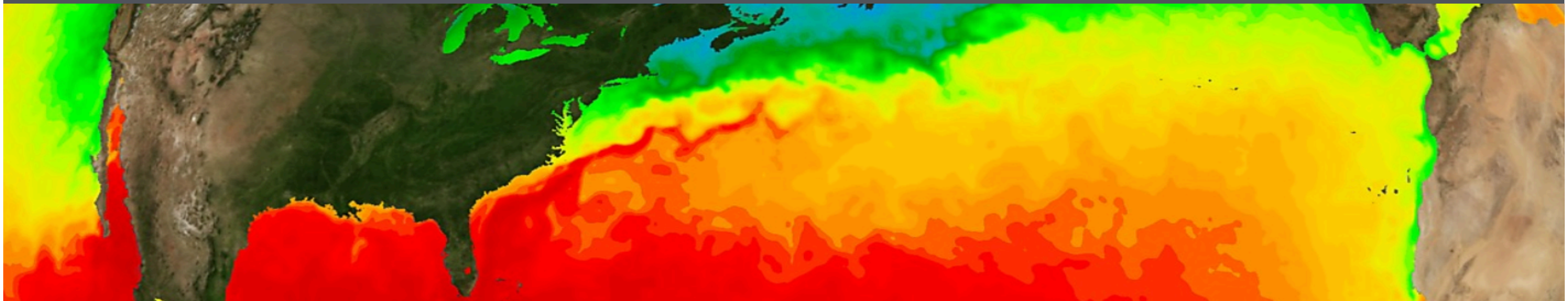
Department of Meteorology
National Centre for Earth Observation

University of Reading

Metrology-inspired approaches to characterisation of uncertainty in Earth observations



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Metrology-inspired approaches to characterisation of uncertainty in Earth observations

Developed for the world of standards

- SI traceability
- **Evaluation of the uncertainty in measured quantities**

Rigorous framework of definitions and methods related to uncertainty in measurement

H2020 projects including FIDUCEO have applied metrology to satellite data

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

Metrology-inspired approaches to characterisation of uncertainty in Earth observations

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Given a **measured value**, the **uncertainty** characterizes the **plausible magnitude of deviations** within which true value of the measurand should lie

Estimate the distribution of plausible errors
→ (standard) uncertainty is their standard deviation

For multiple measured values: are errors related?

What does “characterization of uncertainty” mean for a satellite sensor?

The capability to consider **any two measured radiance values** and evaluate:

- **the uncertainty in each value**
- **and the correlation between the errors in the values**

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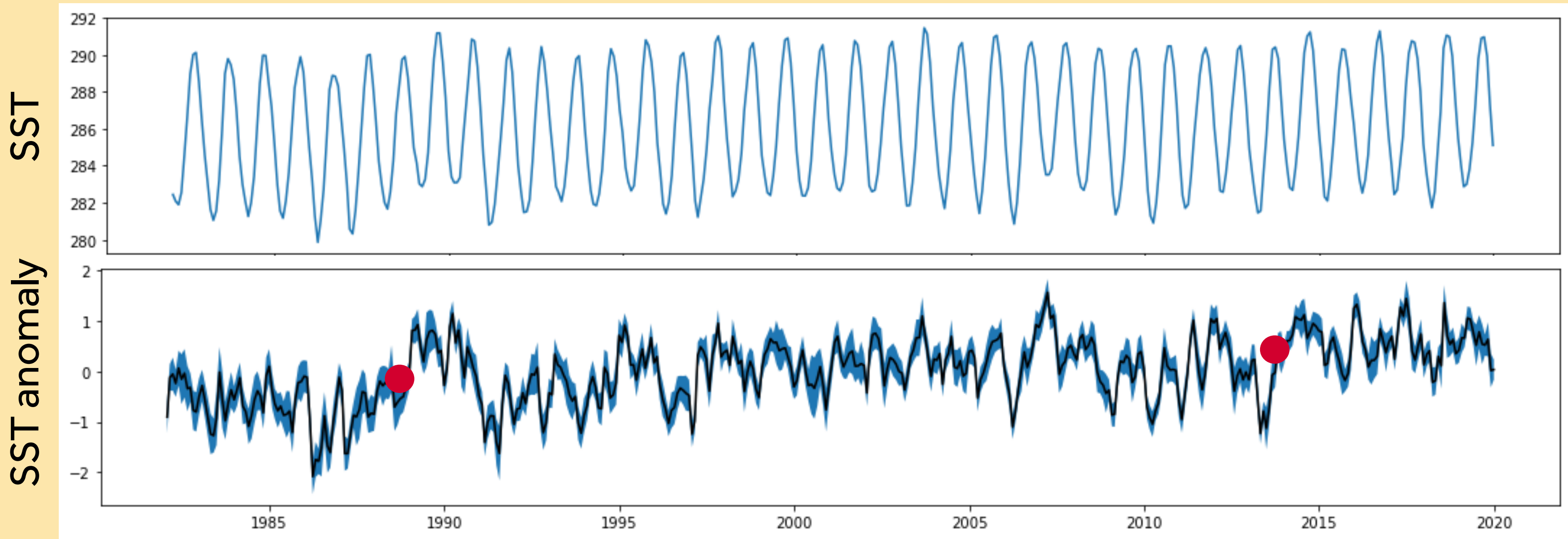
My motivation is EO-based climate data records



sst cci

ESA SST CCI data for the sea north of Brittany using timeseries tool at **www.surftemp.net**

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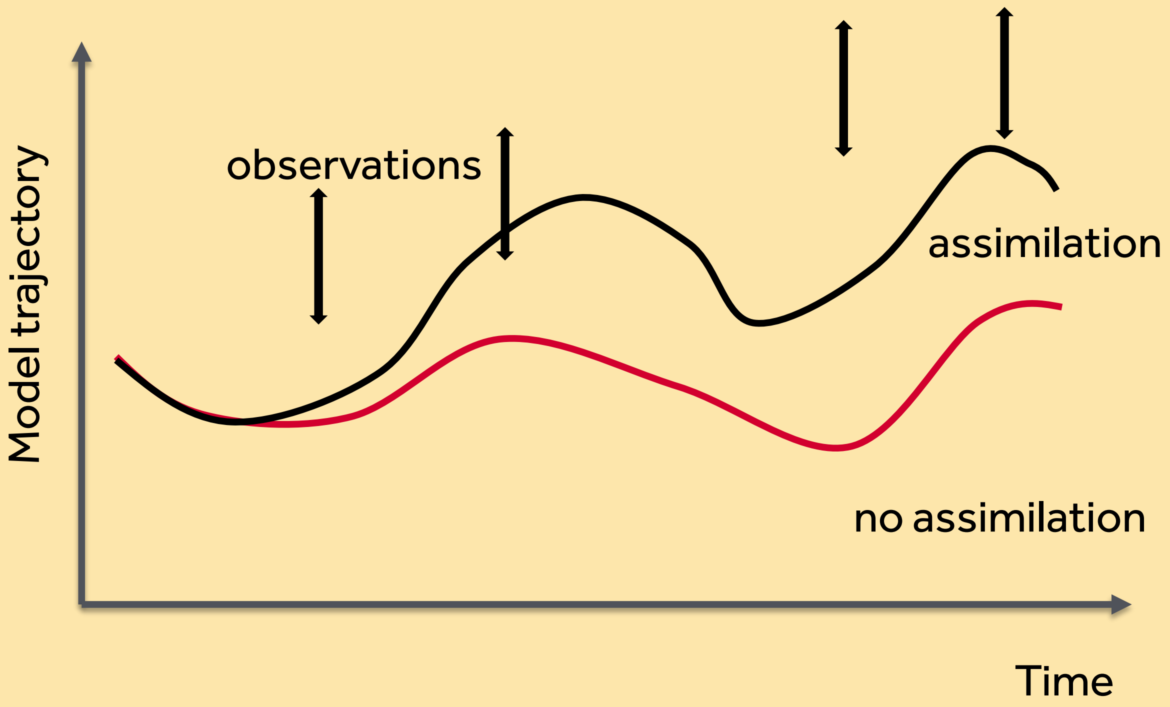
Additional motivations in context of data assimilation



Interpretation of O-B differences

How much of the obs. uncertainty plausibly from systematic effects?

