

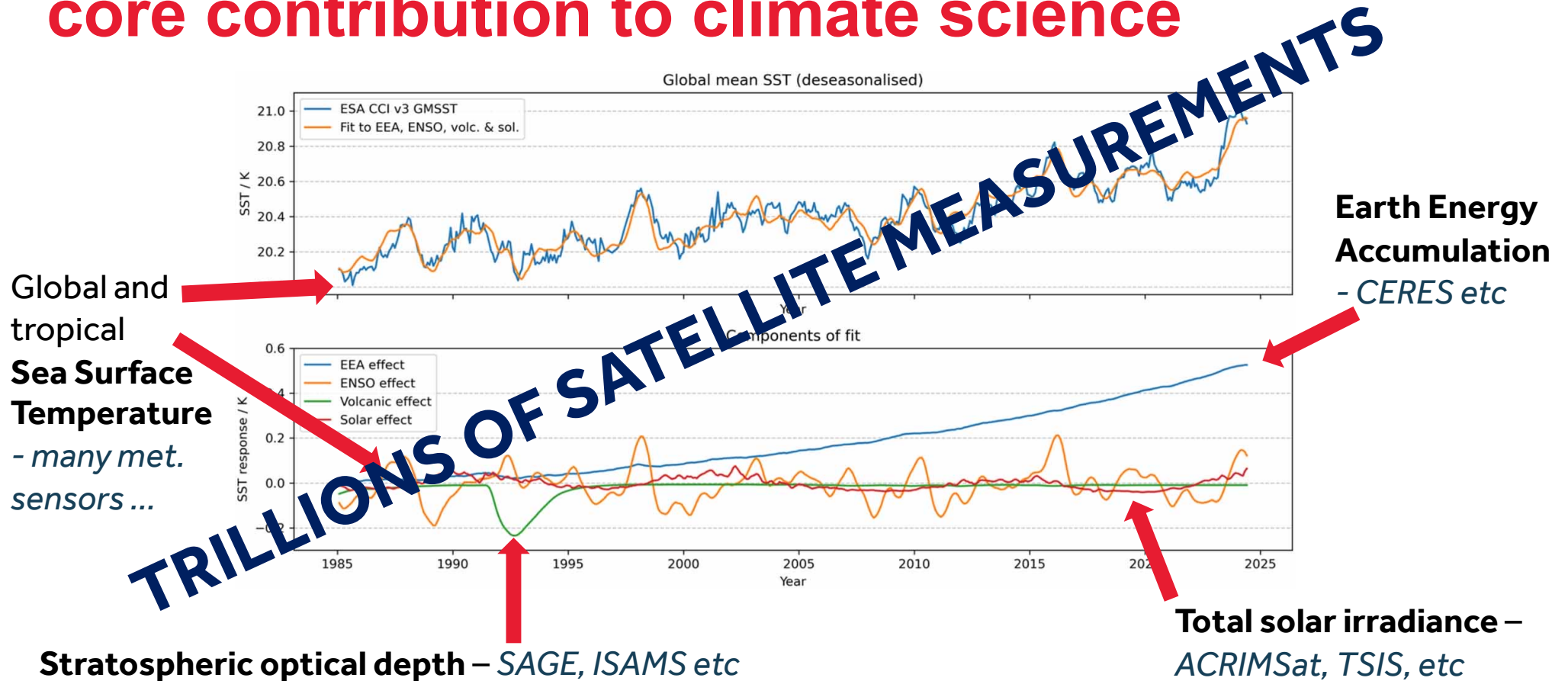
Satellite Observations of Climate Change Uncertainty and Stability



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National Centre for Earth Observation

**Uncertainty Quantification for
Climate Science**
November 2025

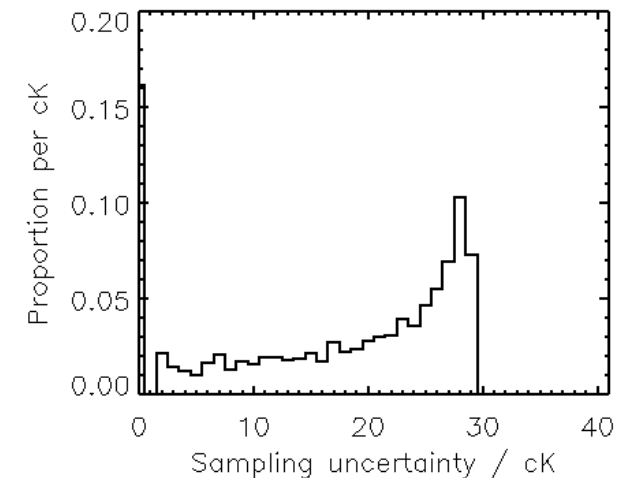
Observations from space make a core contribution to climate science



Merchant, Allan and Embury, *Quantifying the acceleration of multidecadal global sea surface warming driven by Earth's energy imbalance*, Env. Res. Lett., 2025. <https://iopscience.iop.org/article/10.1088/1748-9326/adaa8a>

What uncertainty information enables

- The purpose of uncertainty information in CDRs : **not fooling ourselves**
- Uncertainty information enables users to
 - distinguish data that have higher or lower uncertainty
 - interpret apparent differences over time or space appropriately
 - attribute uncertainty to derived indices, averages, etc
- Objective or relative weighting of observations in data assimilation systems ... accounting for error correlation



Outline

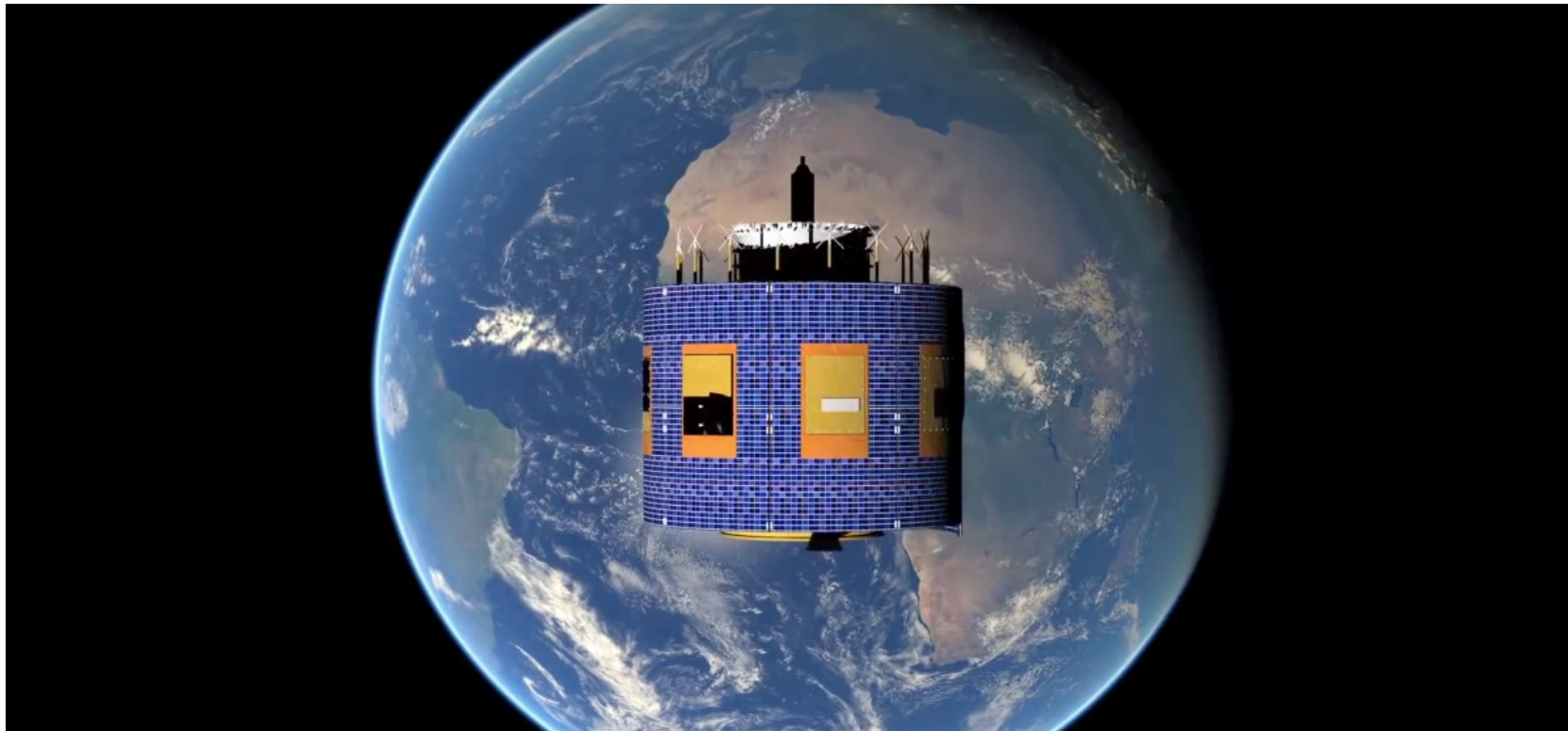
- Measurement and uncertainty characteristics of satellite climate data records
- Metrological approach to uncertainty information
- Stability – a key aspect of uncertainty

