FIDUCEO has received funding from the European Union's
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Traceability and Uncertainty

Lessons learned from FIDUCEO and relevance to ESA-SPPA activities

Merchant, Mittaz, Woolliams, Fox and
many FIDUCEO colleagues

FIDUCEO

- **Ambition**: develop a widely applicable **metrology of Earth observation (EO)**

- **Motivation:** establish **traceable, uncertainty-quantified evidence** for climate and environmental change from space assets

- Project runs March 2015 to February 2019

www.fiduceo.eu

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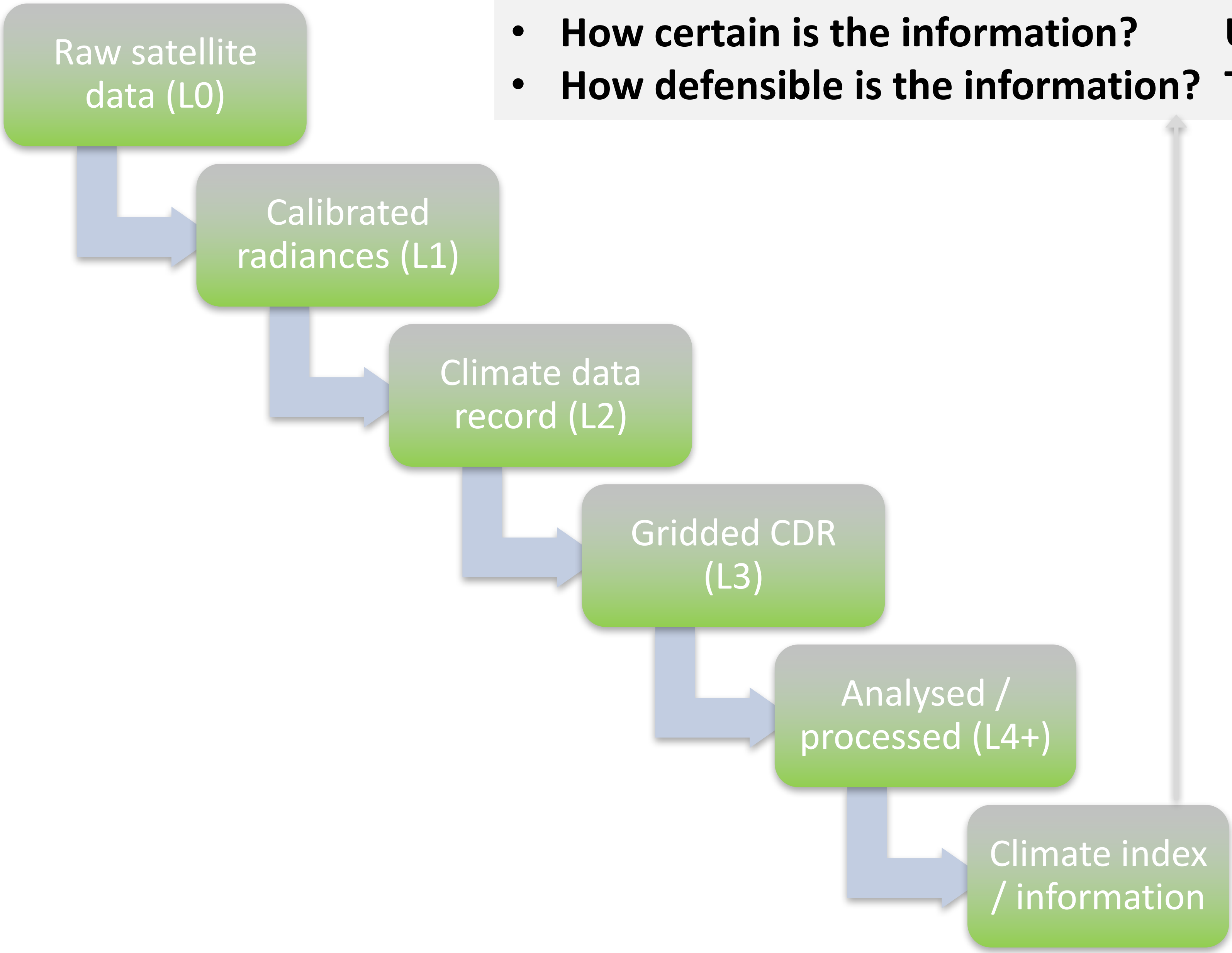
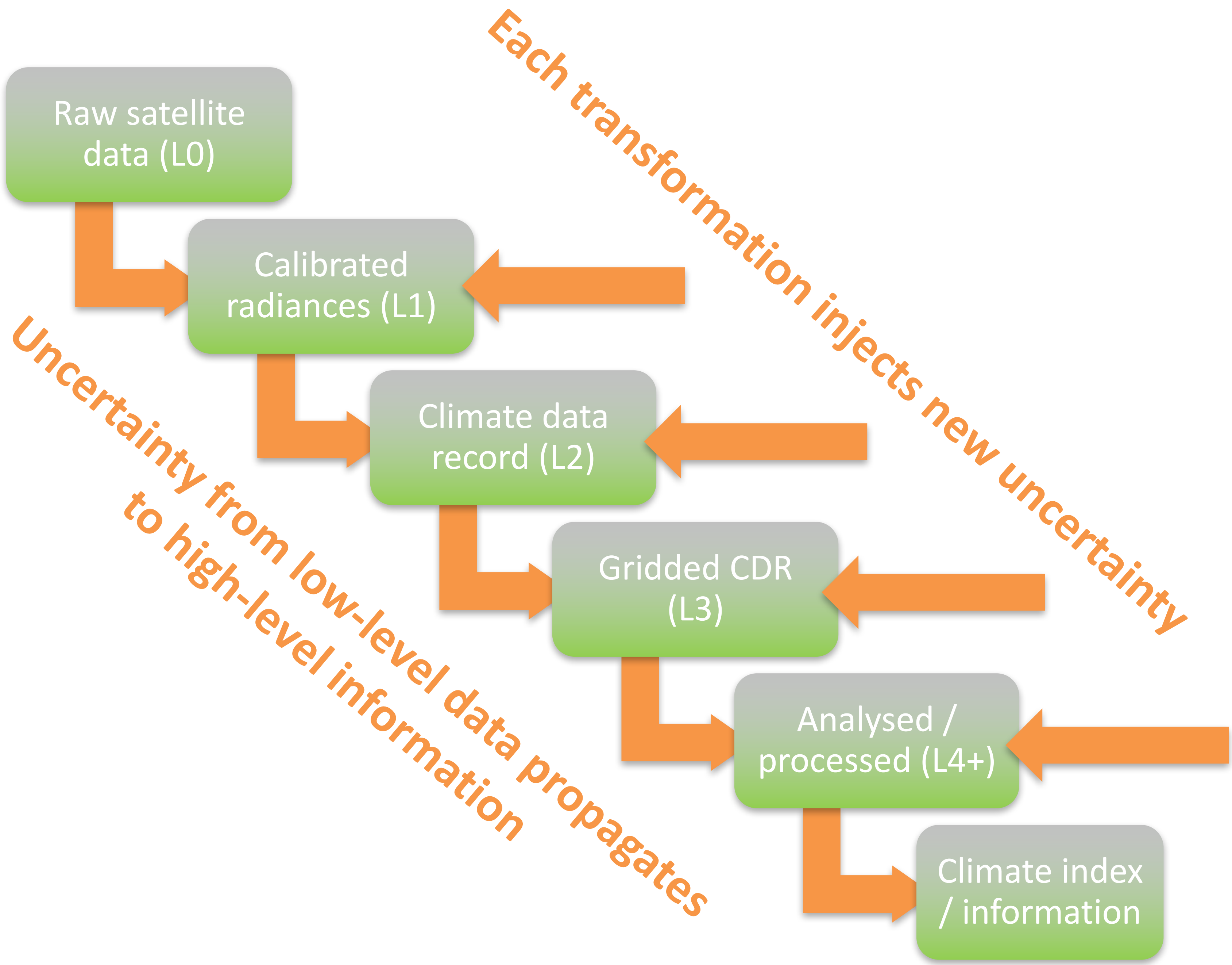
Why *metrology* of EO?