How much bias is plausible in the model?

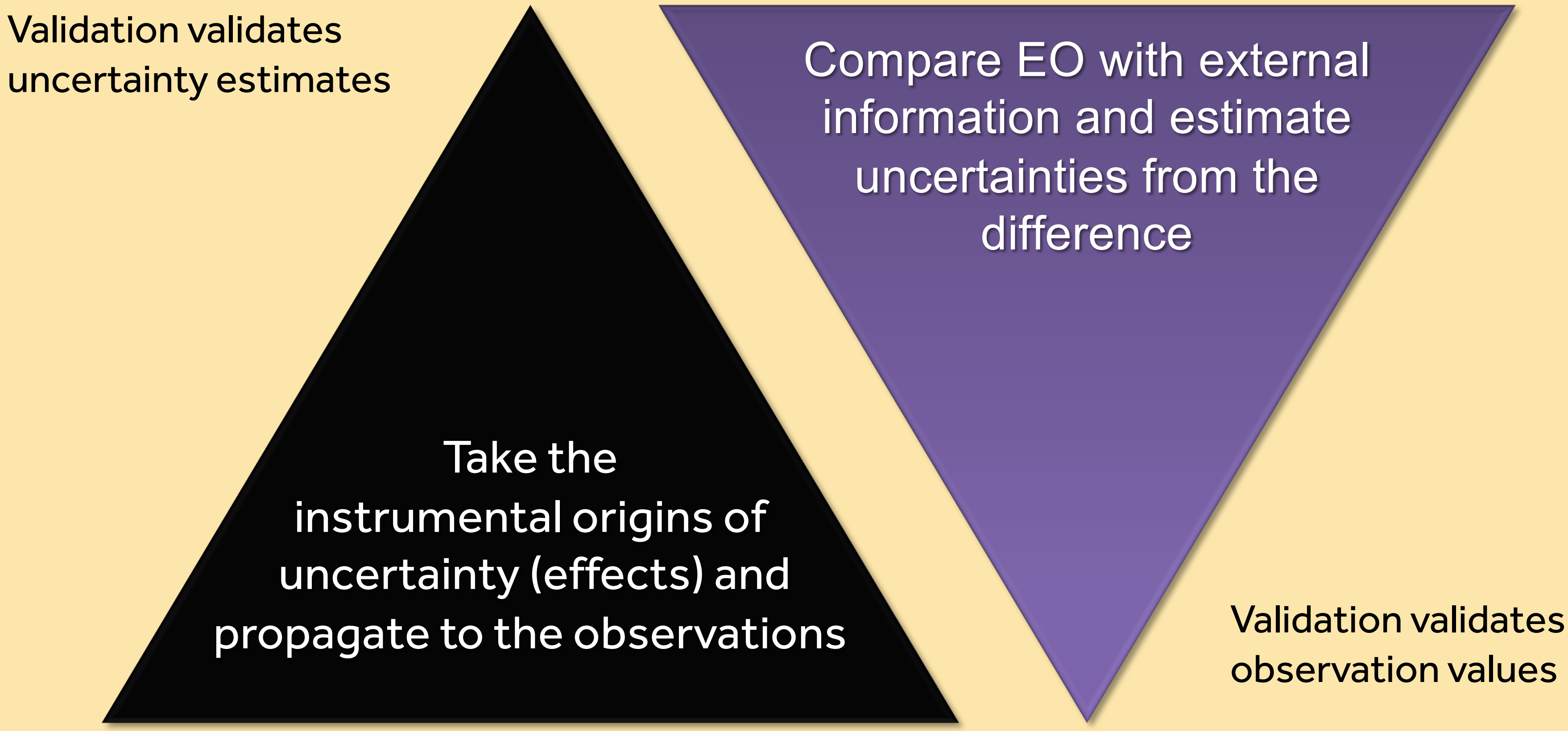
Which obs. are least biased?

Top-down
approach to uncertainty analysis

Compare EO with external information and estimate uncertainties from the difference

