (Met Office)

A drawback of solar Diffuser in RSB Calibration
By Junqiang Sun and Mike Chu, NOAA

News in This Quarter

Highlights of the 2016 GSICS Executive Panel Meeting held in Biot, France
By Kenneth Holmlund (EUMETSAT)

Summary Report on the CEOS/WGCV-GSICS microwave subgroups joint meeting held at Beijing, China from July

AIRS ATMOSPHERIC INFRARED SOUNDER

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Harmonization and Recalibration: A FIDUCEO perspective

By Emma Woolliams (National Physical Laboratory (NPL), UK), Jon Mittaz (NPL and University of Reading (UOR)), Chris Merchant (UOR) and Arta Dilo (NPL)

Obtaining information about long-term environmental and climate trends requires the analysis of decadal-scale time series of observations made by different sensors. To ensure that such, comparisons are meaningful, it is essential to quantify the stability of satellite sensors and to determine the radiometric differences between sensors and the uncertainties associated with those differences.

This paper describes the principles adopted within the Fidelity and uncertainty in climate data records from Earth Observations (FIDUCEO) project

derived geophysical datasets, i.e. five important Climate Data Records (CDRs).
One important aspect of the work of

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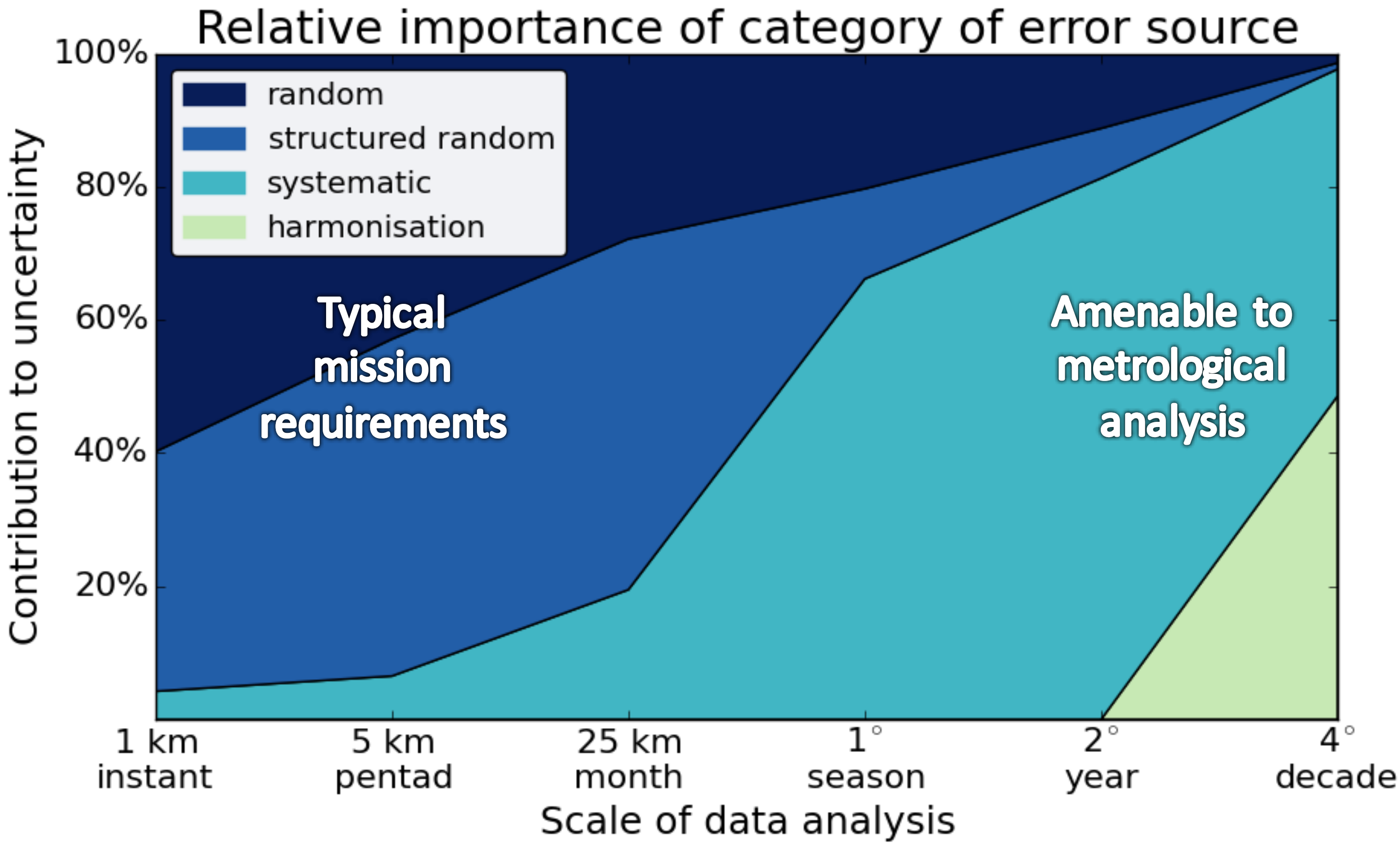
Why consider **all** sources of uncertainty?



If you compare two measurements on different space-time scales the dominant sources of uncertainty in that difference change.

