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Metrology-Inspired Methods in the FIDUCEO Climate Research

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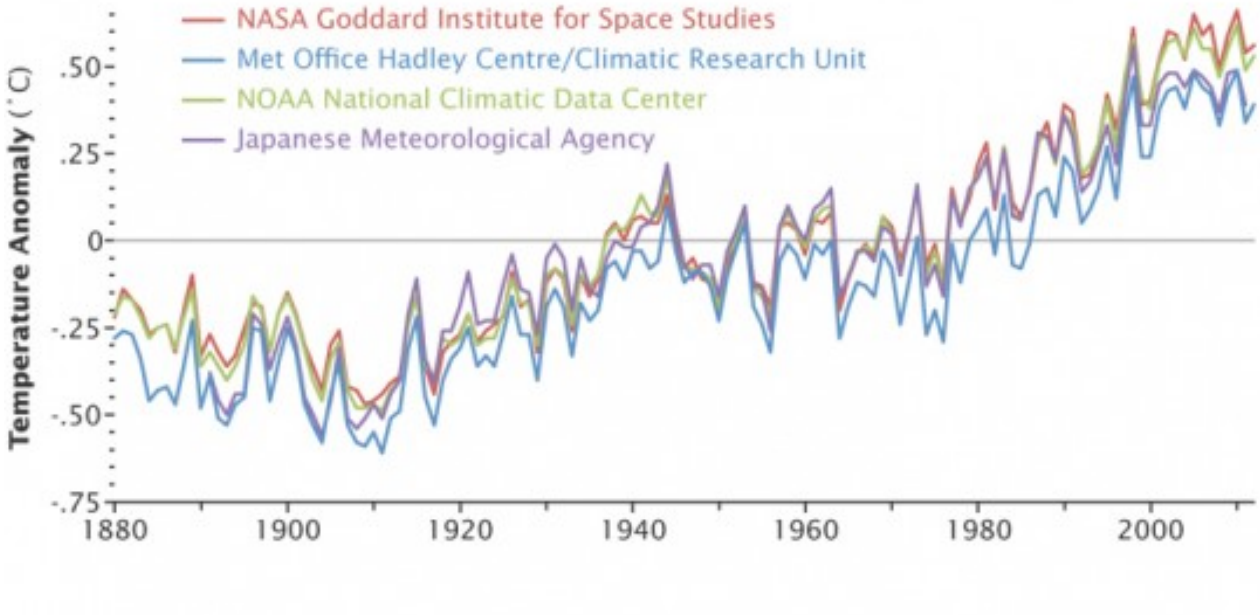
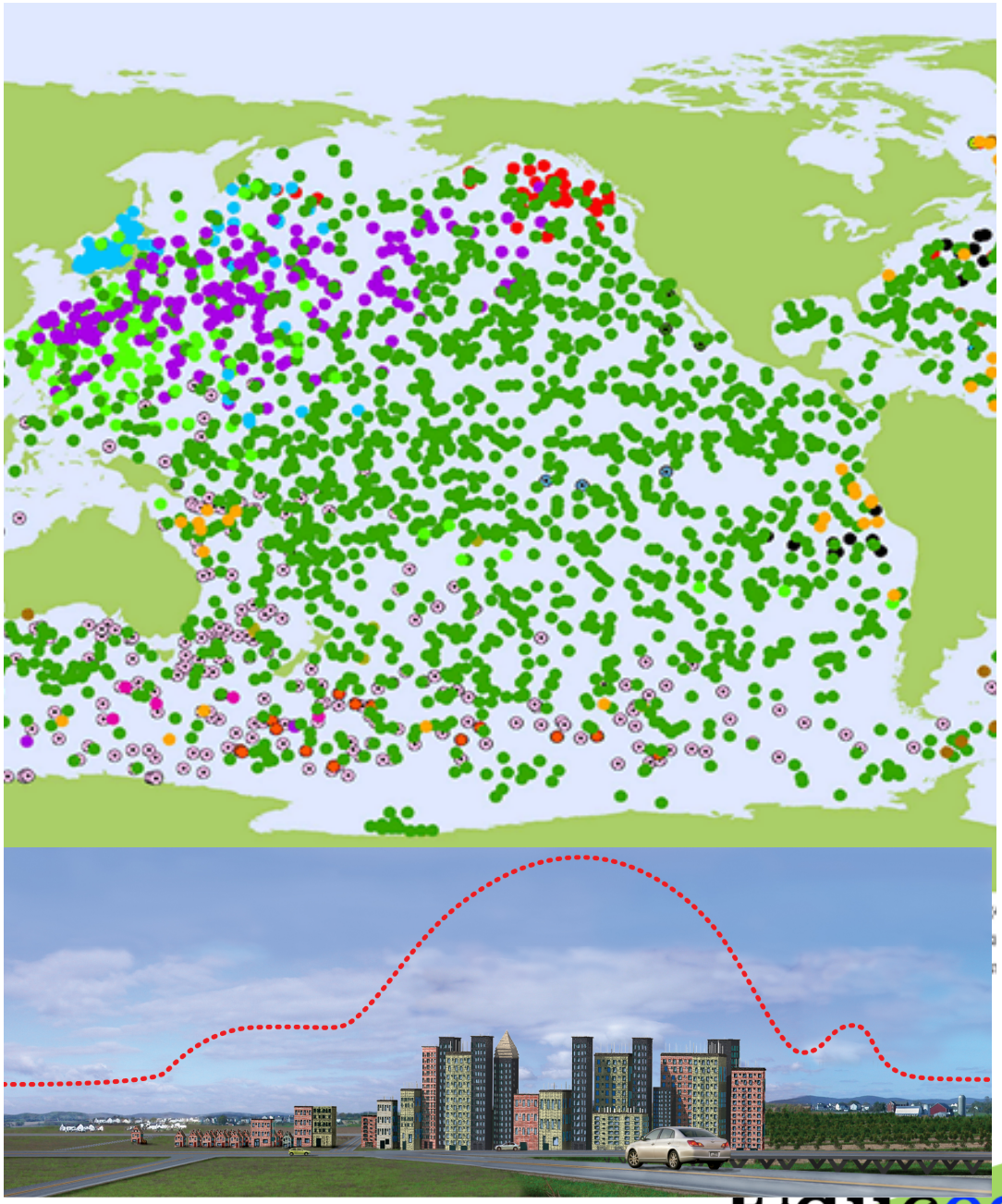
Measuring Global Climate Change