Validation validates observation values

Top-down vs. bottom-up approach to uncertainty analysis



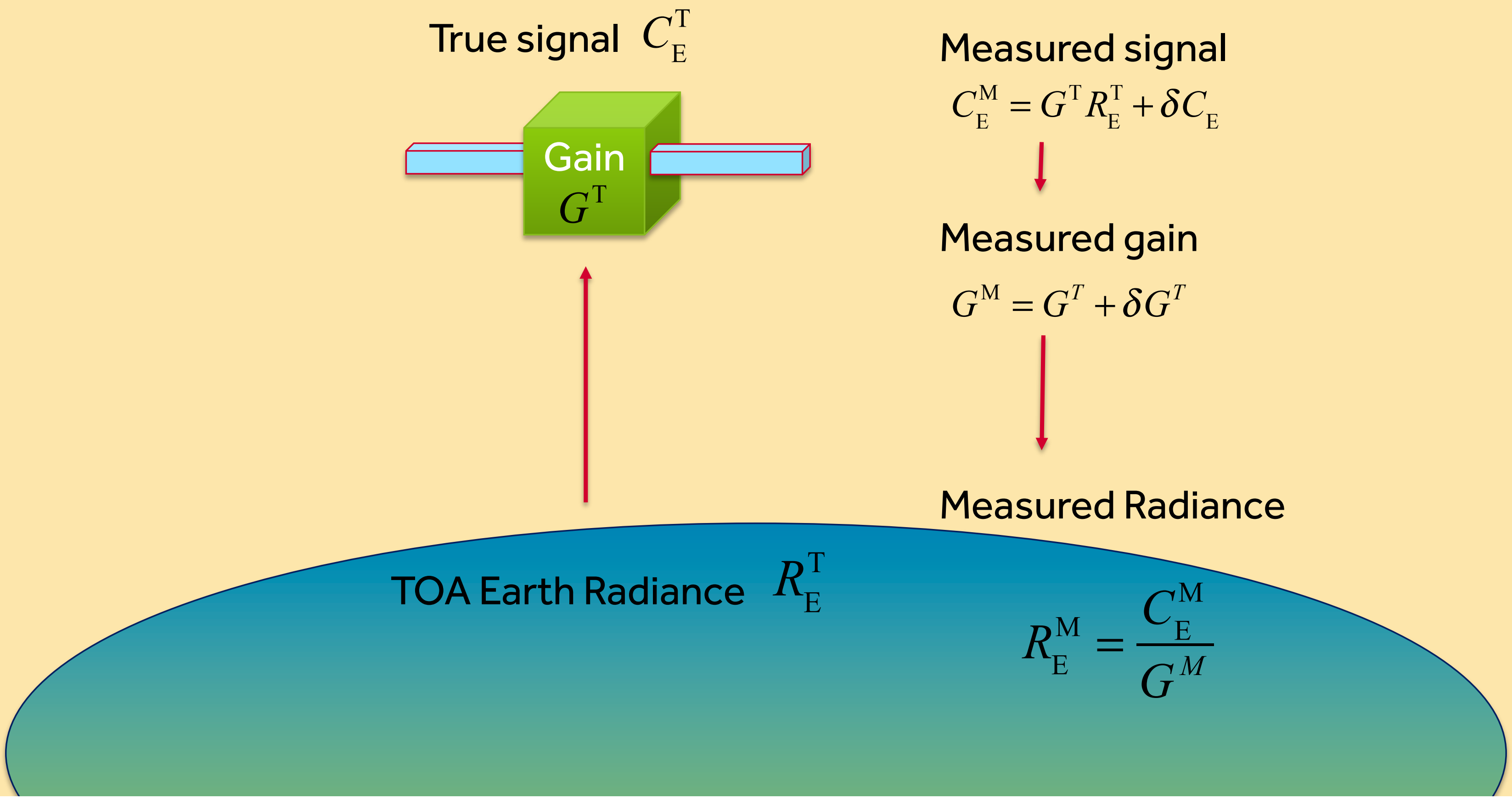
EO Uncertainty Analysis

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

- **Structured approach centred on measurement equation**

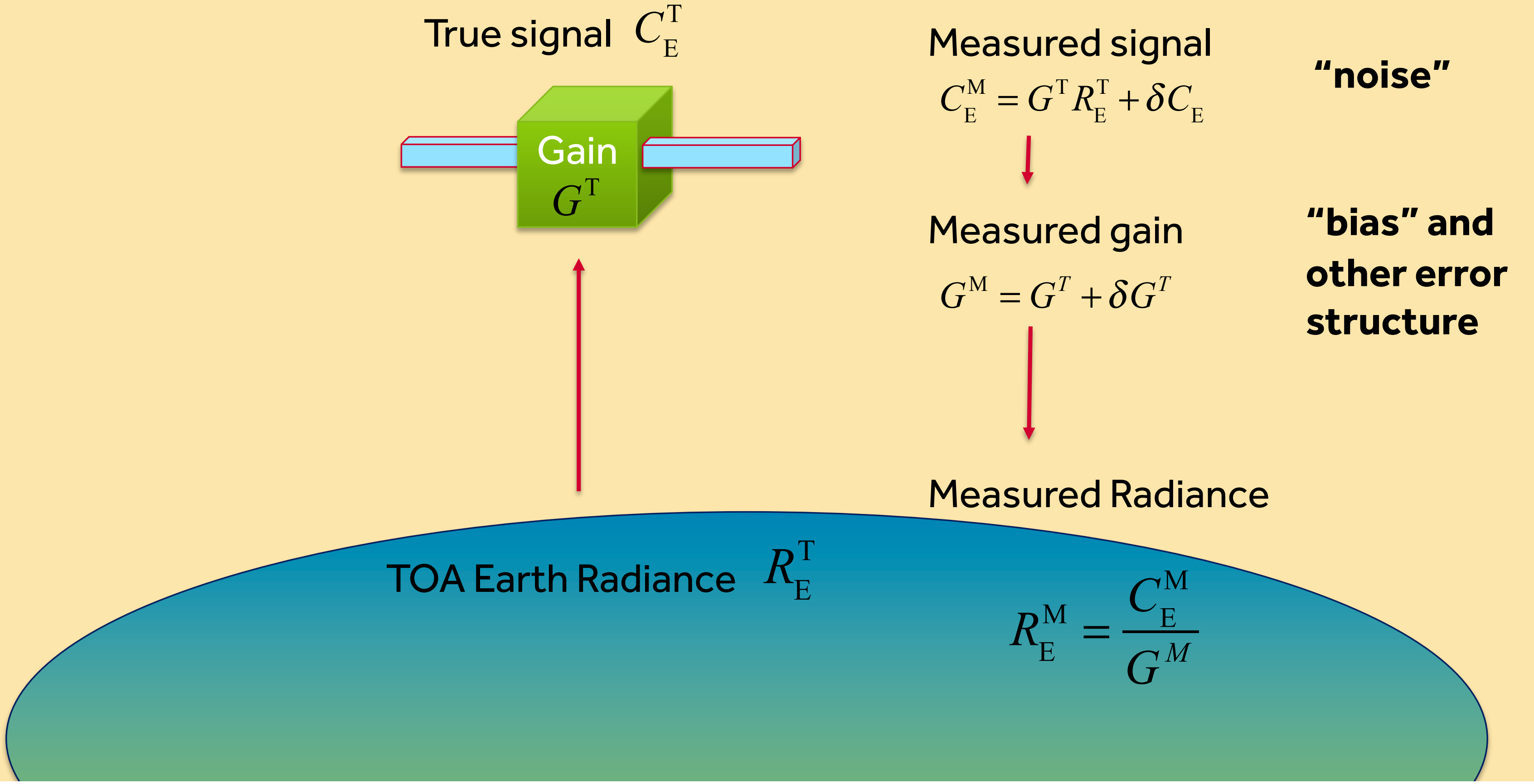
Measurement equation

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



Measurement equation

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



Uncertainty diagram

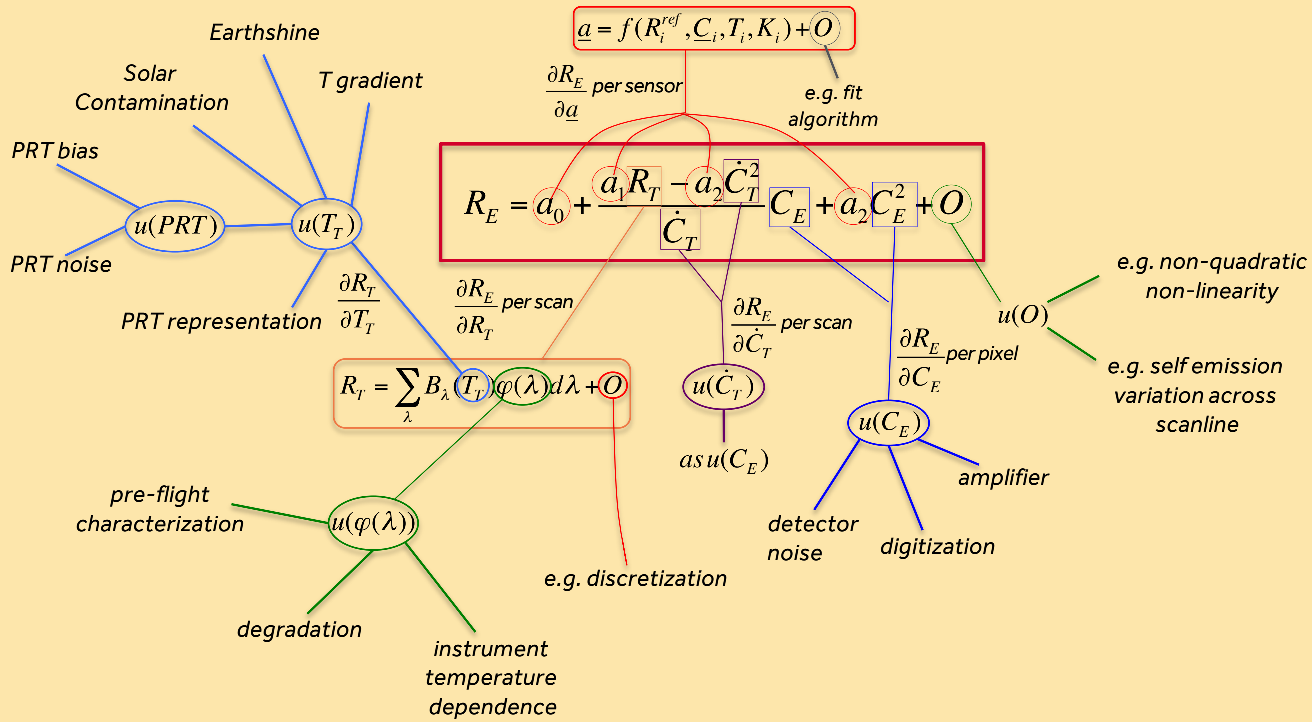
Example measurement equation: AVHRR

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

Uncertainty diagram

