Metrological Traceability in space

Nigel Fox, Emma Woolliams
Sam Hunt, Pieter De Vis
Earth Observation, Climate & Optical grp, NPL
Magna Carta - 1215

“There is to be one measure of wine and ale and corn within the realm, namely the London quarter, and one breadth of cloth, and it is to be the same with weights.”

‘measurements’ (as opposed to observations) of the Earth if they are to be trusted, meaningful and should be treated in the same way i.e. traceable to international agreed standards.

For EO and Climate ECVs needs some translation & adaptation of standards and methods:
Obtaining confidence in a measured value requires a quantitative statement of its quality, which in turn necessitates the evaluation of the uncertainty associated with the value. The basis for the value and the associated uncertainty is traceability of measurement, involving the relationship of relevant quantities to national or international standards through an unbroken chain of measurement comparisons.

**Why SI Traceability?** Unequivocally linking an ‘observation’ to an invariant constant of nature (international system of units) with a robust estimate of uncertainty ensures the ‘measurement’ can be: trusted, coherent and comparable with others, have longevity ‘improves with age’
Societal grand challenge

Mitigation and adaptation to climate change whilst sustaining economic growth and quality of life
Earth’s climate is changing with catastrophic impact on society!

‘Fit for purpose’ mitigation and adaptation strategies require confidence in measurement of trends in (54) ‘Essential Climate Variables’ (ECVs) – Trends are so small they require decades to be large enough to detect

Unambiguous detection relies on trustable measurements - anchored to invariant references i.e. SI

~ 2/3 of ECVs have optical related measurands

>50% can only be measured from space (further 25% require some space observation)

Many ECV’s are Bio/Geo-physical in nature and need traceability in-situ (deserts, oceans, atmosphere & space) at uncertainties close to primary realisations
Observation Cycle

- Climate Data (ECVs)
- Climate Models
- Integrated Assessment Models
- Climate Policy
- Observations
- Real Climate
Observation Cycle with calibrations (confidence!)

ECV in situ validation

Climate Data (ECVs)

Climate Models

Integrated Assessment Models

Post-launch calibration

Observations

Real Climate

Pre-flight calibration

ECV in situ validation

Climate Data (ECVs)

Climate Models

Integrated Assessment Models

Observations

Real Climate

Pre-flight calibration
Endorsed in 2010, key principles are being widely implemented globally and specifically specified in relevant ESA ITTs
- metrology community played a leadership role in their development
- Continued work to mature and detail their implementation to many applications
- Training and worked case studies at all stages of end to end process
- Has led to increased emphasis on comparisons and concept of Fiducial Reference Measurements (FRM)
What is an F(C)DR?

An FCDR consists of a long, *stabilised* 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*
Fundamental Data Record (FDR)
Fundamental Climate Data Record (FCDR)

- Long $\rightarrow$ multidecadal
- Stabilised $\rightarrow$ combining results from multiple sensors (harmonised)
- Uncertainty quantified $\rightarrow$ enough information to propagate uncertainties properly to the next level
- Calibrated to physical units and located in time and space $\rightarrow$ ready to be used
- With all instrument and ancillary data used to calibrate and to determine uncertainty $\rightarrow$ with what is needed for long term data preservation
Applying principles of metrology to historical Earth observations from satellites

Jonathan Mitra1,2, Christopher J Merchant1 and Emma R Woolliams2
Published 21 May 2019 • © 2019 BIPM & IOP Publishing Ltd
Metrologia, Volume 56, Number 3

Metrologia Vol 56(3)
https://iopscience.iop.org/article/10.1088/1681-7575/ab1705

FIDUCEO received funding from the European Union’s Horizon 2020 Programme for Research and Innovation, under Grant Agreement no. 638822
Prime: Reading University. www.fiduceo.eu
Why F(C)DRs

**Long Term Data Preservation**
- Store all information needed by future scientists to understand data set
- Records origin of data sources
- Records calculation methods
- Records basis of uncertainty and error covariance
- Provides robust basis for long term data records

**Today’s applications**
- Have information needed to propagate F(C)DR into higher level products
- Harmonised set of data from sequential sensors to evaluate long-term trends
- Sufficient uncertainty information in as simple a form as possible
- Provides robust basis for applications
Strategies to help evidence F(C)DR

