Earth Observation and Space
Department of Meteorology

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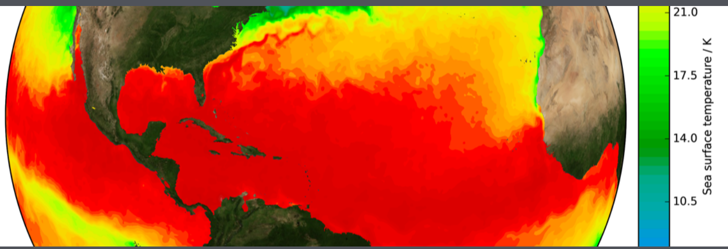
UNCERTAINTY IN CLIMATE DATA RECORDS FROM SATELLITE OBS'NS



Christopher Merchant
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National Centre for Earth Observation
NATURAL ENVIRONMENT RESEARCH COUNCIL

UK SPACE AGENCY

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OUTLINE

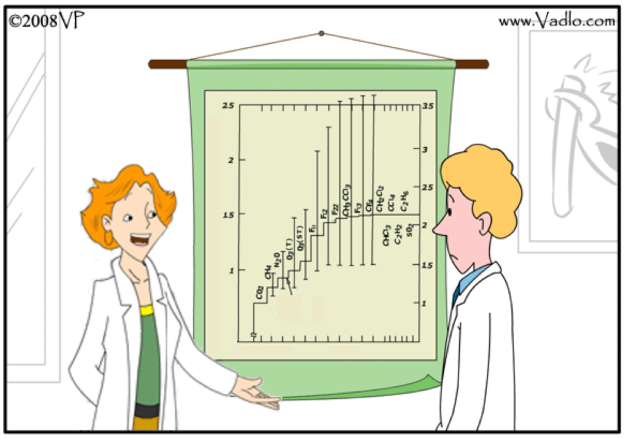
- Why am I talking about this?
- Motivations to improve uncertainty information in climate data records (CDRs)
- Some recommendations for CDRs
- Obstacles to achieving these
- Ongoing scientific developments
- Some recommendations for FCDRs/FDRs
- Proposals to CEOS/CGMS agencies
- Where we want to get to
- Discussion!

RELEVANCE TO ME

- Science Leader for Sea Surface Temperature within the ESA Climate Change Initiative project, and involved in 3 other CCI projects involving uncertainty aspects
- PI (with co-PI Jon Mittaz) of H2020 project Fidelity and Uncertainty in Climate data records from Earth Observation
- Close collaboration with the Earth Observation and Climate group of the National Physical Laboratory, including uncertainty and quality aspects within the Copernicus Climate Change Service

MOTIVATIONS FOR UNCERTAINTY INFORMATION IN CDRS

- Uncertainty estimation is fundamental to any measurement science



Did you really have to show the error bars?

MOTIVATIONS FOR UNCERTAINTY INFORMATION IN CDRS

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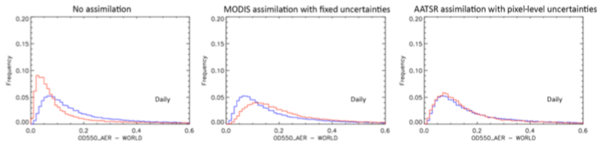
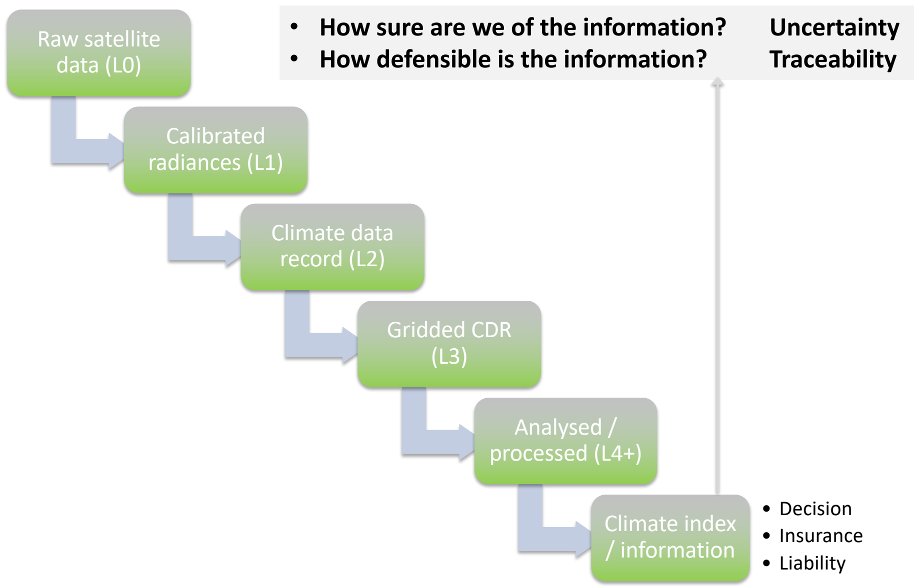
- Uncertainty estimation is fundamental to any measurement science
- Information about observational uncertainty in CDRs is needed in science
  - to quantify the confidence in inferences about changes in the Earth system (do we really know what we think we know?)
  - to support further propagation of uncertainty to higher-level studies
  - for informed model evaluation
  - as an element of observation error covariance in assimilation



