TRUTHS: - Traceable Radiometry to Underpin Terrestrial- and Helio- Studies

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TRUTHS objectives:

• Establish benchmark measurements in solar reflective domain for decadal climate change through:
  – Direct sampling
  – Reference calibration of other sensors

• Support global Earth observing system through:
  – Facilitating upgrade in performance and/or traceability of other sensors for both climate and operational measurements

  • Calibration via near simultaneous overpass
  • Radiometric calibration of Moon
  • Radiometric calibration of CEOS reference standard test-sites (Land and Ocean)
  • BoA Surface studies, atmospheric correction, spot calibrations
Climate studies require:

- Global coverage
- Observations (insensitive to time/location/scale)
- Decadal time scales
- Uncertainties close to primary SI standards/realisations

Solution:

Establish and maintain SI traceability directly in Space on-board the spacecraft

- Adapt terrestrial methodologies and primary standards
What is TRUTHS? (& CLARREO)

Mission to establish benchmark measurements of SI traceable high accuracy spectrally resolved; incident & reflected solar and emitted thermal radiation as well as atmospheric refractivity through GNSS-RO.

To allow observation of decadal climate radiative: forcings, responses and feedbacks from a background of natural variability from:

- its own measurements
- through upgrading of performance of other observing systems: sensors and in-situ by in-flight reference calibration underpinning, CEOS, GMES & GEOSS

**UNCERTAINTY DRIVERS (Climate)**

- Total Solar Irradiance - 0.02 % (2σ)
- Spec solar Irradiance - 0.2 % (2σ)
- Reflected Solar Radiance - 0.3% (2σ)
- IR and GNSS-RO - 0.1 K (3σ)
Climate Absolute Radiance and Refractivity Observatory

4 small satellites: 2 off IR + GNSS RO & 2 off Solar Reflective (SR)

Orbits in pairs 90 deg polar and 90 deg separation at 609 km

Global averages - Nadir spectrally resolved 0.32-2.3 μm <10 nm & 5-50 μm 0.5 cm⁻¹

Expect to Start Phase A 2011 with Launch 2018 – 2020
CLARREO

IR full on-board SI primary standard
SR relative to another satellite
SR GIFOV (500 m)
Global mean nadir averages
Ref calibration (multi-angle)

IR Spectrometer calibrated on-board against “transition point” (Ga freeze) blackbody - emissivity monitored using Quantum cascade laser.
Climate Absolute Radiance and Refractivity Observatory

4 small satellites: 2 off IR + GNSS RO & 2 off Solar Reflective (SR)

Orbits in pairs 90 deg polar and 90 deg separation at 609 km

Global averages - Nadir spectrally resolved 0.32-2.3 \( \mu \text{m} \) \(<10 \text{ nm}\) & 5-50 \( \mu \text{m} \) 0.5 cm\(^{-1}\)

Expect to Start Phase A 2011 with Launch 2018 – 2020

<table>
<thead>
<tr>
<th>CLARREO</th>
<th>TRUTHS</th>
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<td>IR full on-board SI primary standard</td>
<td>SR full on-board SI primary Standard</td>
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<tr>
<td>SR relative to another satellite</td>
<td>GIFOV (40 m) \text{Land (200 m)} \text{Ocean}</td>
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<tr>
<td>SR GIFOV (500 m)</td>
<td>Global nadir spectral radiances (275 channels resolution 1-10 nm)</td>
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<tr>
<td>Global mean nadir averages</td>
<td>Ref Caln &amp; process studies (multi-angle)</td>
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<tr>
<td>Ref calibration (multi-angle)</td>
<td>Polarimetric information</td>
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<tr>
<td><strong>Highly complimentary partnership</strong></td>
<td>- aerosols</td>
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Providing Reference Calibrations