- Graphical Matrix to present summary information
- Rigorous end to end Uc analysis for traceability an design – A simulator to propagate uncertainty

<table>
<thead>
<tr>
<th>Product Details</th>
<th>Product Generation</th>
<th>Ancillary Information</th>
<th>Uncertainty Characterisation</th>
<th>Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product Information</td>
<td>Sensor Calibration &amp; Characterisation Pre-Flight</td>
<td>Product Flags</td>
<td>Uncertainty Characterisation Method</td>
<td>Reference Data Representativeness</td>
</tr>
<tr>
<td>Product Availability &amp; Accessibility</td>
<td>Sensor Calibration &amp; Characterisation Post-Launch</td>
<td>Ancillary Data</td>
<td>Uncertainty Sources Included</td>
<td>Reference Data Quality</td>
</tr>
<tr>
<td>Product Format</td>
<td>Retrieval Algorithm Method</td>
<td>If target mission data product is Level 2</td>
<td>Uncertainty Values Provided</td>
<td>Validation Method</td>
</tr>
<tr>
<td>User Documentation</td>
<td>Retrieval Algorithm Tuning</td>
<td>Geolocation Uncertainty</td>
<td>Validation Results</td>
<td>Validation Results</td>
</tr>
<tr>
<td>Metrological Traceability Documentation</td>
<td>Additional Processing</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Key**

- Not Assessed
- Not Assessable
- Basic
- Intermediate
- Good
- Excellent

- Documentary Framework (Starting at Sensor design) based on Mission requirements define Characterisation and Cal.
  - Collate (and update but not delete) electronically all design/characterisation/cal/val reports
    - From Phase A to Phase E
    - Living Framework becomes robust searchable archive for LTDP
FIDUCEO created two versions – the full FCDR for LTDP and the easy FCDR for use now.

**Long Term Data Preservation**

- Consolidated Input Data
  - counts
  - calibration counts
  - sensor state data
  - [original flags]
  - [original geometry/geolocation]
  - [original timing]

- Codified Effects Tables
  - Fixed data values
  - Virtual variables
  - Pre-calculated data layers

- Radiance measurement function
- Linked code

- Calculation Definitions
  - Harmonisation coefficients

**Today's applications**

- [improved] geometry
- [improved] geolocation
- [improved] timing
- summary input flags

- harmonised radiances
- uncertainty information
  - uncertainty magnitude
  - spatio-temporal length scales
  - cross-channel correlation
  - new flags

**Full FCDR**

**easy FCDR**
Role of metrology

- **STABILITY** over decades
- **INTEROPERABILITY** equivalence world wide
- **COHERENCE** Combining different measurements
- **TRACEABILITY**
- **UNCERTAINTY**
- **COMPARISON**
Fiducial Reference Measurements (FRM) are a sub-set of ‘in-situ’ measurements of satellite measured parameters (L1/L2) that can be robustly compared to those independently derived from a satellite to:

- Validate the sensor performance and any processing
- Provide a means to bridge any potential data-gaps
- Facilitate interoperability between sensors and anchor/establish FDRs
  - Providing they are of sufficient accuracy!
  (Noting that the comparison process has its own Uc)

FRMs MUST:

- have documented evidence of metrological traceability to SI (or appropriate international community standard) including full uncertainty budget (instrumentation and usage), which must be at a level commensurate with the application.
- be independent of any satellite geophysical retrieval process.
- be carried out following community agreed protocols
From Space: Harmonisation not homogenisation (understanding bias)

$$R_{E,\text{sensor},i} - R_{E,\text{reference},i} = K_{\text{sensor-reference},i}$$

Maintain sensor characteristics in viewing ‘reference’ do not force sensor A to appear to be sensor B otherwise likely to have scene dependent biases

- Look to compare against ‘truth’ &/or sensor to sensor
- Developing & using community standardised methods/references
Summary of Steps to an FDR

1. Define the measurand and the measurement function that calculates the measurand

2. Establish the traceability –
   • using a traceability chain diagram (for processing steps that must take place in a certain order) and/or
   • an uncertainty tree diagram (to show the origin of data for each term in the measurement function)
   • Ideally start this process before the sensor is fully designed!!

