TRUTHS-Lite: A Microsatellite Based Climate Benchmark Mission

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10th IAA Symposium on Small Satellites for Earth Observation, Berlin, Germany, April 2015
Introduction

Climate studies require:

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

EO “customers” (via GMES, GEOSS + £services) seek:

- Timely, reliable & “fit-for-purpose” knowledge from:
  - integrated sources
  - international harmonised
  - affordable cost
  - (some) at climate quality
- Must have quality system
  - traceable uncertainty
  - e.g. QA4EO
Optical uncertainty requirements (GCOS) for decadal climate change

<table>
<thead>
<tr>
<th>Objectives for SI traceability</th>
<th>Climate Requirement</th>
<th>Pre-flight</th>
<th>In-flight</th>
<th>Terrestrial</th>
<th>Primary</th>
</tr>
</thead>
<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>

“Strategy!”: 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
SI Traceability

Traceability Strategy:
- mimic that used on ground at standards labs
- Primary reference standard is cryogenic radiometer (CSAR) compares heating effect of monochromatic optical optical power

Also

measures Total Solar Irradiance (TSI)

Directly analogous to the instruments already in space for TSI (but cryogenic)
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) & achieved**

- Total Solar Irradiance - 0.02% (2σ)
- Spec solar Irradiance - 0.2% (2σ)
- Ref solar Earth spectral Radiance - 0.3% (2σ)
- IR and GNSS-RO - 0.1 K (3σ)
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 Gbit/s per day
• **TRUTHS**’ primary goal is to provide benchmark measurements of both **incoming** (solar) and **outgoing** (reflected solar) radiation.

• Measuring global spectrally resolved (10 nm) Earth radiances, continuously sampled (spectrally and spatially) with GIFOV of ~50m from 340 - 2340 nm and the corresponding solar spectral irradiances both with **uncertainties traceable to SI units of <0.3%**

• Although not selected in the ESA EE8 call, TRUTHS received a strong recommendation of support and encouragement that an early implementation should be explored as part of a wider international collaborative effort.

• In support of that goal this paper proposes a low-cost TRUTHS precursor mission (**TRUTHS-Lite**).

• This would offer **risk reduction** on the key enabling technologies of TRUTHS.
The TRUTHS-Lite mission would be based on a new 50kg micro-satellite platform being developed by Surrey Satellite Technology Ltd. (SSTL) – the SSTL-X50.

<table>
<thead>
<tr>
<th>Payload Instrument Mass</th>
<th>Up to 45 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload Volume</td>
<td>Width 530 mm, Depth 430 mm, Height 400 mm</td>
</tr>
<tr>
<td>Payload Orbit Average Power</td>
<td>Typically 35 W</td>
</tr>
<tr>
<td>Payload Peak Power</td>
<td>Typically 85 W</td>
</tr>
<tr>
<td>Payload Data Bus</td>
<td>Gigabit per second to on-board storage or high speed downlink.</td>
</tr>
<tr>
<td>Attitude Control</td>
<td>Earth referenced or inertial; stability: 18 arc-seconds/second; knowledge: 10 arc-seconds; control 0.07 degrees</td>
</tr>
<tr>
<td>Typical Orbit</td>
<td>Low-Earth Orbit – Sun-Synchronous</td>
</tr>
<tr>
<td>Platform Lifetime</td>
<td>5 to 7 years</td>
</tr>
<tr>
<td>Total Mass</td>
<td>50 kg typical – up to 75 kg</td>
</tr>
</tbody>
</table>
The **TRUTHS-Lite** payload would be a cut-down version of that proposed for TRUTHS and would comprise just the **key instruments**:

- **Cryogenic Solar Absolute Radiometer (CSAR)** – a self-contained SI primary standard, which includes an innovative **cryo-cooler**, and a **total solar irradiance (TSI)** cavity.

