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Chair: CEOS WGCV IVOS

UK SPACE AGENCY NPL National Physical Laboratory

Traceable Radiometry Underpinning Terrestrial- & Helio- Studies

Proposed as an ESA Earth WATCH mission

Enabling a space-based Climate & calibration observatory

Contributing science team

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RAL (UK)
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NCEO (UK)
- Prof. John Remedios

PML (UK)
- Mr. Steve Groom
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MSSL (UK)
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CICERO (N)
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JRC (EC)
- Dr. M Verstraete
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Zurich University (CH)
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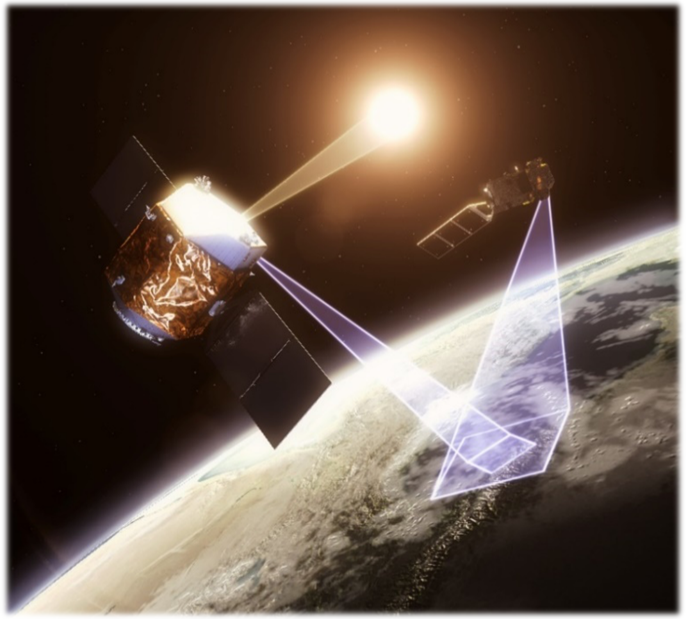
PMOC (CH)
- Prof. Werner K. Schmutz

U of Leth (Can)
- Prof. Philippe M Teillet

DLR (D)
- Dr Andreas Mueller

What is TRUTHS?



- TRUTHS is a UK-led proposed ESA Earth WATCH 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.
- This enables TRUTHS to **increase confidence in data** from other EO satellites through in-flight cross-calibration.
- More trustworthy data will **accelerate climate model predictions** and reduce their uncertainty, thus enabling policymakers to make **better and earlier strategic investment decisions**
- In addition**, hyperspectral data** from TRUTHS will address **challenges across all Earth science disciplines**

Traceable
Radiometry
Underpinning
Terrestrial- &
Helio-
Studies

NB: Presentation relates to technical activities primarily carried-out in the UK funded by UKSA and BEIS with support from PMOD Switzerland

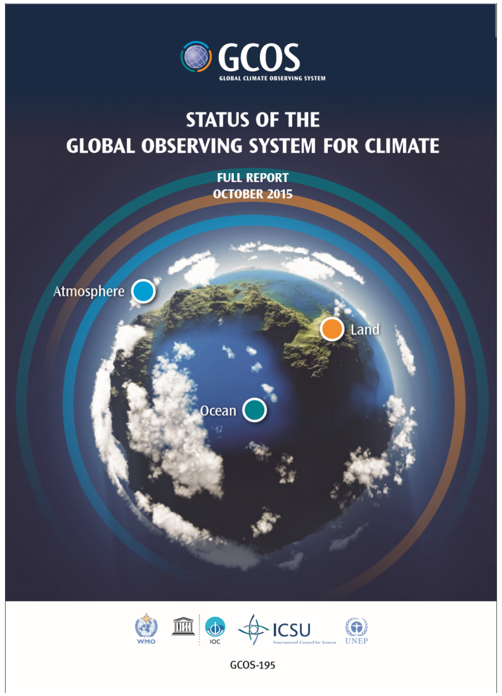
*subject to subscription at the ESA ministerial council Nov 2019 - will start Phase A/B1 in Q2 2020 aiming for a target launch date 2026

International Demand

Strategy Towards an Architecture for Climate Monitoring from Space

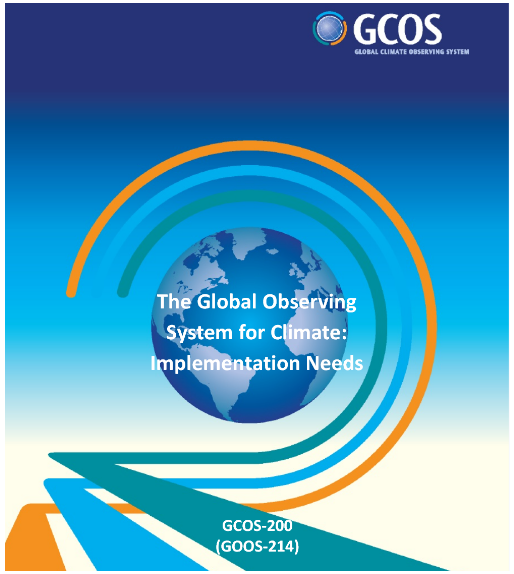
"….a dedicated mission flying an SI traceable calibration reference standard would be an important element of a future architecture (see CLARREO and TRUTHS)."

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**

GSICS
Global Space-based Inter-Calibration System



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

What is the TRUTHS mission?

- **TRUTHS is primarily a climate mission.**

  To measure the incoming & outgoing energy from the climate system, including the spectral fingerprint needed to observationally attribute climate processes & the accuracy needed to detect climate trends in the shortest possible time.

  - **Enabling a space-based Climate & Calibration Hyperspectral observatory through increasing confidence (Trustability) in information derived from EO data**
    - **Near-term**: Facilitate an internationally integrated climate quality Earth observing system
    - **Long-term:** Benchmark state of the planet **(a)** to allow climate model forecast testing **(b)** provide unequivocal observational evidence of climate change in shortest time possible
- **'Reference Calibration' to upgrade performance/confidence of global EO system inc retrieval algorithms**
- **Hyperspectral data to match spectral signature of many Bio/geo-physical/chemical parameters**

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 – >30	NA	NA	>500	Daily	0.02
Solar/Lunar Spectral Irradiance (SSI)	~<0.32 - 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