Near Simultaneous Nadir Observation (SNO) sensor Calibration

TRUTHS 90 deg polar orbit
- allows many overpasses with other sensors
  - different cross-over times/locations
  - ToA reflectances/radiances ± 5 mins
- Platform pointing to co-align view angles
- relatively low (609 km) orbit increase dwell time
- high spectral and spatial resolution to match sensor under calibration
- Can upgrade performance of others sensors to facilitate “climate quality” data

Surface sites (Bottom of Atmos.) & (Top of Atmos.)
- Polarimetry improves atmospheric correction
- Calibrate Aeronet
- High accuracy leads to improved retrieval algorithms
- Multi-angle, hyper-spectral, 40 m spatial, - supports:
  albedo, canopy structure, FLUXNET, Carbon sequestration....
Operational calibration service through “CEOS standard” sites/methodologies

CEOS endorsed test sites for Land and Ocean can be used as standards to cross-compare between sensors and to ground data providing each site is compared to each other.

Networks of test sites and methodologies can become operational calibration service improved through use of reference standard SI traceable sensor e.g. TRUTHS.
TRUTHS satellite

~ 1 m³ – Platform (SSTL 150)
Orbit: 90 deg – 609 km
Agile platform >2° /s slew rate
Payload mass – 165 kg including (2 off coolers for redundancy)
Payload peak power – 185 W
Daily data download – 4500 Gbits per day
Traceability Strategy:

- mimic that used on ground at standards labs

- Primary reference standard is cryogenic radiometer (CSAR) compares heating effect of monochromatic optical power

Also

measures Total Solar Irradiance (TSI)

Directly analogous to the instruments already in space for TSI (but cryogenic)
Cryogenic Solar Absolute Radiometer (CSAR): Primary standard & TSI

CSAR is an electrical substitution radiometer operating at ~ 20 K.

Technology is same as used for primary standards at national standards labs for 25 yrs (at ambient temps 100 yrs - also in space: 1970’s for TSI)

In space, cooled by Astrium 10 K cooler (dual for redundancy).

4 – TSI cavities (exposure varied)

2 – High sensitivity cavities (μW)

6 – primary Apertures on wheel at ambient temps

Cavity absorptance only potential source of optical degradation (>0.99998)
Cryogenic Solar Absolute Radiometer (CSAR): Primary standard & TSI

For Video of CSAR see
http://www.youtube.com/npldigital#p/a/u/0/aQAREkaZjfl
Observation instruments (science)

*Cryogenic Solar Absolute Radiometer (CSAR)*
- Total Solar Irradiance

Earth Imager
- 320 to 2450 nm (275 channels inc polarisation analysis)
- 40 m at nadir - 40 km swath

Solar Spectral Irradiance Monitor (SSIM)
- 200 to 2500 nm (0.5 to 1 nm bandwidth)

*Polarising Transfer Radiometer (PTR)* (2 OFF)
- off-nadir polarised radiance (~13 chan’s) for aerosols (atmospheric correction)
Cryogenic Solar Absolute Radiometer (CSAR): Primary standard & TSI

An “engineering model” designed and built currently operating in a vacuum can at Davos for terrestrial TSI.

In space, cooled by Astrium 10 K cooler (dual for redundancy).

4 – TSI cavities (exposure varied)
2 – High sensitivity cavities ($\mu$W)
6 – primary Apertures on wheel at ambient temps

Cavity absorptance only potential source of optical degradation (>0.99998)
Traceability Strategy:

- mimic that used on ground at standards labs
- Primary reference standard is cryogenic radiometer compares heating effect of monochromatic optical power to electrical power
- Tuneable monochromatic Optical beam (monochromator dispersed solar) calibrates other TRUTHS instruments

Optical fibre bundle moves "monochromatic" radiation between CSAR and Transfer radiometer (PTR)
Traceability Strategy:
- mimic that used on ground at standards labs
- Primary reference standard is cryogenic radiometer compares heating effect of monochromatic optical power to electrical power
- Tuneable monochromatic Optical beam (monochromator dispersed solar) calibrates other TRUTHS instruments

Fibre moves radiation between PTR and Solar Spectral Irradiance Monitor (SSIM)
Traceability Strategy:

- Mimic that used on ground at standards labs.
- Primary reference standard is a cryogenic radiometer that compares heating effect of monochromatic optical power to electrical power.
- Tunable monochromatic optical beam (monochromator dispersed solar) calibrates other TRUTHS instruments.
- Earth imager aperture illuminated by diffuse solar radiation from deployable diffuser (or Moon, or Earth).
- Radiance measured by multi-channel Polarised Transfer Radiometer (PTR) calibrated traceable to CSAR.