 The logo for Fiduceo features the word "Fiduceo" in a blue serif font. The letter "i" has a vertical bar through it. The letters "uceo" are set against a green trapezoidal background that tapers to the right.

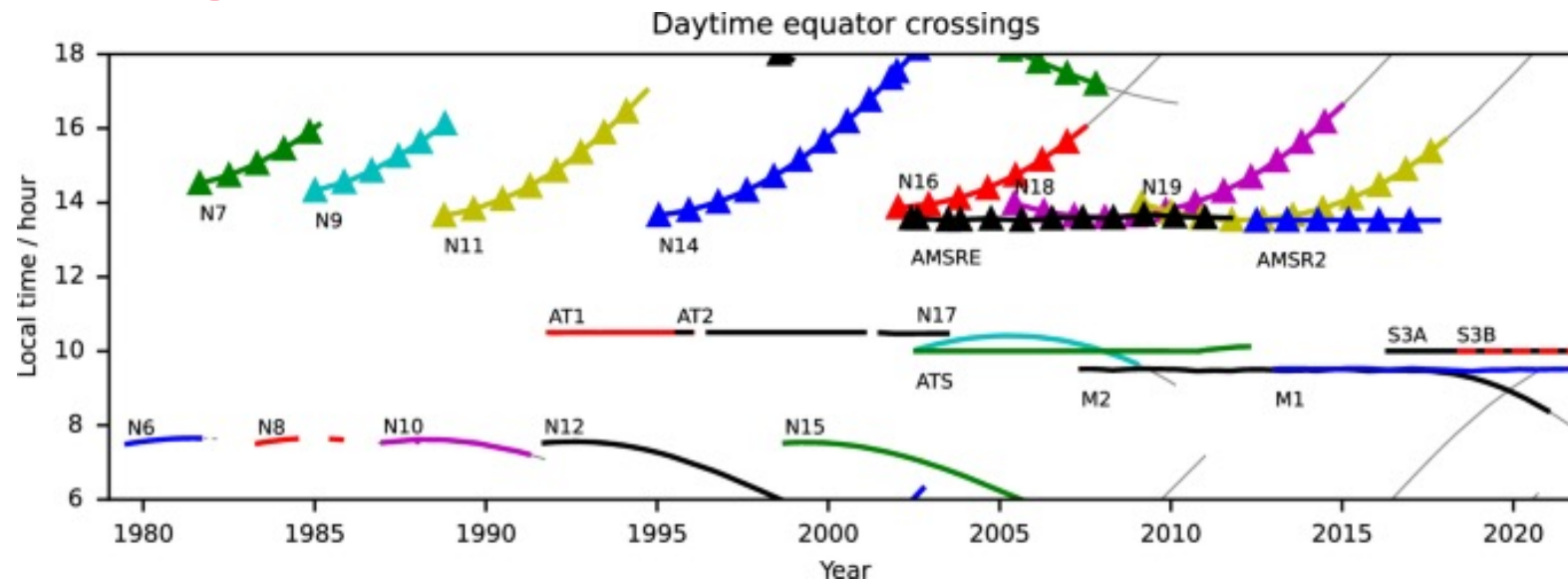
research.reading.ac.uk/fiduceo/



Global sampling – but constrained



Evolving constellations of missions



- Aliasing of daily cycles of ECV quantity unless corrected
 - Space environment changes with local time, affects calibration
 - Instrument particularities, and designs change (improve)
 - Harmonisation of missions leaves residual relative uncertainty
- sampling
 - calibration
 - retrieval
 - series

Limited metrology in space

- On-board calibration systems usually fall short of fully traceability to standards
- Measurements are never repeatable (unlike lab.)
- Calibration occurs on a temporal cycle relative to measurements
- Calibration system has some level of error



Complex error correlation

It is never "noise" + "bias"

Inverse quantities

- Inverting measurements of radiance nonlinearly related to **properties of interest**

$$L_{\lambda}(s_2) = L_{\lambda}(s_1)T_{\lambda}(s_1, s_2) + \int_{s_1}^{s_2} B_{\lambda}(T(s))k_{abs,\lambda}\rho T_{\lambda}(s, s_2)ds$$

- Irrespective of inverse method, raises questions of
 - Influence of prior information and indeterminacy
 - Propagation of radiance measurement errors
 - Knowledge of radiance-matter interaction