See blog article http://www.fiduceo.eu/node/237

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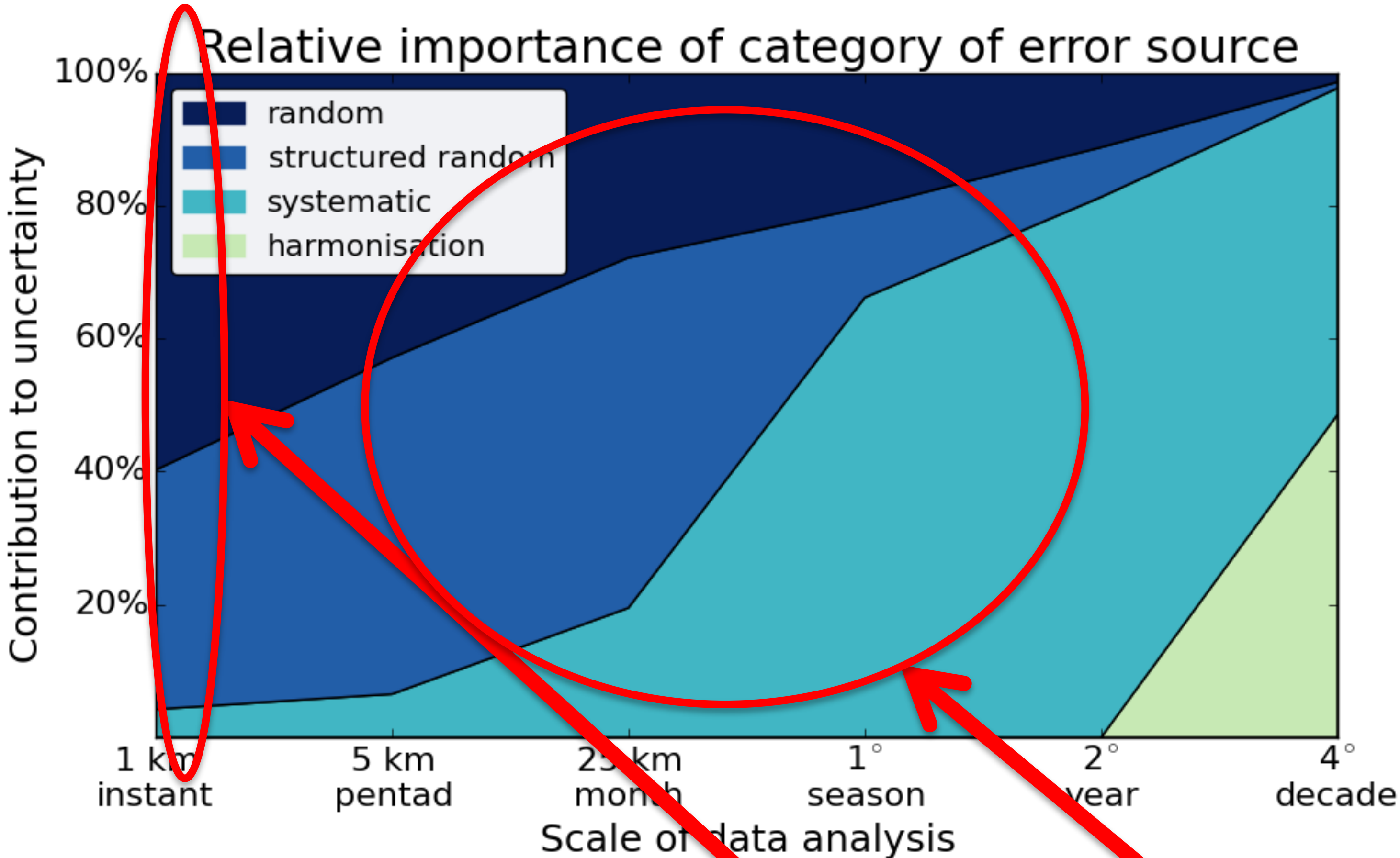

Specifying an "accuracy" target here ...

... only weakly constrains the requirement here

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OUTCOMES?

Products

DATASET	NATURE	USE
AVHRR FCDR	Harmonised infra-red radiances and best available reflectance radiances, 1982 - 2016	SST, LSWT, aerosol, LST, phenology, cloud properties, surface reflectance …
HIRS FCDR	Harmonised infra-red radiances, 1982 - 2016	Atmospheric humidity, NWP re-analysis, stratospheric aerosol …
MW Sounder FCDR	Harmonised microwave BTs for AMSU-B and equivalent channels, 1992 – 2016	Atmospheric humidity, NWP re-analysis …
Meteosat VIS FCDR	Improved visible spectral response functions and radiance 1982 to 2016	Albedo, aerosol, NWP re-analysis, cloud, wind motion vectors,…

DATASET	NATURE	USE
Surface Temperature CDRs	**Ensemble** SST and lake surface water temperature	Most of climate science … model evaluation, re-analysis, derived/synthesis products ..
UTH CDR	From HIRS and MW, 1992 - 2016	Sensitive climate change metric, re-analysis …
Albedo and aerosol CDRs	From M5 – 7 (1995 – 2006)	Climate forcing and change, health …
Aerosol CDR	2002-2012 aerosol for Europe and Africa from AVHRR	Climate forcing and change, health …

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But what is new about the data?

