UK SPACE AGENCY

NPL National Physical Laboratory

Traceable **R**adiometry **U**nderpinning **T**errestrial- & **H**elio- **S**tudies

Proposed as an ESA Earth Watch mission

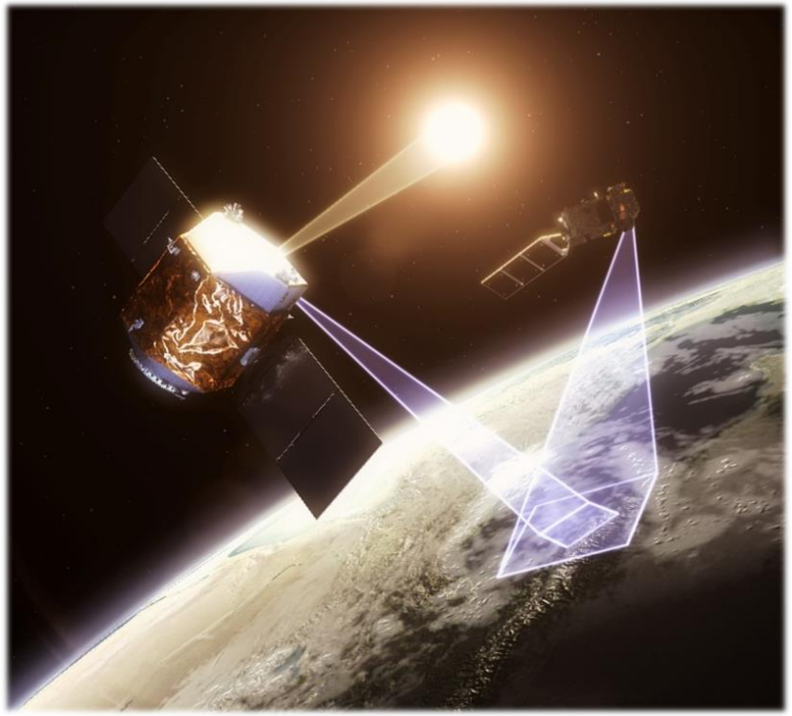
Enabling a space-based climate–calibration observatory

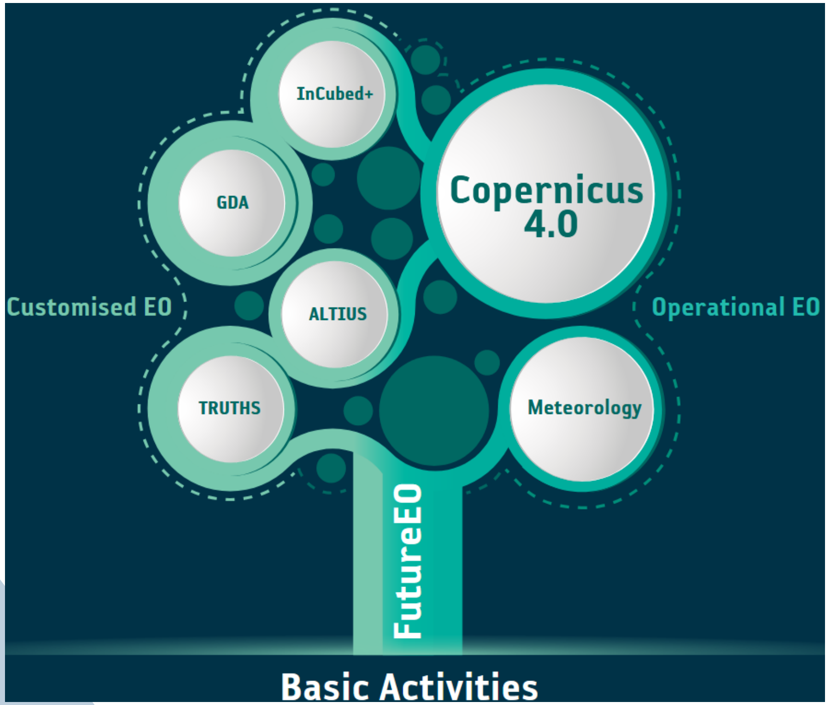
Principle Investigator:

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

What is TRUTHS?

- TRUTHS is a UK-led operational Earth Observation mission that will initiate **a space based climate & calibration observatory**.
- TRUTHS will measure incoming and reflected solar radiation **10 times more accurately (traceable, in-space, to SI units)** than is currently possible.
- Proposed to ESA Earth watch program (member state decision Nov 27-28 (ESA Space 19+) to start Phase A/B1
- launch 2026-28.



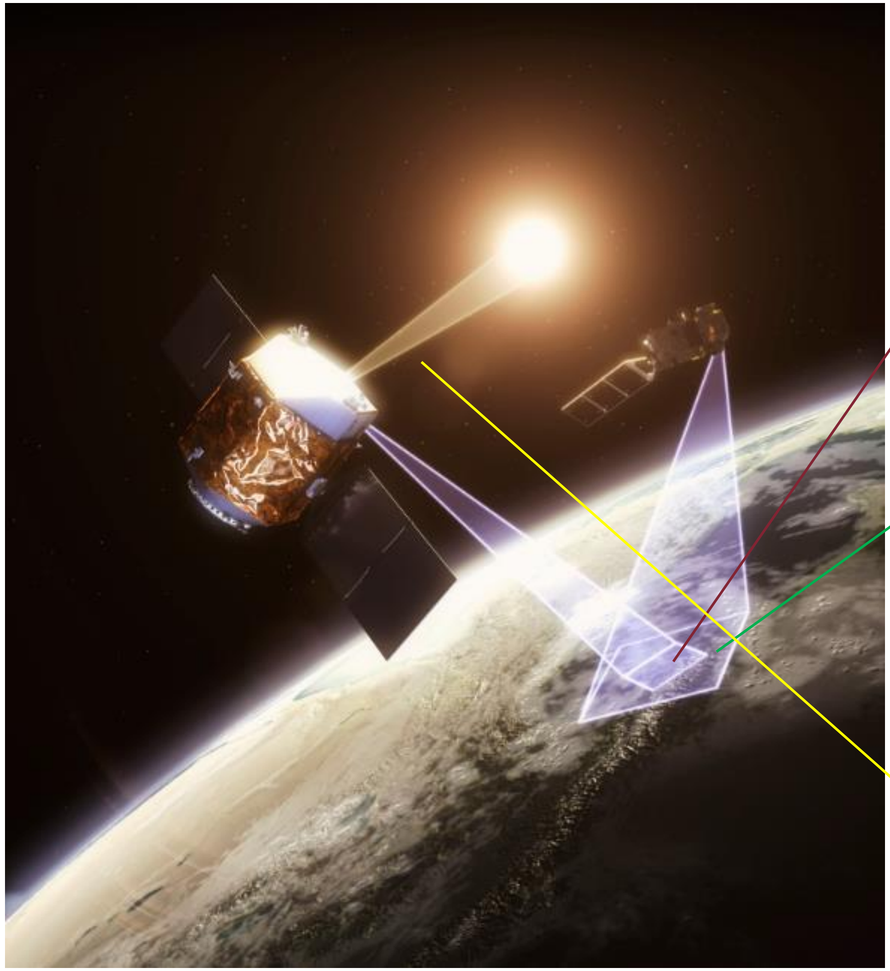


Traceable
Radiometry
Underpinning
Terrestrial- &
Helio-
Studies

"In addition to providing validation of observations, the TRUTHS mission outputs will lead to a reduction in uncertainties of Earth Observations that will ultimately lead to better evidence to support climate change policy decisions internationally. Furthermore, the personnel with the skills necessary to deliver this mission reside largely within the UK and supporting this mission would preserve these skills and retain the knowledge within the EU"

Professor John Loughhead, Chief Scientific Advisor, Department of Business, Energy and Industrial Strategy

Mission Objectives



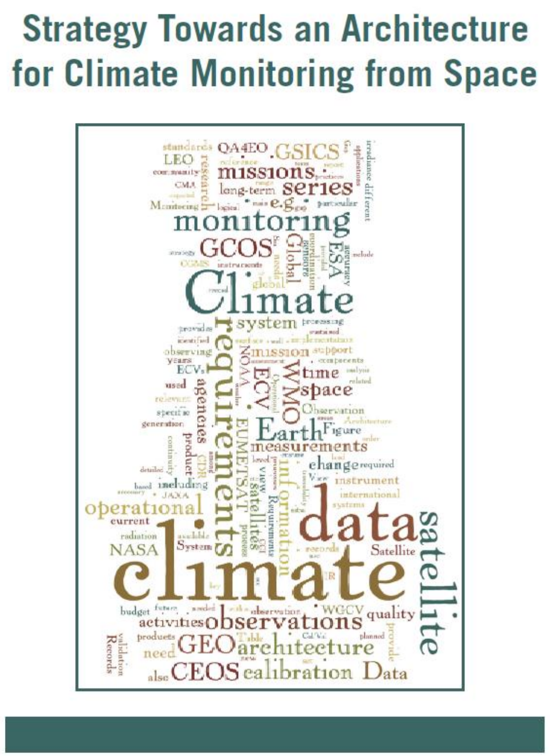
TRUTHS is an **operational climate-focused mission**, aiming to:

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

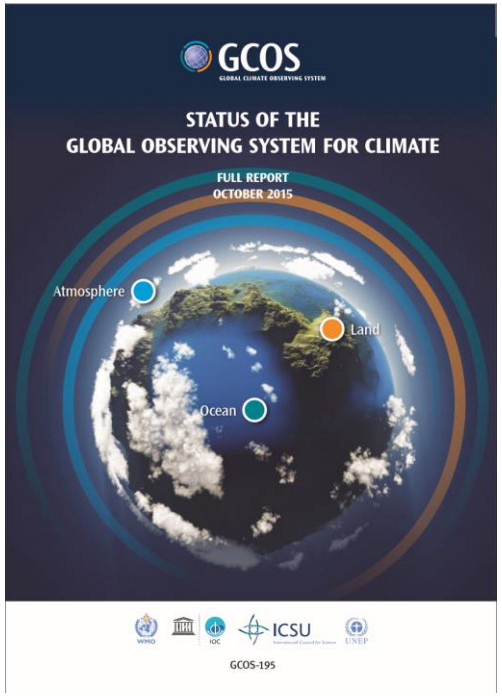
3. provide SI-traceable measurements of the **solar spectrum** to address direct science questions and climate.

International Demand



"….a dedicated mission flying an SI traceable calibration reference standard would be an important element of a future architecture (see CLARREO and TRUTHS)."

CEOS/CGMS/WMO (2013)



"TRUTHS has important potential contributions to make both directly through well-calibrated measurements and indirectly through facilitating inter-calibration of the data from other platforms" **GCOS 2015** 2015

Action A16:	Implementation of satellite calibration missions
Action	Implement a sustained satellite climate calibration mission or missions
Benefit	Improved quality of satellite radiance data for climate monitoring
Who	Space agencies
Time frame	Ongoing

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;

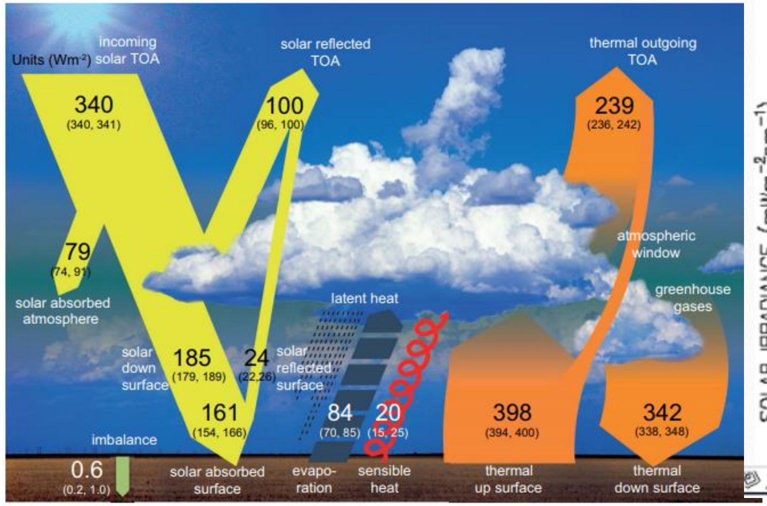
→ **Climate benchmark, solar measurement**

- L2: Spectral Surface Reflectance, at ground level (320nm to 2450nm);

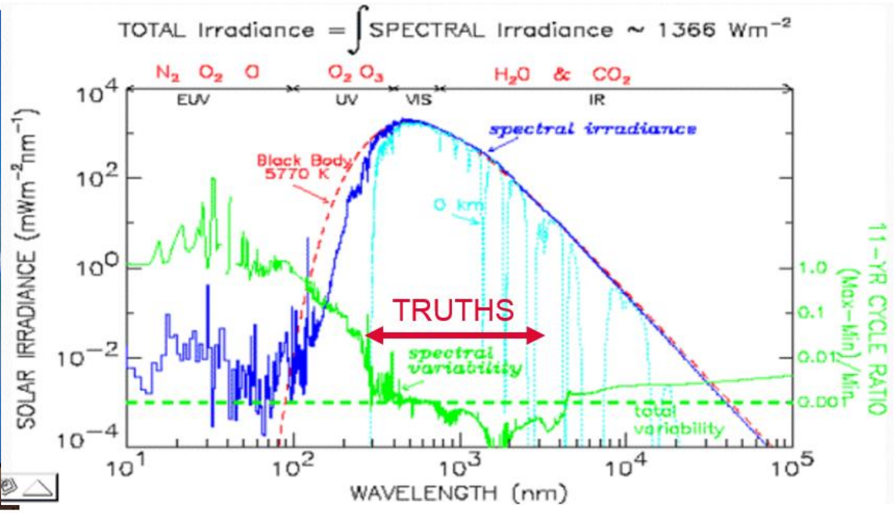
→ **Earth science**

- calibration coefficients & match-up products to determine biases for TBD other sensors over multi-scene types and view angles.

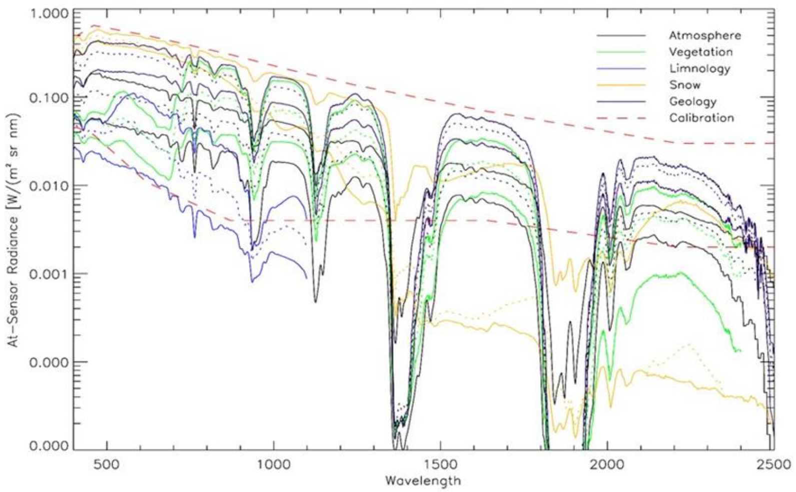
→ **Cross-calibration**



Radiation balance



Solar spectral irradiance



Surface reflectance

Key performance requirements

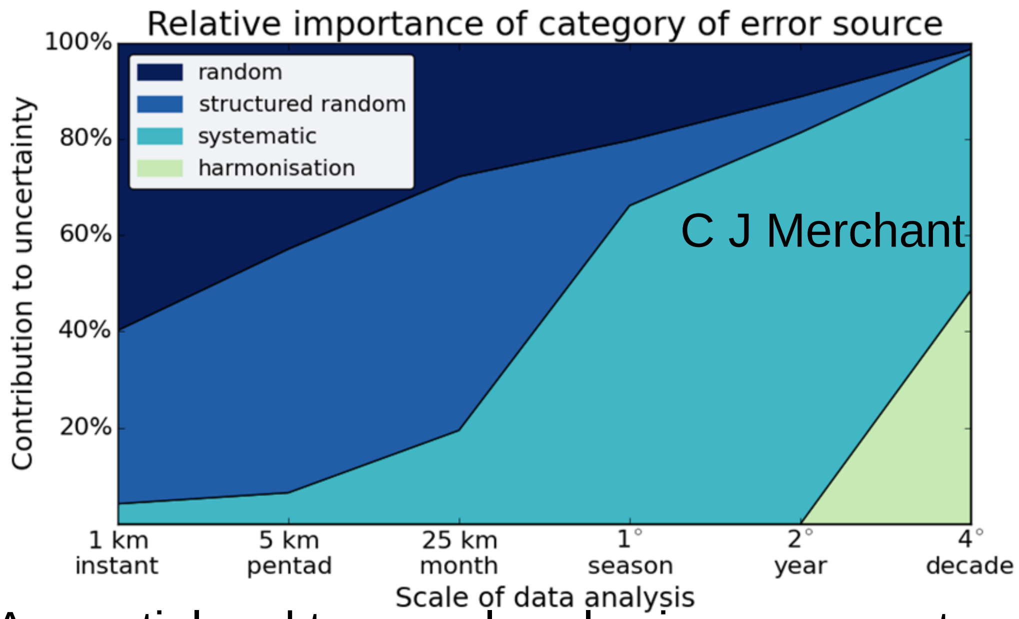
Parameter	Spectral range /µm	Spectral resolution / nm	GIFOV / m	SNR	Sampling	Uncertainty / % (2σ)
Earth Spectral Radiance	0.32 - 2.4	~5 to 10	~50 250	~300 (Vis-NIR) >2000 Blue	Global nadir 50-100 km swath + multi-angle	0.3
Total Sol Irradiance (TSI)	0.2 – 35	NA	NA	>500	Daily	0.02
Solar/Lunar Spectral Irradiance (SSI)	~0.30 - 2.4	1 to 10	NA	>300	Daily	0.3
Surface Reflectance	0.32 - 2.4	~5 to 10	~50 250	~300 (Vis-NIR) >2000 Blue	Global nadir + multi-angle	<1

