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

FIDUCEO

Fidelity and uncertainty in climate data records from Earth Observations

Chris Merchant, University of Reading

with thanks to many colleagues!

GAIA-CLIM & FIDUCEO Joint Assembly Day

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

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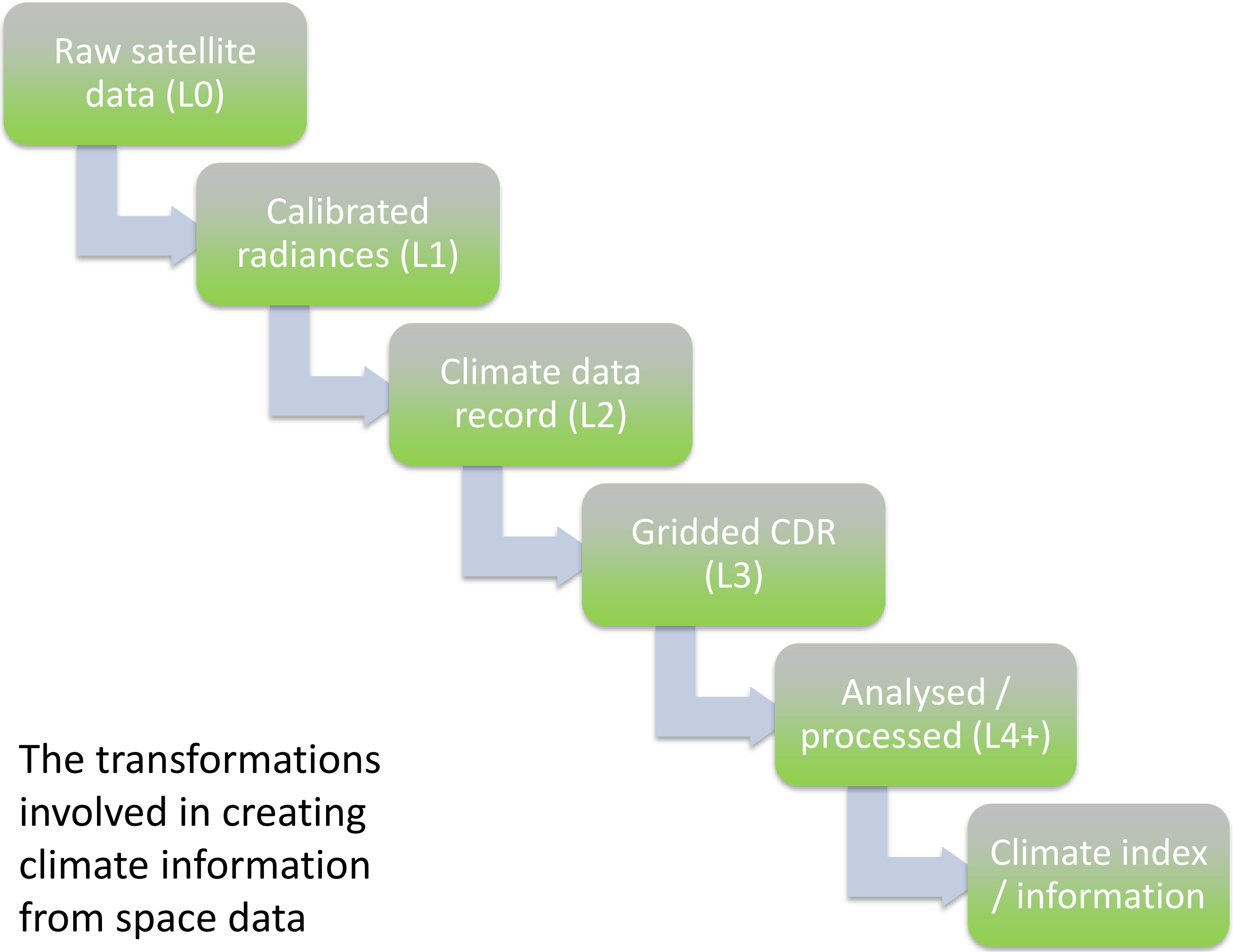