SI Units

TERRESTRIAL

TRUTHS

Cryogenic radiometer
Primary Standard
Reference photodiode
Laser

Earth imager

PTR

Imager

Lambertian Diffuser

Radiance (T via Planck)

Spectrometer Radiance / Irradiance

Filter-radiometer
Blackbody 3500 K

CSAR

SCM monochromatic radiation

PTR measures radiance

Solar Diffuser

TRUTHS Earth Imager

- Earth imager aperture illuminated by diffuse solar radiation from deployable diffuser (or Moon, or Earth)
- Radiance measured by multi-channel Polarised Transfer Radiometer (PTR) calibrated traceable to CSAR.
Traceability for Earth Radiances

Calibrated PTR moved to view Earth target or Moon simultaneous with Earth Imager. Traceability established/monitored at ~13 bands across spectrum

SSIM can also view Moon to link both instruments and evaluate traceability chains

Solar illuminated lambertian diffuser deployed to fill Earth Imager FOV also viewed by PTR (same angles)
On-Board SI Traceability (calibration/performance)

*Cryogenic Solar Absolute Radiometer (CSAR)*
- Primary SI reference standard

Spectral Calibration Monochromator (SCM)
- Spectrally dispersed monochromatic radiation from Sun for calibration system

*Polarising Transfer Radiometer (PTR)* (2 OFF)
- ~13 spectral bands to link calibration from CSAR to Earth Imager
<table>
<thead>
<tr>
<th>Climate variable</th>
<th>Role</th>
<th>TRUTHS providing direct observation</th>
<th>TRUTHS providing reference calibration</th>
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<tbody>
<tr>
<td>Solar irradiance</td>
<td>Climate forcing</td>
<td>yes</td>
<td>yes</td>
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<tr>
<td>Earth radiation budget</td>
<td>Climate forcing, feedback</td>
<td>yes</td>
<td>yes</td>
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<tr>
<td>Surface albedo</td>
<td>Albedo feedback</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Cloud cover</td>
<td></td>
<td>yes</td>
<td>yes</td>
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<tr>
<td>Cloud particle size distribution</td>
<td></td>
<td></td>
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<tr>
<td>Cloud effective particle size</td>
<td>Cloud feedback</td>
<td>yes, through spectral benchmarking</td>
<td>yes</td>
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<td>Cloud ice/water content</td>
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<td></td>
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<tr>
<td>Cloud optical thickness</td>
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<td>Water vapour</td>
<td>Column water vapour response</td>
<td>yes</td>
<td>yes</td>
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<tr>
<td>Ozone</td>
<td>Stratospheric ozone Feedback</td>
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<td>yes</td>
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<tr>
<td>Aerosols Optical Depth</td>
<td>Climate forcing</td>
<td>no (limited temporal/spatial coverage) yes</td>
<td>yes</td>
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<td></td>
<td>Atmospheric correction</td>
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<td>Ocean Colour</td>
<td>Carbon cycle</td>
<td>yes</td>
<td>yes</td>
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<tr>
<td>Ice and snow cover</td>
<td>Albedo feedback</td>
<td>yes</td>
<td>yes</td>
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<tr>
<td>Vegetation</td>
<td>Carbon Cycle and Albedo feedback</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Land Cover/Land Use</td>
<td>Surface Radiative Forcing</td>
<td>yes</td>
<td>yes</td>
</tr>
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</table>
Traceability for Total Solar Irradiance

