Accurate radiometry from space: An essential tool for climate studies

Dr Nigel Fox
25 Jan 2011

~ 700 km
Remote sensing of the Earth from Space: Utilising full EM spectrum

>100 EO satellites launched in 2000 – 2010
>200 expected to be launched in current decade at a cost of $20B
Operated by > 34 countries Surface resolutions <1 m
Observing and interpreting the Earth’s systems (optical domain)

**Incoming Solar Radiation**
Drives all the processes of the Earth System and potentially damaging (UV) to Biosphere (Human health)

**Solar Reflected (SR) Radiation**

- **Atmosphere**
  - Aerosol (size & distribution)
  - clouds
  - pollution
  (impact on health)

- **Water**
  - pollution (originator)
  - algae plumes (carbon cycle)

- **Land**
  - usage / condition
  - type/quantity of vegetation
  - minerals
  - Carbon & hydrological cycles

- **Governments**
  - treaties, tax, planning

EO can indicate good areas to fish (temp, phytoplankton, algae)

**Thermal Emitted Radiation**

- **Atmosphere**
  - Atmospheric chemistry

- **Water**
  - Temperature

- **Land**
  - Temperature, Fires, Volcanoes,
  “Planet” - Radiation budget
Life cycle of Wheat

Dep of Geography University of Zurich

May 2

May 18

June 16

June 24

July 5

July 17

July 26

August 12
Observing and interpreting the Earth’s systems (optical domain)

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**Spatial variability requires good stability and SNR (signal to noise ratio) from a single sensor - but long-term studies “climate change” need measurements over decades and harmonised data sets from multiple satellites and other observing systems.**

**Must have robust knowledge of uncertainty - SI traceability**
The Group on Earth Observations (GEO)’s (founded 2002) Global Earth Observation System of Systems (GEOSS) must deliver comprehensive “knowledge / information products” worldwide and in a timely manner to meet the needs of its nine “societal benefit areas”.

- This will be achieved through the synergistic use and combination of data derived from a variety of sources (satellite, airborne and in-situ) through the coordinated resources and efforts of the GEO members.

- Achieving this vision (2015) requires the establishment of an operational framework to facilitate interoperability and harmonisation.
Climate Change

Key Societal Questions

- Is the Earth warming?
- If so how much?
- What is the cause?
- Can we detect it?
- Can we stop it?
- Do we care?

**Northern Hemisphere Temperature Reconstructions**

![Temperature Anomaly Chart](chart.png)
Climate Change

Key Societal Questions

- Is the Earth warming?
- If so how much?
- What is the cause?
- Can we detect it?
- Can we stop it?
- Do we care?

Earth Radiation budget (balance)

Energy \textit{in} = \textit{Energy out}

No additional warming

\therefore \; \text{No Climate change}
Climate Change

Key Societal Questions

- Is the Earth warming?
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Radiation Budget
Climate Change

Key Societal Questions

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- If so how much?
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Climate Change

Key Societal Questions

- Is the Earth warming?
- If so how much?
- What is the cause?
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Carbon Fluxes

Sources of Carbon (colour Key)

- Anthropogenic
- Pre-industrial (Natural)
All climate models reliably predict the past (nearly) but provide wide variances in their prediction of the future.

Uncertainty in data/feedbacks limits ability to discriminate to ~ 30 yrs!!

Need to test and constrain models with data more accurate than natural variability.
Reducing uncertainty in impact by constraining the models

Blue = Solar reflective (SR) (0.3 – 2.3 μm)
Red = Infra-Red (> ~5 μm)

- Temperature
- Water Vapour
- Clouds
- Radiation
- Snow/Ice Cover

Cloud Feedback
Water Vapour/Lapse Rate Feedback
Snow/Ice Albedo Feedback

Roe and Baker, 2007

- Greenhouse Gases
- Surface Albedo
- Aerosols
Time to detect Cloud Radiative Forcing (CRF) from natural variability

TRUTHS or (CLARREO) (proposed satellites) accuracy (0.3% k=2) near optimum to the perfect observing system for 100% cloud feedback