How does TRUTHS impact climate?: similar to CLARREO with a few differences

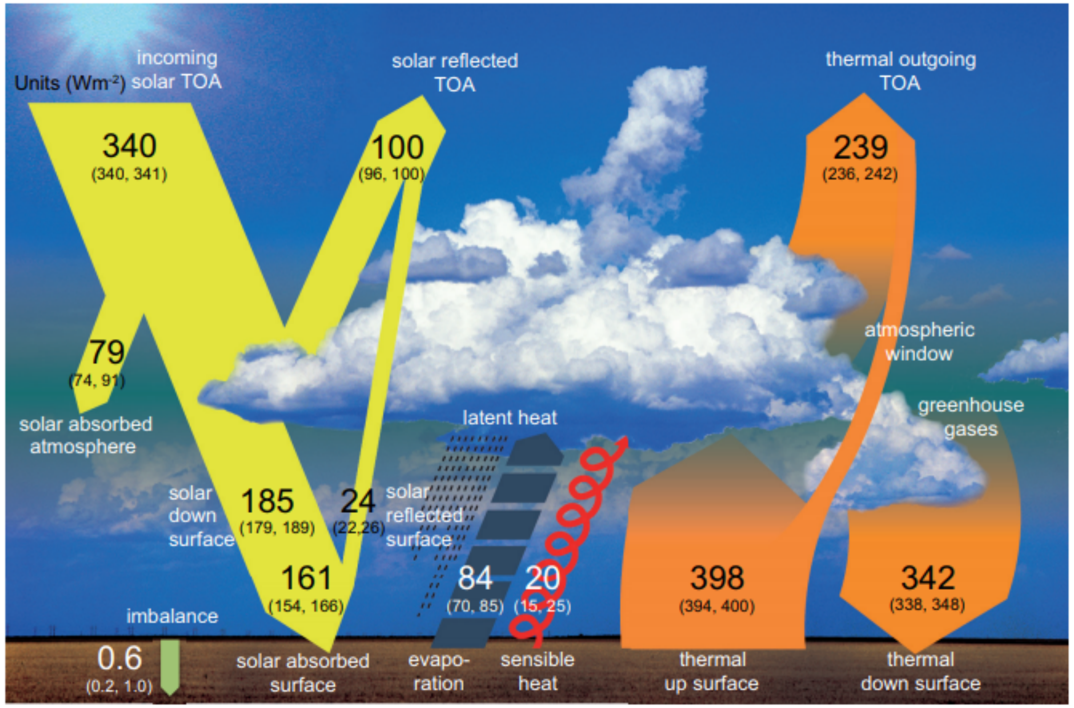
TRUTHS provide a benchmark or 'snapshot' of the state of the climate from which to monitor change

<u>Radiation Balance</u>

It provides a high accuracy spectrally resolved measure of SW element of Earth leaving radiation balance
And
All of the incoming radiation