- Decision
- Insurance
- Liability

The transformations involved in creating climate information from space data

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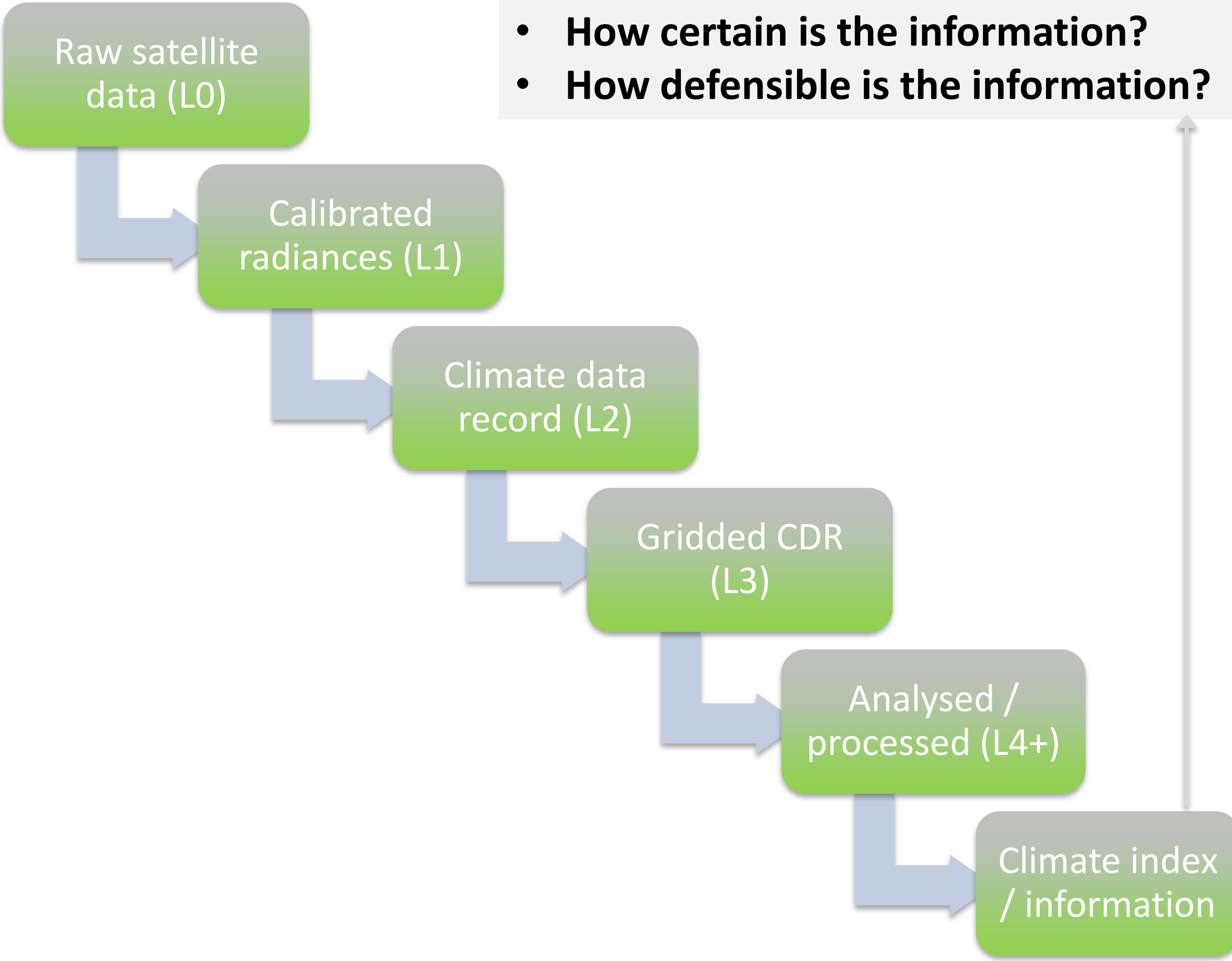
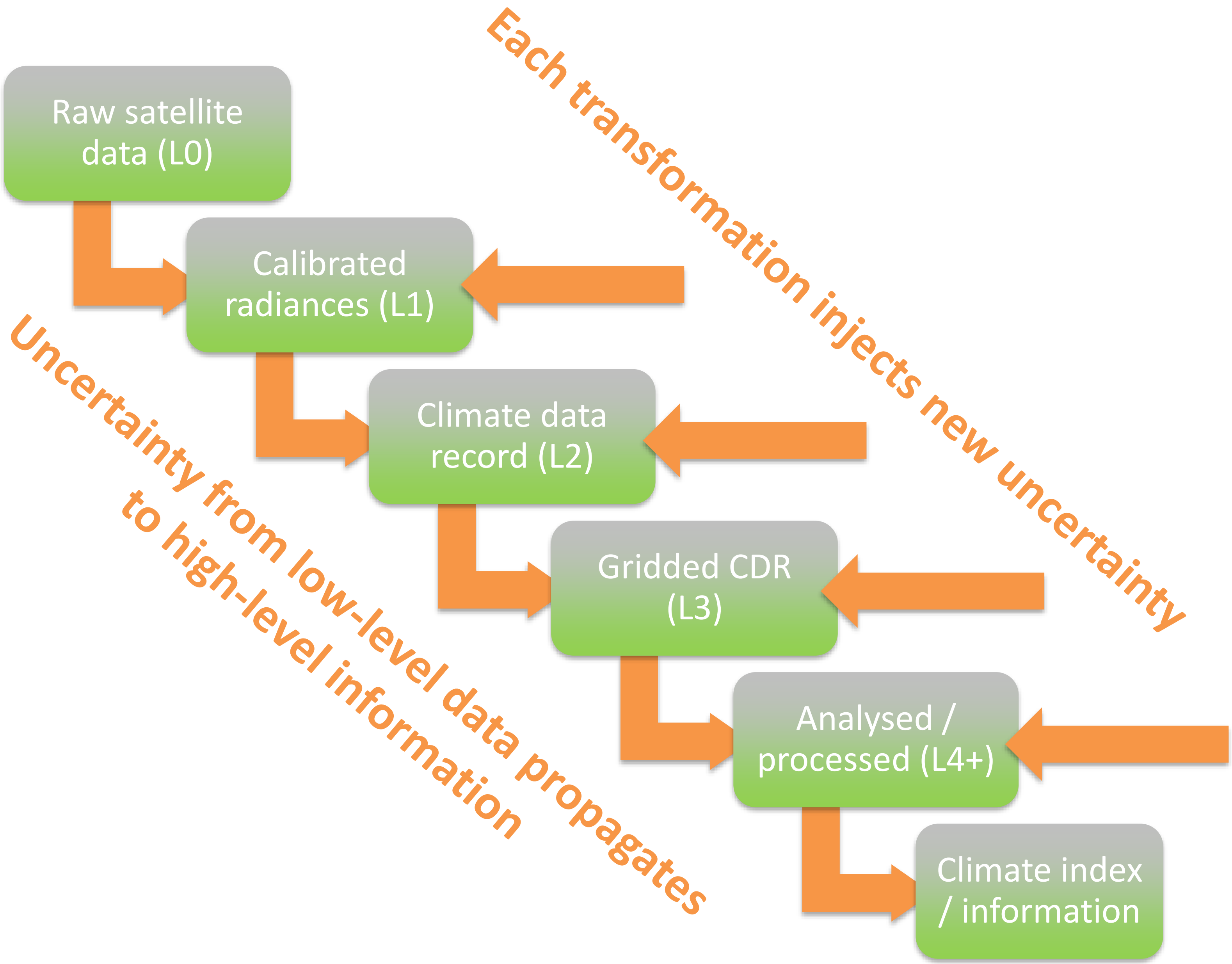
- **How certain is the information?** **Uncertainty**
- **How defensible is the information?** **Traceability**



