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Applying Metrological Techniques to Satellite Fundamental Climate Data Records

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What is an FCDR?

An FCDR consists of a long, *harmonised* record of *uncertainty-quantified* sensor observations that are *calibrated* to physical units and located in time and space, together with all ancillary and lower-level instrument data used to calibrate and locate the observations and to estimate uncertainty.

Definition drafted at FIDUCEO Workshop 2018 - Under consideration by CEOS/CGMS Working Group Climate

FCDR Metrological Questions

Look at three metrological issues for FCDRs tackled by the FIDUCEO project:

- Understanding Sources of Uncertainty
- Error Correlation
- Series stability/inter-calibration

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UNDERSTANDING SOURCES OF UNCERTAINTY

General Principles from the CCI Project

1. Include quantitative uncertainty information within the dataset. (Don't expect users to find uncertainty information by reading related papers.)
2. Follow metrological practice for quantifying uncertainty. The baseline good practice is to provide the total standard uncertainty for numerical variables.
3. Uncertainty estimates (or the means to calculate them) should be provided per datum in CDRs for which uncertainty varies significantly so that the uncertainty information discriminates which data are more and less certain.
4. Assuming per-datum uncertainty information is provided, avoid redundancy of this information with quality flags. Do not flag high-uncertainty data as "bad" if a valid estimate of that high uncertainty is provided; instead, use quality flags to indicate the level of confidence in the validity of the provided uncertainty and retrieval assumptions.
5. Define what uncertainty information is given in the CDR in the product documentation.
6. Describe in the product documentation the main effects causing errors, how uncertainty varies within the dataset, how errors may be correlated in time and space, and under what circumstances estimated uncertainty may be invalid (and flagged as such).
7. Use validation to evaluate both retrieved quantities and associated uncertainty estimates.
8. Propagate uncertainty appropriately (accounting for error correlation) and consistently when creating aggregated products.

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C. J. Merchant *et al.*, "Uncertainty information in climate data records from Earth observation," *Earth Syst. Sci. Data*, vol. 95194, pp. 511–527, 2017.

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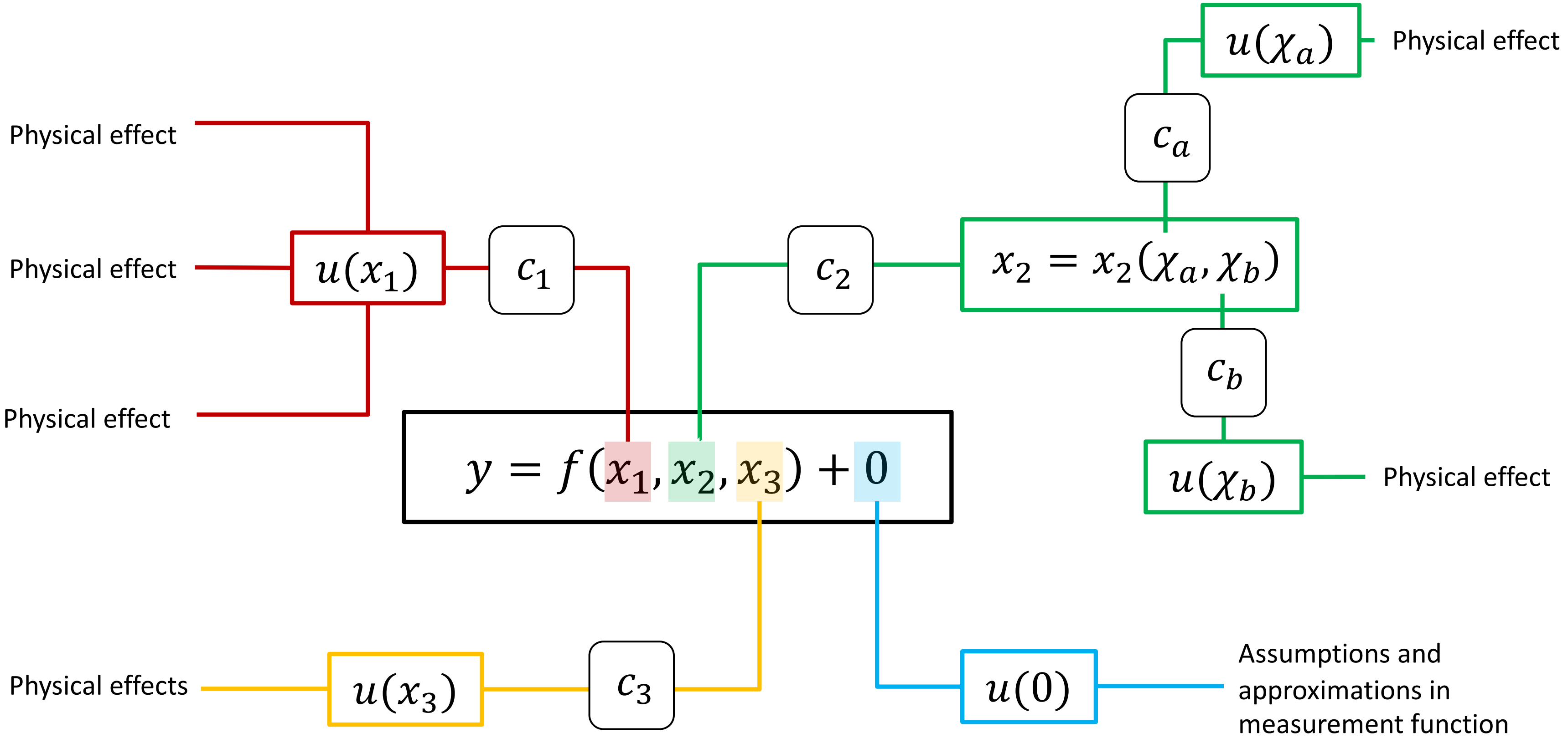
Methodologies – Uncertainty Tree Diagram



