FRM4SOC & FRM4STS: Data quality control and metrological traceability

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Summary of the presentation

1. Context
   • Fiducial Reference Measurements (FRM)
   • Metrological foundation

2. The FRM4SOC Project
   • Project outline
   • Data quality and metrological traceability

3. The FRM4STS Project
   • Project outline
   • Data quality and metrological traceability
1. Context

**Fiducial Reference Measurements (FRM)** are a suite of independent, fully characterized, and traceable ground measurements that follow the guidelines outlined by the GEO/CEOS Quality Assurance framework for Earth Observation (QA4EO).

**fiducial** (adj) *Regarded or employed as a standard of reference, as in surveying*
[Late Latin fiducialis, equivalent to fidi(a) trust, from fidere, to trust.]
1. Context:

Metrological Foundation – key terminology (simplified)

**Metrological Traceability:** *property of a measurement result* whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty *(Vocabulary International Metrology (VIM ISO guide 99))*

- **Error** – difference from a “true” value or a “bias” that can often be corrected for.
- **Uncertainty** – how well we believe we know the value
  - “Type A” or random – statistically determinable by experiment
  - “Type B” – any other means of estimating uncertainty (can be educated guess)
- **Quality Indicator (QI)** – an indicator of performance or quality of the result of a process/activity derived from an uncertainty estimate but can be a text descriptor / flag / numeric value. Can be binary
- **Traceability (document link)** – Archived and accessible, complete documentary linkage of all steps in a process chain tied to a result
- **Standard (reference)** – “reference” against which performance can be determined
1. Context: Metrological Foundation - Uncertainty

- Follow the GUM – Guide to the expression of Uncertainty in Measurement
  - The foremost authority and guide to the expression and calculation of uncertainty in measurement science
  - Written by the JCGM and BIPM (NPL input)

- Law of propagation of uncertainties

\[
\begin{align*}
  u_c^2(y) &= \sum_{i=1}^{n} \left( \frac{\partial f}{\partial x_i} \right)^2 u^2(x_i) + 2 \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \frac{\partial f}{\partial x_i} \frac{\partial f}{\partial x_j} u(x_i, x_j)
\end{align*}
\]

- Adding in quadrature
- Correlation term
- Sensitivity coefficient times uncertainty
- Sensitivity coefficients times covariance

N.B. Can be done analytically or using Monte Carlo analysis

2 because symmetrical:
1. Context: Metrological Foundation

Traceability and Uncertainty Propagation

Cryogenic radiometer 0.01 %

Primary irradiance standard 0.4 %

Calibration lamp use 1.2 %

Field spectrometer calibration 2.5 %

Vicarious calibration reference 3.2 %
Main aim of FRM4SOC:
To establish and maintain SI traceability of ground-based fiducial reference measurements (FRM) for satellite ocean colour radiometry (OCR).

Specific Objectives:
a. Develop, document, implement and report OCR measurement procedures and protocols. Design, document and implement both laboratory and field inter-comparison experiments for OCR to verify their FRM status.
b. International coordination activities to define next generation of ocean colour system vicarious calibration infrastructure (FRM4SOC workshop).
2. The FRM4SOC Project

International context:
• Under the auspices of CEOS WGCV and in support of the CEOS OCR virtual constellation.

• Helping fulfil the IOCCG in situ OCR white paper objectives and contribute to the relevant IOCCG WGs and task forces (e.g. uncertainty, future of OC-SVC, satellite sensor calibration).

• Contributing to Copernicus and the success of the Sentinel series of satellite sensors.