- **Spectral Calibration Monochromator (SCM)** – an On-Board Calibration Reference light source used in conjunction with the CSAR.
The hyperspectral **Earth Imager (EI)** would have to be sacrificed from TRUTHS-Lite due to volume constraints, and this would be replaced by a simple (small) multi-spectral Earth Imaging Camera.

Similarly, the **Polarising Transfer Radiometer (PTR)** and **Solar Spectral Irradiance Monitor (SSIM)** would not be carried.

However, the EI could be flown on a **companion satellite**.
Mission & Payload Concept

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

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

Cavity absorptance only potential source of optical degradation (>0.99998)
Mission & Payload Concept

- When the spacecraft is in **Sun-pointing** mode, the **CSAR** instrument can measure the absolute radiance of the Sun over the spectral range 0.32 to 2.45 \( \mu \text{m} \) wavelength in 13 spectral bands with spectral bandwidths varying from 1 to 10 nm, via the On-Board **Spectral Calibration Monochromator (SCM)**.
- This will allow radiometric measurements to be made to an accuracy of 0.3%.
- The **Total Solar Irradiance (TSI)** monitor measures the total solar irradiance over 0.2 to 35 \( \mu \text{m} \) wavelength to 0.01% accuracy by absorbing radiation into a blackbody cavity.
- By pointing the spacecraft at the **Earth**, similar measurements can be made of the Top of Atmosphere (ToA) reflected solar spectrum.

![Image of spacecraft and CSAR instrument](image1.png)

**20 mm diameter TSI cavity**

![Exploded view of CSAR instrument](image2.png)

**Thermal shields**, **Mounting surface**, **Total Solar Irradiance cavity**, **Thermal shields and light trap**, **Aperture wheel**

**High-sensitivity cavity**, **Detector stage**, **Shutter wheel**
Mission & Payload Concept

- Flying a companion **hyperspectral imaging micro-satellite** of a similar class would benefit both missions, in that it would provide extra information on the ground reference sites targeted by TRUTHS-Lite, whilst also providing a means of calibrating the hyperspectral data to an SI tracable standard.

- SSTL’s **CHRIS** imager is available now, and **CHRIS-2** is in development. Similarly, the ESA **APEX** instrument could be used.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>14kg</td>
</tr>
<tr>
<td>Power (when imaging)</td>
<td>&lt;9W</td>
</tr>
<tr>
<td>Focal length</td>
<td>746mm</td>
</tr>
<tr>
<td>Field of view</td>
<td>1.24°</td>
</tr>
<tr>
<td>Sensor array</td>
<td>748 x 748 CCD detector</td>
</tr>
<tr>
<td>Digitisation</td>
<td>12 bit</td>
</tr>
<tr>
<td>GSD</td>
<td>17m at 560km</td>
</tr>
<tr>
<td>Swath width</td>
<td>13km at 560km</td>
</tr>
<tr>
<td>Spectral resolution</td>
<td>1.3-11.3 nm</td>
</tr>
<tr>
<td>Spectral range</td>
<td>415-1050 nm</td>
</tr>
<tr>
<td>Simultaneous bands @ half spatial resolution</td>
<td>61 (34m GSD)</td>
</tr>
</tbody>
</table>
Mission & Payload Concept

- **SSTL CHRIS-2 Earth Imager**
  - Mirror telescope
  - Spectrometer
    - Prism dispersion
    - Spherical mirrors
  - Split between 2 detectors
    - Si CCD for visible/NIR
    - Cooled MCT for short-wave IR
  - CHRIS 2 specification (~ EnMap)
    - GSD = 19m
    - SNR >100:1 (all bands)
    - Spectral range 400 - 2500nm
    - Spectral resolution <10nm to 20nm
  - Developments
    - Smaller telescope for 100m GSD
    - Higher spectral resolution
    - Relaxed aperture for spectrometer
By selecting a Sun-Synchronous orbit at approximately 600km altitude and approximately 10.30am Local Solar Time of Ascending Node (LTAN), measurements can be made at times and locations to match a number of existing Earth-imaging spacecraft, thus allowing cross-calibration of their data with an absolute, SI-traceable, radiometric standard.