Example: AVHRR Thermal Channels

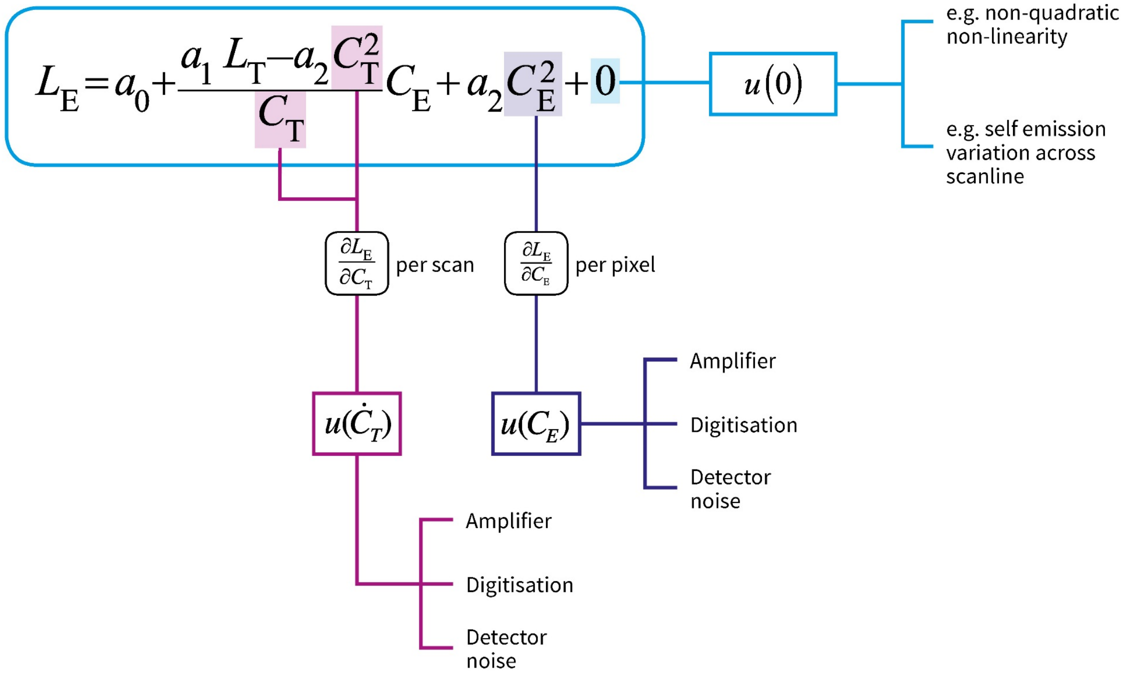
$$L_{\mathrm{E}} = a_0 + \frac{a_1\, L_{\mathrm{T}} - a_2 C_{\mathrm{T}}^2}{C_{\mathrm{T}}} C_{\mathrm{E}} + a_2 C_{\mathrm{E}}^2 + 0$$