- Is the earth's climate changing?
- If so, at what rate?
- Are the causes natural or human induced?
- What will the climate be like in the future?
- UN summit in Paris next month



Measuring Global Surface Temperatures

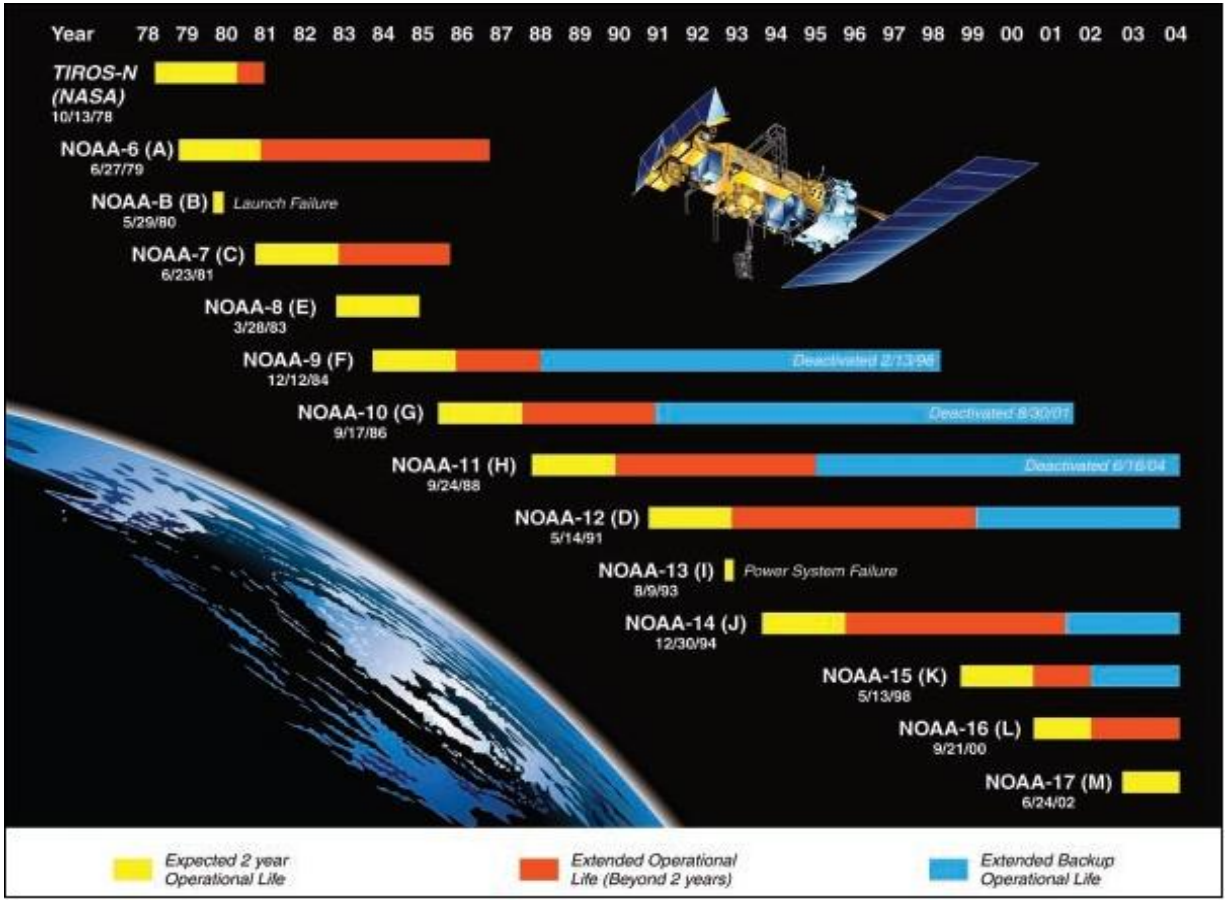
- Ocean data from buoys different from ships
- Engine intake thermometers different from bucket seawater
- Bias corrections for land stations
- 15-year hiatus in warming?



