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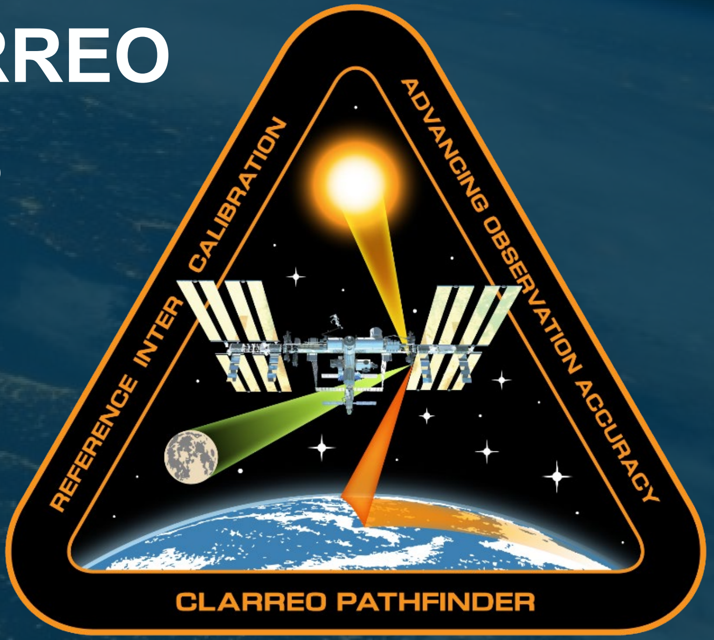
Toward a Climate and Calibration Observatory in space: NASA CLARREO Pathfinder (CPF) and ESA TRUTHS



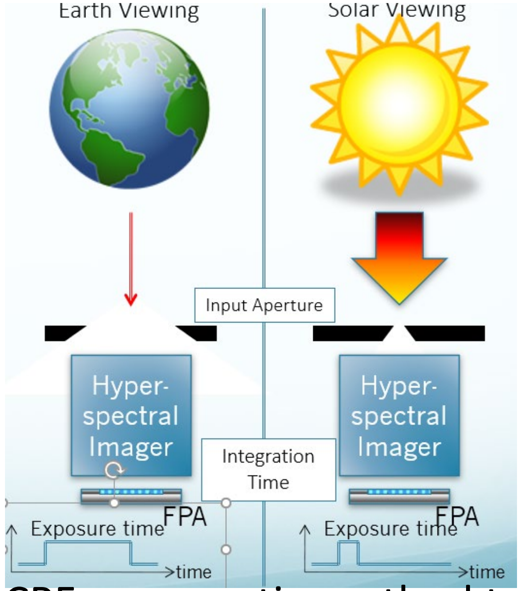
Nigel Fox: National Physical Laboratory, UK
Yolanda Shea: NASA Langley, USA
Thorsten Fehr: ESA, Europe
Gary Fleming: NASA Langley, USA
Constantine Lukashin: NASA Langley, USA
Peter Pilewskie: University of Colorado (LASP), USA
John Remedios: NCEO, University of Leicester, UK
Paul Smith: University of Colorado (LASP), USA

For more information contact:

TRUTHS – nigel.fox@npl.co.uk
CPF – yolanda.shea@nasa.gov

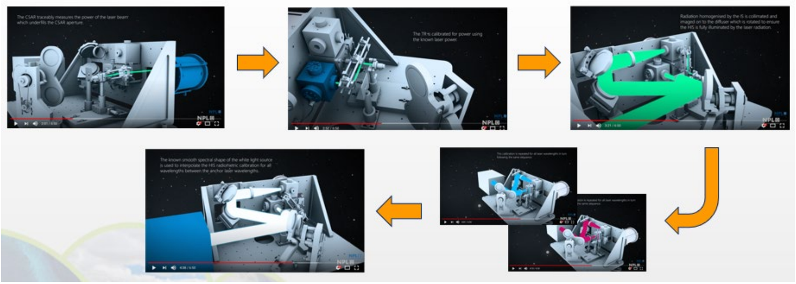
SUMMARY

- Climate action requires robust unequivocal observations from space of sufficient accuracy to allow trends to be detected in a timely manner.
- SI-Traceable Satellites (SITSats) are under development that will revolutionise Earth Observation and deliver for the first time truly climate quality data.
- TRUTHS and CLARREO Pathfinder (CPF) whilst having different routes to obtain traceability offer the prospect of a factor of 10 improvement in accuracy of not only their own observations but also those of other satellites through reference in-flight calibration.
- Both missions deliver spectrally resolved measurements of the Earths Radiance/reflectance (<350 - >2300 nm) and can create a benchmark of the state of the planet from which to monitor change – they also establish the moon and Earth Deserts as intermediate transfer standards. TRUTHS also measures the Sun



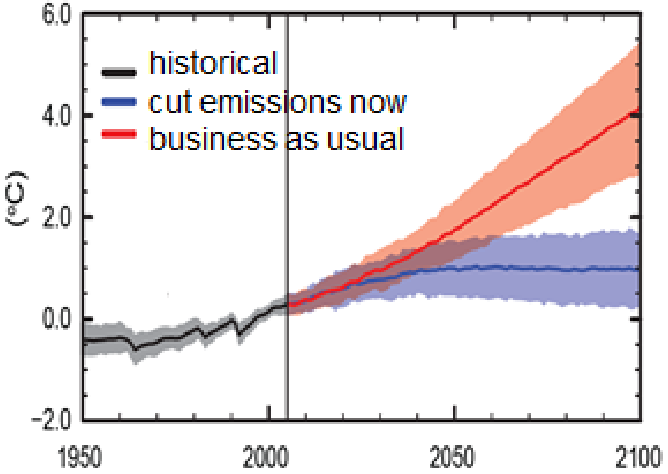
CPF uses a ratio method to determine reflectance

- CPF is a demonstrator on-board the ISS operational from 2024 whilst TRUTHS is in a 90° Polar orbit both asynchronous to the sun launch towards end of decade they have many cross-overs with other satellites
- Flying together they will provide a synergistic constellation cross comparing to each other and allowing different target missions – CPF has 500 m IFOV and TRUTHS 50 m



TRUTHS mimics in orbit a typical pre-flight calibration process and flies a primary standard as an absolute reference – needs to operate @ <60 K

Societal Challenge: sustainable growth in a changing environment

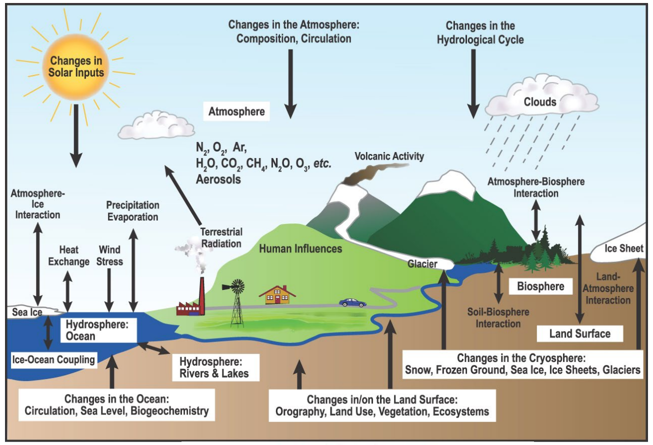


NEED

- Trustworthy observations to monitor, understand and mitigate impact and contributors to climate change facilitating necessary action

REQUIRES

- Integrated, interoperable, coherent global observing system
- Quantitative, comprehensive (adequate) measurements of the Earth system with robust uncertainties (clarity of confidence) that can be relied upon for decades
- Sufficient accuracy, to enable detection of a signal and/or 'trend' from a background of natural variability in as short a timescale as possible
- Transparency and international acceptance



Metrological Traceability to internationally agreed standards the SI

(at the location of making the measurement)

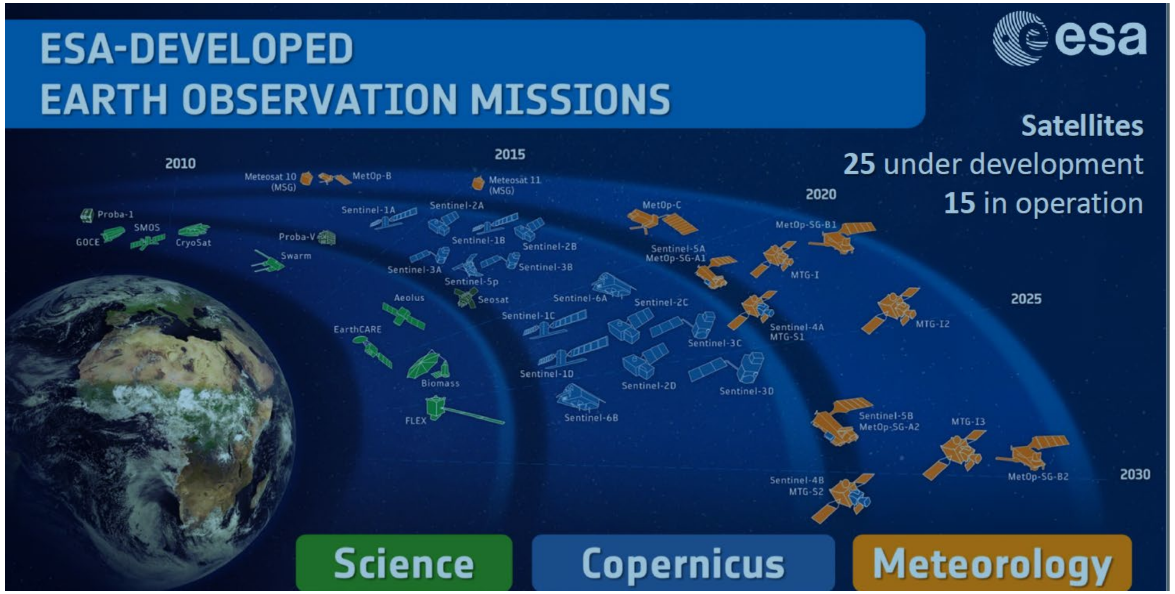
Many satellites but need to work together as a global EO system

GEO GROUP ON EARTH OBSERVATIONS

WMO

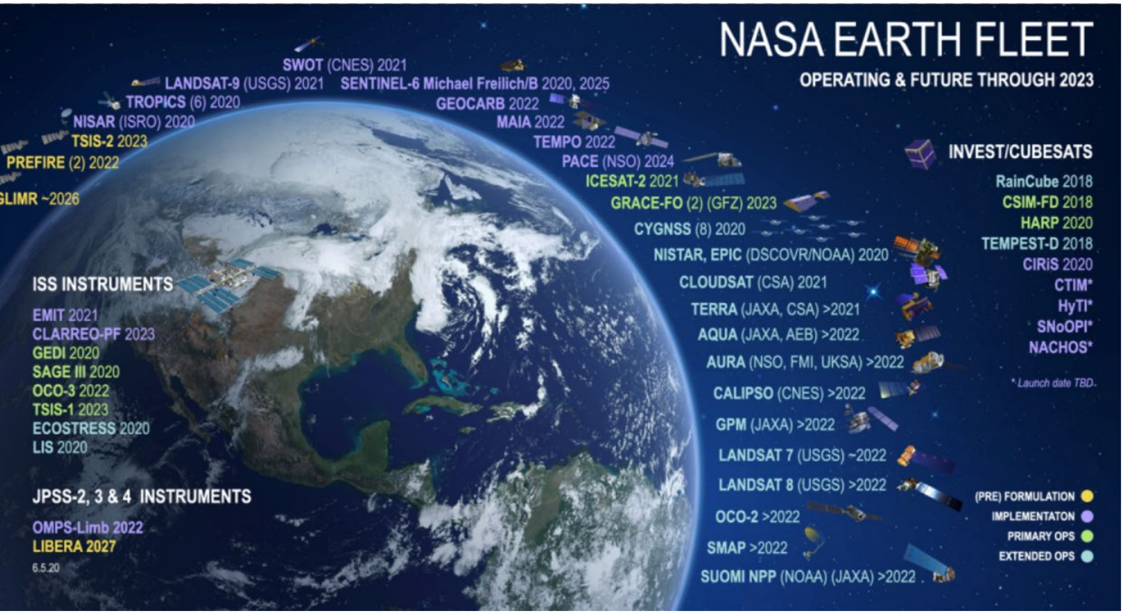
CEOS

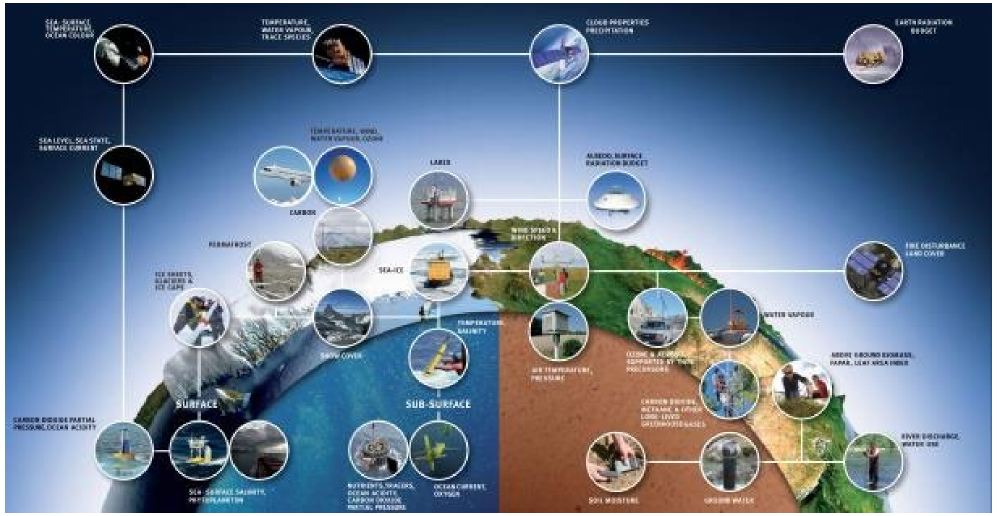
GSICS Global Space-based Inter-Calibration System