- Harmonised
  - Reconciled so that the differences between sensors are what we expect from known differences between instruments
  - This is a precursor for building a stable CDR from an FCDR
- Improved in other ways
  - Various insights for different sensors allows new corrections and quality control to be applied

But what is new about the data?

- Uncertainty-quantified FCDR
  - At all data set scales (from pixel level in product through to multi-annual stability) there is sufficient quantification of uncertainty to propagate uncertainty across all data transformations accounting for error correlation structures
- Uncertainty-quantified CDR
  - Uncertainty information in product that (i) discriminates more and less certain data, (ii) is validated as being realistic in magnitude, (iii) is traceable back to the FCDR uncertainty information

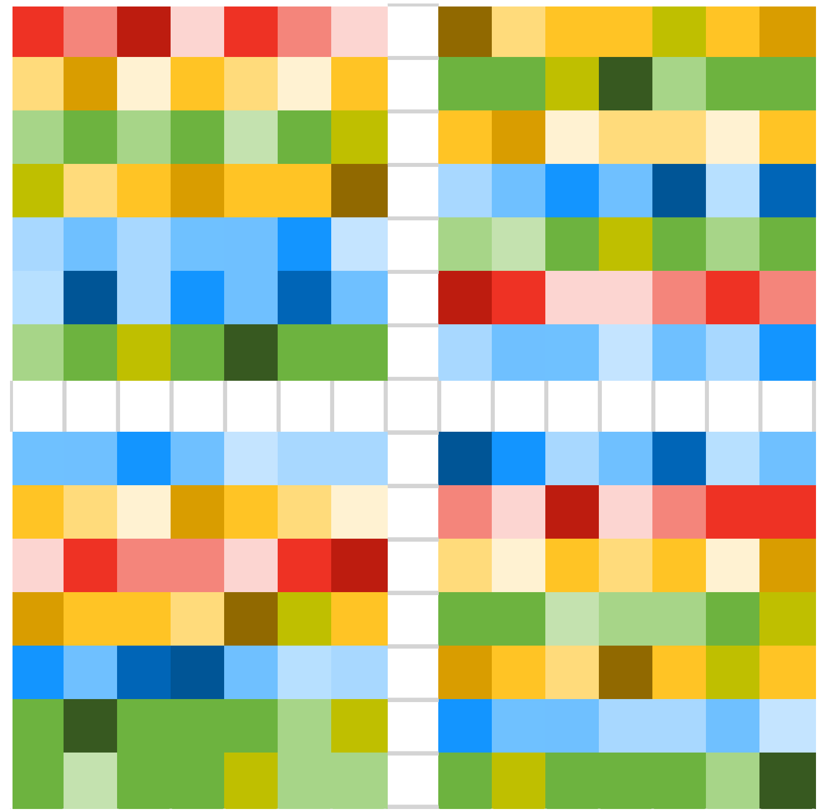
Two ways to share FCDR

- Uncertainty data by correlation structure

$$
\begin{aligned}
u^2\left(R_{\mathrm{E},ijk}\right) = {} & c_{a_0}^2 u^2\left(a_0\right) + c_{C_{\mathrm{E},ijk}}^2 u^2\left(C_{\mathrm{E},ijk}\right) \\
& + c_{R_{\mathrm{ICT},jk}}^2 u^2\left(R_{\mathrm{ICT},jk}\right) \\
& + c_{\delta R_{\mathrm{ICT},0}}^2 u^2\left(\delta R_{\mathrm{ICT},0}\right) \\
& + c_{\delta R_{\mathrm{ICT},0,\mathrm{grad},jk}}^2 u^2\left(\delta R_{\mathrm{ICT},0,\mathrm{grad},jk}\right) \\
& + c_{C_{\mathrm{ICT},jk}}^2 u^2\left(C_{\mathrm{ICT},jk}\right)
\end{aligned}
$$

Correlation structure	Sources of uncertainty with this correlation structure
Totally random	$C_{\mathrm{E},ijk}$
Totally systematic	a_0, $\delta R_{\mathrm{ICT},0}$
Structured random: 51 scan lines	$R_{\mathrm{ICT},jk}$, $C_{\mathrm{ICT},jk}$
Structured random: random walk	$\delta R_{\mathrm{ICT},0,\mathrm{grad},jk}$

- Ensemble of realisations



Exemplar, tools, cookbook

- Standardised exemplars for
  - traceability diagrams
  - effects tables
  - documented (traceable) uncertainty
- Tools that can be re-used
  - adapted-Allan variance tool
  - error-instance generator
  - regridding uncertainty propagation with structured errors
- Above and methodology gather in "cookbooks"

Influence

- A future in which
  - **every FCDR has pixel-level uncertainty** (error covariance) information …
  - … based on measurement-equation-centred analysis ***as routine part of mission development***
  - CDR producers also undertake measurement-equation-centred analysis …
  - ... and propagate **uncertainties in CDR products at all spatio-temporal scales**
  - climate **scientists believe and exploit** the uncertainty information in climate data sets
  - **decision makers are informed** of uncertainty in climate information, and trust it is traceable