And may provide integrated LW element

Addresses key radiation feedbacks:
Cloud & albedo



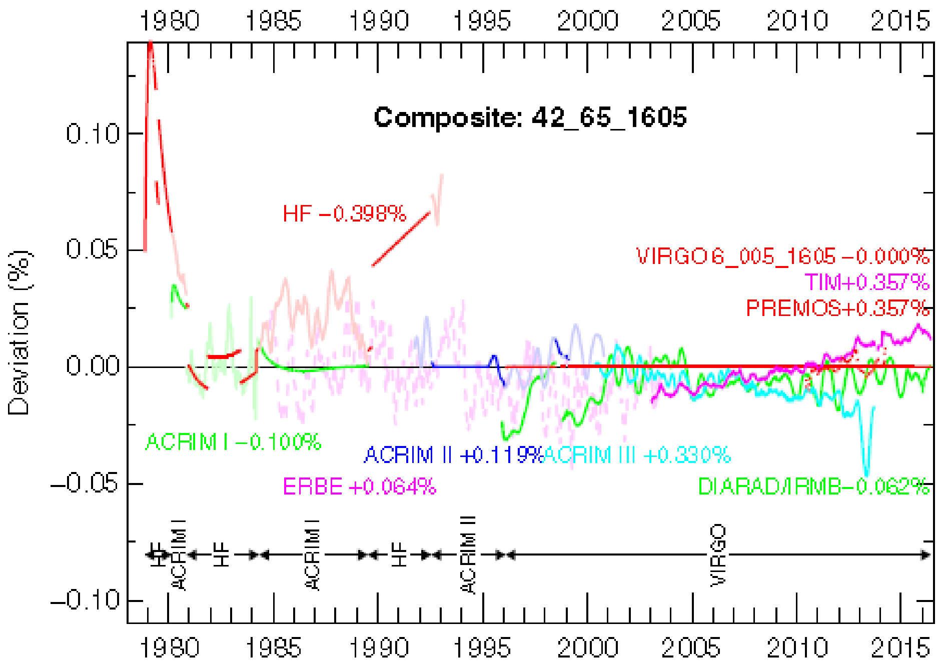
IPCC AR5 02.11

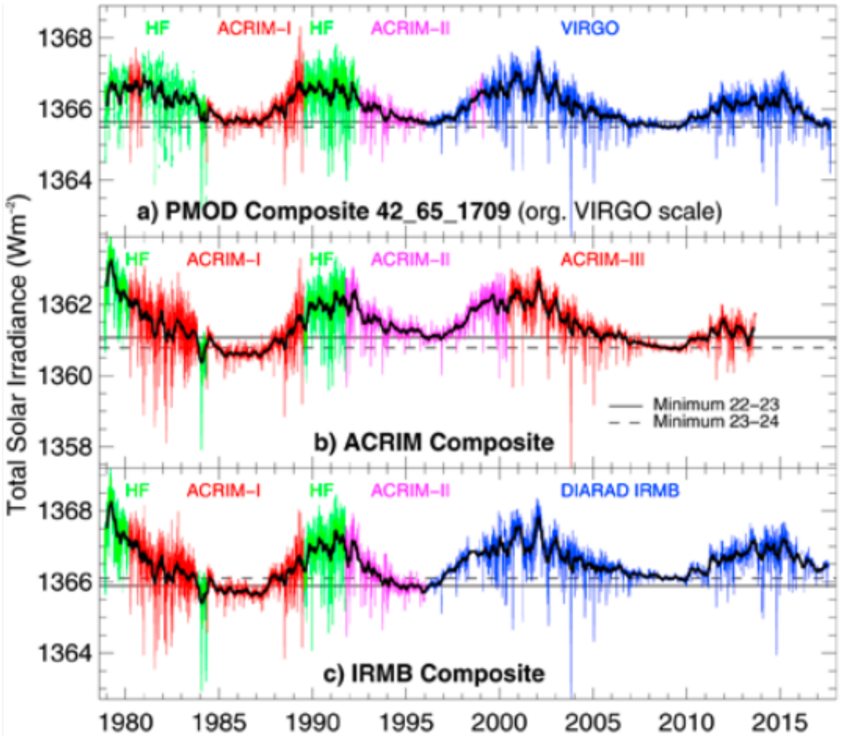
TRUTHS for Solar Impacts on Earth

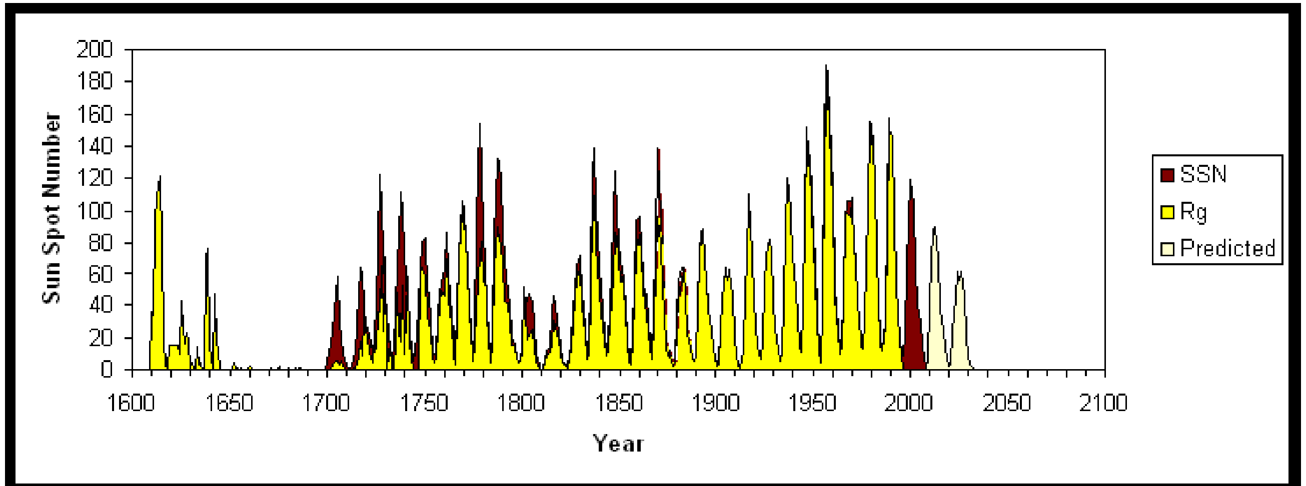
- The Sun is the major source of energy to the earth small changes will have an influence on climate. Over recent (11 yr) cycles Total Solar Irradiance (TSI) output change has been of the order of 0.1%, translating to ~1.4 Wm^{-2}. However, longer-term solar variation is expected to be much higher, and has been so in the past!. Some debate on current change!!

- Although not currently a dominant effect on climate change, this could change in the future (positive or negative)

- To best serve long term records an accuracy of 0.01% (k=1) is needed in TSI.

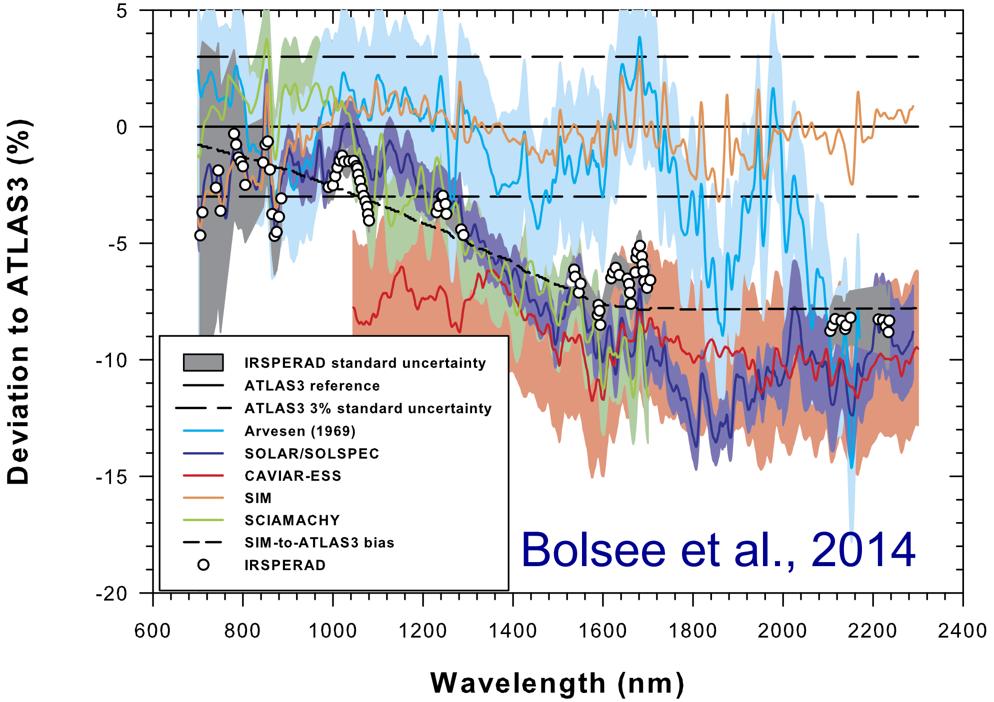


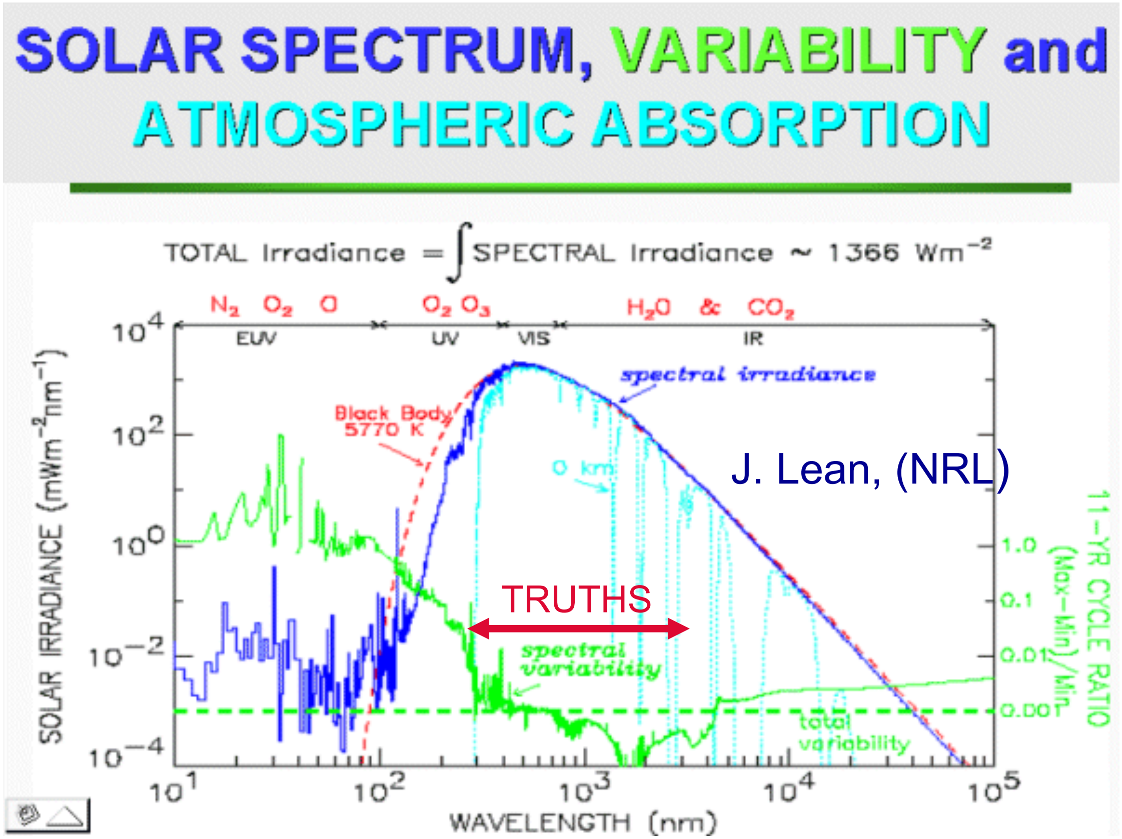




Solar Spectral Irradiance

Most variance in Solar Irradiance is spectral in nature and has direct short-term impacts on climate: UV atmospheric chemistry and heat transfer, NIR/SWIR atmospheric temp/water (vapour continuum)





TRUTHS spectral range (limited by technology/complexity) will span a significant part of the solar spectrum (variability) and enable true Earth reflectance products utilising same spectrometer

Note: Significant controversy over satellite observations and instrument corrections – leading to a ~ 10% anomaly > ~1400 nm!