- Decision
- Insurance
- Liability



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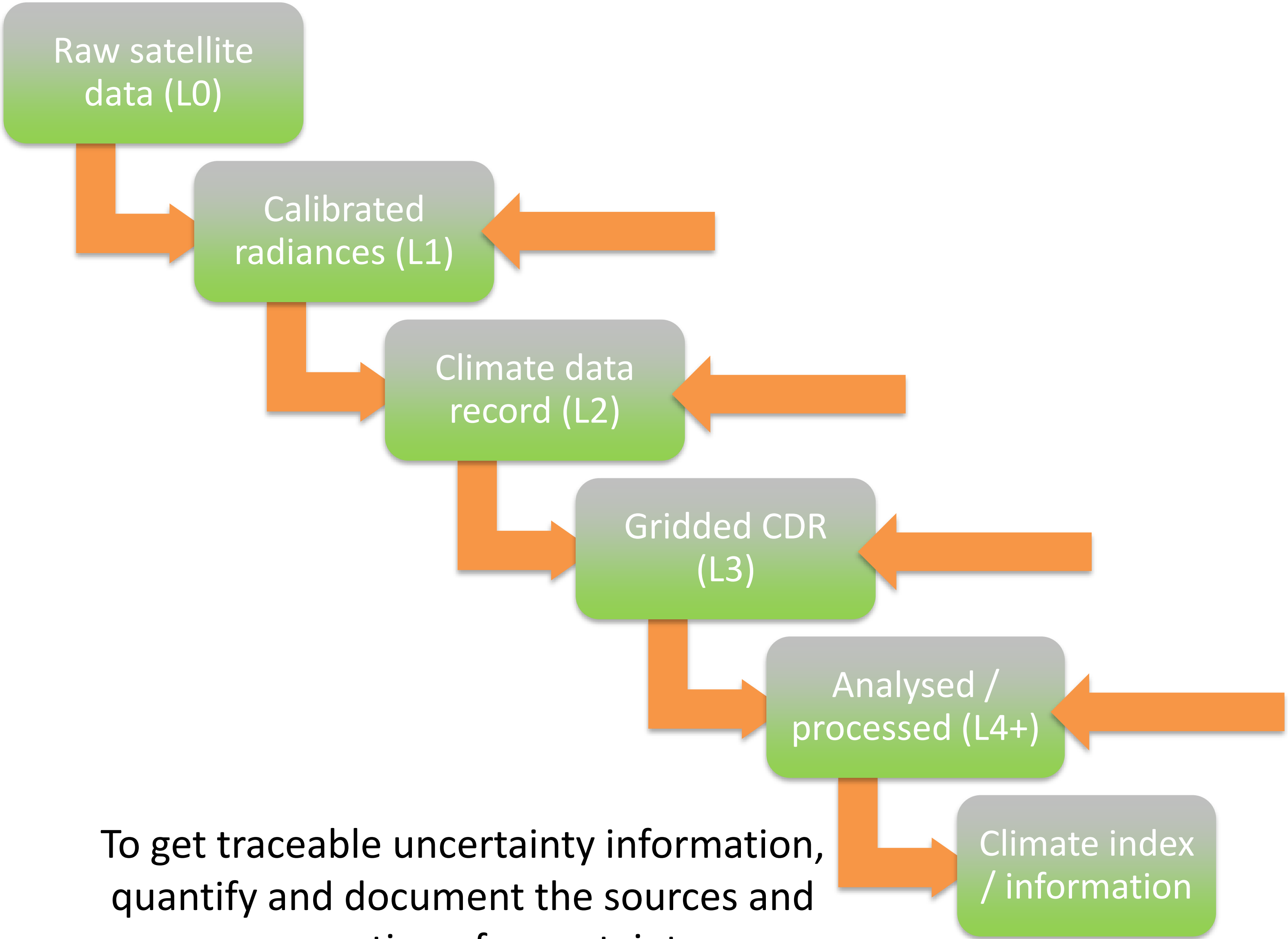

To get traceable uncertainty information, quantify and document the sources and propagation of uncertainty

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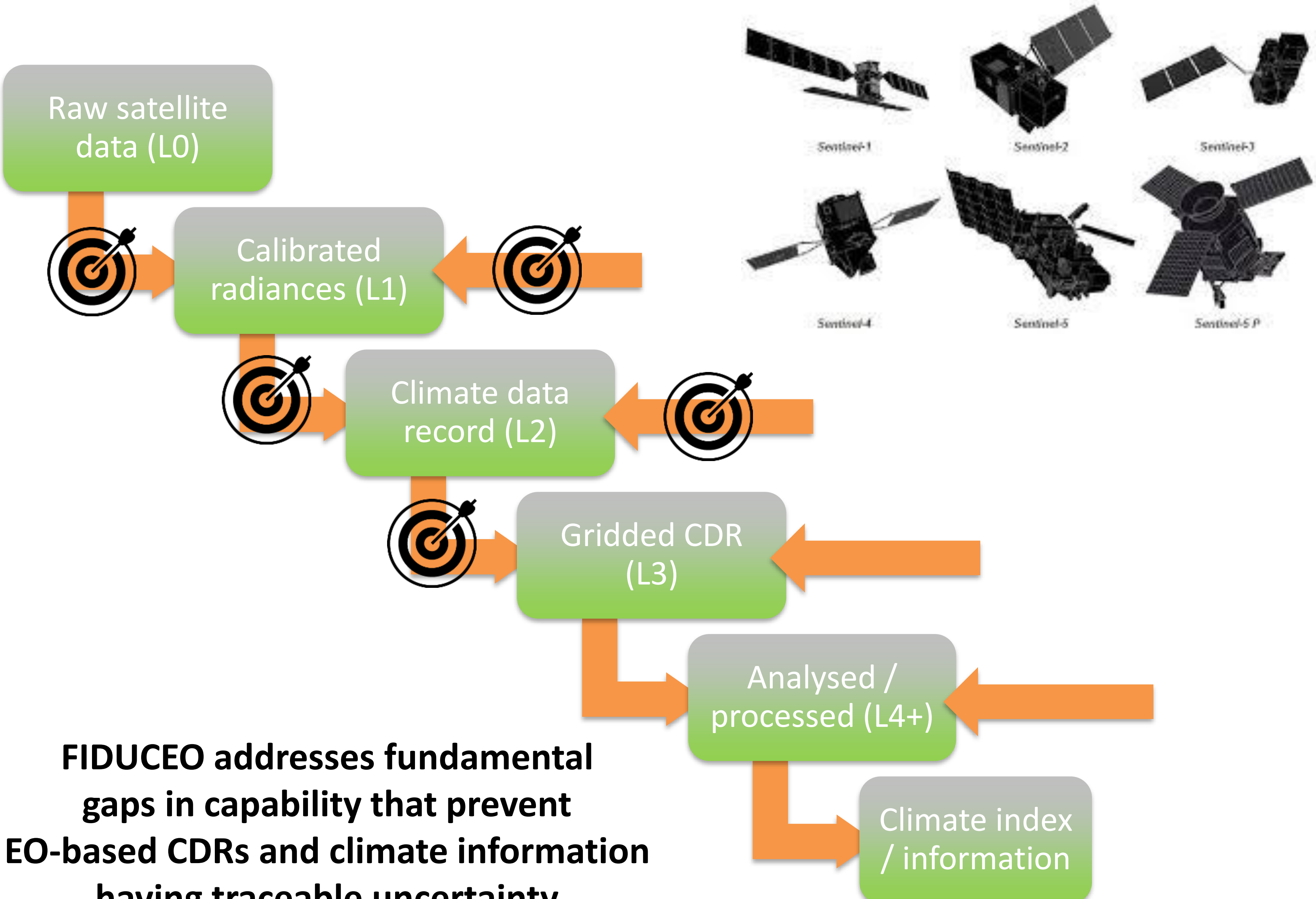

