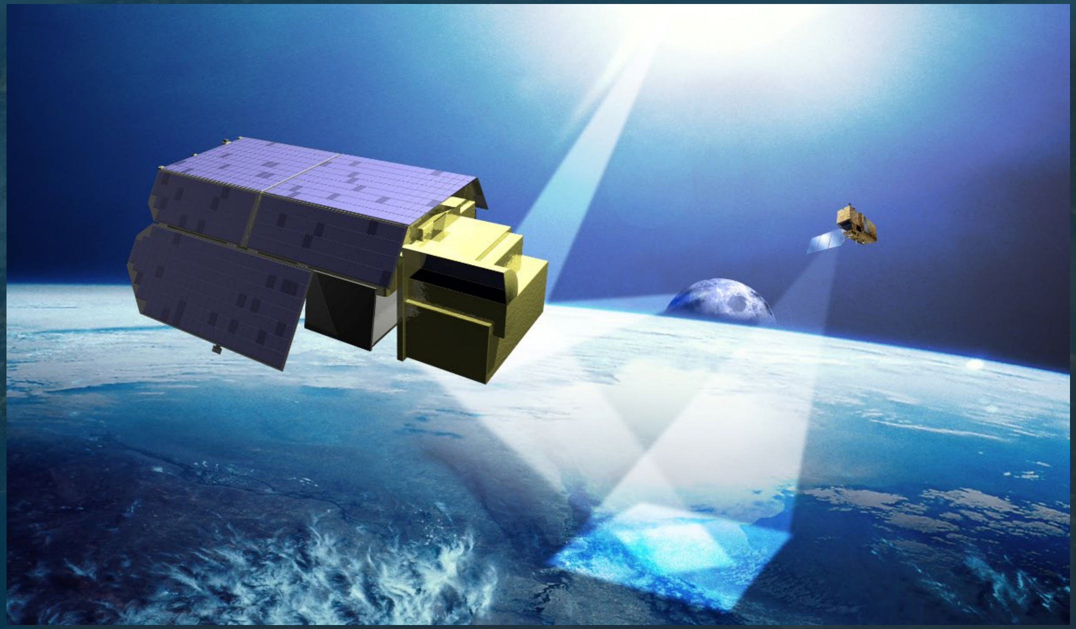
T raceable **R** adiometry **U** nderpinning **T** errestrial- & **H** elio- **S** tudies

An ESA EarthWatch mission



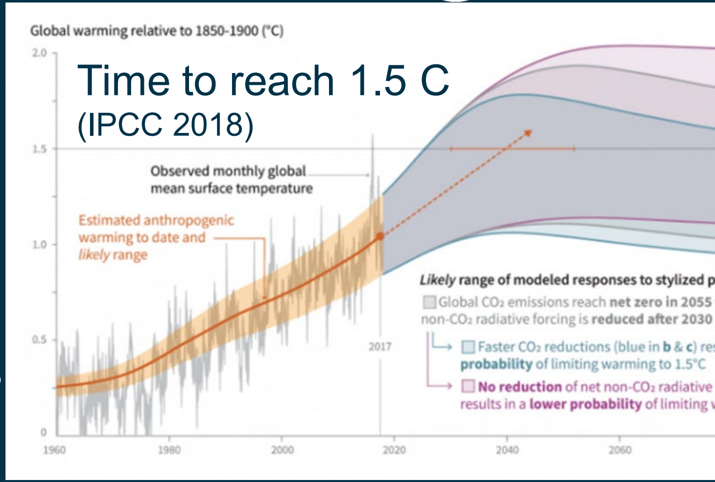
A 'gold standard' reference in space to support the climate emergency

Nigel Fox, Paul Green, Samuel Hunt, NPL,
Andrea Marini, Thorsten Fehr, ESA
Kyle Palmer, Airbus
+++++

Societal Challenge: sustainable growth in a changing environment – 'damage limited' by climate action

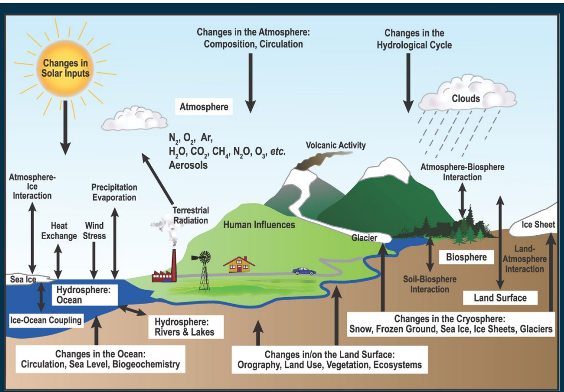
NEED:- Trustworthy observations from space to:

- Monitor and assess progress resulting from mitigation
- Improve understanding of climate sensitivities, dependencies & forecasts
- Support adaptation, Food security emergency response, de-risk investments



REQUIRES

- Quantitative, comprehensive, accessible, useable data
- Integrated, interoperable global observing system (space and in-situ)
- Robust reference(s) (benchmarks) against which to reliably measure change in as short a timescale as possible
- International acceptance

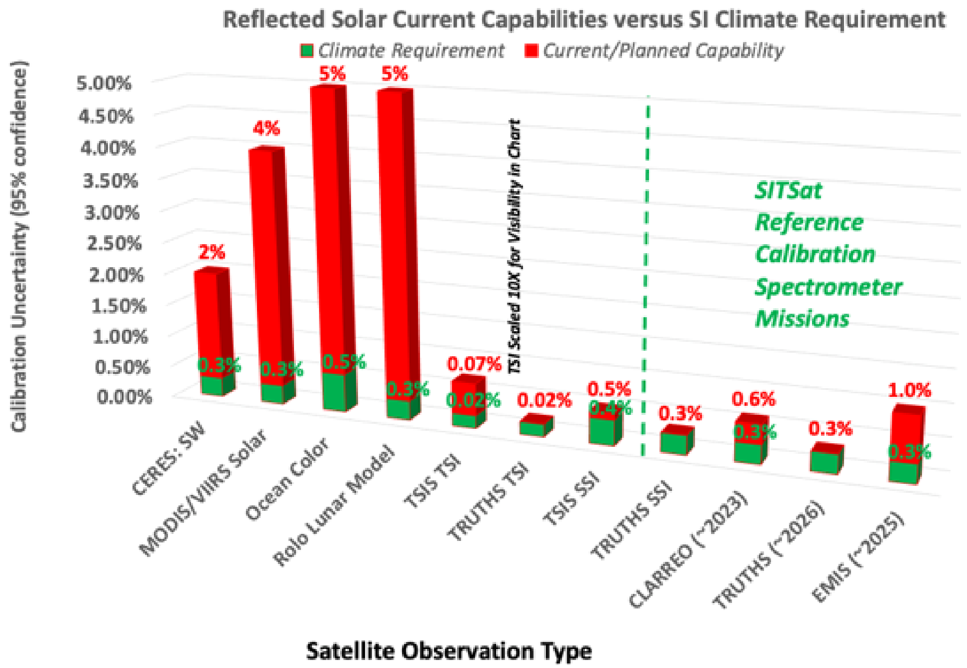


Confidence from metrological traceability to international standards (SI) at location of measurement

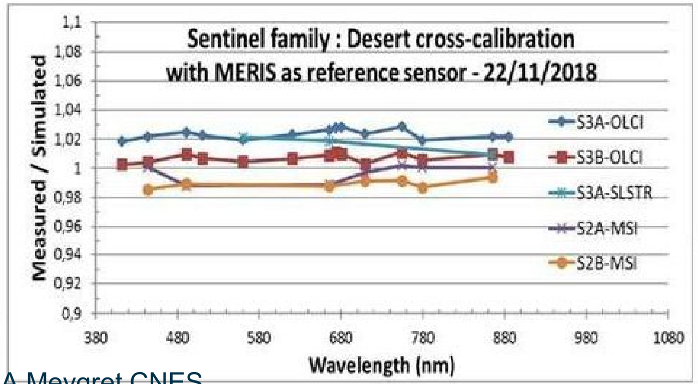
Is Net Zero the right target?

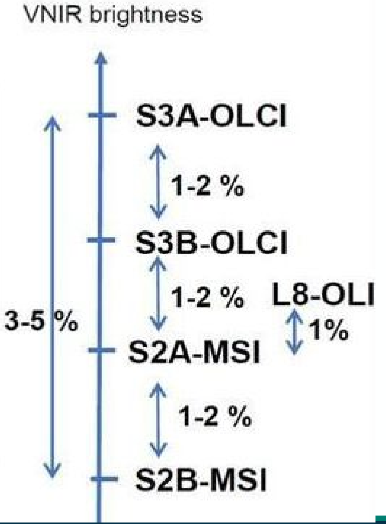
When & how big do we build the next Thames barrier?

Climate Need & observation challenges



Most satellites not designed for climate: performance to suit application

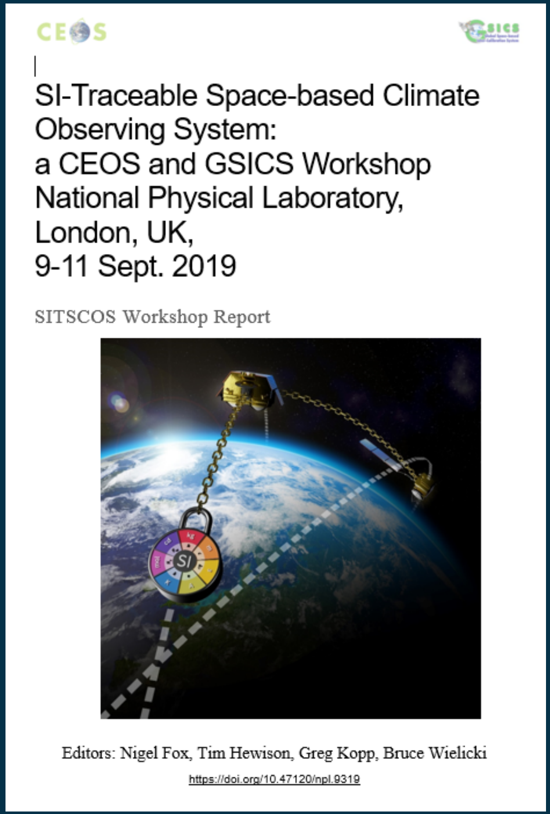




A Meygret CNES

What is the Truth?

Libya 4, a CEOS PICS site is a desert with a relatively stable long-term reflectance, but absolute value of reflectance les certain.


CEOS

SI-Traceable Space-based Climate Observing System:
a CEOS and GSICS Workshop
National Physical Laboratory,
London, UK,
9-11 Sept. 2019

SITSCOS Workshop Report

Editors: Nigel Fox, Tim Hewison, Greg Kopp, Bruce Wielicki

https://doi.org/10.47120/npl.9319

Trustable harmonised time series require stable/understood sensors anchored to invariant references

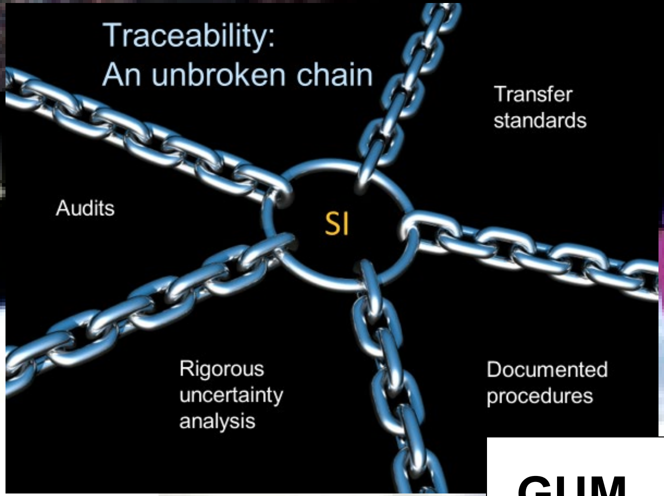
http://calvalportal.ceos.org/report-and-actions

https://doi.org/10.47120/npl.9319

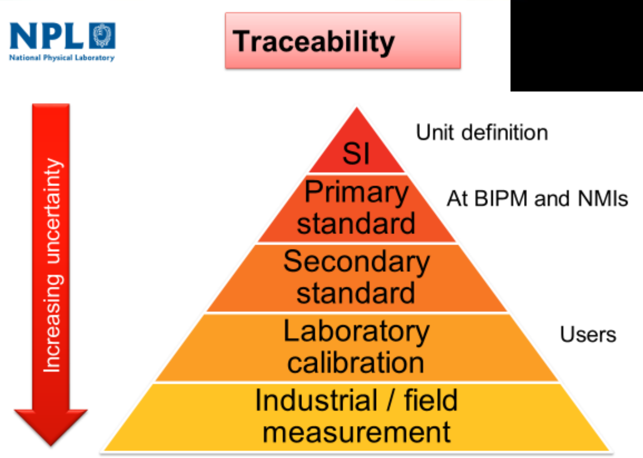
Long-time-base & societal/economic critical applications like Climate require robust ‘trustworthy’ data:

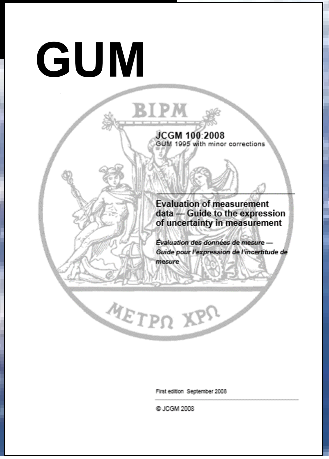
e.g detection of small signals of change out of a noisy background of nat variability

At location of observation



- Interoperable
- Century-long stability
- Coherence
- Absolute accuracy

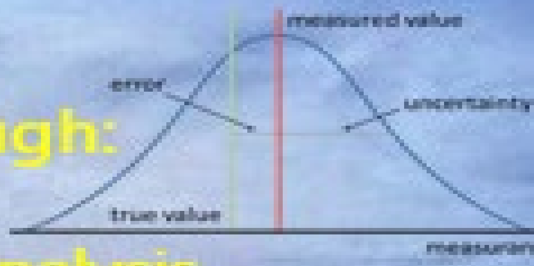




Achieved through:

- Traceability
- Uncertainty Analysis
- Comparison

All documented and accessible



CEOS QA4EO A QUALITY ASSURANCE FRAMEWORK FOR EARTH OBSERVATION

Interoperable observing system

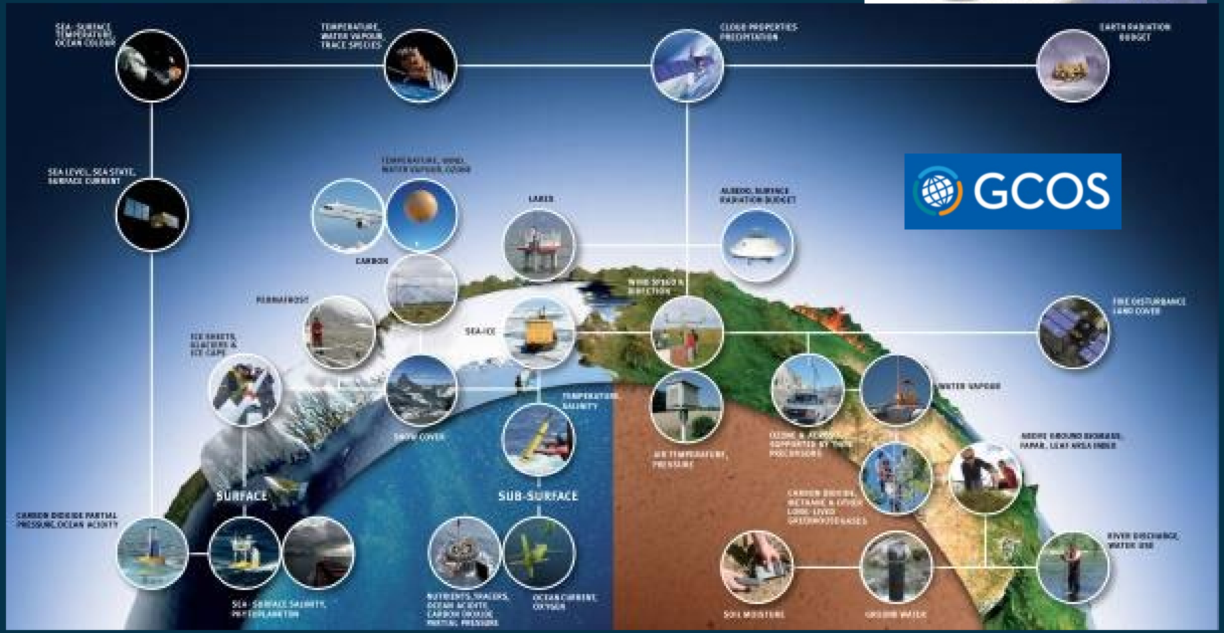
GROUP ON EARTH OBSERVATIONS

CEOS

WMO

GSICS Global Space-based Inter-Calibration System

QA4EO



New Space!