Inversion

Instrument

Forward model

Bringing metrology to Earth observation

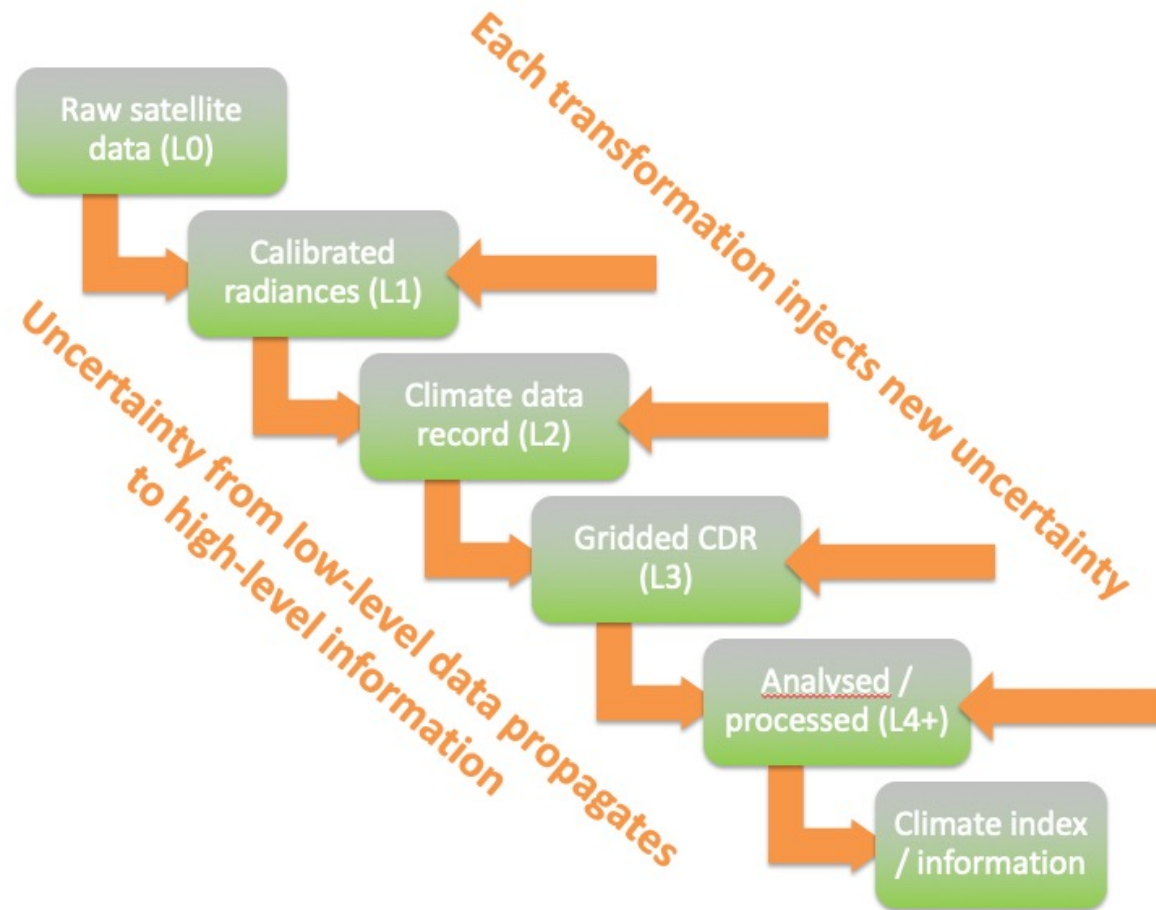


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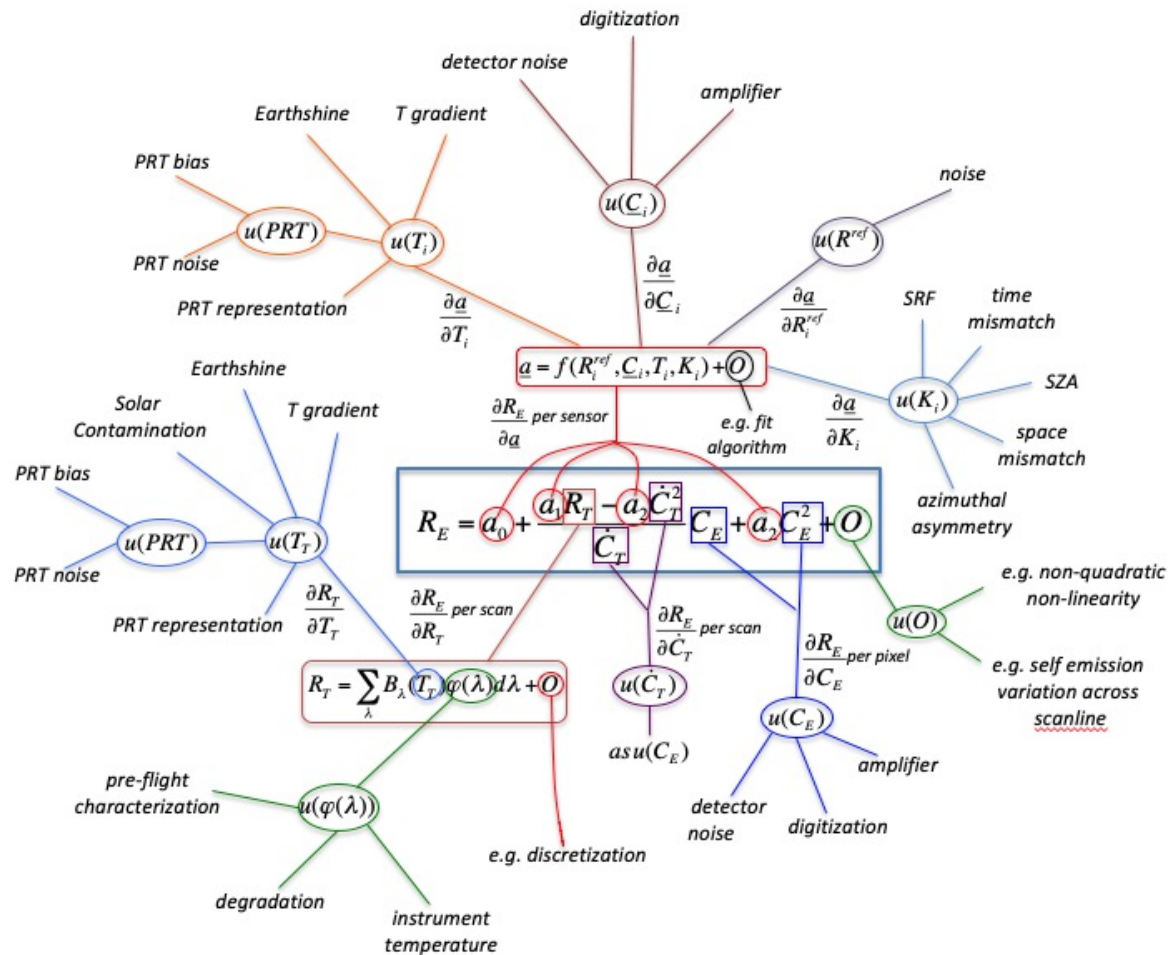
research.reading.ac.uk/fiduceo/

- EO as an extension of metrology: key principles and methods
 - Mittaz, J., Merchant, C. J. and Woolliams, E. R. (2019) Applying principles of metrology to historical Earth observations from satellites. *Metrologia*, 56 (3). doi: 10.1088/1681-7575/ab1705
- Practical mathematics for error covariance of satellite radiances
 - Merchant, C. J. , Holl, G., Mittaz, J. P. D. and Woolliams, E. R. (2019) Radiance uncertainty characterisation to facilitate climate data record creation. *Remote Sensing*, 11 (5). 474. doi: 10.3390/rs11050474
- Application to a series of atmospheric sounders
 - Holl, G., Mittaz, J. P.D. and Merchant, C. J. (2019) Error correlations in High-Resolution Infrared Radiation Sounder (HIRS) Radiances. *Remote Sensing*, 11 (11). 1337. ISSN 2072-4292 doi: 10.3390/rs11111337