3. Define the sources of uncertainty and fill out an effects table for each source of uncertainty (defines what you know about uncertainty and about error correlation structures)

4. If appropriate harmonise a data series from multiple sensors

5. Store the full information in an appropriate file format (FIDUCEO defined NetCDF file structures) for long term data preservation

6. Calculate a simplified “easy FCDR” with three error correlation structures and store that in an appropriate file format (e.g. FIDUCEO NetCDF format)

7. Catalogue and collate all evidence in a single indexed electronic depository
Establishing SI Traceability in Space

The traceability chain is broken

No reference in space ... yet
Angles of illumination and observation

Atmospheric transfer
- standardise?
- comparison (ACIX)
- New ‘community code’ ‘Eradiate’

Spectral BRDF of ground
- high resolution spectral reflectance
  TOA spectrometer / measurements?
- Community model? Parametrisation inputs

Solar Irradiance
New CEOS reference

TOA reflectance/radiance

Spectral response function
Societal Grand Challenge: Sustainable growth whilst avoiding catastrophic planetary disaster

- Timely decisions on adaptation/mitigation investments
  - Trust of climate forecasts / unequivocal reference to monitor decadal change

- Paris Accord 2015 (UK 2050): Audit / Environmental impacts/recovery

- Interoperable cost effective Climate/Earth observing system
  - SI traceable data (Truth), invariant ‘gold standard’
  - Multi-application sensors / maximise value from assets
  - Low cost access to space ‘science quality’ Micro-sats

- Address anomalies between observations/models

What is the Truth?
Traceable Radiometry Underpinning Terrestrial- & Helio-Studies

Enabling a space-based Climate & calibration observatory

Principal Investigator:
Professor Nigel Fox
National Physical Laboratory, UK
Vis Prof Univ of Reading
Chair: CEOS WGCV IVOS

Approved as an ESA Earth WATCH mission (28 Nov 19)
TRUTHS is an operational climate-focused satellite mission, aiming to:

1. **Climate benchmarking**: enhance by an order-of-magnitude our ability to estimate the Earth radiation budget (and attributions) through direct measurements of incoming & outgoing energy,

2. **Satellites cross-calibration**: establish a ‘metrology laboratory in space’ to create a fiducial reference data set to cross-calibrate other sensors and improve the quality of their data, robustly anchored to a primary SI reference in space.

and

3. provide SI-traceable measurements of the solar spectrum to address direct science questions and climate.
Mission Products

- **L1**: Earth-reflected Spectral Radiance (ToA), Solar Spectral Irradiance, Lunar Spectral Irradiance – all in the range 320nm to 2450nm;
- **L1**: Total Solar Irradiance integrated in the range 200nm to 30000nm;
- **L2**: Spectral Surface Reflectance, at ground level (320nm to 2450nm);
- Calibration coefficients & match-up products to determine biases for TBD other sensors over multi-scene types and view angles.

**Climate benchmark, solar measurement**

**Earth science**

**Cross-calibration**

**Radiation balance**

**Solar spectral irradiance**

**Surface reflectance**
Climate: Examples

- Robust anchor for long-time-base FCDRs
  - Can provide a bridge between data gaps
  - Remove any ambiguity in data quality
- Enables trends in Key feedbacks like cloud to be detected significantly earlier limited by natural variability
- Most accurate measure of Short-wave ‘radiation balance’ (in and out)

As spatial and temporal scales increase, systematic uncertainties dominate

Time to detect trend (e.g. cloud rad forcing) based on Uncertainty of sensor

Need to test & constrain Variance in climate model forecasts (IPCC)
Key questions: Carbon & Radiation imbalance

TRUTHS data will also help understand efficiency and status of natural sinks of Carbon dioxide (forests and oceans) and support monitoring of land use change and agriculture amongst many others.