Three types of international intercomparison exercises:

Comparison 1 for OCR radiance and irradiance calibration sources
Comparison 2 for OCR calibration, lab & “controlled” outdoor measurements
Comparison 3 for OCR field measurements (AMT & AAOT)
(End-to-end uncertainty evaluation for FRM4SOC carried out by NPL)
2. The FRM4SOC Project
Comparison 1: Reference Irradiance and Radiance Sources

- NPL (UK pilot) with 11 participants from around the world, including:
  - Tartu (Estonia)
  - JRC (EC)
  - NOAA (USA)
  - Satlantic (Canada)
  - CSIRO & IMO (Australia)
  - NIVA (Norway)
  - NERC (UK)
  - LOV & Cimel (France)
  - DLR (Germany)

- Aimed at verifying the performance of irradiance and radiance sources used to calibrate ocean colour radiometers (OCRs)

- Part 1- Irradiance. Took place 03-07 April 2017 at NPL. Participant labs supplied their irradiance sources to NPL for SI traceability check, measurement using the NPL Spectral Radiance and Irradiance Primary Scales (SRIPS) facility & Reference Spectroradiometer System (RefSpec) and performance intercomparison

- Part 2 – Radiance. Between June 2017 and February 2018 transfer radiometers are being sent to each participant lab for radiance source measurements with periodic checks against the NPL derived radiance scale
2. The FRM4SOC Project:

Comparison 2: Lab and “controlled” outdoor OCR measurements

- Took place at Tartu Observatory, Estonia 08-13 May, 2017
- Aimed at verifying the performance (i.e., absolute radiometric calibration and characterization) of FRM Field Ocean Colour Radiometers (OCR) used for Satellite Validation
- ~40 OCRs calibrated and used to measure irradiance and radiance in the lab and simultaneously in a “controlled” outdoor environment
2. The FRM4SOC Project: Comparison 3: OCR field measurements

1. The **Acqua Alta Oceanographic Tower (AAOT)**, Gulf of Venice, Italy.
   8 days, in **July 2018** (date tbc).

   Purpose built steel tower with instrument house platform to conduct optical measurements under stable conditions to tilt and roll and illumination geometry.

2. The **Atlantic Meridional Transect (AMT)** No.27. **Sept-Oct 2017**.

   AMT cruises are conducted between UK & South Atlantic on a NERC ship.

   AMT passes through a wide range of environmental conditions and biogeochemical provinces.
FRM4SOC International Workshop on Options and Approaches to the Long-term Vicarious Adjustment of Sentinel- OLCI & MSI A/B/C and D Instruments

• Took place at ESA-ESRIN, Frascati, Italy, 21-23 Feb, 2017
• 30+ participants from Europe, USA, Canada, Australia & S.Korea
• Included many of the world’s leading experts in the field
• Consensus reached on many key points
2. The FRM4SOC Project

Metrological Traceability

Cryogenic Radiometer

The Optical Radiation Primary Standard

- Optical Power (W)

Trap Detector Calibration

- Current (A)

Trap Detector

Tunable laser

- Ti Sapphira

Filter Radiometer

- Current (A)

Current (A)

Filter Radiometer Calibration

SRIPS Blackbody

The Spectral Emission Primary Standard

- Spectral Radiance Responsivity (A/Nm²str/³/hr)

Filter Radiometer

SRIPS Blackbody Calibration

- Current (A)

SRIPS Blackbody Current (A)

SRIPS Spectral Radiance

- Source (e.g., FEL Lamp)

SRIPS Blackbody

Diffuser Calibration

- Diffuser Current (A)

Diffuser Calibration

NRR Lamp Current (A)

NRR Lamp

SRIPS Blackbody Irradiance Source

- Current (A)

OGR Irradiance Source

- Calibration

OGR Irradiance Source Calibration

Calibrated Ocean Colour Radiometer

- Calibrated Spectral Panel

Ocean Colour Radiometer

- Radiometer Current (A)

National Reflectance Reference Facility (NRR)

The Reflectance Primary Standard

- Spectral Reflectance Panel (Diffuser)

- Detectors (silicon diodes for visible, InGaAs for IR)

FEL Lamp

SV Spectral Filter

Spectral Panel (Diffuser)

NRR Lamp

Calibrated Ocean Colour Radiometer

Satellite Ocean Colour Sensor (e.g., Sentinel 3 OLCI)