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

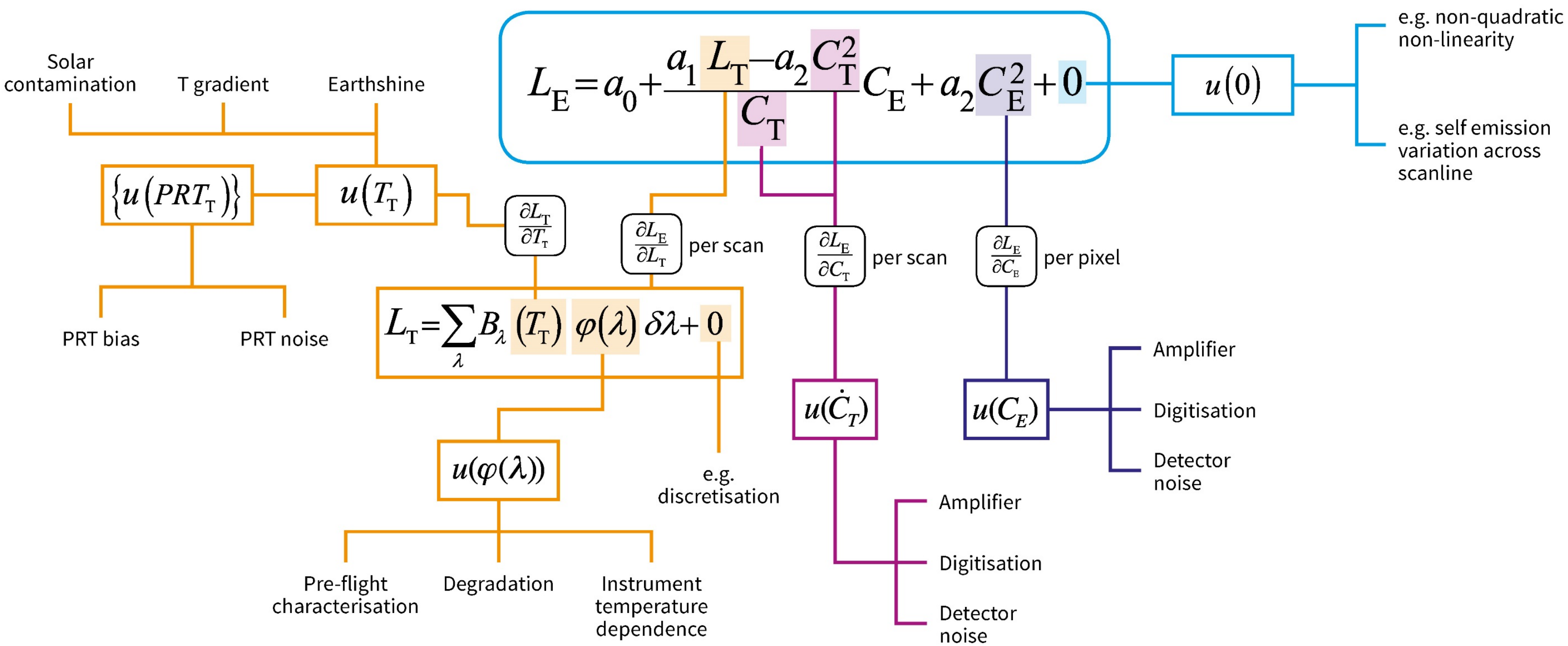
$$\boxed{u(0)}$$

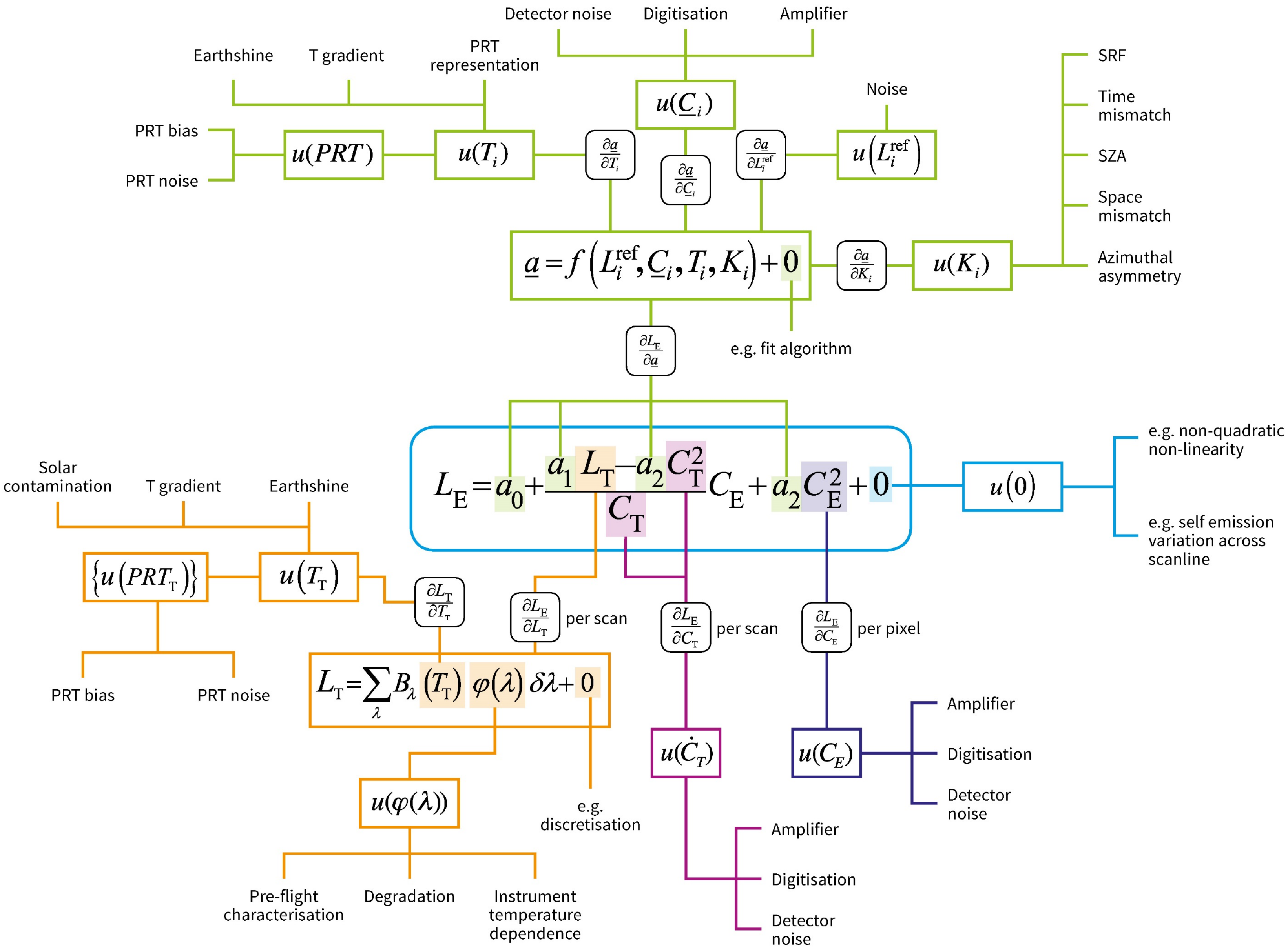
e.g. non-quadratic
non-linearity

e.g. self emission
variation across
scanline



$L_E = a_0 + \frac{a_1 L_T - a_2 C_T^2}{C_T} C_E + a_2 C_E^2 + 0$
$u(0)$
e.g. non-quadratic non-linearity
e.g. self emission variation across scanline
$\frac{\partial L_E}{\partial C_T}$ per scan
$\frac{\partial L_E}{\partial C_E}$ per pixel
$u(\dot{C}_T)$
$u(C_E)$
Amplifier
Digitisation
Detector noise
Amplifier
Digitisation
Detector noise