Focus on Needs of ECV's: indicative

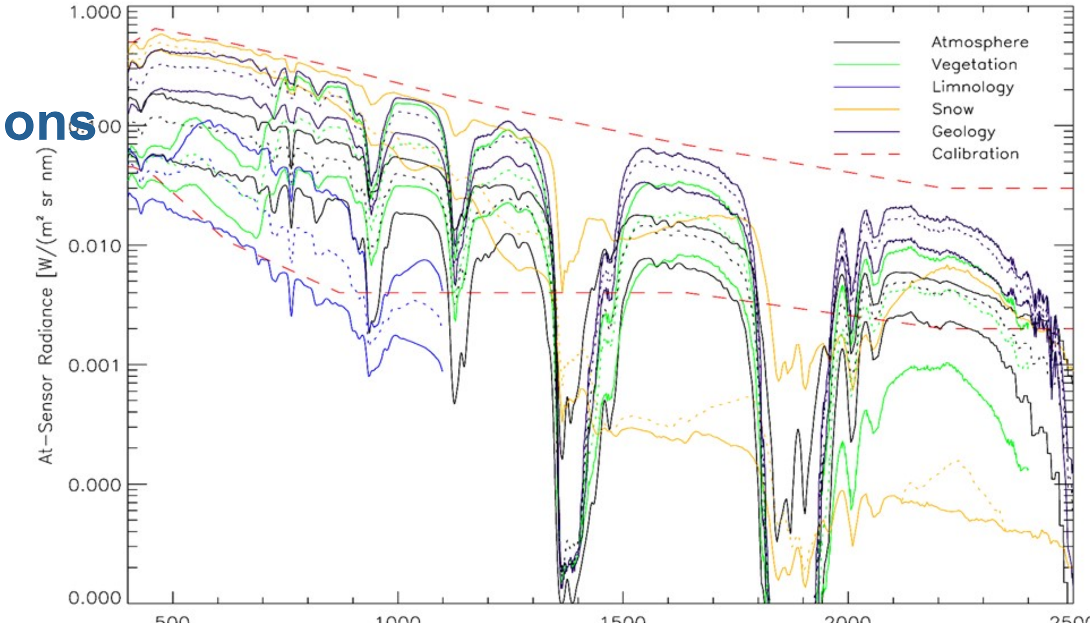
Climate variable	Role	TRUTHS providing direct observation	TRUTHS providing reference calibration
Solar irradiance	Climate forcing	yes	yes
Earth radiation budget	Climate forcing, feedback	yes	yes
Surface albedo	Albedo feedback	yes	yes
Cloud cover	Cloud feedback	yes	yes
Cloud particle size distribution		yes, through spectral benchmarking	yes
Cloud effective particle size			yes
Cloud ice/water content		yes	yes
Cloud optical thickness		yes	yes
Water vapour	Column water vapour response	yes	yes
Ozone	Stratospheric ozone Feedback	no (limited resolution)	yes
Aerosols Optical Depth	Climate forcing Atmospheric correction	no (limited temporal coverage) yes	yes yes
Ocean Colour	Carbon cycle/ sinks	yes	yes
Ice and snow cover	Albedo feedback	yes	yes
Vegetation	Carbon Cycle and Albedo feedback	yes	yes
Land Cover/Land Use	Surface Radiative Forcing	yes	yes
GHGs	Climate forcing: emissions	Yes? Large scale screening	Yes

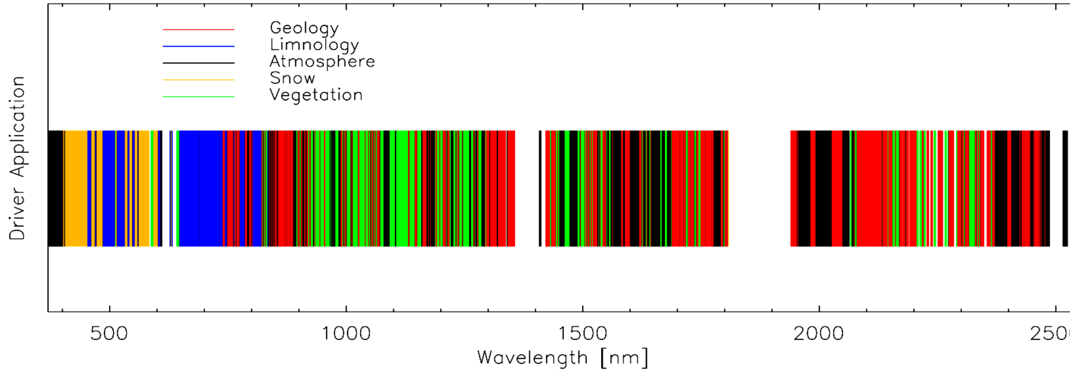
Hyper-spectral applications: Surface reflectance