Uncertainty relevant at every step

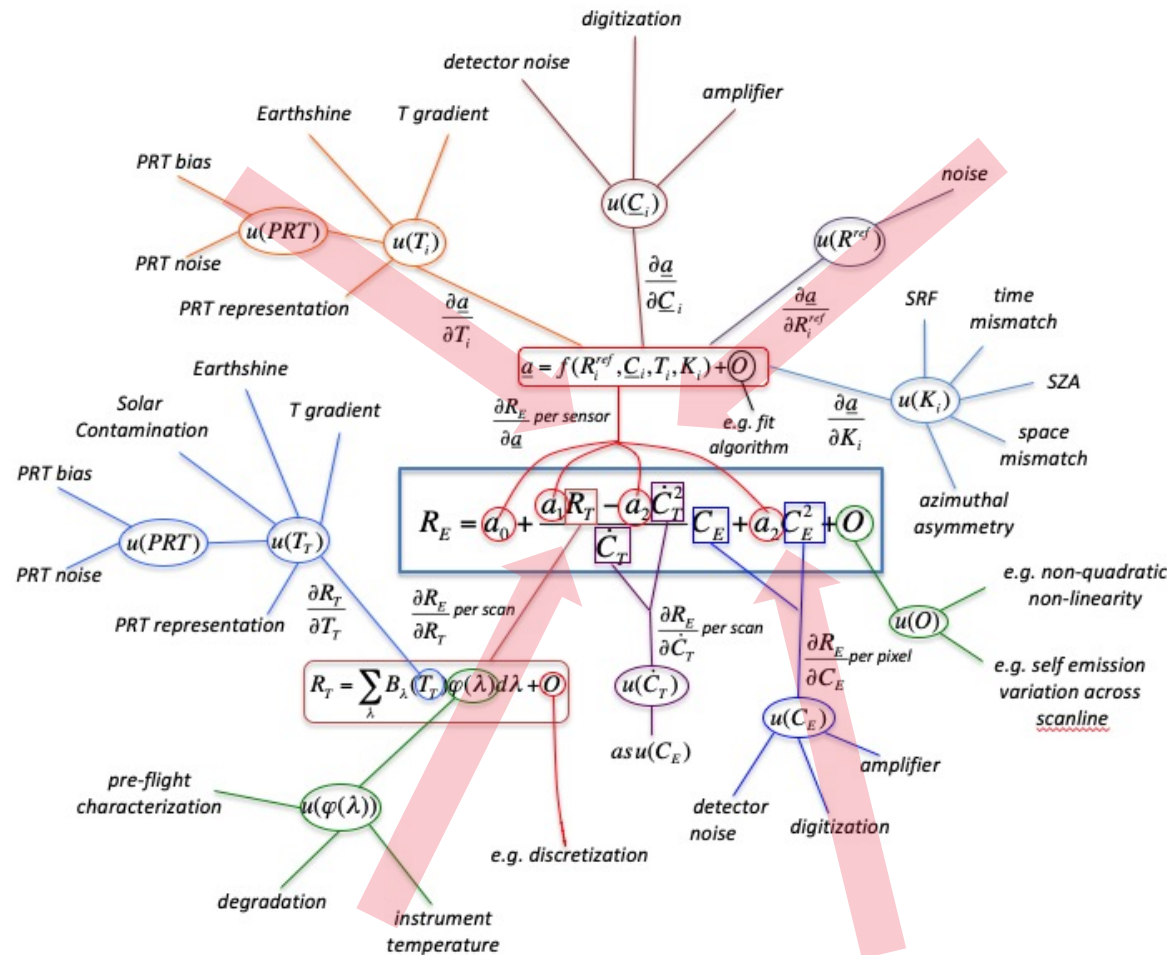


Structured uncertainty analysis



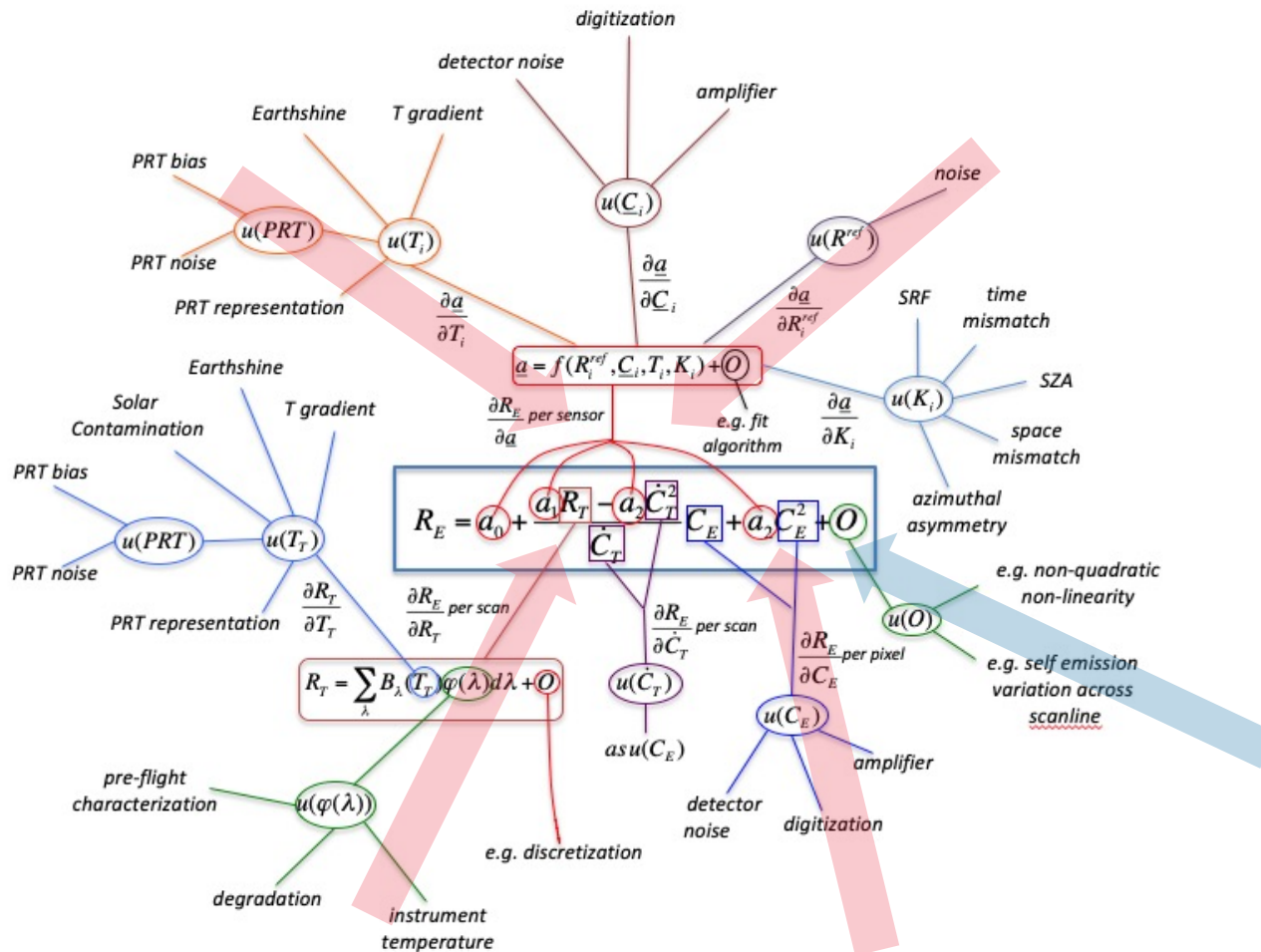
Best done at stage of developing a new satellite mission ...
 ... partial adoption by space agencies

Structured uncertainty analysis



Propagation of uncertainty from more fundamental quantities to derived quantities