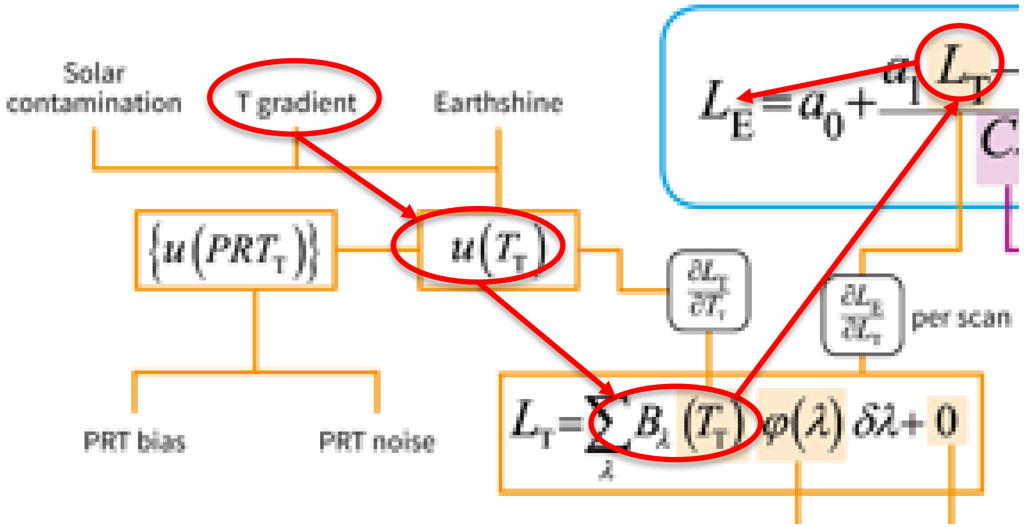

$L_E = a_0 + \frac{a_1 L_T - a_2 C_T^2}{C_T} C_E + a_2 C_E^2 + 0$
$u(0)$
e.g. non-quadratic non-linearity
e.g. self emission variation across scanline
Solar contamination
T gradient
Earthshine
$\{u(PRT_T)\}$
$u(T_T)$
$\frac{\partial L_T}{\partial T_T}$
$\frac{\partial L_E}{\partial L_T}$ per scan
$\frac{\partial L_E}{\partial C_T}$ per scan
$\frac{\partial L_E}{\partial C_E}$ per pixel
PRT bias
PRT noise
$L_T = \sum_\lambda B_\lambda(T_T)\,\varphi(\lambda)\,\delta\lambda + 0$
$u(\dot{C}_T)$
$u(C_E)$
Amplifier
Digitisation
Detector noise
$u(\varphi(\lambda))$
e.g. discretisation
Pre-flight characterisation
Degradation
Instrument temperature dependence
Amplifier
Digitisation
Detector noise



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

Source uncertainties - example

- Calibration Target temperature
  - Structured uncertainty component
  - Arises from errors in mapping estimates of calibration target temperature to calibration target radiances
  - Propagates through Planck function/spectral response function convolution to an uncertainty on the ICT radiance to a Gain uncertainty to the final Earth radiance
  - Uses the sensitivity coefficients to propagate uncertainties to the measurand



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ERROR CORRELATION

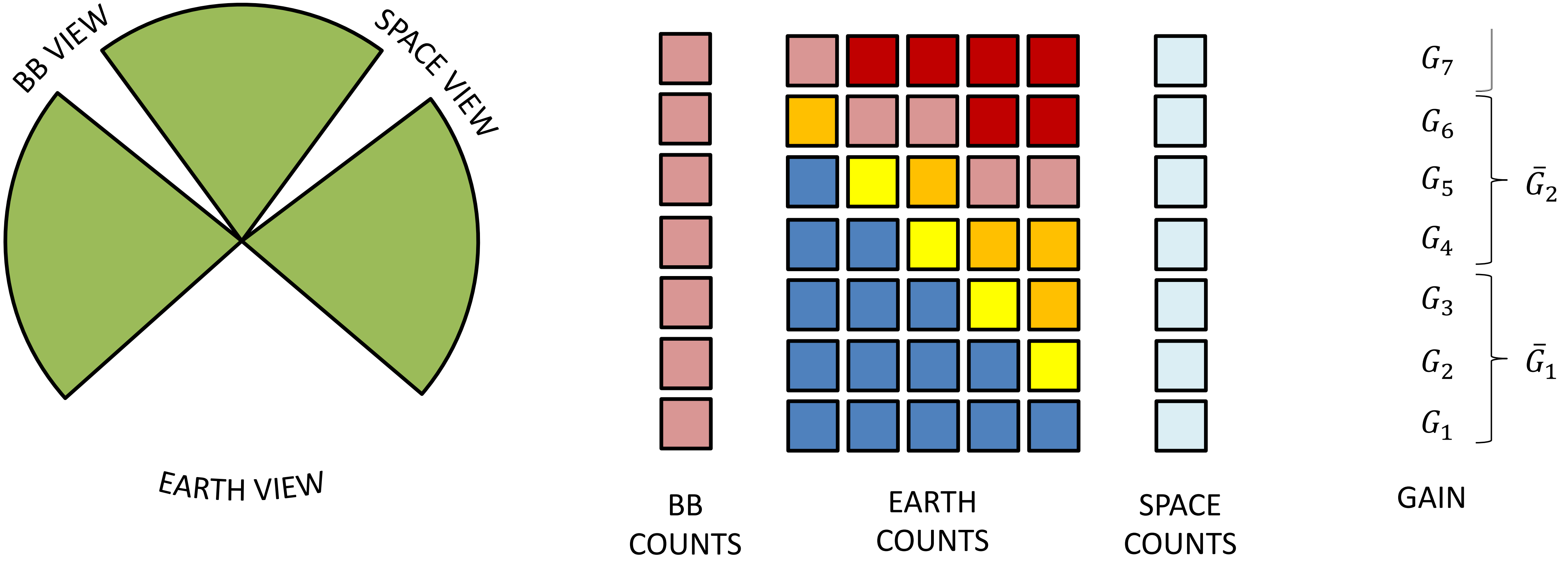
RANDOM

SYSTEMATIC

The Errors-in-Satellite-Data "Zoo"

NOISE	… ERM, NOT QUITE SURE WHAT TO CALL THIS …		BIAS	Traditional "Noise/Bias" classification
INDEPENDENT RANDOM	STRUCTURED RANDOM	STRUCTURED SYSTEMATIC	COMMON SYSTEMATIC	Two-part taxonomy