TRUTHS ~ 12 yrs
CERES ~ 25 yrs
MODIS ~ 40 yrs

For 50% difference > 20 yrs

Other parameters e.g. Albedo have similar curves

Wielicki et al 2010
Total Solar Irradiance (TSI) or “solar constant”: the driving force of the planet

30 yr record shows “regular” 11 yr cycle and No significant Variation

Thus No impact on climate

Different normalisation strategies give different results!
Total Solar Irradiance (TSI) or “solar constant”: the driving force of the planet

30 yr record shows “regular” 11 yr cycle and **No** significant Variation [www.pmodwrc.ch](http://www.pmodwrc.ch)

Thus No impact on climate

**Thames Frost Fair (1684)**

Mini-Ice age caused by ~ 0.3 % reduction in solar output.

- No sunspots for 50 yrs
- 2008 to 2010 (unusually low sunspot activity!!!)

Can we rely on 30 yrs of ??? measurements to rule out solar contribution to climate?
Solar Spectral variability may lead to surprises!

J D Haigh et al Nature 467 p696 Oct 2010

TOA measurements of Solar Spec irradiance by NASA SIM indicate significant variance in expected spectral content at end of solar cycle 23. ⇒ surprises when used in and compared to models:

2004 - 2007 TSI↓ UV↓↓ Vis↑

O₃ (>45 km ↓ ~35 km ↑) T↑

Cooler Sun - Warmer Earth!
## Summary of measurand Requirements (SR domain)

<table>
<thead>
<tr>
<th>Mission requirement</th>
<th>Parameter: proposed value</th>
<th>Driving mission objective</th>
<th>Required</th>
<th>Desired</th>
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</thead>
<tbody>
<tr>
<td>SI traceable measurement of the solar reflected spectrum</td>
<td>Spectral range: 320 nm – 2450 nm</td>
<td>Nadir Reflectance Spectral Climate Change Benchmarks</td>
<td>320 nm – 2350 nm</td>
<td>From 320 to 2500 nm</td>
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<tr>
<td>““</td>
<td>Earth Radiation budget</td>
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<tr>
<td>““</td>
<td>Plant optical traits and minerals</td>
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<td>380 nm – 2450 nm</td>
<td>Up to 2500 nm</td>
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<td></td>
<td>Accuracy: 0.3% (2σ)</td>
<td>Trend estimation of cloud feedback</td>
<td>0.3 % (2σ)</td>
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<td>Spectral resolution: 1-10 nm</td>
<td>Nadir Reflectance Spectral Climate Change Benchmarks</td>
<td>1-10 nm</td>
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<td></td>
<td>40 m (land) 200 m (ocean)</td>
<td>Cloud masking</td>
<td>&lt; 500 m</td>
<td>&lt;100 m</td>
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<tr>
<td>SI traceable measurement of total solar irradiance</td>
<td>Spectral range: 0.2 to 35 μm</td>
<td>Solar variability and Earth Radiation Budget</td>
<td>0.2 to 35 μm</td>
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<tr>
<td></td>
<td>Accuracy: 0.01% (2σ)</td>
<td>Solar variability and Earth Radiation Budget</td>
<td>&lt; 0.01% (2σ)</td>
<td></td>
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<tr>
<td>SI traceable measurement of spectral solar irradiance</td>
<td>Spectral range: 200-2500 nm</td>
<td>Solar variability and ozone</td>
<td>200-2500 nm</td>
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<td>Accuracy: 0.1% (2σ)</td>
<td>Solar variability</td>
<td>0.1% (2σ)</td>
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<td>Reference calibrations</td>
<td>As for radiance above</td>
<td>Reference Intercalibration</td>
<td>320 nm – 2450 nm</td>
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</table>
Optical uncertainty requirements (GCOS) for decadal climate change