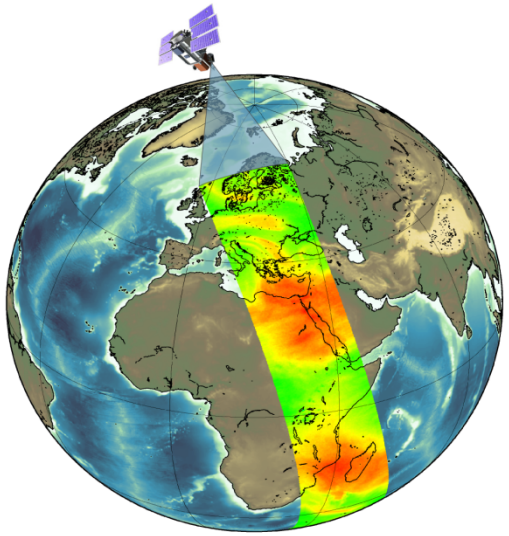
Observations From Space

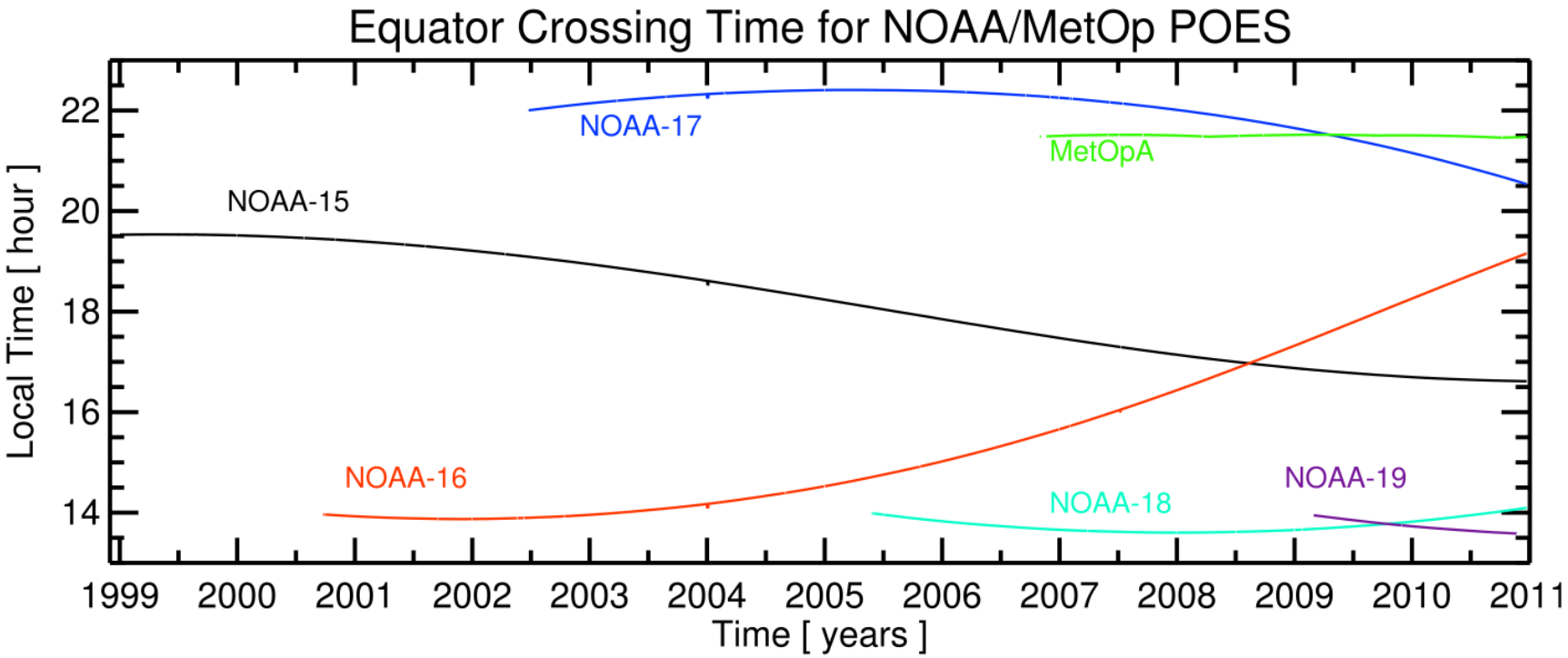
US Polar Meteorological Programs

- Usually several satellites with very similar instruments at same t in orbit
- Calibration of older instruments not optimized for climate research
- Problem: Creating a time series of ≈ 30 years for essential variables



Simultaneous Nadir Overpasses





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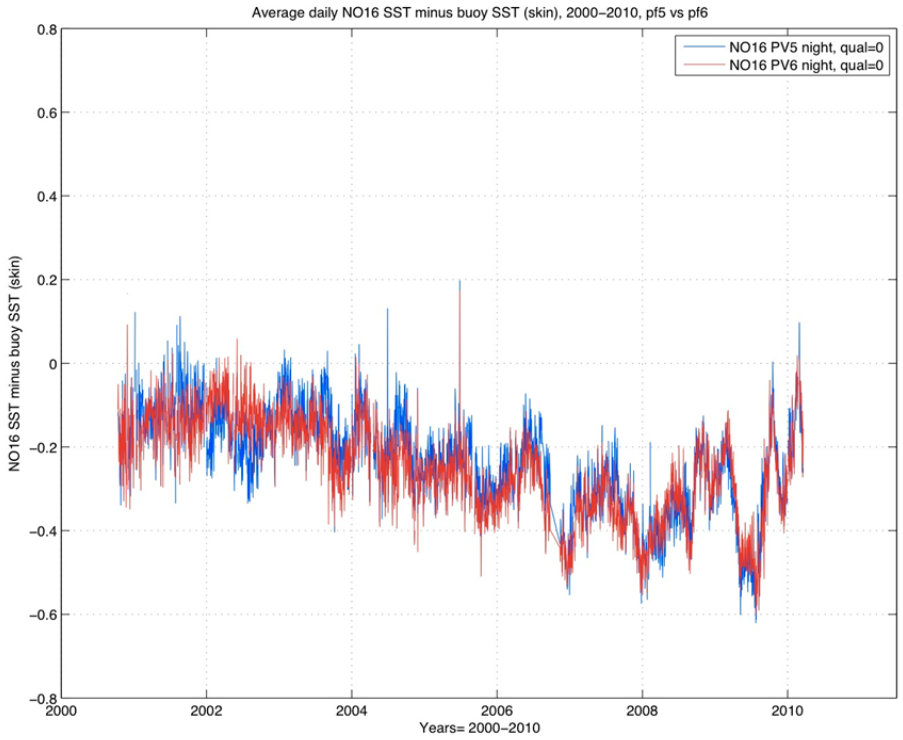
Time dependent biases

- e.g. present in current AVHRR operational data



Time variable structure in this SST dataset caused by time dependent biases in the AVHRR calibration related to the AVHRR Instrument temperature

MAIN BAD ASSUMPTION

Change in thermal state of the AVHRR caused by orbit drift not important

- Should have been spotted by validation process
- Traceability chains would force an estimate of time dependent uncertainties which will be crucial for climate related studies

What are the aims of FIDUCEO?

- FIDelity and Uncertainty in Climate data records from Earth Observation
- Derive methods for Fundamental Climate Data Records for a range of instruments taking a metrological approach
- Derive methods and best practice for Climate Data Records for a range of ECVs taking a metrological approach
- Create traceable uncertainties
  - Evidence of all processes involved in deriving data
  - Documented uncertainties required for Climate use
- Provide data in easy formats incl. pixel level uncertainties
- Provide cookbooks and toolkits on best practice methods

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Why is it important to take a new approach to FCDR/CDR generation?

- Past history has shown that much of the satellite data used as FCDRs/CDRs developed can have significant biases/errors associated with them
  - Not good for climate studies…
  - Need to provide answers to the question
    - **"To what level can I trust this data?"**
  - How can we approach both satellite calibration and CDR algorithms to reduce the introduction of possible errors into the data?
  - How can we demonstrate the trustworthiness of the data?