Example: Structured Random Error Correlation in Cross Track Scanners



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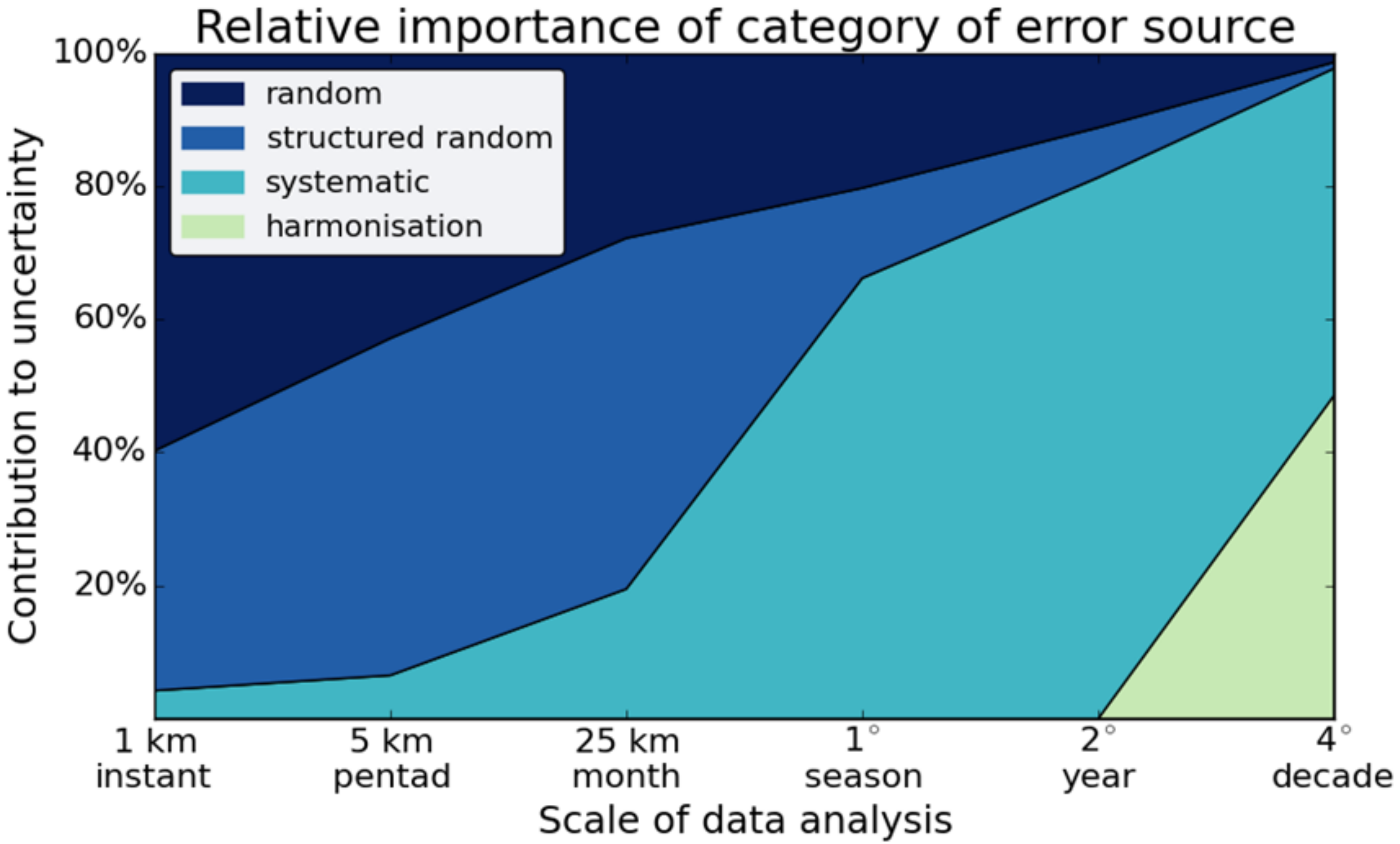
Error Correlation Structures: Why do we care?



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Methodologies – Error Correlation

- Comprehensive *Effects Table* for recording error correlation information

- Define a file format that efficiently summarises this information for users

		Comments
Name of effect		A unique name
Affected term in measurement function		Name and standard symbol
Instruments in the series affected		List names
Correlation type and form	Pixel-to-pixel [pixels]	From a set of defined correlation forms
	from scanline to scanline [scanlines]	
	between images [images]	
	Between orbits [orbit]	
	Over time [time]	
Correlation scale	Pixel-to-pixel [pixels]	As needed to define type
	from scanline to scanline [scanlines]	
	between images [images]	
	Between orbits [orbit]	
	Over time [time]	
Channels/bands	List of channels / bands affected	Channel names
	Error correlation coefficient matrix	A matrix
Uncertainty	PDF shape	Functional form
	units	Units
	magnitude	
Sensitivity coefficient		Value, equation or parameterisation of sensitivity of measurand to term