UN Global Climate Observing System

<table>
<thead>
<tr>
<th>Objectives for SI traceability</th>
<th>Climate Requirement</th>
<th>Preflight</th>
<th>In-flight</th>
<th>Terrestrial</th>
<th>Primary</th>
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<tbody>
<tr>
<td>Solar Irradiance</td>
<td>0.01%</td>
<td>0.2%</td>
<td>?</td>
<td>0.2%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Spectral radiance (clouds, albedo)</td>
<td>0.3%</td>
<td>2% - 5%</td>
<td>?</td>
<td>-1%</td>
<td>&lt;0.05%</td>
</tr>
<tr>
<td>Water-leaving radiance (Ocean Colour)</td>
<td>1%</td>
<td>5%</td>
<td>-5%</td>
<td>-1%</td>
<td>&lt;0.05%</td>
</tr>
</tbody>
</table>

Need to monitor change – not necessarily absolute values

- Sensors only require “sensitivity” and stability (or means to check) and sufficient overlap with another sensor to avoid data gap

High risk:
- Guaranteed Data continuity - high cost – “data-gaps” likely
- Small drifts undetected - potential bias build-up with time
- Discourages innovation
- Sensitive to natural fluctuations (particularly during “overlaps”)

SI Traceability (maintained in operation) – Flexible observing, innovation, coherence between methods (traceability routes) and observing systems
All optical sensors drift from pre-flight calibrations – also biases between sensors?

Ratio of Band 1 to Band 2 should be continuous straight line

Only reliable (low risk) solution is to establish robust traceability to international agreed standards “SI units” in common with other terrestrial applications but must have traceability “in flight”
All optical sensors drift from pre-flight calibrations – also biases between sensors?

Sensor biases & drifts also major issue for Operational data

- Satellite repeat times (at best days)
  - Link data sets from different sensors: agencies, footprints, spectral bands ... How?

- Commercial & Regulatory services
  - International harmonisation, interoperability GEOSS, GMES (QA4EO)

Existing Post-launch calibration strategies (on-board and vicarious) limited in accuracy and traceability

Ratio of Band 1 to Band 2 should be continuous straight line

Only reliable (low risk) solution is to establish robust traceability to international agreed standards “SI units” in common with other terrestrial applications but must have traceability “in flight”
Radiometric traceability at sensor (terrestrial)

Cryogenic Radiometry

Spectral Responsivity

Black body

Photometry

Planck’s Law

Spectral radiometry

Filter radiometer

Thermometry (Radiation)

Solar

Remote Sensing

Lighting

Transport

Aerospace

Medicine

Industry

Environment
Radiometric traceability at sensor (space)

Spectral Responsivity

Planck’s Law

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

Black body

Spectroscopic radiometry

Filter radiometer

(IR)Radiiances achievable

but challenging!
**Optical power**

$$P_o$$

**Absorbing black coating**

**Electrical Heater Power**

$$P_E$$

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

$$P_o=P_E$$

**Callendar radio balance**

(1910)

**Ångström compensation pyroheliometer**

(1893)

**SOHO (1996)**

**Total Solar Irradiance from Space (1975)**

**Electrical Substitution Radiometry:** A 100 yr old technology - SI primary standard of choice for optical radiation measurements

**National Physical Laboratory**
**Electrical Substitution Radiometry:** A 100 yr old technology - SI primary standard of choice for optical radiation measurements

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

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

- Optical power = $P_o$
- Absorbing cavity (~ 0.99999)
- Shutter

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

- Thermal shroud

Cryogenic cooling ($T < 20$ K)

Cooling improves sensitivity by 1000 X

**Principle of Cryogenic radiometry**
History of Cryogenic Radiometers - NPL

Quinn & Martin (70’s – 80’s)  
(Designed for $\sigma$ & T)

Martin, Fox, Key (80’s – 90’s)

Fox, Martin, Haycock (90’s –)

Liquid Helium  
$\sim 2 – 5$ K

Mechanically cooled  
$\sim 10 – 20$ K

Winkler, Fox, Usadi, Finsterle Fehlman, Blattner (10’s –)

Space-flight
National Laser Radiometry Facility (NLRF)

Continuously tuneable CW laser radiation from 210 nm to 11 μm power stabilised <0.001% drift
Radiometrically calibrated filter radiometers

Spectral response of filter radiometer determined over full spectral bandwidth using tuneable lasers:

Uncertainty in spectral radiance $\sim 0.02\%$
“Customer” requirement

- Satellite Pre-flight Calibration
- Satellite In-flight Calibration
- Lamp
- Solar illuminated Diffuser
- Vicarious
- Atmosphere/Model
- Data products

Traceability ??