- Adopting language and tools of measurement science brings
  - conceptual clarity
  - rigorous practice
  - well-tested tools
  - better climate data records
- But the process is also *extending* the discipline of metrology in some ways
  - EO raises aspects not present in the laboratory

- **How certain is the information? Uncertainty**
- **How defensible is the information? Traceability**



- Decision
- Insurance
- Liability



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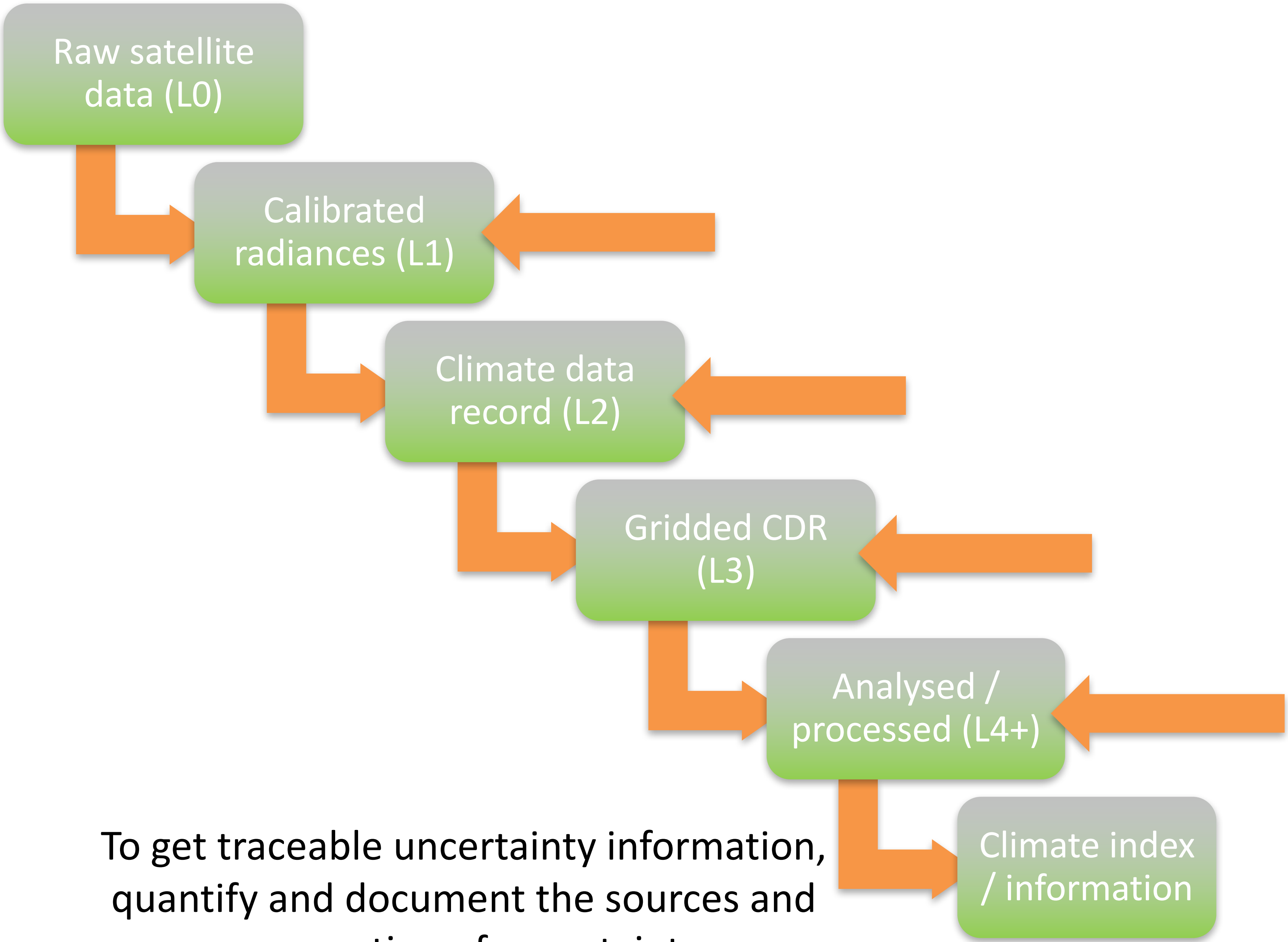

To get traceable uncertainty information, quantify and document the sources and propagation of uncertainty