RANDOM

SYSTEMATIC

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INDEPENDENT RANDOM	STRUCTURED RANDOM	STRUCTURED SYSTEMATIC	COMMON SYSTEMATIC	Two-part taxonomy

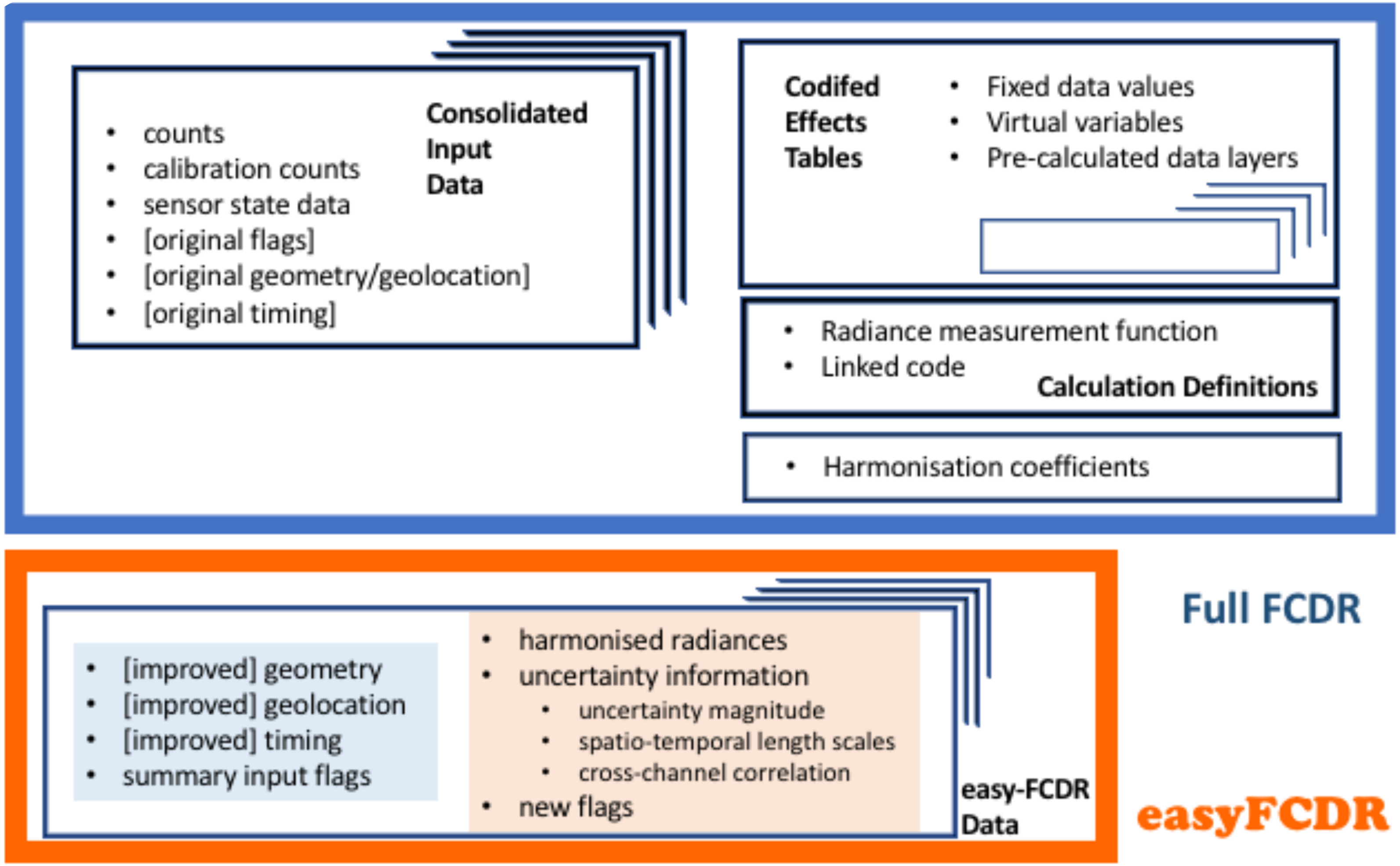
INDEPENDENT

STRUCTURED

COMMON

Can be further described by the nature of the error correlations caused by the structure … if necessary!

FCDR Full & Easy Overview



INTER-CALIBRATION - HARMONISATION

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Aim

FCDRs combine radiance measurements from a series of sensors.

Experience is that after nominal calibration unexpected sensor-to-sensor differences remain. This effect may be significant in terms of derived geophysical parameters.

How to achieve a harmonised calibration of a series of satellite instruments?