FIDUCEO addresses fundamental gaps in capability that prevent EO-based CDRs and climate information having traceable uncertainty

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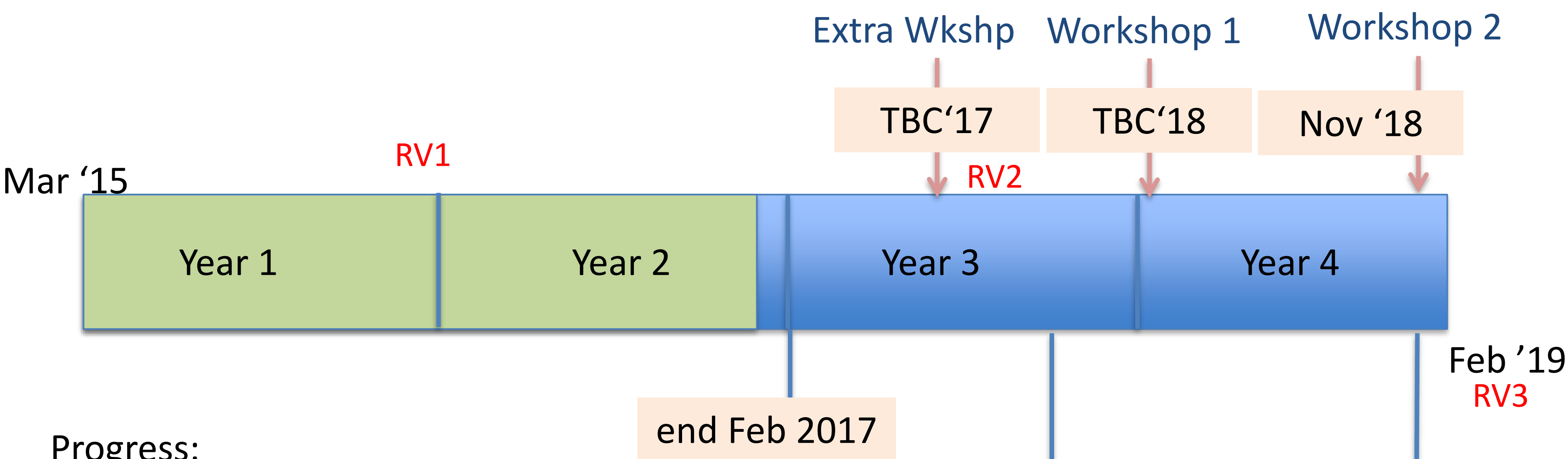
Why *metrology* of EO?

- 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

FIDUCEO project timelines



Progress:

- EO metrology framework
- Many methodologies
- Data acquisition / prep.
- User consultation
- Vocabulary
- FCDR concept
- Harmonisation concept

Beta version FCDRs - AVHRR, HIRS, MVIRI

Nov 2017

Beta version MW FCDR

CDRs:

- *SST & LSW*
- *UTH*
- *Albedo and Aerosol*
- *Aerosol (from AVHRR)*

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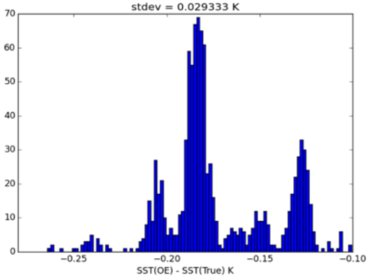
FIDUCEO and Copernicus

- *C3S Quality Assurance for ECV Products Derived from Observations*
  - incorporating some QA4ECV and FIDUCEO
- C3S contract to EUMETSAT on reprocessed satellite observations
  - FIDUCEO methods on MW FCDRs propagated to CM-SAF sounder projects
  - FIDUCEO methods to be applied to Meteosat IR recalibration
  - FIDUCEO recalibration of AVHRR (global) to inform stewardship of AVHRR local (hi-res) FCDR



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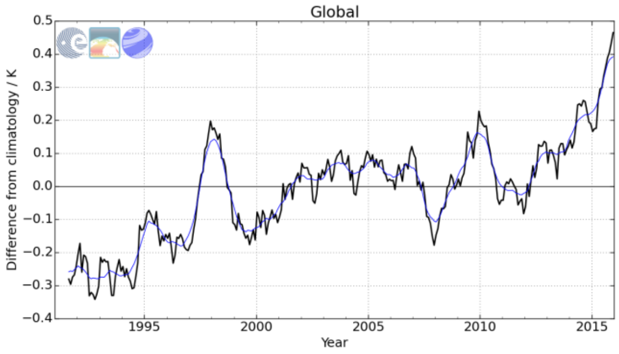
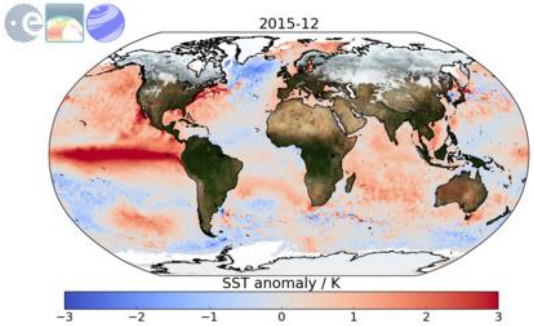
FIDUCEO and Copernicus

- Sea surface temperature (SST) climate data to C3S
  - The FIDUCEO ensemble SST CDR will be brokered through C3S once released
  - first ensemble CDR from EO (to our knowledge)
  - great interest in this approach from major users





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FIDUCEO and Copernicus

- FIDUCEO ensemble SST likely also to comprise a component of future CCI+ SST CDR v3
  - therefore in turn serving both C3S and the Copernicus Marine service, CMEMS
- FIDUCEO lake surface water temperature CDR
  - potential input to CCI+ Lake ECV
  - potential brokering through Copernicus Land Service (not yet discussed)