50% of ECV requires space observations – Satellites suffer biases and degradation in performance due to launch and harshness of space. Needs of climate far surpass most other EO mission performance requirements (typically a factor of 10)

Dedicated SI-Traceable Satellites (SITSats) offer prospect of new epoch of an interoperable Climate observing system





What are SITSats? & specifically:

CLARREO Pathfinder (CPF) & TRUTHS

*Space borne missions specifically designed, characterised and documented to provide **high accuracy SI-Traceable** ‘reference’ measurements.*

CPF/TRUTHS primary objectives

- Demonstrate SI-Traceability and have detailed uncertainty budget of its own payload on-orbit
- Establish/Demonstrate a ‘benchmark’ measurement of the outgoing radiation state of the planet (radiance and reflectance) in the short wave (Solar reflective) domain both integrated and also of sufficient spectral/spatial resolution and accuracy to allow change to be detected in as short a time as possible
- Transfer SITSat traceability and upgrade performance of other EO satellite missions and associated calibration infrastructure e.g. Moon, Pseudo Invariant Calibration Sites (PICS) through reference calibration

In addition TRUTHS also

- Establishes a ‘benchmark’ measurement of incoming solar radiation spectrally resolved and total at uncertainty levels specified by GCOS

*A **benchmark measurement** is one with characteristics (documentation, SI-Traceable uncertainty, representative sampling) that allows it to be unequivocally considered a ‘reference’ of the specified measurand against which future measurements of the same measurand, can be compared.*

CPF & TRUTHS: Similarities and differences

Both missions share a common vision and an informal partnership of more than a decade. Some of the differences stem from the necessity that CPF is nominally a 'demonstration' of a more comprehensive CLARREO mission, and is focussed on climate missions for calibration. TRUTHS has a slightly wider remit to additionally address more fully the needs of the operational EO sector as well. It also measures the Sun

Characteristic	**CPF**	**TRUTHS** (some characteristics may be subject to change as design develops)	**Comment**
Platform/orbit	Int Space Station/ 52°	Own sat / 90°	Both asynchronous TRUTHS observes full globe
Operational / lifetime	2024 (1 yr seeking 5)	2028 (5 – 8 yrs)	Potential overlap if CPF life extended (5+ yrs needed for benchmark)
Spectral range	350 -2300 nm	320 – 2400 nm	
Spectral Resolution	3-6 nm	4–8 nm Earth 1-8 nm Sun	Bandwidths to facilitate cross-calibration
Radiometric accuracy	0.6 % (k=2)	0.3 % (k=2) 0.02 % (k= 2) (total solar irradiance	Spectrally resolved and band integrated
IFOV / Swath	500 m / 70 km	50 m / 100 km	50 m to additionally target land imagers, new space, EO applications
Measurands (direct)	Earth/lunar spec reflectance	Earth spec (radiance/reflectance) Solar/lunar Spec (irradiance) Total Solar Irradiance	CPF can obtain radiance/irradiance through solar values from TSIS mission
Route to SI-Traceability	Ratio (sun to earth) with attenuation using apertures & time integration	On-board calibration system mimicking ground including primary standard	Comparison of different methods provides opportunity for rigorous confirmation of uncertainties

Reference calibration of EO missions

A key feature of CPF and TRUTHS is the ability to transfer their on-board radiometric accuracy to other satellites to assess and remove biases caused by ageing/launch etc.

Although practised for decades, using surface characterised and/or stable desert test sites, observations of the moon, and/or with the aid of a designated reference satellite, uncertainties are typically limited to at best 3-5%, a factor 10 below that required by climate. All methods rely on the observation of a common target with known characteristics as observed ToA by the satellite under test.

One of the principle limitations stems from differences in how satellites observe the target often driven by the predictable but invariant generally sun-synchronous orbit (each satellites views a location at its own same time but one that is different than other satellites)

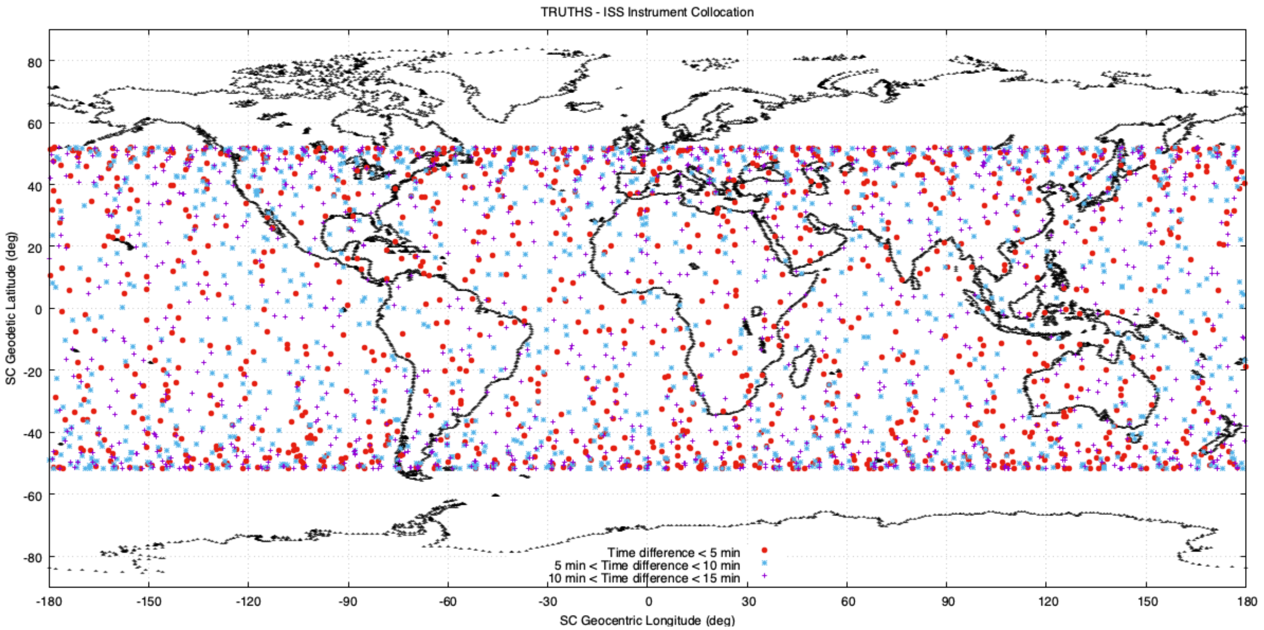
Cross-calibration challenges overcome by CPF and TRUTHS:

- **Asynchronous orbits** allow direct Simultaneous Nadir Observations (SNO) with other satellites at different locations across the globe – removing time differences impacting atmosphere and sun illumination angle differences (+- 5 minute overlap windows are considered optimum) (agile pointing also allows angle matching for wide swath and scan mirror sensors
- **Spectral resolution** <~4-8 nm (depending on sensor undertest bandwidth) allows robust spectral matching of sensor bandwidths for a wide range of scene types (<0.3 % contribution)
- **Continuous spectral sampling** over the 350 – 2300 nm allows any short wave sensor to be calibrated and provides, as an integral, a measurement of > 99% of Earth reflected radiance
- **IFOV Spatial footprint** of 500 m is adequate to match spatial footprint of climate focussed sensors whose footprint is many kms and calibration can be based on large areas sampling – Smaller IFOV with adequate SNR allows improved matching for higher resolution imaging sensors like Sentinel 2, Landsat and Newspace and with reduced area for sampling and number of matches.
- **Swath** of > 70 km allows FOV of many sensors to be covered and full global sampling of the Earth (within orbital inclination limits)
- **ToA lunar calibration** with high radiometric accuracy (no atmosphere) and for a range of libration/phase angles will establish this stable source as a radiometrically calibrated reference
- **Characterisation of PICS** at different solar illumination conditions and view angles (agile platform of CPF and TRUTHS) reduce seasonality (BRF) effect allowing these sites also to become improved intermediate standards

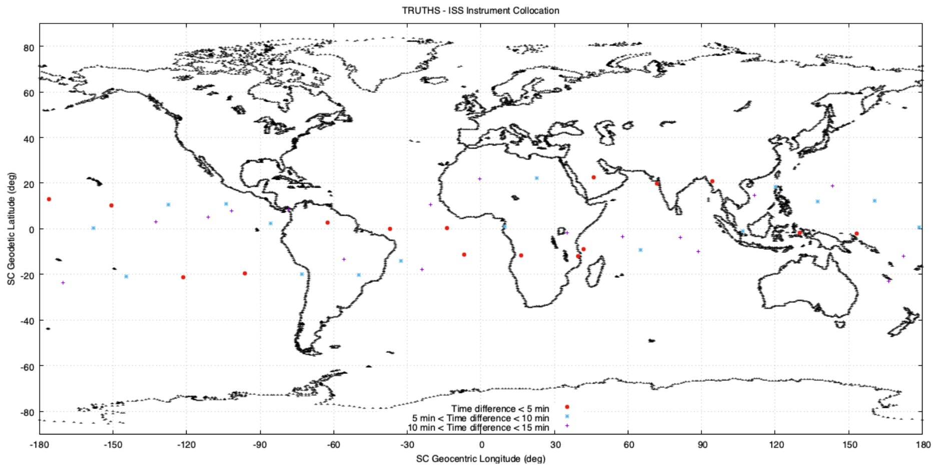
Calibration uncertainties of the sensor under test can approach that of the reference sensor with most other effects reduced by adequate sampling

Summary

- Details for each individual mission can be found in the following slides
    - Sensor/mission characteristics
    - Means of achieving SI traceability
    - Specific primary and secondary objectives
- Synergy/complementarity and timeliness between the two missions provides an opportunity to unequivocally demonstrate the capabilities and trust that an integrated space observing system can deliver
    - Direct intercomparison between the two in-orbit will provide most robust evidence of SI-traceability and strengthen the argument for a comprehensive SITSat enabled operational climate observing system with an ongoing series of missions spanning a broad spectral range UV-µWave
    - Common observations of the Moon and PICS will provide an intermediate comparison capability
    - Dual operation in space if possible allows each to potentially focus efforts on different sensors to maximise value to the EO system as a whole and not overly compromise other science objectives
- Establishment of an independent SI-Traceable benchmark (even if only in demonstration mode for CPF) provides the starting point to remove one of the biggest sources of uncertainty in global net-zero ambitions – climate sensitivity and its response to anthropogenic induced change



Simultaneous nadir observations of TRUTHS and CPF over a 1 yr period (no pointing) **above**
red < 5 min, Blue < 10 min, Purple < 15 min
Below 5 day period

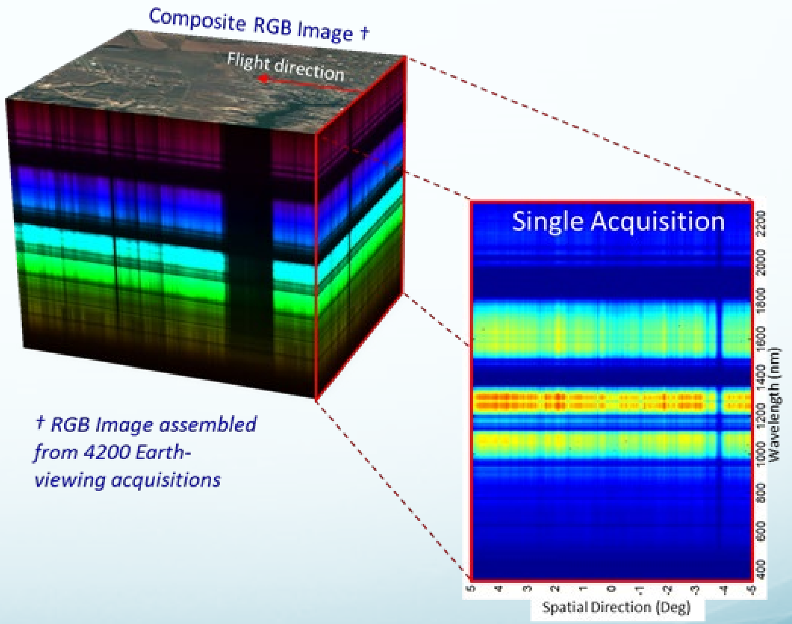


CLARREO Pathfinder on ISS Summary

CLARREO Pathfinder

- **Mission Purpose:** Demonstrate ability to achieve climate-critical high accuracy reflectance measurements of Earth reflectance and inter-calibration with CERES (broadband) & VIIRS (multi-spectral)
- LASP-Led Reflected Solar Spectrometer (350 – 2300 nm) & Payload
- Category 3, Class D Mission
- Nominal 1-year mission operations + 1-year science data analysis
- Currently in Phase C – Passed [Virtual] Critical Design Review in March 2020
- Launch Readiness: Late 2023