Validation

Si-Traceable Calibrated OCR

- Diffuser Current (A)

- Radiometer Current (A)
2. The FRM4SOC Project

Uncertainty Budgets

- $\lambda_i$: Wavelength 0.01%
  - Random 0.00%
  - Systematic 0.00%
- $\frac{\pi R}{\lambda}$: Geometric factor 0.04%
  - BB Aperture Diameter 0.01%
  - Sphere Aperture Diameter 0.05%
  - Distance 0.02%
- $L_{BB}(\lambda, T)$: BB Radiance 0.21%
  - Temperature dependent 0.20%
  - Other 0.08%
- $E_{lamp}(\lambda_i)$: Lamp irradiance 0.14%
  - Lamp current stability 0.00%
  - Lamp current accuracy 0.00%
  - Alignment 0.14%
- $V_{BB}(\lambda_i, T)$ and $R_{SRIPS}(\lambda_i)$
  - Blackbody signal and System signal 0.19%
- $V_{lamp}(\lambda_i)$ and $R_{SRIPS}(\lambda_i)$
  - Lamp signal and System signal 0.19%
  - SEOM (random effect) 0.04%
  - Medium term system stability 0.10%
  - SCF repeatability 0.14%
  - Stray light and detector linearity 0.08%
  - SEOM (random effect) 0.03%
  - Medium term system stability 0.10%
  - SCF repeatability 0.14%
  - Stray light and detector linearity 0.08%

Signal uncertainty 0.00%
- Geometric factor 0.05%
- Amplifier Gain 0.01%
- FR Temp correction 0.06%
- Absolute Lens Transmittance 0.04%
- SSE 0.06%
- BB Uniformity 0.01%
- BB Emissivity 0.02%
- BB Stability 0.06%
- FR Absolute Responsivity 0.06%
- FR Relative Responsivity

SRIPS uncertainty 0.39%

Uniformity 0.01%
- Emissivity 0.02%
- Absorption 0.06%
- BB stability 0.06%
## 2. The FRM4SOC Project

### Uncertainty Budgets

<table>
<thead>
<tr>
<th>Source</th>
<th>400 nm</th>
<th>442.5 nm</th>
<th>490 nm</th>
<th>560 nm</th>
<th>665 nm</th>
<th>778.8 nm</th>
<th>865 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Radiometer</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Certificate</td>
<td>0.89</td>
<td>0.74</td>
<td>0.74</td>
<td>0.74</td>
<td>0.74</td>
<td>0.76</td>
<td>0.83</td>
</tr>
<tr>
<td>Instability</td>
<td>0.5</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.5</td>
<td>0.7</td>
<td>0.9</td>
</tr>
<tr>
<td>Alignment</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Temperature</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.03</td>
<td>0.09</td>
<td>0.2</td>
<td>0.38</td>
</tr>
<tr>
<td>Signal, uA</td>
<td>0.074</td>
<td>0.025</td>
<td>0.023</td>
<td>0.016</td>
<td>0.017</td>
<td>0.024</td>
<td>0.04</td>
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<tr>
<td>Non-Linearity</td>
<td>0.1</td>
<td>0.06</td>
<td>0.05</td>
<td>0.04</td>
<td>0.07</td>
<td>0.08</td>
<td>0.18</td>
</tr>
<tr>
<td>Stray light</td>
<td>0.3</td>
<td>0.4</td>
<td>0.4</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>FEL source</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shunt</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>Current</td>
<td>0.15</td>
<td>0.14</td>
<td>0.12</td>
<td>0.11</td>
<td>0.09</td>
<td>0.08</td>
<td>0.07</td>
</tr>
<tr>
<td>Distance</td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>Alignment</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Combined (k=1)</td>
<td>1.09</td>
<td>0.92</td>
<td>0.92</td>
<td>0.85</td>
<td>0.94</td>
<td>1.09</td>
<td>1.37</td>
</tr>
<tr>
<td>Expanded (k=2)</td>
<td>2.2</td>
<td>1.8</td>
<td>1.8</td>
<td>1.7</td>
<td>1.9</td>
<td>2.2</td>
<td>2.7</td>
</tr>
</tbody>
</table>