TRUTHS is a complementary mission to other satellite based earth observation missions providing a more complete picture of the Earth’s radiation imbalance which drives global warming.
TRUTHS: Underpinning operational ECV retrievals for climate monitoring and model improvement

<table>
<thead>
<tr>
<th>TRUTHS contributions</th>
<th>Climate data records</th>
</tr>
</thead>
<tbody>
<tr>
<td>Provides reference calibration</td>
<td>Cloud properties, ozone, aerosol optical depth, greenhouse gases</td>
</tr>
<tr>
<td>Provides reference calibration AND direct observation</td>
<td>Solar irradiance, Earth radiation budget, surface albedo, cloud cover, cloud particle size, water vapour, ocean colour, ice and snow cover, vegetation indices such as leaf area index, land cover</td>
</tr>
</tbody>
</table>

- **Ocean colour**: direct TOA cross-calibration of sensors to absolute radiometric accuracy of ~0.5%, meeting GCOS requirements
- **Aerosols**: “Climate closure points” unifying ground networks and multiple optical sensors through the TRUTHS FCDR.
- **CO₂**: Referencing Copernicus and multi-agency CO₂ constellations at 0.5-1.0% radiometry through cross-calibration.
Hyper-spectral applications: Surface reflectance

Hyperspectral data can be convolved for many applications enabling an earth system science approach:

- directly
- upgrading other sensors
- Test & Improve retrieval algorithms
- Complimentary to EnMAP, PRISMA, CHIME ….
- Land-cover change
- Forest
- Agriculture
- Pollution
- Resource prospecting
- ……
Strategies to identify/remove biases and harmonise the Earth Observing system are well-established:

But what is the Truth?

Graph courtesy of Meygret, CNES
TRUTHS Cross-Calibration with Sentinel

TRUTHS orbit is directly pole to pole allowing many opportunities to overpass orbit of sun-synchronous sensors – sampling dynamic range and orbital variations of gain.

Red shows nadir overlap between Sentinel 2 GSD and TRUTHS within ±5 minute window.

Summary after 6 months.

Agile platform of TRUTHS allows additional angle matching for off-pointing and also to evaluate Swath effects of sensors.
Reference Calibration

- Enables interoperability & Harmonisation
  - Prospect of ‘certified calibration’
- Spectral & spatial scale allows matching of footprints and bandwidths
- For Ocean colour sensors allows ToA SI traceability at uncertainties needed for climate
  - multiple sites including coastal zones

TRUTHS provides the means to transform global EO system, including constellations of micro-sats so they deliver traceable scientific/climate quality observations -

Sentinel 2 & TRUTHS match-ups for 1 yr (30 minute window)

Polar orbit allows many near simultaneous cross-overs with other satellites Nadir (SNO) or by pointing to angle match
- Reduces uncertainties due to:
  - Illumination and view angles
  - Atmospheric changes
  - Allows many scene types
E.g. Sentinel 2 using Libya 4 desert TRUTHS can improve accuracy <1 % for all bands
Traceability to CEOS Cal/Val infrastructure
Key performance requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Spectral range /µm</th>
<th>Spectral resolution / nm</th>
<th>GIFOV / m</th>
<th>SNR</th>
<th>Sampling</th>
<th>Uncertainty / % (2σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth Spectral Radiance</td>
<td>0.32 - 2.4</td>
<td>~5 to 10</td>
<td>~50</td>
<td>~300 (Vis-NIR)</td>
<td>Global nadir 50-100 km swath + multi-angle</td>
<td>0.3</td>
</tr>
<tr>
<td>Total Sol Irradiance (TSI)</td>
<td>0.2 – 35</td>
<td>NA</td>
<td>NA</td>
<td>&gt;500</td>
<td>Daily</td>
<td>0.02</td>
</tr>
<tr>
<td>Solar/Lunar Spectral Irradiance</td>
<td>~0.30 - 2.4</td>
<td>1 to 10</td>
<td>NA</td>
<td>&gt;300</td>
<td>Daily</td>
<td>0.3</td>
</tr>
<tr>
<td>Surface Reflectance</td>
<td>0.32 - 2.4</td>
<td>~5 to 10</td>
<td>~50</td>
<td>~300 (Vis-NIR) (&gt;2000 Blue)</td>
<td>Global nadir + multi-angle</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>

- **Radiometric demands** of the climate application ➔ *Payload and calibration*
- **Geometric** to optimally match other sensors (calibration) and secondary applications ➔ *FoV, Swath & SNR*
- **Orbit**: optimal sampling to quantify the climate and facilitate cross-calibration ➔ *Satellite and launch*
The Satellite

- **Single satellite:**
  - placed on a LEO (~600km) polar (90°, non-SSO, precessing) orbit;
  - Small/medium class” (<1 ton, <1kW);
  - “agile” (repointing at each orbit to Earth / Sun);
  - able to support high payload data volume (~4500 Gbits daily) & rate (X-band, ~600 Mbps), some on-board processing needed.