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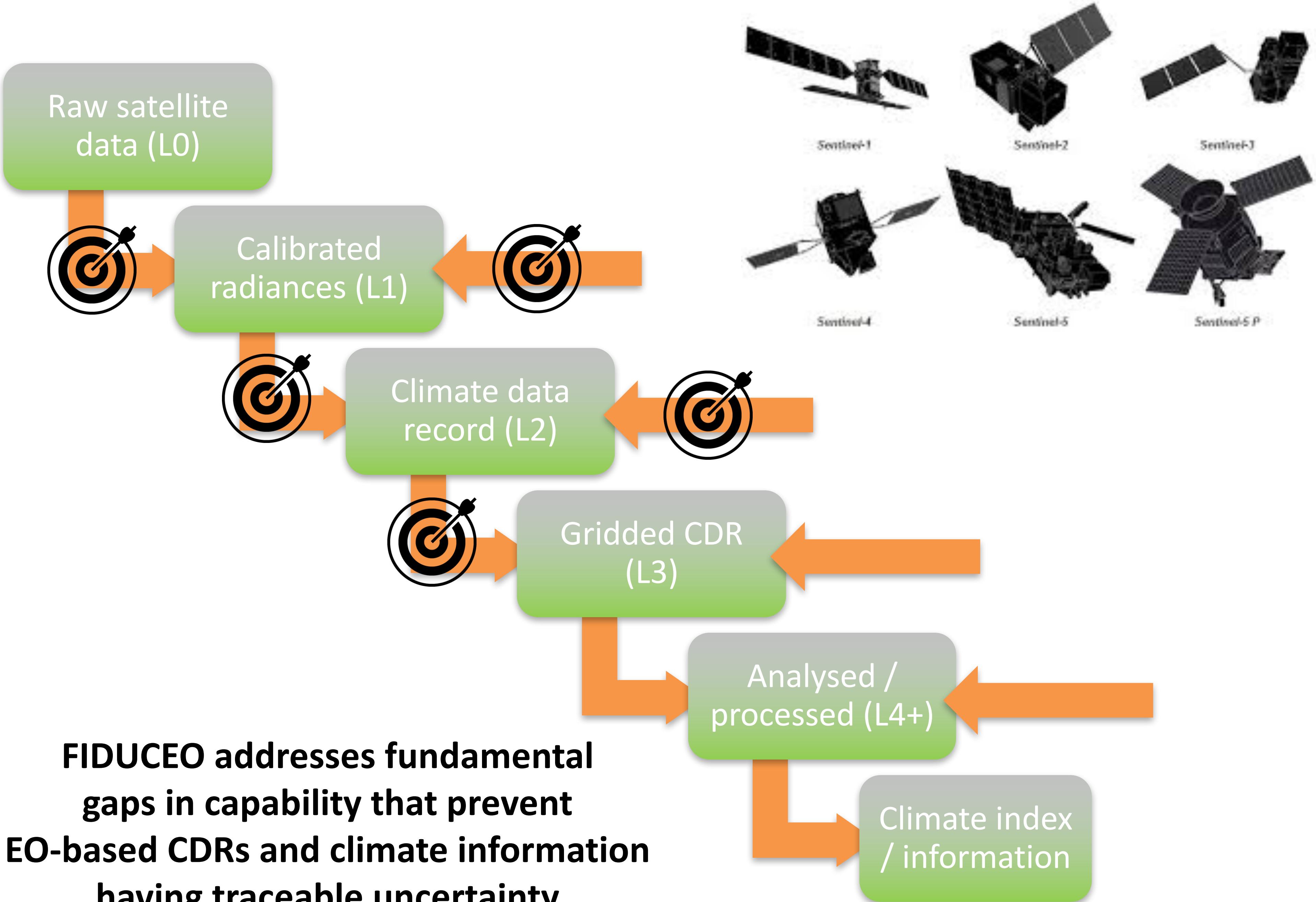

FIDUCEO addresses fundamental gaps in capability that prevent EO-based CDRs and climate information having traceable uncertainty

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FIDUCEO core concepts

Dissemination to users of traceable,
per-datum uncertainty information in level 1 (FCDR)

Harmonisation of FCDR radiances

Propagation of FCDR uncertainty to
uncertainty-quantified higher-level products (CDRs)

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FIDUCEO FCDRs (L1)

FCDR: fundamental climate data record (calibrated radiances)
from which climate data can be derived

DATASET	NATURE	POSSIBLE USES
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,…

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FIDUCEO CDRs (L2/L3)

CDR: climate data record, the evidence base for high-level climate information and services

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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FCDR Uncertainty

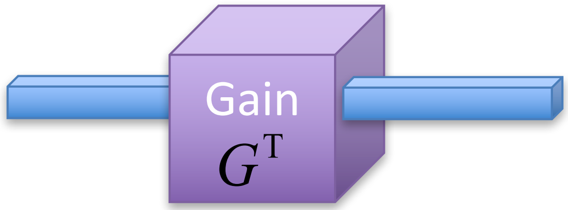
- Understand the **measurement equation**
- Quantify the **sources of error** (effects)
- Quantify their **error structures**
- Propagate to get radiance **uncertainty**

- **Structured approach centred on measurement equation**

Measurement equation

The equation used to calculated “calibrated radiance” in the FCDR

True signal C_E^T



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

TOA Earth Radiance R_E^T

Measured Signal

$$C_E^M = G^T R_E^T + \delta C_E$$

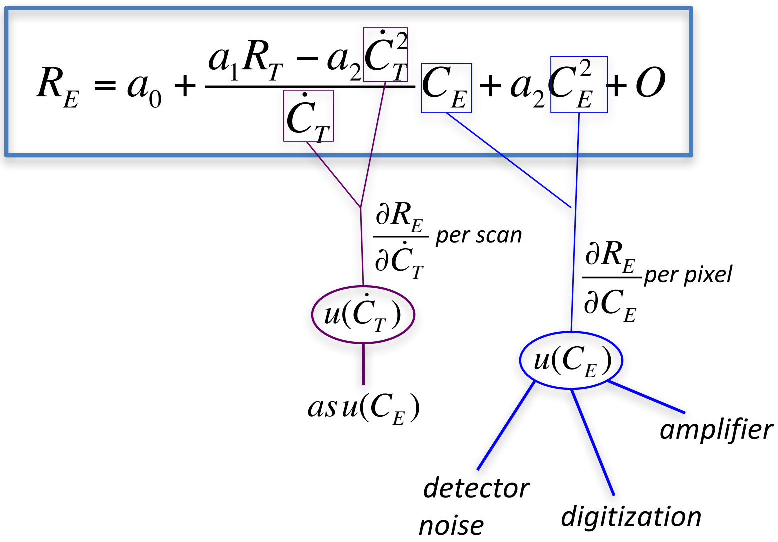
Measured gain

$$G^M = G^T + \delta G^T$$

Measured Earth Radiance

$$R_E^M = \frac{C_E^M}{G^M}$$

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


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

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Capture in an effects table

		Value / Expression	Notes
Name of effect			
Affected term in measurement function			
Channels / bands			
1. Correlation type and form	within scanline [pixels]		
	from scanline to scanline [scanlines]		
	between images/orbits [orbits]		
	Across time [appropriate time units e.g. days, months, years]		
	between channels / bands		
1. Correlation scale	within scanline [pixels]		
	from scanline to scanline [scanlines]		
	between images/orbits [orbits]		
	Across time		
	between channels / bands		
Uncertainty PDF shape			
Uncertainty units			
Uncertainty magnitude			
Sensitivity coefficient			