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A Metrological Approach

- Metrology is the science of measurement
- Provides a framework for the assessment of the quality/useability of the end product
  - Traceability chains
    - Must be quantitative
    - Should detail all linkages and processes so can easily assess the data processing chain
      - Where does all the information used come from?
      - **Should highlight all assumptions made**
    - Enables potential problems in analysis to be highlighted/spotted
    - Provides documentary evidence for the final uncertainties
  - Rigorous analysis of uncertainties
    - Includes random effects, systematic effects and correlation effects
    - Important for Climate analysis that the different types of uncertainties are handled correctly
      - E.g. random and systematic cases average very differently

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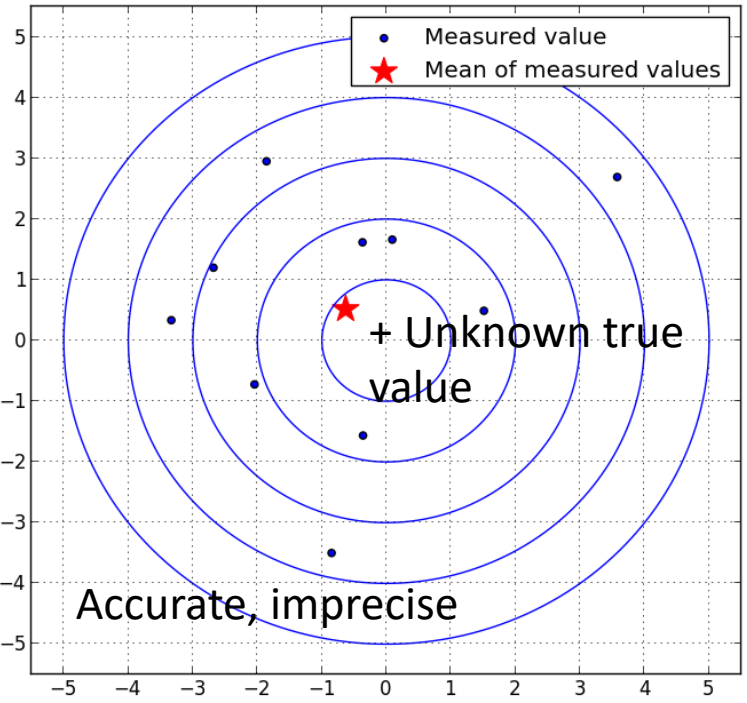
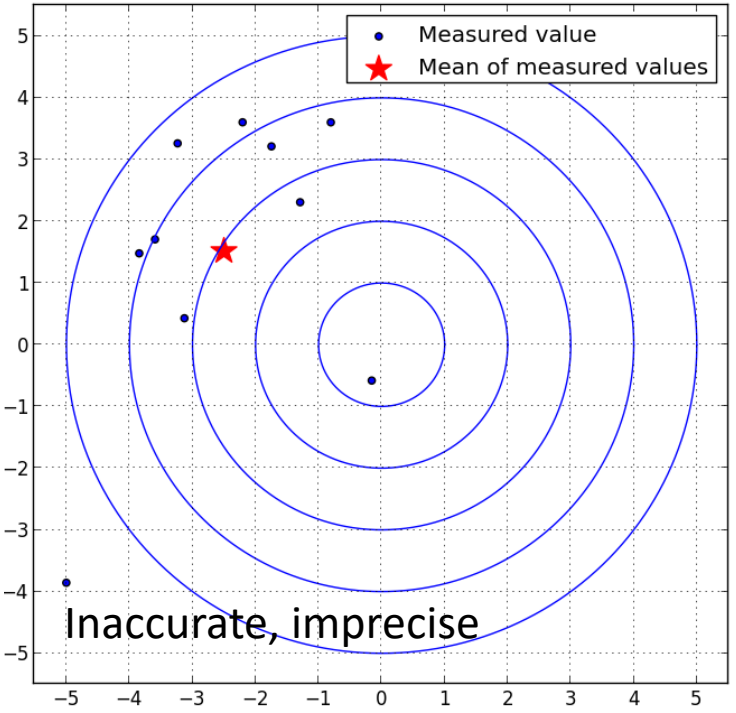
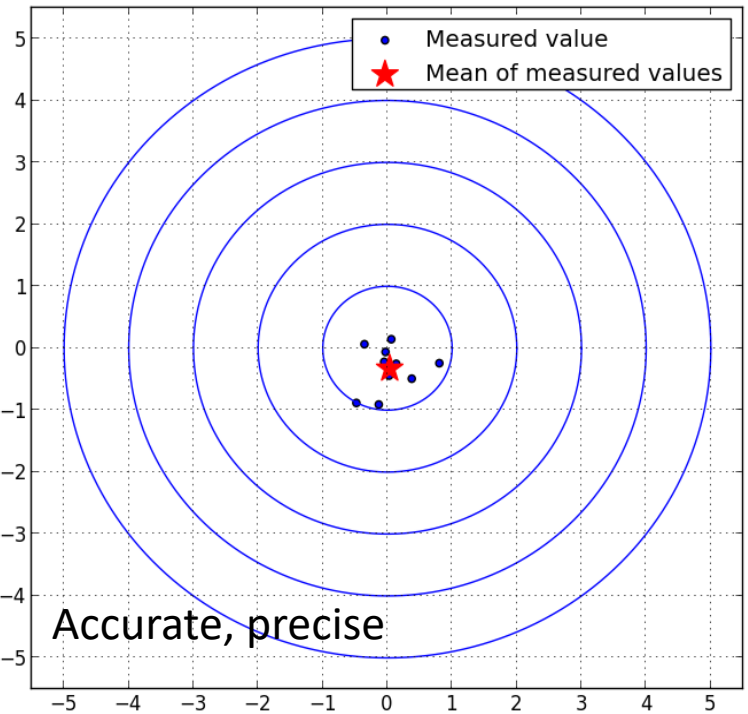
Mostly it's about a dialogue between EO and Metrology