The TRUTHS design is driven by:

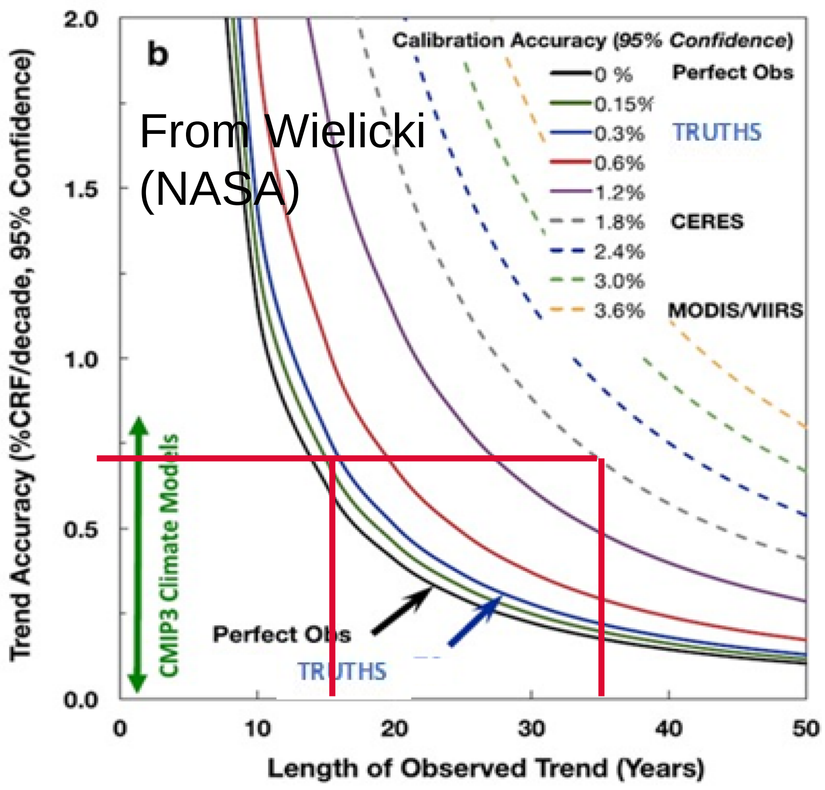
- **Radiometric demands** of the climate application ➔ *Payload and calibration*
- **Geometric** to optimally match other sensors (calibration) and secondary applications ➔ *FoV, Swath & SNR*
- **Orbit**: optimal sampling to quantify the climate and facilitate cross-calibration ➔ *Satellite and launch*

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)**

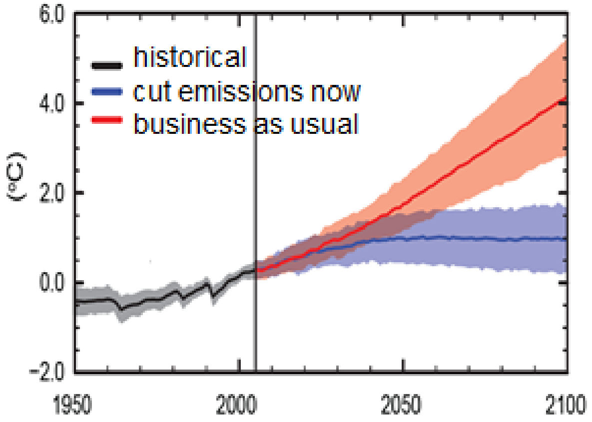


As spatial and temporal scales increase, systematic uncertainties dominate



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

Need to test & constrain Variance in climate model forecasts (IPCC)

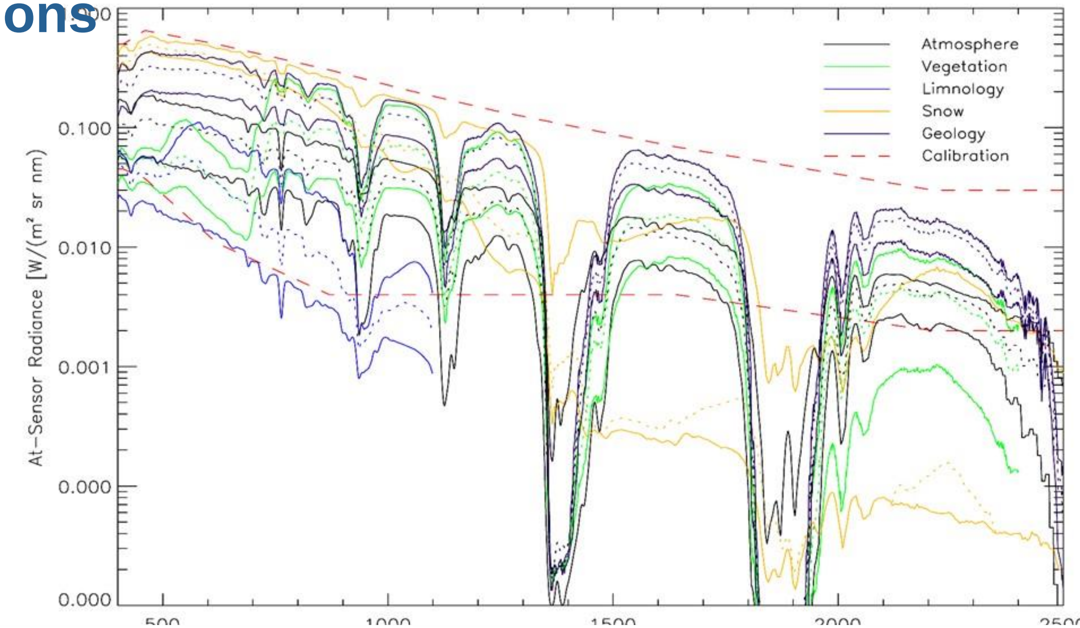


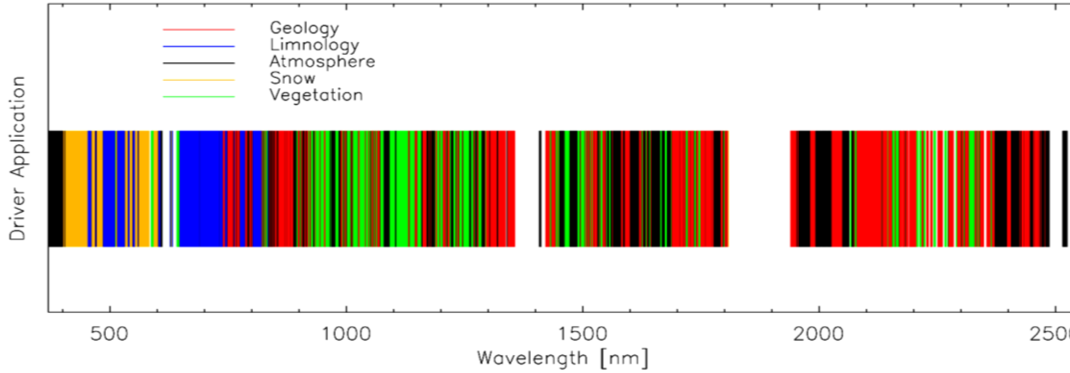
Hyper-spectral applications

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**
- **Agriculture**
- **Pollution**
- **Resource prospecting**
- **…….**

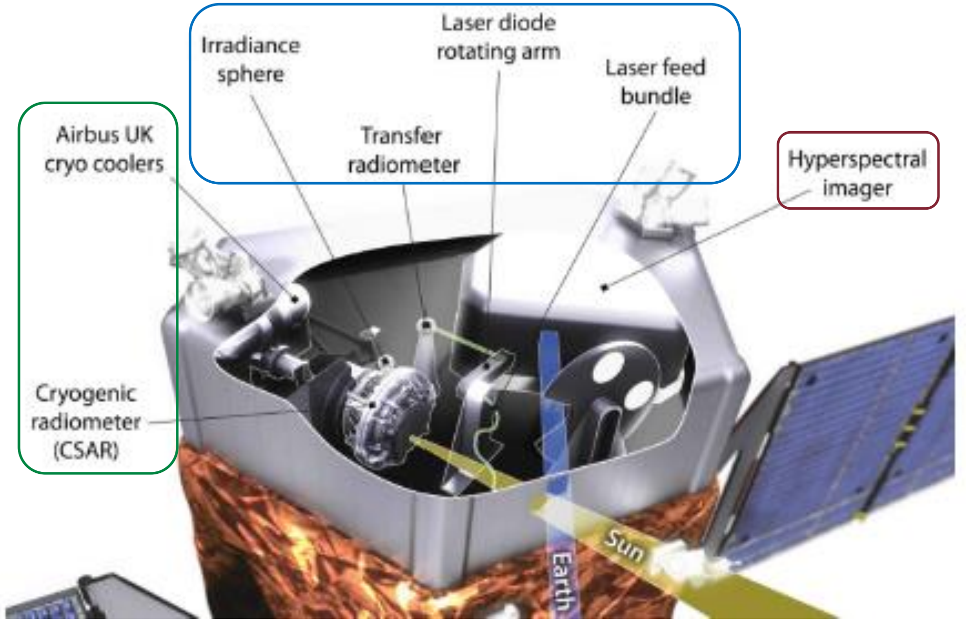




The Satellite

- **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.