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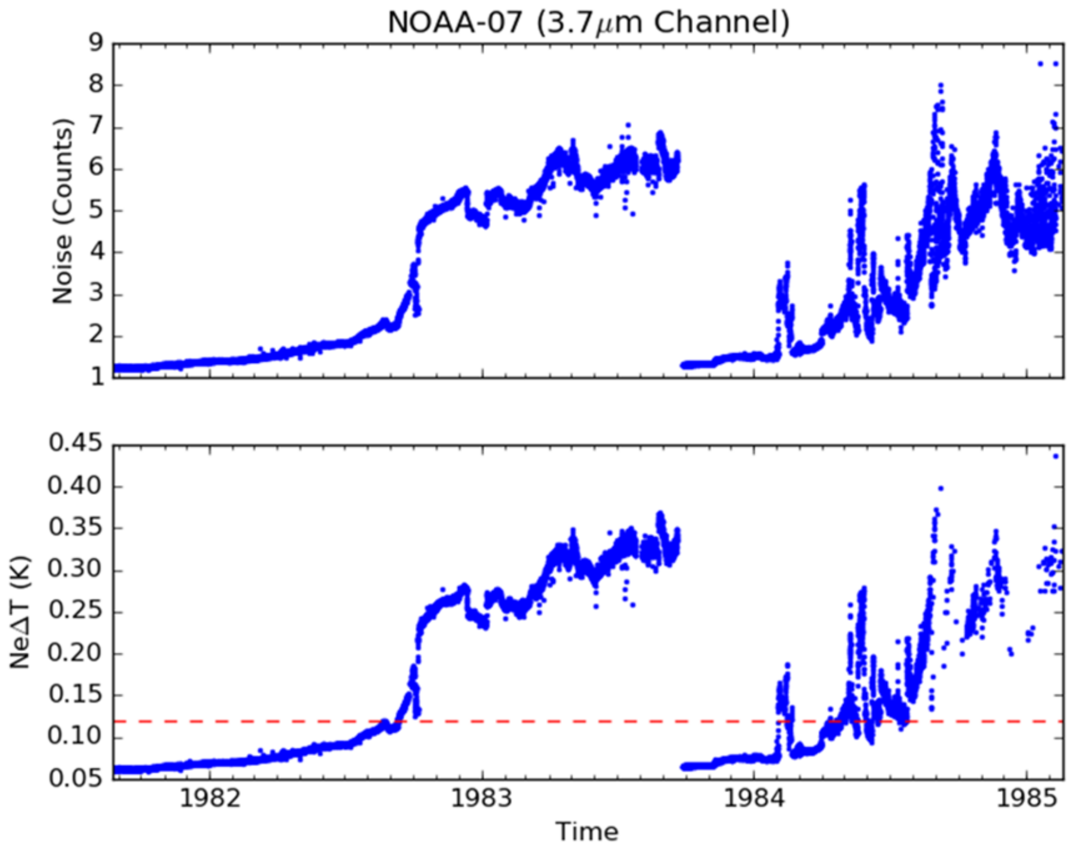
Need evidence of noise components for ‘twigs’

- Even the noise at the counts level can be surprisingly complex



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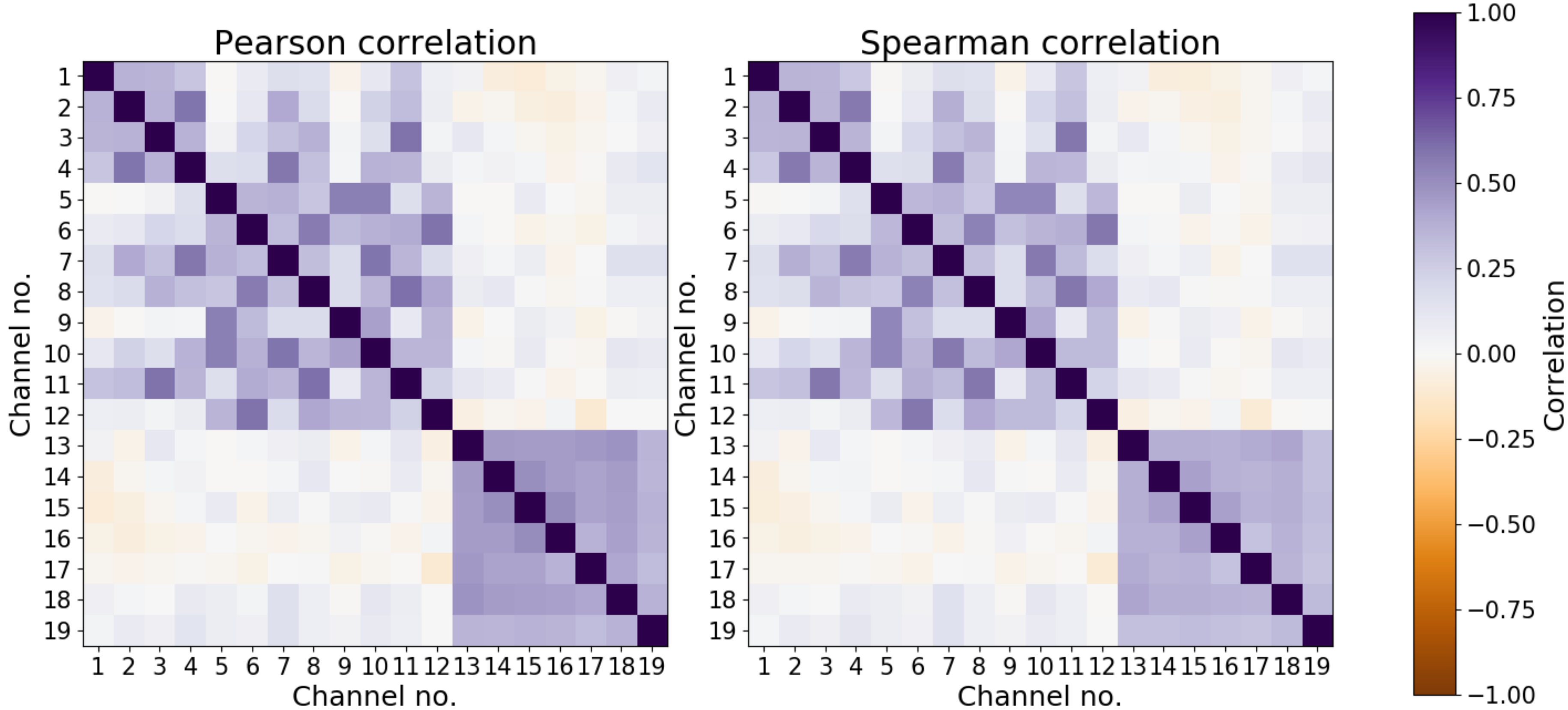
Must consider correlated effects