- **Satellite elements:**
  - **Platform** (reference Astrobus-S/M, TBC);
  - Hyperspectral Imaging Spectrometer (**HIS**);
  - Cryogenic Solar Absolute Radiometer (**CSAR**);
  - On-Board Calibration System (**OBCS**).
Optical Radiometric Traceability

Primary Standard ITS-90

SI

BIPM

Cryogenic Radiometry

~0.1 %

Spectral Responsivity

~0.01 %

Black body

Planck’s Law

\[ I(\lambda) = \frac{2hc^2}{\lambda^5} \cdot \left( e^{\frac{hc}{\lambda RT}} - 1 \right) \]

Spectral radiometry

Filter radiometer

~0.5 %

Thermometry (Radiation)

‘working’ Standard

Generalisation / dissemination

‘Lab’ Instruments

Photometry

Spectral radiometry

Solar

Remote Sensing

Lighting

Transport

Aerospace

Medicine

Industry

Environment
Radiometric traceability for EO sensor

Space Instruments

Cryogenic Radiometry

~0.01 %

BIPM
ITS-90

~0.1 %

Planck’s Law

\[ L_{\lambda} = \frac{2\pi c^2}{\lambda^5 \left(e^{h\lambda/\kappa T} - 1\right)} \]

~0.5 %

Filter radiometer

Spectral radiometry

Black body

NPL National Physical Laboratory

Transfer spectro-radiometer

(IR)Radiances achievable but challenging!
**Electrical Substitution Radiometry:** A 100 yr old technology - SI primary standard of choice for optical radiation measurements

When thermometer temperature $T = T_o = T_E$ then $P_o = P_E$

- Optical power $= P_o$
- Absorbing black coating
- Electrical Heater Power $= P_E$
- Copper disk

**Main Sources of Uncertainty**

- Surface Reflectance
- Lead (Joule) heating
- Background Temperature/radiation changes
- Electrical/optical non-equivalence

- Typical overall uncertainty $\sim 0.1\%-0.3\%$
**Electrical Substitution Radiometry:** A 100 yr old technology - SI primary standard of choice for optical radiation measurements

When thermometer temperature $T = T_o = T_E$ then $P_o = P_E$

Optical power $= P_o$

Absorbing black coating

Electrical Heater Power $= P_E$

Copper disk

---

Callendar radio balance (1910)

Ångström compensation pyroheliometer (1893)

Total Solar Irradiance from Space (1975)

SOHO (1996)
**Electrical Substitution Radiometry:** A 100 yr old technology - SI primary standard of choice

**Benefits of Cryogenic operation**

- Super-conducting leads
- High thermal diffusivity
  - Reduced non-equivalence
  - Large cavity – high absorbance
- Low radiative coupling
- Achievable Uncertainty ~ <0.002 %

**Principle of Cryogenic radiometry**

\[ \text{Optical power} = P_o \]

\[ \text{Electrical Heater Power} = P_E \]

When thermometer temperature \( T = T_o = T_E \) then \( P_o = P_E \)

**Cryogenic cooling (T < 20 K)**

- Cooling improves sensitivity by 1000 X
- Achievable Uncertainty ~ <0.002 %
What makes TRUTHS different to other optical satellite missions?

TRUTHS includes an on-board calibration system, that replicates the SI-traceable calibration chain employed in National Metrology Institutes (NMIs) globally, including flight of a primary standard - a Cryogenic Solar Absolute Radiometer (CSAR) (see calibration video).

The hyperspectral imager on-board TRUTHS is routinely re-calibrated, with SI-traceability.