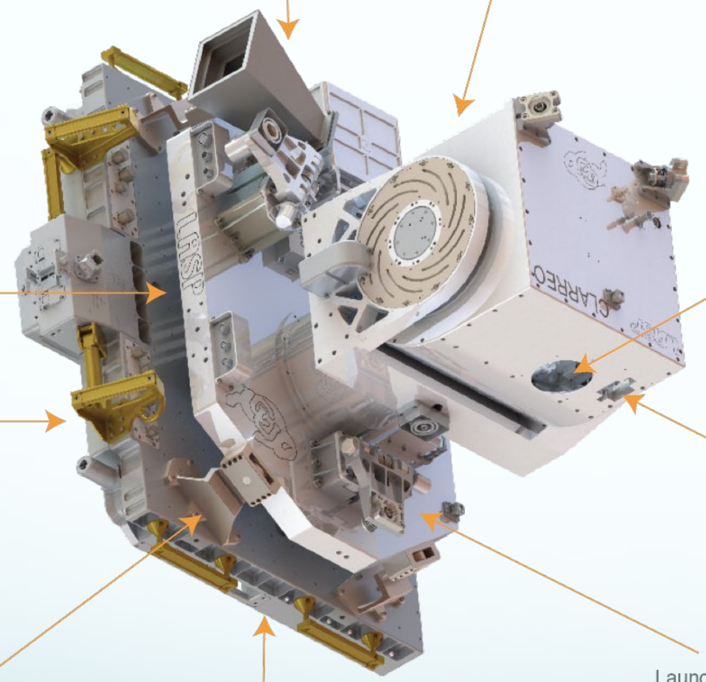
Spectrally-Resolved Earth Reflectance



LASP

CLARREO Pathfinder Payload

HySICS: Hyperspectral Imager for Climate Science

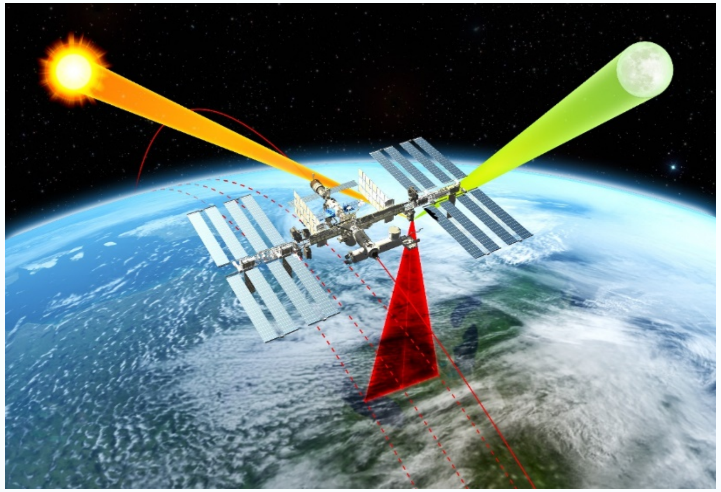


Radiometric Uncertainty	0.3% (1-sigma)
Spectral Range	350 nm – 2300 nm
Spectral Sampling	3 nm
Swath Width	10° (70 km nadir)
Spatial Sampling	0.5 km
Sampling Rate	15 Hz

Kopp et al 2017

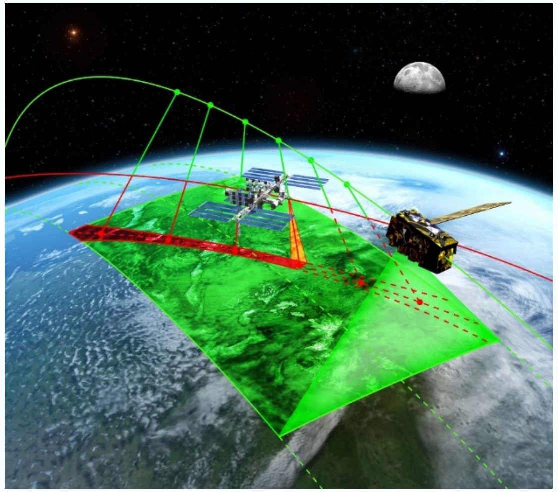
CLARREO Pathfinder Objectives

Objective #1: High Accuracy SI-Traceable Reflectance Measurements



Demonstrate on-orbit calibration ability to reduce reflectance uncertainty by a factor of *5-10 times* compared to the best operational sensors on orbit.

Objective #2: Inter-Calibration Capabilities



Demonstrate ability to transfer calibration other key RS satellite sensors by inter-calibrating with CERES & VIIRS.

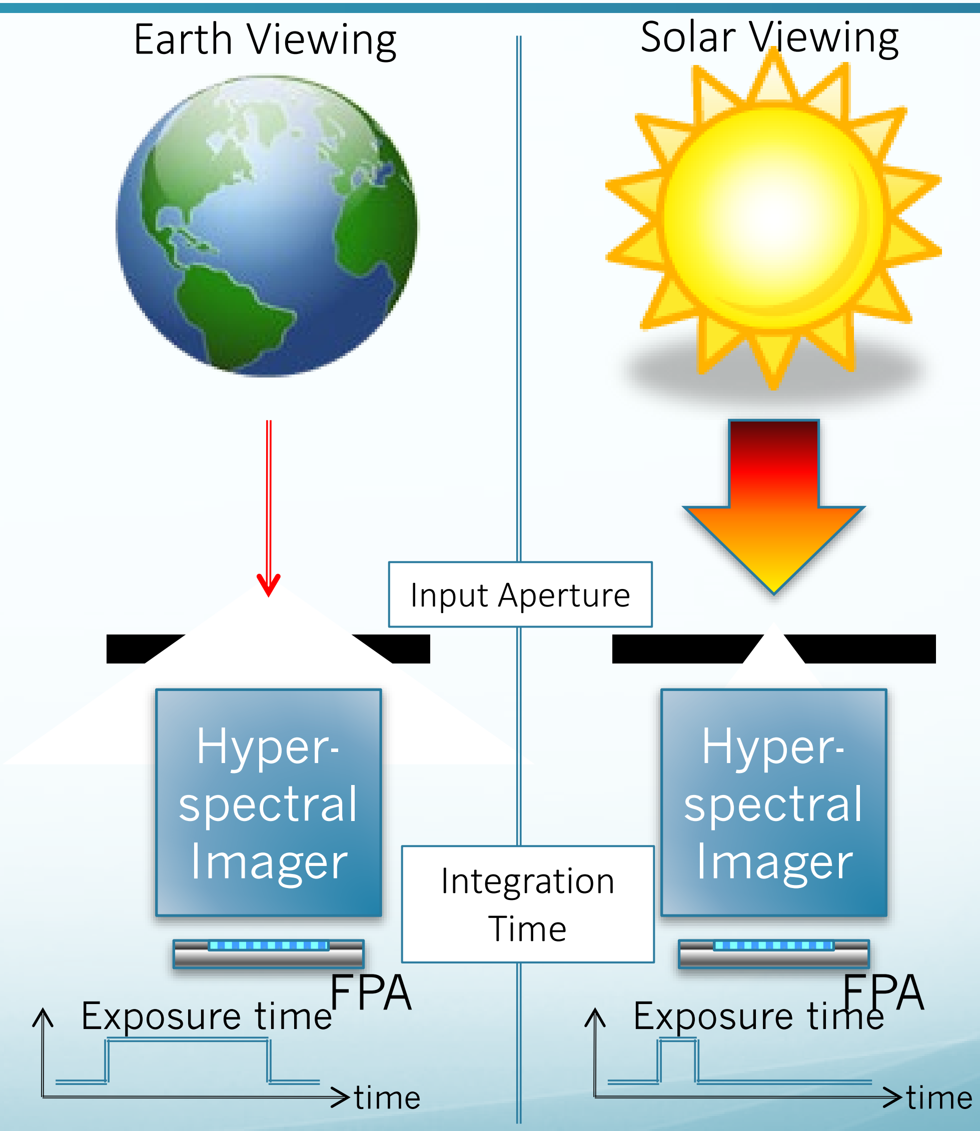
	Objective #1	Objective #2
Uncertainty	Spectrally-resolved & broadband reflectance: ≤0.3% (1σ)	Inter-calibration Data Matching: ≤0.3% (1σ)
Data Product	Level 1A: Highest accuracy, best for inter-cal Level 1B: Approx. consistent spectral & spatial sampling, best for science studies using nadir spectra	Level 4: One each for CPF-VIIRS & CPF-CERES inter-cal. Merged data products including all required info for inter-cal analysis

Novel, Rigorous Calibration Approach

- Earth reflectance will be obtained using a band-ratioing radiometer approach
- To effectively view both Sun & Earth with nearly identical optical paths, attenuation methods must be used

Attenuation Method	Earth	Sun	Attenuation Magnitude
Aperture Size	20 mm	0.5 mm	> 3 Orders
Integration Time	66 ms	1.17 ms	> 2 Orders

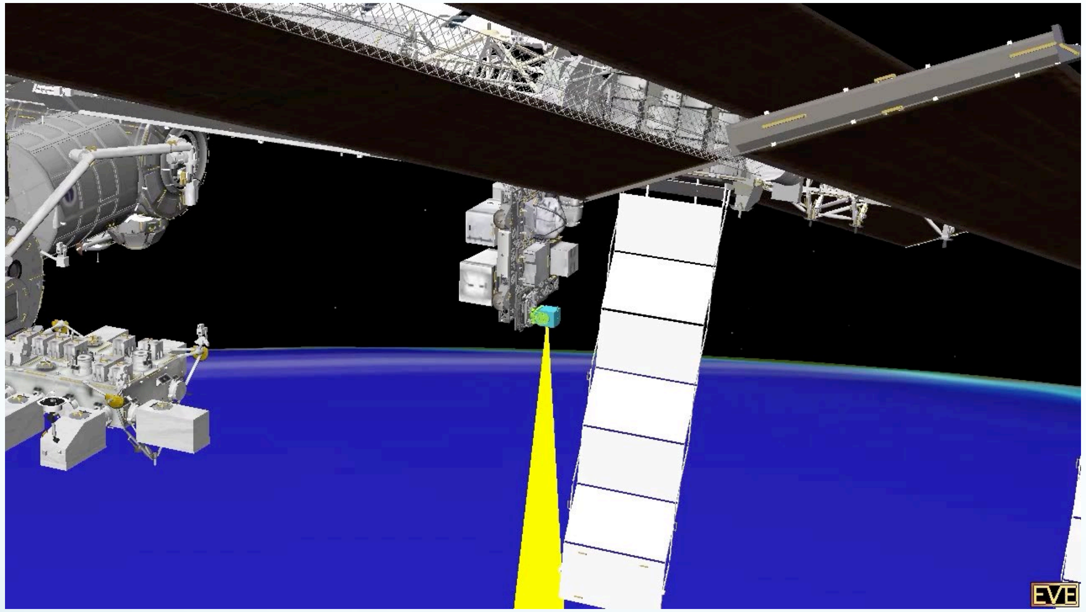
- Solar measurements & on-orbit calibration
  - Cross-slit scan
  - Flat fielding for both apertures – along-slit scan
  - Pen-ray lamp measurement

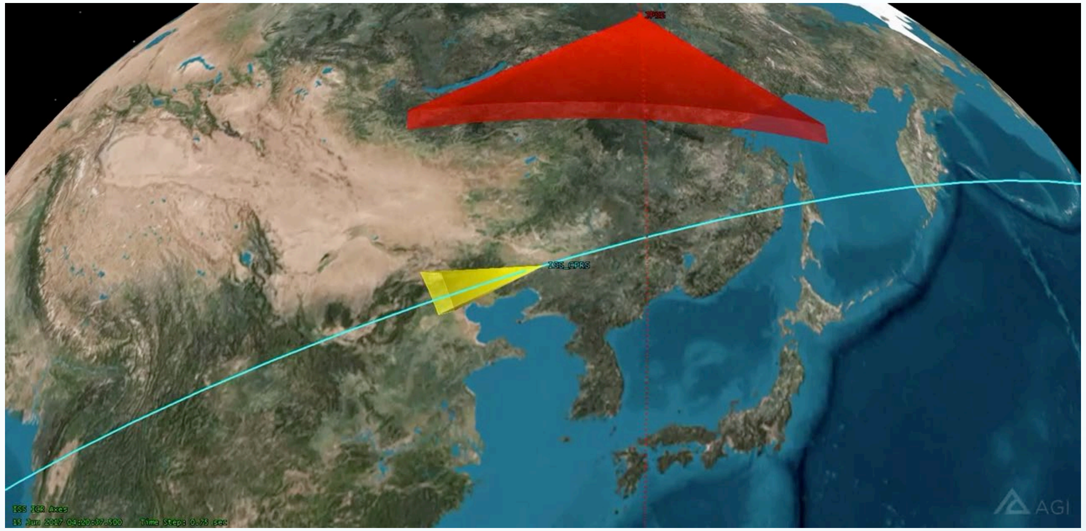


P. Smith (LASP)

A Novel Inter-calibration Approach

CPF low uncertainty inter-calibration approach is enabled by the two-axis pointing capability of the CPF payload.



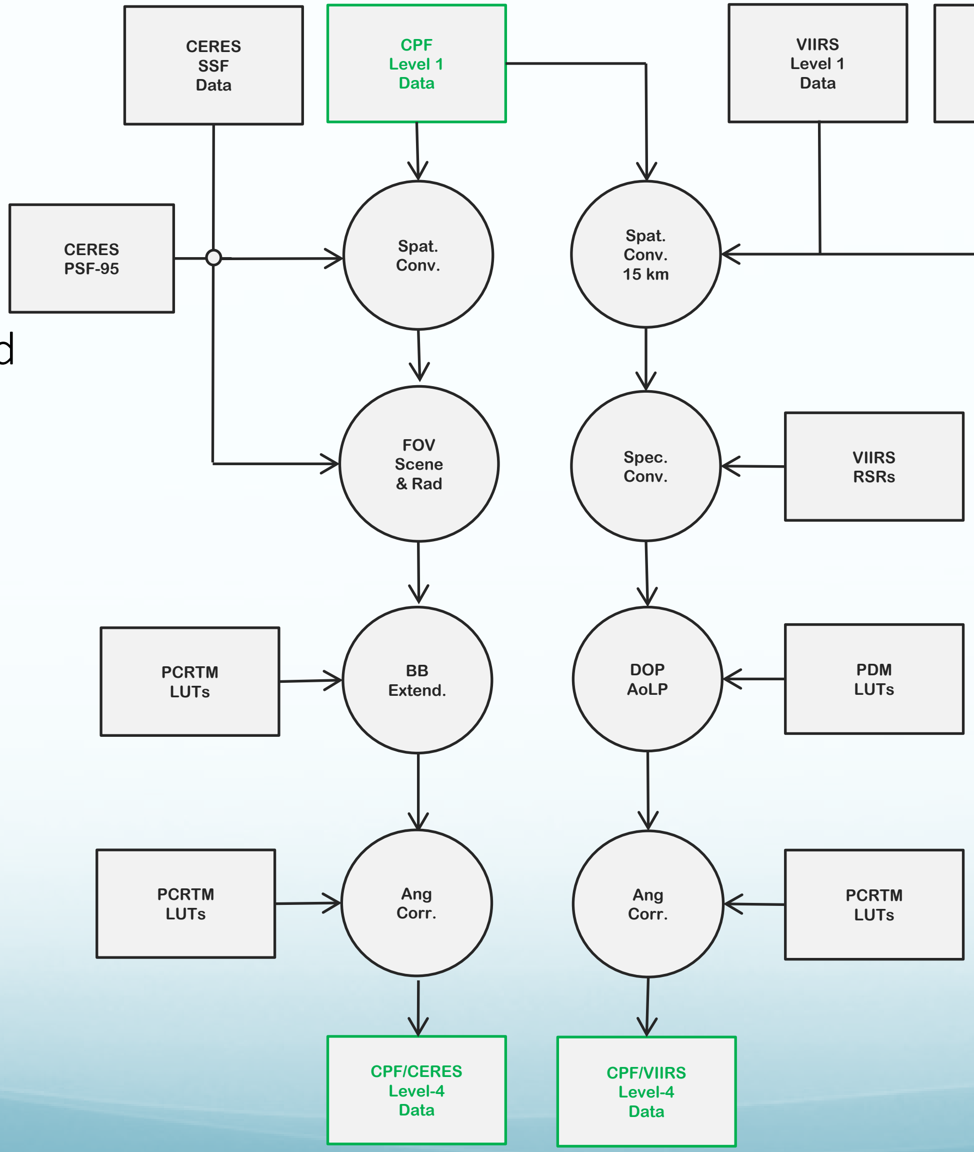


The payload roll & pitch maneuver and scanning capability helps to increase inter-cal opportunities (not just nadir), and closely matches boresight line of sight of target sensor.