Structured uncertainty analysis



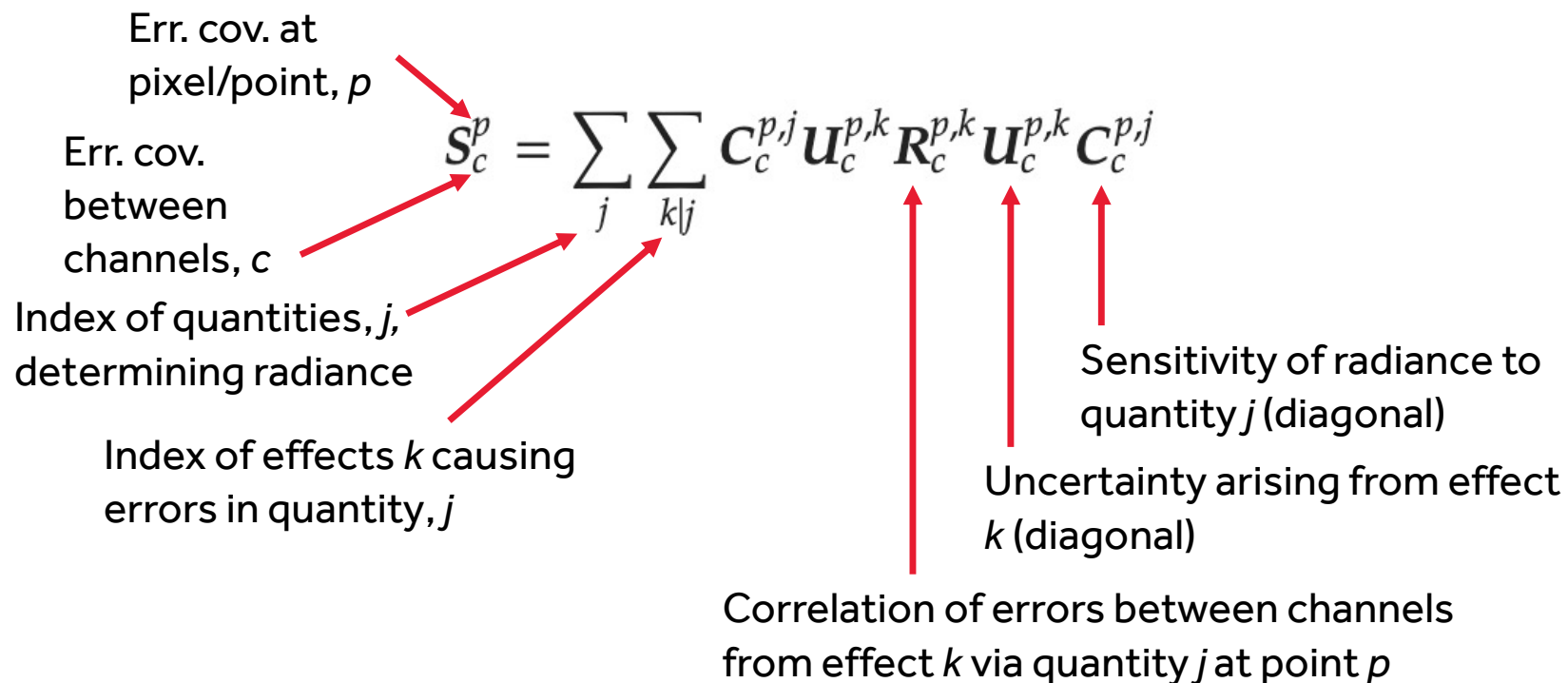
Propagation of uncertainty from more fundamental quantities to derived quantities

Injection of uncertainty via limitations of the measurement equation

Propagation of uncertainty

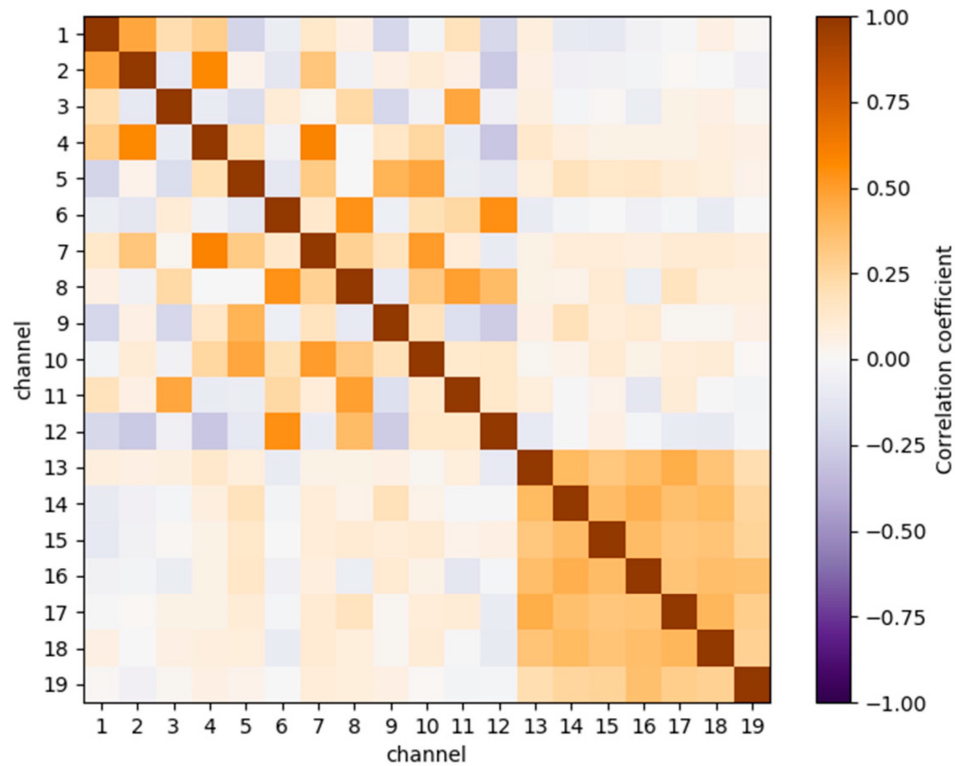
$$u = \sqrt{\sum_{i=1}^n \left(\frac{\partial y}{\partial x_i} u_{x_i}\right)^2}$$

- For example, **cross-channel error covariance of radiances**
- Used to find uncertainty in a subsequent retrieval.