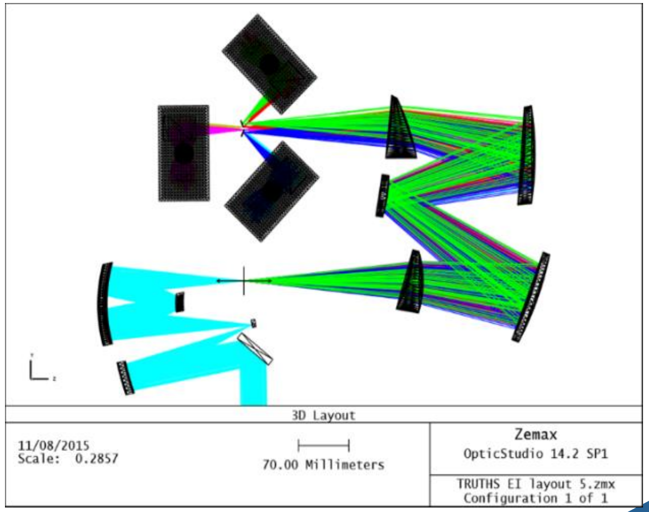
- **Satellite elements:**
  - **Platform** (reference Astrobus-S/M, TBC);
  - Hyperspectral Imaging Spectrometer (**HIS**);
  - Cryogenic Solar Absolute Radiometer (**CSAR**);
  - On-Board Calibration System (**OBCS**).



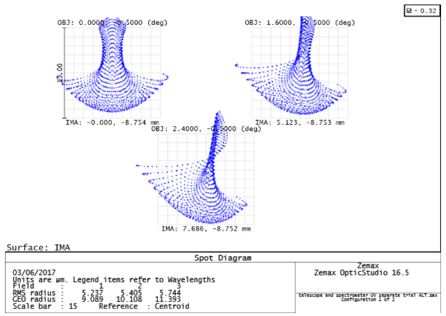
Hyperspectral Imager (HIS): Indicative design (based on CHRIS Proba)

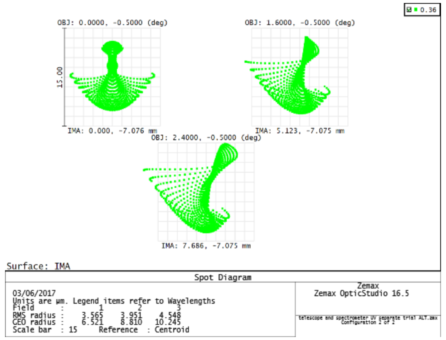
- Wide spectral range <320 – ~2450 nm
- Polarisation scrambler <0.5%
- Single Telescope ~45 mm entrance diameter
- 2 and 3 detector designs studied
- Provisional baseline design
  – Prism based 2 Detector
- Baseline Teledyne/E2V Chroma D (Vis-SWIR)
- “ “ Silicon CMOS (UV)

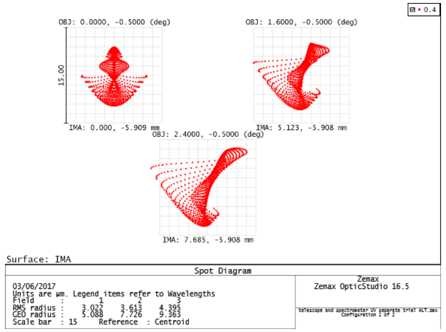
Indicative HIS above. Below: an optical layout



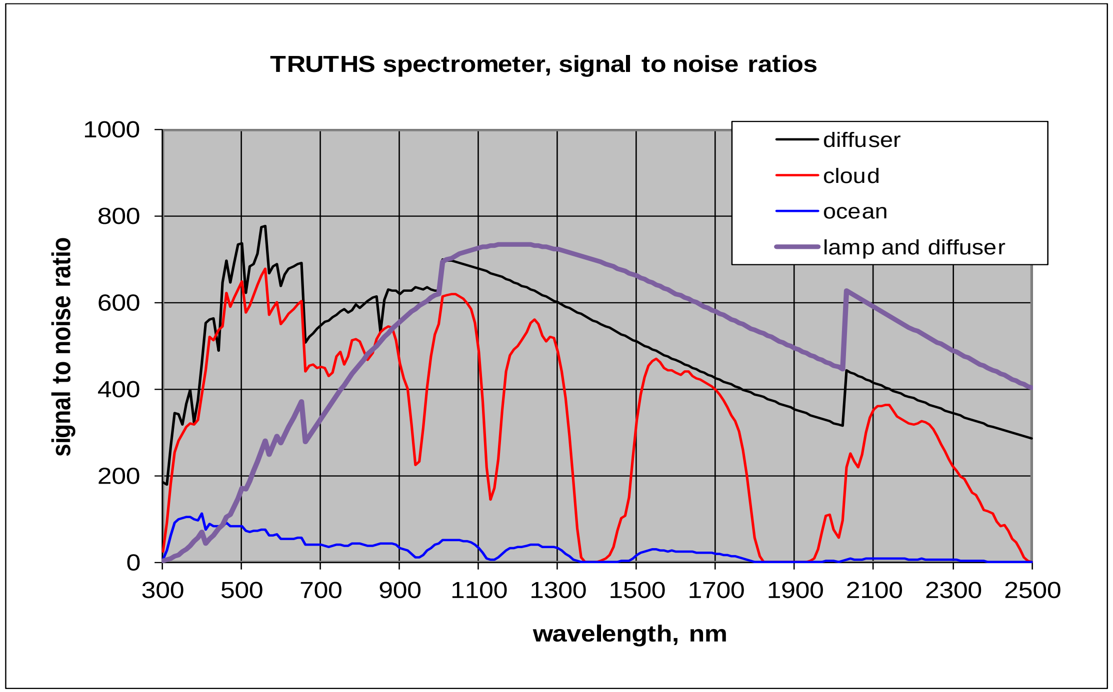
Imager modelled performance







Boxes 15 um Sq (nominal detector pixel)



Imager performance for 18 ms sample (50 m) can gain significantly by spatial binning (X5) and platform pointing (X3)

- **SNR for 50 m GIFOV**
- **Ocean = 100 @420 nm**
- **Bin to 250 m = ~X5 gain**
  Ocean = 500 @420 nm
- **Cross-Cal/special targets increase dwell time ~ X3**
- **Ocean = 1500 @420 nm**

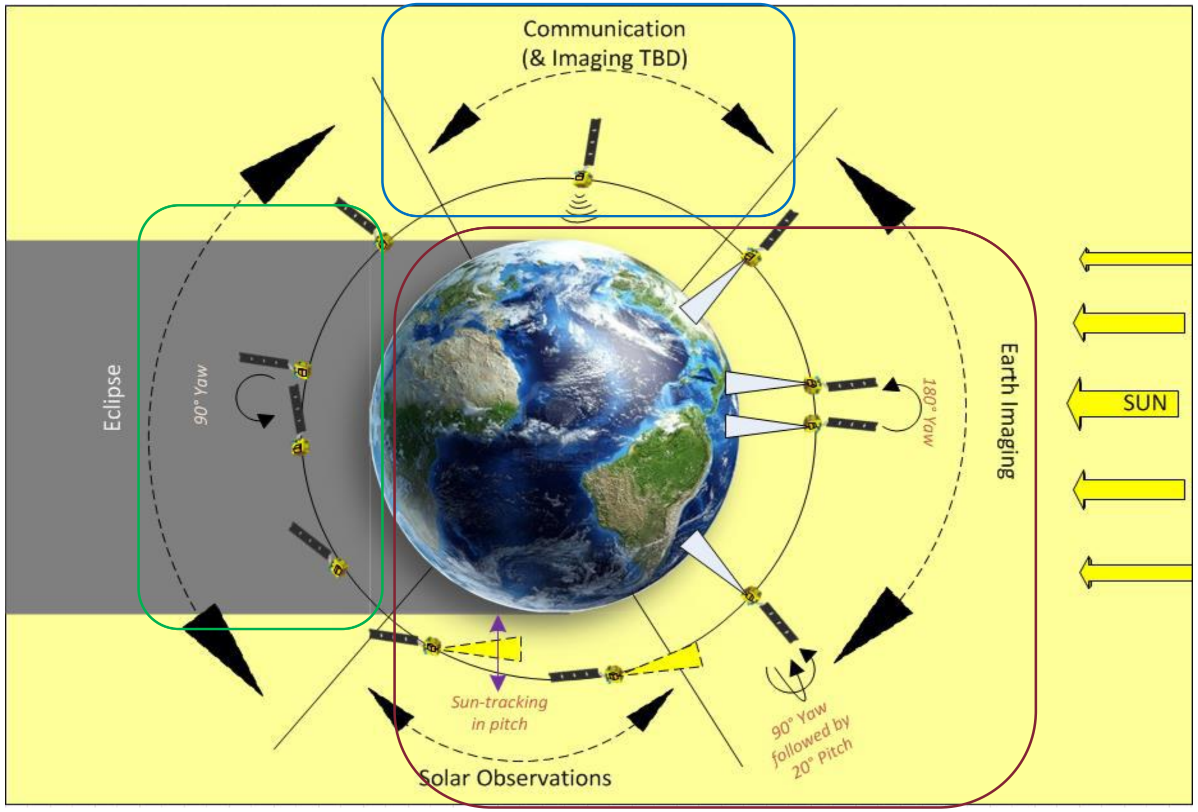
DATA RATE

Optimised (land/ocean requirements) data transmission (single svalbard station) 4500 Gb /day