With a downlink capability of 80-160 Mbps, the TRUTHS-Lite spacecraft would be able to return ~280 Gbit of data per day – approximately 1/16th of that of the full TRUTHS mission – but without the need for transmitting the data-heavy (0.38 Gbit per image) hyperspectral images.
Cross-Calibration Tools

• **Objective:** estimation of the radiometric uncertainty of a cross-calibration using TRUTHS as a reference sensor → output to update the cross-calibration methodology and instrument design.

• **Structure:** initial version of four independent modules addressing the major uncertainty contributions affecting a typical CEOS prioritized land based calibration site: surface altitude/slope, spectral response, aerosol content, and surface reflectance heterogeneity.

• **Uncertainty methodology:** Monte-Carlo Method for uncertainty propagation as in GUM-S1 and QA4EO → cross-calibration uncertainty estimates based on probability distribution function of the associated parameters.

• **Software implementation:**
  - *Portable and accessible:* open-source code (Python), embedded algorithms (e.g. slope calculation) and open-access libraries (e.g. GDAL)
  - *JASMIN supercomputer cluster:* Memory and processing limitations overcome. Large memory units and code parallelization.
Spectra Module

• **Inputs:**
  - *DIMITRI ToA reflectance:* reference spectrum interpolated at 0.0005 nm.
  - *Sentinel 2 spectral response* interpolated at 0.0005 nm.
  - *TRUTHS Imager design:* native sampling/resolution and binning.

• **TRUTHS spectral response:**
  - triangular shape native bands (low aberration optical design).
  - Sampling matches native resolution as FWM (slit width = pixel size)

• **TRUTHS ToA measurement:**
  - Convolution with DIMITRI ToA at native bands and binning accounted for final TRUTHS bands
  - Reconstruction of the DIMITRI ToA reflectance at same sampling steps using interpolation (justified by the low accuracy of TRUTHS measurements) and no-prior knowledge of the signal assumed (conservative approach).
• **Sampling/resolution error:** the Sentinel 2 is convolved first with the ToA reflectance reference and then with the reconstructed one by TRUTHS. An error for each Sentinel 2 band is obtained.
Knowledge/stability uncertainty: the ToA reflectance using TRUTHS measurements is reconstructed and convolved with a Sentinel 2 band $n$ times. A dispersion of the convolved ToA reflectance is obtained.
Conclusions (1)

- **High precision** radiometric data is required to enable the unequivocal detection of climate change with the ability to constrain and test climate forecast models on a decadal time scale.

- **TRUTHS-Lite** makes use of the new generation of small microsatellites, being developed by SSTL, to fly a key enabling technology – the **Cryogenic Solar Absolute Radiometer (CSAR)** – to provide very high precision radiometric calibration data – **traceable to SI standards**.

- Flying a companion **hyperspectral imaging** micro-satellite of a similar class would benefit both missions, in that it would provide extra information on the ground reference sites targeted by TRUTHS-Lite, whilst also providing a means of accurately calibrating the hyperspectral data.
Conclusions (2)

- A series of tools are being developed to make use of TRUTHS data in the **cross-calibration of other EO spacecraft** – e.g. DMC, SENTINEL-2, so that, ultimately their data can be traced back to **National Metrology Institute** (NMI) laboratory standards.

- The further development of this tool is envisaged, such that it will enable the full estimation of uncertainty in **sensor to sensor cross-calibration** in an automated manner.

- This **Radiometric Uncertainty Tool** is currently the subject of PhD research being carried out at the Surrey Space Centre, sponsored, supported and in conjunction with the UK National Physical Laboratory.

- The **CSAR instrument** is currently subject to development to TRL 5-6 under a £1M CEOI/Airbus D&S development programme.