Maximise utility of data

>60% of ECVs requires space observations (TRUTHS supports ~>1/2 of these)

Satellites can suffer biases and degradation in performance due to launch and harshness of space.

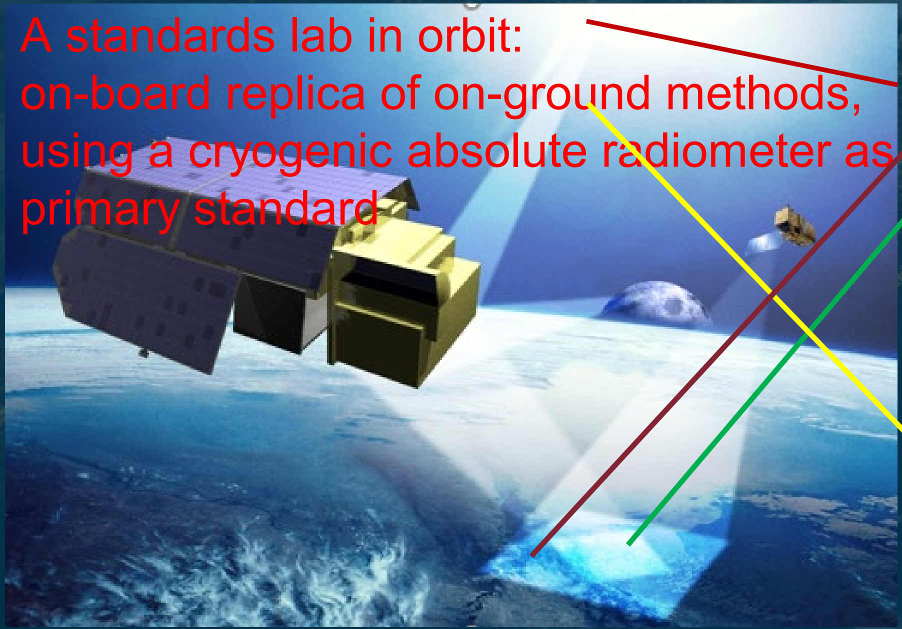
SITSats such as TRUTHS/CPF can help enable a new epoch for space-based Earth Observation

SITSats and TRUTHS Mission Objectives

*What is a SITSat?: 'Space borne missions specifically designed, characterised and documented to provide **high accuracy SI-Traceable** 'reference' measurements.' (Evidencing comprehensive uncertainty to SI, 'in-space', of all contributors to observations made from the satellite)*

TRUTHS is an **operational climate mission**, aiming to:`

A standards lab in orbit:
on-board replica of on-ground methods, using a cryogenic absolute radiometer as primary standard



1. **Climate benchmarking:** enhance our ability to estimate the **Earth Radiation Budget** (and attributions) through direct measurements of incoming & outgoing energy and reference calibration of other ERB & similar missions.
2. **Satellite cross-calibration:** establish a 'standards laboratory in space' to create a '**gold standard'** reference data set to cross-calibrate other sensors and improve the quality and interoperability of their data throught: simultaneous observations, surface reference sites and the moon
3. provide SI-traceable measurements of the **solar spectrum (incoming & reflected)** to address its impact on climate and interactions with the atmosphere and surface

*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.*

What does TRUTHS do?

Measures incoming and earth reflected radiation from the sun
- 320 to 2400 nm @ ~4 nm intervals (1 nm for solar UV)
- Global nadir @ 50 m ground resolution with 100 km swath (capability)
- Target uncertainty of 0.3% (k=2)

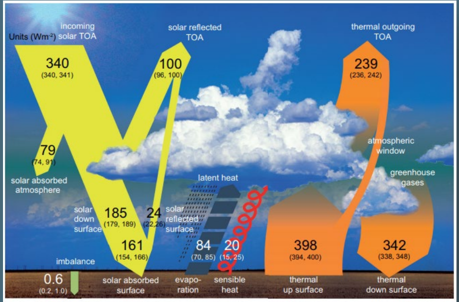
Establishing a benchmark of the radiation state of the planet at ToA (radiance/reflectance) & BoA surf reflectance to help enable:

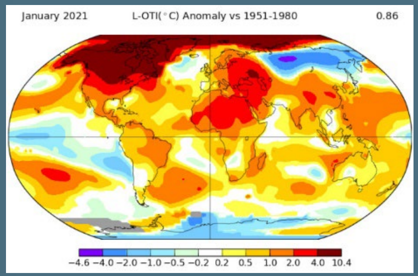
Observations
- Benchmark
- monitoring
- Litigation
- algorithm improvement

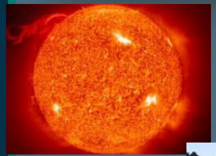
Calibration
- Interoperability
- data-gaps
- performance
- Utility

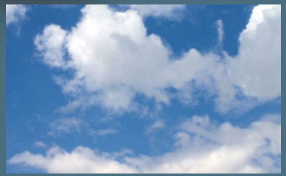
Climate action: Supporting 'Net Zero'

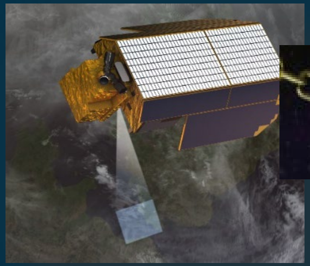
Climate sensitivity/response

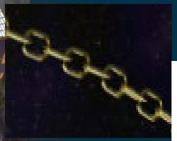






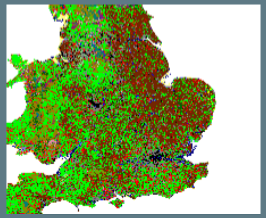


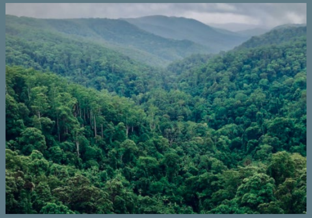




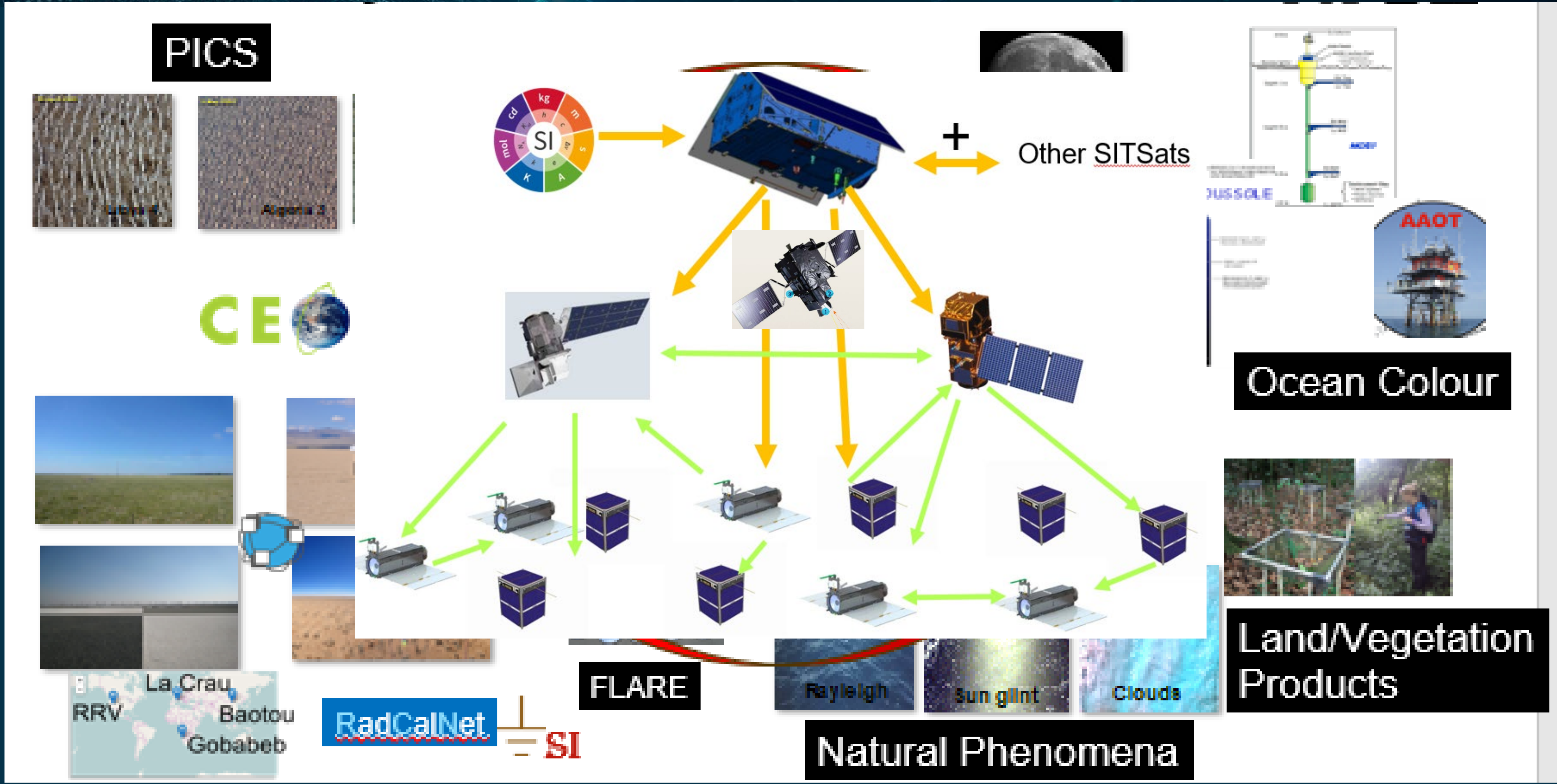
Adaptation/sustainability

Climate action/mitigation



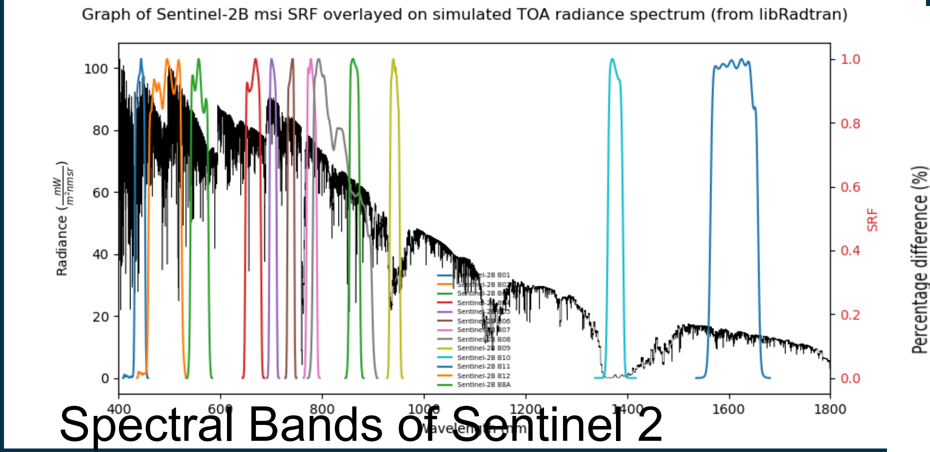


SI-Traceability to Cal/Val infrastructure

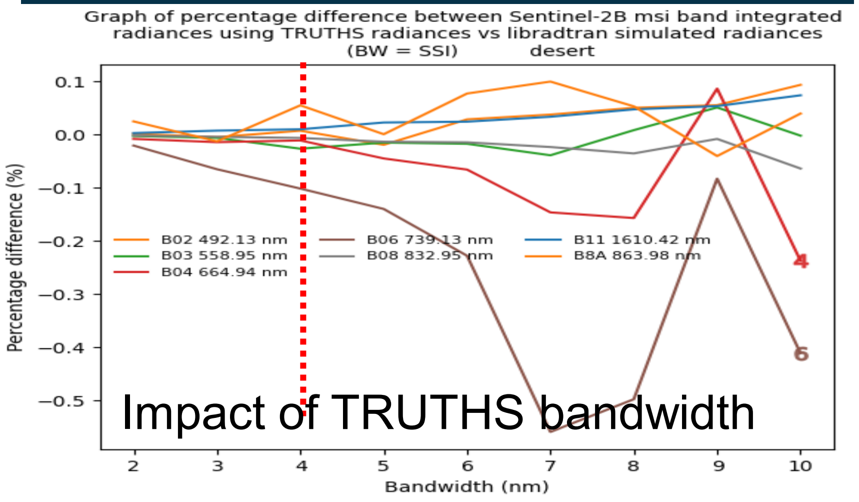


Transferring TRUTHS accuracy to other Sensors: establishing mission requirements (S2S calibration

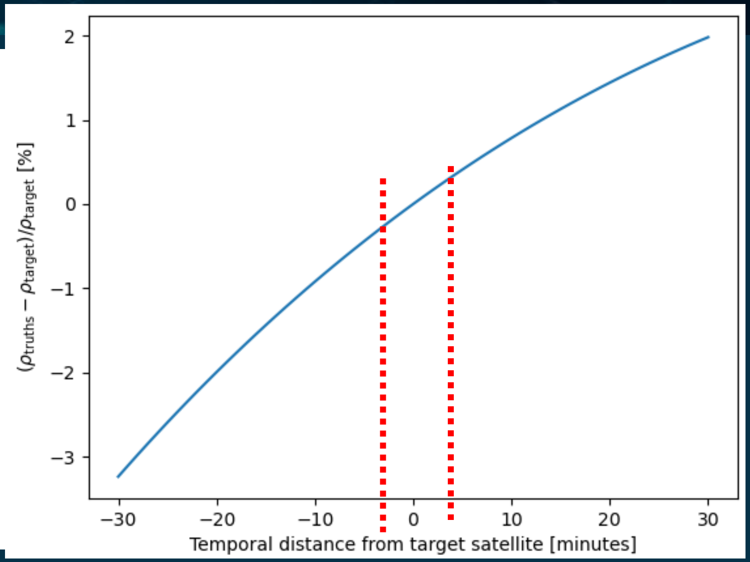
(Fahy, Hunt, Stedman, Gorrono)