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

- directly
- upgrading other sensors
- Test & Improve retrieval algorithms

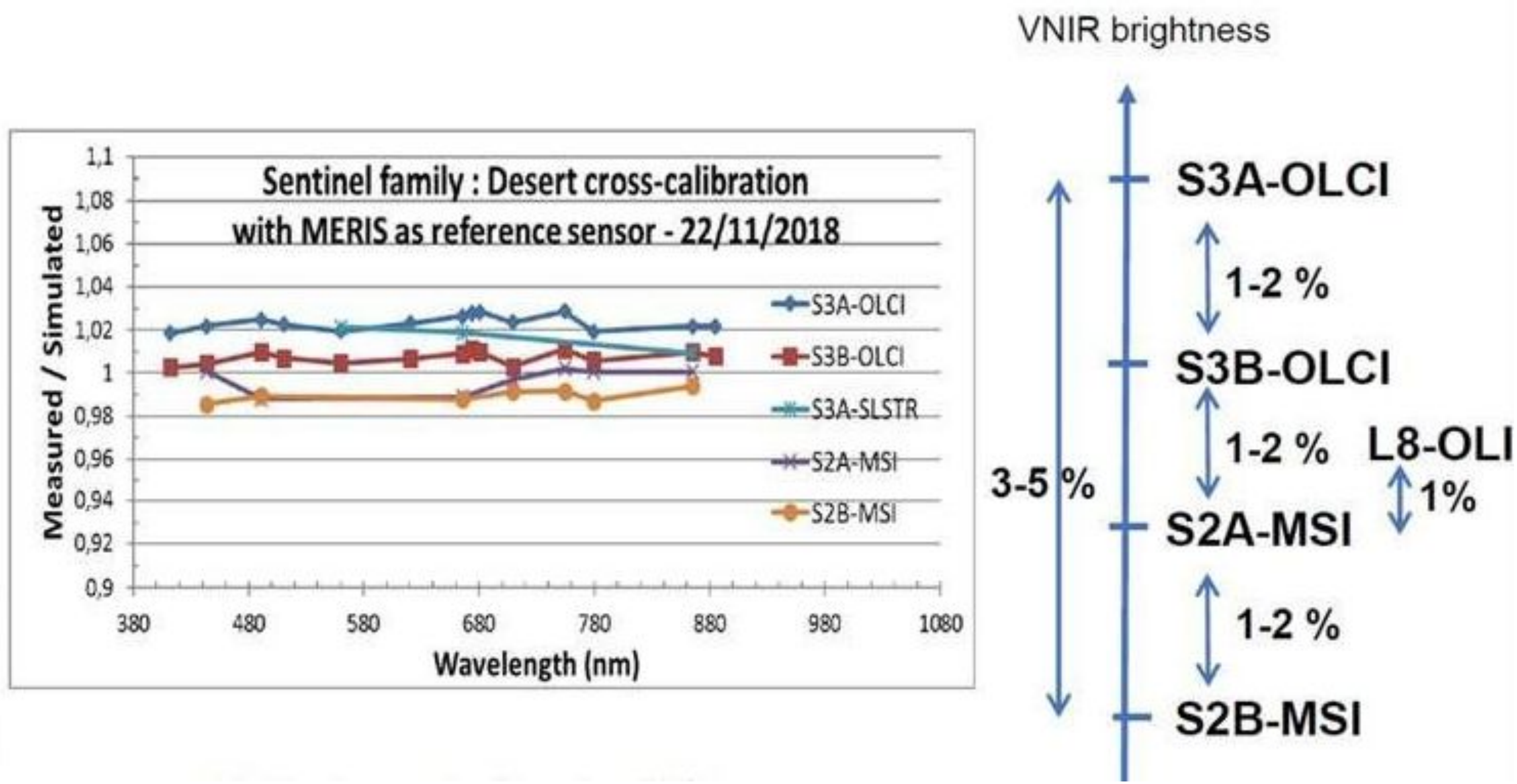
- **Complimentary to EnMAP, PRISMA, CHIME ….**
- **Land-cover change**
- **Agriculture**
- **Pollution**
- **Resource prospecting**
- **…….**





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

But what is the Truth?



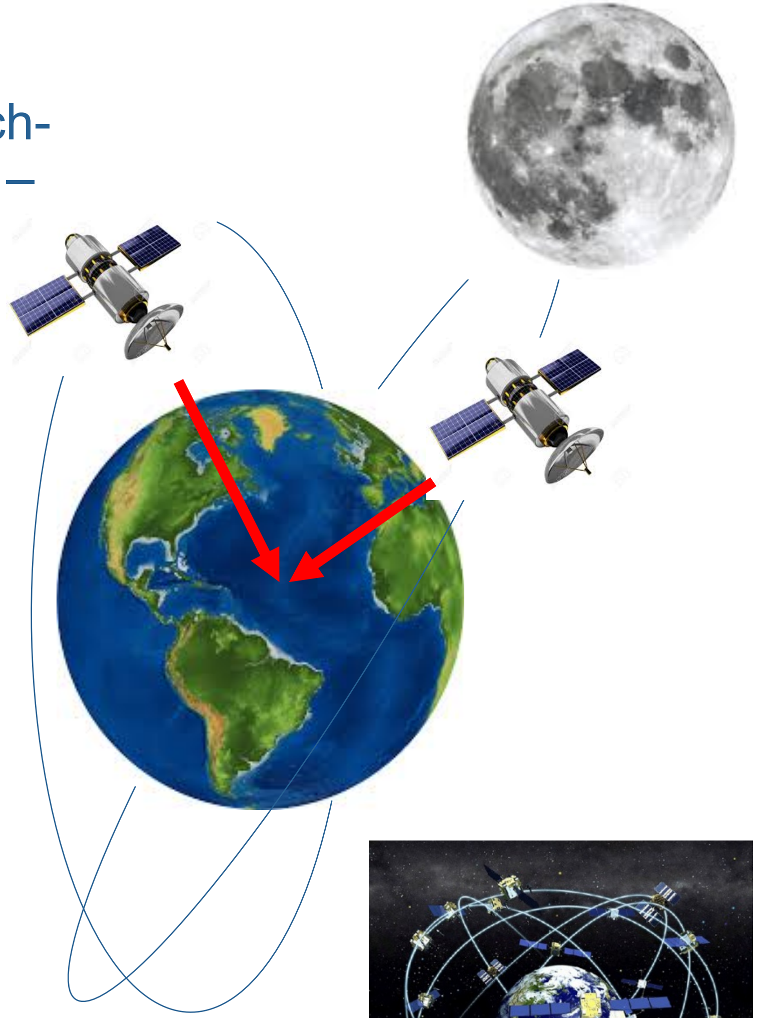
Graph courtesy of Meygret, CNES

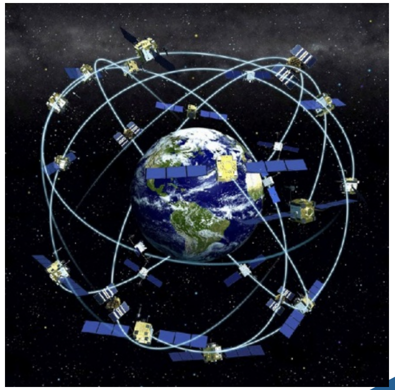
TRUTHS for inter-operability

- 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.

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

- Inter-calibration accuracy is dominated by the reference sensor absolute radiometric calibration uncertainty.
- Studies to determine the inter-calibration accurate 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