Example measurement equation: AVHRR

Analysis would be best done during mission development

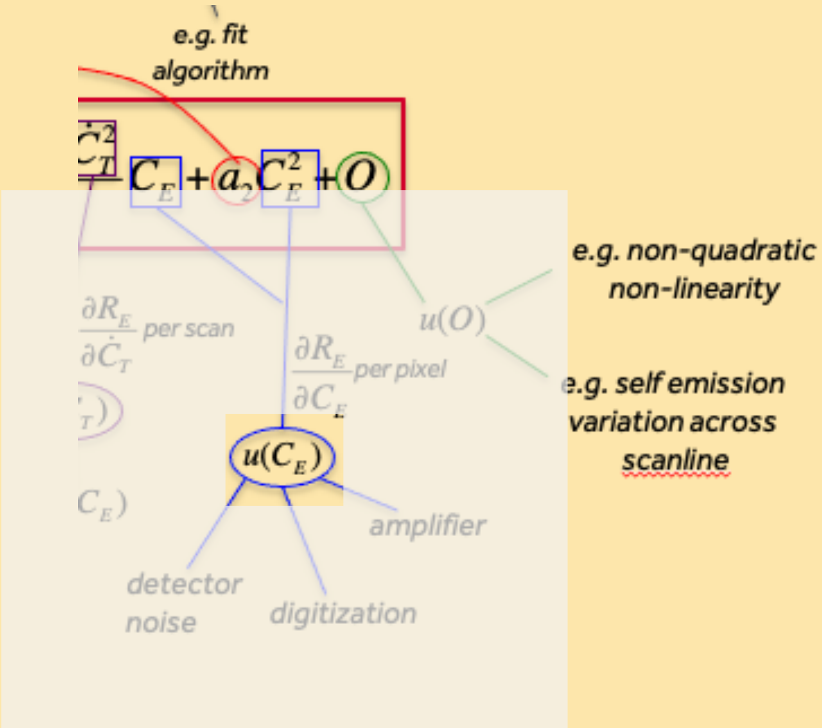


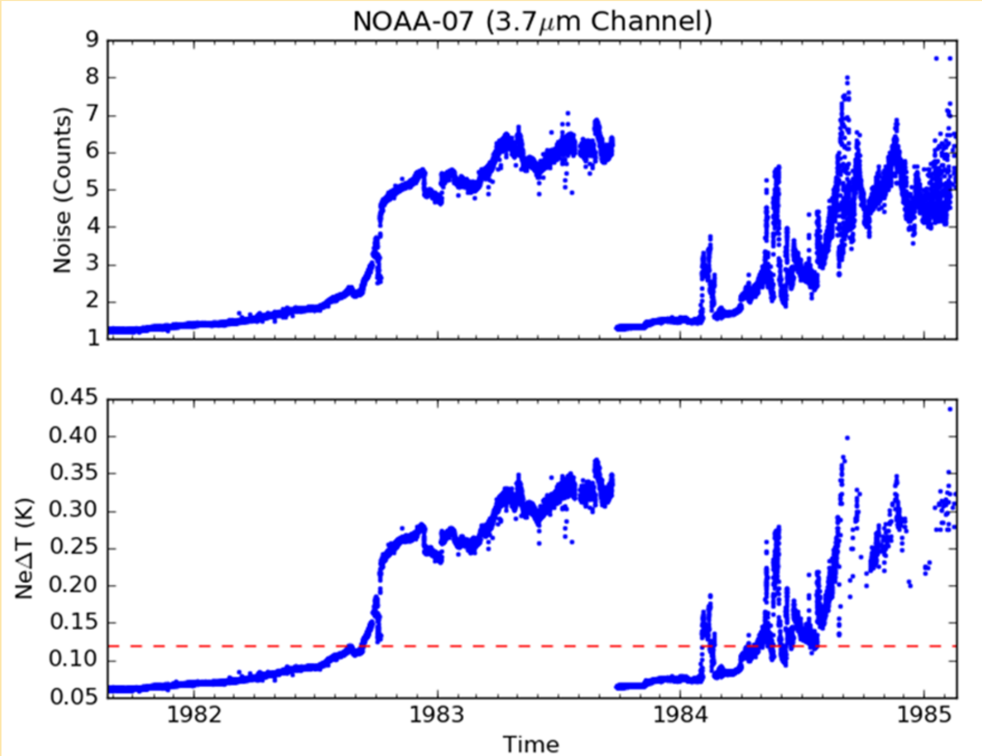
Quantify each error source

- Quantify the uncertainty in each input quantity from each error source that affects it
- Describe the correlation structure(s) of the errors
  - between pixels in an image
  - between spectral bands
- Quantify the sensitivity
  - the factor which propagates input uncertainty to radiance uncertainty

Quantify uncertainty in input quantity

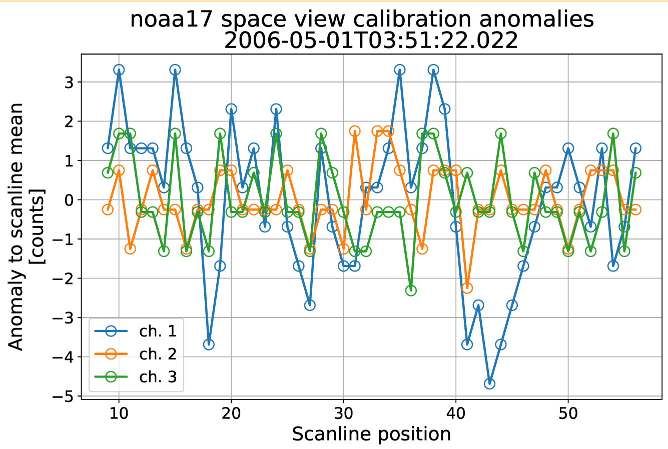
- Various forms of evidence for uncertainty: on-board data, pre-flight cal., model …



