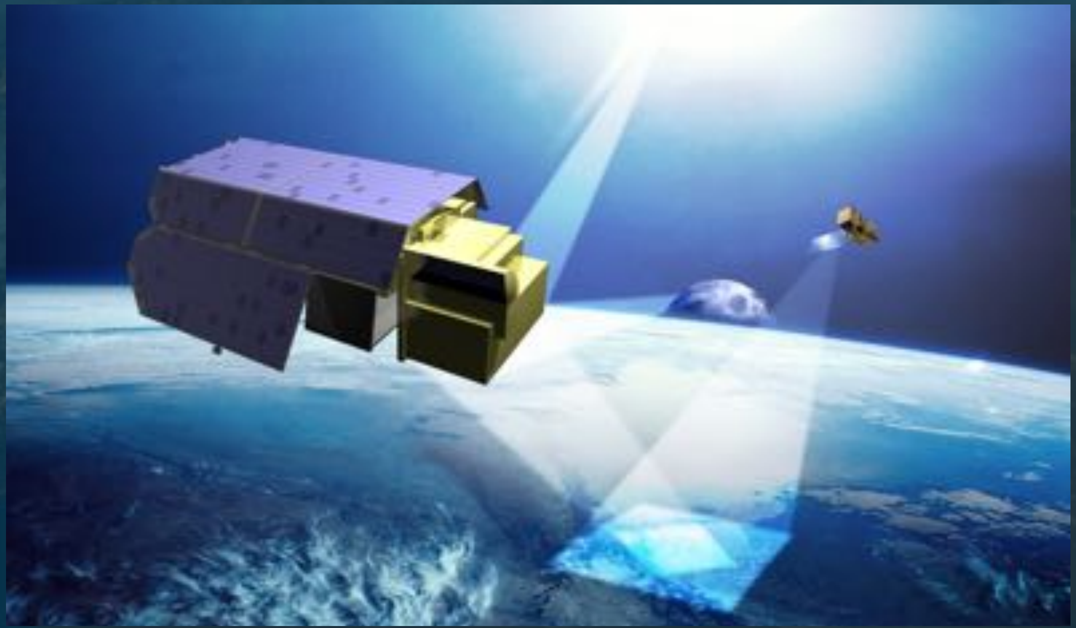
T raceable **R** adiometry **U** nderpinning **T** errestrial- & **H** elio- **S** tudies

An ESA EarthWatch mission



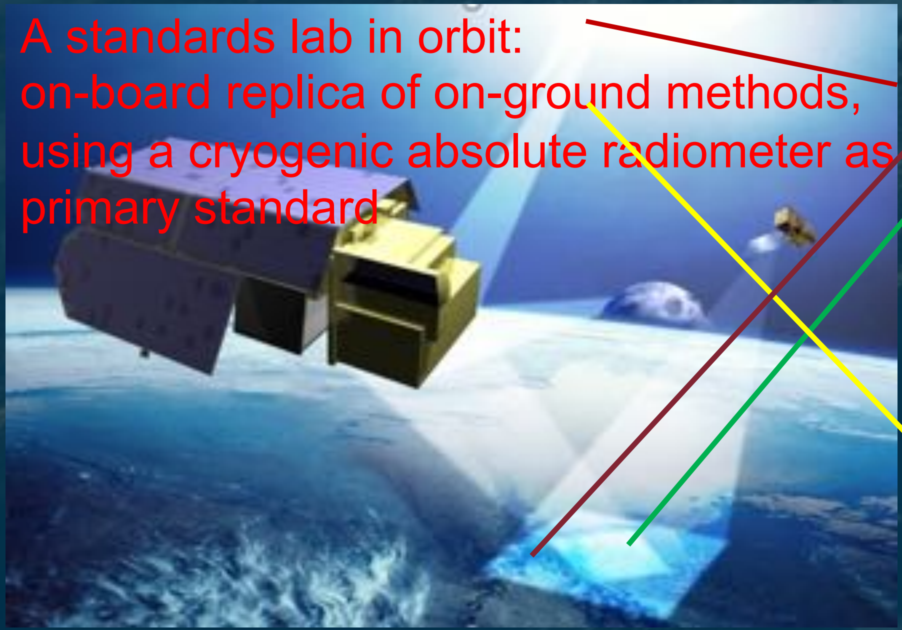
A 'gold standard' reference in space to support the climate emergency

Nigel Fox, Paul Green, Samuel Hunt, NPL,
Andrea Marini, Thorsten Fehr, ESA
Kyle Palmer, Airbus (now ESA)
John Remedios NCEO Univ Leicester
+++++

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:`



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 & Earth/Moon reflected radiation from the Sun

- 320 to 2400 nm @ ~4 nm intervals (1 nm for solar UV)
- Global nadir @ 50 m ground resolution (capability) with 100 km swath
- 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:

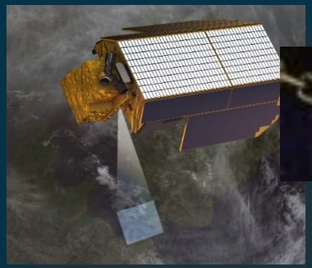
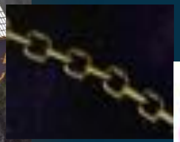
Observations

- Benchmark
- monitoring
- Litigation
- algorithm improvement

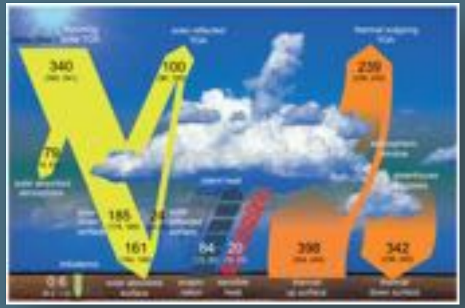
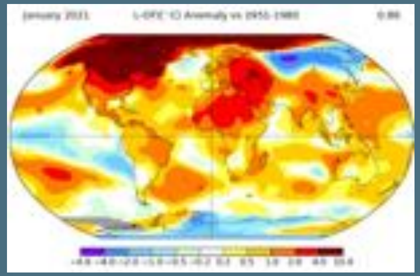
Calibration