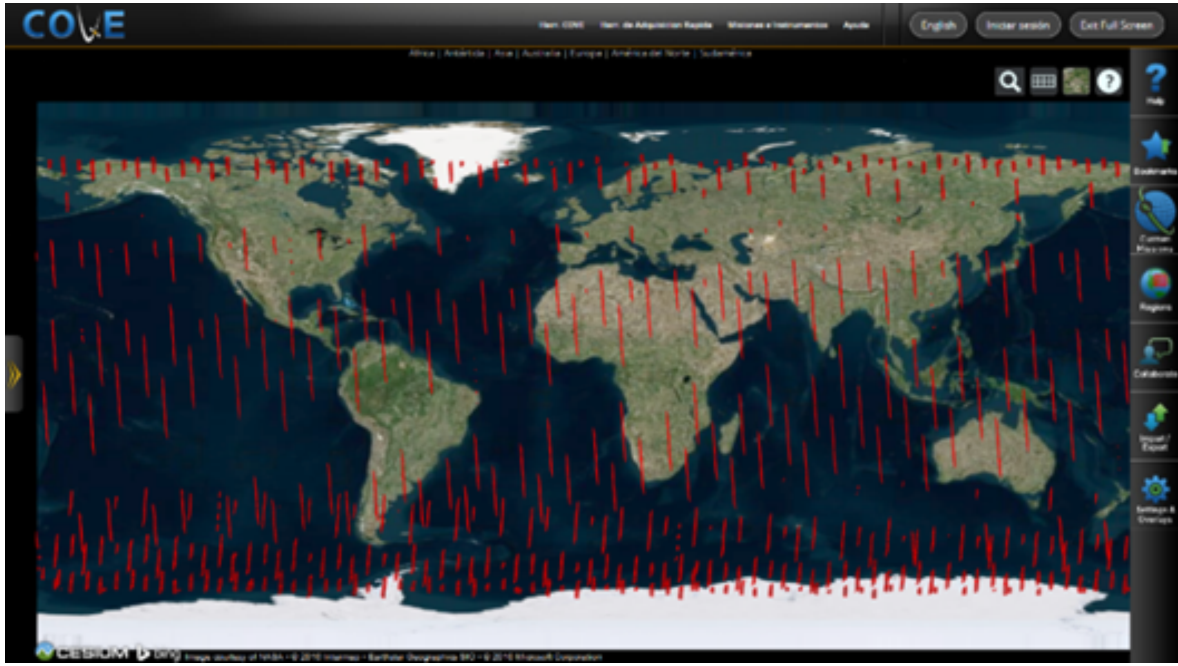


Each inter-comparison component (μ) has a typical magnitude of 0.1% - 0.5% (k=1) compared to the current reference sensor (2%).

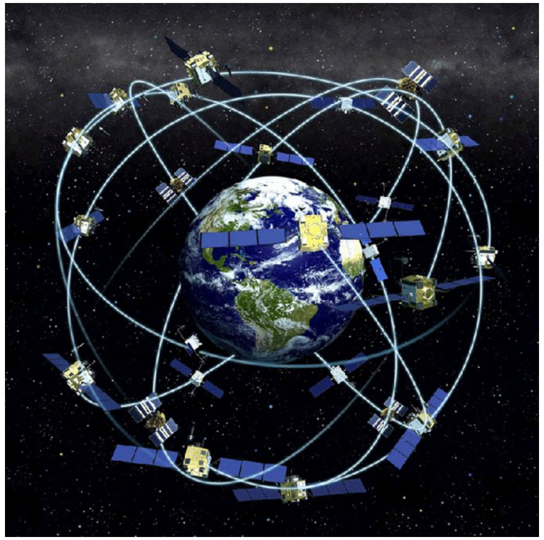
- Anchoring existing stable Caln targets e.g. Moon - TRUTHS can back correct the satellites already launched – improving the quality of their data making the most of existing and historical investments and improving FCDRs & CDRs.

Reference Calibration

- Enables interoperability & Harmonisation
- 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



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

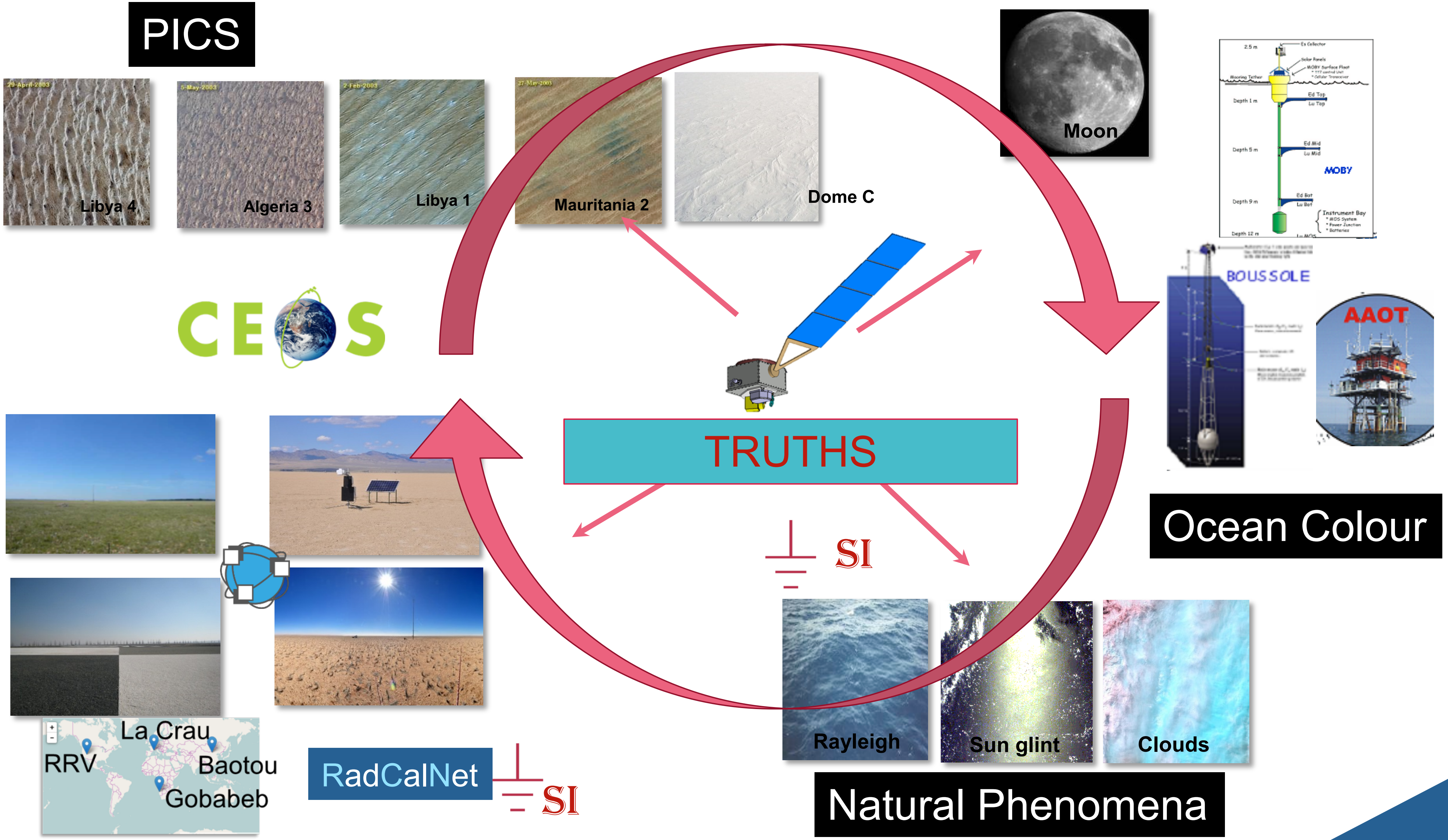
- Reduces uncertainties due to:
  - Illumination and view angles
  - Atmospheric changes
  - Allows many scene types