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Summary and conclusion

- Essence of method:
  - measurement-equation + harmonisation + propagation
- Records across sensor families with improved
  - transparency
  - scientific rigour/integrity
  - applicability to climate
  - estimates of uncertainty
  - stability and consistency
- … and containing better data for science and applications
- Metrological practice
  - brings conceptual clarity and rigorous expert tools
  - requires extension to address new EO-specific challenges

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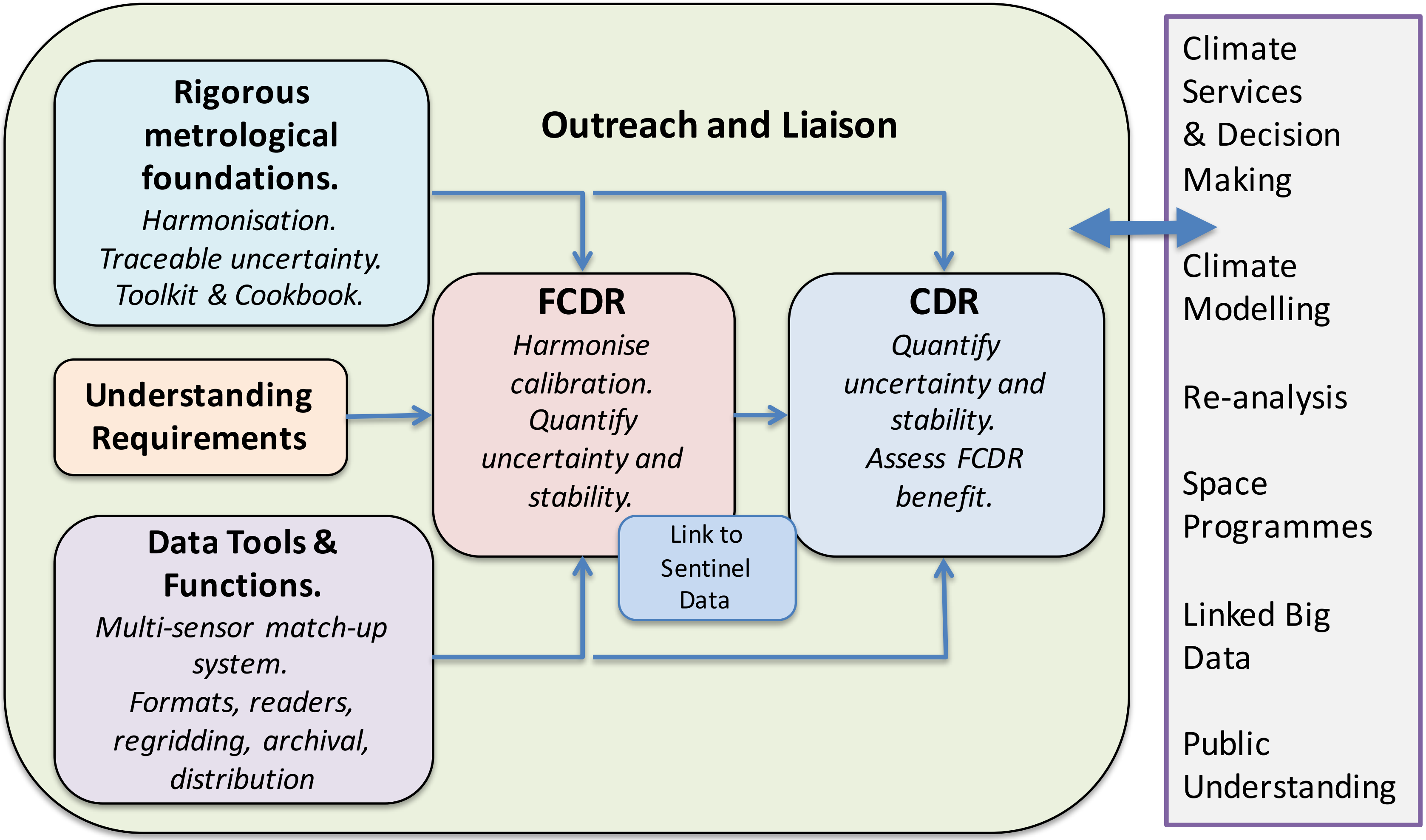
EXTRA SLIDES WITH FURTHER ILLUSTRATIONS AND POINTS FOR POTENTIAL DISCUSSION …