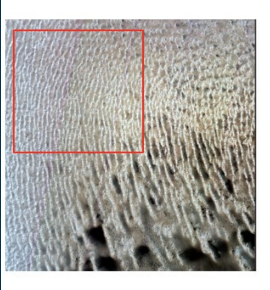


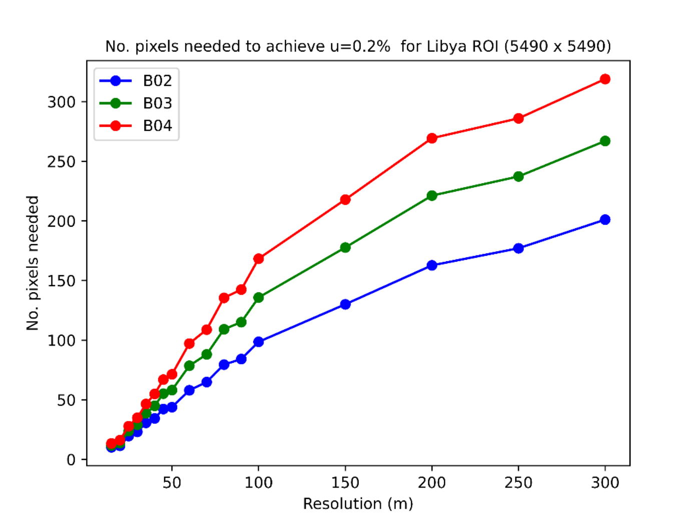
Spectral Bands of Sentinel 2



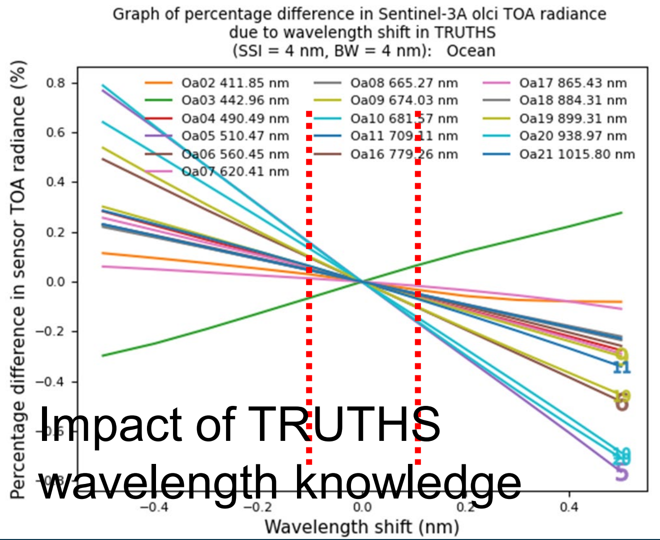
Impact of TRUTHS bandwidth



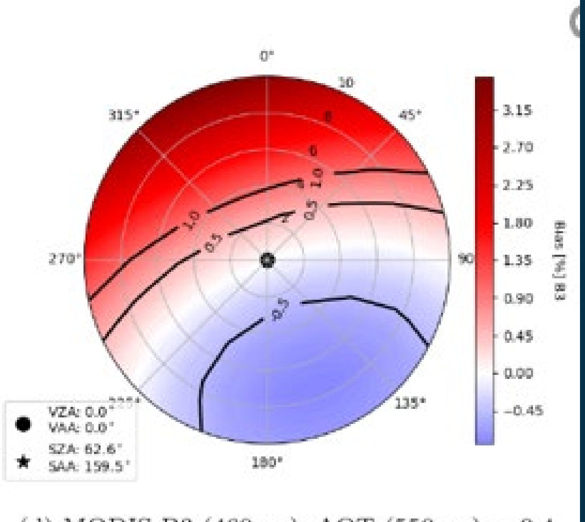




Uniformity of Cal Target (Libya 4) area to be sampled (2.5 km to achieve 0.2% @ 50 m)



Impact of TRUTHS wavelength knowledge

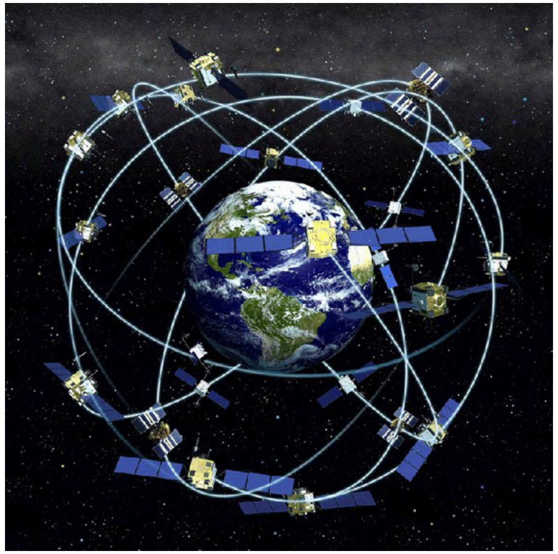


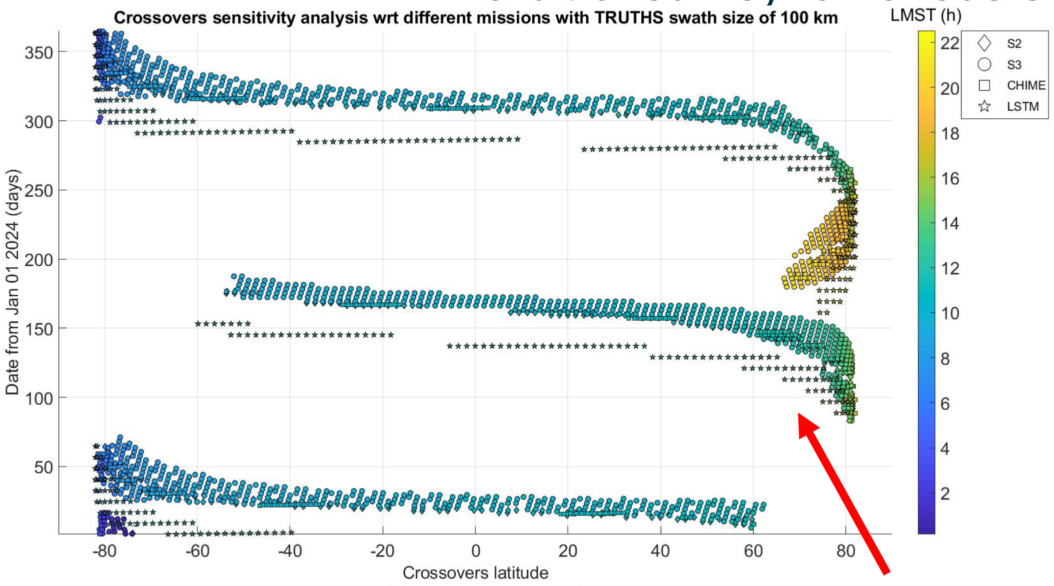
(d) MODIS B3 (460nm); AOT (550nm) = 0.4

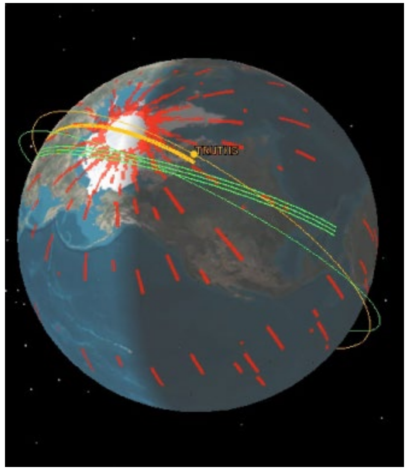
Reference Calibration

- **Enables interoperability & Harmonisation**
  - **Prospect of 'certified calibration'**

TRUTHS 90°pole to pole orbit, observing through the diurnal cycle, allows many opportunities to overpass orbit of sun-synchronous sensors







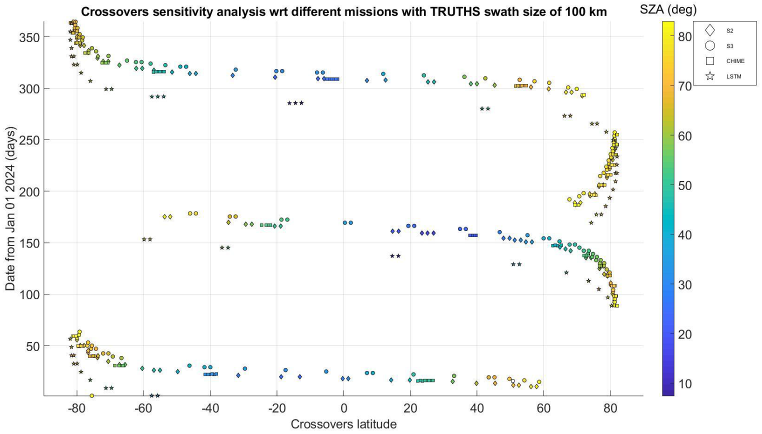
TRUTHS provides the means to transform global EO system, including constellations of micro-sats so they deliver traceable scientific/climate quality observations -

<30 s time difference Swath overlap

1 year of near perfect nadir overlaps for TRUTHS & satellite under test

(<1° (no pointing) <30 s time difference

Summary after 6 months



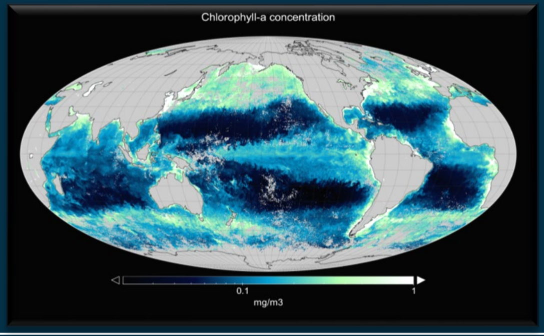
Uncertainty budget for TRUTHS – satellite comparisons (Gorrono et al)

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 %**

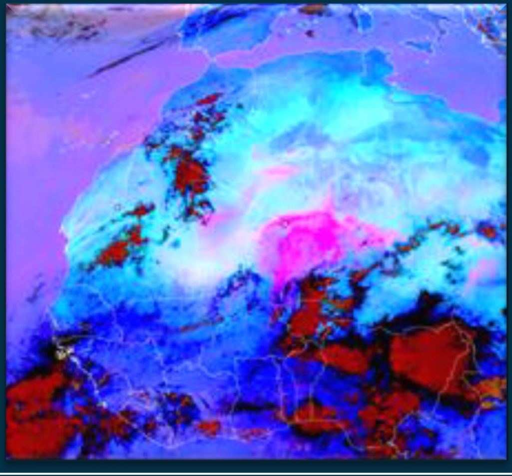
TRUTHS: Underpinning operational ECV retrievals for climate monitoring, data set harmonisation, data-gap risk mitgation and model improvement

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 …..

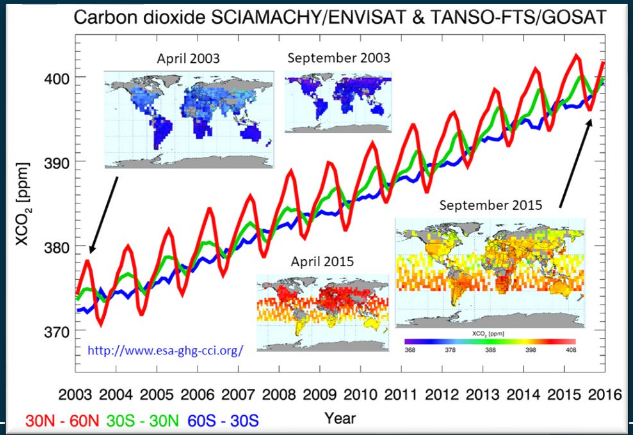
- **Ocean colour:** direct TOA cross-calibration of sensors to absolute radiometric accuracy of ~0.5%, meeting GCOS requirements – global 200 m observations but poor temporal coverage



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



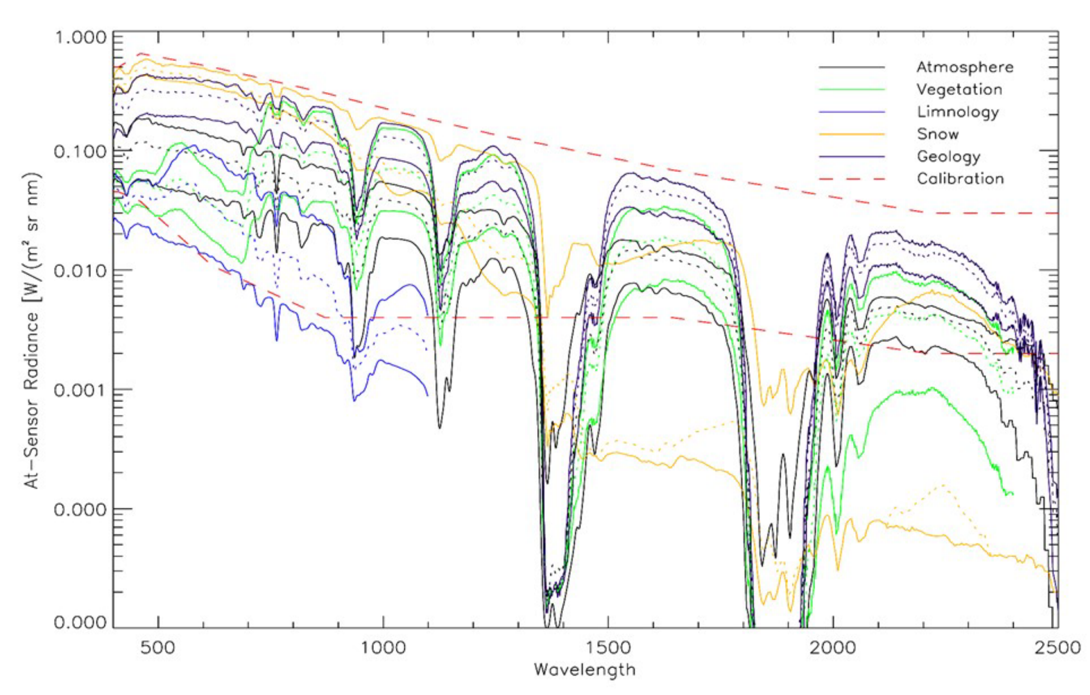
- **GHG:** Referencing Copernicus and multi-agency CO_2 constellations at 0.5-1.0% radiometry through cross-calibration. Large scale GHG emissions detection



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

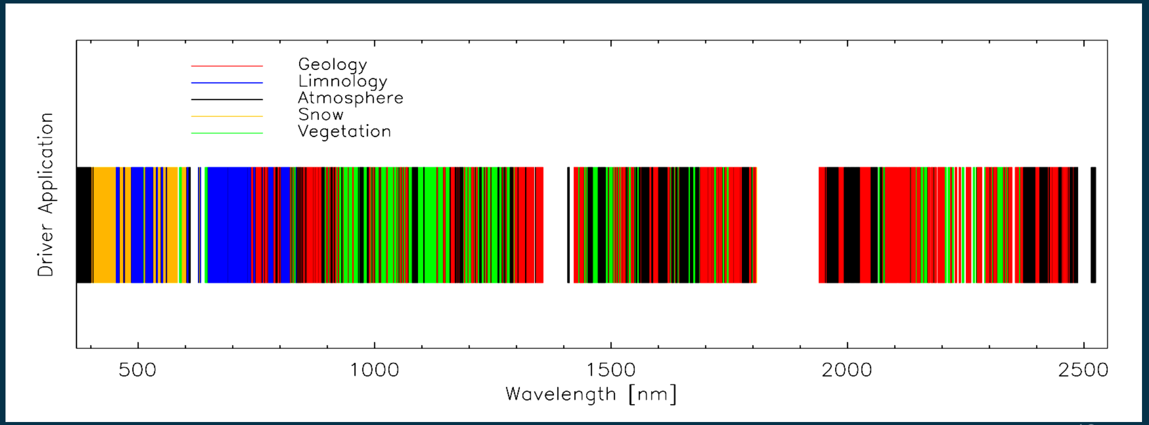
Hyperspectral data can be convolved for many applications enabling an earth system science approach (not temporally critical applications (61 day repeat)

- **Directly**
- **Upgrading other sensors**
- **Test & Improve retrieval algorithms**
- **Validation establishing references surface reflectance e.g. Fluxnet**



Complementary to EnMAP, PRISMA, CHIME, SBG ….

- Land-cover change
- Forest
- Surface Albedo
- Agriculture
- Pollution
- Resource prospecting
- …….