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

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

Lunar absolute and cycles for in-space calibration

Traceability to CEOS Cal/Val infrastructure



User Requirements: Esa study underway to consolidate/optimise requirements for all applications

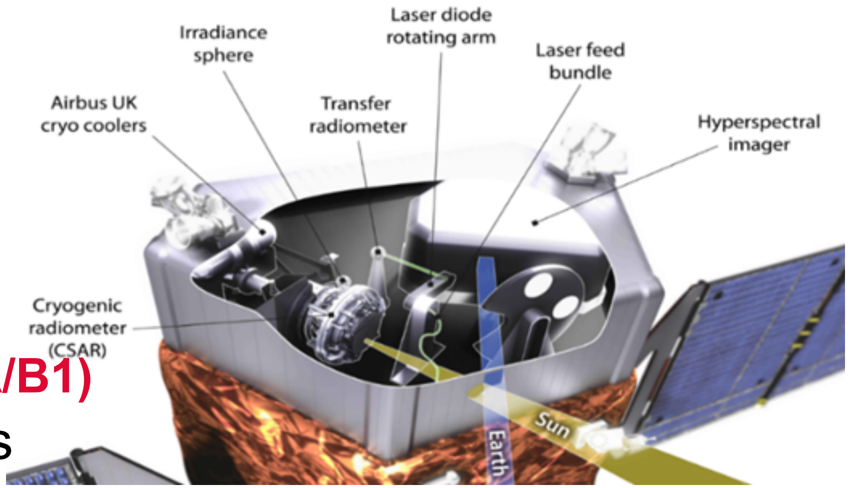
Climate

Level 1 products	Mission Requirement				
	Spectral range (nm)	Bandwidth (nm)	Uncertainty (%) (k=2)	SNR	GIFOV (m)
Earth/lunar spectral radiance	320-2450	8 – 25 nm	0.3	~300 (Vis-NIR) >1000 (blue)	250
Solar Spectral Irradiance	<320 – 2450	1 (<400), 5 (<1000), 10 (<2350)	0.3	300	NA
Total Solar Irradiance	Total	200-30000	<0.02	<500	NA

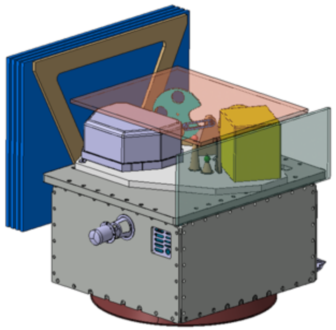
Reference 'operational' Calibration

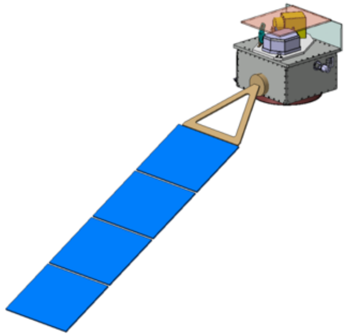
Level 1 products	Mission Requirement				
	Spectral range (nm)	Bandwidth (nm)	Uncertainty (%) (k=2)	SNR	GIFOV (m)
Earth/lunar spectral radiance	320-2450	<5 for < 1000 nm <10 for >1000 nm	<1.0	~300 (Vis-NIR) >2000 (blue)	50 250
Solar Spectral Irradiance	NA	NA	NA	NA	NA
Total Solar Irradiance	NA	NA	NA	NA	NA

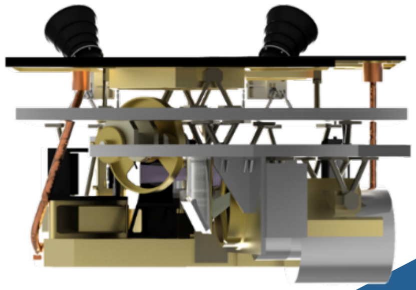
Mission overview (indicative)



- **Small/Medium Agile Satellite – 5 – 8 yr planned life**
  - Provisional accommodation studies for both Astrobus-S/M and SSTL platforms, others possible (TBD Phase A/B1)
- **Orbit: 90° precessing 609 km (from CLARREO) (TBC phs A/B1)**
  - Facilitates multiple cross-overs (many locations) and increases dwell time for Satellite calibration
  - Provides 2 diurnals cycles pa for climate
- **Downlink communications**
  - Svalbard (TBD Phase A/B1)
- **Payload**
  - Hyperspectral imager (HIS) nominal single telescope/spectrometer (2/3 detector options) (TBD Phs A/B1)
  - **Disruptive calibration system including primary SI standard (Cryogenic radiometer) (mimics terrestrial methods)**
  - Mass ~ 150 kg with margin
  - Power ~ 280 W continuous with margin
  - Data ~ 4500 Gb per day (optimised)