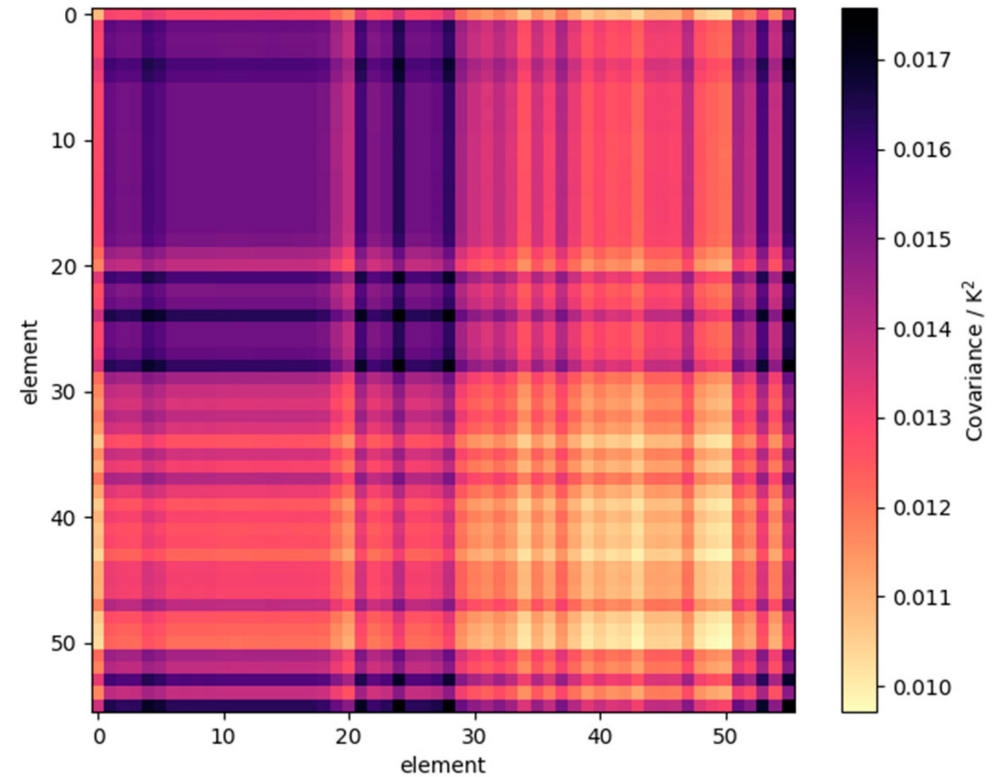
Example: an infrared sounder

Cross-channel error correlation matrix due to correlated noise



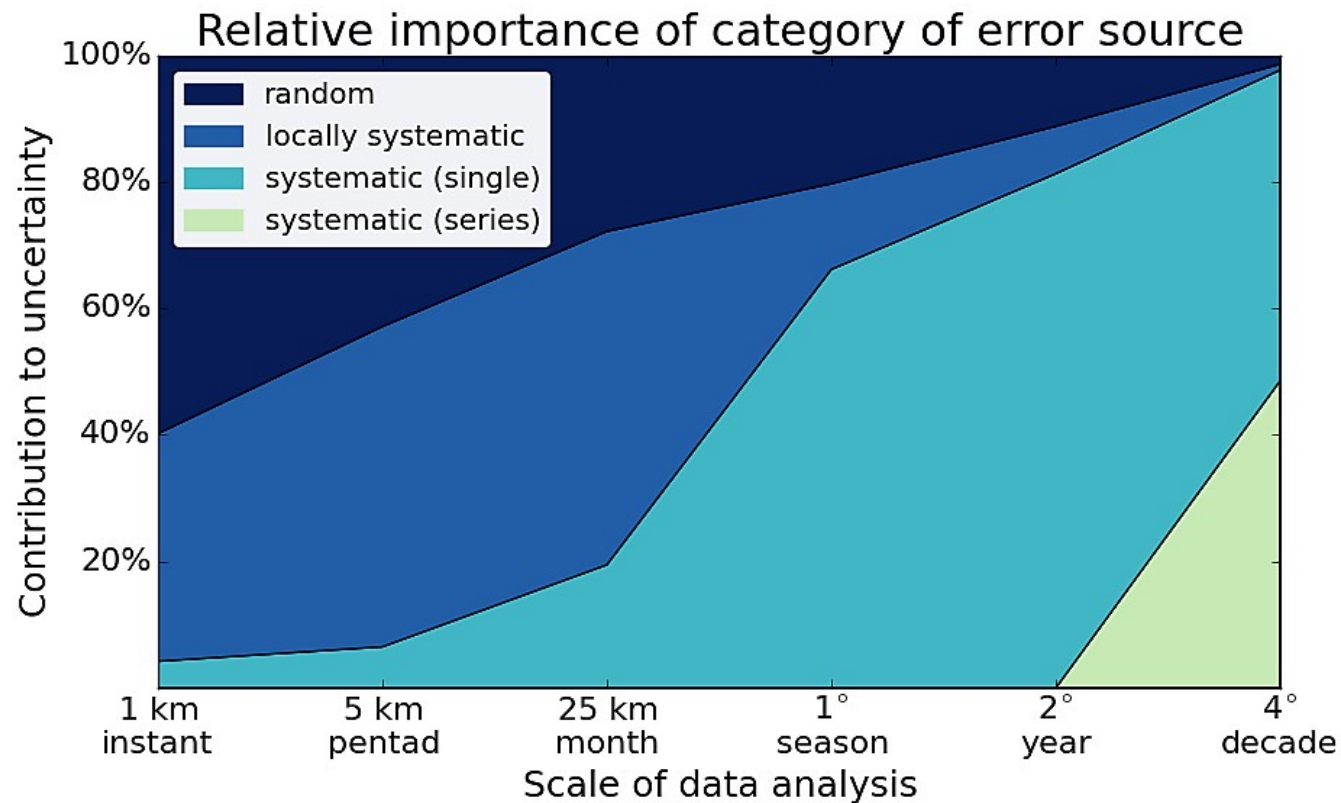
from noise in electronics

Cross-element error covariance matrix

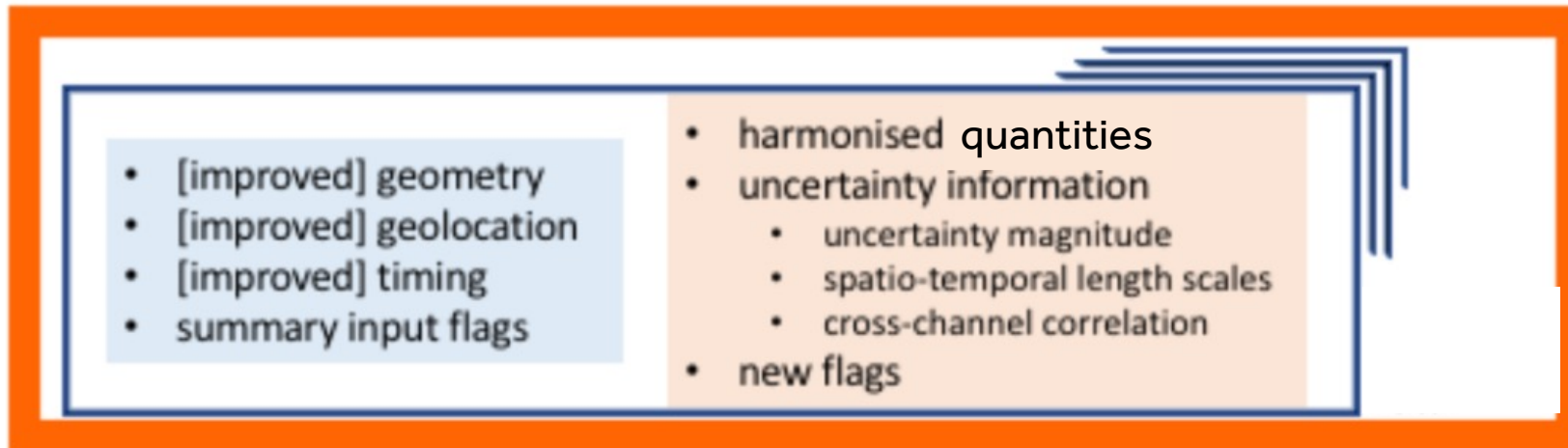


from structured effects in calibration

For climate application, can't just do the "big" sources of error



Viable uncertainty information in climate datasets



Concept underpinning development of uncertainty standards for the climate-forecasting conventions for model and observational climate datasets