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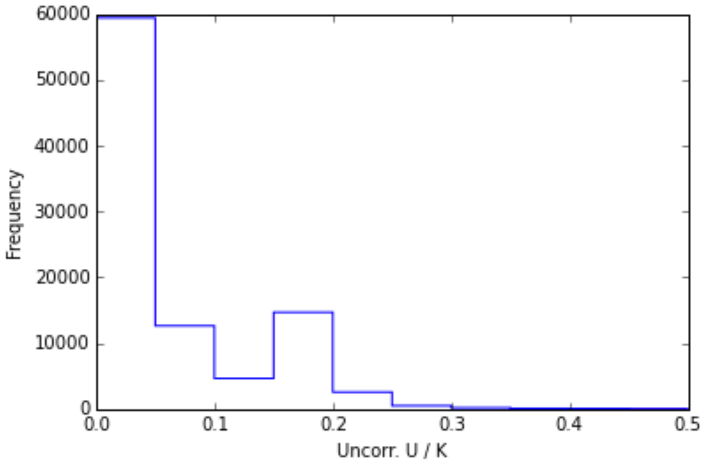
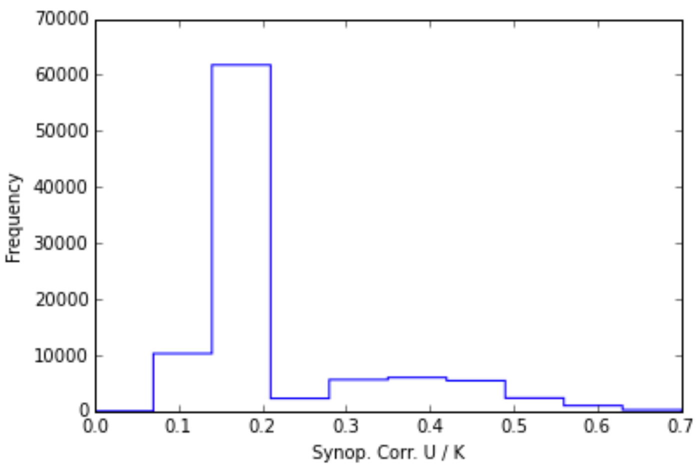
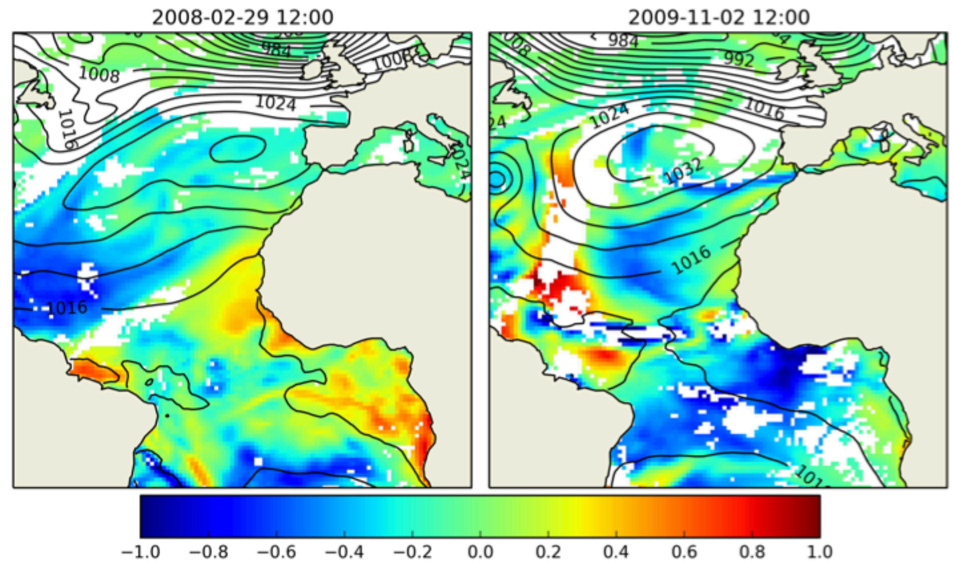
Structured random effects in CCI sea surface temperature