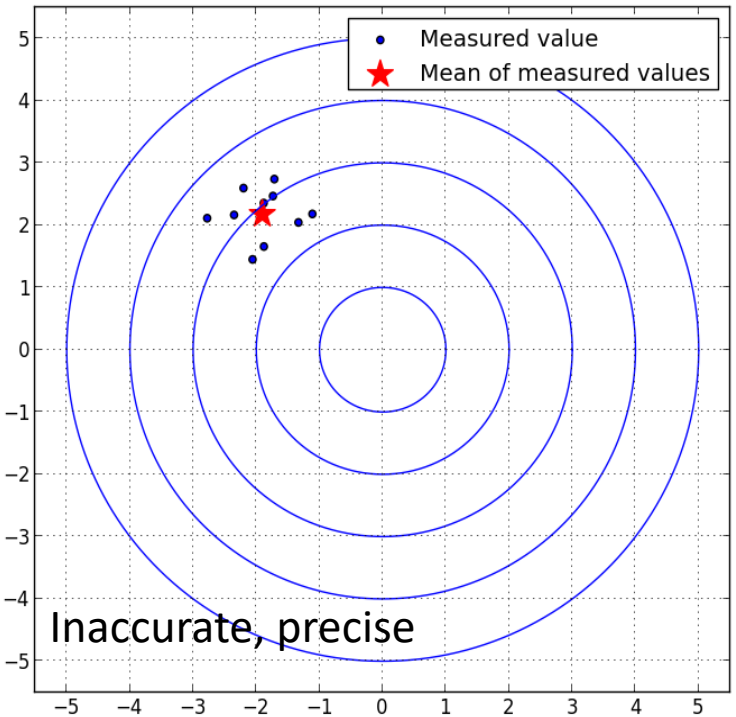
High random

Random and systematic effects

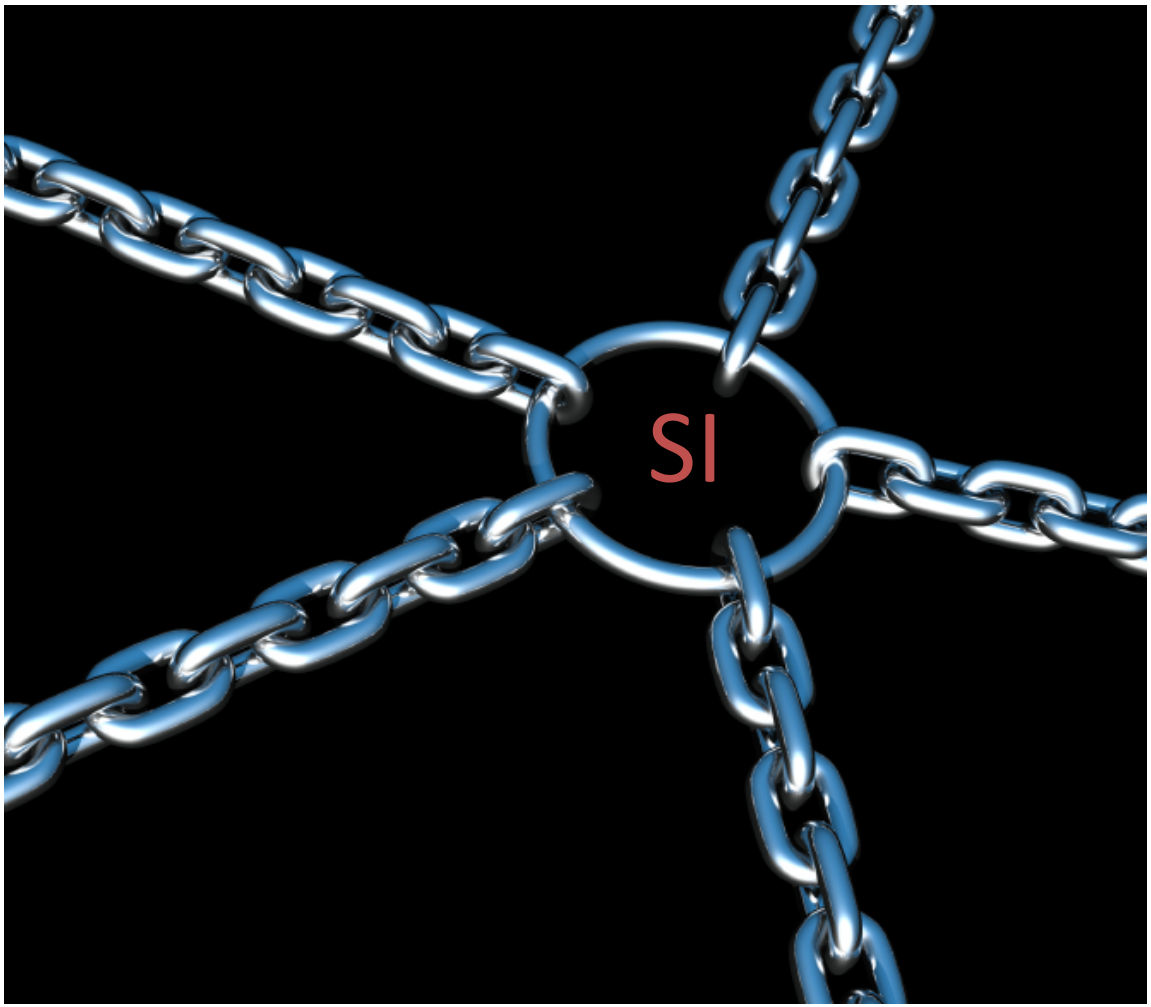




High Systematic



Traceability



Traceability "requires":

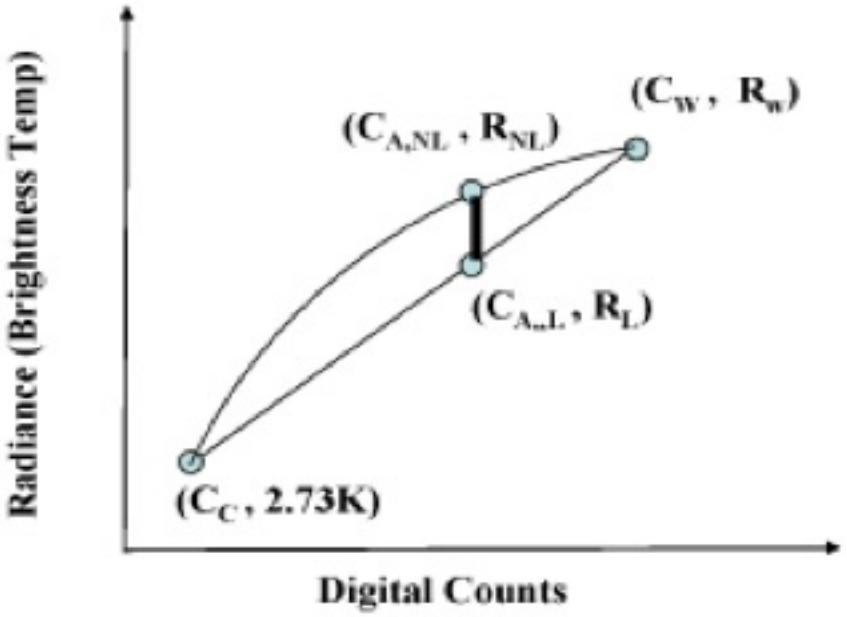
- Documented procedures for each stage
- Uncertainty budget for each stage
  - Forces a review of all processes
- Audit / peer review of the calibration process

Achieving Traceability

- Start with the measurement equation
  - Essentially the calibration equation but includes terms for known unknowns if possible
- Detail the uncertainty per term in measurement equation
- Detail correlations/covariances

Calibration Equation

- On board calibration standard: BB with PRTs
- Pre-flight characterization in thermal vacuum chamber at calibration facility