Can DO

n.b. Earth projected pixel size 10’s to 100’s m

“Fitness for purpose” (Quality indicator / uncertainty)

n.b. Earth projected pixel size 10’s to 100’s m

e.g. Reflectance of Sunlight from ground “a reflectance standard”
Reference stds for radiometric gain (land imagers) Ideally Need Ten!

- Spatially uniform, bright, large (pixels from 10’s to 100’s m)
- Standardised procedures to aid characterisation (and for new sites)
- Comparisons of “field measurement” instruments & techniques to ensure consistency and “traceability”
CEOS WGCV IVOS: “stability” Reference standards:
inaccessible for direct surface measurements but temporally stable
Characterisation to enable SI traceability has its challenges!

- Reflectance factor over large areas in short time as illumination source (sun) angle moves
- (Laboratory instruments/concepts need to be adapted to the field)
- Extremes of temperature
- Atmosphere well-characterised & no clouds
- Uncertainty (for climate) factor 5 to 10 too high
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 \( \mu m \) <10 \( nm \) & 5-50 \( \mu m \) 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 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)

Highly complimentary partnership

TRUTHS
SR full on-board SI primary Standard
GIFOV (40 m) Land : (200 m) Ocean
Global nadir spectral radiances
(275 channels resolution 1-10 nm)
Ref Caln & process studies (multi-angle)
Polarimetric information
- aerosols
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

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

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
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
TRUTHS Payload: Solar & Earth view axis

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 radianc (~13 chan’s) for aerosols (atmospheric correction)
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)

If $\Delta T_{\text{opt}} = \Delta T_{\text{Elec}}$ then $P_{\text{opt}} = P_{\text{Elec}}$

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)
Cryogenic Solar Absolute Radiometer (CSAR): Primary standard & TSI

For Video of CSAR see

http://www.youtube.com/npldigital#p/a/u/0/aQAREkaZjfl
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 (μW)

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 cryogenic radiometer 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.
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).
**TRUTHS Payload: On-board SI traceability**

*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
## Needs of ECV's

<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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</thead>
<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>
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<tr>
<td>Cloud cover</td>
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<td>Cloud particle size distribution</td>
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<td>Cloud effective particle size</td>
<td>Cloud feedback</td>
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<td>Cloud optical thickness</td>
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<td>Water vapour</td>
<td>Column water vapour response</td>
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<td>Climate forcing</td>
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<td></td>
<td>Atmospheric correction</td>
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<td>Ocean Colour</td>
<td>Carbon cycle</td>
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<td>Ice and snow cover</td>
<td>Albedo feedback</td>
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<tr>
<td>Vegetation</td>
<td>Carbon Cycle and Albedo feedback</td>
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<td>yes</td>
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<tr>
<td>Land Cover/Land Use</td>
<td>surface Radiative Forcing</td>
<td>yes</td>
<td>yes</td>
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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”
## Contributing Science team led by Dr Nigel Fox:

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
<th>Country</th>
<th>Location</th>
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</thead>
<tbody>
<tr>
<td>Dr. Richard Allan</td>
<td>Met office</td>
<td>UK</td>
<td></td>
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<tr>
<td>Dr. Richard Bantges</td>
<td>Imperial College</td>
<td>UK</td>
<td></td>
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<td>Dr. Xavier Briottet</td>
<td>ONERA</td>
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<td>Dr. Helen Brindley</td>
<td>Imperial College</td>
<td>UK</td>
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<tr>
<td>Mr. Steve Groom</td>
<td>PML</td>
<td>UK</td>
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<td>Prof. Joanna Haigh</td>
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<td>National Physical Laboratory</td>
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Thankyou
Nigel.Fox@npl.co.uk

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