Concept of Operations

Primary & Secondary mission

- ❑ **Climate benchmarking (HIS)**
  each orbit (~35min), Earth (nadir) pointing
- ❑ **Solar/Lunar measurement (HIS/ CSAR)**
  each orbit (~10min), Sun/Moon pointing
- ❑ **Cross-Satellite calibration**
  when required, Earth (non-nadir) pointing
- ❑ **Special (angle critical) observations (BRF)**
  when required, Earth (non-nadir) pointing



Calibrations

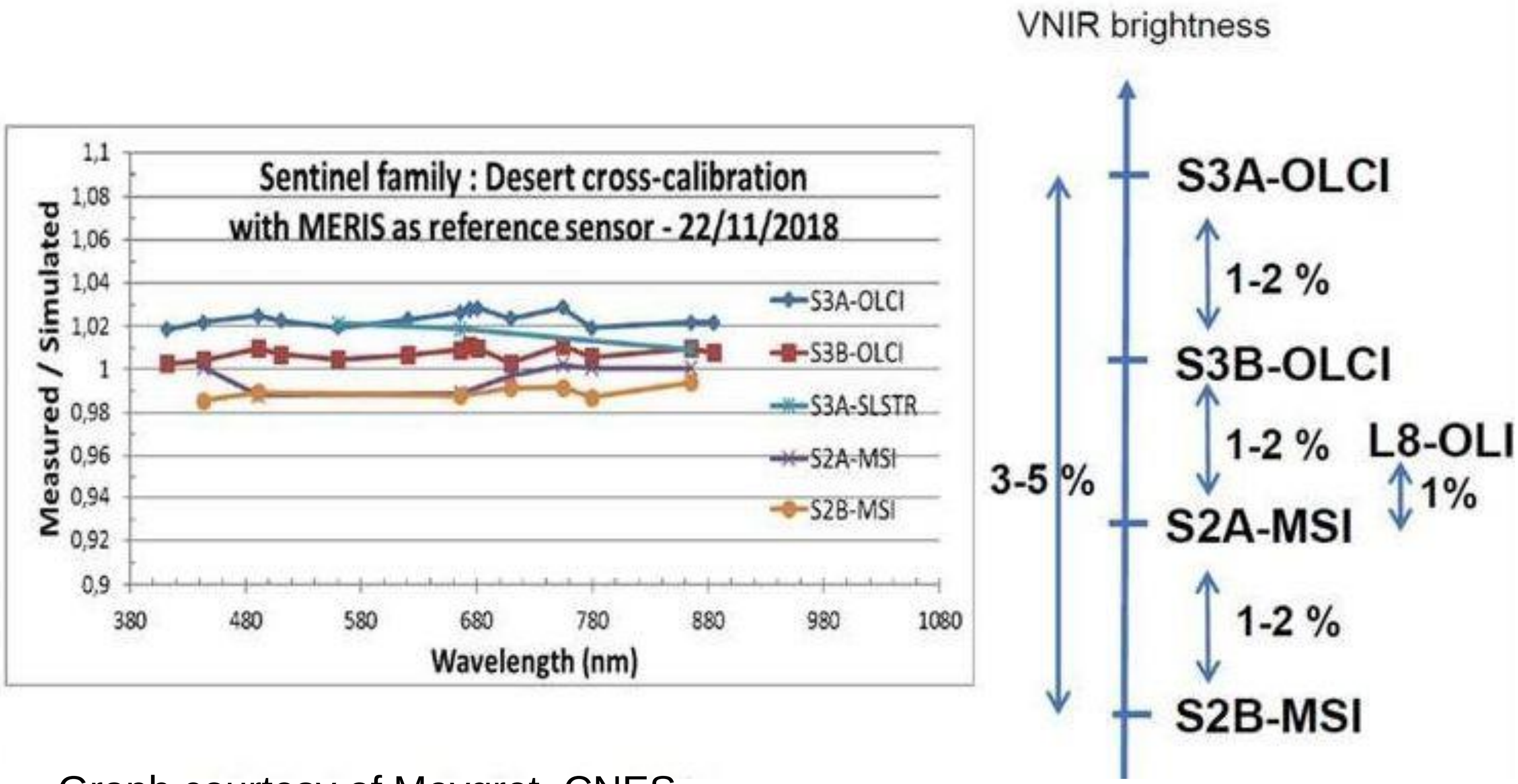
- ❑ **HIS⇔CSAR calibration**
  Nominal each orbit (~30min), by internal diffuser and laser/lamps in dark phase

Others

- ❑ **Communications with Ground**
  each orbit (~10min), Earth (nadir) pointing

Strategies to identify/remove biases and harmonise/homogenise the Earth Observing system are well-established:

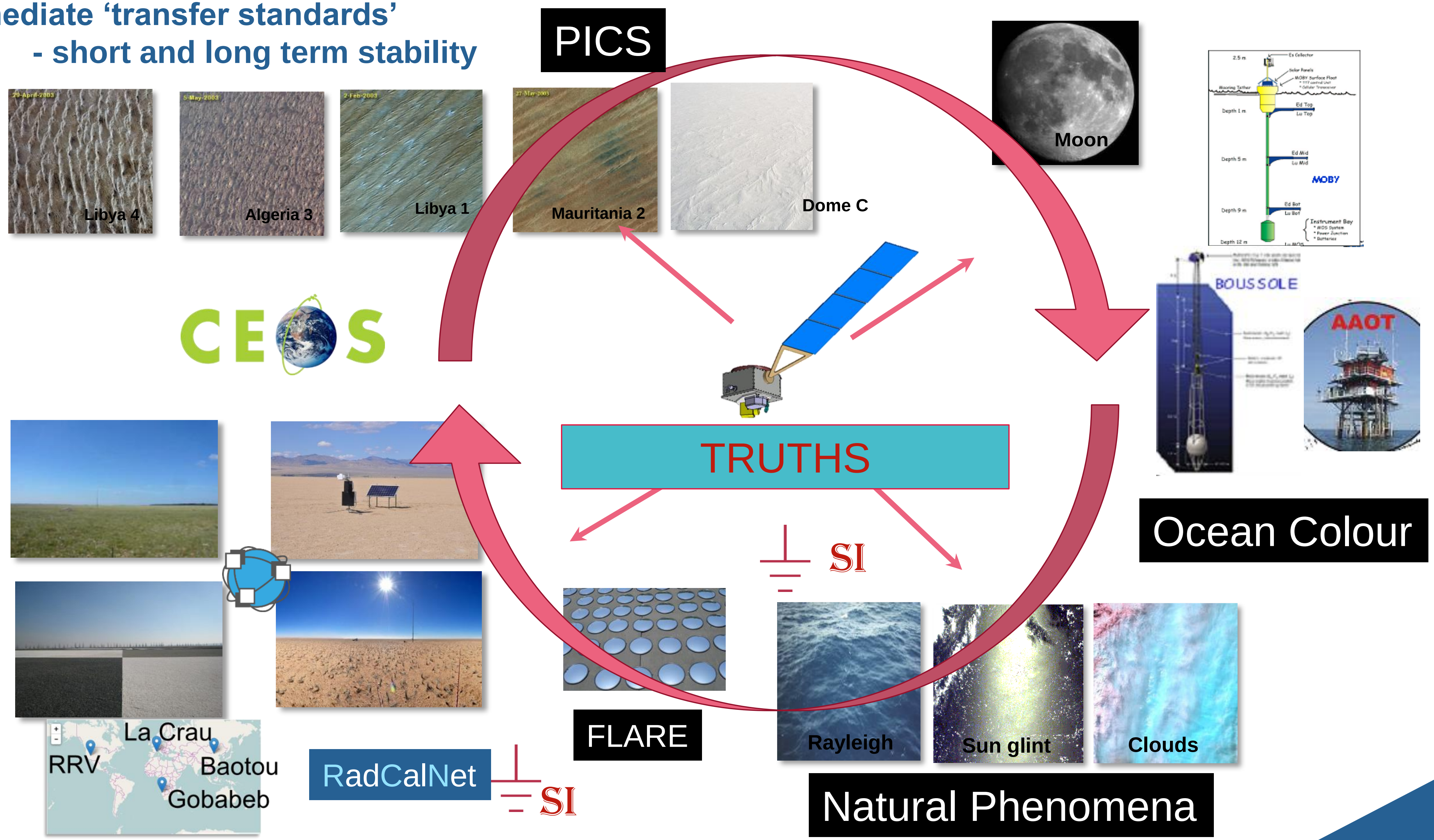
But what is the Truth?