FIDUCEO and GAIA-CLIM

- Two highly complementary projects on metrology of climate observations
- Co-ordination through mutual representation on advisory boards
- Scientific opportunity to close the metrological uncertainty budget of a reference-network-to-satellite comparison for at least one FIDUCEO CDR
  – first fully rigorous validation of 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)

FCDR Uncertainty

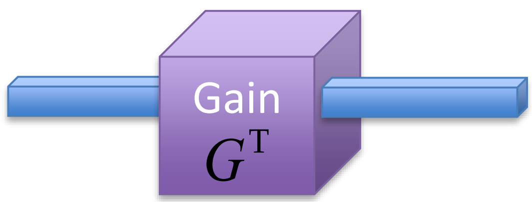
- Understand the **measurement equation**
- Quantify the **sources of error** (effects)
- Quantify their **error structures**
- Propagate to get radiance **uncertainty**

- **Structured approach centred on measurement equation**

Measurement equation

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

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



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

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

Measured Signal

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

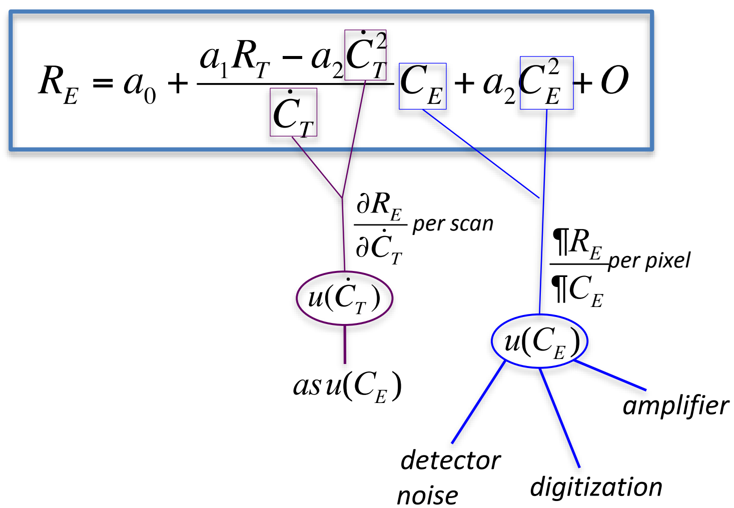
Measured gain

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

Measured Earth Radiance

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

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



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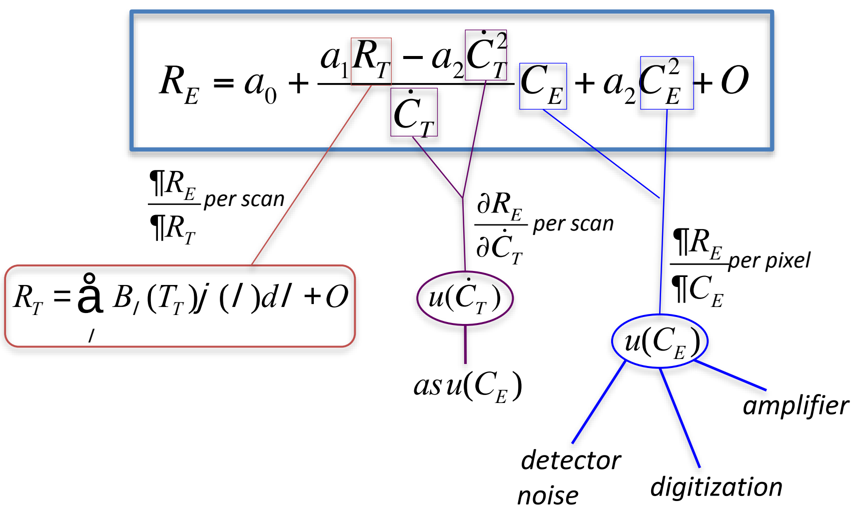
Quantify each error source

- 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

Capture in an effects table

<table>
<tr><th colspan="2"></th><th>Value / Expression</th><th>Notes</th></tr>
<tr><td colspan="2">Name of effect</td><td></td><td></td></tr>
<tr><td colspan="2">Affected term in measurement function</td><td></td><td></td></tr>
<tr><td colspan="2">Channels / bands</td><td></td><td></td></tr>
<tr><td rowspan="5">1. Correlation type and form</td><td>within scanline [pixels]</td><td></td><td></td></tr>
<tr><td>from scanline to scanline [scanlines]</td><td></td><td></td></tr>
<tr><td>between images/orbits [orbits]</td><td></td><td></td></tr>
<tr><td>Across time [appropriate time units e.g. days, months, years]</td><td></td><td></td></tr>
<tr><td>between channels / bands</td><td></td><td></td></tr>
<tr><td rowspan="5">1. Correlation scale</td><td>within scanline [pixels]</td><td></td><td></td></tr>
<tr><td>from scanline to scanline [scanlines]</td><td></td><td></td></tr>
<tr><td>between images/orbits [orbits]</td><td></td><td></td></tr>
<tr><td>Across time</td><td></td><td></td></tr>
<tr><td>between channels / bands</td><td></td><td></td></tr>
<tr><td colspan="2">Uncertainty PDF shape</td><td></td><td></td></tr>
<tr><td colspan="2">Uncertainty units</td><td></td><td></td></tr>
<tr><td colspan="2">Uncertainty magnitude</td><td></td><td></td></tr>
<tr><td colspan="2">Sensitivity coefficient</td><td></td><td></td></tr>
</table>