- Requirements in society
  - to inform users (decision makers etc) about the data they are using



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Cross-ECV efforts in CCI

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6 Uncertainty characterization

6.1 Common Definition of Terms

Recommendation UC-1

> ***All CCI projects should use the same definition of terms in their work on Uncertainty Characterisation.***

The following example text could be used as Section 2 of the 'Uncertainty Characterization Document'. If individual CCI project teams chose to provide their own Section 2 they should not modify the given definitions.

Describing error and uncertainty

A measurement is a set of operations having the object of determining the value of a quantity. Following BIPM (2008) it is helpful to define the term measurand as

- **Measurand:** particular quantity subject to measurement

so that the phrases 'true value of a quantity' and value of the measurand are synonymous.
Very few instruments directly measure the measurand. Generally an instrument reports the effect of a quantity from which the magnitude of the measurand is estimated. As an example, an instrument sensitive to infrared light might be used to measure the temperature of an object.
The process of measurement is inexact, so that difference between a measured value and the value of the measurand is called the error. Traditionally (e.g. Beers, 1975) the word 'error' has also meant a numerical value that estimates the variability of the error if a measurement is repeated (i.e. a width of the distribution of possible errors). This dual meaning of "error" can lead to confusion or ambiguity. To separate these meanings and avoid confusion the BIPM (2008) definitions are used, i.e.

- **Error (of measurement)**: result of a measurement minus a true value of the measurand

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Volume 9, issue 2

Article | Peer review | Metrics | Related articles

Review article 25 Jul 2017

Uncertainty information in climate data records from Earth observation

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Abstract. The question of how to derive and present uncertainty information in climate data records (CDRs) has received sustained attention within the European Space Agency Climate Change Initiative (CCI), a programme to generate CDRs addressing a range of essential climate variables (ECVs) from satellite data. Here, we review the nature, mathematics, practicalities, and communication of uncertainty information in CDRs from Earth observations. This review paper argues that CDRs derived from satellite-based Earth observation (EO) should include rigorous uncertainty information to support the application of the data in contexts such as policy, climate modelling, and numerical weather prediction reanalysis. Uncertainty, error, and quality are distinct concepts, and the case is made that CDR products should follow international metrological norms for presenting quantified uncertainty. As a baseline for good practice, total standard ... CDR on the large space scales and long timescales that are highly relevant for some climate applications. For this reason, identifying and characterizing the relevant sources of uncertainty for CDRs is particularly challenging. The characterization of uncertainty caused by a given

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Uncertainty recomendations for CDRs

- **Provide uncertainty estimates**
- Follow metrological conventions
- Give u per datum if necessary
- Uncertain ≠ Bad quality
- Explain the uncertainty info
- Give advice to users on usage
- Validate the uncertainties
- Error correlation matters
- Put uncertainty information in the dataset, rather than expect users to hunt the literature for values
- Information should be quantitative
  - standard uncertainty
  - standard fractional uncertainty
  - error covariance matrices
  - probability of mis-classification
  - variability across repeat evaluations …

- DOI 10.5194/essd-9-511-2017

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- Don't re-invent what the measurement science community spent decades deliberating about
- **Nomenclature** for unambiguous communication
  - Measurand, effects, error, uncertainty, …
- Tried-and-tested **methodologies** for estimating uncertainty

- Numerical data by default should be associated with an estimate of **standard uncertainty**