Graph courtesy of Meygret, CNES

Traceability to CEOS + Cal/Val infrastructure

Intermediate 'transfer standards'
- short and long term stability

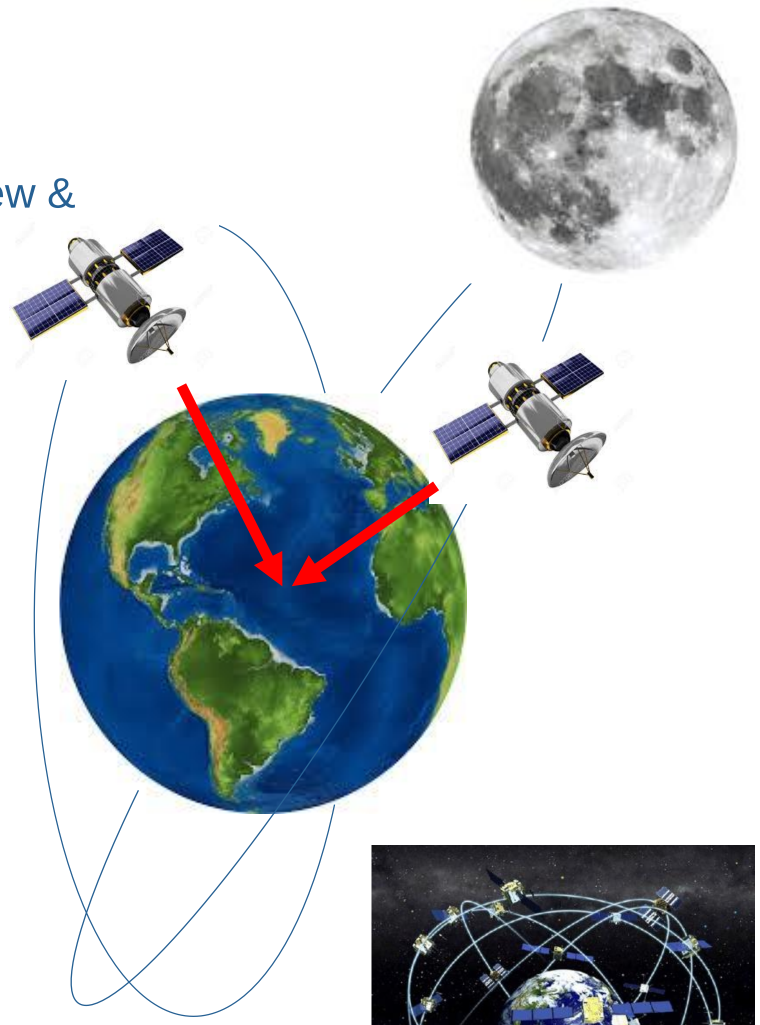


TRUTHS for inter-operability

- The orbit is asynchronous to the SSO of many EO satellites, to allow match-up with multiple sensors over a variety of scenes, surfaces & times of day – with coincident view & illumination angles
- At each coincident observation the high accuracy calibration of TRUTHS can be ‘transferred’ to the partner sensor.

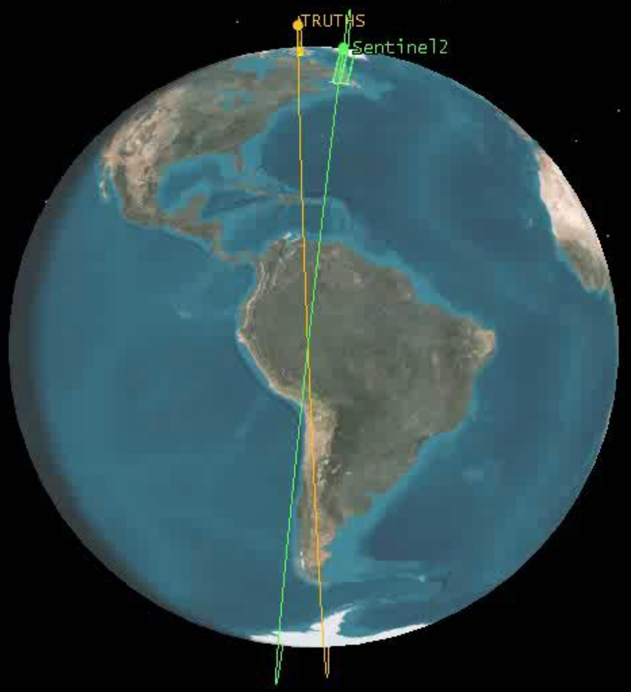
$$L_x - L_{TRUTHS} < \sqrt{\sigma_x^2 + \sigma_{TRUTHS}^2 + \mu^2}$$

- Cross-calibration accuracy is dominated by the reference sensor absolute radiometric calibration uncertainty.
- Studies to determine cross-calibration accuracy must consider reference & partner sensor intrinsic uncertainties as well as the representational uncertainties (μ), such as:
    - Spectral (resolution & sampling)
    - Spatial (geolocation knowledge)
    - Viewing angle & SZA
    - Polarisation sensitivity
    - Temporal mismatch (10 - 30 mins) including atmos. Variation.
    - BRF mismatch
- Use the near-simultaneous view [corrected for representative errors (μ)] to assess the partner sensor uncertainty, σ_x and from statistics correct biases enabling inter-operability & data product fusion of global assets.
- Anchoring existing stable Cal targets e.g. Moon - TRUTHS can back correct the satellites already launched – improving the quality of their data making the most of our existing and historical investments and improving FCDRs & CDRs.



TRUTHS Cross-Calibration with Sentinel 2

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

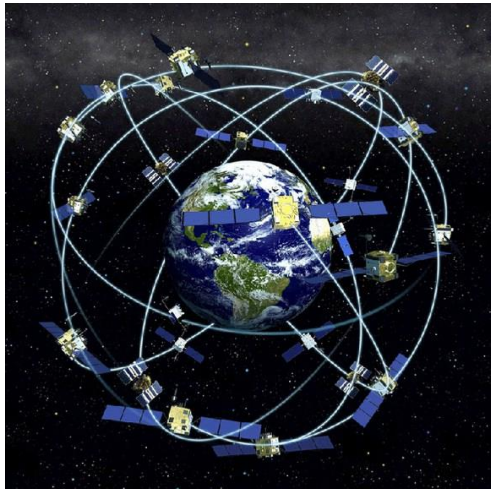
2 Mar 2025 15:00:50.000

AIRBUS

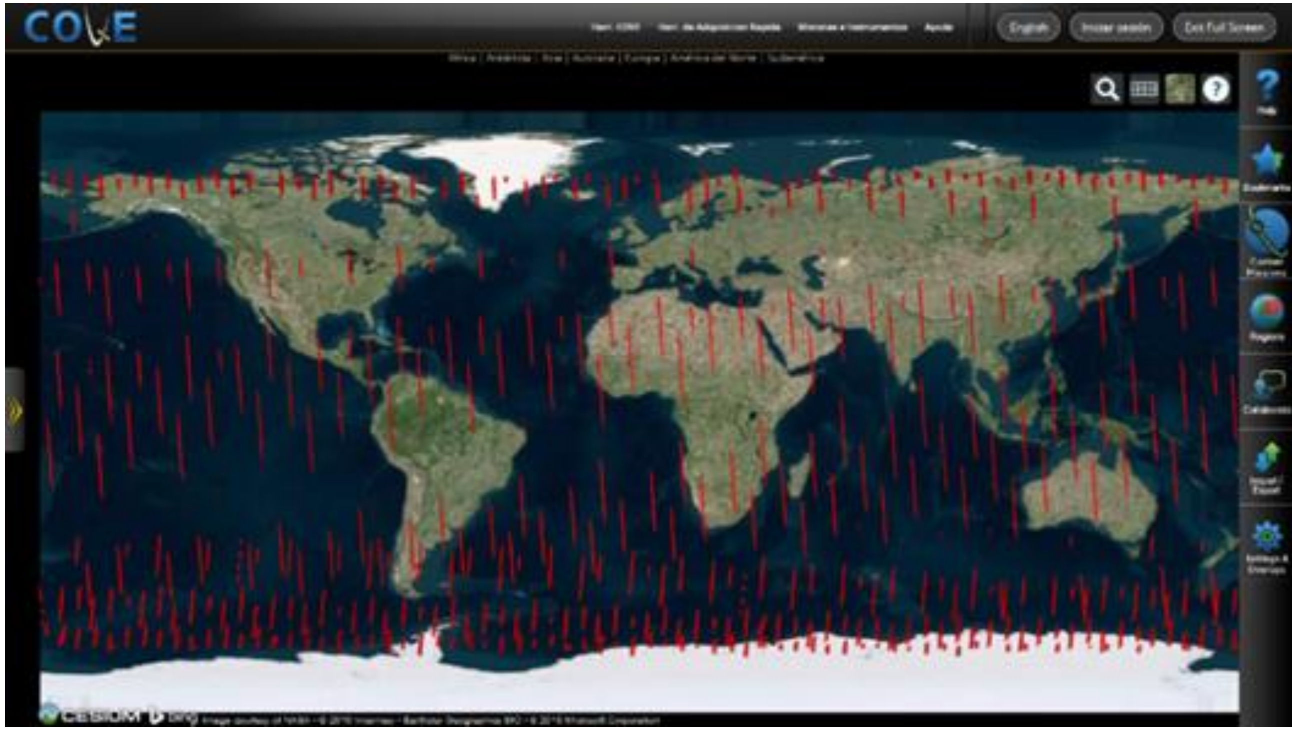
Agile platform of TRUTHS allows additional angle matching for off-pointing and also to evaluate Swath effects of sensors