Source: Tartu Observatory
2. The FRM4SOC Project
Uncertainty Budgets

BOUSSOLE

\[ R_{RS} = \frac{L_w}{E_s} \]

\[ R_{RS} = \frac{L_w f_{cal} f_s \exp \left[ z_4 \left( \frac{-\ln \left( L_w f_{cal} f_s / L_w f_{cal} f_s \right)}{z_9 - z_4} \right) \right]}{E_s f_{cal} f_{cos} f_{tilt} f_{dir} + (1 - f_{dir}) E_s f_{cal}} \]

Sources of uncertainty in current data set

<table>
<thead>
<tr>
<th>INSTRUMENT RELATED</th>
<th>absolute radiometric calibration ((f_{cal})), diffuser cosine response ((f_{cos})),</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENVIRONMENTAL</td>
<td>shading ((f_s)), buoy tilt ((f_{tilt})), (z_4) and (z_9) are the actual instruments depths corrected for buoy tilt,</td>
</tr>
<tr>
<td>MODELLING</td>
<td>extrapolation to surface correction using Hydrolight simulation ((f_H)), the constant for water-air interface fraction of the direct to total solar irradiance ((f_{dir})),</td>
</tr>
</tbody>
</table>
FRM4STS: Fiducial Reference Measurements for validation of Surface Temperature from Satellites (ceos cv8)

Nigel Fox (Chair CEOS WGCV IVOS)
NPL coordinating ESA Project
WGCV Plenary # 40
3. The FRM4STS Project:

Main Aim of FRM4STS: to establish and maintain SI traceability of global Fiducial Reference Measurements (FRM) for satellite derived surface temperature product validation and help develop a case for their long term sustainability

Specific Objectives:

• Design and implement a laboratory-based comparison of the results of participants calibration processes for FRM TIR radiometers (SST, LST, IST)
• Design and implement a laboratory-based comparison to verify TIR blackbody sources used to maintain calibration of FRM TIR radiometers.
• Conduct outdoor comparison ‘experiments’ of LST and WST to evaluate environmental effects e.g. sky radiance
• Design and implement field inter-comparisons of SST using pairs of FRM TIR radiometers on board ships to build a database of knowledge over several years
• Conduct field-campaigns for FRM TIR of LST and IST to assess environmental effects in real world sites.
• Develop a set of best practise protocols for the calibration, operation and performance of FRM of Surface temperatures.
• Carry out comparisons and analysis to SI standards with full metrological rigour (e.g. detailed uncertainty breakdown).
• Perform a study of means to establish traceability and potential benefits to satellite validation and CDRs of high accuracy ocean temperature measurements using buoys and similar floating systems.
3. The FRM4STS Project:
SI traceability lab comparison (June 2016 at NPL)

19 participants assessed biases to SI under Laboratory conditions

- NPL BB
- PTB BB
- ITS-90
- T = ~223 – 325 K
- Non-vacuum

NPL Rad (AMBER)  PTB Rad

BB1  BB 2  BB 3  BB 4  BB n

Rad 1  Rad 2  Rad 3  Rad 4  Rad n
3. The FRM4STS Project:
Water Surface Temp – “controlled” outdoor comparison (near NPL - Jun/Jul 2016)
3. The FRM4STS Project: Uncertainty Contributions