Uncertainty recomendations for CDRs

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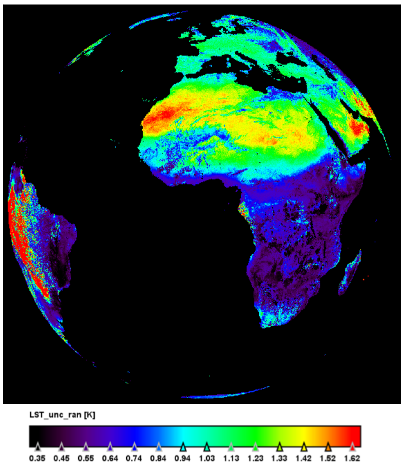
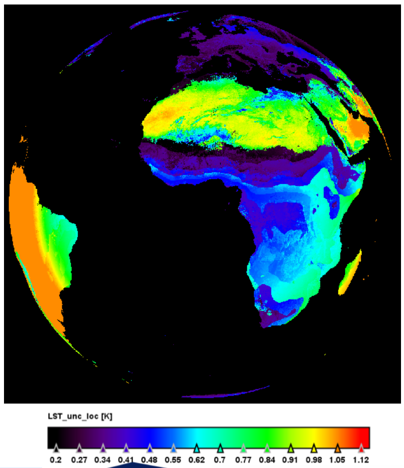
Land Surface Temperature Uncertainties

Random (Radiance and Emissivity)



Locally correlated (Atmosphere & Em.)



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- Given per datum uncertainty estimates, a highly uncertain estimate is not poor quality …
- … if that uncertainty is confidently estimated and is provided to the user

CCI+ Collocation

Uncertainty recomendations for CDRs

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- Not only the definition of the uncertainty information, but examples of how you recommend users to exploit the information

Uncertainty recomendations for CDRs

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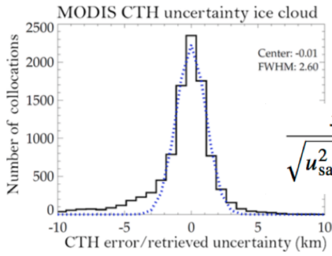
- Validation is sometimes used to generate uncertainty estimates, which is not what is meant here
- Where we model and provide quantitative uncertainty, those numbers should also be validated



$$\frac{x_{\mathrm{sat}} - x_{\mathrm{ref}}}{\sqrt{u_{\mathrm{sat}}^2 + u_{\mathrm{ref}}^2 + u_{\mathrm{mis}}^2}}$$

Uncertainty recomendations for CDRs

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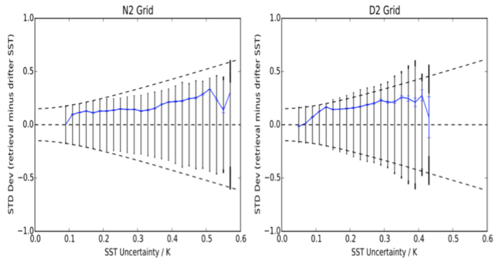

Uncertainty recomendations for CDRs

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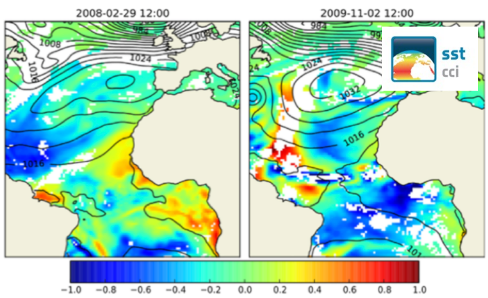
- Where CDR products are generated on different scales (e.g., full res and gridded variants) consistent uncertainty information can only be propagated if error correlation is accounted for



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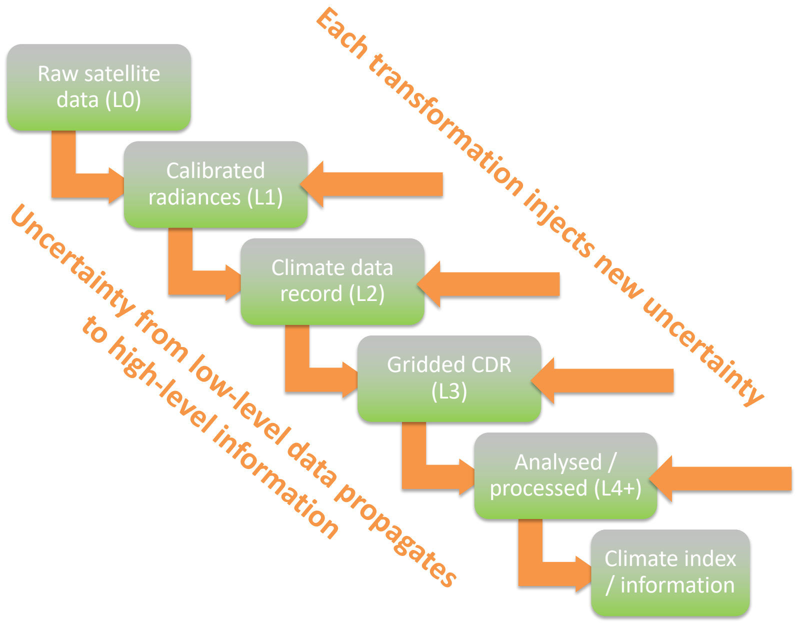
OBSTACLES TO PROVIDING UNCERTAINTY INFORMATION