System Drivers: 90 deg precessing 61 day, ~605 km polar orbit for satellite cross-cal & for uniform diurnal sampling for Climate benchmark

esa

Driving requirements in Red

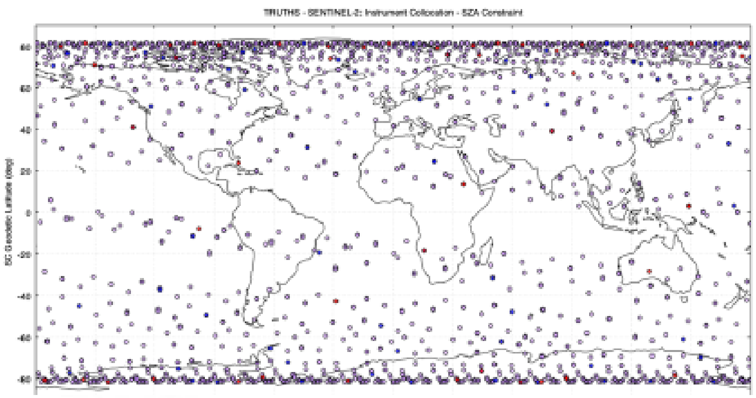
Climate 'Benchmark'

Earth Observation

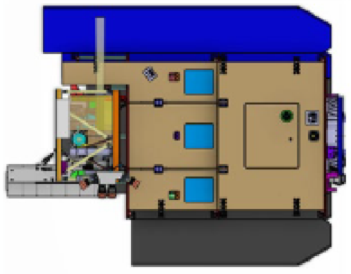
Level 1/2	Mission Requirement					
Application	Spectral range (nm)	Spectral Resolution (SSI) (nm)	Uncertainty (%) (k=2) G	Uncertainty (%) (k=2) T	SNR @ sensor SSI & 50 m	GIFOV
Earth spectral radiance (Climate)	350-2200 320-350 2200-2400	<10 – 20 nm	0.3 <1.0	<1.0 <3.0	>~20 @0.3 albedo >15	<300 m (scene ID) 10 - 100 km gridded
Solar Spectral Irradiance	<320 – 2400	<1 (<400), <5 (<1000) <10 (<2400)	0.3	<1.0	>1000 (time integration)	NA
Total Solar Irradiance	200-30000	NA	<0.02	<0.05	>10000 (time integration)	NA
Climate Sensor Cal/Val	320-350 350-800 800-2400	<20 <4 <6-8	0.3	1.0	>15 @0.3 albedo (large footprints)	<300 m-~1000 m(UV)
Earth sensor (Cal/Val)	<380 ~2400	<4 (< 1000 nm) <8 (>1000 nm)	<1.0	<2.0	>100 @ 0.4 albedo	<50 - 100
Ocean Colour	<350 -1000	<10 - 20 <4 Cal	<0.5	<2.0	>25 @~0.1 albedo (<400 nm) >50 (400 – 490 nm) >40 (>490 nm)	<300 m Cal/Coastal <~1000 m for Ocean
Land Surface Imaging	~380-1000 1000-2400	<10-20 <20	<1 <2	<2	>100 @0.3 albedo >60	<50-100 m
Atmosphere	400 - 2400	<5 - 10	1	2	>100	<100 – 1000
Lunar Irradiance	350 – 380 380 - 2400	<~20-30 <~10-20	0.3	1	>1000 (time averaged)	NA

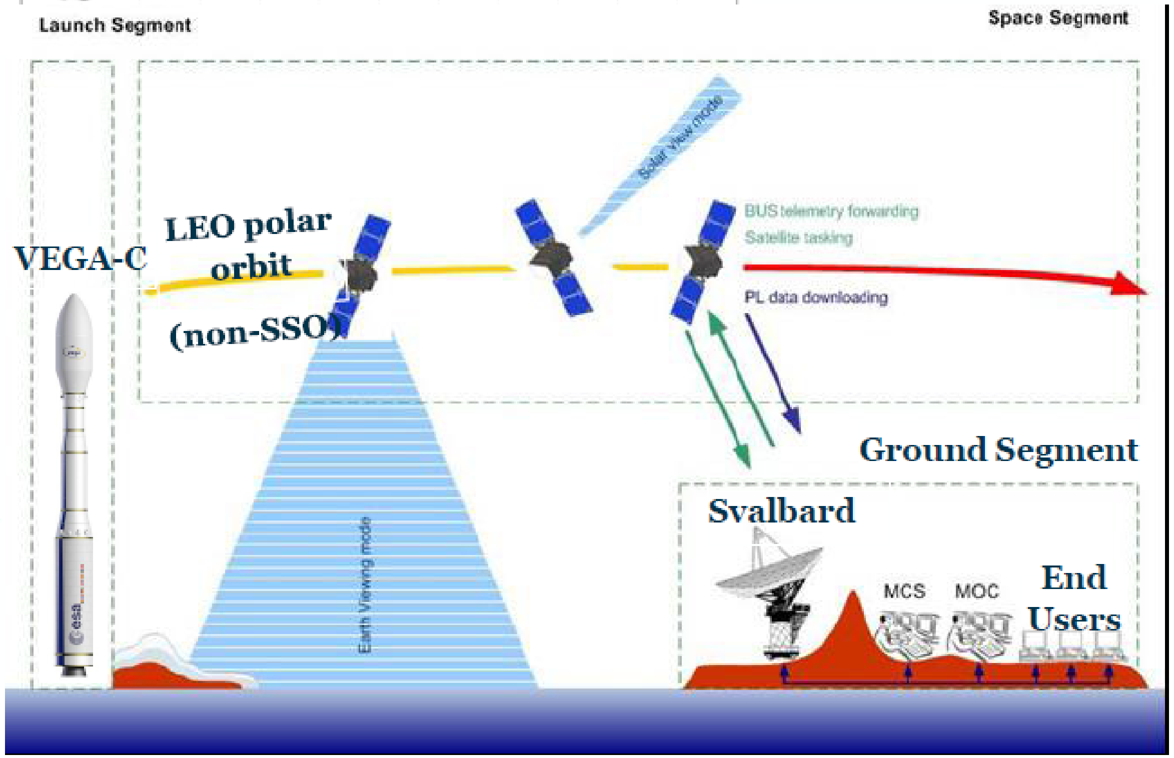
System Architecture

- Lifetime 5 years + 3 extension
- Space Segment:
  - Orbit 614 km, polar (90º) non-SSO
  - 1 satellite – agile, design for non-SSO
  - Novel Payload
- Launch Segment:
  - Vega-C (-E) single launch
  - Option co-passenger explored
- Ground Segment
  - 1 polar station baselined, lossless compression baselined
  - LEOP/early commissioning @ ESOC
  - Routine FOS in UK (Flight control center hand-over before IOCR)
  - PDGS in UK + data access at ESRIN (ESA open data access policy)

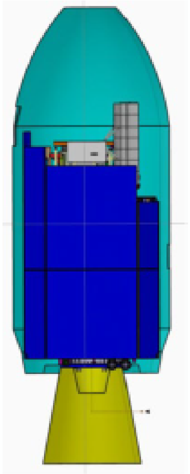


Space Segment





Launch Segment



Payload Overview

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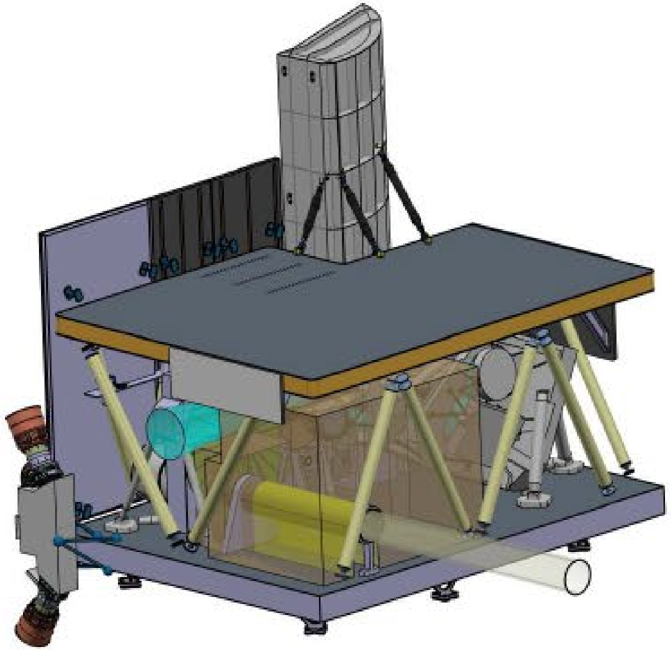
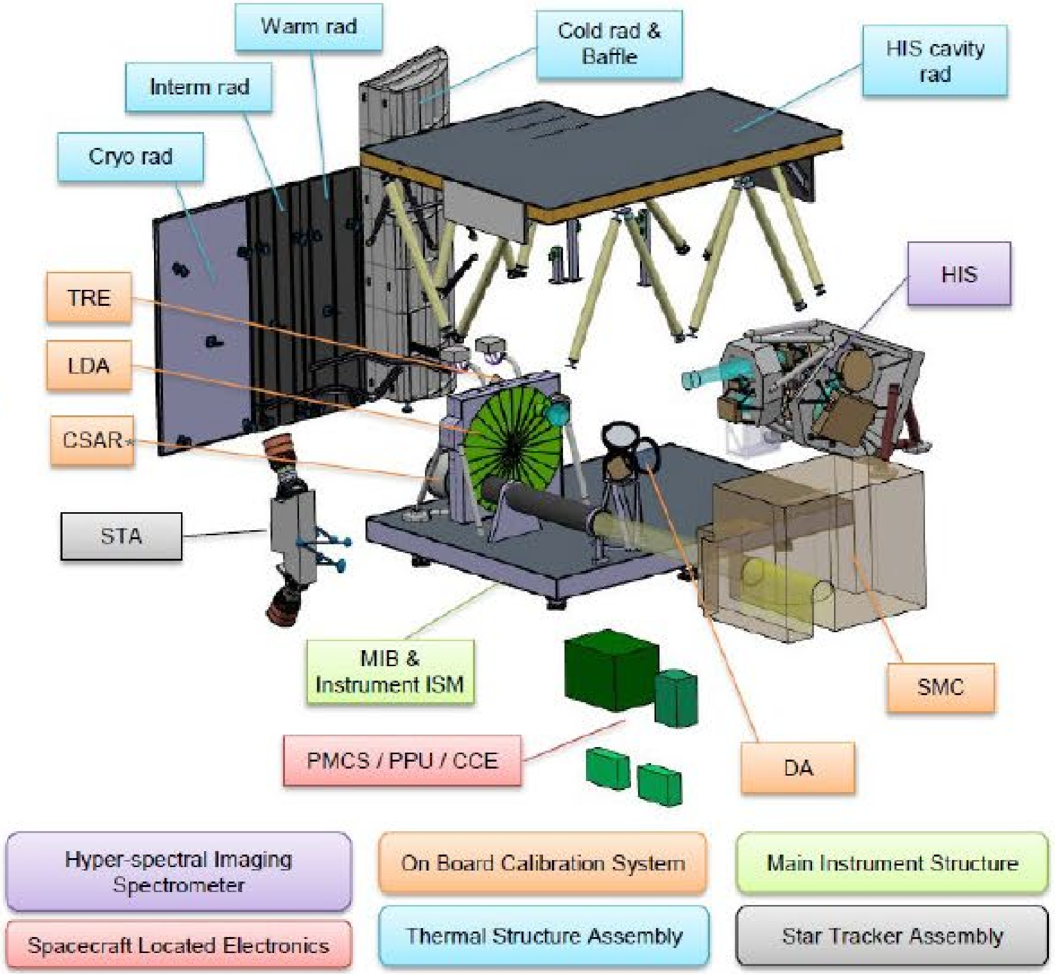
Payload, composed of three elements:

- **HIS (**Hyperspectral Imaging Spectrometer) –
  UV to SWIR (320-2400 nm), single detector, 50 m resolution, 100 km swath. Detector cooled at 150 K passively
- **CSAR** (Cryogenic Solar Absolute Radiometer) –
  operated at 60 K (cryocooler*), the "primary standard"
- **OBCS** (On-Board Calibration System) –
  transferring the CSAR solar absolute (SI) measurement to the HIS

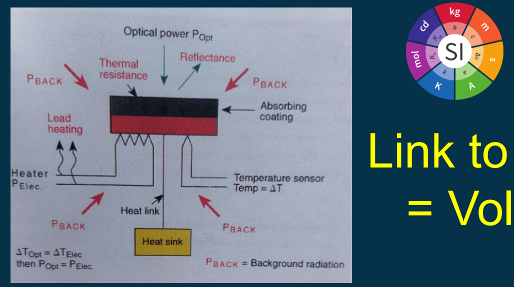


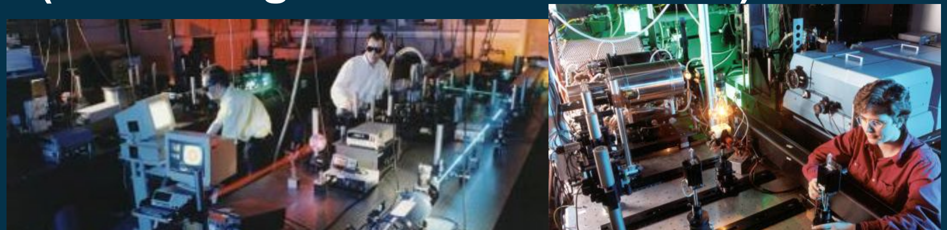


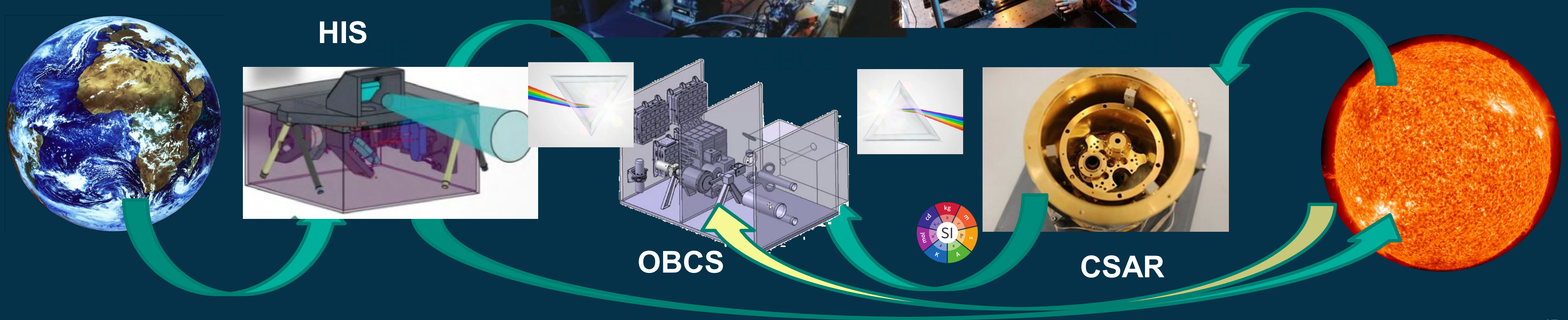
**Cryo-cooler Assembly – recurrent from THRISHNA mission at ISRR baseline*

Metrology laboratory in-space

- Measuring energy from the sun, providing the direct traceability to International Standards (CSAR)
  - Compares heating effect of optical power with electrical power (Volt)
- ‘Camera’ (Hyperspectral Imaging Spectrometer, HIS) observing the direct incoming and Earth reflected sunlight at high spectral and spatial resolution
- Novel on-board calibration system (OBCS) ensuring traceability to the absolute reference (Cryogenic, 60K, Solar Absolute Radiometer, CSAR)   (mimicking terrestrial methods)