Direct Inter-calibration Algorithms

CPF-CERES Inter-calibration Processing

CPF-VIIRS Inter-calibration Processing



Green Boxes: CPF-distributed data products

These Algorithms cover:

- Spatial Convolution
- Spectral Convolution, Integration, and/or Extension
- Angular Correction
- Scene polarization characterization (if applicable)

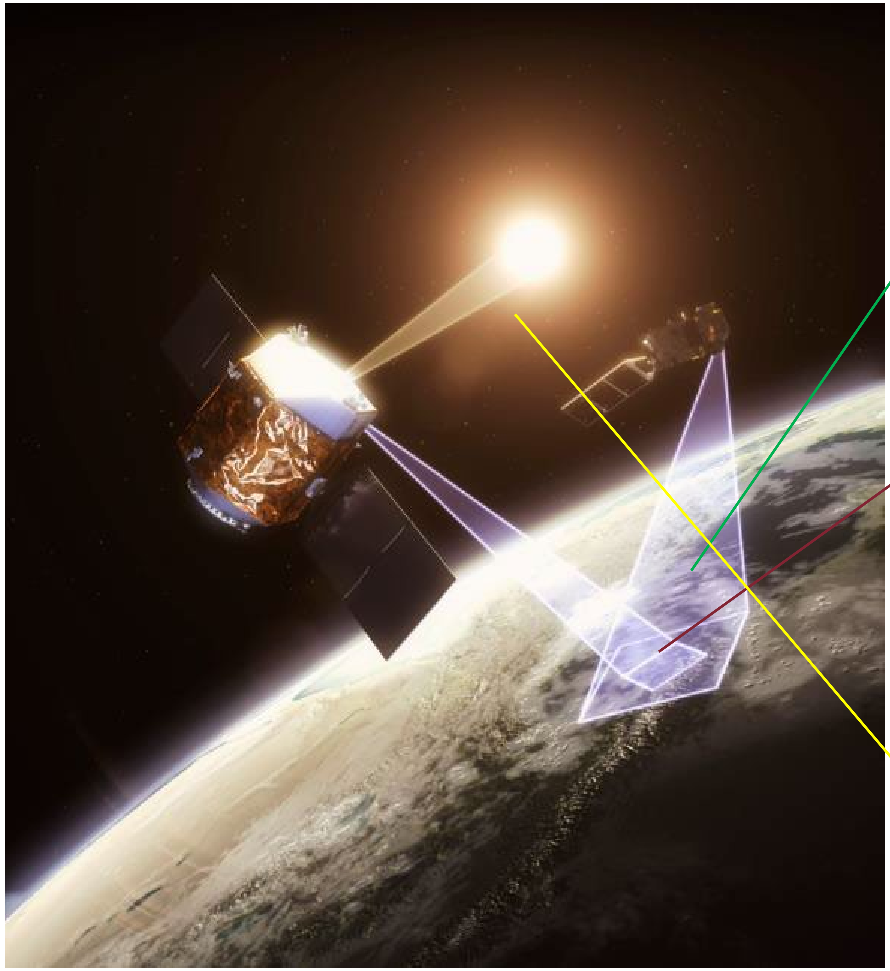
Versatility in Science Observations

Launch-Ready: Late 2023 | Nominal Mission : ~2024 | 2025-2029 (?)

Observation Type	1-Year Mission	Potential Extended Mission (TBC)
On-orbit Instrument Calibration	• Demonstrate success of calibration approach over 1 year	• Confirm success of calibration approach over longer period
Earth Reflectance and Radiance Nadir Spectra	• Demonstrate meeting calibration, geolocation, etc requirements	• Develop climate benchmark prototype • Potential overlap with TRUTHS • Additional opportunities for use in science studies
LEO On-orbit Inter-calibration	• Measurements *and* data analysis for CERES and VIIRS Only • Potential additional LEO measurements (not analysis)	• Additional flexibility to inter-calibrate other on-orbit LEO sensors (Pending project-community-stakeholder negotiations)
GEO On-orbit Inter-Calibration	• Demonstration measurements with one GEO	• Potential to expand GEO IC measurements (Pending project-community-stakeholder negotiations)
Enhanced Pseudo-Invariant Calibration Site (PICS) Characterization	• Measurements over high-priority PICS	• Additional PICS added with additional viewing opportunities
Improved characterization of the Moon	• Leveraging existing ops mode to cover phase angles and libration states	• Additional sampling within phase angles and libration states contribute to improved lunar models

Mission Requirements (solid box) | Additional Opportunities (dashed box)

Traceable Radiometry Underpinning Terrestrial- and Helio- Studies (TRUTHS): Mission Objectives



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

1. **Climate benchmarking:** significantly enhance our ability to estimate the Earth radiation budget (and attributions) through direct measurements of incoming & outgoing energy & reference calibration,
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.

An Agile platform allows observations of Sun, Moon and Earth with the same sensor together with view angle matching for optimum cross-calibration & ability for surface BRF characterisation

Mission Products

- L1: Earth-reflected Spectral Radiance (ToA), Solar Spectral Irradiance, Lunar Spectral Irradiance – all in the range <320nm to ~2400nm; across Earth diurnal and lunar cycles
- L1: Total Solar Irradiance integrated in the range 200nm to 30000nm;

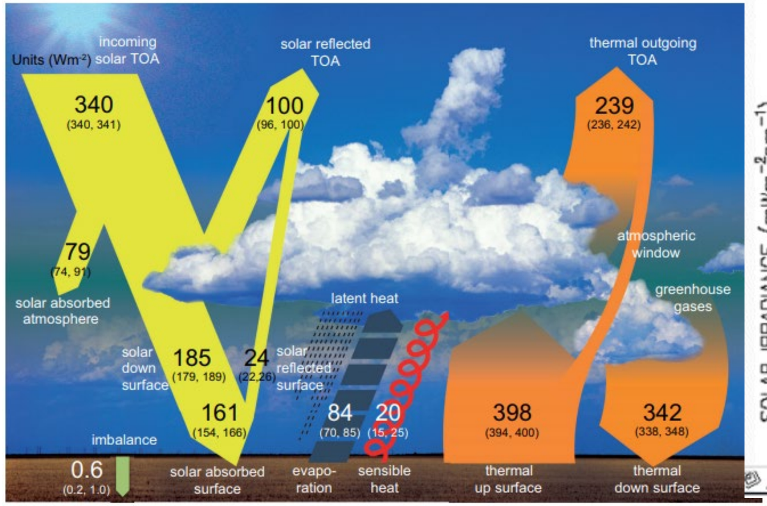
→ **Climate benchmark, solar measurement**

- L2: Spectral Surface Reflectance, at ground level (~400nm to ~2400nm); primarily as a reference

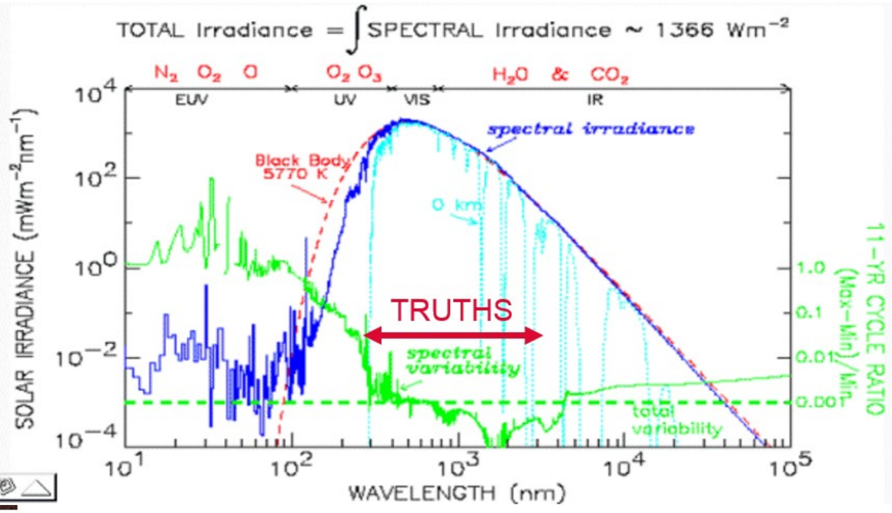
→ **Earth science**

- calibration coefficients & match-up products to determine biases for TBD other sensors over multi-scene types and view angles, (climate sensors & geo-spatial).

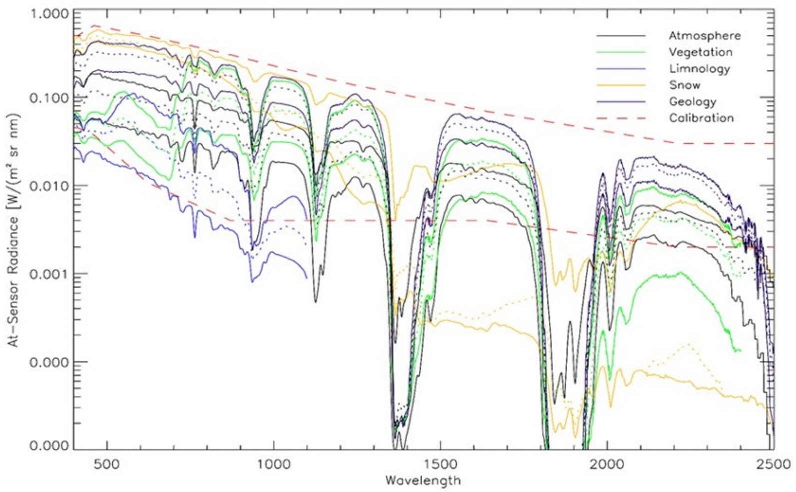
→ **Cross-calibration**



Radiation balance

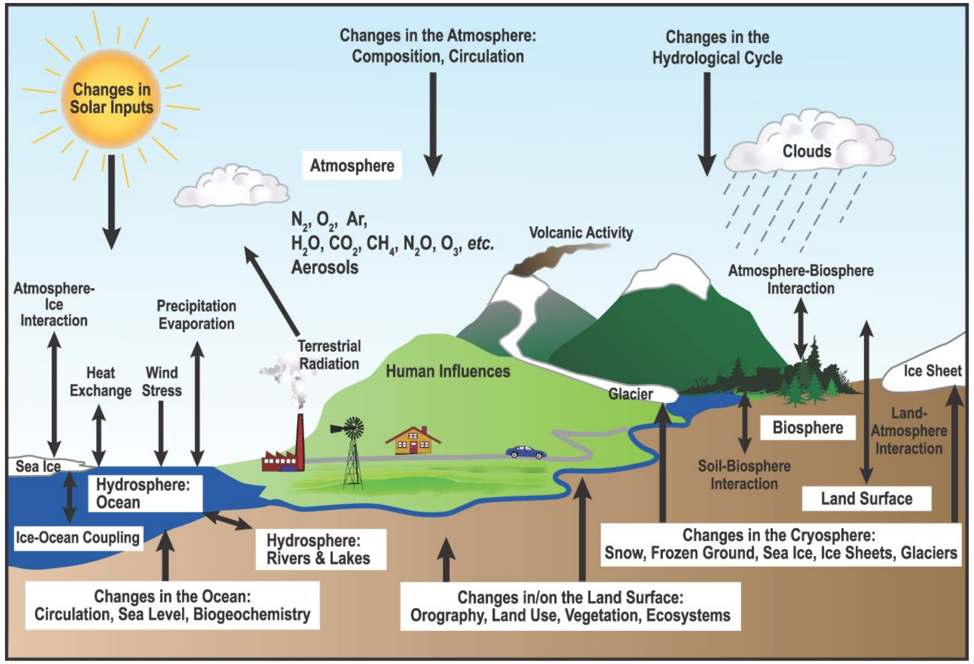


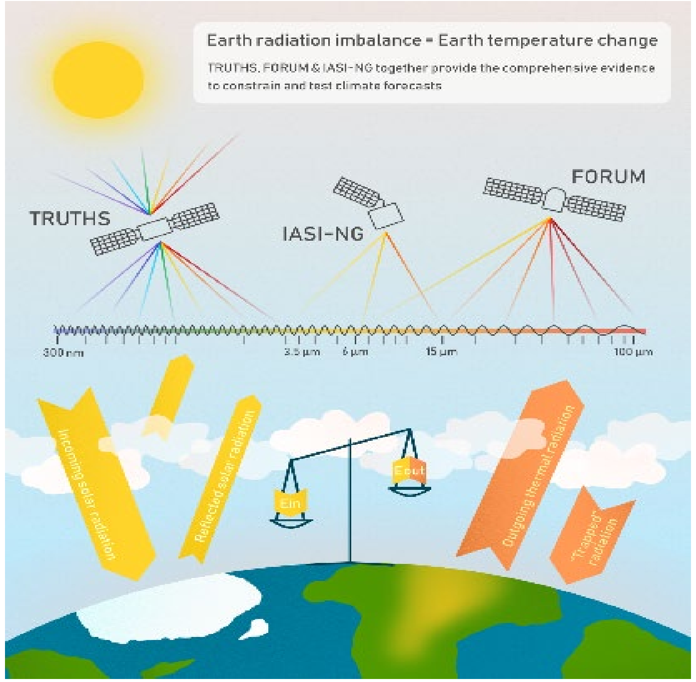
Solar spectral irradiance



Surface reflectance

Key questions: Carbon & Radiation imbalance





TRUTHS data will also help understand efficiency and status of natural sinks of Carbon dioxide (forests and oceans) and support monitoring of land use change and agriculture amongst many others primarily be reference calibration