- Lack of expertise, confusion about uncertainty concepts, unawareness of best practice
    - Adopt, extend and communicate the concepts from laboratory metrology
    - Need "EO metrology"
- Resources, since uncertainty estimation roughly doubles the effort of creating data
    - Funding aspect
    - Tools, guidelines, precedents
- Scepticism that user communities will use the information
    - Trail-blazing that demonstrates value
- And …



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FIDUCEO

- **Fidelity and Uncertainty in Climate data records from Earth observation**
- **Ambition**: develop a widely applicable **metrology of Earth observation (EO)**
- **Motivation:** establish **defensible**, **uncertainty-quantified evidence (CDRs)** for climate and environmental change from space assets
- **Limitation of the status quo:** the level-1/radiance/FCDR uncertainty is not characterised, and **therefore cannot be propagated to the CDR**

More info, blog etc at: www.fiduceo.eu

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Quantifying radiance uncertainty

- Understand the **measurement equation**
- Quantify the **sources of error** (effects)
- Quantify each effects' **magnitude** and **error structures**
- Propagate to get radiance **uncertainty**

- **Structured approach centred on measurement equation**

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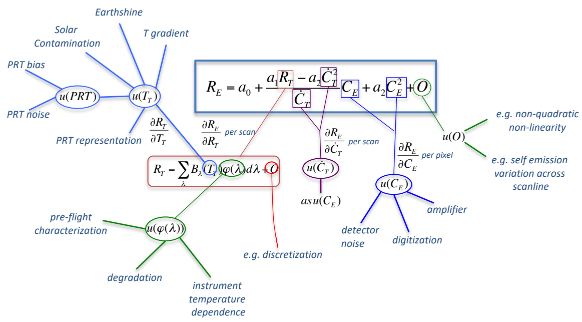
Organise analysis around measurement equation



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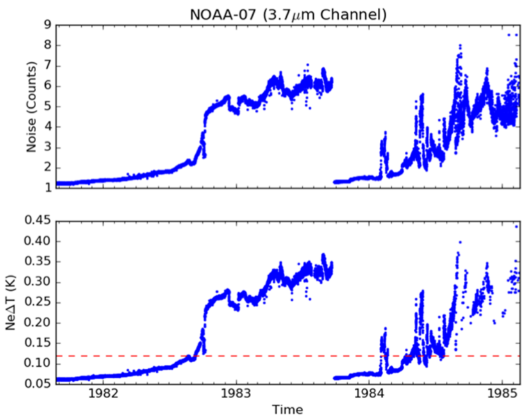
Magnitude of uncertainty

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



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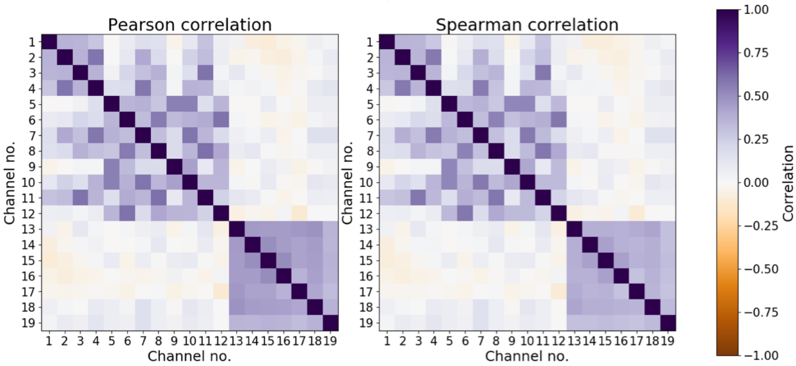
Correlated effects