- Interoperability
- data-gaps
- performance
- Utility

Climate action: Supporting 'Net Zero'


Climate sensitivity/response




Adaptation/sustainability

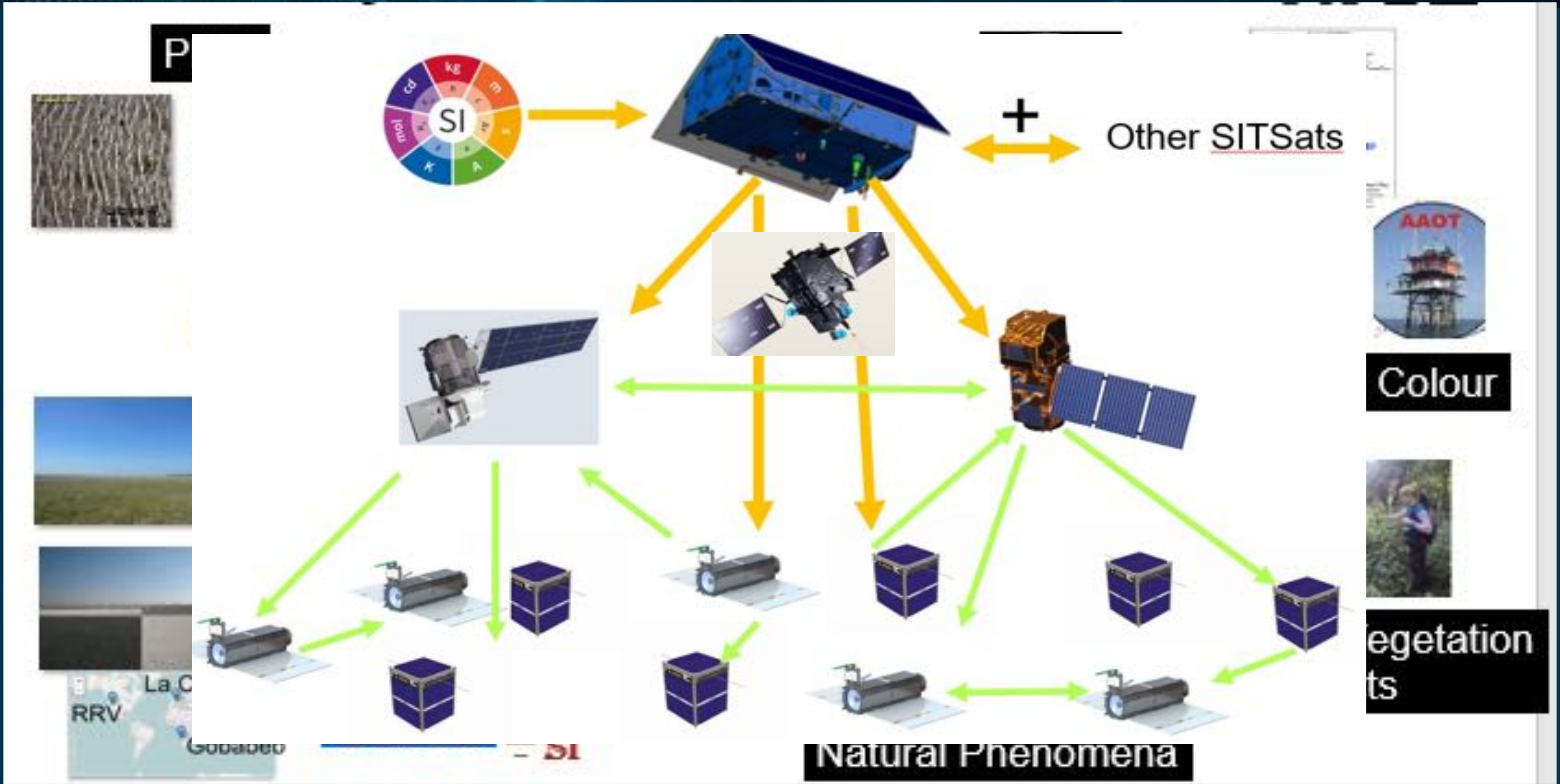


Climate action/mitigation



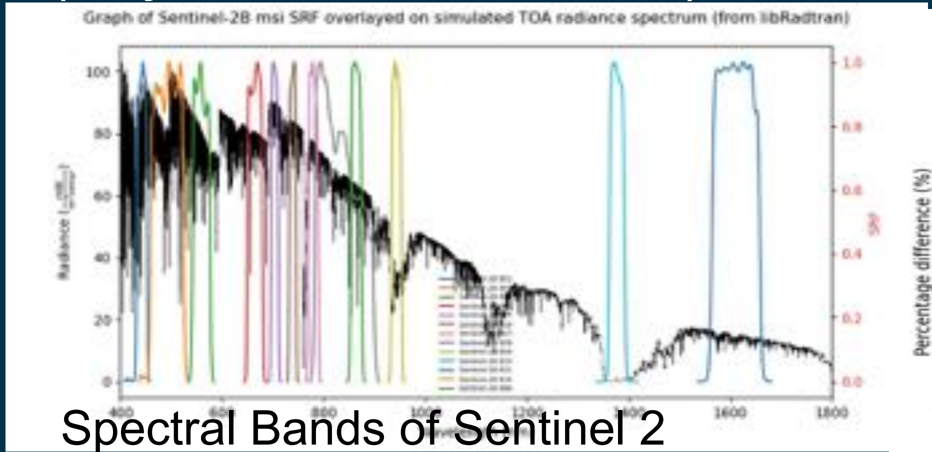


SI-Traceability to Cal/Val infrastructure

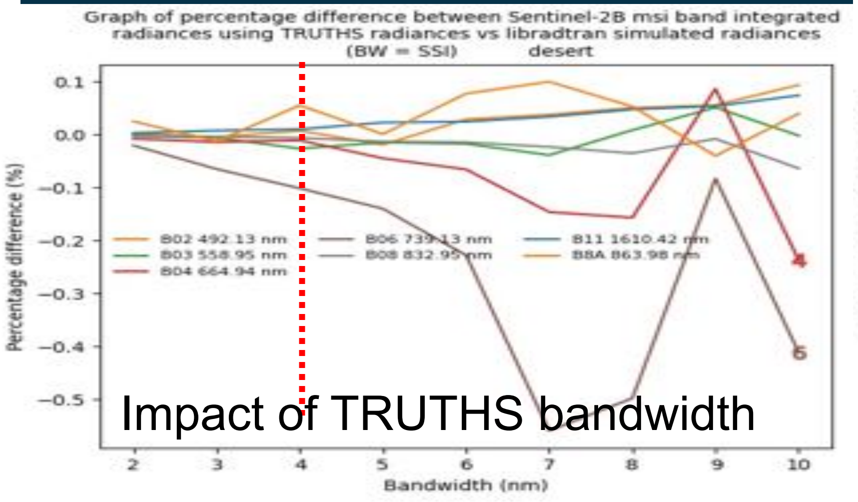


Transferring TRUTHS accuracy to other Sensors: establishing mission requirements (S2S calibration)

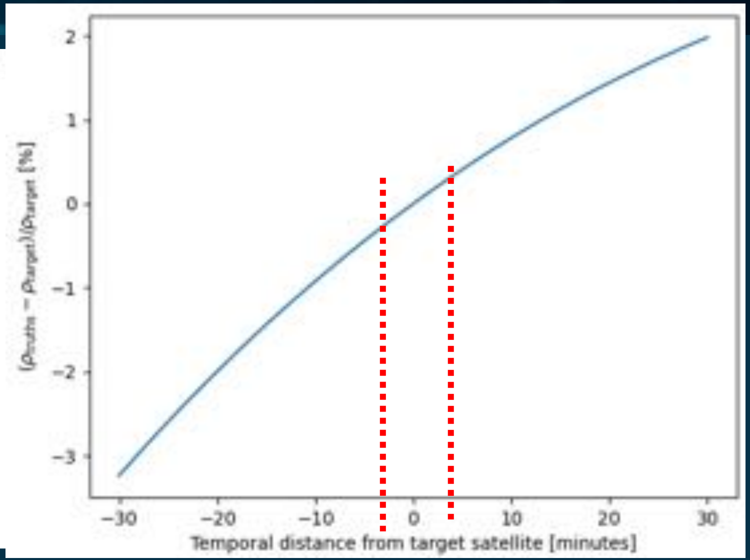
(Fahy, Hunt, Stedman, Gorrono)