TRUTHS is a complementary mission to other satellite based earth observation missions providing a more complete picture of the Earth's radiation imbalance which drives global warming

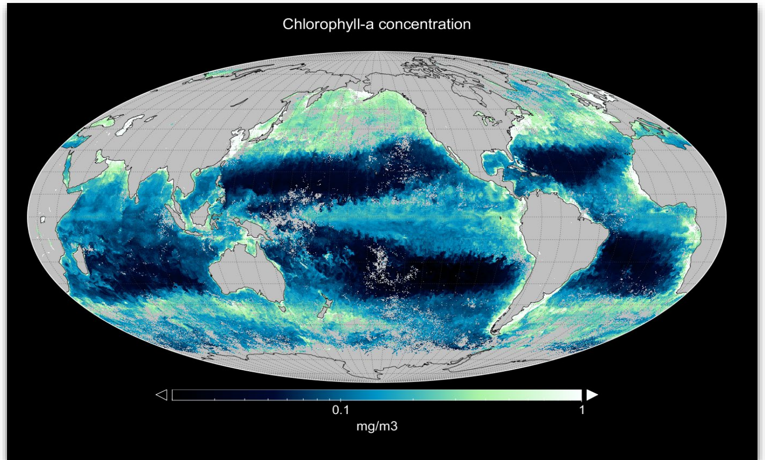
Together with IASI-NG and FORUM can provide a comprehensive spectral radiation observing system

Spanning UV to Far-Infrared

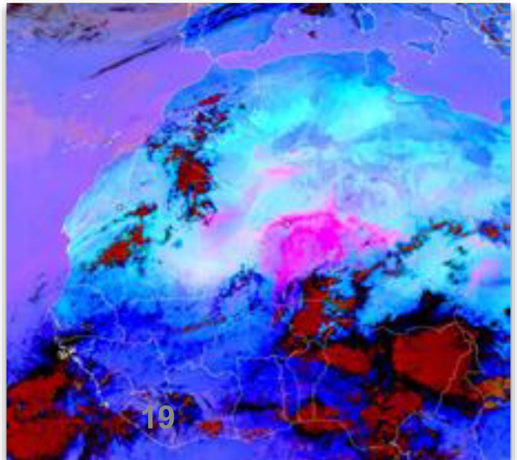
TRUTHS: Underpinning operational ECV retrievals for climate monitoring and model improvement

TRUTHS contributions	Climate data records
Provides reference calibration	Cloud properties, ozone, aerosol optical depth, greenhouse gases
Provides reference calibration AND direct observation	Solar irradiance, Earth radiation budget, surface albedo, cloud cover, cloud particle size, water vapour, ocean colour, ice and snow cover, vegetation indices such as leaf area index, land cover …..

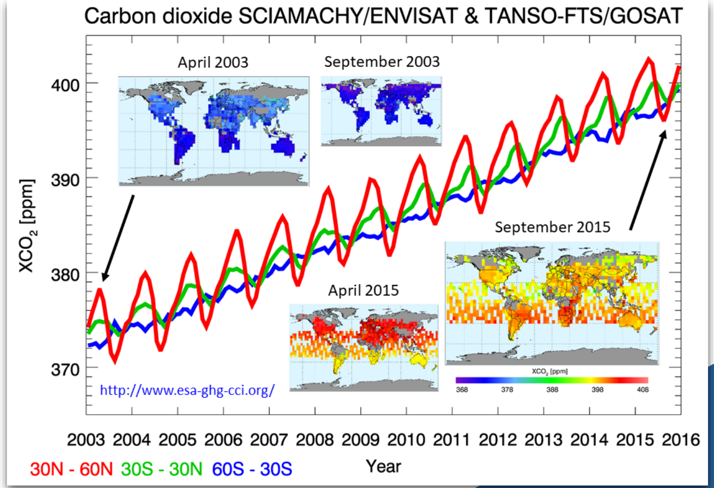
- **Ocean colour:** direct TOA cross-calibration of sensors to absolute radiometric accuracy of ~0.5%, meeting GCOS requirements



- **Aerosols:** "Climate closure points" unifying ground networks and multiple optical sensors through the TRUTHS FCDR.



- **CO_2:** Referencing Copernicus and multi-agency CO_2 constellations at 0.5-1.0% radiometry through cross-calibration.

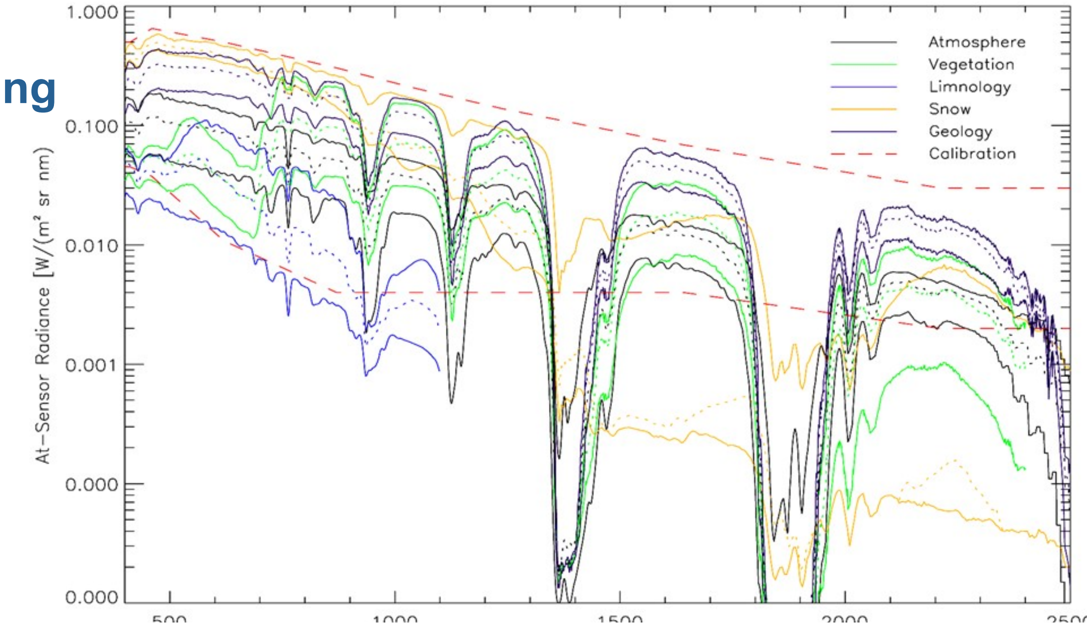


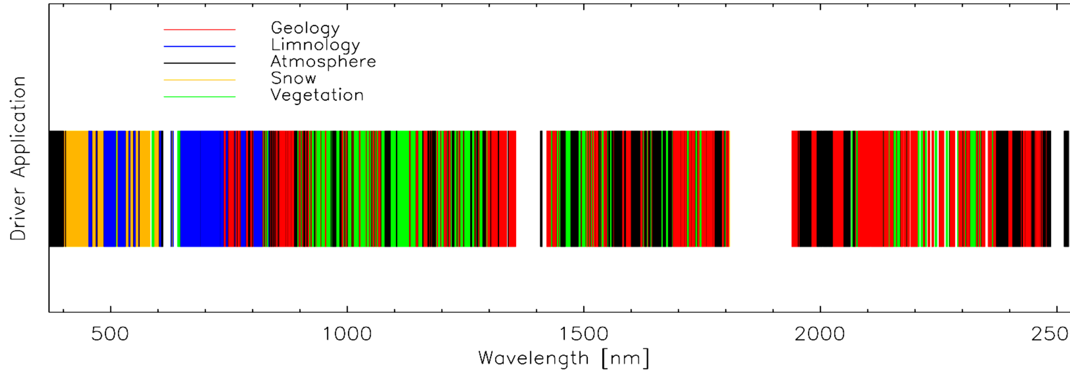
Hyper-spectral applications: ‘Analysis Ready’ (ARD) Surface reflectance

Hyperspectral data can be convolved for many applications enabling an earth system science approach:

- directly
- upgrading other sensors
- Test & Improve retrieval algorithms
- Validation establishing references surface reflectance e.g. Fluxnet

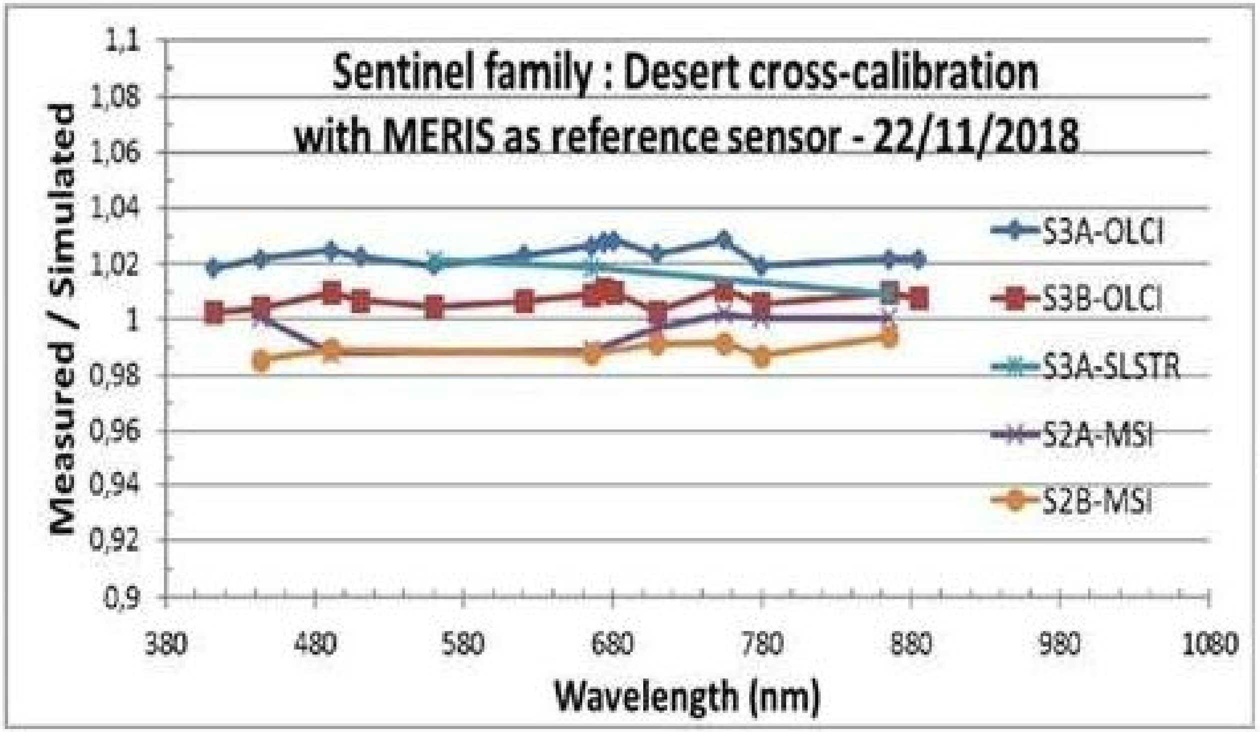
- **Complementary to EnMAP, PRISMA, CHIME ….**
- **Land-cover change**
- **Forest**
- **Surface Albedo**
- **Agriculture**
- **Pollution**
- **Resource prospecting**
- **…….**

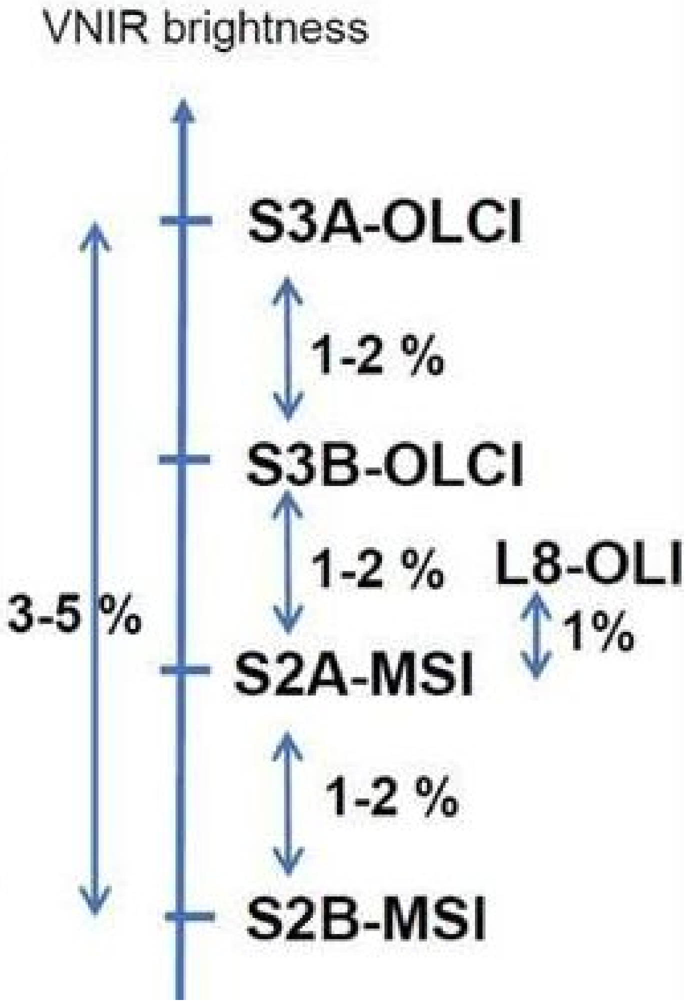




Strategies to identify/remove biases and harmonise the Earth Observing system are well-established:

But what is the Truth?