- For HIRS strong correlations in noise between channels



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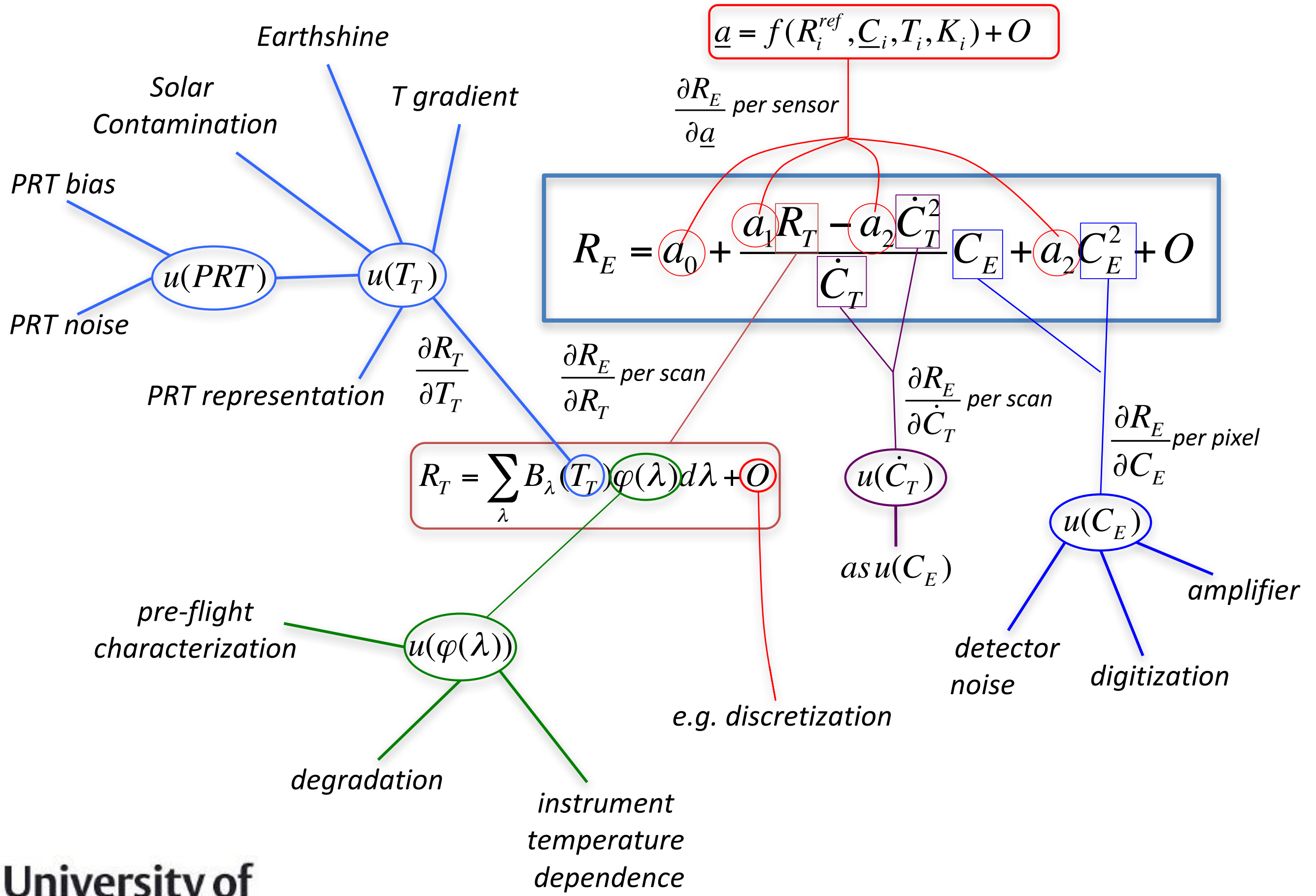
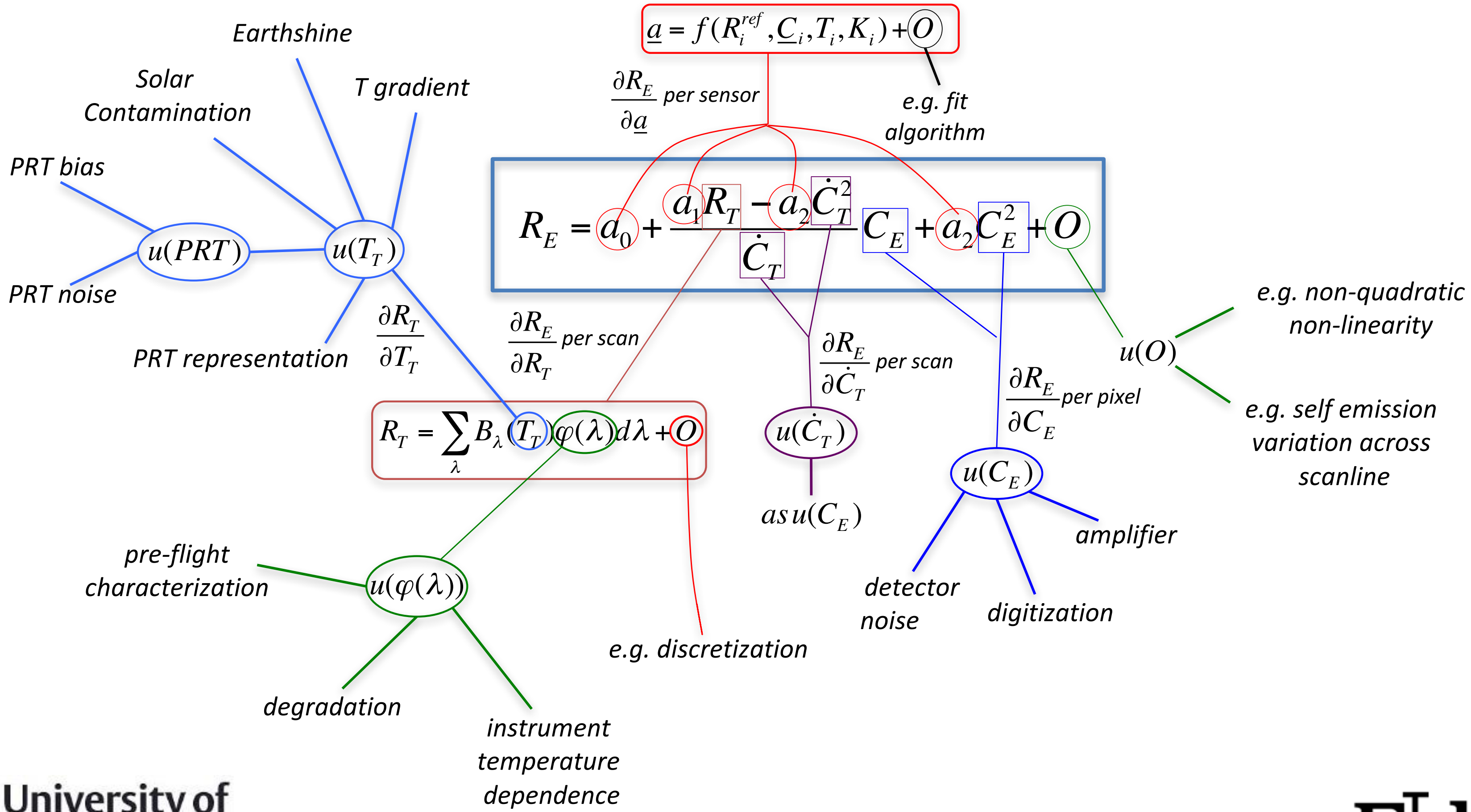