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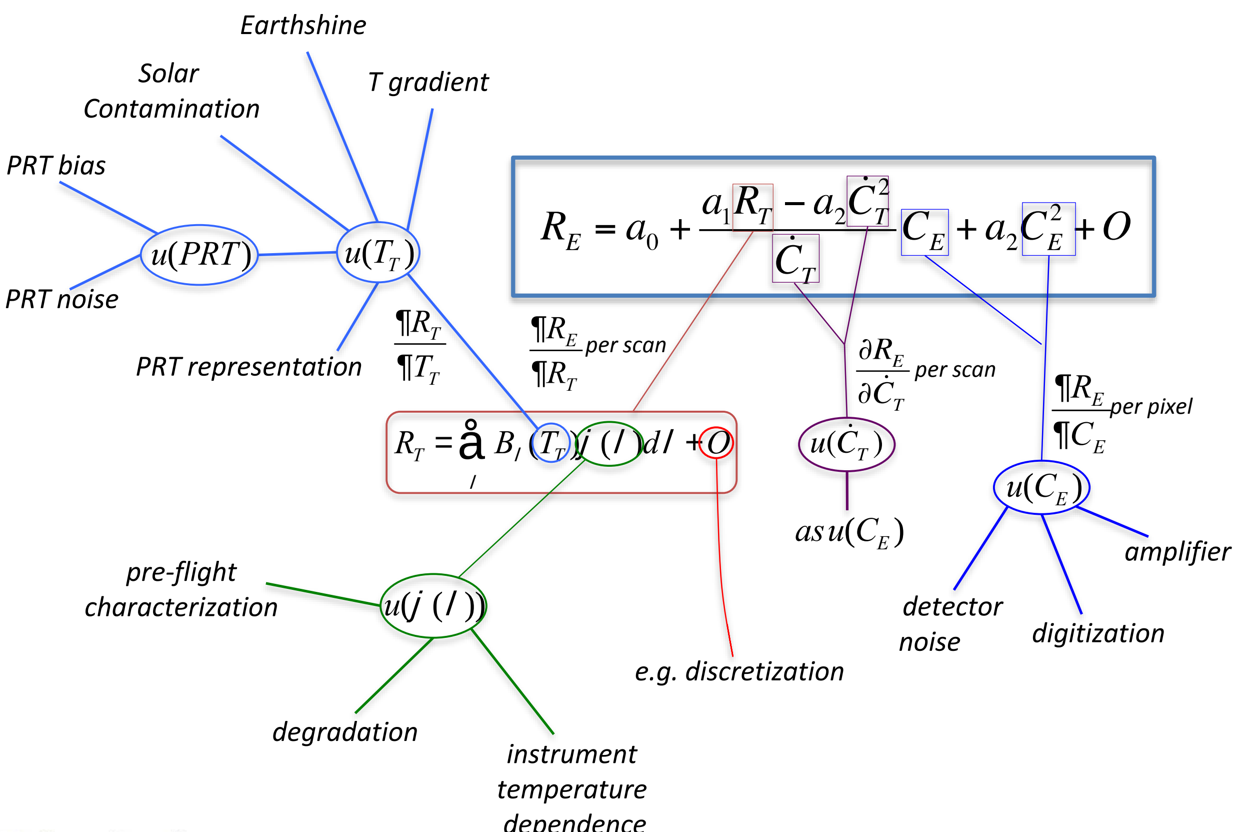
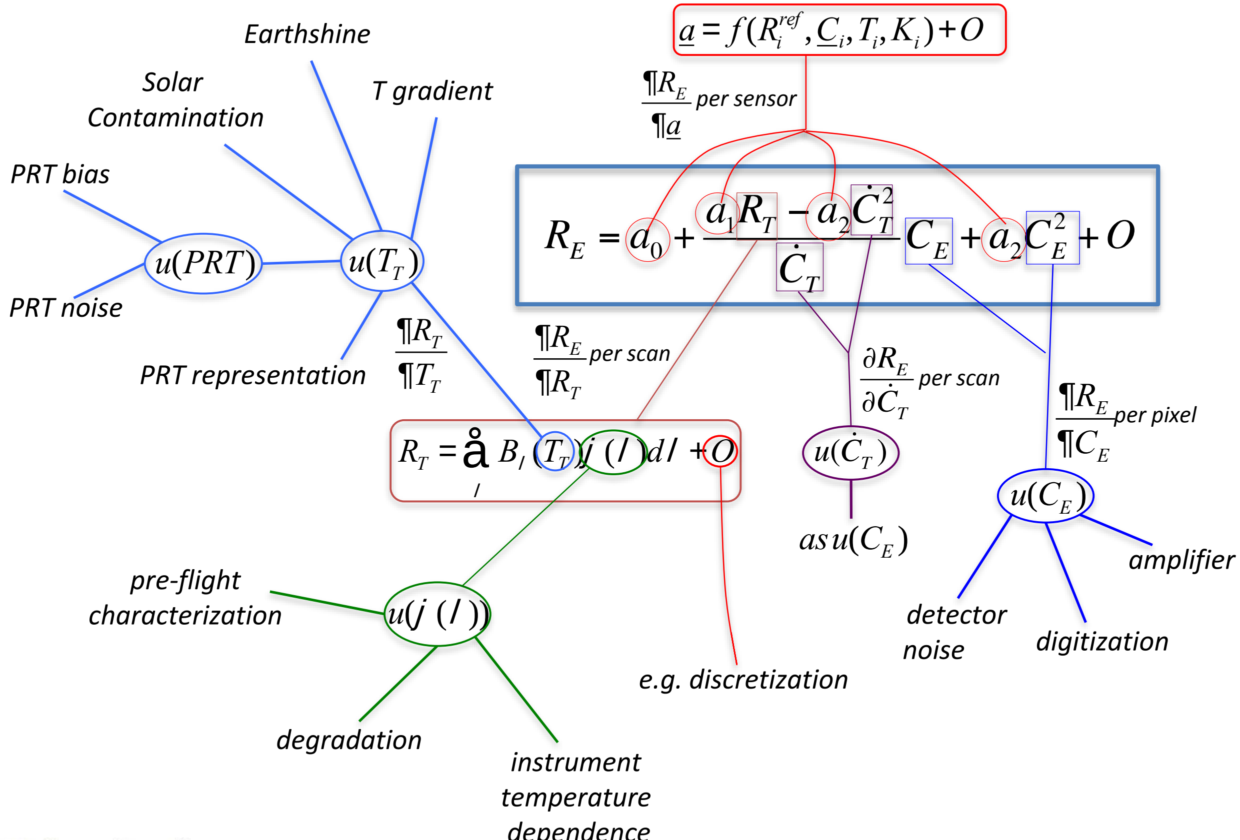
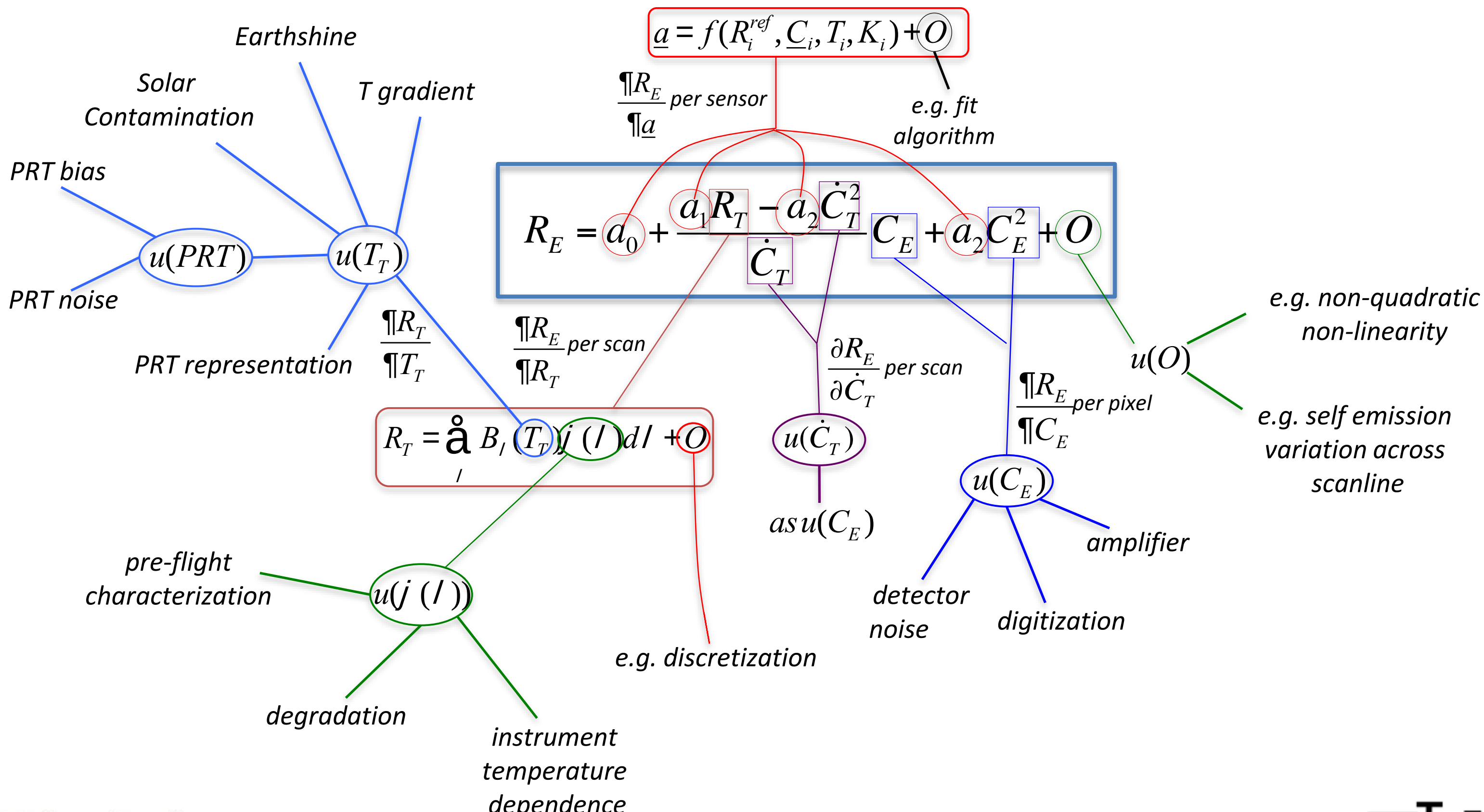