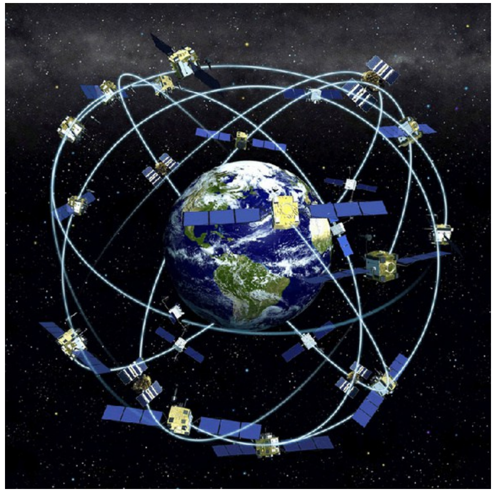




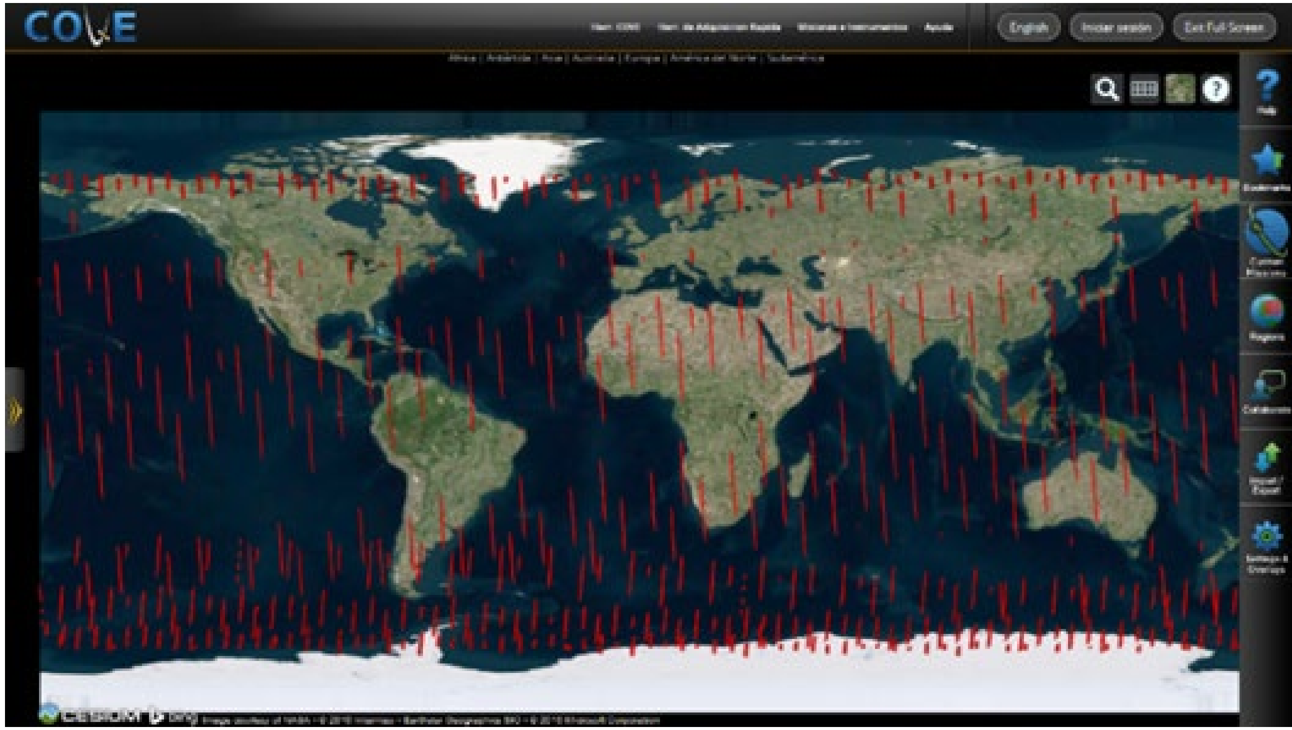
Graph courtesy of Meygret, CNES

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 -



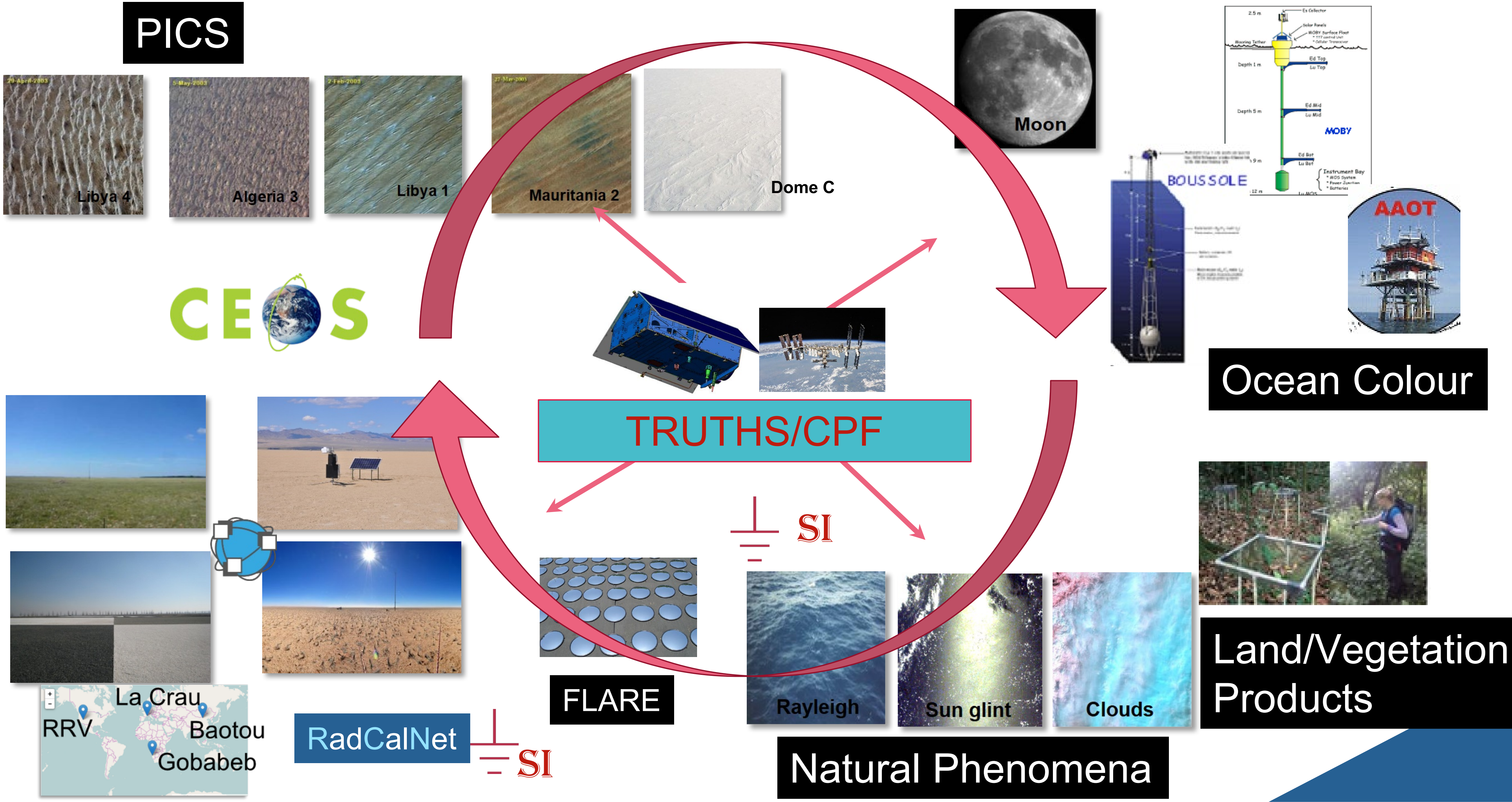
Sentinel 2 & TRUTHS match-ups for 1 yr (30 minute window)

90 deg Polar orbit allows many near simultaneous cross-overs with other satellites Nadir (SNO) or by pointing to angle match

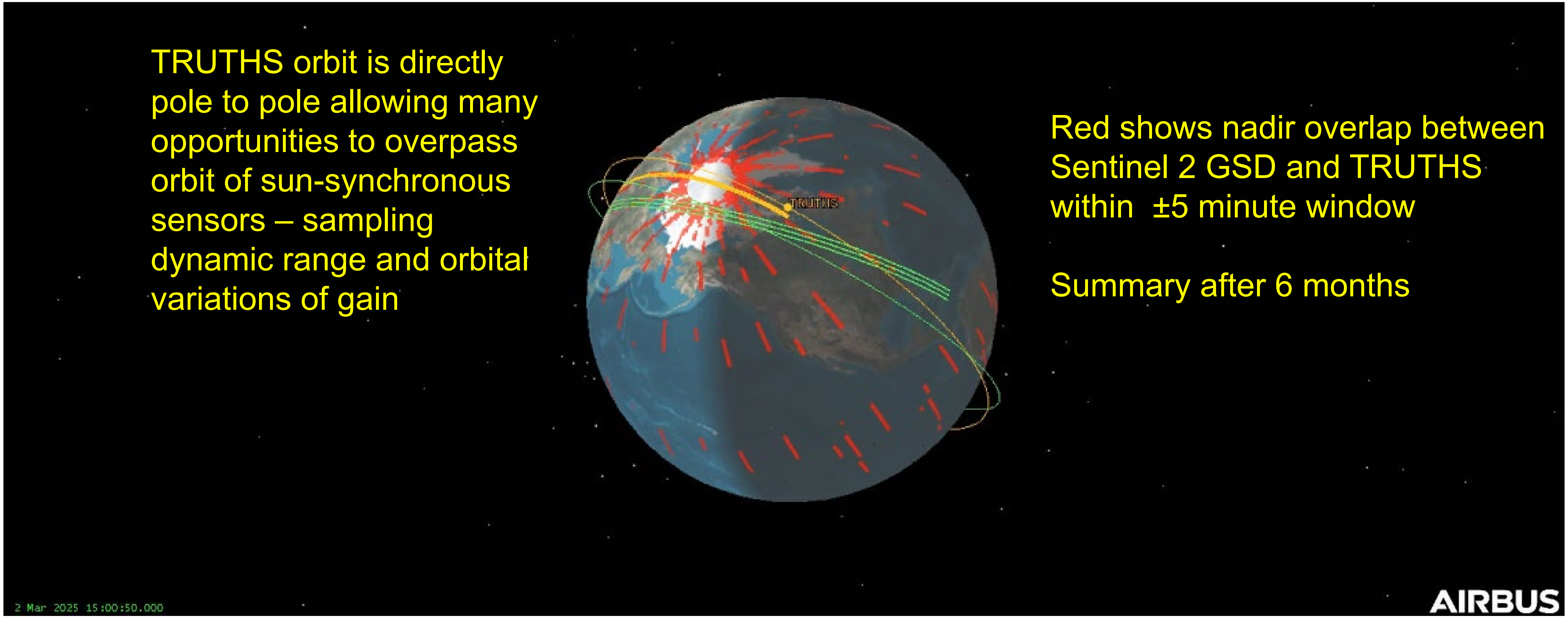
- **Reduces uncertainties due to:**
  - Illumination and view angles
  - Atmospheric changes
  - Allows many scene types

E.g. Sentinel 2 using Libya 4 desert TRUTHS can improve accuracy <1 % for all bands

Traceability to CEOS+ Cal/Val infrastructure



TRUTHS Cross-Calibration with Sentinel 2



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

Key performance Requirements Goals: Driving

Parameter	Spectral range /µm	Spectral resolution (SSI) / nm	GSD / m	SNR @ 4 nm & 50 m (Lref) (250 m<380nm)	Sampling	Uncertainty/ % (k=2)
Earth Spectral Radiance Benchmark & Ref Cal	0.32 - 2.4	~4 < 1000 8 >1000	~50 @ >400 nm 250 @<400 nm Climate only <250 T	>50 <350 >100@ 350-380 >100 @ 380-2400 For water >300 @ 380-1000 & @ 250 m	Global nadir ~100 km swath + multi-angle	0.3 G 1 T
Surface Reflectance	0.4 - 2.4	<~5			Global nadir + multi-angle	<2 G <5 T
Solar/Lunar Spectral Irradiance (SSI)	~0.32 - 2.4 T <0.29 G	<1 <400 nm <5 400-1600 <10 >1600	NA	>300 (time integrated)	Daily	0.3

Total Solar Irradiance (TSI) Uncertainty <0.02% (k=2)