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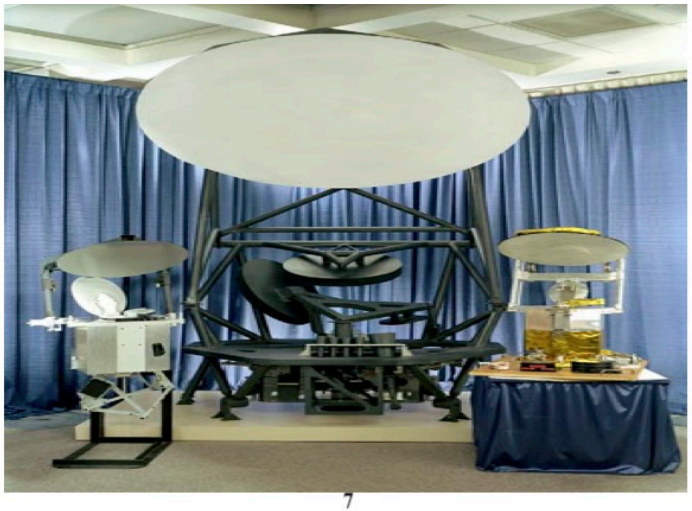
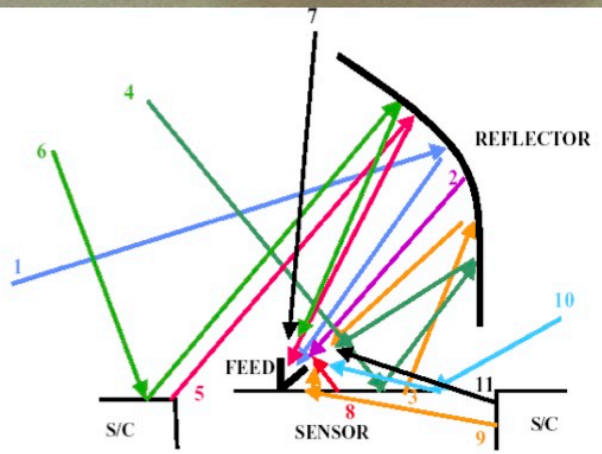
Example for Uncertainties: Contributions to Scene Rad.

1. **Earth Scene Radiation**
2. Reflector emission
3. Sensor emission viewed through reflector,
4. Sensor reflection viewed through reflector,
5. Spacecraft emission viewed through reflector,
6. Spacecraft reflection viewed through reflector,
7. Spillover directly from space,
8. Spillover emission from sensor,
9. Spillover reflected off sensor from spacecraft,
10. Spillover reflected off sensor from space,
11. Spillover emission from spacecraft





Achieving Traceability

- Start with the measurement equation
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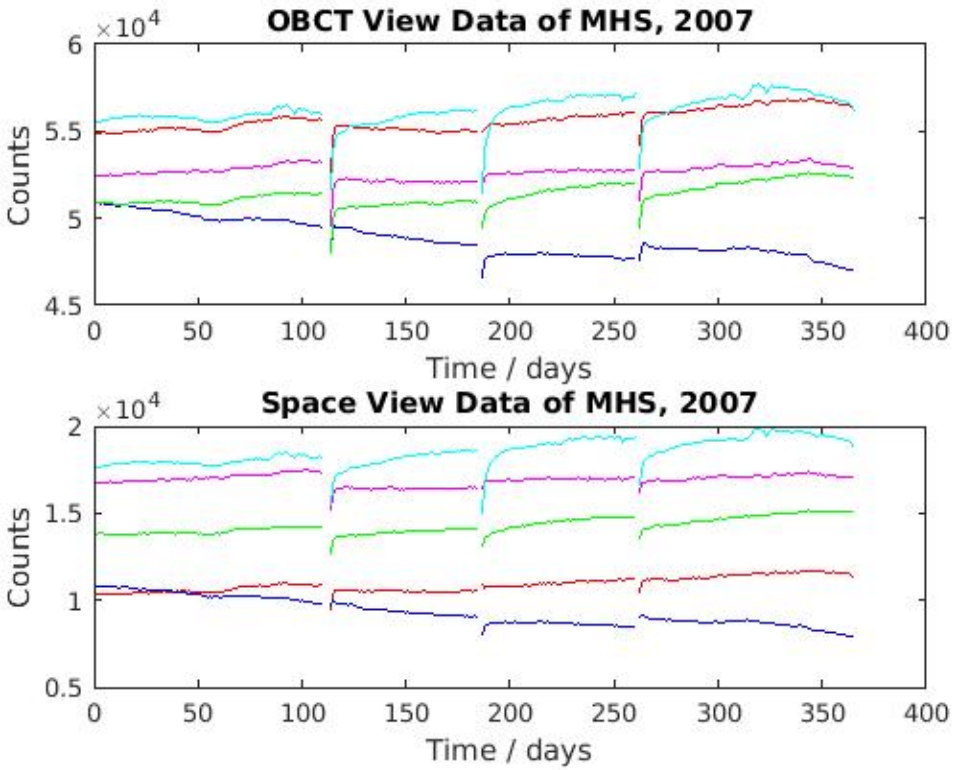
Different Terms in the Cal. Eq. Can be Correlated

- In general, a term in the calibration equation has several different sources of uncertainty
- A given source of uncertainty can affect several terms in the calibration equation
- Analytic uncertainty propagation can become complicated
- Alternative: Monte Carlo analysis of uncertainties.



The Law of Propagation of Uncertainties (GUM)

$$u_c^2(y) = \sum_{i=1}^{n} \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i) + 2 \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \frac{\partial f}{\partial x_i} \frac{\partial f}{\partial x_j} u(x_i, x_j)$$