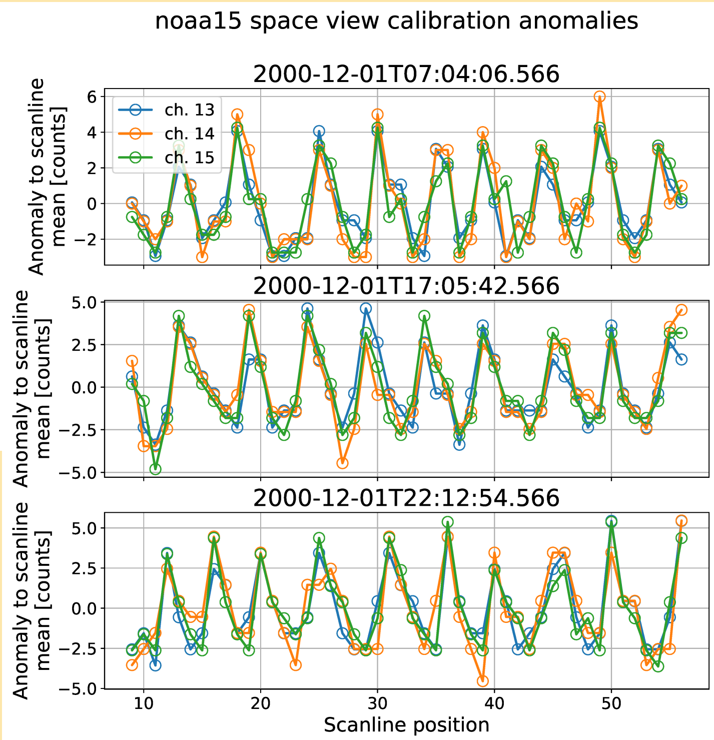


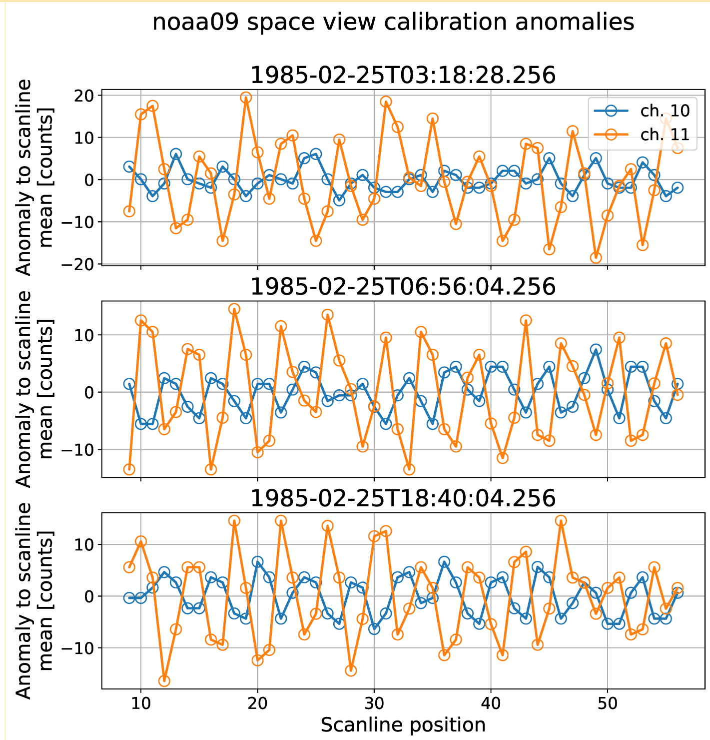
E.g., noise in an AVHRR channel evaluated by Allan deviation, over three years

Quantify error correlation structures



Holl et al., 2019, Rem Sens.,
doi.org/10.3390/rs11111337





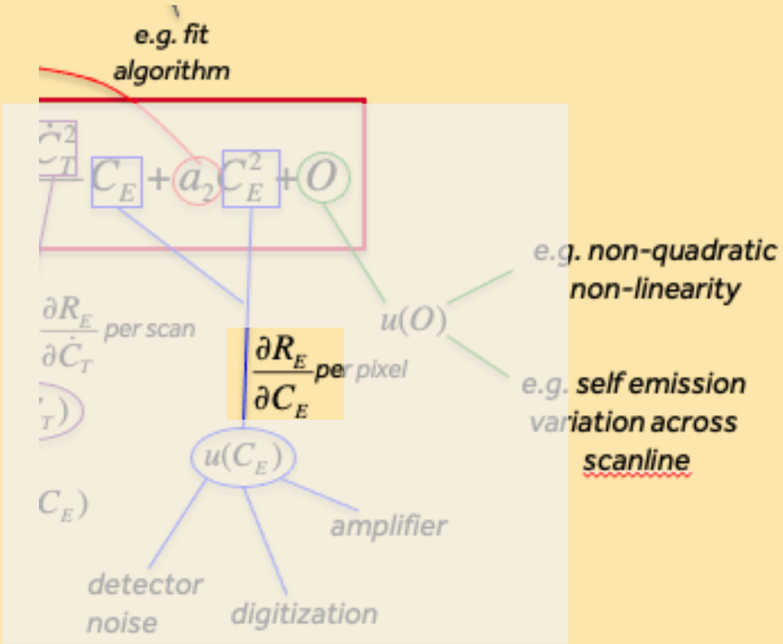
Uncorrelated noise

Correlated ‘noise’

Anti-correlated ‘noise’

Examples from three different HIRS sensors, looking at a (uniform) space view in two or three different channels

Calculate the radiance sensitivity to the effect



- Evaluate a derivative of output value to input value for target input quantity

- Not usually a constant

Capture in an effects table

Table descriptor		Comments	Example
Name of effect		A unique name	Internal calibration target count noise
Affected term in measurement function		Name and standard symbol	$\tilde{C}_{\mathrm{ICT}}$
Instruments in the series affected		Identifier	All instruments all satellites
Correlation type and form	Pixel-to-pixel [pixels]	One of the types	Rectangular absolute
	from scanline to scanline [scanlines]		Triangular relative
	between images [images]		N/A for orbiting satellite
	Between orbits [orbit]		Random
	Over time [time]		Random
Correlation scale	Pixel-to-pixel [pixels]	As needed to define type	[-∞,∞] (fully correlated across scan)
	from scanline to scanline [scanlines]		n = 51 (51 scanlines averaged in rolling average)
	between images [images]		N/A for orbiting satellite
	Between orbits [orbit]		0
	Over time [time]		0
Channels/bands	List of channels / bands affected	Channel names	All channels
	Error correlation coefficient matrix	A matrix	Identity matrix (diagonal).
Uncertainty	PDF shape	Functional form	Gaussian
	units	Units	Counts
	magnitude		Given once per orbit file
Sensitivity coefficient		Value, equation or parameterisation of sensitivity of measurand to term	$\frac{\partial L_{\mathrm{E}}}{\partial \tilde{C}_{\mathrm{ICT}}}$

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https://doi.org/10.1088/1681-7575/ab1705

Combine effects to characterize uncertainty

- Sum over effects for a selected set of observations to obtain error covariance

$$\boldsymbol{S}_c^p = \sum_j \sum_{k|j} \boldsymbol{C}_c^{p,j} \boldsymbol{U}_c^{p,k} \boldsymbol{R}_c^{p,k} \boldsymbol{U}_c^{p,k} \boldsymbol{C}_c^{p,j}$$

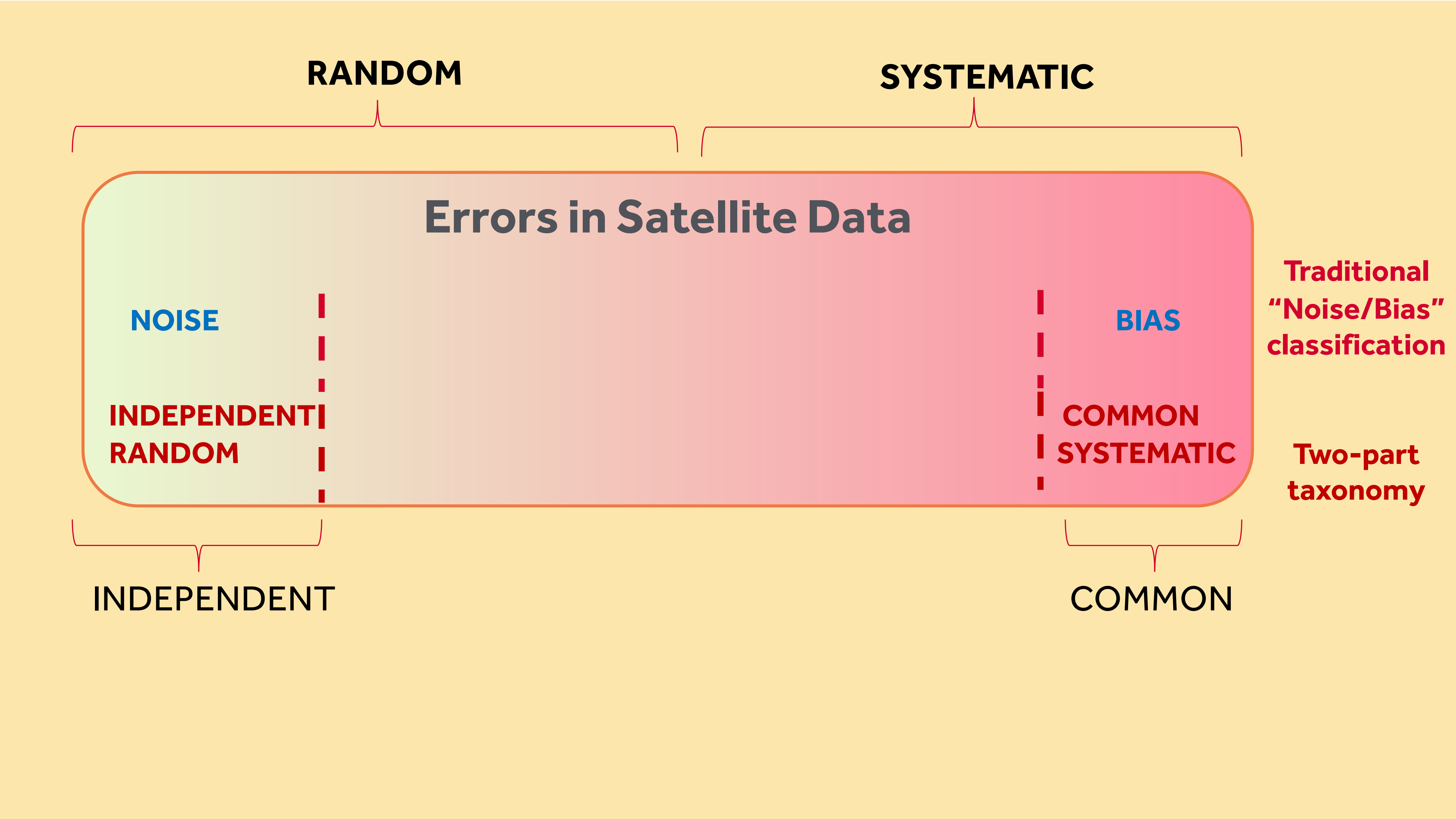
Correlation of the effect over observations