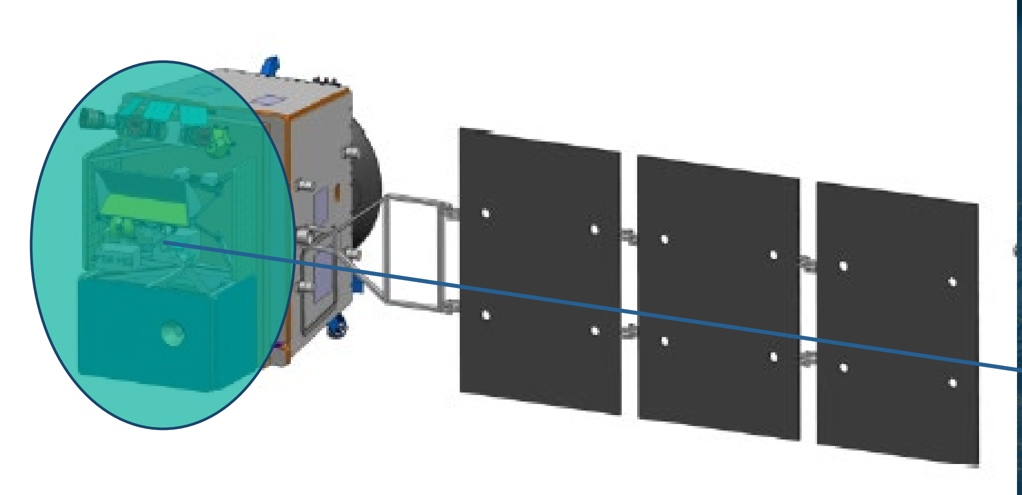
Note: SNR determined to be comparable with performance of Sent 2 (equivalent bandwidths) following binning

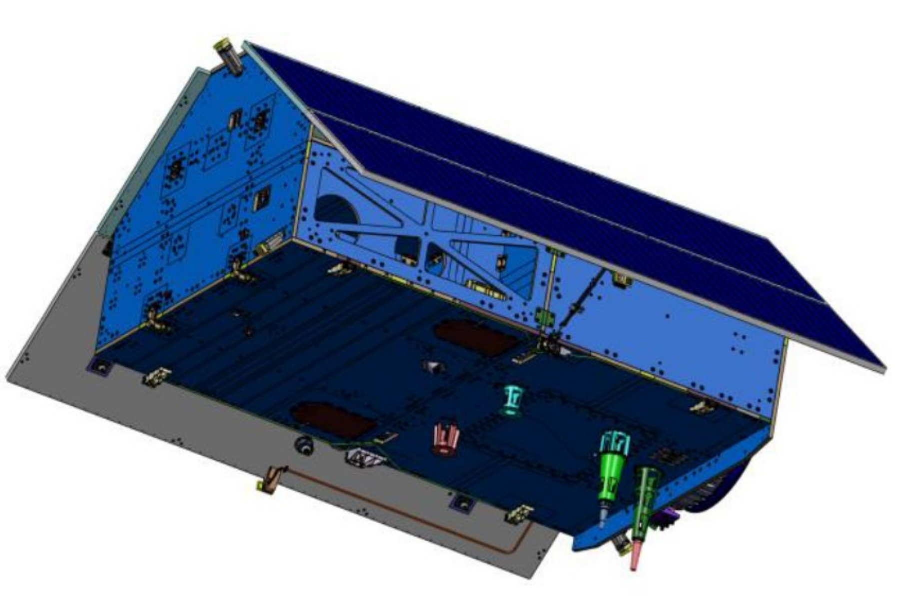
For OC (most demanding ECV) requires SNR > 2000 (in visible) but only @ ~1km resolution & 10 nm resolution so achievable by spectral and spatial binning

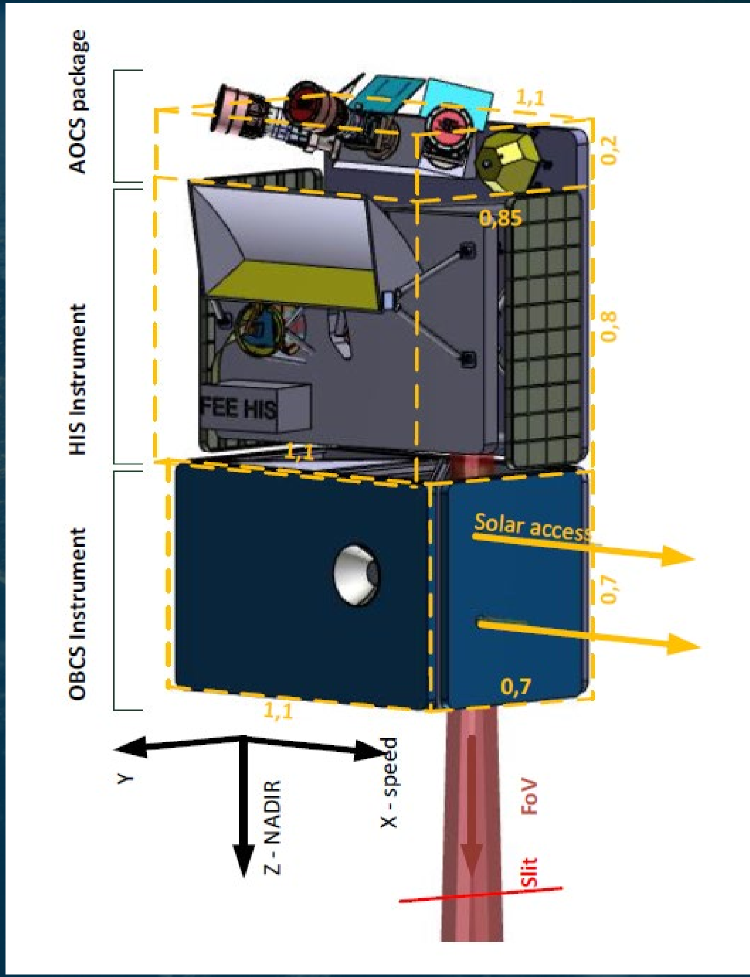
The TRUTHS design is driven by:

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

Preliminary Satellite concept

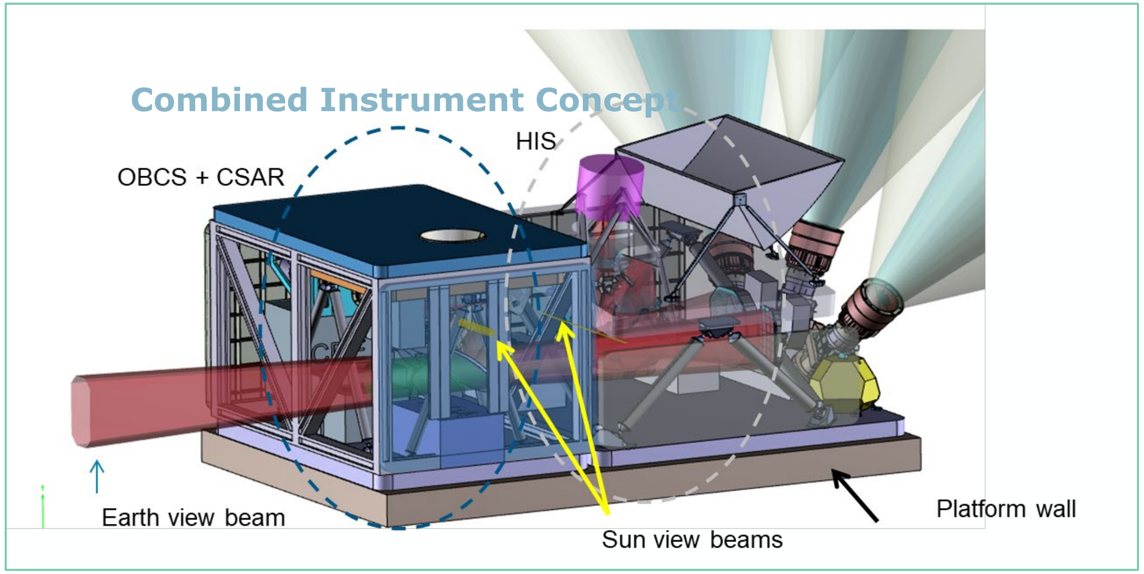


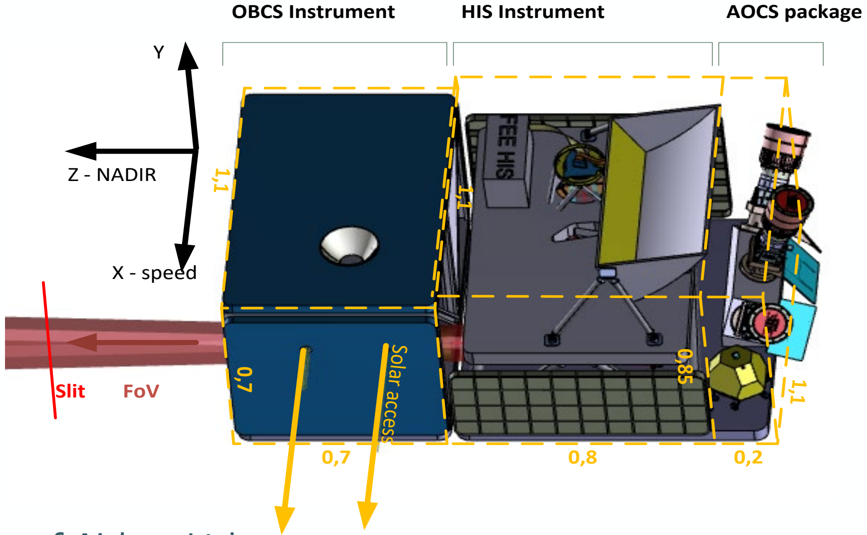


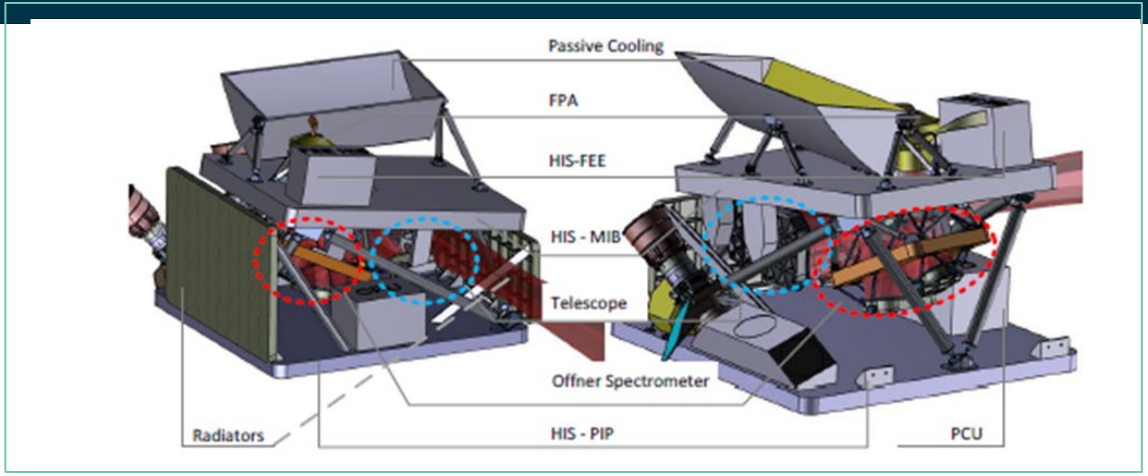


Courtesy of Airbus Ltd

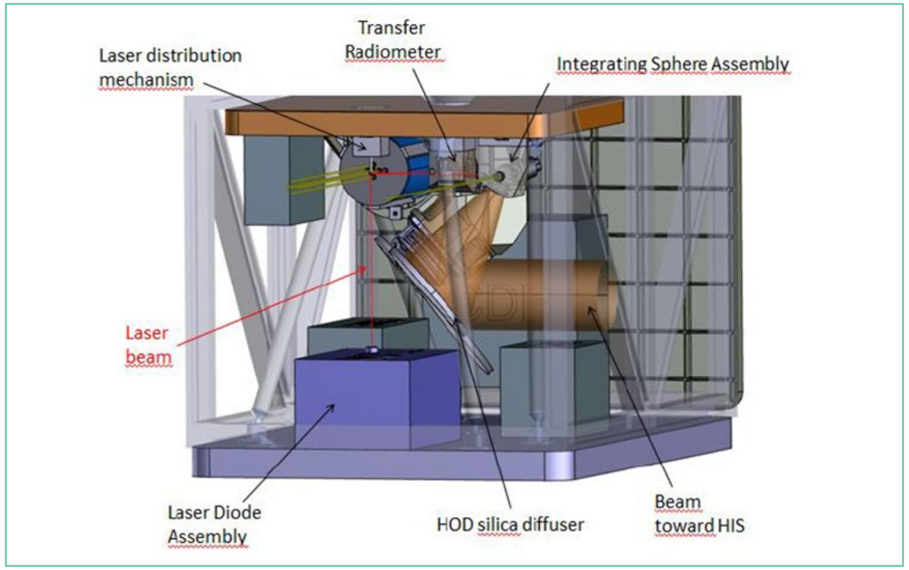
TRUTHS Payload Overview







Hyperspectral Imaging Spectrometer (HIS)



On Board Calibration System (OBCS) & Cryogenic Absolute Solar Radiometer (CSAR)

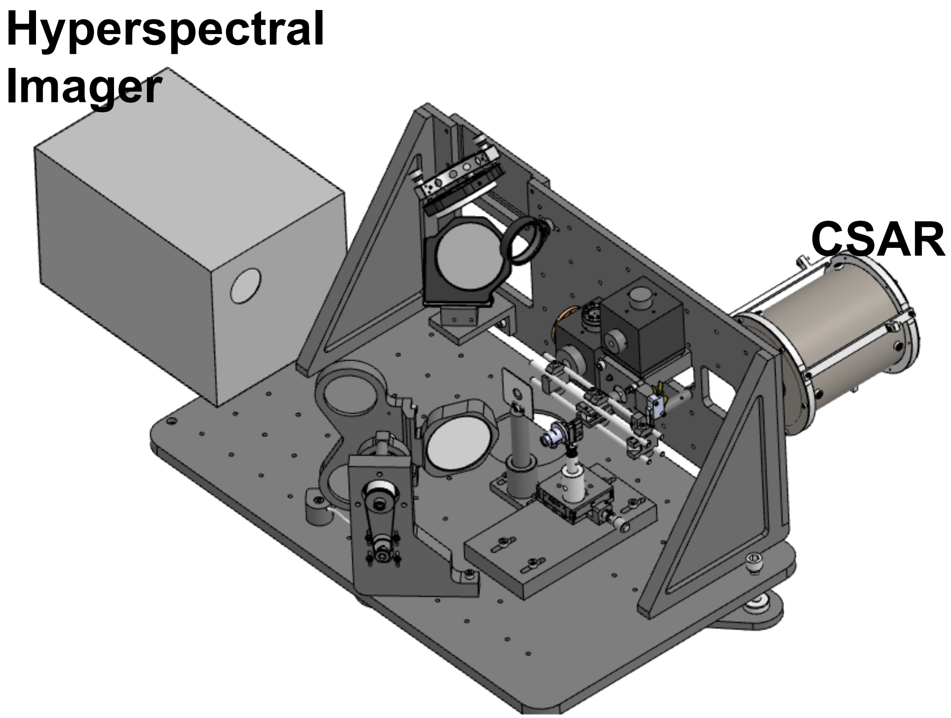
Courtesy of Airbus Ltd

What makes TRUTHS different to other optical satellite missions?