$\underline{a} = f(R_i^{ref}, \underline{C}_i, T_i, K_i) + O$
$\frac{\partial R_E}{\partial \underline{a}}$ per sensor
$R_E = a_0 + \frac{a_1 R_T - a_2 \dot{C}_T^2}{\dot{C}_T} C_E + a_2 C_E^2 + O$
Earthshine
Solar Contamination
T gradient
PRT bias
PRT noise
PRT representation
$u(PRT)$
$u(T_T)$
$\frac{\partial R_T}{\partial T_T}$
$\frac{\partial R_E}{\partial R_T}$ 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
$u(\varphi(\lambda))$
degradation
instrument temperature dependence
e.g. discretization



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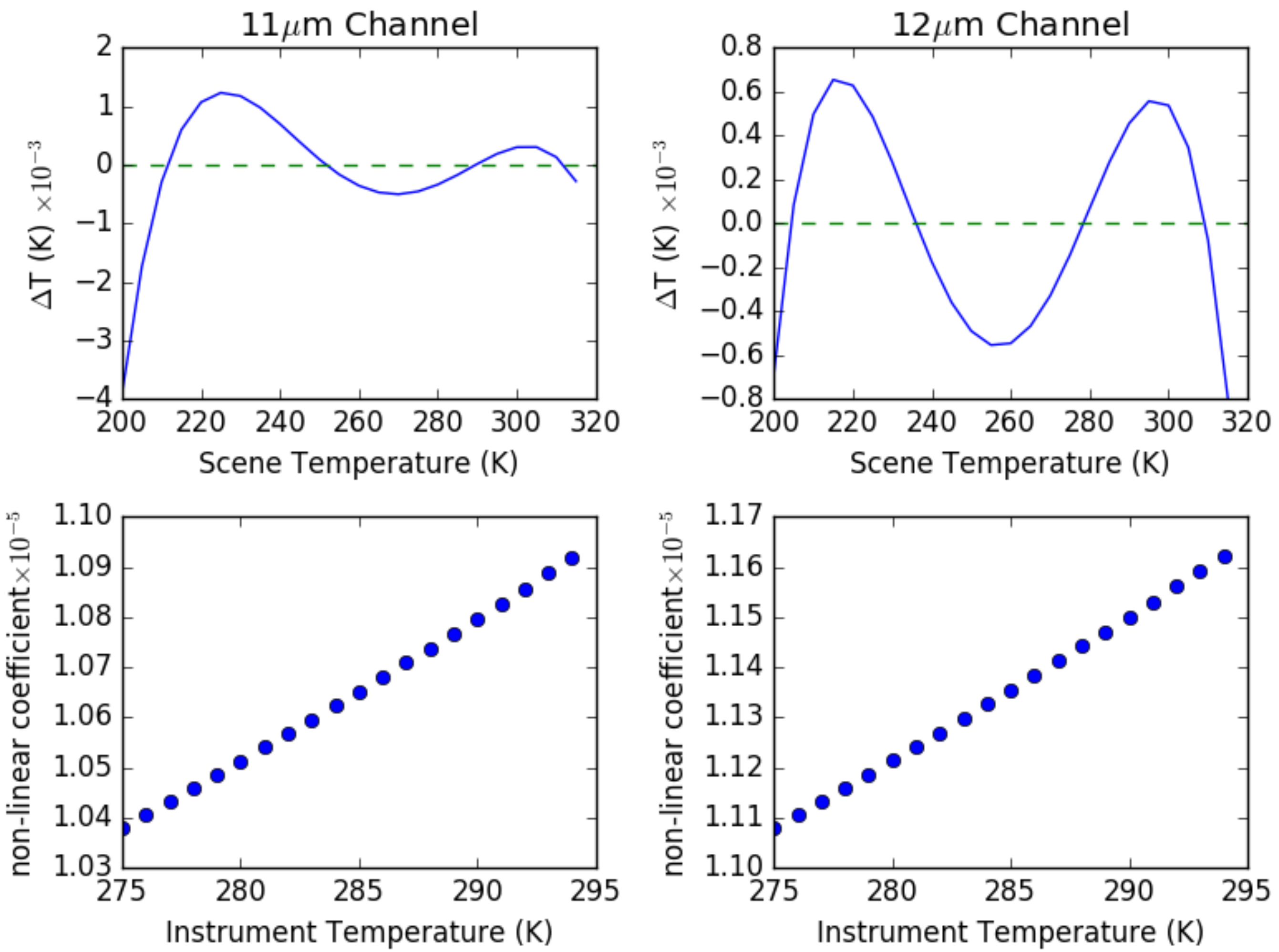
"+O": beyond quadratic