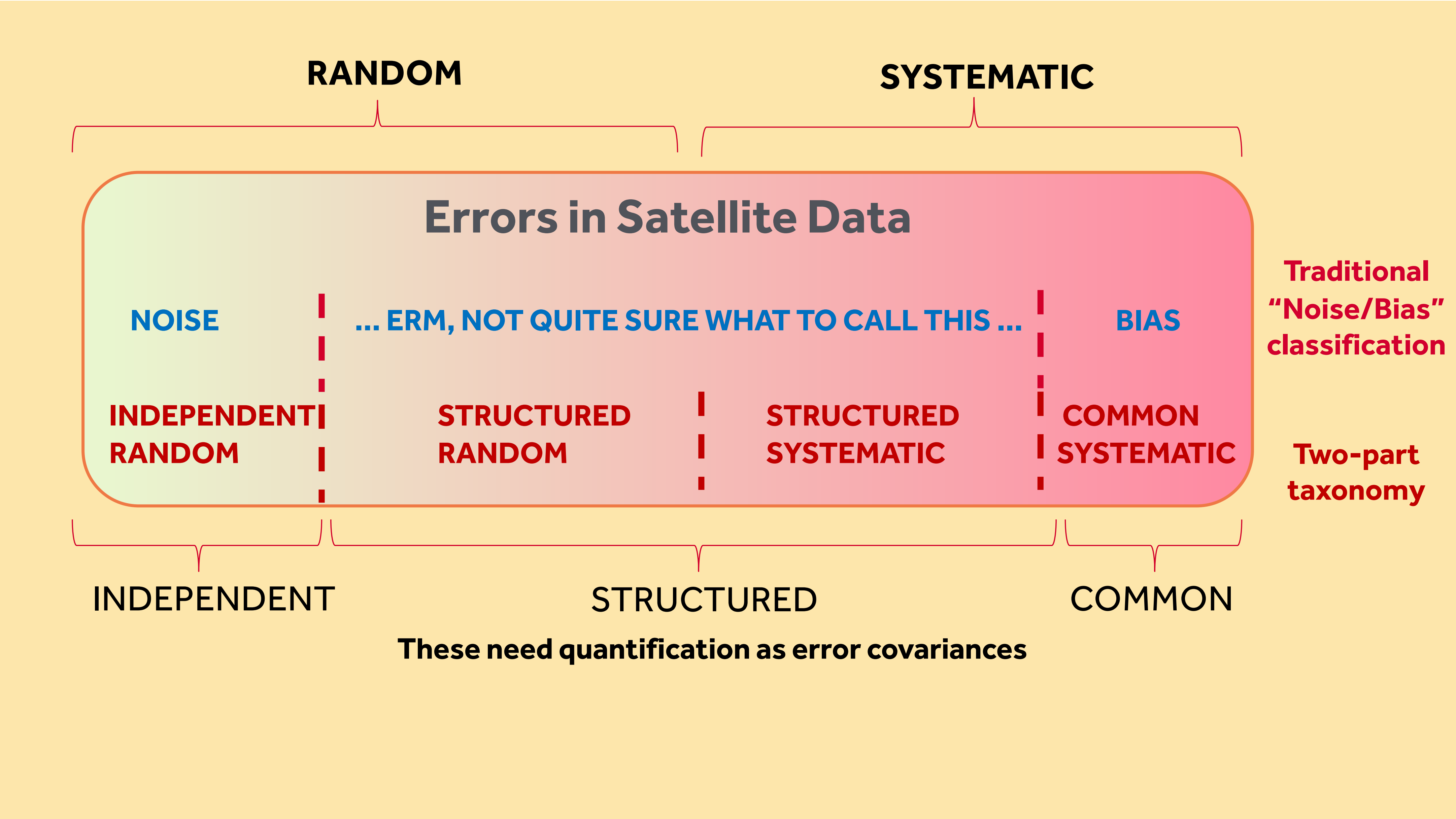
Uncertainty from the effect in the input values

Sensitivities of the observations to the effect

Summation over the various terms and effects

Merchant et al., 2019, Radiance uncertainty characterization, Rem. Sens., **doi.org/10.3390/rs11050474**


RANDOM
SYSTEMATIC
Errors in Satellite Data
NOISE
BIAS
Traditional "Noise/Bias" classification
INDEPENDENT RANDOM
COMMON SYSTEMATIC
Two-part taxonomy
INDEPENDENT
COMMON