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

Uncertainty budget for TRUTHS – satellite comparisons

(similar analysis results from Chander et al 2013 showing main Uc due to reference sensor and non-simultaneity)

(single overpass – reduces for multiple overpasses)

Uncertainty	**Best S2 bands**	**Worst S2 bands**
Spectral resolution TRUTHS	0.1 %	0.6 %
Spectral accuracy TRUTHS	0.1 %	0.2 %
Spatial co-alignment mismatch	0.1 % (Libya) 0.12 % (La Crau)	0.1 % (Libya) 0.5 % (La Crau)
30 minute time difference (atmospheric effects)	0.1 % (if corrected) 0.3 % (if atmosphere not known)	0.1 % (if corrected) 2 % (if atmosphere not known)
30 minute time difference (surface BRF)	0.2 %	0.4 %
Combined with reasonable corrections	**0.4 % - 0.5 %**	**0.7 %**

Different inter-cal effects (1/2)

5 main sources considered in the inter-calibration process:

Spectral, spatial (no optimisation/correction considered)

viewing angle, polarisation and temporal (considered minimisation and/or correction)

Note: CEOS PICSCAR shows Libya 4 stable to <0.5% in 10 yrs

Spectral

Resolution/sampling

<0.3% for most bands S2 and <0.5% for S3 OLCI in no absorption bands

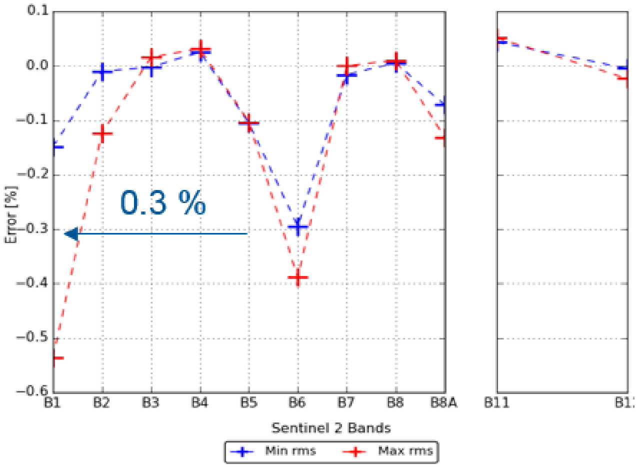
Spectral wavelength knowledge

<0.2% for S2 bands

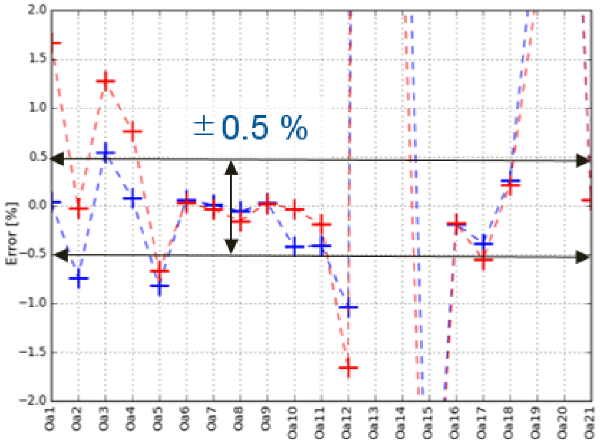
Spatial

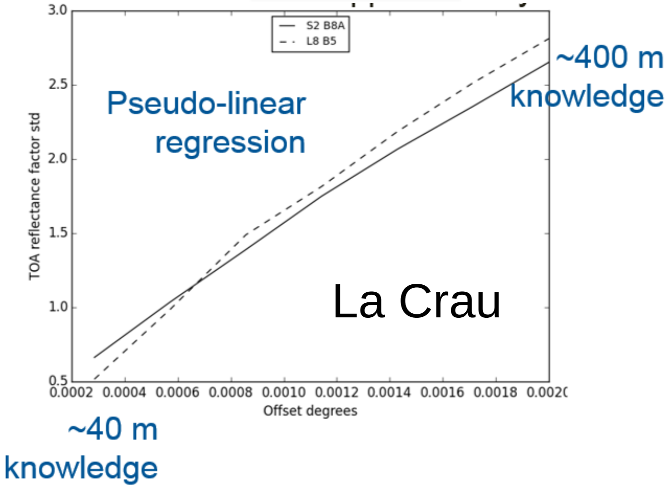
<0.5% for 40 m geolocation knowledge over a relatively non-uniform area such as La Crau

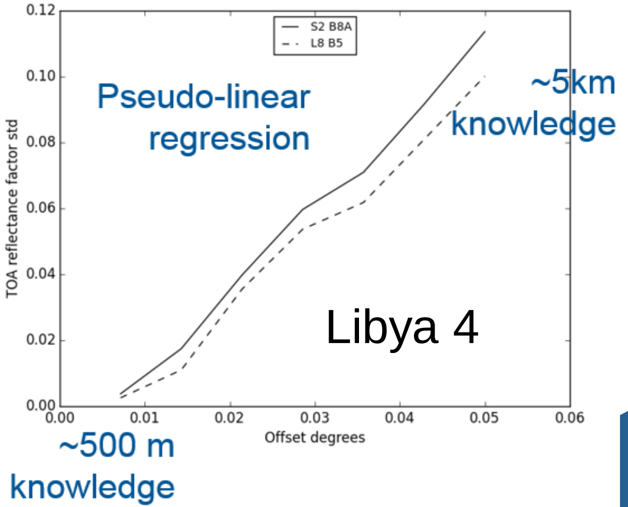
S2 MSI



S3 OLCI







Different inter-cal effects (2/2)

Viewing angle

Minimised for PICS areas and/or angle matching optimisation

Potential correction using radiative modelling. PCRTM model considered for CPF mission (Q. Yang et al. 2016).

Polarisation

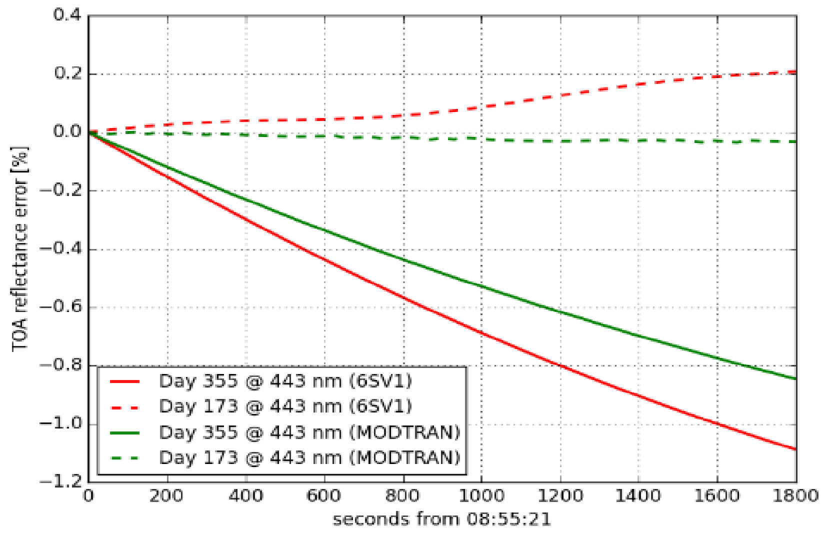
Low polarisation sensitivity 0.5% (k=2) for λ<1000 nm and 0.75% (k=2) for λ>1000 nm. Impact for most scenes <0.1%

Possibility to account for polarisation correction models as in (Sun and Lukashin 2013)

Temporal

Time delay minimisation (<10min)

Greater delay (<30min) by modelling the sun angle impact over selected areas (e.g. PICS)



Libya 4 error due to sun angle (BRF) if uncorrected and not SNO/angle matched

Uncertainty budget propagation

CSAR (On-board SI Traceability primary standard) → HIS (On board calibration system) → SNO inter-calibration between 2 satellites → L2+ application product

Element	Uc (%)
Measurement of electrical power	0.010
Cavity absorptance	0.010
Scattered light	0.004
Random noise	<0.06
TOTAL	**0.02-0.07**