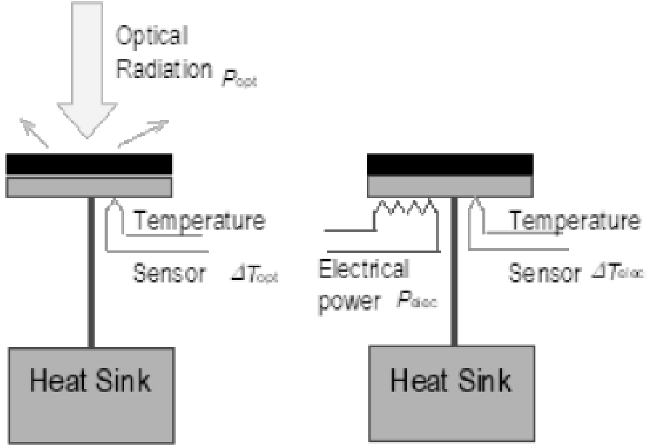


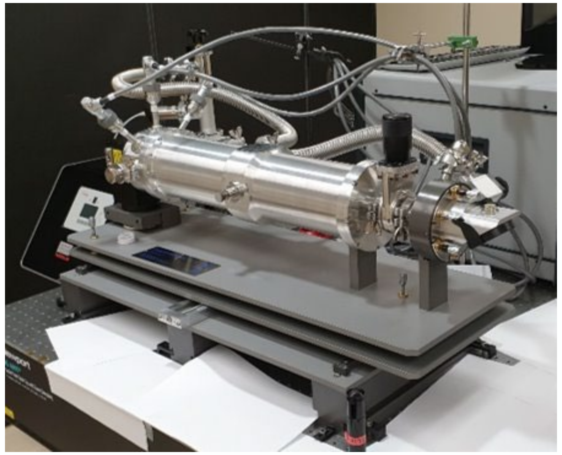


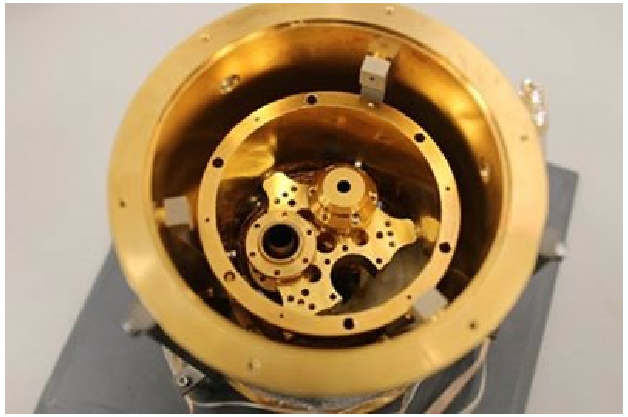


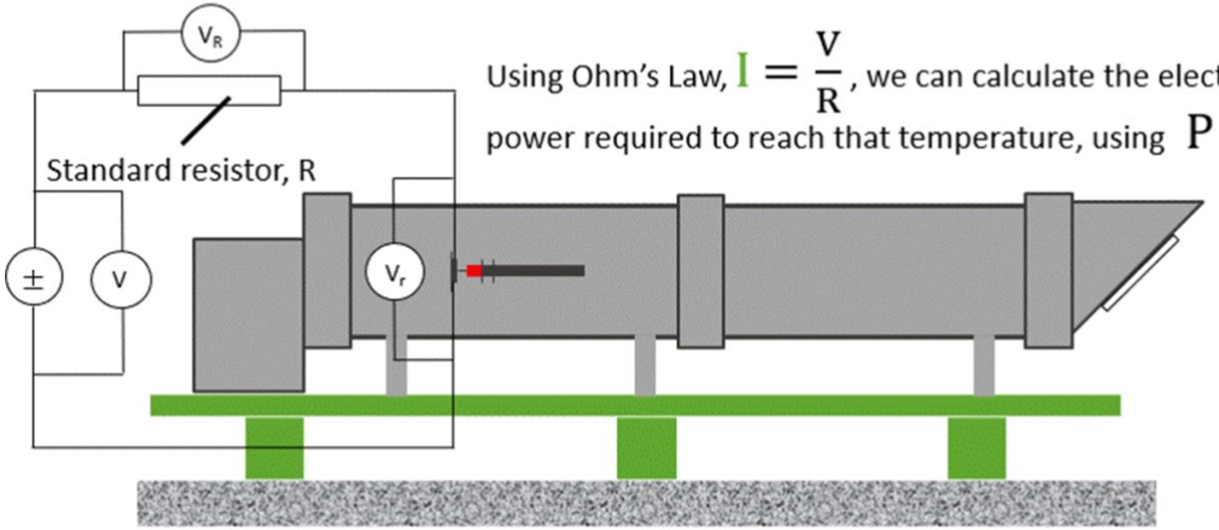
In-Orbit Primary Standard – CSAR: (RD01, Rev 36)

- Cryogenic Solar Absolute Radiometer (CSAR)
- Evolution of the terrestrial cryogenic radiometer used for four decades in NMIs
- Electrical substitution method (equivalence in optical and electrical heating of a cavity) (>120 yrs of use)
- Traceable to electrical standards - V & Ω
- Performance limited to cavity absorptance (>0.99995)
- Stability of Voltage Ref









TRUTHS on-orbit calibration philosophy: (Rev 36)

1. **CSAR measures optical power in SMC output then calibrates TR**

SMC generates beam of 'monochromatic radiation from sun which can be distributed to different parts of the calibration system

2. **The transfer radiometer (TR) serves two purposes**

Conversion from power to radiance

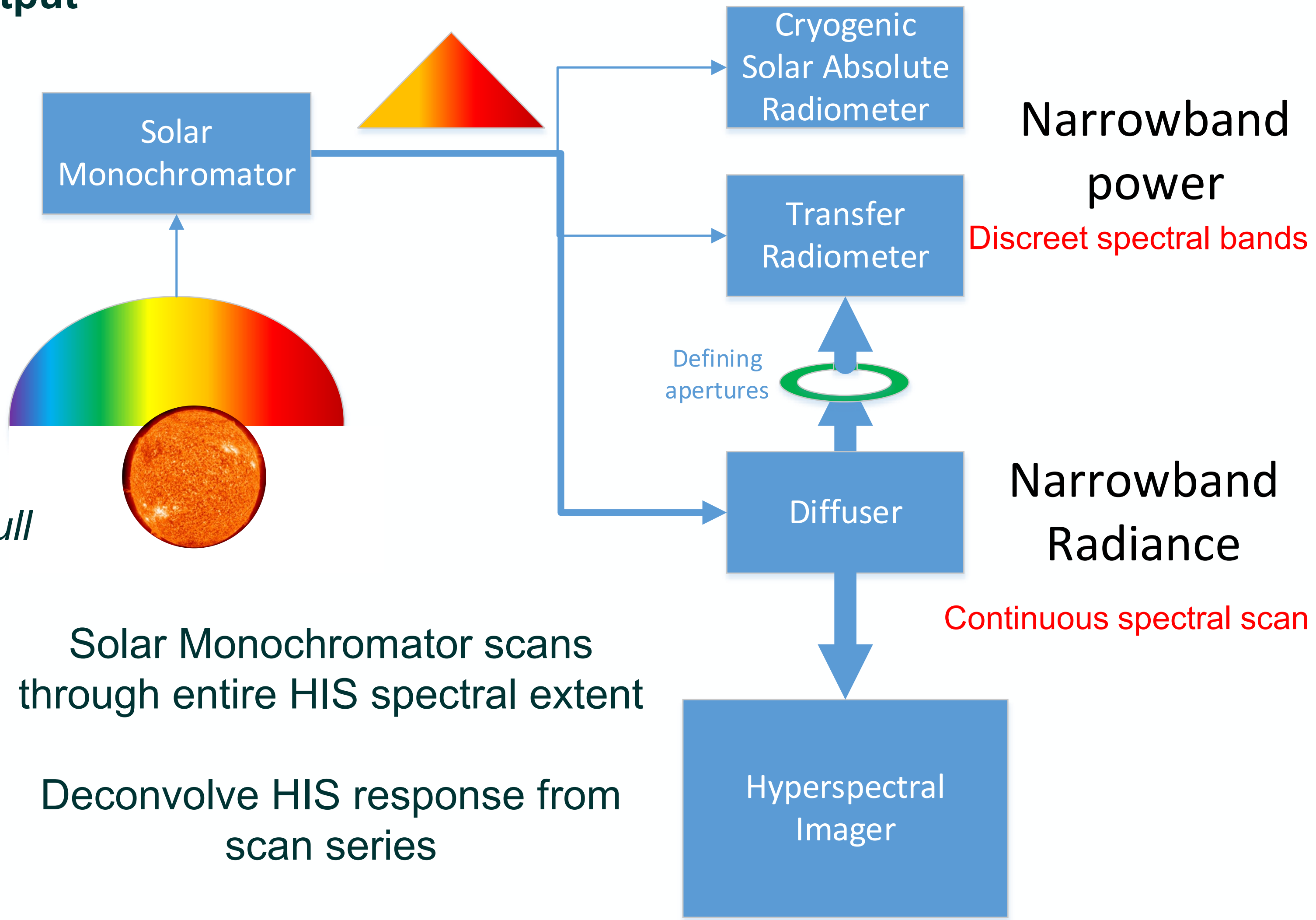
Intermediate 'fast' radiance reference allowing full spectral calibration of HIS

3. **Concept of Operations based on**

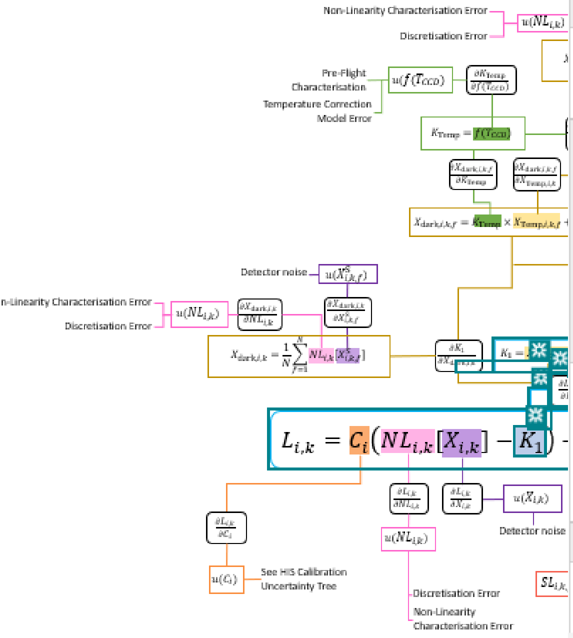
geometric knowledge & stability,

Calibrating out in-flight degradation

only repeatability assumptions based on mechanical and thermal control.



Open access data with full transparency of uncertainties and traceability – a ‘metrology lab in space’



CSAR power correction						
Name of effect		Cavity temperature characterisation error (Shuttered)	Cavity temperature characterisation error (open)	Sensor reference resistor voltage fluctuation error	Reference resistor characterisation error	Cavity sensitivity characterisation error
Affected term in measurement function		$T_{cav,c}$	$T_{cav,i}$	$V_{r\_cav,i}$	$R_{r\_h\_cav}$	S_{cav}
Image error-correlation type, form and scale	Across track (k)	Systematic	Systematic	Random	Systematic	Systematic
	Along track (f)	Systematic	Systematic	Systematic	Systematic	Systematic
	Between spectral pixels (i)	Systematic	Systematic	Systematic	Systematic	Systematic
Uncertainty	PDF shape	Rectangular	Rectangular	Gaussian	Rectangular	Rectangular
	units	K	K	V	Ω	KV^{-1}
	magnitude	TBD	TBD	TBD	TBD	TBD
Source						
Sensitivity coefficient		$\frac{\partial L_{i,k}}{\partial T_{cav,c}}$	$\frac{\partial L_{i,k}}{\partial T_{cav,i}}$	$\frac{\partial L_{i,k}}{\partial V_{r\_cav,i}}$	$\frac{\partial L_{i,k}}{\partial R_{r\_h\_cav}}$	$\frac{\partial L_{i,k}}{\partial S_{cav}}$

Fahy & Hunt

TRUTHS HIS Earth Radiance Uncertainty Tree

‘effects table’ for each error source

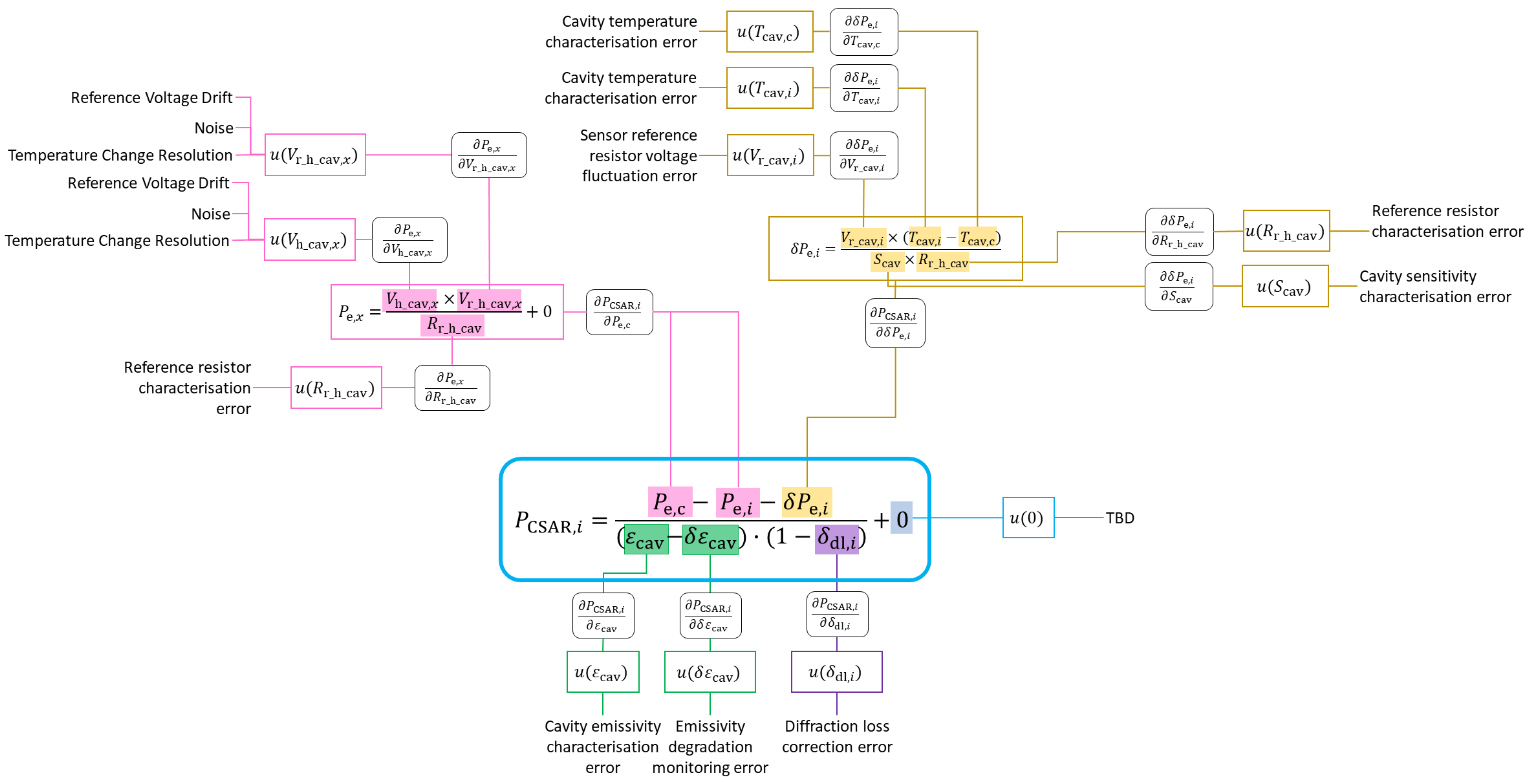
Fiduceo like analysis of end to end traceability and uncertainties – an exemplar for other missions

- **Upto ~4 Tbytes a day download**
- **UK ‘Data processing hub’**
- **Baseline ‘archived’ Level 1B products**
  - **ToA Earth, Moon, Sun**
- **Toolbox to enable customisable ‘on-demand’ processing of Level 1B, 1C and 2 (BoA reflectance) with pixel level uncertainties**
- **Coefficients to facilitate sensor SI-traceability and/or recalibration**
- **Unequivocal litigation quality data**