Distribution of noise-related uncertainty

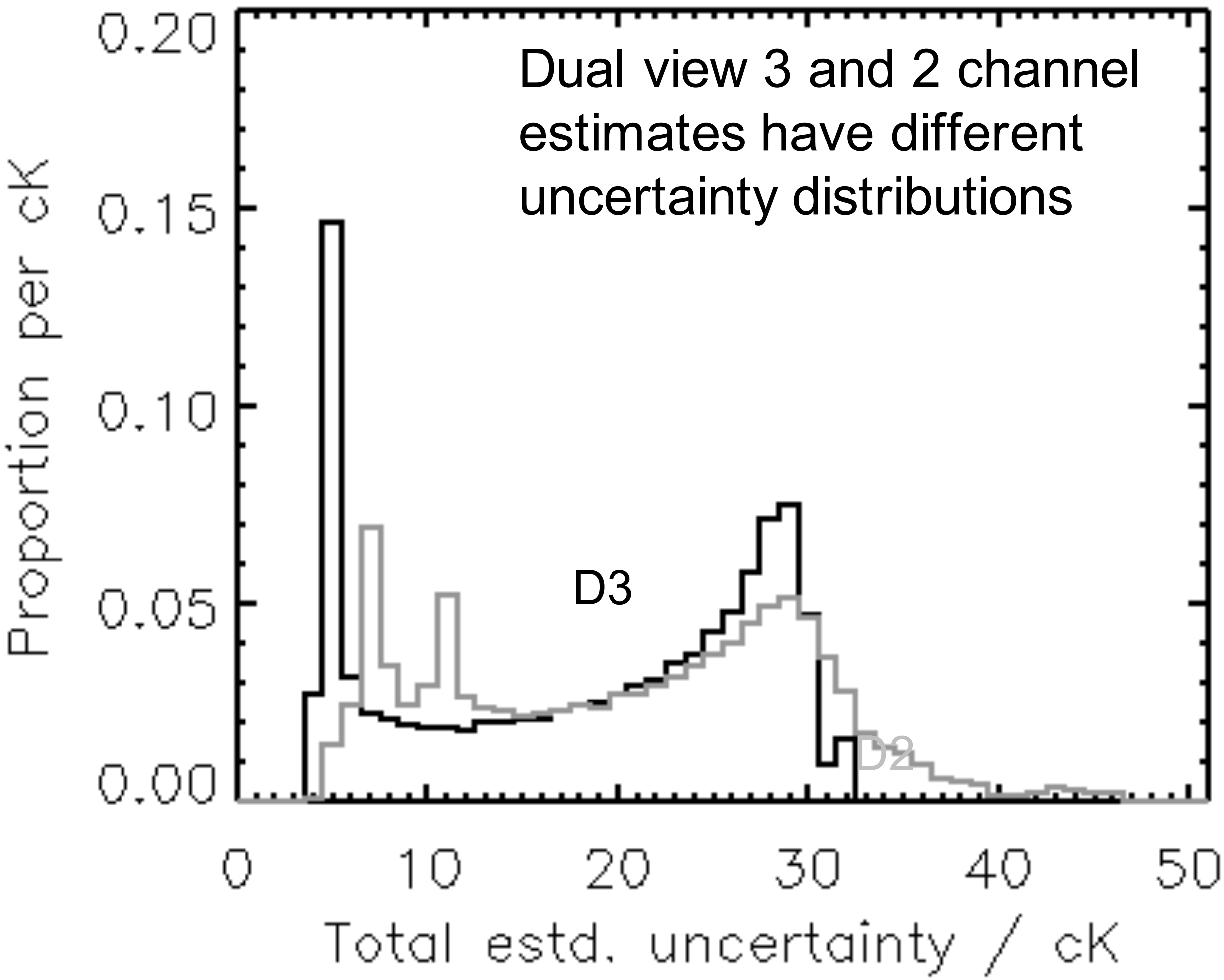


Distribution of retrieval uncertainty

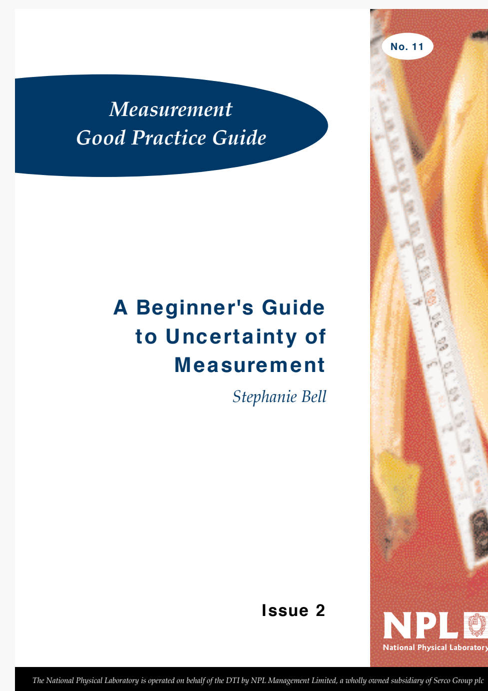




Optical Radiometry for Ocean Climate Measurements (EMPS Vol 47) Chapter 4.3


Dual view 3 and 2 channel estimates have different uncertainty distributions
D3
D2
Proportion per cK
0.20
0.15
0.10
0.05
0.00
0
10
20
30
40
50
Total estd. uncertainty / cK

GUM is recommended



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

Two definitions

- Error
  - Concept: How different is the measured value from the (unknown) true value of the measurand?
  - “WRONGNESS”
- Uncertainty
  - Concept: Given the measured value, what range of values is it reasonable to attribute to the measurand?
  - “DOUBTFULNESS”
- These are the correct scientific definitions and also match the usage of normal people
- Only (ill-informed!) scientists write things like “the error in this value is +/-X” and think it makes sense

More terms

- **Standard uncertainty** – usual quantification of uncertainty as standard deviation of the estimated distribution from which errors are drawn
- **(Independent) Random effect** – a source of errors that are uncorrelated between repeated measured values
  - note: errors can be random (uncorrelated); uncertainty cannot be random (or systematic)
- **Systematic effect** – a source of correlated errors that you could correct for if you understood it
  - note: this is a broader definition than just bias
- **Structured random effect** -- still can never correct for this, but nonetheless has predictable patterns or scales of correlation

The Law of Propagation of Uncertainties (GUM)

NPL National Physical Laboratory

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

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:

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

Alternatively, Monte Carlo Analysis

How should uncertainty be presented?

"Separate out main components of uncertainty" (20%)

"Just give me one number" (60%)

Total uncertainty (35%)
Confidence interval (25%)

"A probability distribution of error would be nice." (15%)

"Ensemble, please." (5%)

Result of SST CCI User Survey, 2010

How should uncertainty be presented?

“Ensemble, please.”