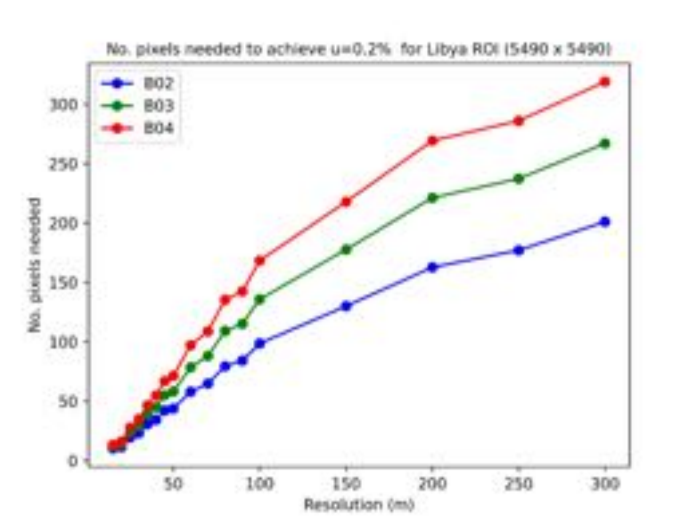


Spectral Bands of Sentinel 2

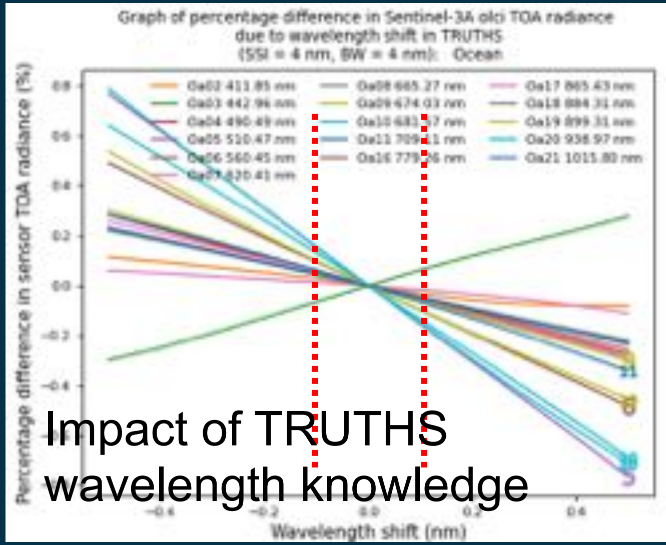


Impact of TRUTHS bandwidth

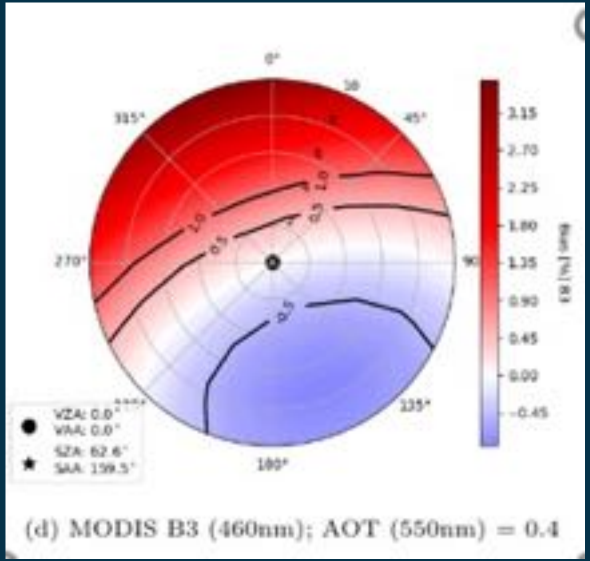




Uniformity of Cal Target (Libya 4) area to be sampled (2.5 km to achieve 0.2% @ 50 m)



Impact of TRUTHS wavelength knowledge

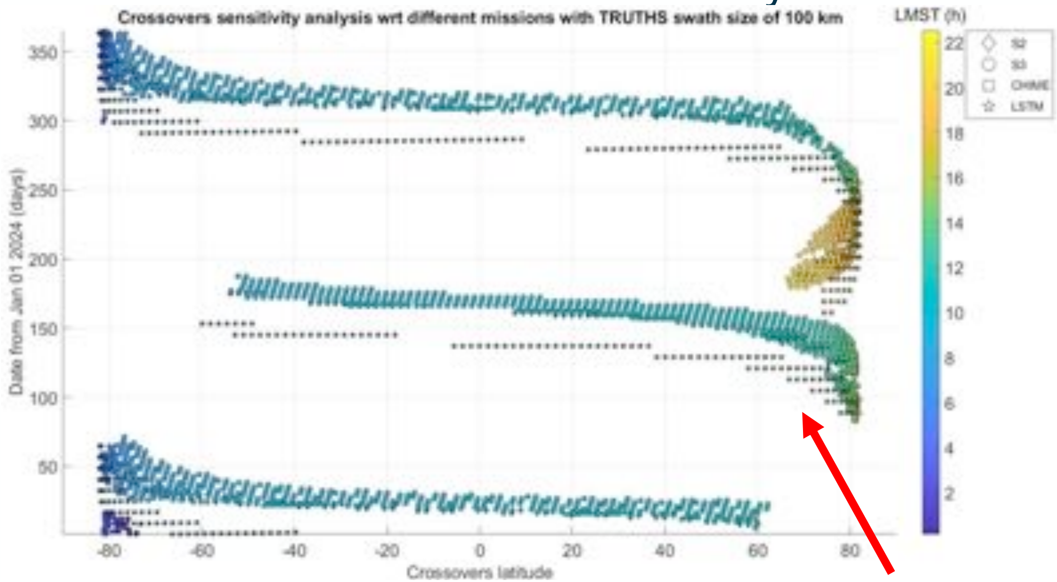


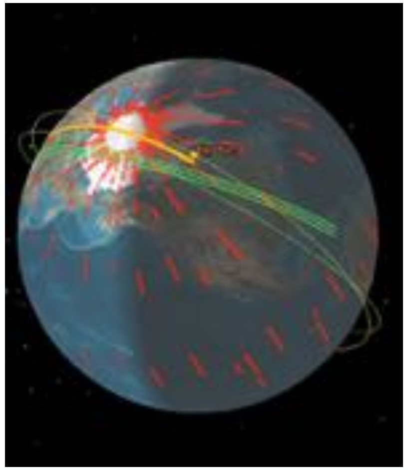