But ... the problem of trend uncertainty

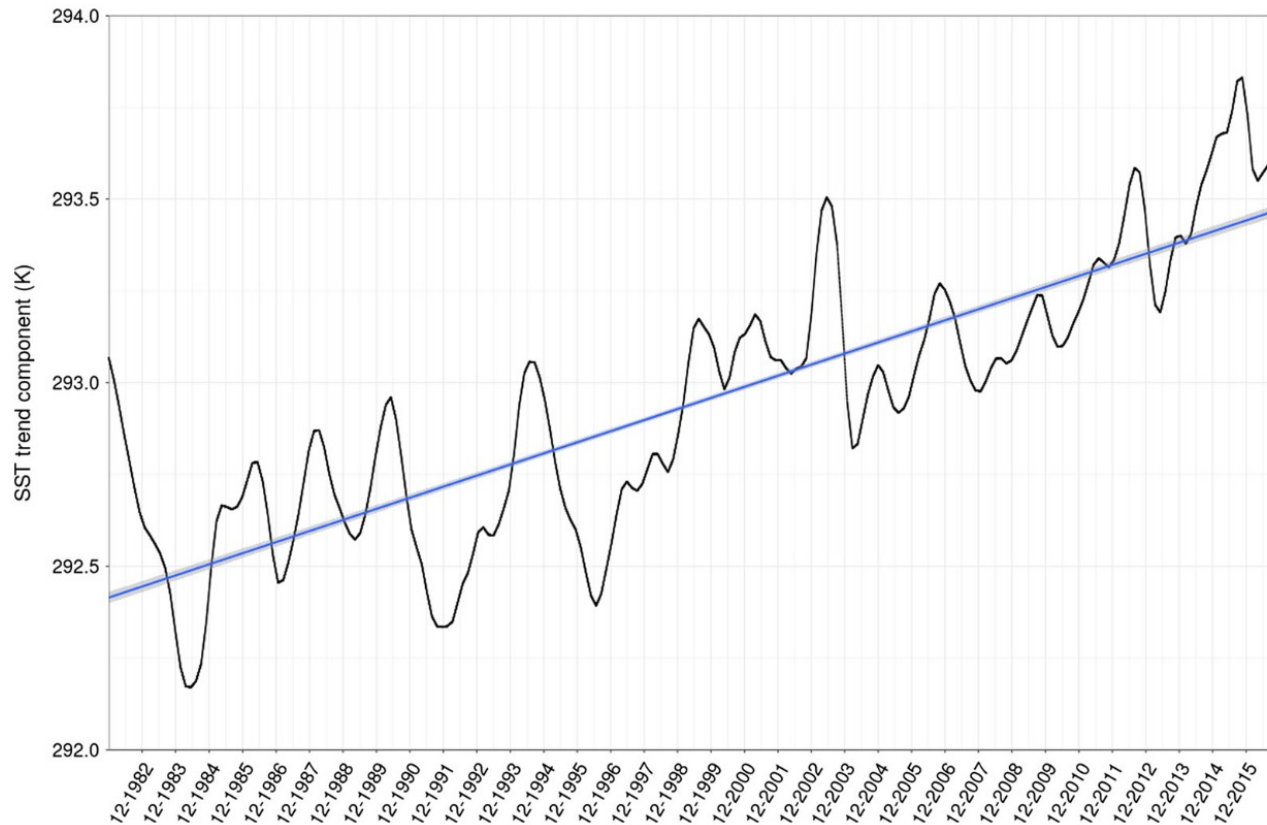


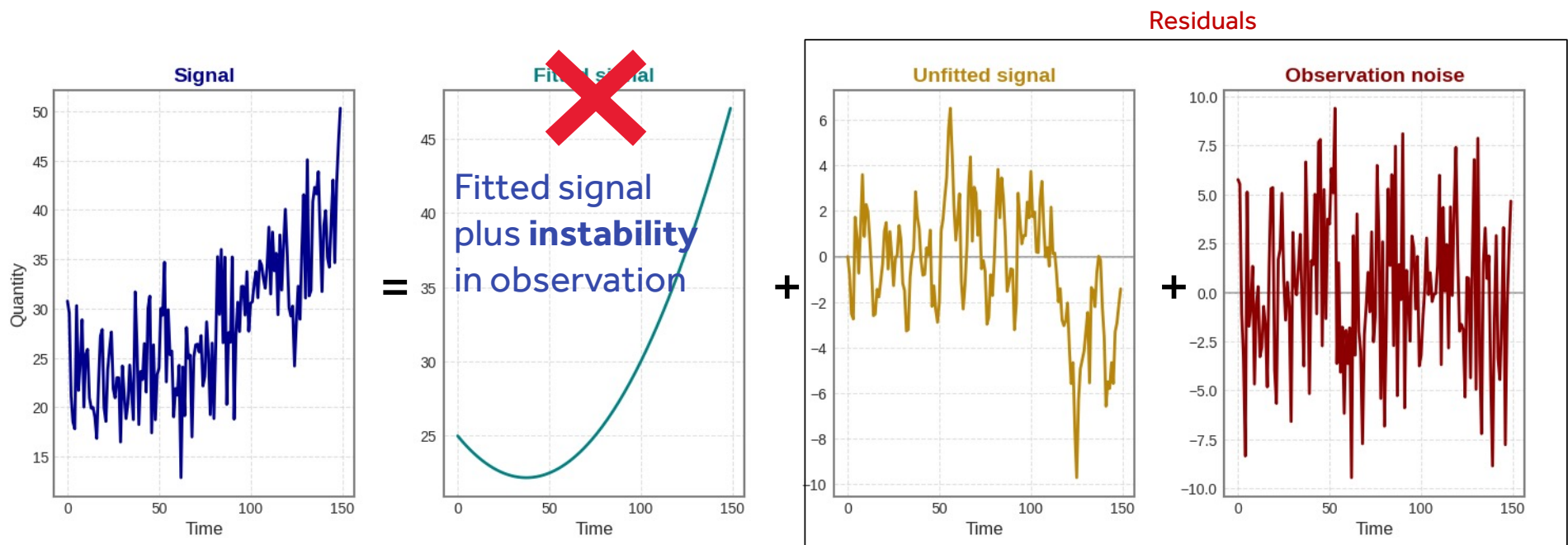
Figure 3
SST linear trend for 1982–2016 (grey shaded area shows 99% confidence interval)

The slope parameter uncertainty output from the stats package is NOT the uncertainty in the geophysical trend.

(Reference suppressed out of compassion)

Origin of the problem

- Mathematical development: Gobron K., et al, *A Unified Framework for Trend Uncertainty Assessment in Climate Data Records* (in review, *Surv. Geophys.*)
- When fitting, the quoted uncertainties assume:



GCOS definition of stability

- GCOS set requirements to limit the magnitude of “false trends” in data (trends arising from observation problems, not real change)
- Expressed as a “stability requirement”
- GCOS define the quantity of stability as

“the change in bias over time ... quoted per decade” [GCOS-245]

“the maximum permissible cumulative effect of systematic changes”
[secretariat presentation]

Observational stability (GCOS)

3.1.3 ECV Product: CO₂ column average dry air mixing ratio

Name	CO ₂ column average dry air mixing ratio				
Definition	2D column integrated number of molecules of the target gas (CO ₂) divided by that of dry air expressed in mole fraction.				
Unit	μmol mol ⁻¹				
Note					
Requirements					
Item needed	Unit	Metric	[1]	Value	Notes
Horizontal Resolution	km		G	1	imaging
			B	5	~OCO-2/3
			T	10	CO ₂ M, CEOS document - LEO, GEO
Vertical Resolution			G	-	N/A
			B	-	
			T	-	
Temporal Resolution	h		G	1	geostationary
			R	12	Blue report
			T	72	CO ₂ M
Timeliness	d		G	1	
			B	7	
			T	14	
Required Measurement Uncertainty (2-sigma)	ppm		G	0.6	1-sigma: 0.3ppm TCCON / Green report
			R	1	1-sigma: 0.5ppm Expert judgment based on improving CO ₂ M requirements
			T	1.6	1-sigma: 0.8ppm CO ₂ M requirements, WMO Report #242
Stability	ppm/decade		G	0.1	Within accuracy / 5
			B	0.2	Within accuracy / 5
			T	0.3	Within accuracy / 5

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Problems with the GCOS-245 definition

- Literal meaning differs from intent
- “Stability” is the wrong name for the numerical requirement
- Missing precision about:
 - Coverage factor / coverage probability
 - Scale of application in space and time

Merchant et al., *Stability specifications for climate data records: their meaning and application in evaluating geophysical trend uncertainty*, in review, *Surv. Geophys.*

Proposed clarifications

Terminology for stability

**(observational)
stability**

closeness of agreement between an observed value of change with time and a true value of change with time

stability error

difference of an observed trend value from a true (or reference) trend value of an essential-climate-variable quantity