Adding in quadrature

Sensitivity coefficient times uncertainty

Correlation term

$$u(x_i, x_j) = u(x_i) u(x_j) r(x_i, x_j)$$

Sensitivity coefficients times covariance

2 because symmetrical:

$$u(a,b) = u(b,a)$$

Achieving Traceability

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Tools

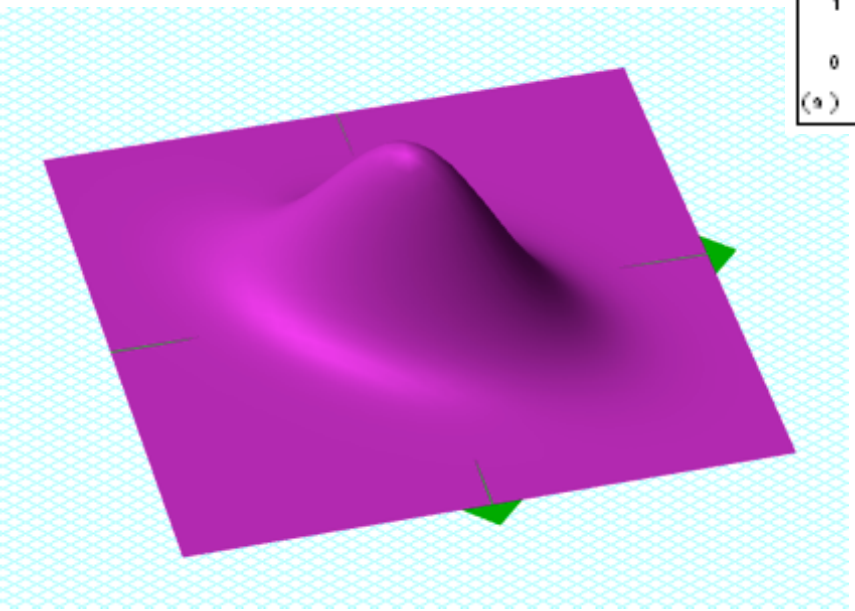
- Complete uncertainty information will seem very complicated to users not steeped in thinking about errors
- Therefore tools need to be available to work on this format to do things they want

Examples of Tools

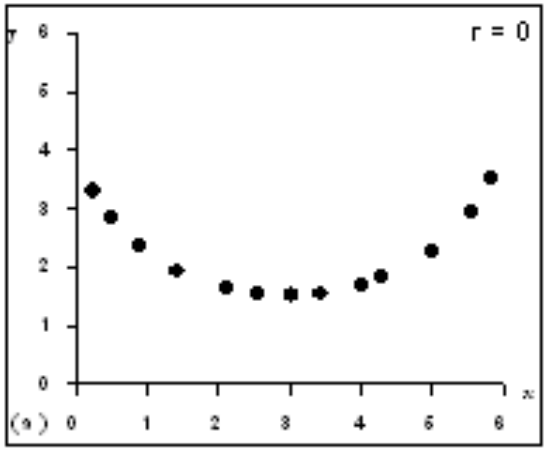
- File reader with optional on-the-fly calculation to simplified uncertainty values (total, or random/structured/systematic)
- Covariance matrix calculator
- Spatial regridding with propagated uncertainty
- Uncertainty and error-instance visualisers
- Monte Carlo propagation of error distributions through complex non-linear transformations

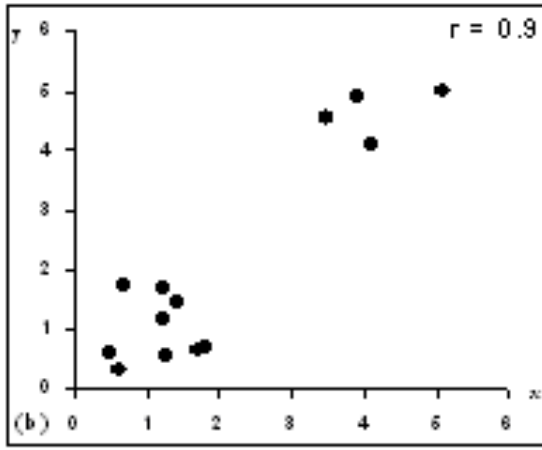
Covariances Are Described in Matrix

PDF Often Approximately Multidimensional Gaussian



Careful With Covariances!





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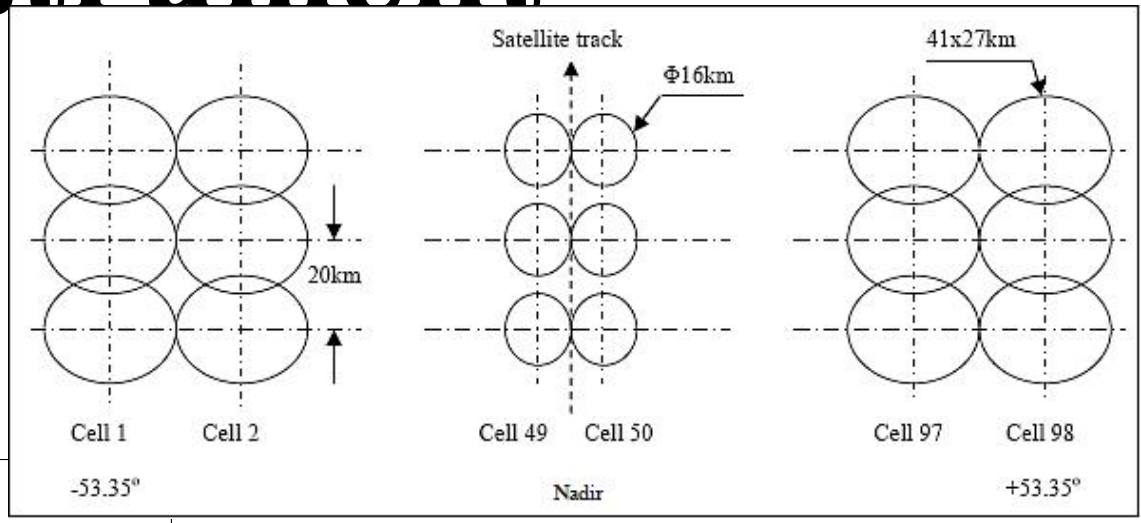
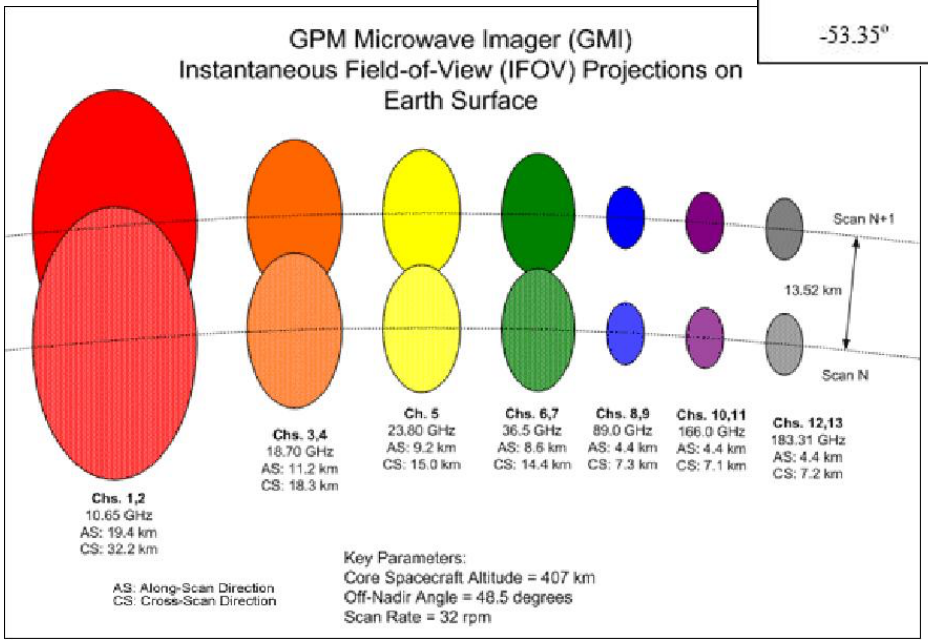
Footprints Can Be Different For the Same Instrument