Reference Calibration

- **Enables interoperability & Harmonisation**
  - **Prospect of ‘certified calibration’**

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

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





<30 s time difference Swath overlap

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

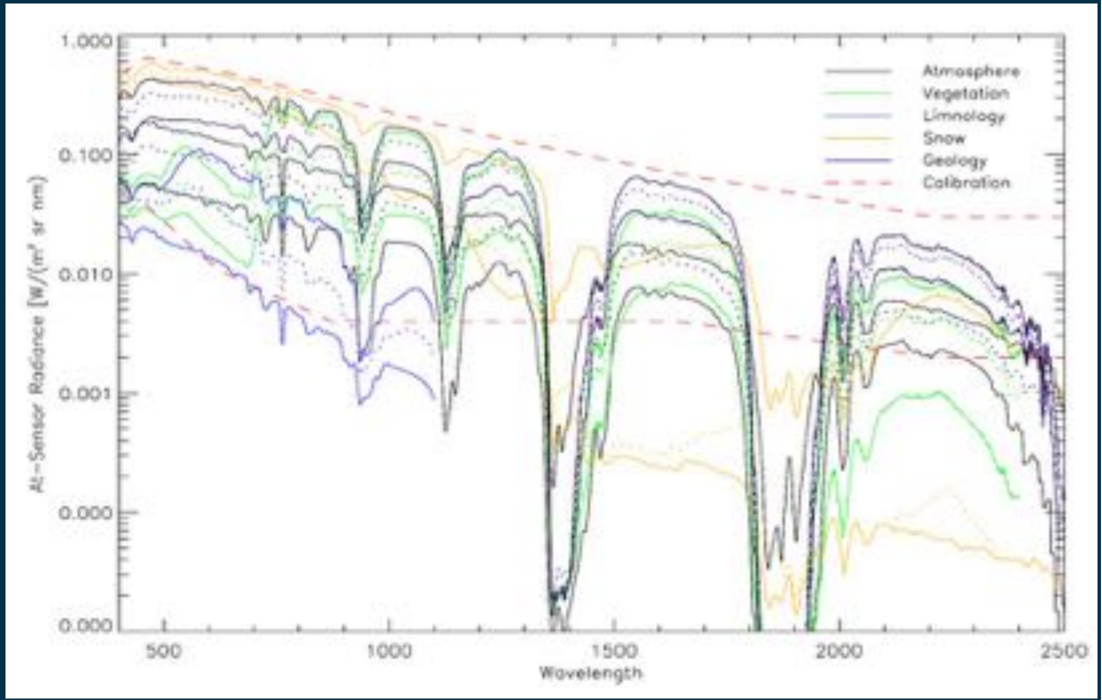
(<1° (no pointing) <30 s time difference