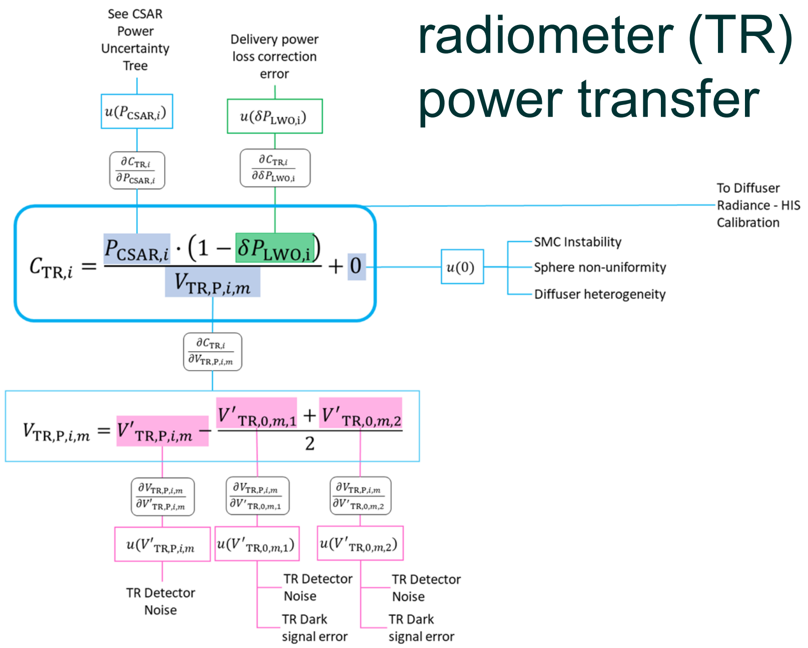
Application of metrological principles: (RD04, Rev33,36)

Establish measurement equation and errors sources together with associated uncertainties for the end to end measurement. Subdivided into modules for convenience. This allows to define critical paths and contributors including pre-and on-board calibration and characterisation and ultimately basis for coding as simulator

CSAR power calibration



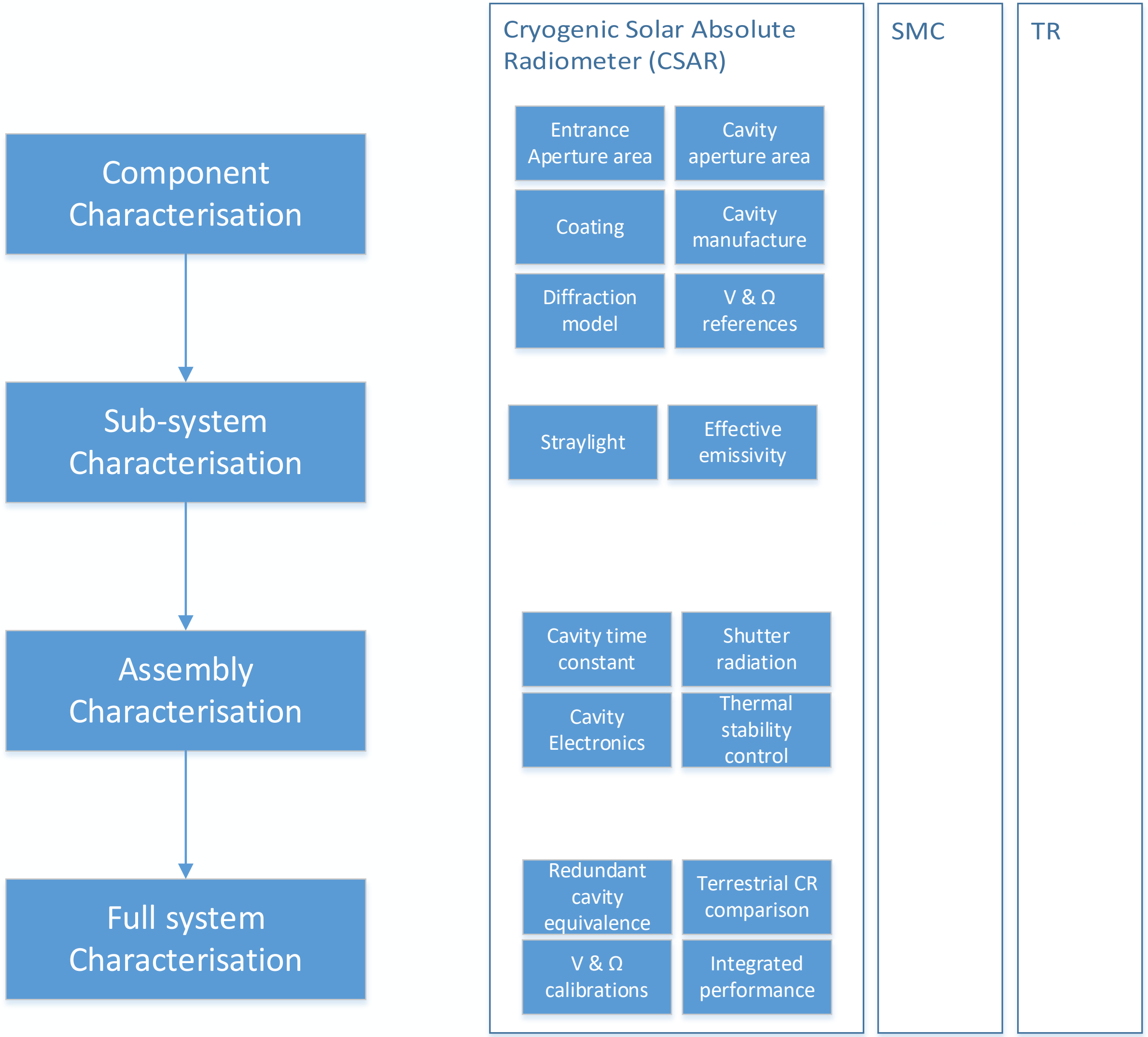
Transfer radiometer (TR) power transfer



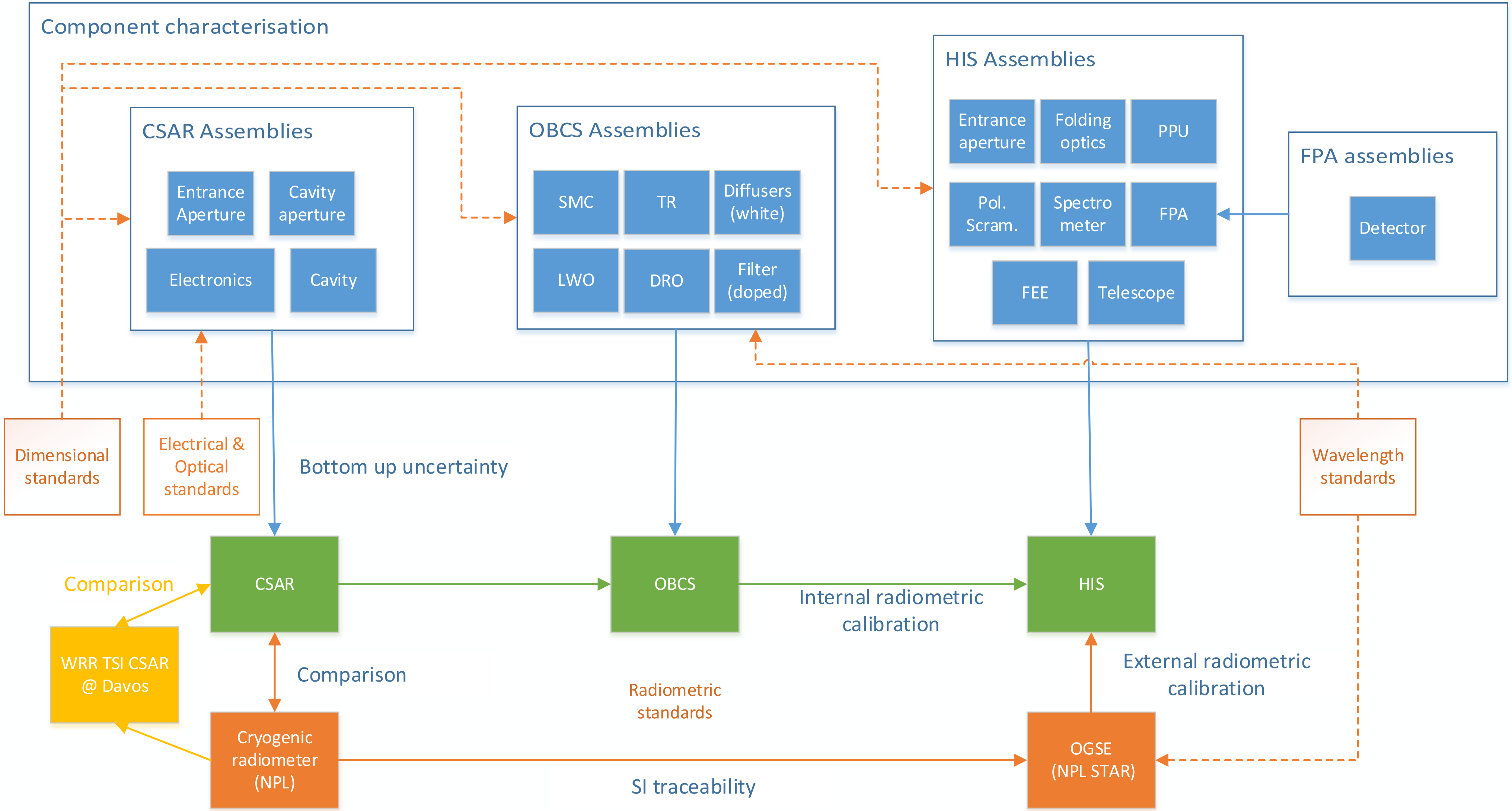
Pre-flight calibration & characterisation philosophy

Objective: to confirm design/build specification and to facilitate comparison with Terrestrial SI-standards

- Tiered hierarchy of characterizations and calibrations
- Mirrors the uncertainty budget bottom-up approach
- Includes algorithm approach and concept of operations assumptions.

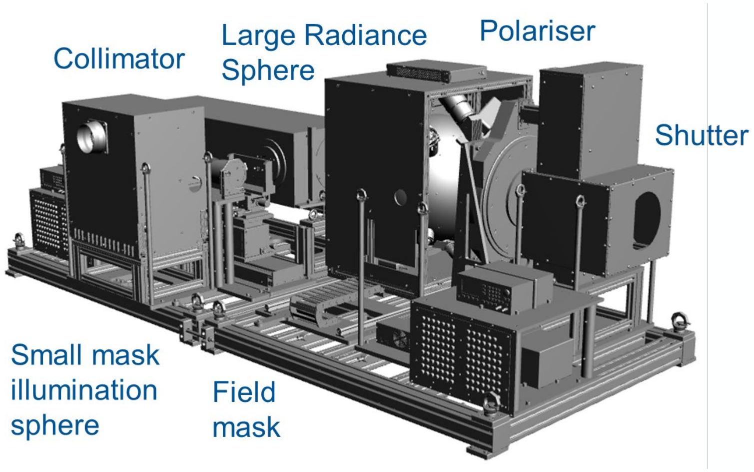


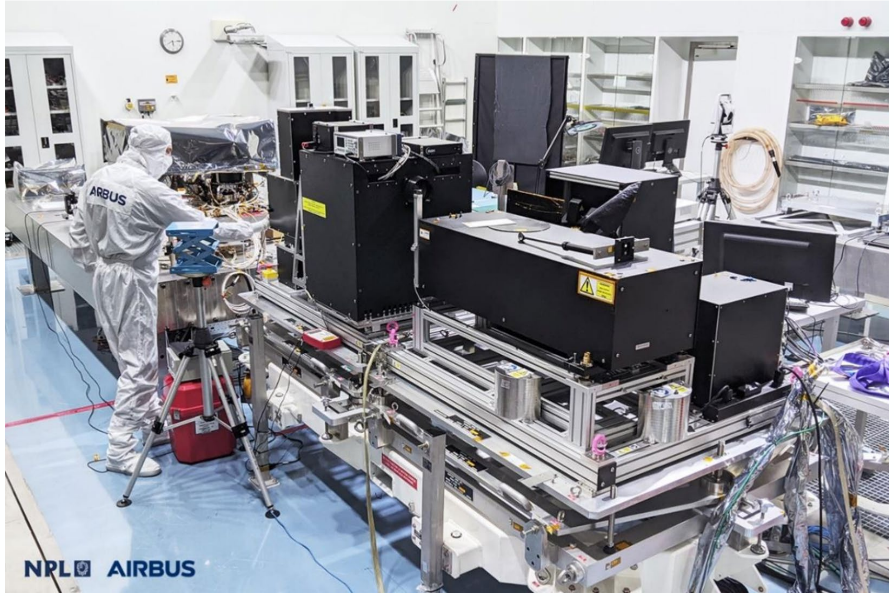
Pre-flight radiometric calibration philosophy



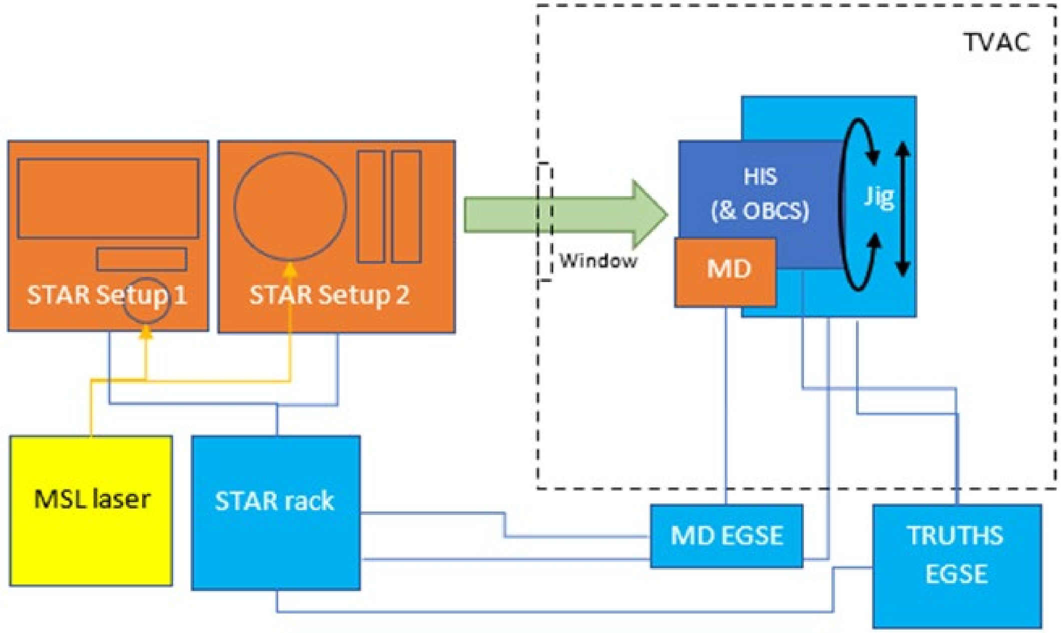
STAR-CC-OGSE Overview:

- STAR-CC-OGSE provides radiometric calibration and characterization of satellite sensors.
- Fully automated and SI-Traceable
- The main components of the STAR-CC-OGSE system are:
  - A collimated beam source, with field mask for optical performance (geometric) characterization & 200 mm diameter exit port ntegrating sphere for flat-field radiometric calibration.
  - A CW laser allowing monochromatic continuous tuneability from 260 nm to 2700 nm with a broadband (white light) source extending over the same spectral extent (for both illuminations).
  - A vacuum-compatible SI-traceable radiance detector module containing both broadband photodiodes & a spectrometer, installable in TVAC at the sensor-under-test entrance aperture





Terrestrial HIS pre-flight calibration



Spectral calibration

- Monochromatic via tuneable laser traceable via high accuracy wavemeter to the metre & frequency standard.
- Simultaneous measurement of spectral straylight and ISRF etc.