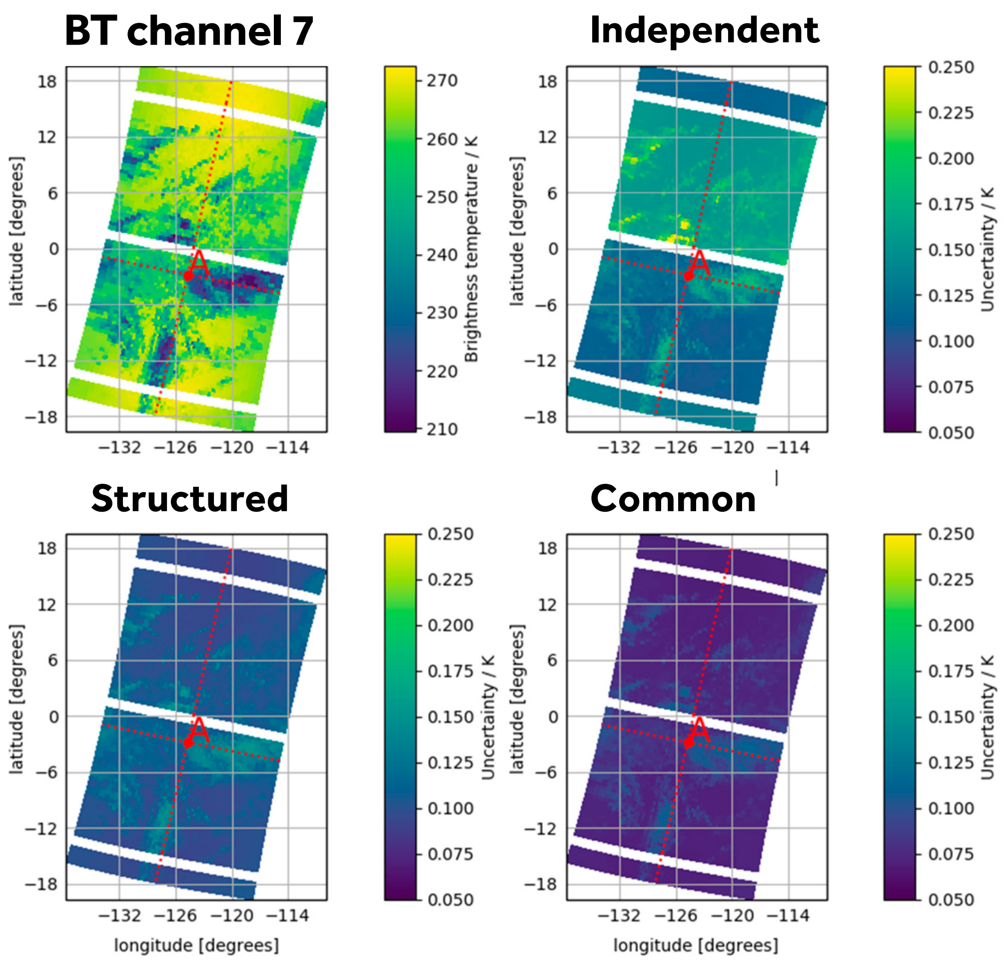

RANDOM
SYSTEMATIC
Errors in Satellite Data
NOISE
... ERM, NOT QUITE SURE WHAT TO CALL THIS ...
BIAS
Traditional "Noise/Bias" classification
INDEPENDENT RANDOM
STRUCTURED RANDOM
STRUCTURED SYSTEMATIC
COMMON SYSTEMATIC
Two-part taxonomy
INDEPENDENT
STRUCTURED
COMMON
These need quantification as error covariances

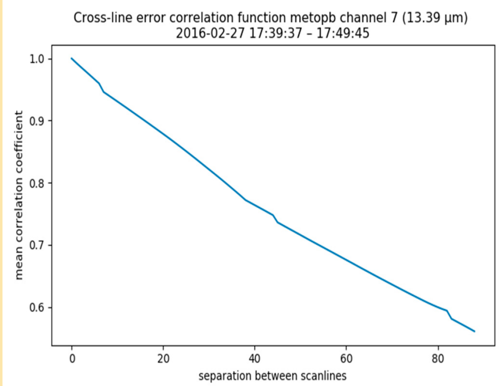
Practical summary of uncertainty in EO

- Three components of uncertainty **per pixel**
  - **Independent**
  - **Structured**
  - **Common**
- Averaged information provided **per product** for structured component
  - **Spatio-temporal error correlation length-scales**
  - **Cross-channel error correlation matrix**

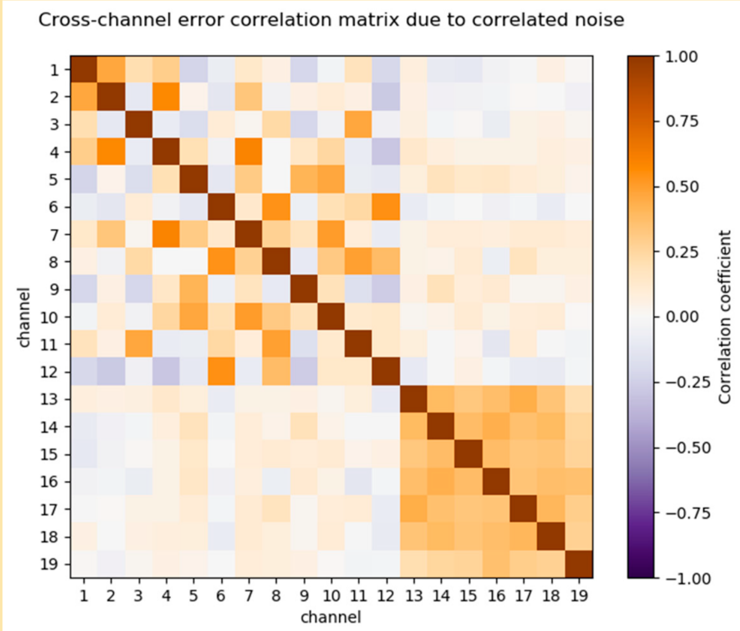
Merchant et al., 2019, Radiance uncertainty characterization, Rem. Sens., **doi.org/10.3390/rs11050474**

Example scene from HIRS Metop B



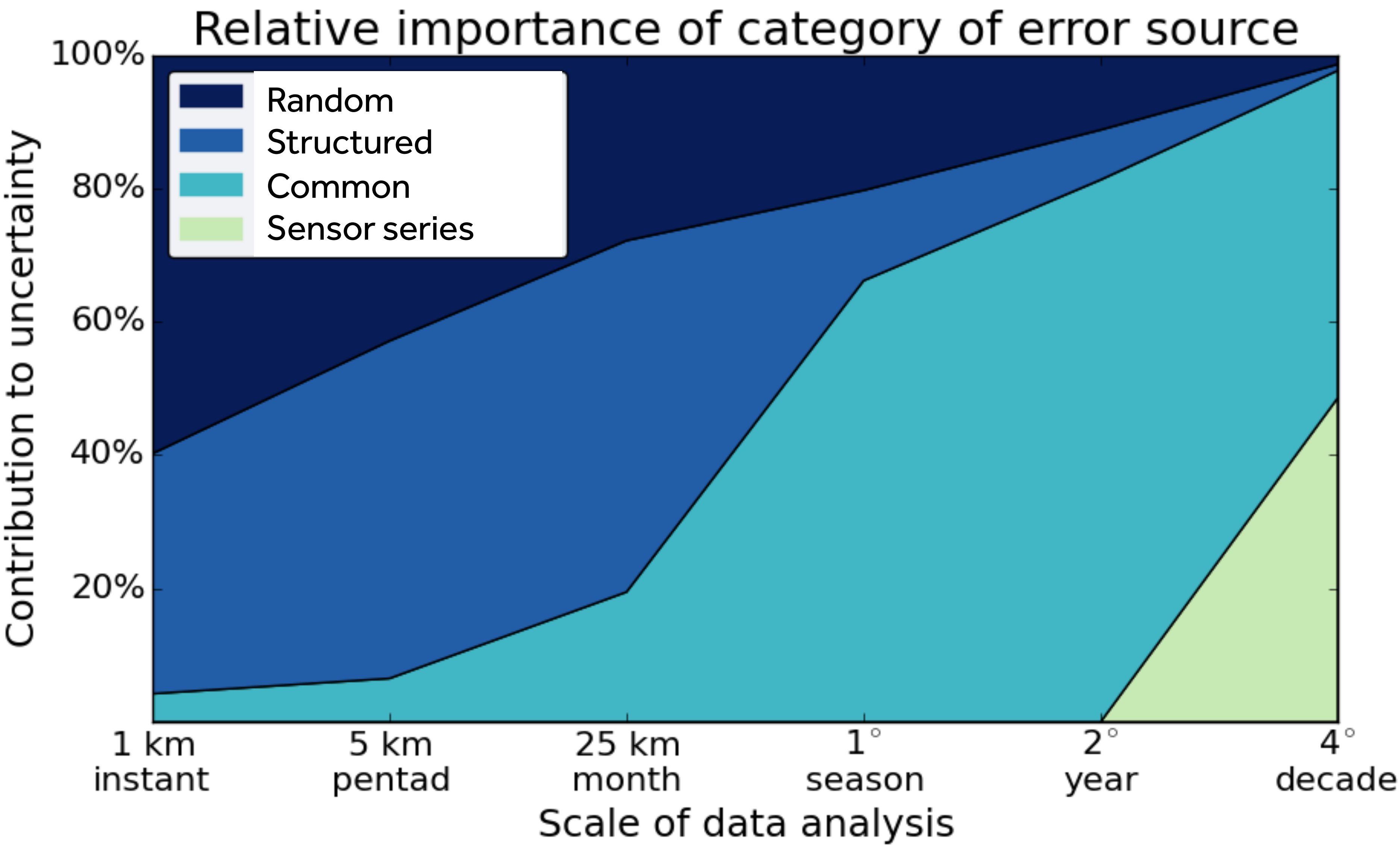


Correlation function along-track



Cross-channel correlation function

Merchant et al., 2019, Rem. Sens., **doi.org/10.3390/rs11050474**


Relative importance of category of error source
100%
80%
60%
40%
20%
Contribution to uncertainty
Random
Structured
Common
Sensor series
1 km
instant
5 km
pentad
25 km
month
1°
season
2°
year
4°
decade
Scale of data analysis