Maintaining it’s SI-traceable high radiometric performance throughout the mission lifetime.
In-flight Traceability: Radiance/irradiance

Traceability Strategy:
- mimic that used on ground at standards labs
- Primary reference standard is cryogenic radiometer (CSAR)
  - compares heating effect of monochromatic optical power to electrical power
- Low power Laser diode (few \( \lambda \)) Calibrates Transfer radiometer against primary standard CSAR
  - LD illuminates lambertian diffuser via integrating sphere to condition beam - fills aperture of imager (monochromatic radiance)
- Calibrated Transfer radiometer measures radiance of diffuser
  - Repeat for other \( \lambda \) smooth spectral shape of diffuser minimises number
- LDs also provide \( \lambda \) calibration and spectral stray light check in-orbit
How TRUTHS on-board Cal System works

https://www.npl.co.uk/research/earth-observation/truths/satellite-calibration
### Uncertainty budget propagation

**CSAR** (On-board SI Traceability primary standard)

<table>
<thead>
<tr>
<th>Element</th>
<th>( U_c (%) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement of electrical power</td>
<td>0.010</td>
</tr>
<tr>
<td>Cavity absorptance</td>
<td>0.010</td>
</tr>
<tr>
<td>Scattered light</td>
<td>0.004</td>
</tr>
<tr>
<td>Random noise</td>
<td>&lt;0.06</td>
</tr>
<tr>
<td>TOTAL</td>
<td>0.02-0.07</td>
</tr>
</tbody>
</table>

**HIS** (On-board calibration system)

<table>
<thead>
<tr>
<th>Element</th>
<th>( U_c (%) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSAR</td>
<td>&lt;0.06</td>
</tr>
<tr>
<td>Prism arm</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Transfer radiometer</td>
<td>0.03</td>
</tr>
<tr>
<td>External aperture</td>
<td>0.02</td>
</tr>
<tr>
<td>Traceability issues</td>
<td>&lt;0.08</td>
</tr>
<tr>
<td>HIS thermal control (1K)</td>
<td>0.01-0.20</td>
</tr>
<tr>
<td>HIS SNR</td>
<td>0.03</td>
</tr>
<tr>
<td>TOTAL</td>
<td>0.16-0.26</td>
</tr>
</tbody>
</table>

**SNO** inter-calibration between 2 satellites

<table>
<thead>
<tr>
<th>Element</th>
<th>( U_c (%) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRUTHS HIS</td>
<td>0.16-0.26</td>
</tr>
<tr>
<td>Spectral mismatch</td>
<td>0.1-0.2</td>
</tr>
<tr>
<td>Spatial mismatch</td>
<td>0.1</td>
</tr>
<tr>
<td>View Angle</td>
<td>0.1-0.2</td>
</tr>
<tr>
<td>Atmos. corr.</td>
<td>0.1-0.3</td>
</tr>
<tr>
<td>BRDF</td>
<td>0.1</td>
</tr>
<tr>
<td>TOTAL</td>
<td>0.4-0.7</td>
</tr>
</tbody>
</table>

**L2+ application product**

<table>
<thead>
<tr>
<th>Element</th>
<th>( U_c (%) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>GHG retrievals</td>
<td>1% = 0.1ppm</td>
</tr>
<tr>
<td>Ocean Colour</td>
<td>0.5% = 5% WLR</td>
</tr>
<tr>
<td>Cloud Radiative Forcing</td>
<td>0.3%</td>
</tr>
</tbody>
</table>

Note: Transfer \( U_c \) is dominated by reference sensor \( U_c \) (depending on time interval/number of samples) Gorrono et al.
Summary

Non-preparedness (adaptation/mitigation) for impacts of climate change will be catastrophic for global society

- Global observations from space are critical tool
  - **Must be:** Reliable/trustable/comprehensive
  - **Need:** global coordinated resources
  - **Can also:** provide commercial opportunities

- Coherent observing system requires
  - Invariant trustable references from space and ‘terrestrial’
  - Documented evidence of traceability

- **TRUTHS provides a first step for a climate/calibration ‘constellation’**
  - Worlds EO assets tied to SI
    - Space/in-situ
    - Prototype sensor 2 sensor calibration tool
  - ‘Trustable’ Climate & EO information services

- Opportunity to prototype metrological approach to mission ‘reporting’
  - End 2 End simulator