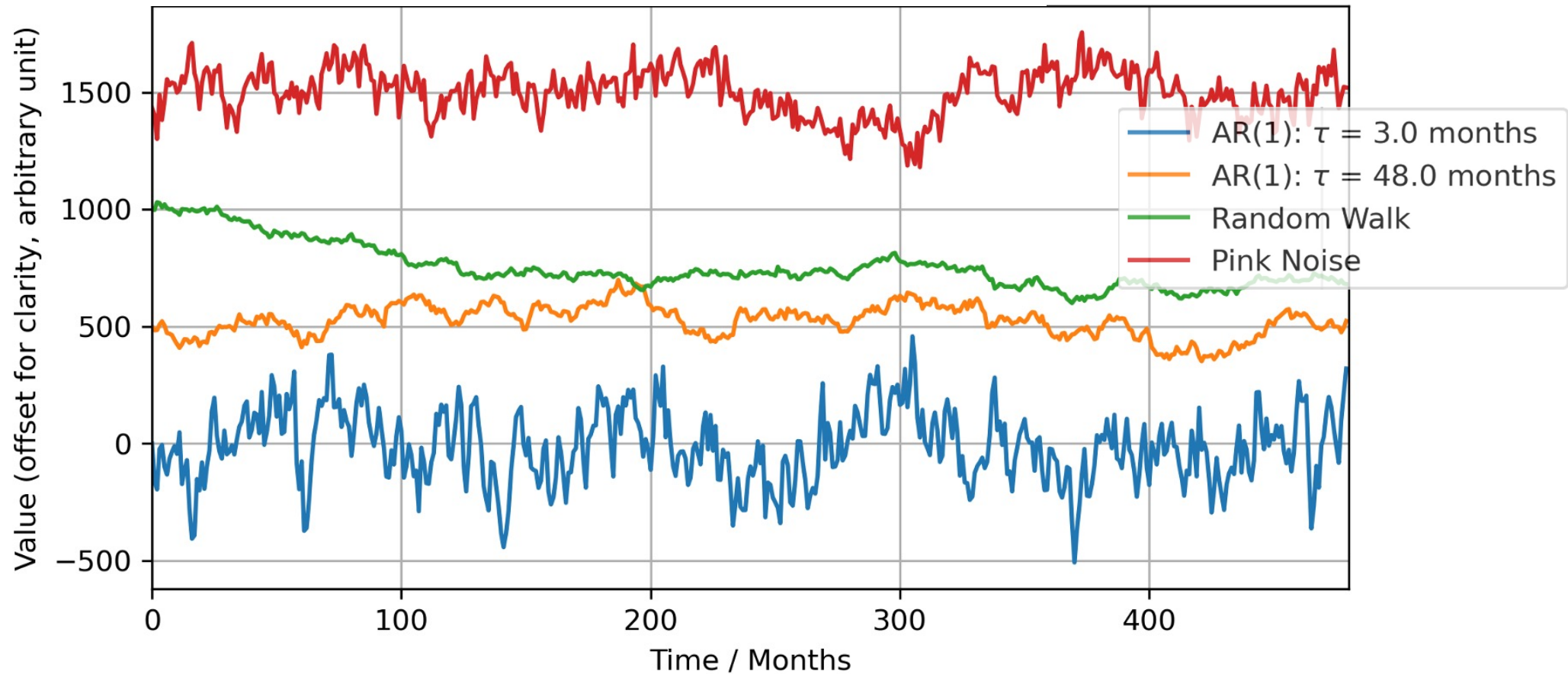
stability uncertainty

parameter characterizing the dispersion-arising-from-observation-errors of the trend values being attributed to an essential-climate-variable quantity

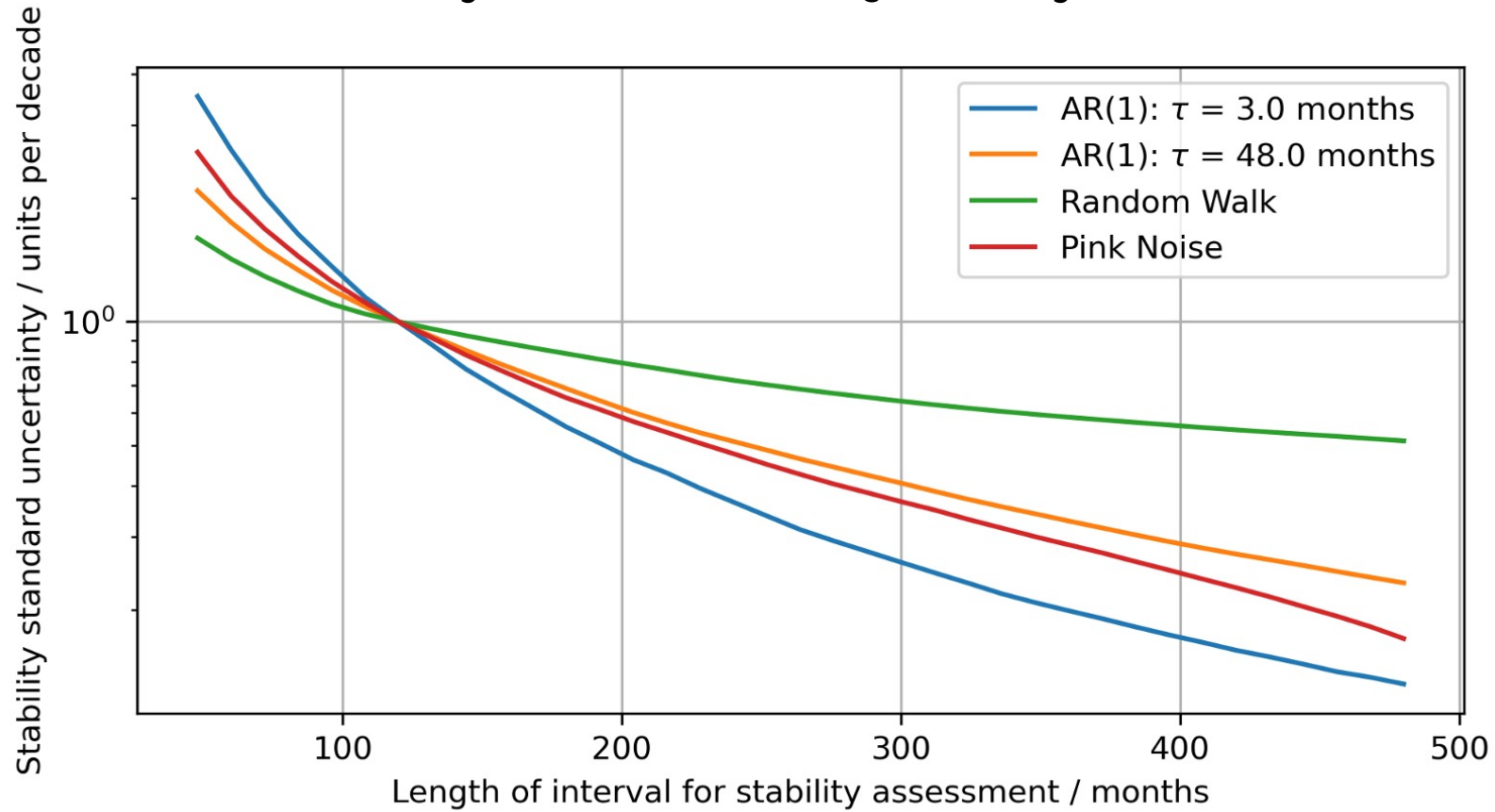
**stability standard
uncertainty**

stability uncertainty expressed as a standard deviation

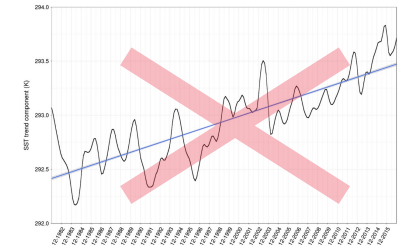
Sample of time series of observational errors



The uncertainty in linear trend injected by observation errors



Practical upshot and implication



- **Users calculating trends will understand that the trend uncertainty is never smaller the stability standard uncertainty of the observations**
- **Data producers need to provide estimates of stability uncertainty to users**
 - A metrological clear definition enables them
 - to know what to estimate
 - meaningfully compare to stated (GCOS) requirements
 - But understanding of **how** to estimate stability practically is not a solved problem
 - what FIDUCEO did for EO uncertainty needs to be done for CDR stability

Conclusions

- The basic principle that every measurement should be stated with an associated uncertainty is not easily applied to satellite data and climate data records
- But techniques now exist to
 - systematically calculate uncertainty and error correlation information
 - and condense and summarise these in useful forms for users
- Because of the interest of climate users in trends, a particular form of uncertainty requiring close attention is stability uncertainty, where there is still much work to do