FIDUCEO has produced software to do this in metrologically rigorous manner.
See poster session for more!

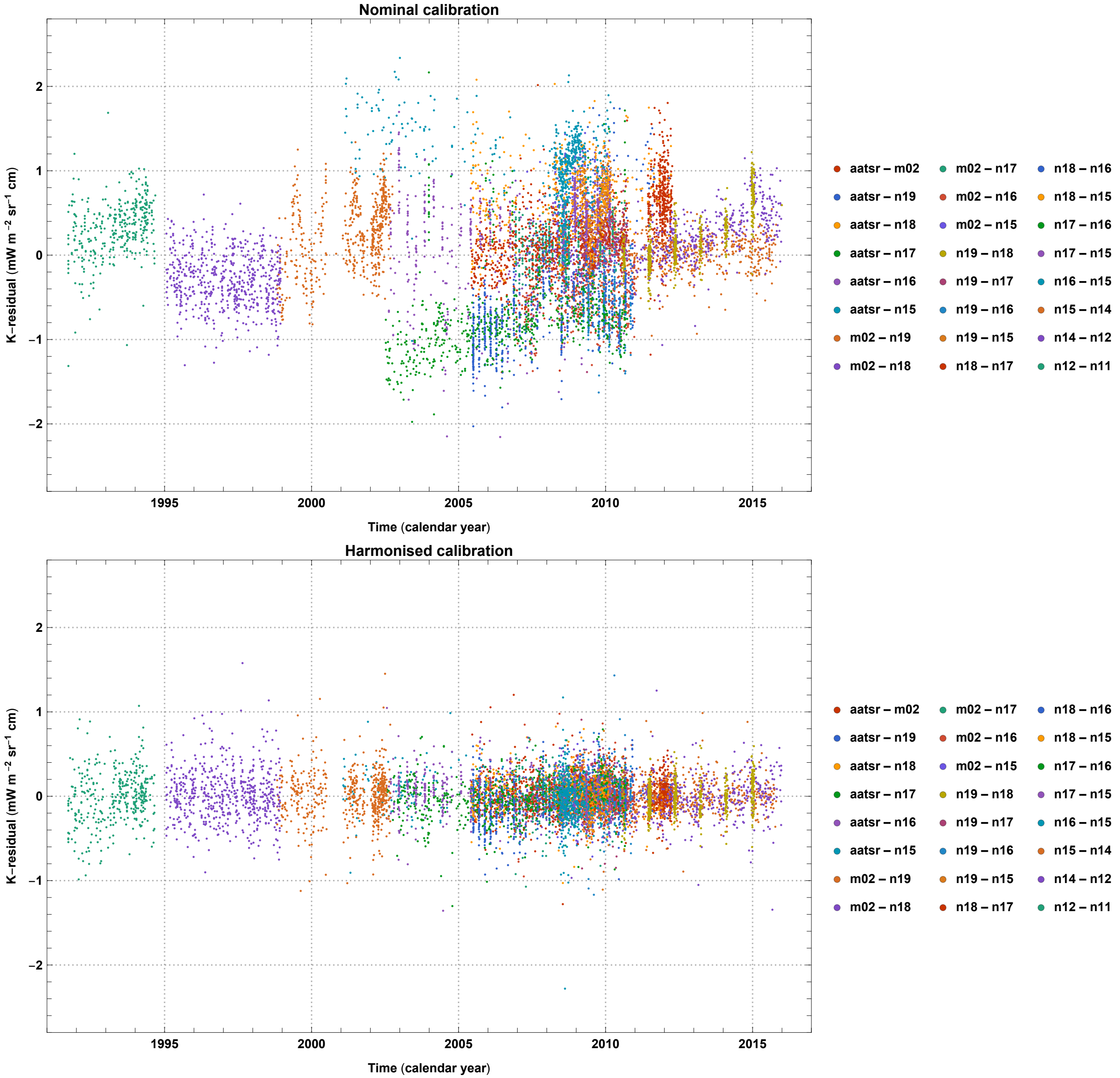

Figure – R. Quast, FastOpt GmbH

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Methods – Summary

- Measurement Function Centred Analysis
- Effects Table Reporting
- Consistent File format

+ Harmonisation of Historic Series

Outcomes

- 4 uncertainty-quantified FCDRs – AVHRR, HIRS, MW and MVIRI
- Exemplar CDRs – SST, Aerosol, Surface Reflectance, UTH
- Software tools: https://github.com/fiduceo
- Training Material: http://www.fiduceo.eu/
- Number of scientific papers, including:

J. Mittaz, C. J. Merchant, and E. R. Woolliams, “Applying principles of metrology to historical Earth observations from satellites,” *Metrologia*, vol. 56, no. 3, p. 032002, Jun. 2019.