Radiometric calibration

- State-of-the-art following philosophy employed by NMIs for thermodynamic temperature determination (0.03%,)
- here <0.2% (k=2)

			Si		InGaAs	
Symbol	Source of Uncertainty	Probability Distribution	Value	ui	Value	ui
uAbs	Photodiode Absolute Calibration	Normal	0.05%	0.05%	0.05%	0.05%
uRel	Photodiode Spectral Response Calibration	Normal	0.08%	0.08%	0.10%	0.10%
uSp	Spectrometer	Uniform	0.05%	0.03%	0.05%	0.03%
UC	Combined Uncertainty (k=1)			0.10%		0.11%
U95	Expanded Undertainty (k=2)			0.19%		0.23%
	Photodiode Abs + Rel only (k=1)			0.09%		0.11%
	Photodiode Abs + Rel only (k=2)			0.19%		0.22%

On-orbit spectral calibration: critical for S2S cal:

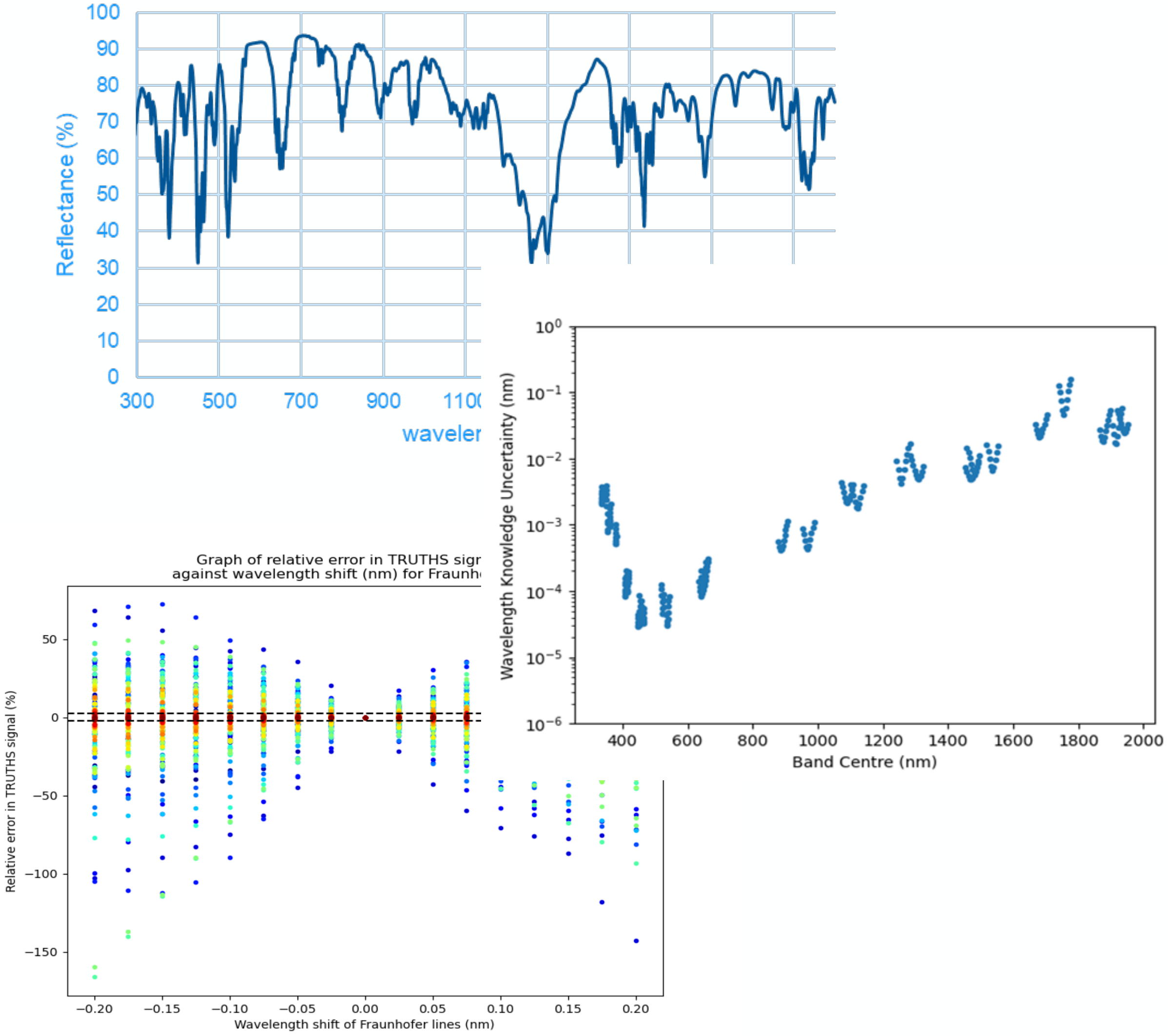
Fraunhofer lines

- 33 identified lines/groups
- 300 nm - 900 nm
- Use Solar spectral irradiance observation – few seconds
- <0.025 nm accuracy est.

Onboard Rare-earth oxide doped filter reference

- Features over 300 – 1950 nm
- Solar illuminated convolved with Fraunhofer lines, but feature width allows reliable determination.
- <0.1 nm accuracy est.

Overlap region adds confidence.

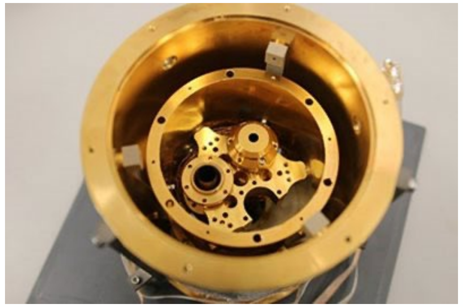


TRUTHS: SI-Traceability summary

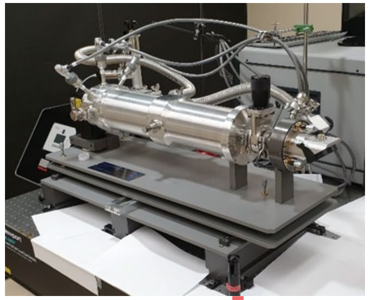
In-flight (space)

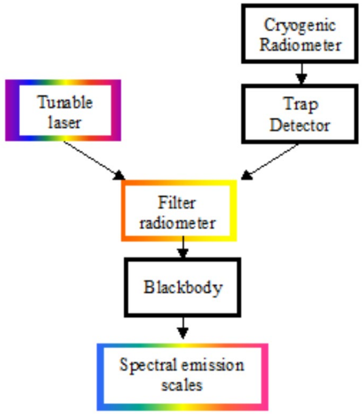
Pre-flight (Ground)

CSAR



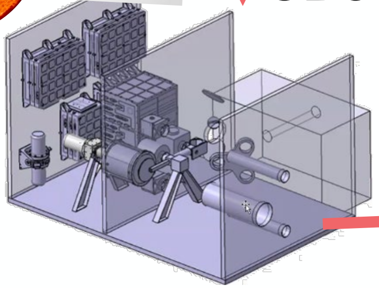
Cryogenic Radiometer (Lab)



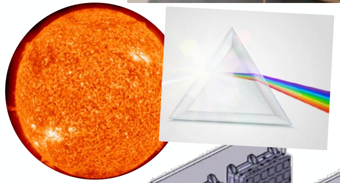


COMPARISON

OBCS

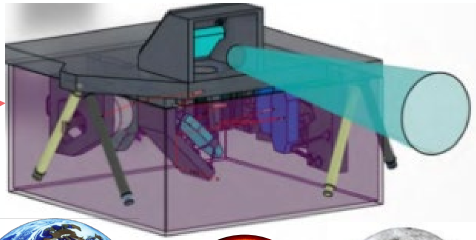


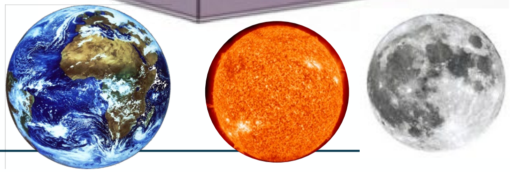
Solar with SMC

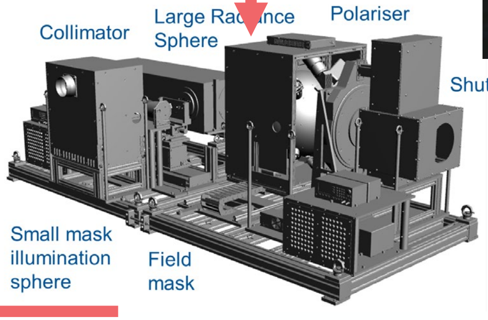


Laser radiation

HIS







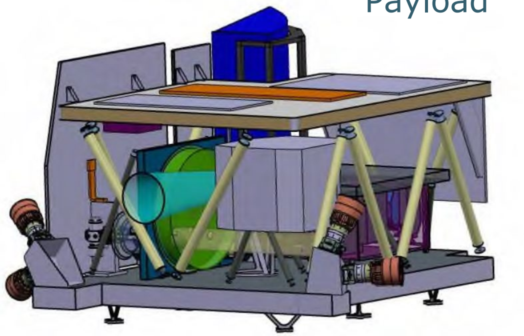
STAR

Completing Phase A/B1 to provide a mature concept

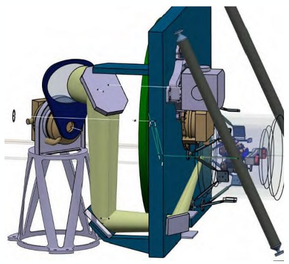
- Agile Platform recurrent from **CRISTAL**
- Payload key technical features:
  - ✓ **HIS:** Four-mirror anastigmatic telescope, Offner (two-prisms) spectrometer, single MCT detector at 150 K, thermally stable optical bench.
  - ✓ **CSAR**– three high-absorbance cavities, operated at 60 K with cryocooler, design heritage of NPL (UK) and PMOD/WRC (CH)
  - ✓ **OBCS** (On-Board Calibration System) – traceable set of absolute wavelength anchors (solar monochromator + TBD filter), high-dynamic transfer radiometer, precise and stable wavelength scanning mechanism, relay optics, diffuser to HIS
  - ✓ **Calibration process:** novel methodology, heritage of metrology lab (NPL), rigorous traceability of uncertainties, need for demanding on-ground calibration
- Pre-developments running for all critical items (detector, coating, CSAR, mirror, calibration detectors…)
- Phase A/B1 led by Airbus UK completed Mid June.
- Gate review (July 22) confirmed technical, scientific and programmatic maturity of the proposed solution ready for subscription in CM 22

TRUTHS satellite

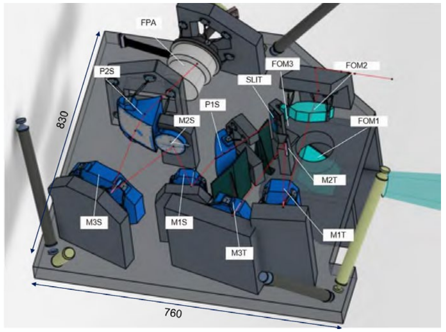
TRUTHS Payload



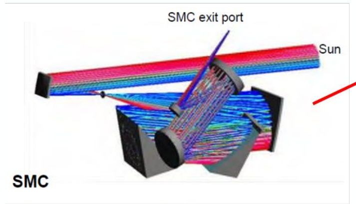
CSAR layout/OBCS I/F

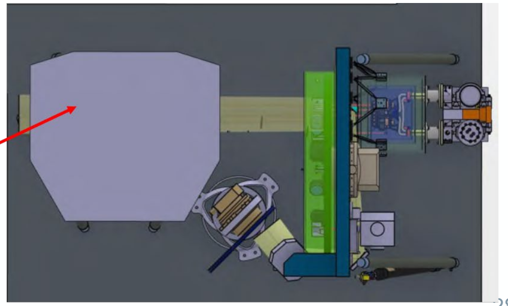


HIS layout



SMC - OBCS layout

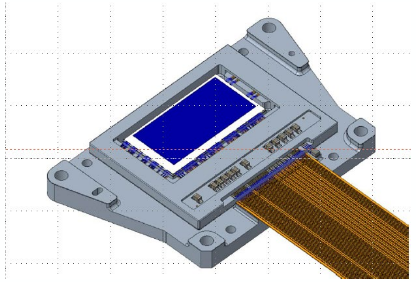




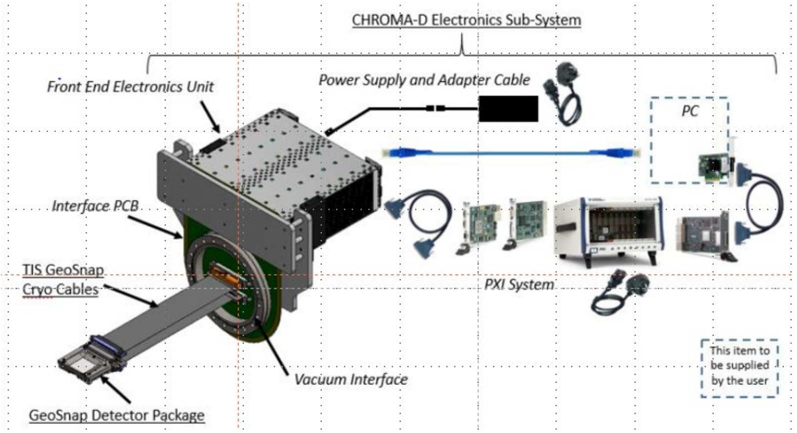
All images courtesy of Airbus, PMOD, NPL

TRUTHS technology gallery

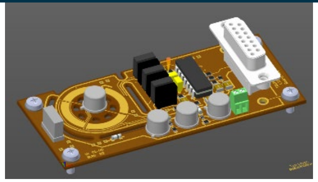
T-E2V Detector layout and FEE test assembly