- For some HIRS strong correlations in noise between channels



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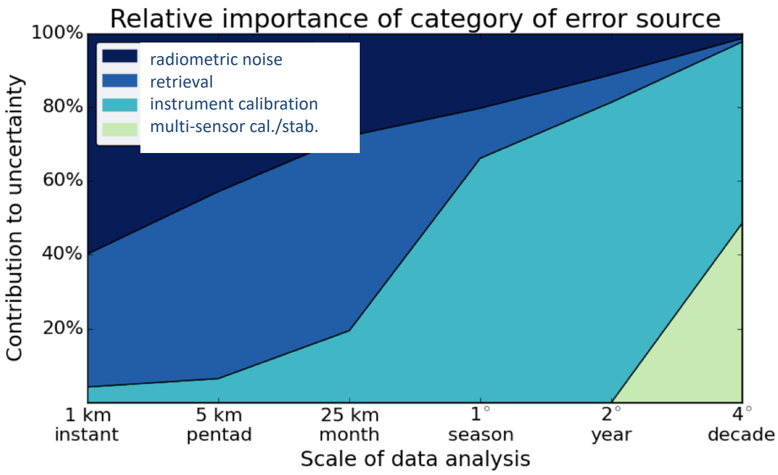
Dominant effects depend on scale (eg SST)



If you compare two measurements on different space-time scales the dominant sources of uncertainty in that difference change.

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See blog article http://www.fiduceo.eu/node/237

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UNCERTAINTY QUANTIFICATION

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- Radiance (reflectance, brightness temperature,…) uncertainty quantification should include:
  - Standard uncertainty estimates
    - Per datum or parameterised if highly variable
    - In components with different spatial correlation structures if necessary, along with correlation information
    - In FIDUCEO, 3-component model (independent, structured and common components)
  - Cross-channel error correlation matrix
    - For geophysical propagation, assimilation etc

THAT WOULD LET L1 USERS …

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- Propagate radiance uncertainty to L2 CDR
  - Geophysical quantities on satellite projection with U
  - Accounting for error covariance (avoid underestimate)
- Quantify spatio-temporal error correlations L2 CDR
  - Necessary to propagate uncertainty consistently to L3+ CDRs, and climate indices from space data
- Work with CDR users (modellers, etc) to exploit
  - Model evaluation, assimilation, index information …

- At what investment?
  - U characterization **is** a significant task. But …

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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FCDR Uncertainty: An Aim

Not just for heritage sensors

To support Climate Data Records and environmental applications in general, space agencies should develop and provide:

Fundamental Climate Data Records, comprising a continuous, harmonised record of calibrated, geolocated, **uncertainty-quantified** sensor observations in geophysical units (such as radiance), together with all ancillary and underlying data used to calibrate the observations **and estimate uncertainty**.

CF. GCOS-154: The term "Fundamental Climate Data Record" (FCDR) denotes a well-characterized, long-term data record, usually involving a series of instruments, with potentially changing measurement approaches, but with overlaps and calibrations sufficient to allow the generation of products that are accurate and stable in both space and time to support climate applications. FCDRs are typically physical measurements such as calibrated radiances, backscatter of active instruments, or radio occultation bending angles. FCDRs also include the ancillary data used to calibrate them.

Mittaz, et al, *Metrologia*, submission imminent

Considerations for CEOS/CGMS agencies

- EO measurements are a major data stream quantifying Earth's environments, yet the good practice of providing uncertainty information is not standard at L1/FCDR
  - Some data streams (e.g. in Copernicus) have some uncertainty estimates, at a basic level
- Uncertainty information adequate for CDRs and climate indices is (seen to be) complex
  - More than an uncertainty value, since spatio-temporal and cross-channel error correlation is relevant on multiple scales of climate applications
  - Need for demonstrations of methods, good practice and utility, both at L1/FDR, L2/CDR and propagation to applications and climate indices: a metrology of EO is needed (QA4ECV and now FIDUCEO have started this)
- Providing radiance/L1 uncertainty to users will require some investment and product development, but …
- … a significant part of the instrument characterisation need to provide uncertainty is developed in Phase B-D and pre-flight cal., but not communicated to users
- Considerable progress towards L1/FCDR uncertainty can therefore be made by updating and exploiting existing mission/instrument practice for this purpose
  - There are practical challenges, such as structuring industry contracts and reports so that user-oriented uncertainty information is made available in products and user guides
  - Currently, from the radiance user point of view, much instrument characterisation is "under-exploited" – not made available to users, either at all, or in an applicable form

http://www.fiduceo.eu/blogs

Beyond FIDUCEO – link to "Green paper"

Satellite missions: metrological upgrade

Harmonisation and Recalibration

Why worry about all sources of errors?

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Brief conclusion

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- **Ideas, methods and tools are emerging 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, for example, are applicable to prospective missions, not only FIDUCEO case studies and space agency archives**
- **Much of the necessary insight into instrument errors could be gained by bringing a "metrology focus" to phase B-D satellite development**

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

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