**Blackbody Comparisons**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Type A Uncertainty in Value / %</th>
<th>Type B Uncertainty in Value / (appropriate units)</th>
<th>Uncertainty in Brightness temperature K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repeatability of measurement</td>
<td>$U_{\text{repeat}}$</td>
<td>$U_{\text{repeat}}$</td>
<td>$U_{\text{repeat}}$</td>
</tr>
<tr>
<td>Reproducibility of measurement</td>
<td>$U_{\text{repro}}$</td>
<td>$U_{\text{repro}}$</td>
<td>$U_{\text{repro}}$</td>
</tr>
<tr>
<td>Blackbody emissivity</td>
<td>$U_{\text{emiss}}$</td>
<td>$U_{\text{emiss}}$</td>
<td>$U_{\text{emiss}}$</td>
</tr>
<tr>
<td>BB Thermometer Calibration</td>
<td>$U_{\text{thermo}}$</td>
<td>$U_{\text{thermo}}$</td>
<td>$U_{\text{thermo}}$</td>
</tr>
<tr>
<td>BB cavity temperature non-uniformity</td>
<td>$U_{\text{non}}$</td>
<td>$U_{\text{non}}$</td>
<td>$U_{\text{non}}$</td>
</tr>
<tr>
<td>BB temperature stability</td>
<td>$U_{\text{stab}}$</td>
<td>$U_{\text{stab}}$</td>
<td>$U_{\text{stab}}$</td>
</tr>
<tr>
<td>Reflected ambient radiation</td>
<td>$U_{\text{refl}}$</td>
<td>$U_{\text{refl}}$</td>
<td>$U_{\text{refl}}$</td>
</tr>
<tr>
<td>Radiant heat/loss gain</td>
<td>$U_{\text{rad}}$</td>
<td>$U_{\text{rad}}$</td>
<td>$U_{\text{rad}}$</td>
</tr>
<tr>
<td>Convective heat/loss gain</td>
<td>$U_{\text{conv}}$</td>
<td>$U_{\text{conv}}$</td>
<td>$U_{\text{conv}}$</td>
</tr>
<tr>
<td>Primary Source</td>
<td>$U_{\text{prim}}$</td>
<td>$U_{\text{prim}}$</td>
<td>$U_{\text{prim}}$</td>
</tr>
<tr>
<td>RMS total</td>
<td>$((U_{\text{repeat}}^2 + (U_{\text{repro}}^2))^3)$</td>
<td>$((U_{\text{repeat}}^2 + (U_{\text{repro}}^2))^3)$</td>
<td>$((U_{\text{repeat}}^2 + (U_{\text{repro}}^2))^3)$</td>
</tr>
</tbody>
</table>

**Radiometer Comparisons**

<table>
<thead>
<tr>
<th>Uncertainty Contribution</th>
<th>Type A Uncertainty in Value / %</th>
<th>Type B Uncertainty in Value / (appropriate units)</th>
<th>Uncertainty in Brightness temperature K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repeatability of measurement</td>
<td>$U_{\text{repeat}}$</td>
<td>$U_{\text{repeat}}$</td>
<td>$U_{\text{repeat}}$</td>
</tr>
<tr>
<td>Reproducibility of measurement</td>
<td>$U_{\text{repro}}$</td>
<td>$U_{\text{repro}}$</td>
<td>$U_{\text{repro}}$</td>
</tr>
<tr>
<td>Primary calibration</td>
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<td>$U_{\text{prim}}$</td>
<td>$U_{\text{prim}}$</td>
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<tr>
<td>Linearity of radiometer</td>
<td>$U_{\text{lin}}$</td>
<td>$U_{\text{lin}}$</td>
<td>$U_{\text{lin}}$</td>
</tr>
<tr>
<td>Drift since calibration</td>
<td>$U_{\text{drift}}$</td>
<td>$U_{\text{drift}}$</td>
<td>$U_{\text{drift}}$</td>
</tr>
<tr>
<td>Ambient temperature fluctuations</td>
<td>$U_{\text{amb}}$</td>
<td>$U_{\text{amb}}$</td>
<td>$U_{\text{amb}}$</td>
</tr>
<tr>
<td>Size-of-Source Effect</td>
<td>$U_{\text{sos}}$</td>
<td>$U_{\text{sos}}$</td>
<td>$U_{\text{sos}}$</td>
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<tr>
<td>Atmospheric absorption/emission</td>
<td>$U_{\text{atm}}$</td>
<td>$U_{\text{atm}}$</td>
<td>$U_{\text{atm}}$</td>
</tr>
<tr>
<td>RMS total</td>
<td>$((U_{\text{repeat}}^2 + (U_{\text{repro}}^2))^3)$</td>
<td>$((U_{\text{repeat}}^2 + (U_{\text{repro}}^2))^3)$</td>
<td>$((U_{\text{repeat}}^2 + (U_{\text{repro}}^2))^3)$</td>
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</table>