Summary after 6 months

Uncertainty budget for TRUTHS – satellite comparisons (convolution & Uc demonstrated also for hyperspectral mission

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 %**

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

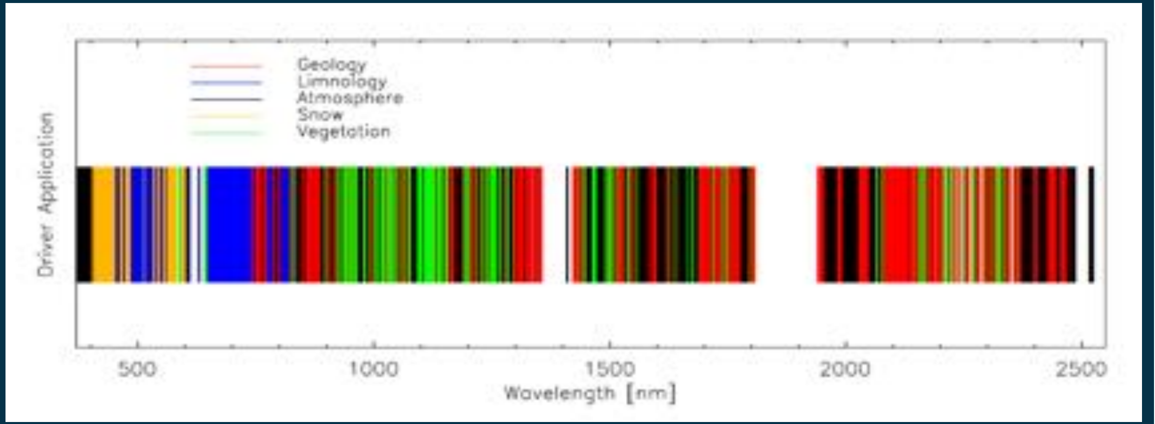


Hyperspectral data can be convolved for many applications enabling an earth system science approach (not temporally critical applications (61 day repeat – although <~20 days for Europe!))

- **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

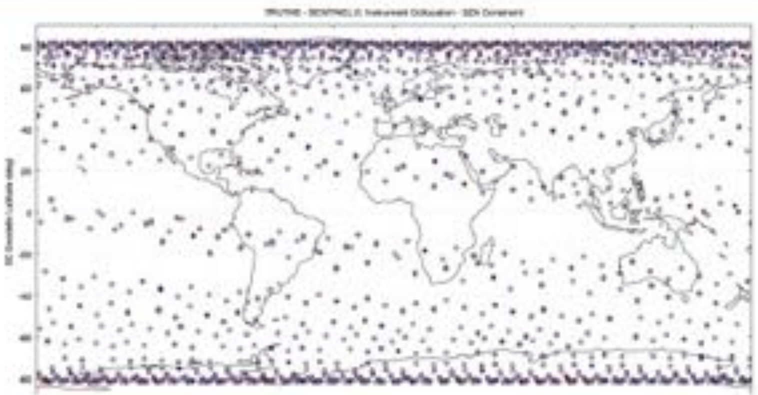
Climate 'Benchmark'

Earth Observation

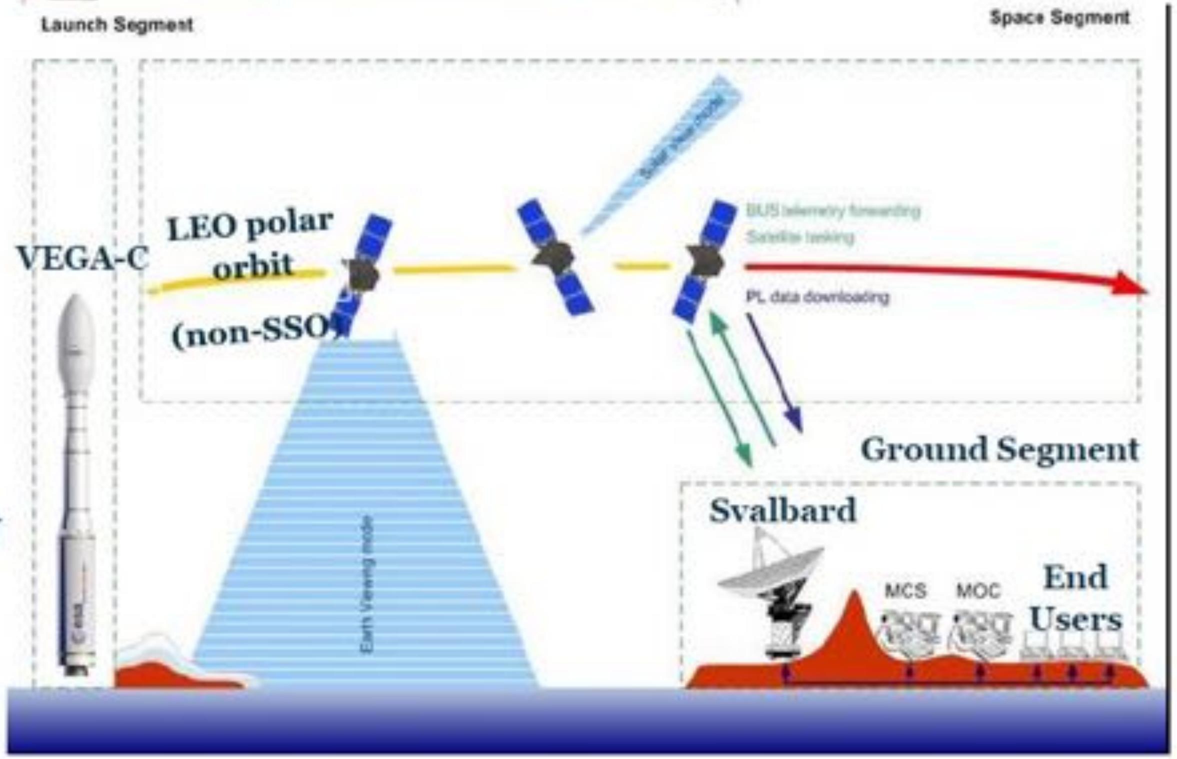
Level 1/2	Mission Requirement					
Application	Spectral range (nm)	Spectral Resolution (SSI) (nm)	Uncertainty (%) (k=2) G	Uncertainty (%) (k=2) T	SNR @ sensor SSI & 50 m	GIFOV
Earth spectral radiance (Climate)	350-2200 320-350 2200-2400	<10 – 20 nm	0.3 <1.0	<1.0 <3.0	>~20 @0.3 albedo >15	<300 m (scene 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