- Detailed model of detector physics (Auger, etc)
- Shows quadratic expression is an approximation (upper plots)
- Lower plots show that the quadratic coefficient isn't constant with instrument temperature either



(data based on numerical model of HgCdTe detector)

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Note for traceability need some kind of estimate for all possible effects even for things we don't have a good measure of…

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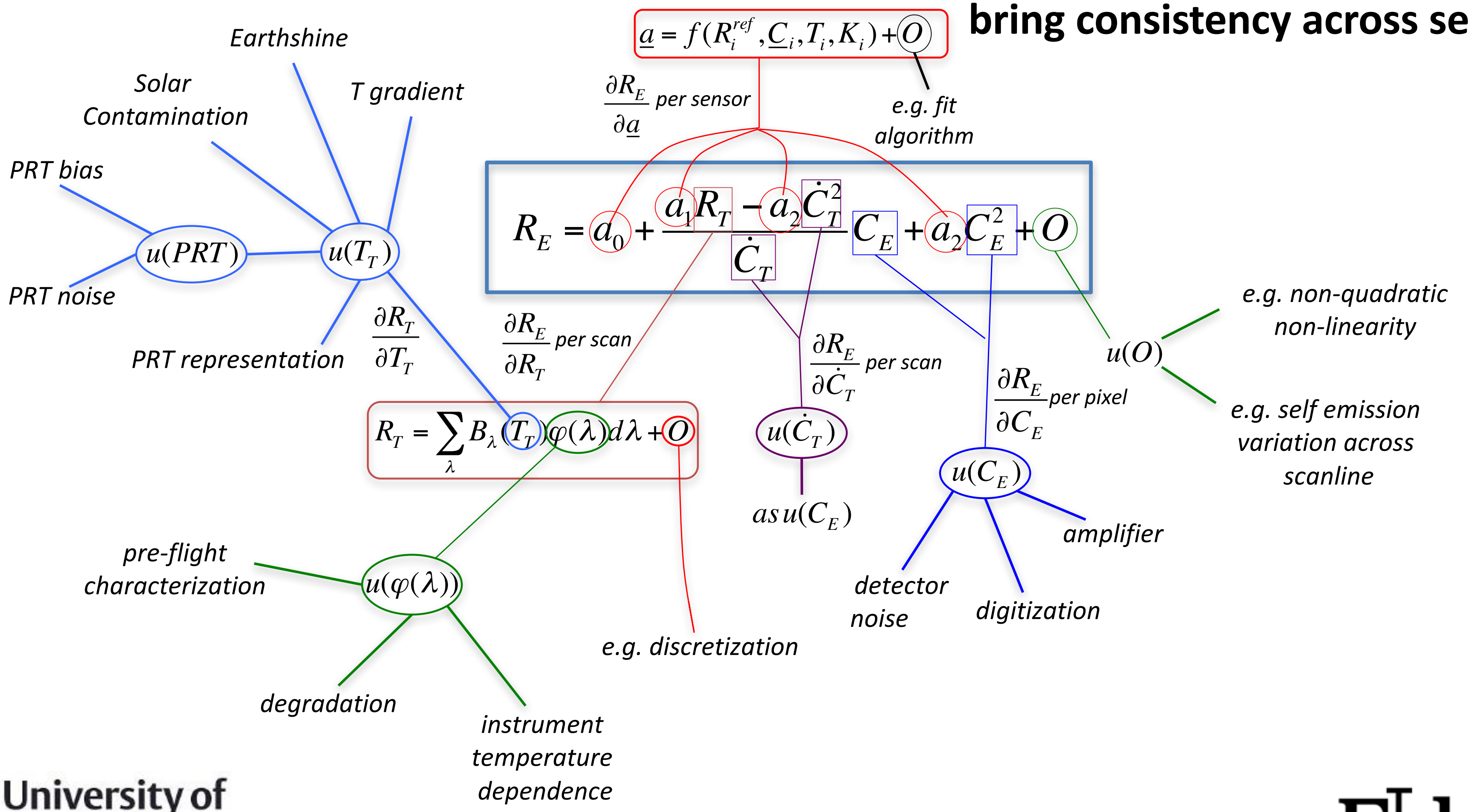
Traceable uncertainty

- Traceability diagram, measurement centred
  - to organise
  - to document
- Branching structure reflects the nature of the problem
- Standardised "effects table" per "twig"
  - systematic documentation
  - this is codified into a full FCDR format
- Same for deriving higher-order products (CDRs)
  - uncertainty from L1 is simply one of the effects in L2

Harmonisation

Recalibration of parameters in measurement equation to bring consistency across sensors



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GSICS Global Space-based Inter-Calibration System

Quarterly

Newsletter– Summer 2016 Issue

2016

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Manik Bali, Editor

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In This Issue

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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 for harmonising satellite data series to obtain long-term stability. The FIDUCEO project aims to develop metrologically-robust Fundamental Climate Data Records (FCDR), i.e. long-term records of satellite L1 products (top-of-atmosphere radiance, reflectance and brightness temperature). These FCDRs will have not only uncertainty information at the pixel level, but also information about the correlation structure of the associated errors. In the second half of the FIDUCEO project we will demonstrate how to propagate this information to derived geophysical datasets, i.e. Climate Data Records (CDRs) for four ECVs. One important aspect of the work of FIDUCEO is to harmonise the data series. The aim of harmonisation is to establish long-term stability in the data record.