Element	Uc (%)
CSAR	<0.06
Prism arm	< 0.01
Transfer radiometer	0.03
External aperture	0.02
Traceability issues	<0.08
HIS thermal control (1K)	0.01-0.20
HIS SNR	0.03
TOTAL	**0.16-0.26**

Element	Uc (%)
TRUTHS HIS	0.16-0.26
Spectral mismatch	0.1-0.2
Spatial mismatch	0.1
View Angle	0.1-0.2
Atmos. corr.	0.1-0.3
BRDF	0.1
TOTAL	**0.4-0.7**

Element	Uc (%)
GHG retrievals	1% = 0.1ppm
Ocean Colour	0.5% = 5% WLR
Cloud Radiative Forcing	0.3%

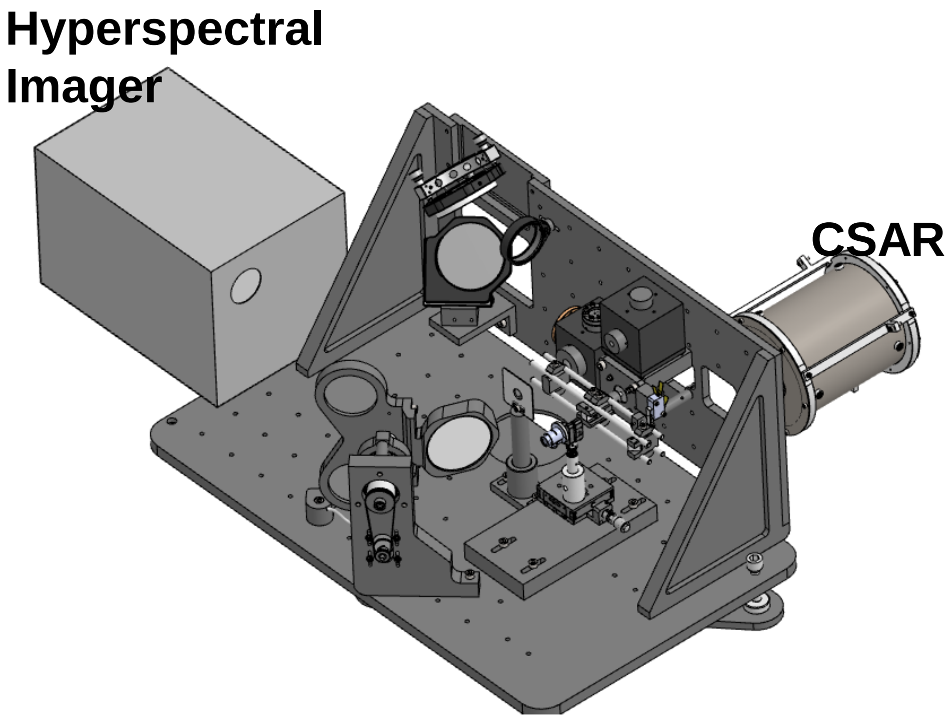
Note: Transfer Uc is dominated by reference sensor Uc (depending on time interval/number of samples) Gorrono et al

What makes TRUTHS different to other optical satellite missions?

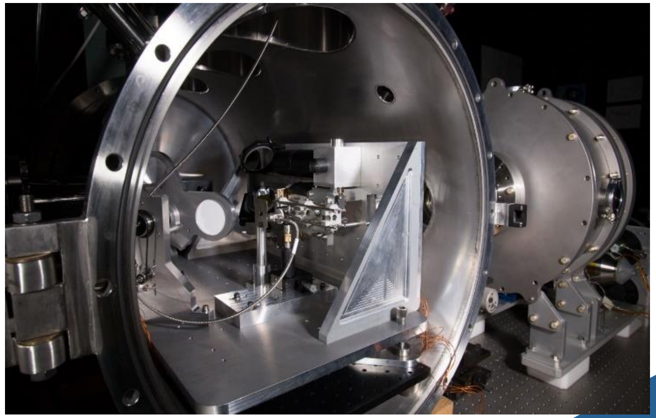
TRUTHS includes an on-board calibration system, that replicates the SI-traceable calibration chain employed in National Metrology Institutes (NMIs) globally, including flight of a primary standard - a Cryogenic Solar Absolute Radiometer (CSAR) (see calibration video).

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

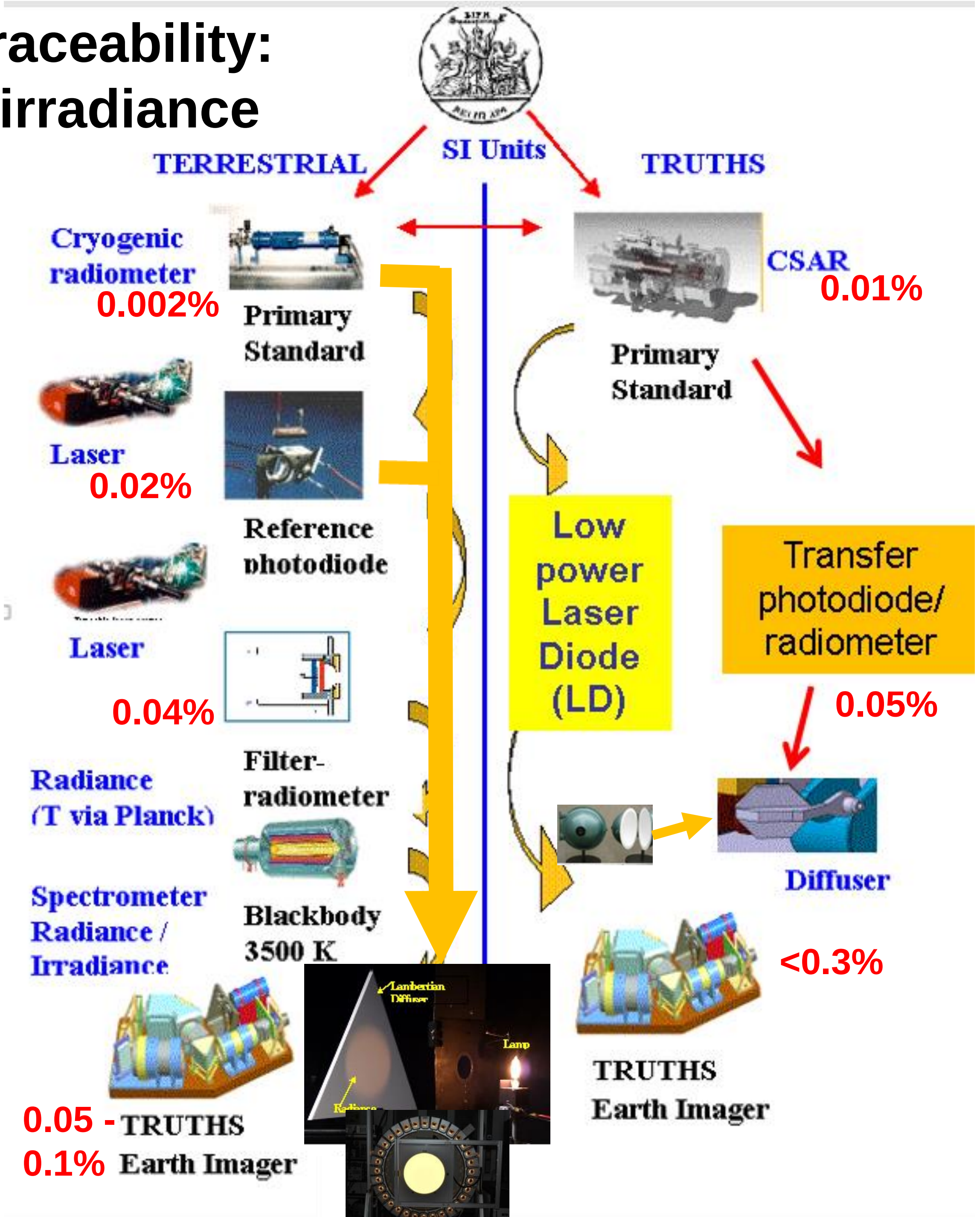
Maintaining it's SI-traceable high radiometric performance throughout the mission lifetime.



Representation of the TRUTHS calibration system



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 λ) 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 λ smooth spectral shape of diffuser minimises number

-LDs also provide λ calibration and spectral stray light check in-orbit

How TRUTHS on-board Cal System works

https://www.npl.co.uk/earth-observation/truths

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Unmet potential in current EO investment

Measurement confidence ‘traceability’ the top of the EO agenda

Unquantified drift in the accuracy of key sensors

The Need

Emerging market for trustable climate services

Climate sensitivity predictions are too wide

Interoperability, integrating cubesats/commercial sensors into the mainstream public services

Low cost access to space and climate data

Trustability , litigation quality, data and services

Interoperability: ARD and data cubes

Economically argued ‘green’ investment

Raising functionality of Copernicus & services

The Benefits

Quality data underpinned by European technology

Public engagement in science and climate

Science/policy exploitation

Encouragement to other Geographical regions: towards building a space-based climate – calibration ‘constellation’

‘Trustable’ EO/Climate services

Major contribution to CEOS/GSICS/GEO