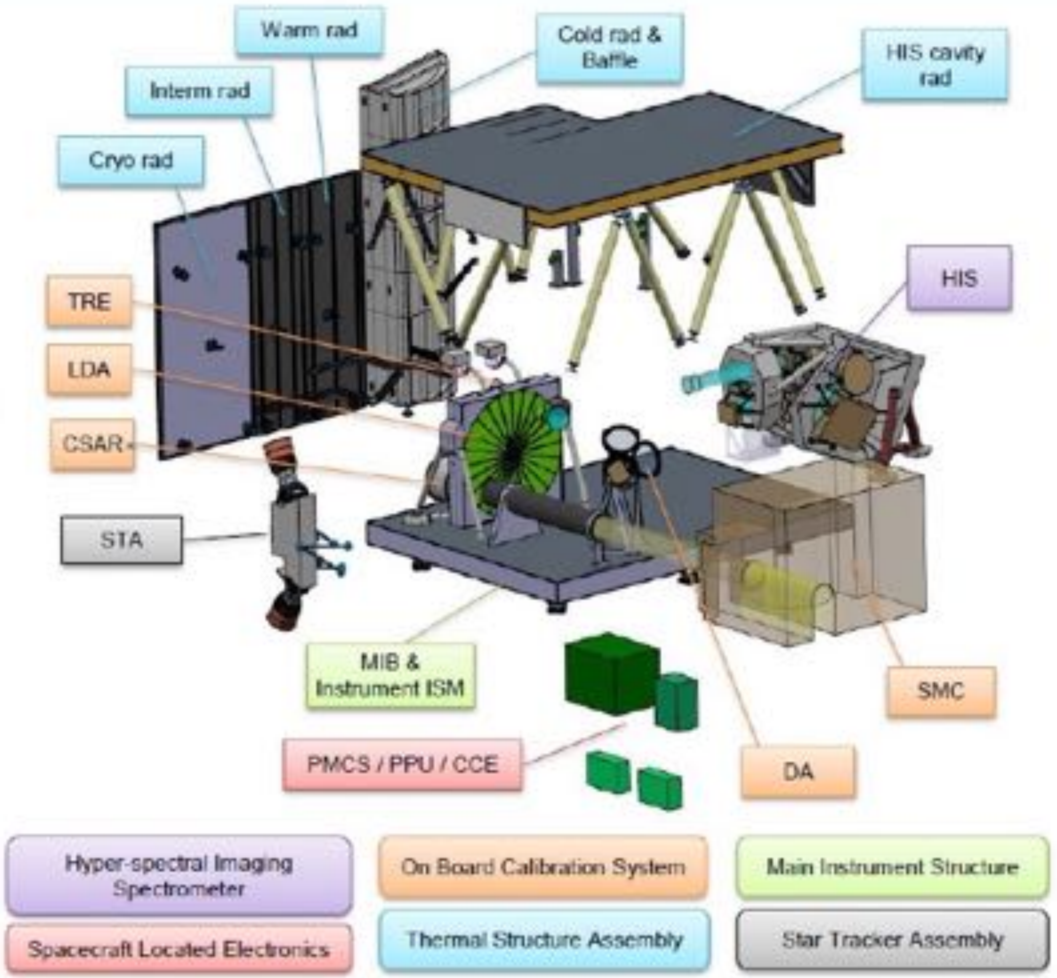


Launch Segment

Payload Overview

Payload, composed of three elements:

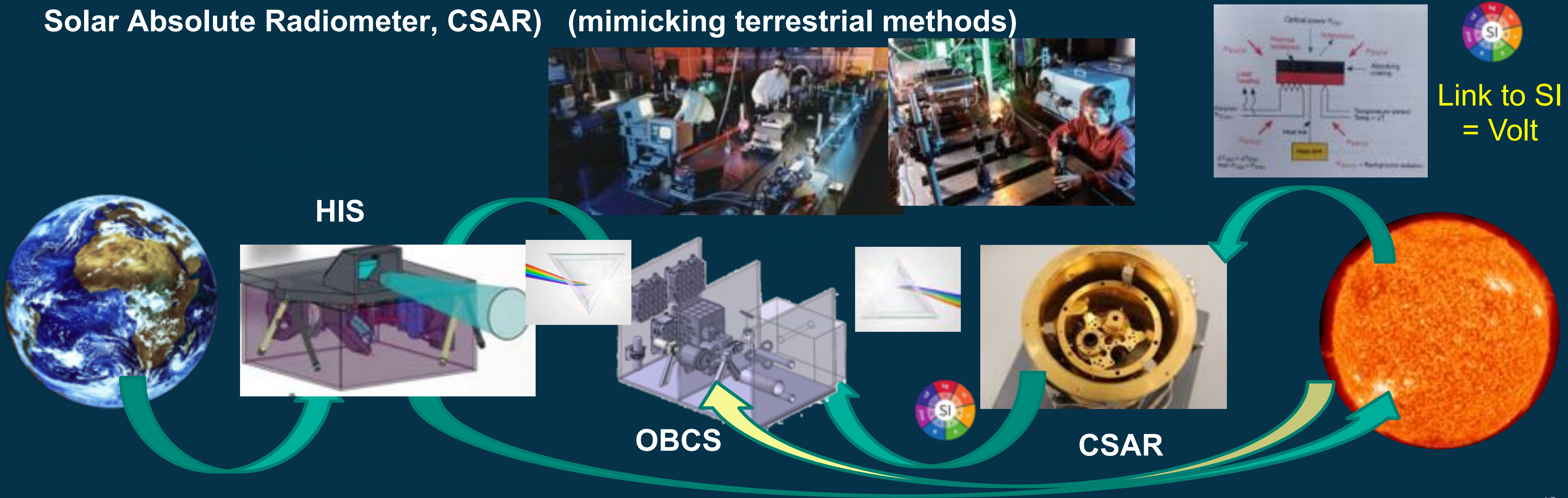
- **HIS** (Hyperspectral Imaging Spectrometer) – UV to SWIR (320-2400 nm), single detector, 50 m resolution, 100 km swath. Detector cooled at 150 K passively
- **CSAR** (Cryogenic Solar Absolute Radiometer) – operated at 60 K (cryocooler*), the "primary standard"
- **OBCS** (On-Board Calibration System)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



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

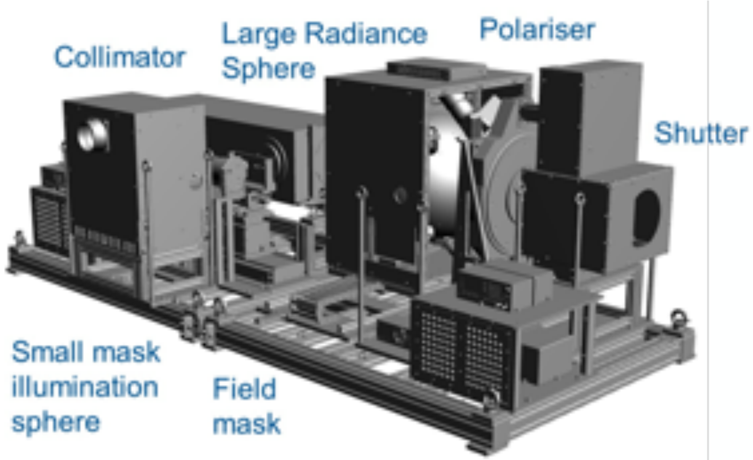
Metrology laboratory in-space

- 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)



STAR-CC-OGSE Overview:

- STAR-CC-OGSE provides radiometric calibration & 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 integrating sphere for flat-field radiometric calibration.
  - A CW laser monochromatic continuous tuneability from 260 nm to 2700 nm plus a broadband (white light) source extending over the same spectral extent (for both illuminations).
  - A vacuum-compatible detector module containing installable in TVAC at the sensor-under-test entrance aperture



			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:

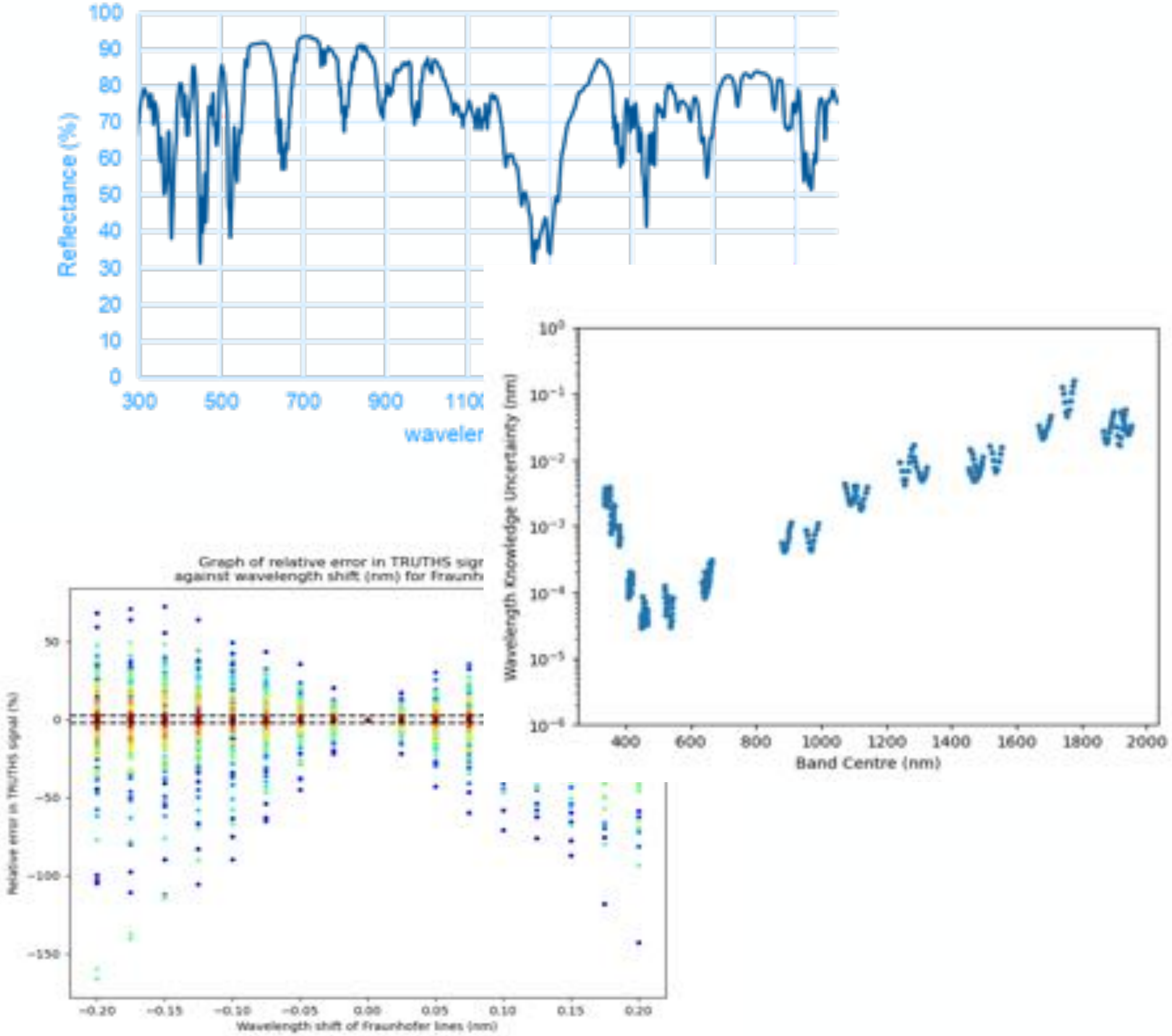
Fraunhofer lines

- 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

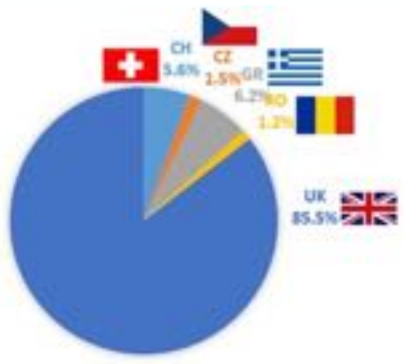
- Features over 300 – 1950 nm
- Solar illuminated convolved with Fraunhofer lines, but feature width allows reliable determination.
- <0.1 nm accuracy est.

Overlap region adds confidence.

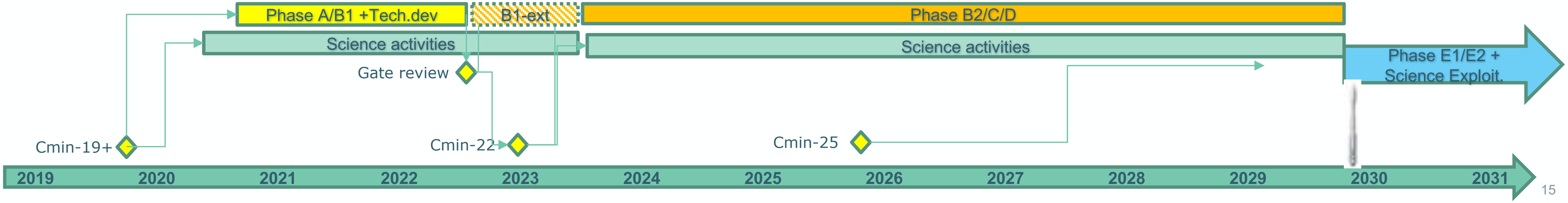


TRUTHS Timeline

- 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

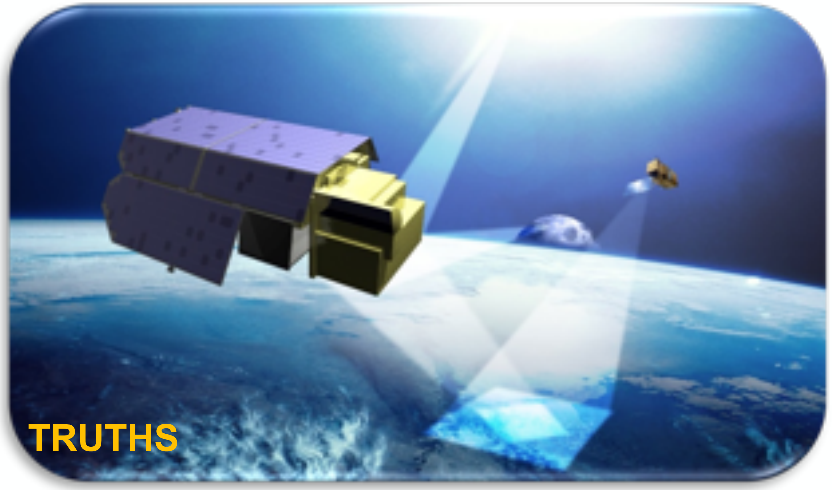
A direct response to international requests

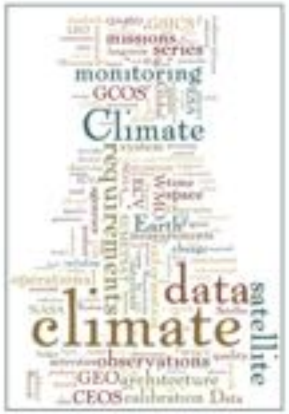
NASA CLARREO-Pathfinder ‘sister mission’ which will be launched to the ISS in 2023/24.

- 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




Strategy Towards an Architecture for Climate Monitoring from Space


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