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Tipping point toolbox (being developed since 2007)

- Anticipating: early warning of climate tipping points based on autocorrelation monitoring (ACF, DFA, with uncertainties evaluation)
- Detecting: potential analysis
- Forecasting: PDF & potential analysis, recently added bayesian techniques

Valerie Livina

Uncertainties: The bigger picture

- So going through the process of traceability is beneficial but also
  - The uncertainty is not just a single number but there can be a range of uncertainties, both random and systematic
    - ESA CCI SST project provides four components of uncertainty
  - Combining different uncertainty components is not necessarily trivial
    - Deal with random and systematic cases differently plus impact of correlations plus uncertainties may be applicable at different spatial/temporal scales
- FIDUCEO will provide these different components plus tools to manipulate them properly

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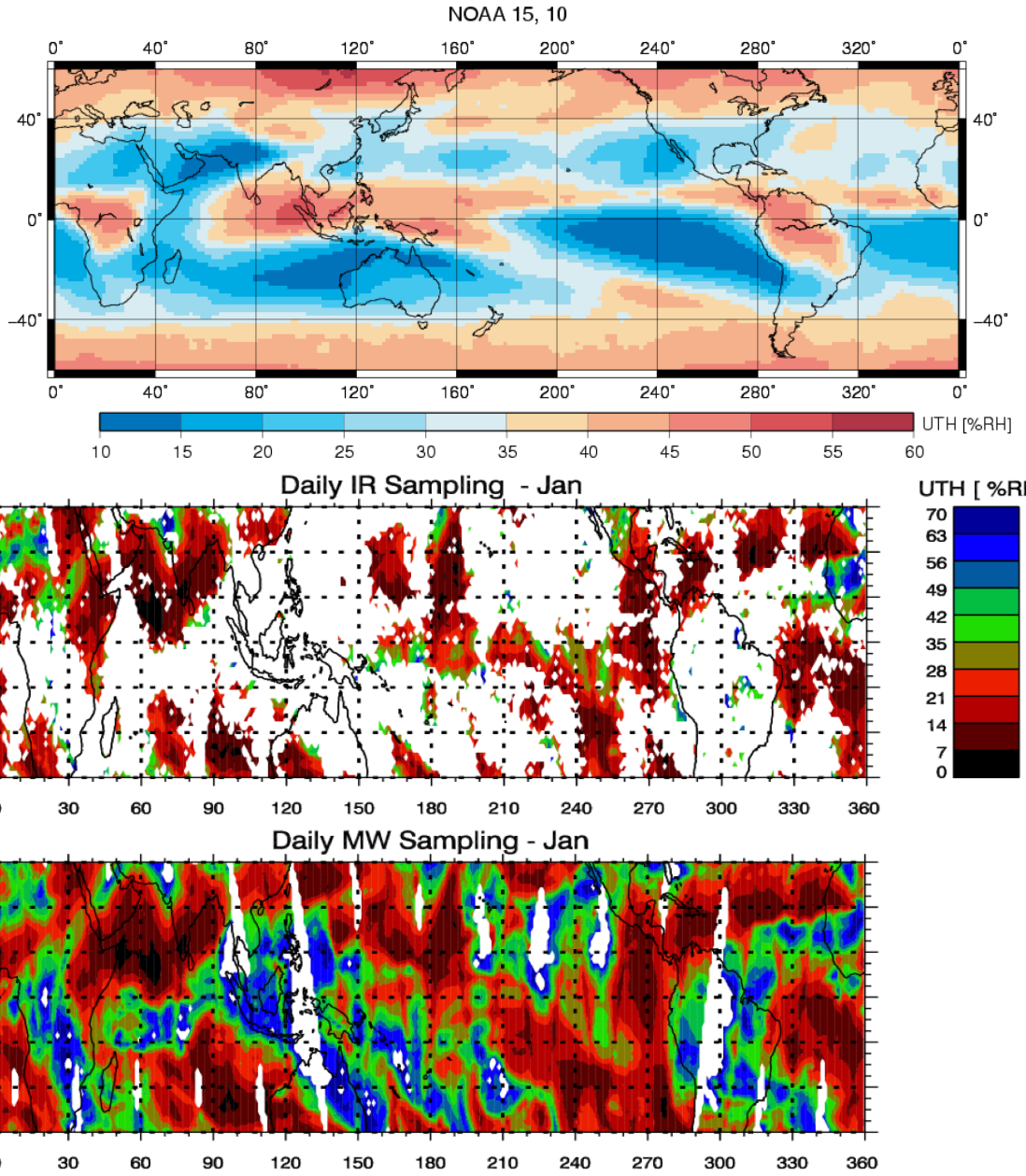
Cross-Comparison µwave Sounders / IR-Radiometer

- Problem: observations at different local times
- Solutions:
  - opportunities for SNOs from orbit drift
  - small diurnal variations in subsidence zones
- Problem: Clouds affect infrared more than microwave
- Solution: Optimize cloud detection algorithms



FIDUCEO Products: Uncertainty-quantified CDRs

DATASET	NATURE	USE
Surface Temperature CDRs	Ensemble SST and lake surface water temperature	Most of climate science … model evaluation, re-analysis
Upper Tropospheric Humidity CDR	From infrared and microwave, 1992 - 2016	Sensitive climate change metric, re-analysis …
Albedo and aerosol CDRs	From Meteosat, 1995 – 2006	Climate forcing and change, health …
Aerosol CDR	2002 – 2012 aerosol for Europe and Africa	Climate forcing and change, health …

Uncertainty information that (i) discriminates more and less certain data, (ii) is validated as being realistic in magnitude, (iii) is traceable back to the FCDR uncertainty information

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Humidity Changing in Time