Significant request from major users at SST CCI user consultation in 2014 (after discussing uncertainty concepts and issues for two days)

Quantify each error source

- Magnitude of uncertainty at parameter level
- Correlation structure of errors
  - between elements
  - between lines (over time)
  - between measurement equation parameters
  - between spectral bands
- Propagate parameter-uncertainty to radiance uncertainty

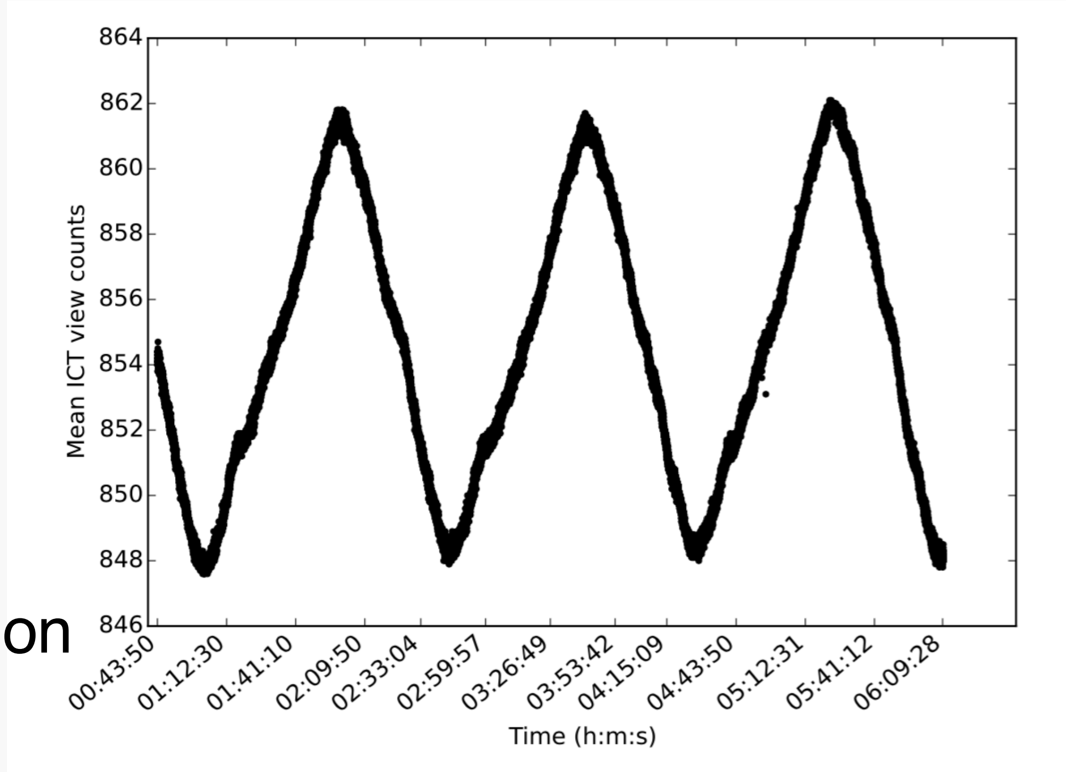
Example: AVHRR noise estimation

Generally quoted as "0.12 K" NEDT

Can look at NEDT on internal calibration target (ICT)

Counts standard deviation

But non-stationary



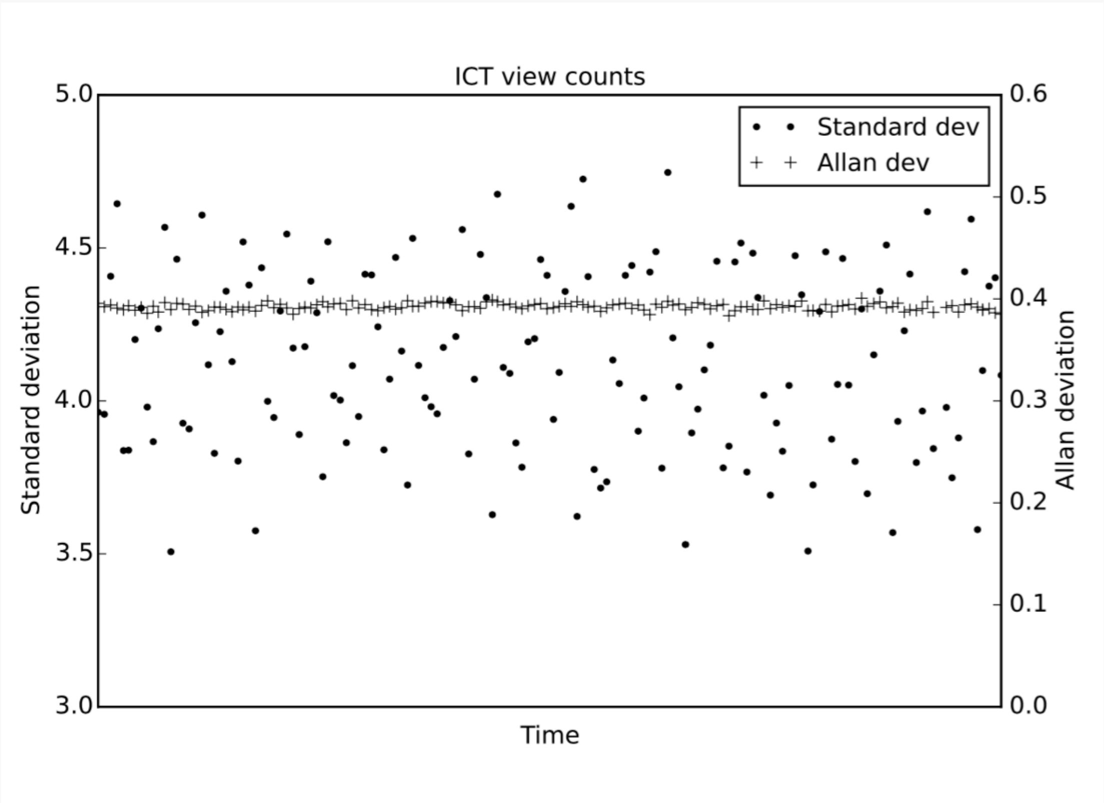
Three orbits of AVHRR ICT counts, NOAA-19