**WST Comparisons**

<table>
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<tr>
<th>Uncertainty Contribution</th>
<th>Type A Uncertainty in Value / %</th>
<th>Type B Uncertainty in Value / (appropriate units)</th>
<th>Uncertainty in Brightness temperature K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repeatability of measurement</td>
<td>$U_{\text{repeat}}$</td>
<td>$U_{\text{repeat}}$</td>
<td>$U_{\text{repeat}}$</td>
</tr>
<tr>
<td>Reproducibility of measurement</td>
<td>$U_{\text{repro}}$</td>
<td>$U_{\text{repro}}$</td>
<td>$U_{\text{repro}}$</td>
</tr>
<tr>
<td>Primary calibration</td>
<td>$U_{\text{prim}}$</td>
<td>$U_{\text{prim}}$</td>
<td>$U_{\text{prim}}$</td>
</tr>
<tr>
<td>Angle of view to nadir</td>
<td>$U_{\text{angle}}$</td>
<td>$U_{\text{angle}}$</td>
<td>$U_{\text{angle}}$</td>
</tr>
<tr>
<td>Linearity of radiometer</td>
<td>$U_{\text{lin}}$</td>
<td>$U_{\text{lin}}$</td>
<td>$U_{\text{lin}}$</td>
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<tr>
<td>Drift since last calibration</td>
<td>$U_{\text{drift}}$</td>
<td>$U_{\text{drift}}$</td>
<td>$U_{\text{drift}}$</td>
</tr>
<tr>
<td>Ambient temperature fluctuations</td>
<td>$U_{\text{amb}}$</td>
<td>$U_{\text{amb}}$</td>
<td>$U_{\text{amb}}$</td>
</tr>
<tr>
<td>Atmospheric absorption/emission</td>
<td>$U_{\text{atm}}$</td>
<td>$U_{\text{atm}}$</td>
<td>$U_{\text{atm}}$</td>
</tr>
<tr>
<td>RMS total</td>
<td>$((U_{\text{repeat}}^2 + (U_{\text{repro}}^2))^3)$</td>
<td>$((U_{\text{repeat}}^2 + (U_{\text{repro}}^2))^3)$</td>
<td>$((U_{\text{repeat}}^2 + (U_{\text{repro}}^2))^3)$</td>
</tr>
</tbody>
</table>
3. The FRM4STS Project:
SST radiometer field comparison – Queen Mary 2 cruise Sep-Nov 2015
3. The FRM4STS Project:
SST Comparisons – Total uncertainty
3. The FRM4STS Project:
SST Comparisons – Type A uncertainty
3. The FRM4STS Project:
SST Comparisons – Type B uncertainty
Summary of the presentation
– key points

1. Metrological traceability is a key component in making fiducial reference measurements. Through SI traceability and uncertainty evaluation at each step it ensures the measurement is trustworthy, coherent and reliable. The resultant uncertainty budget also provides a means of obtaining a quantifiable quality indicator for the data.

2. The ESA FRM projects and NPL under the auspices of CEOS are helping to embed metrological principles and methods in satellite validation and calibration in order to provide more robust and reliable EO measurements.

3. As well as FRM4SOC and FRM4STS, NPL is actively engaged in a number of long-term research projects on the complex task of providing metrological traceability for satellite products of the ocean - open to further collaboration.
Thank you

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Department for Business, Energy & Industrial Strategy

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