Earthshine
Solar Contamination
T gradient
PRT bias
PRT noise
u(PRT)
u(T_T)
PRT representation
¶R_T / ¶T_T
¶R_E / ¶R_T per scan
R_E = a_0 + (a_1 R_T − a_2 Ċ_T^2) / Ċ_T C_E + a_2 C_E^2 + O
∂R_E / ∂Ċ_T per scan
¶R_E / ¶C_E per pixel
R_T = å_l B_l (T_T) j (l) dl + O
u(Ċ_T)
as u(C_E)
u(C_E)
amplifier
detector noise
digitization
pre-flight characterization
u(j (l))
e.g. discretization
degradation
instrument temperature dependence



Earthshine
Solar Contamination
T gradient
PRT bias
PRT noise
PRT representation
u(PRT)
u(T_T)
per sensor
per scan
per scan
per pixel
u(C_E)
amplifier
detector noise
digitization
as u(C_E)
pre-flight characterization
degradation
instrument temperature dependence
e.g. discretization



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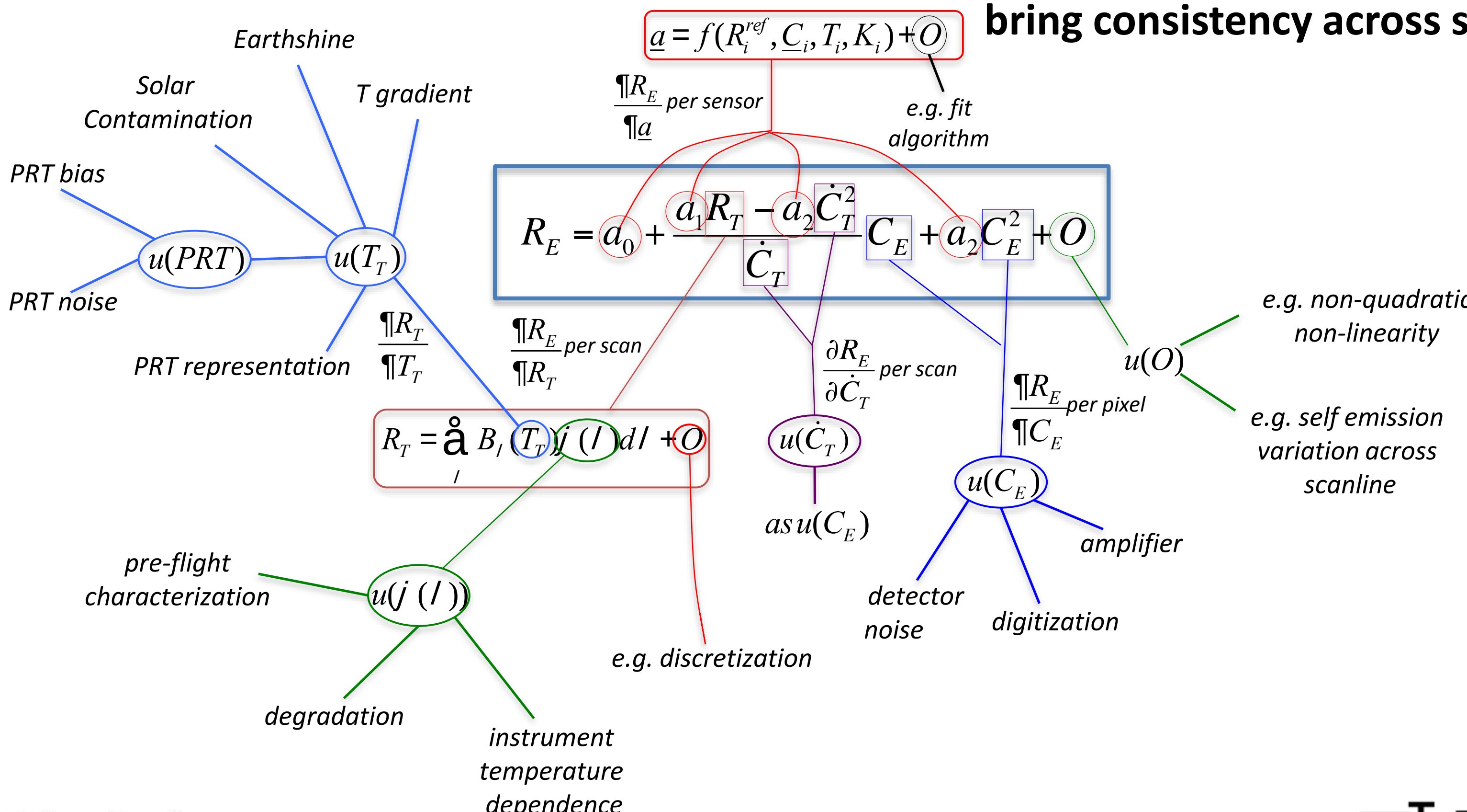
Traceable uncertainty