Example: AVHRR noise estimation

Generally quoted as “0.12 K” NEDT

Metrologists use Allan variances to analyse noise in non-stationary series

True NEDT ~O(0.05 K)



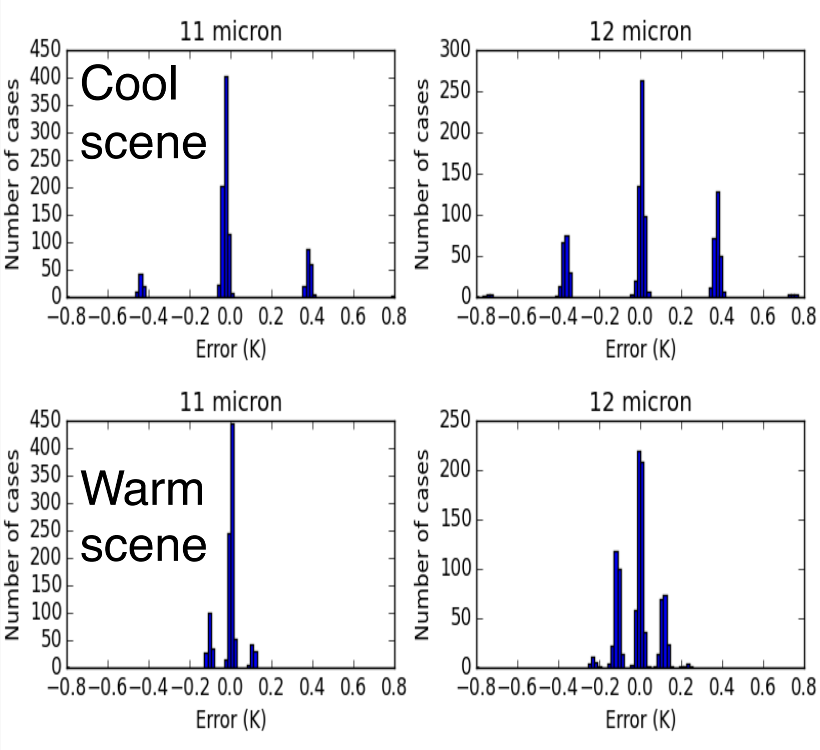
Counts standard deviation, calculated two ways

Error correlation structures

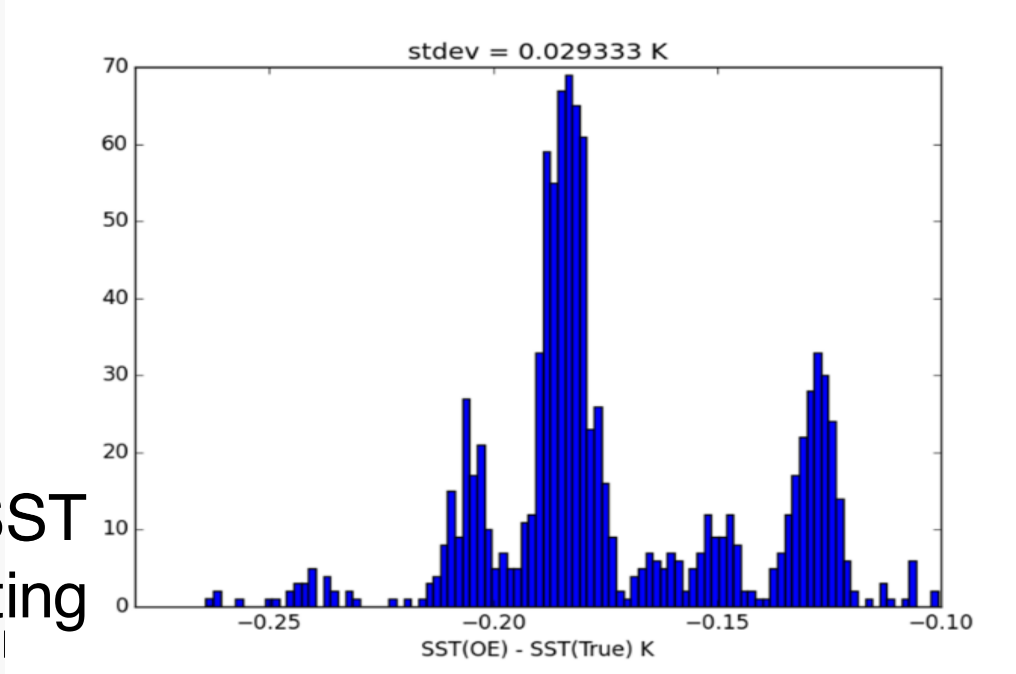
- Pixel noise: independent **random error**
- Many errors are more complex and have a **structured random** or **systematic** form
- Systematic error ≠ bias
- Noise in the calibration cycle produces a structured random error

Propagate to radiance uncertainty (error c

- Analytically or by Monte Carlo simulation



Error distribution in brightness temperatures



Distribution of SST errors resulting