Most sensors are calibrated prelaunch, where *calibration* means establishing the basic model (measurement equation) for translating a measured signal (e.g. in counts) into the required measurand (e.g. radiance). However, this model may also make allowance for in-orbit factors; for example, it may account for gain changes of the instrument throughout the orbit due to variations in self emission by using

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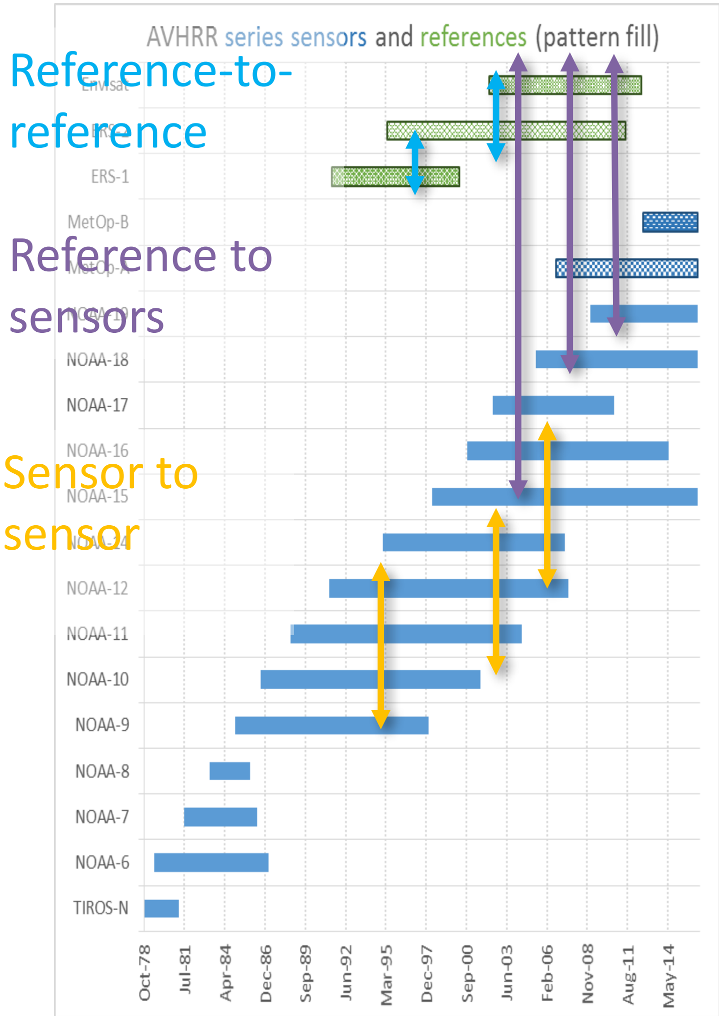
Match-ups for ATSR/AVHRR harmonisation



- Reference radiance, or sensor-to-sensor
- Many (50 million +) matched pairs
- Correlated errors
- Tools for solving now in advance stage of development

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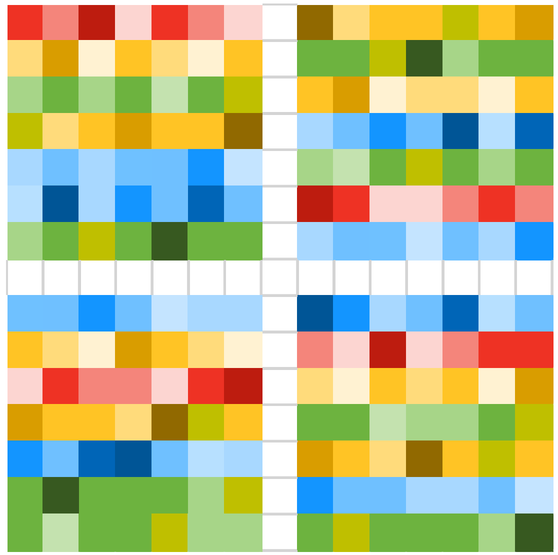
Aim / Method	Bias Correction	Recalibration
Respect satellite SRF differences while reconciling calibration	GSCIS definition for ”sensor equivalent calibration”	**FIDUCEO definition for “harmonisation”**
Adjust for SRF differences and calibration differences	GSICS definition for “reference sensor normalised calibration”	FIDUCEO definition for “homogenisation”

Sharing the FCDR

- Full FCDR:
  - Uncertainty data by correlation structure

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

- Ensemble of realisations



- "Easy FCDR" with guidance

independent random

combined systematic and structured random

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Use of FCDR uncertainties

- For model-observation comparisons in "observation space"
- For data assimilation
- **For proper estimation of Climate Data Record uncertainties across spatio-temporal scales**
  - **FIDUCEO exemplars – coming next year**

Aspiration

- Normal good practice is
  - **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 in climate data and use it when creating climate information
  - **decision makers are informed** of uncertainty in climate information, and have high levels of trust based on traceability

In other words

- We think the principles and techniques we are learning on the historical sensors have much wider applicability
- Particularly, they can be embedded into space agency practice for adding value by adding per-datum uncertainty to L1
  - **reprocessing of archive mission data**
  - **specification of instruments and products for future missions**

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An uncertainty/traceability focus in Phase B-D

Aspect	Compliance focus	Metrology focus
Estimating the magnitude of pixel-level uncertainty (e.g., in radiance)	Worst-case combination of uncertainty from error sources to compared against a (generally) aggregated total uncertainty requirement. Deliberately pessimistic to ensure compliance and acceptance.	Individual models/calculations of uncertainty from error sources, traceably documented per error source. Realistic combination to inform expected in-flight characteristics.
Characterising the error-correlation structure across pixels and channels	Only in response to specific relevant requirements (e.g. cross-talk limits). Not considered for many error sources.	Integral part of uncertainty characterisation for all error sources

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An uncertainty/traceability focus in Phase B-D

Aspect	Compliance focus	Metrology focus
Traceably documenting uncertainty information	Documentation focused on acceptance milestones. Results perhaps mixed with commercially sensitive and confidential material, usually not available in a form supporting traceability	Documentation freely available and organised such as to support systematic traceability
Dissemination of understanding of error sources to users	Not actively or systematically attempted -- generic information may be published. Not quantitatively integrated into satellite products	Understanding is embedded in product processing chain in order to include quantitative uncertainty information directly in satellite products at L1

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Conclusions

- FIDUCEO is ongoing, but some useful ideas, methods and tools are emerging with wider relevance. Aim is to substantially establish “Earth observation metrology”
- Part of this is **proper quantification of L1 uncertainty**, which logically is a problem owned by space agencies
- **FIDUCEO methodologies applicable to both historic and prospective missions**, and not just the FIDUCEO case studies
- Application to ESA archived missions could be foreseen
- For future missions, much of the **necessary insight into instrument errors can be gained by bringing a metrology focus to phase B-D satellite development**, ‘re-using’ the error characterisation for the benefit of users of L1
- FIDUCEO will demonstrate the utility of L1 uncertainty in deriving climate data records (starts 2018)

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