Ongoing projects

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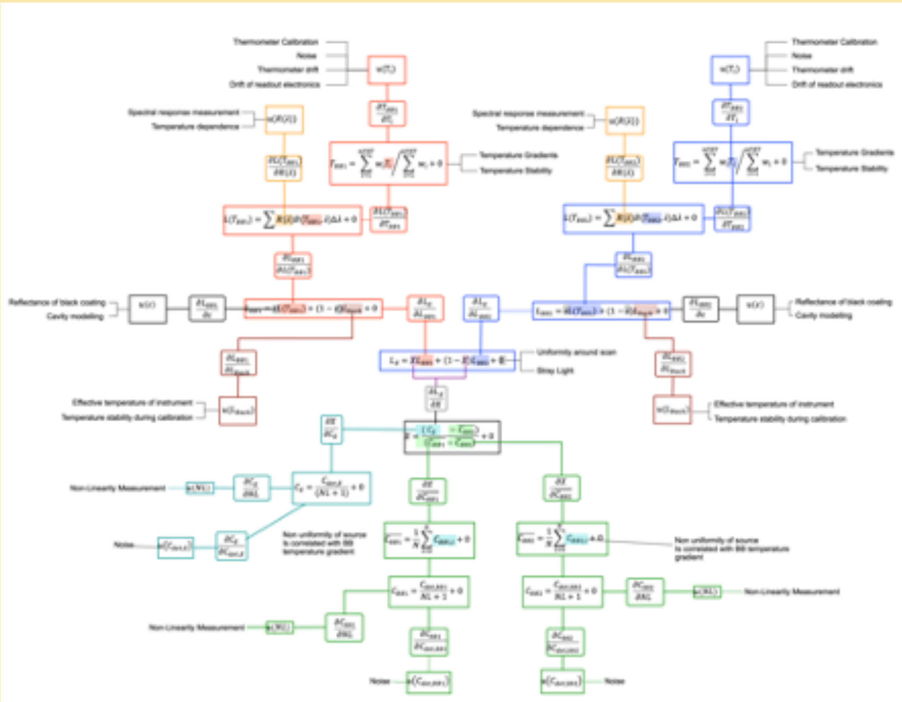
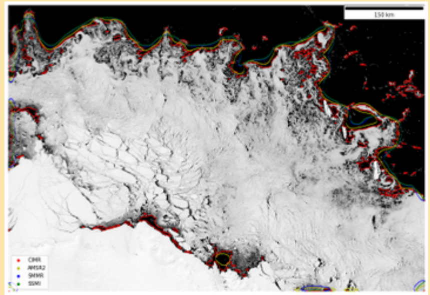
- Sea and Land Surface Temperature Radiometer Mission Performance



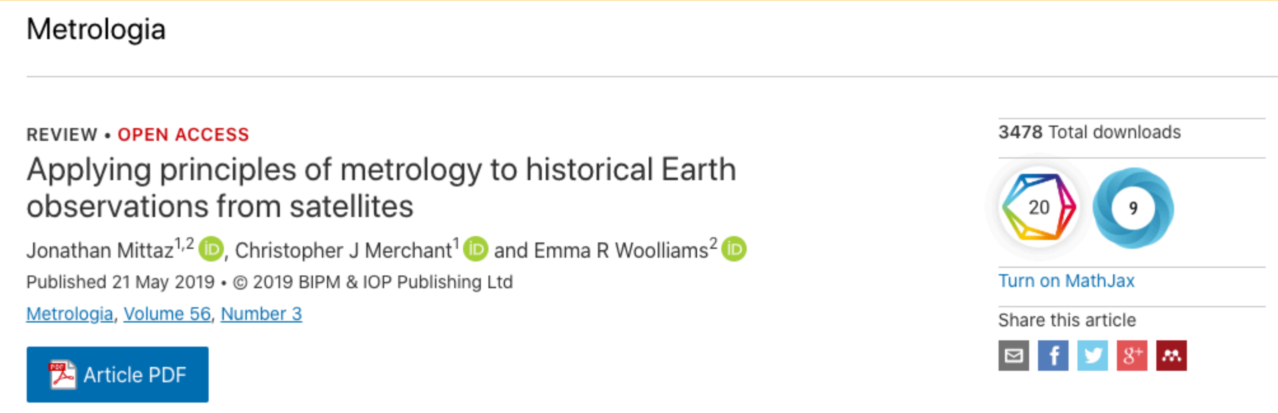
Smith, D., et al, in preparation

- Copernicus Imaging Microwave Radiometer MAG



SST, sea ice conc. & thickness

- C3S Satellite Data Rescue
  - Historic sensor biases



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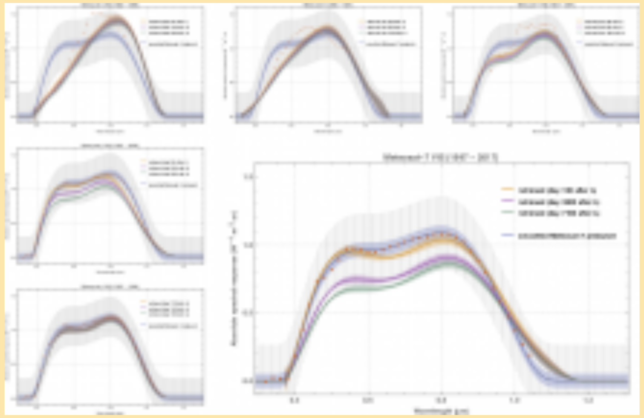
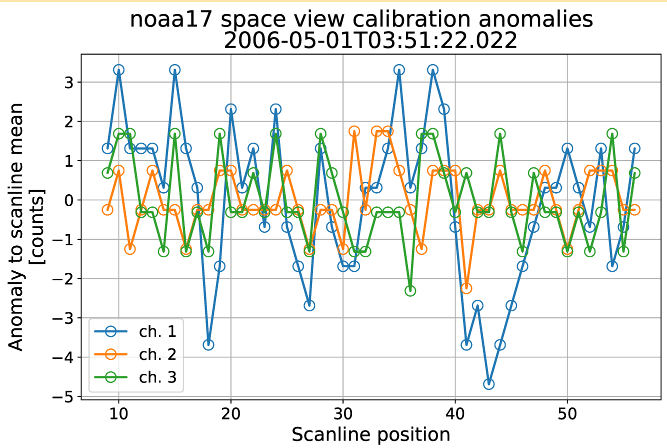


Quast et al, 2019, Retrieval of in-flight visible spectral response, **doi.org/10.3390/rs11050480**



Holl et al., 2019, Rem Sens., **doi.org/10.3390/rs11111337**

$$S_c^p = \sum_j \sum_{k|j} C_c^{p,j} U_c^{p,k} R_c^{p,k} U_c^{p,k} C_c^{p,j}$$

Merchant et al., 2019, Radiance uncertainty characterization, Rem. Sens., **doi.org/10.3390/rs11050474**

FIDUCEO legacy website:
https://research.reading.ac.uk/fiduceo/

Fiduceo

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