Total Solar irradiance
W m$^{-2}$
0.02 %

Total power responsivity
0.02 %

By design

Preflight check of cavity reflectance

In-orbit comparison of 4 cavities

Aperture areas
0.01 %

Preflight calibration

In-Orbit comparison of 5 apertures

Gold boxes = SI traceability
Traceability for Solar Spectral Irradiance

Solar Spectral irradiance
W m$^{-2}$ nm$^{-1}$
0.2%

- Spectral responsivity
  0.2%
  - In-orbit full spectral calibration against PTR
    0.2%
    - Preflight full spectral calibration of PTR
      0.05%
  - In-orbit comparison with CSAR apertures
    0.01%

- Aperture area
  0.01%

- Wavelength accuracy
  - Pre-flight calibration
    0.01%
  - Pre-flight calibration
  - In-orbit check at 2 laser Ås

Solar Absorption lines
SI Traceability for Earth Radiance

Radiance from Earth Imager
\[ \text{W m}^{-2} \text{ sr}^{-1} \text{ nm}^{-1} \]
0.3 %

Radiance Calibration 0.3 %

Wavelength accuracy

Solar Spectral irradiance 0.2 %

Radiance geometry \( \text{m}^2 \text{ sr} \) from PTR apertures <0.1 %

Preflight calibration

Absorption lines in Sun/atmosphere

Diffuser spectral reflectance 0.2 %

In-orbit calibration by SSIM (Fig. XX) 0.2 %

Preflight calibration Full spectral 0.2 %

In-orbit check internal aperture

In-orbit calibration at 13 spectral bandwidths 0.3 %

Preflight calibration <0.06 %

PTR FRs

In-orbit calibration
Conclusion

- International community have identified traceability, accuracy and data quality as key drivers for Earth Observation: GEOSS / GMES and in particular for climate studies
  - WMO/BIPM MoU
  - NMIs must work closely with community to develop “transportable/field-solutions”
  - Uncertainty demands (radiometry) most challenging of any sector
- All aspects/steps of producing EO data products needs validation and traceability (instrument calibration (pre- and post- launch) and algorithms/models) QA4EO (http:www.QA4EO.org) provides a focus
  - European Metrology Centre for Earth Observation and Climate (EMCEOC) linked through a Centre for Carbon Measurement (CCM) will be a key facilitator to address this in conjunction with space agencies (CEOS)
- Traceability (benchmark measurements) from space seen as only plausible solution for studies of decadal climate and the data needed by policy makers to make informed decisions on mitigation and adaptation strategies
  - Need international “climate and calibration observatory (constellation) with in-flight traceability to SI (ideally at least two methods to allow comparisons) CLARREO (US) and TRUTHS (Europe)
- A “grand challenge project” demonstrating impact and criticality of metrology and the SI
  - “An NMI in space”
Summary

- **TRUTHS highly complementary to CLARREO**
  - Climate science requirements and key operational characteristics from CLARREO
  - Methodology for SI Traceability based on on-board primary standard
  - Delivers input solar irradiances on same platform
  - Together can provide international benchmark climate and calibration constellation

- **TRUTHS payload based on existing technologies**
  - (baseline) imager upgrade of ESA- APEX aircraft spectrometer
  - CSAR only new technology now built and under test
  - All could be built in 3 yrs

- **Low cost agile platform capable of increased payload both mass and power**
  - Could add CLARREO instruments

- **Currently under review by ESA “Earth explorer”**
  - Small missions < 100M Euro (excluding launch)
  - Decision on three Nov 2010
  - Potential to partner with NASA

- **Support within UK but national funding ??**
  - UKSA
  - New ESA climate office opened in UK
  - New government
  - National debt
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<thead>
<tr>
<th>Name</th>
<th>Institution</th>
<th>Country</th>
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Thankyou
Nigel.Fox@npl.co.uk

For more details:
www.npl.co.uk/TRUTHS
http://www.youtube.com/npldigital#p/a/u/0/aQAREkaZjfl