- 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 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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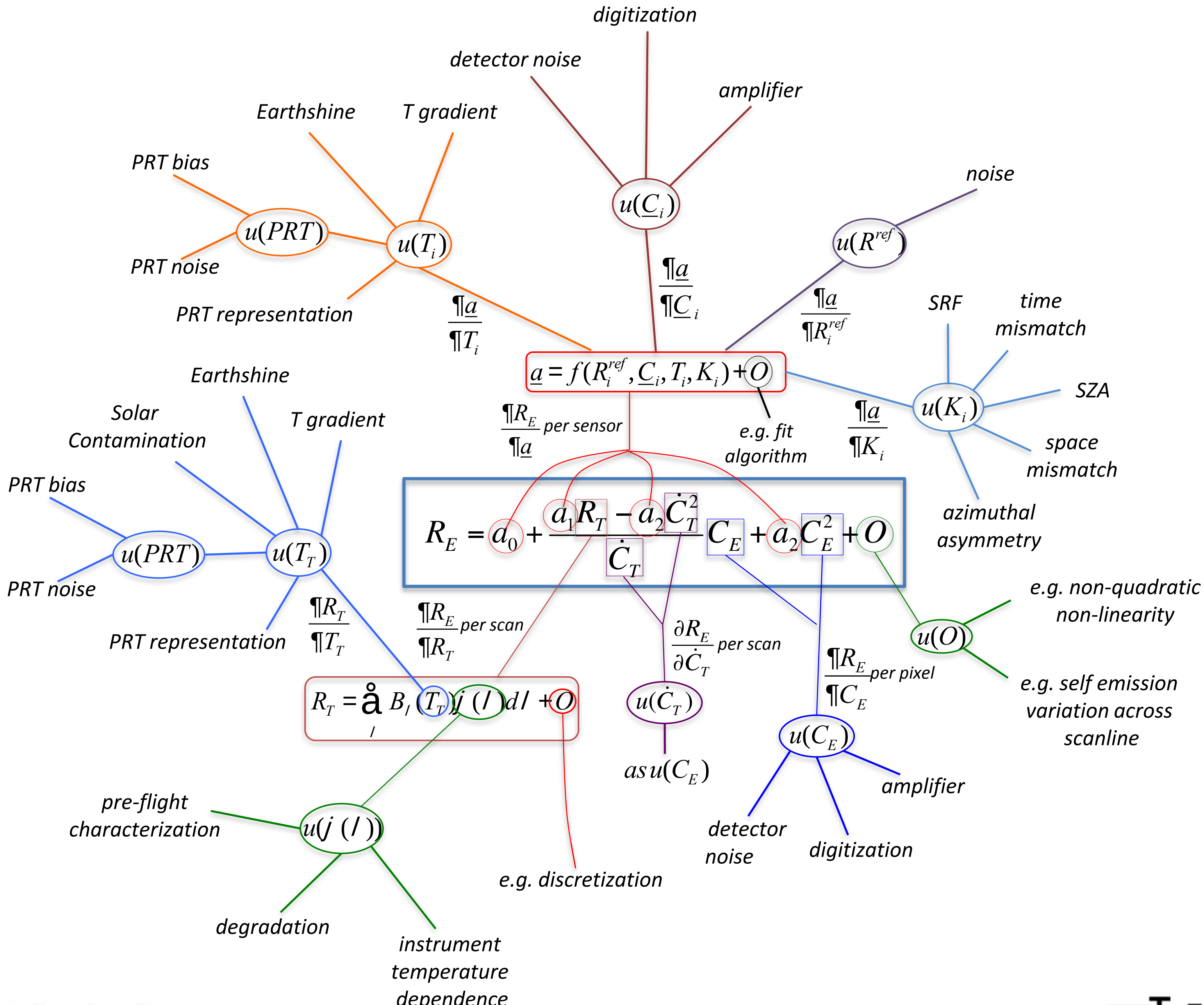

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GSICS Quarterly

Global Space-based Inter-Calibration System

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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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Aim \ Method	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'

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**

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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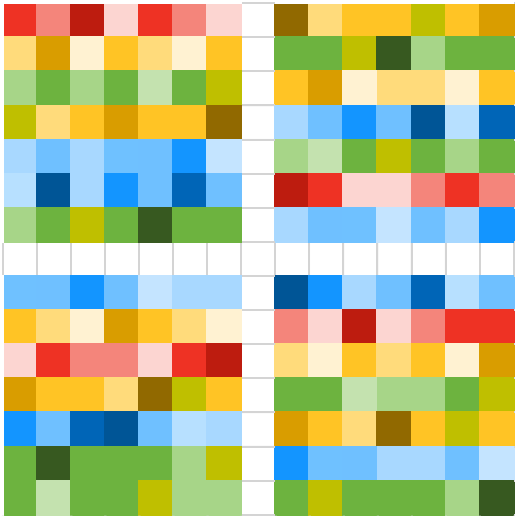
Sharing the FCDR

- 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

systematic and structured random

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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