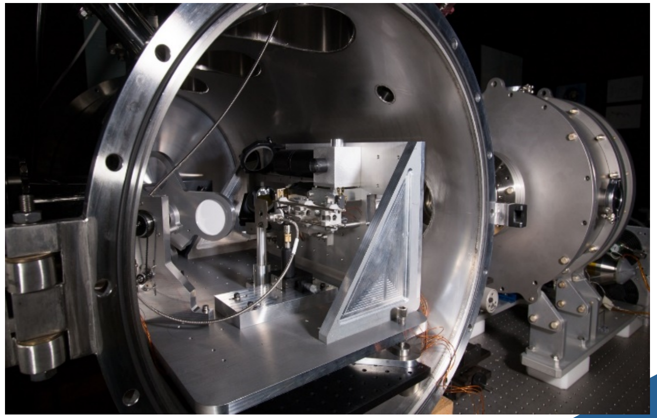
TRUTHS includes an on-board calibration system, that replicates the SI-traceable calibration chain employed in National Metrology Institutes (NMIs) globally, including flight of a primary standard - a Cryogenic Solar Absolute Radiometer (CSAR) (see calibration video).

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

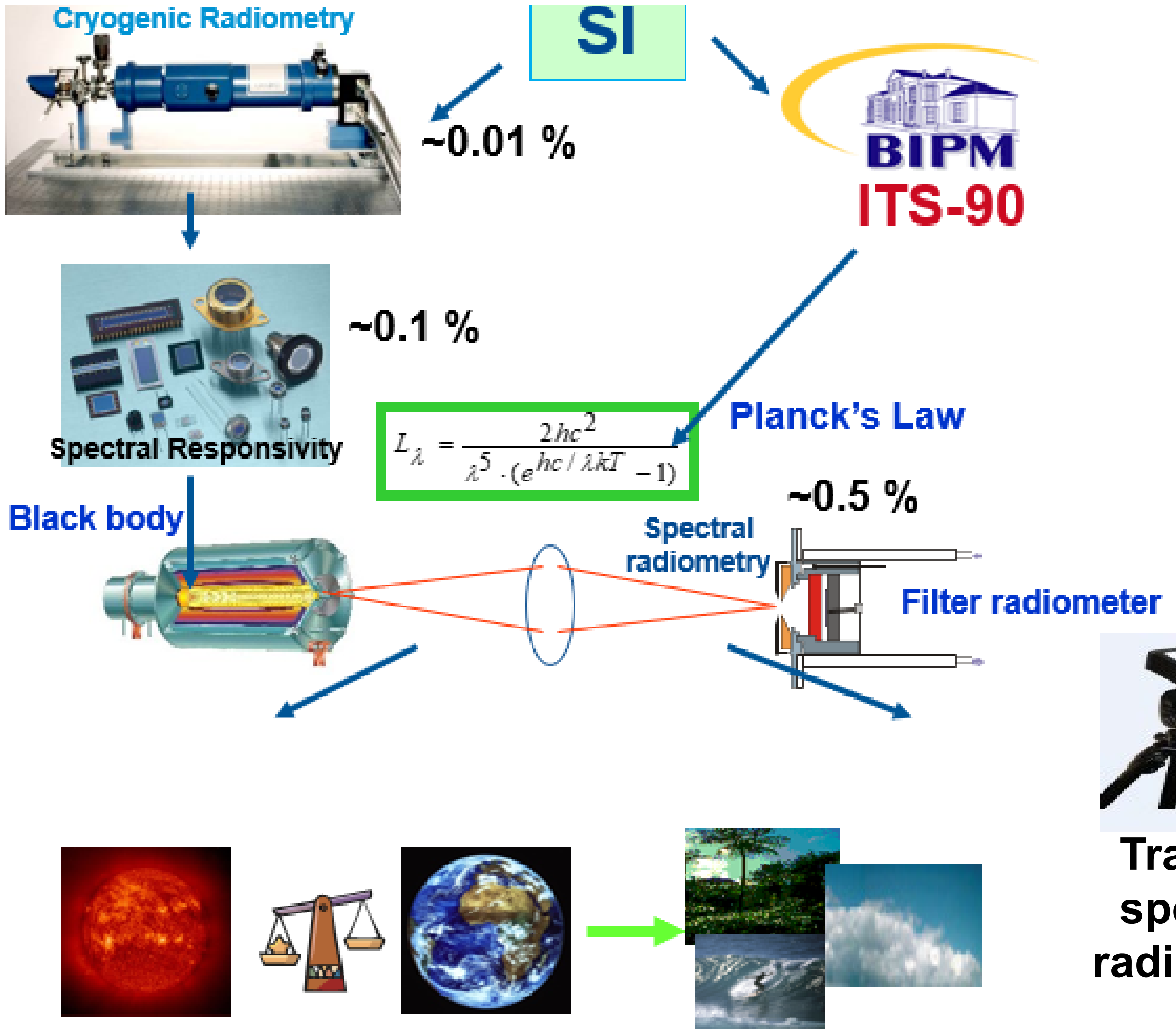
Maintaining it's SI-traceable high radiometric performance throughout the mission lifetime.



Representation of the TRUTHS calibration system



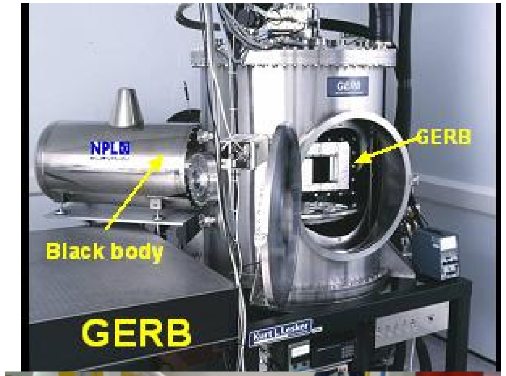
Establishing pre-flight SI-traceability for EO space instruments

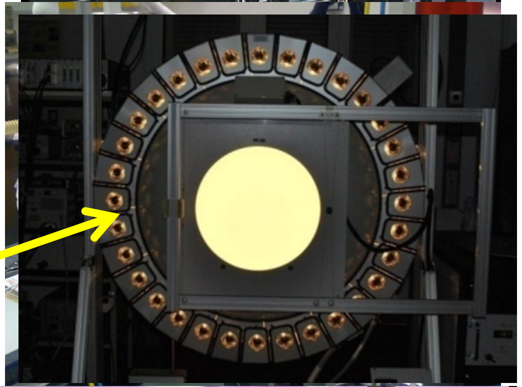


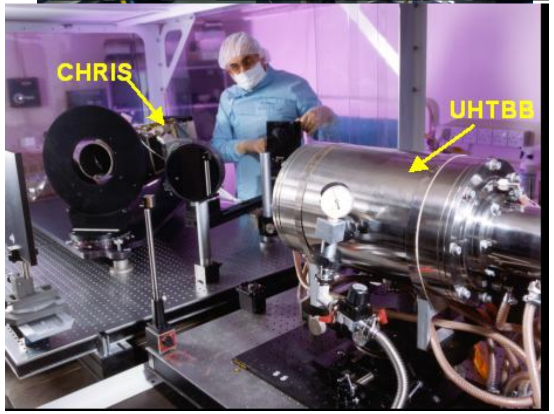
(IR)Radiances achievable but challenging !

Transfer spectro-radiometer

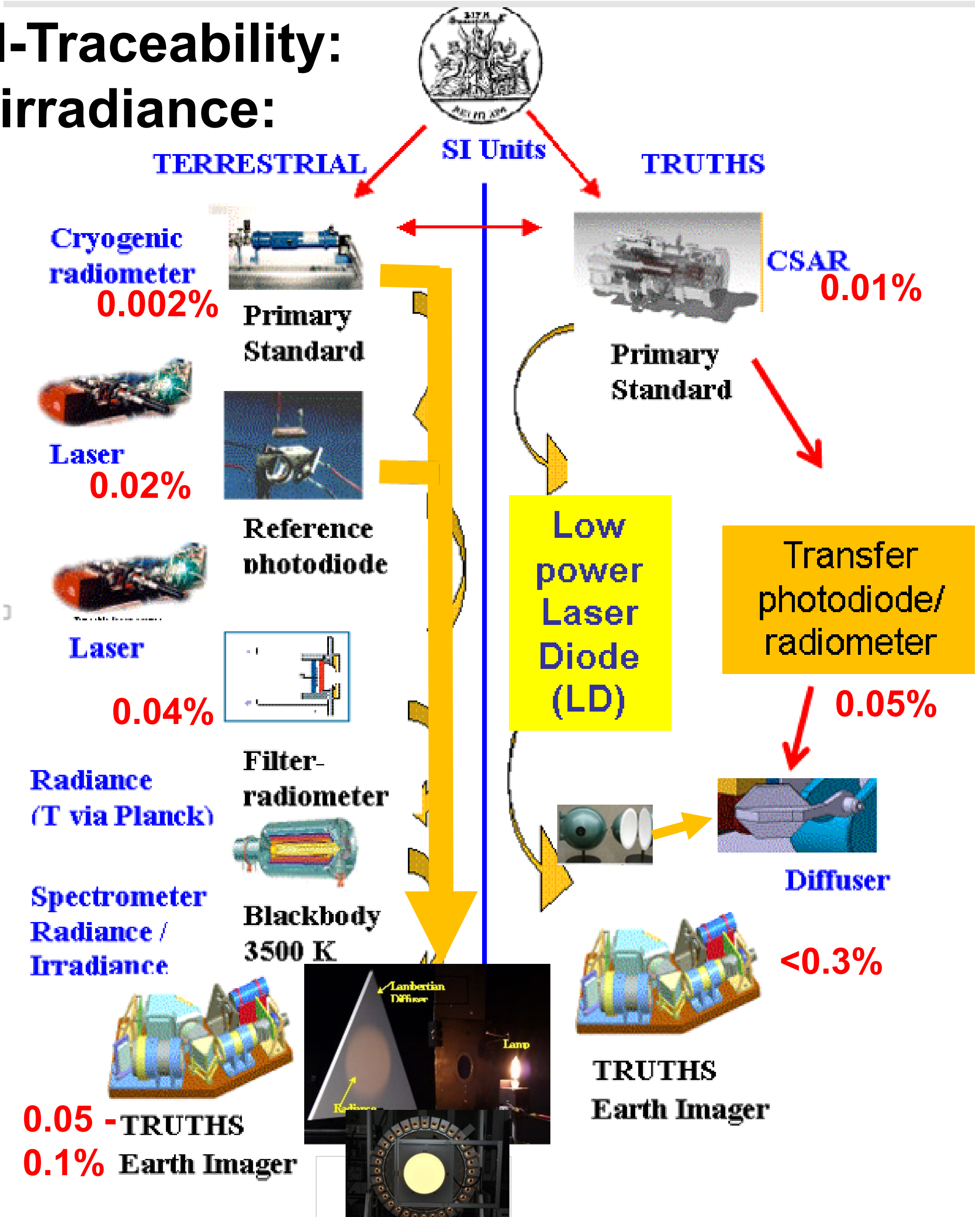
Space Instruments







In-flight SI-Traceability: Radiance/irradiance: summary



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/research/earth-observation/truths/satellite-calibration

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**

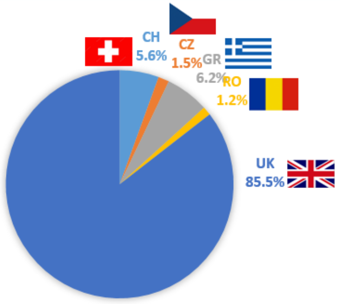
Element	Uc (%)
TRUTHS HIS	0.16-0.26
Spectral mismatch	0.1-0.2
Spatial mismatch	0.1
View Angle	0.1-0.2
Atmos. corr.	0.1-0.3
BRDF	0.1
TOTAL	**0.4-0.7**

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

TRUTHS Status

- Adopted as a funded ESA Earthwatch element as an operational ‘climate and calibration observatory in space’ in Nov 2019: Funding from five member states led by UK at 85%
- Industrial Phase A/B has been implemented
    - Kicked-off in autumn 2020 with Mission Definition Review currently ongoing
    - Programmatic “Gate Review”: Go/No-Go decision by mid-2022
    - Main performance trade-offs are currently being investigated including native spatial sampling (50 vs 100m), spectral range (currently 320-2400 nm), spectral sampling (currently < 6 nm)
- Science Studies have been implemented
    - Independent user requirements study resulting in a Traceable Mission Requirements Review Document
    - TRUTHS Mission Accompanying Consolidation providing scientific support to the ESA Project
- TRUTHS Mission Advisory Group (MAG) established in December 2021
- Target Launch date: 2026-2028



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