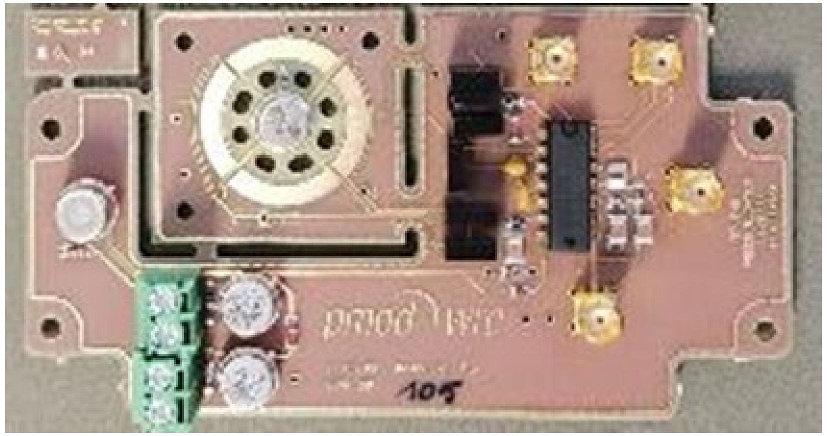


1K X 2K CMT array

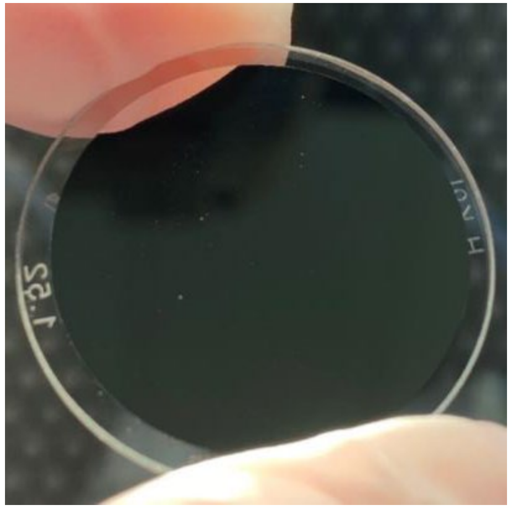


CSAR Voltage Ref: LTZ1000 Board

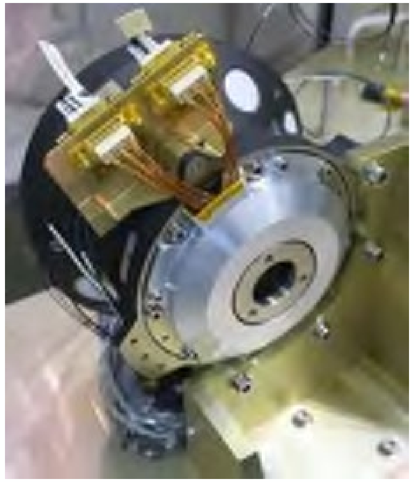




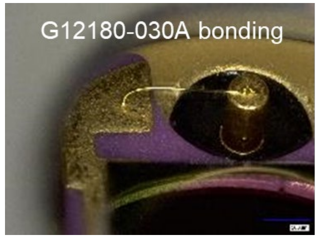
Mirror coatings

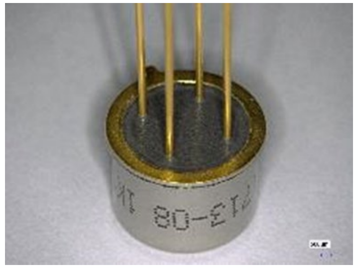


WSM actuator: TRISHNA EM



CA OBCS TR photodiodes

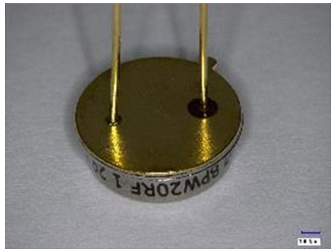




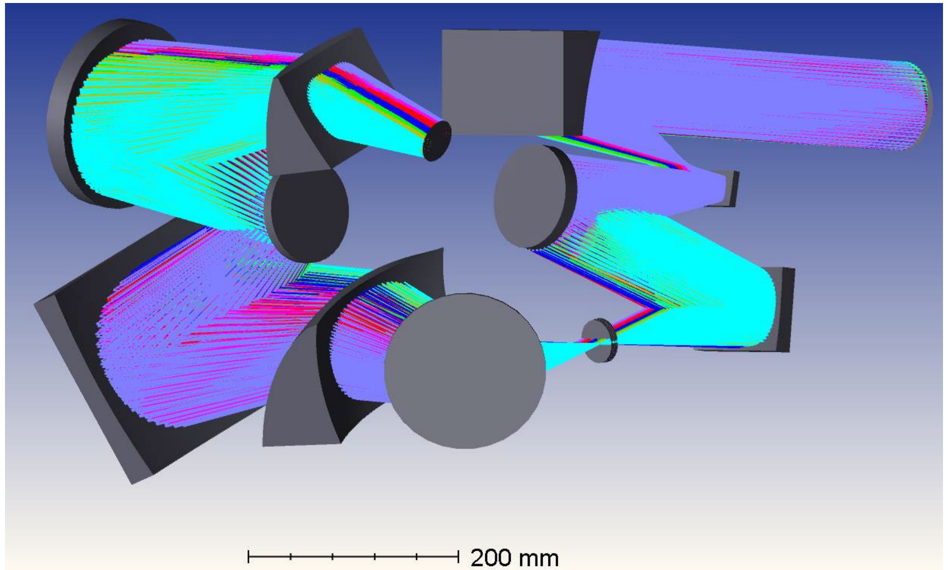
K -1713-08 dual-colour

Visual Inspection

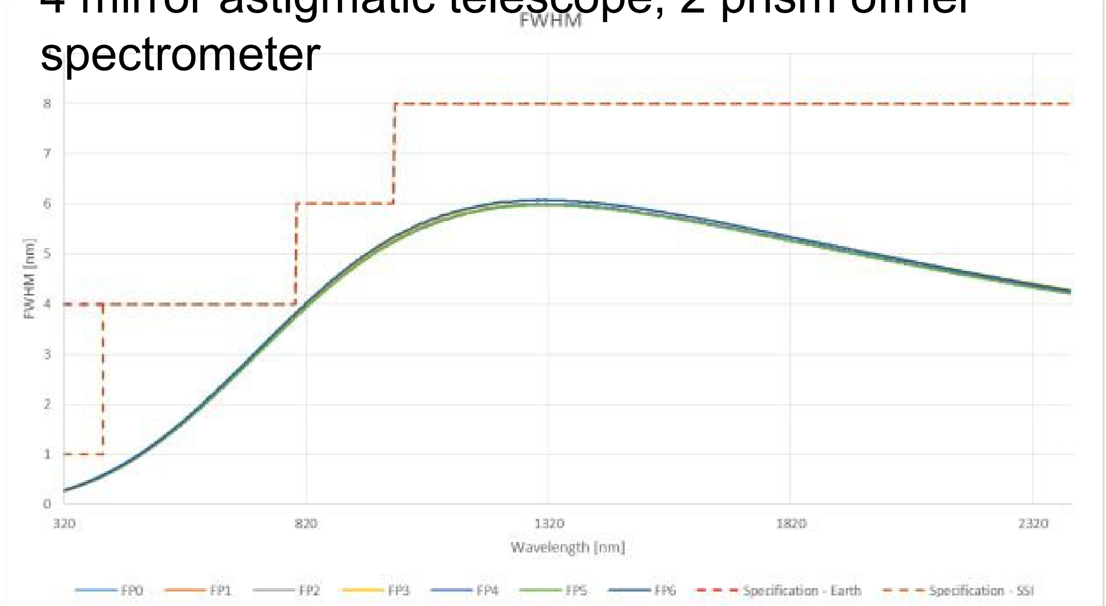
X-ray

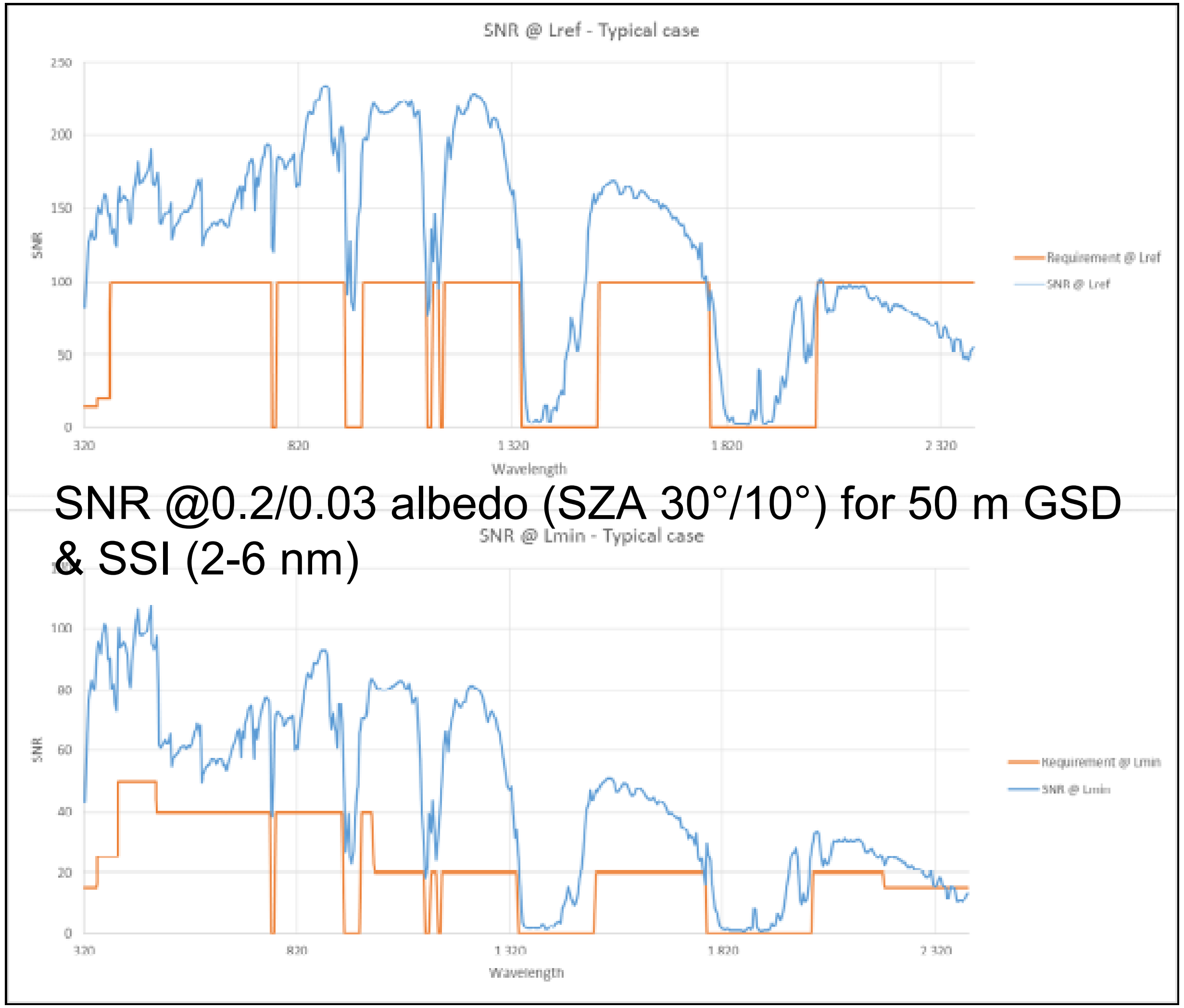


Hyperspectral imager (HIS) current performance



4 mirror astigmatic telescope, 2 prism offner spectrometer

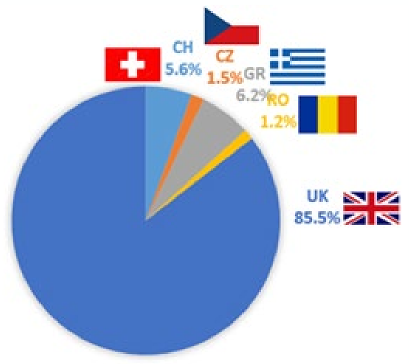




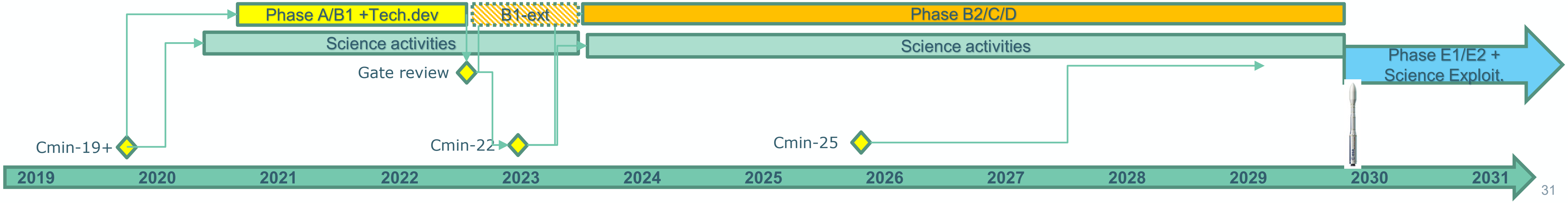
SNR @0.2/0.03 albedo (SZA 30°/10°) for 50 m GSD & SSI (2-6 nm)

TRUTHS Timeline

- TRUTHS was proposed by UKSA in May 2019 as a new Earth Watch (EW) Element.
- TRUTHS Phase A/B1 has been fully subscribed at Space19+ by 5 Participating Countries: UK (85.5%), GR (6.2%), CH (5.6%), CZ (1.5%), RO (1.2%)
- Industrial Phase A/B1 system studies and technology predevelopments initiated in Oct-20.
    - Phase-A kicked-off in Oct-20 and completed at end-July 2021
    - Phase B1 completed in Q2-2022 _ extended for technology maturing and to bridge to B2 phase to start in 2023. (TRL 5/6 by Phase B2 and SRL 5)
- Mission Advisory Group (MAG): Science/Engineering/User expertise primarily from Europe (not limited to funding nations) inc NASA CLARREO Pathfinder
- Programmatic "Gate Review": go decision, taken in July-22, to submit program to CM-22
- Phase B2/C/D/E to be funded at CM-22/-25 -> Program plan being currently prepared



TRUTHS A/B1 SUBSCRIPTION - @SPACE19+



International (CEOS?) climate & calibration Observatory

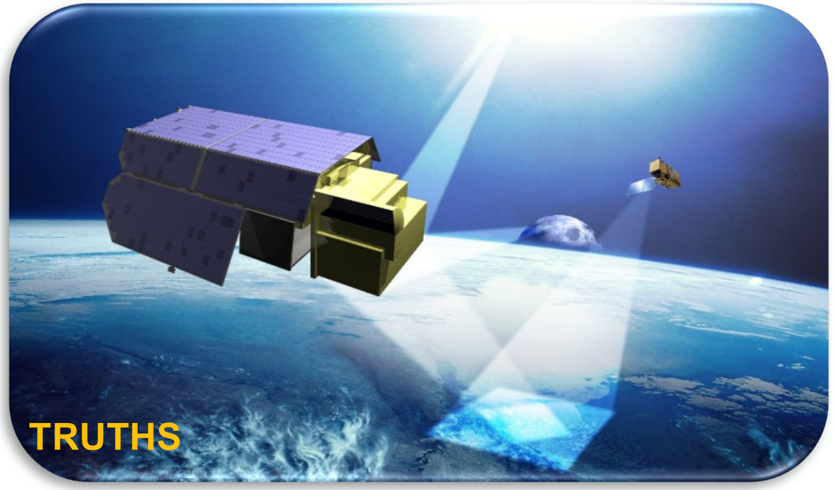
TRUTHS ~ 2029/30 will help initiate a sustainable long-term international climate & calibration observatory

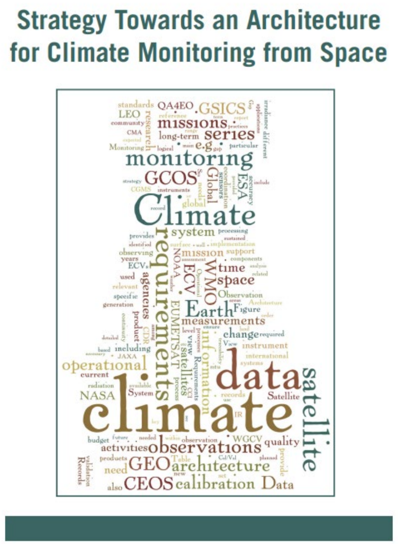
A direct response to international requests

NASA CLARREO-Pathfinder ‘sister mission’ which will be launched to the ISS in 2023/24.

- Hope for overlap!
- Also potential Chinese Libra

TRUTHS & CPF SITSats will provide unique and critical information for understanding and monitoring Climate and environmental change from space and support climate action – A resource for ALL nations



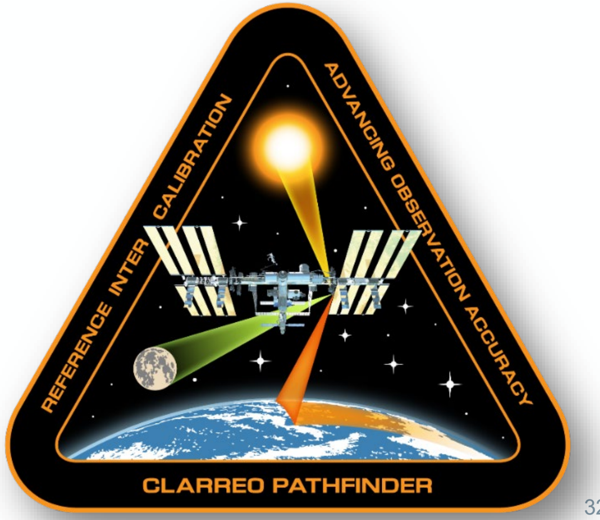



CEOS

SI-Traceable Space-based Climate Observing System:
a CEOS and GSICS Workshop
National Physical Laboratory,
London, UK,
9-11 Sept. 2019

SITSCOS Workshop Report

Editors: Nigel Fox, Tim Hewison, Greg Kopp, Bruce Wielicki



Phase AB1 team

esa

Agencies

Schweizerische Eidgenossenschaft / Confédération suisse / Confederazione Svizzera / Confederaziun svizra
Swiss Confederation
Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI
Swiss Space Office

CSO CZECH SPACE OFFICE

ΕΛΑΟ

rosa

esa

UK SPACE AGENCY

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RAL Space · pmod wrc · ISD S.A. Integrated Systems Development · planetek hellas · CGI
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National Centre for Earth Observation · Swansea University Prifysgol Abertawe · Universität Zürich · Imperial College London · UCL

Science institutes

Industrial Consortium