Contributing Industrial team: UK+ pre-development

TELESPAZIO VEGA
UNITED KINGDOM

SURREY
SATELLITE TECHNOLOGY LTD

NPL
National Physical Laboratory

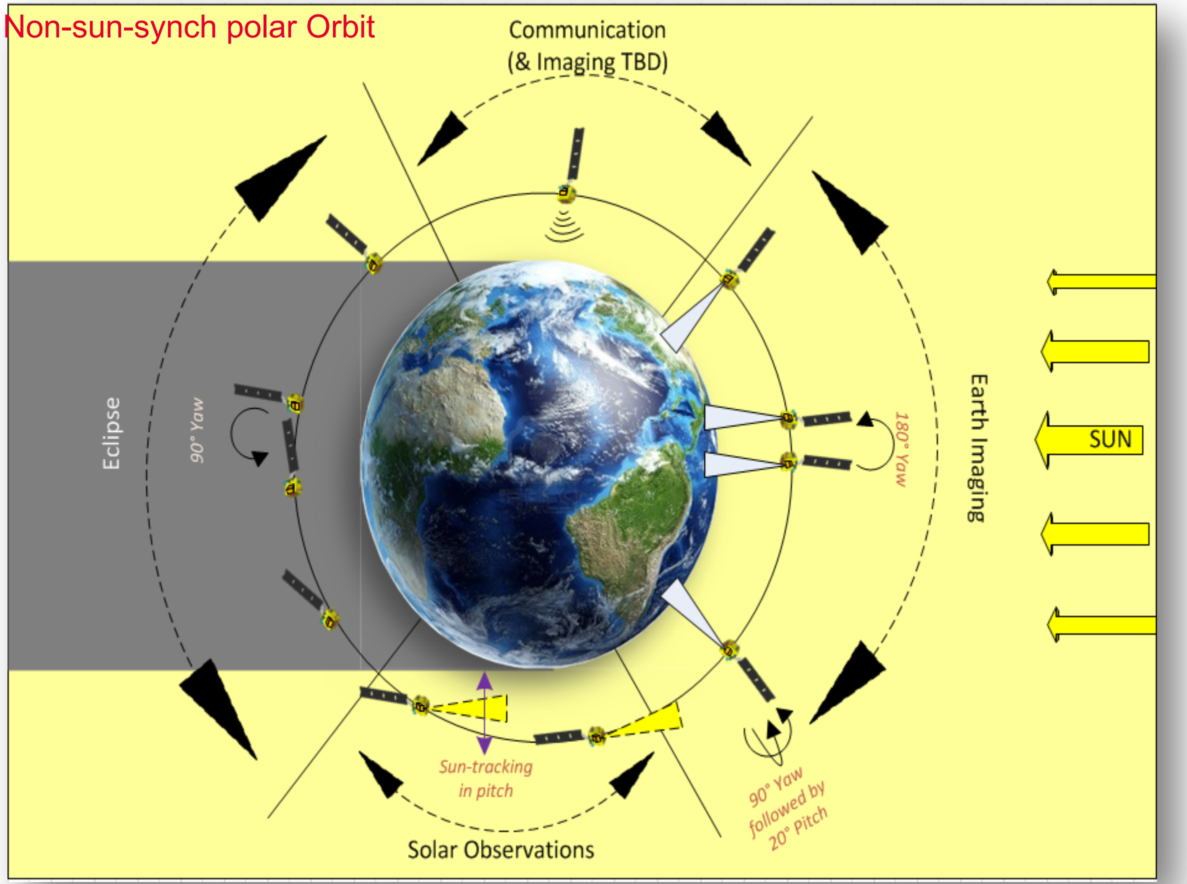
TELEDYNE e2v
Everywhereyoulook™

pmod wrc

AIRBUS
DEFENCE & SPACE

Provisional Thermal / Orbital analysis

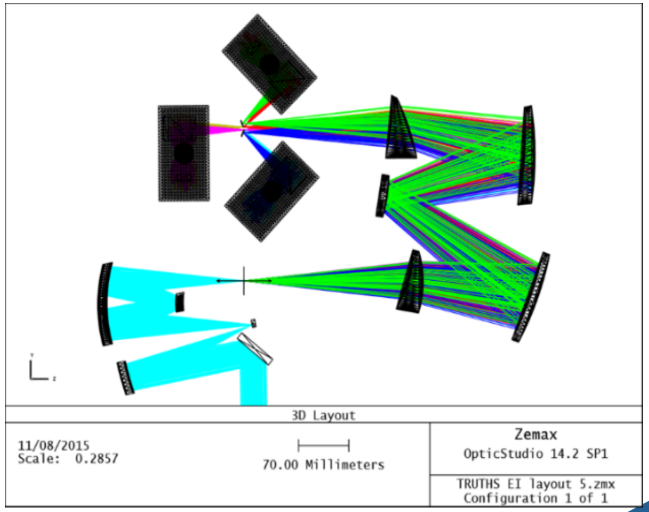
- Heat dissipation via Radiator ~ 1 m^2
  - Orbital manoeuvre to maintain cold space view
- Solar/Lunar views at Transition to eclipse with manoeuvre
- Adequate power from 2 DoF PV single sail
- 10 Minutes per orbit Comms allows date rate (X-band Svalbard)



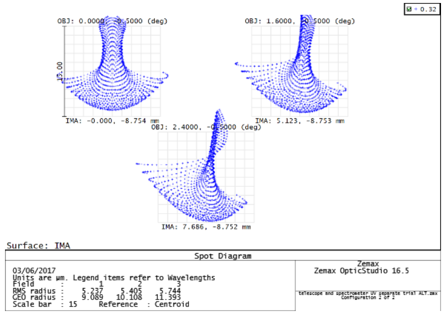
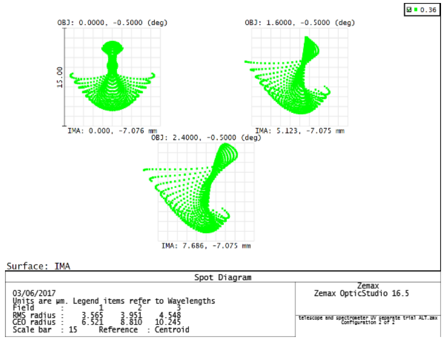
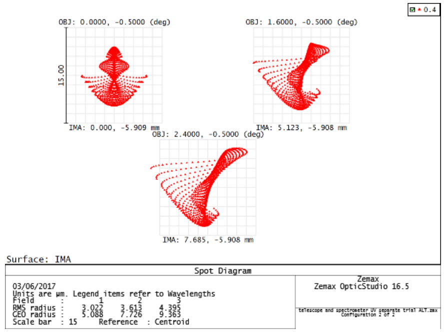
Hyperspectral Imager (HIS): Indicative design

- 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)

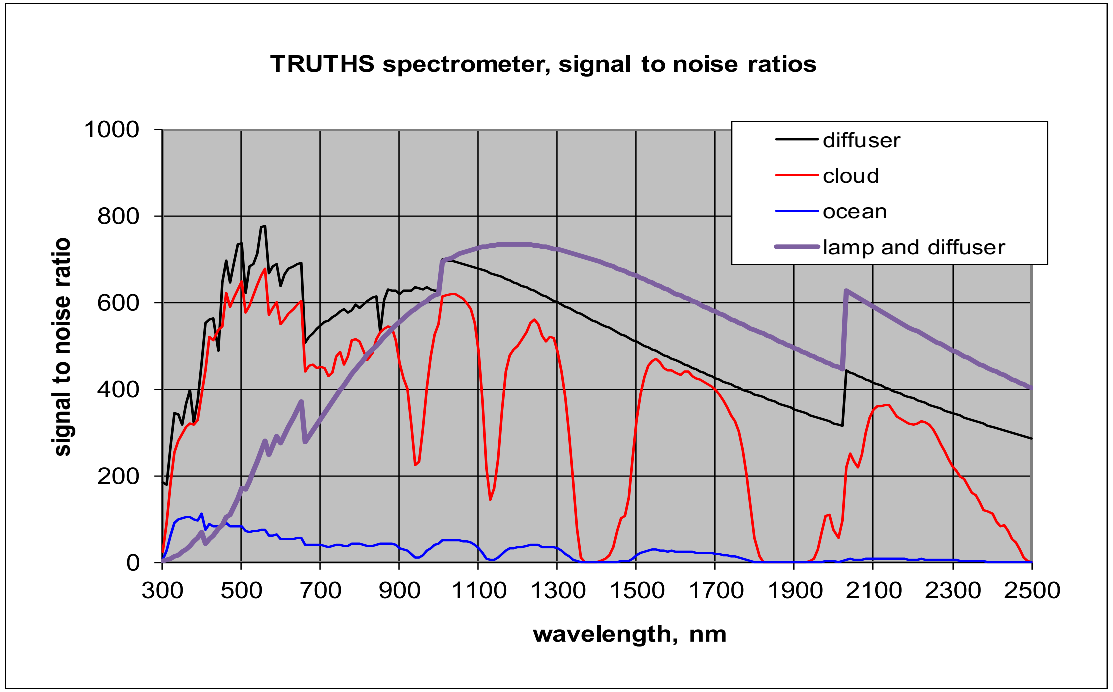
Indicative HIS above. Below: an optical layout



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**

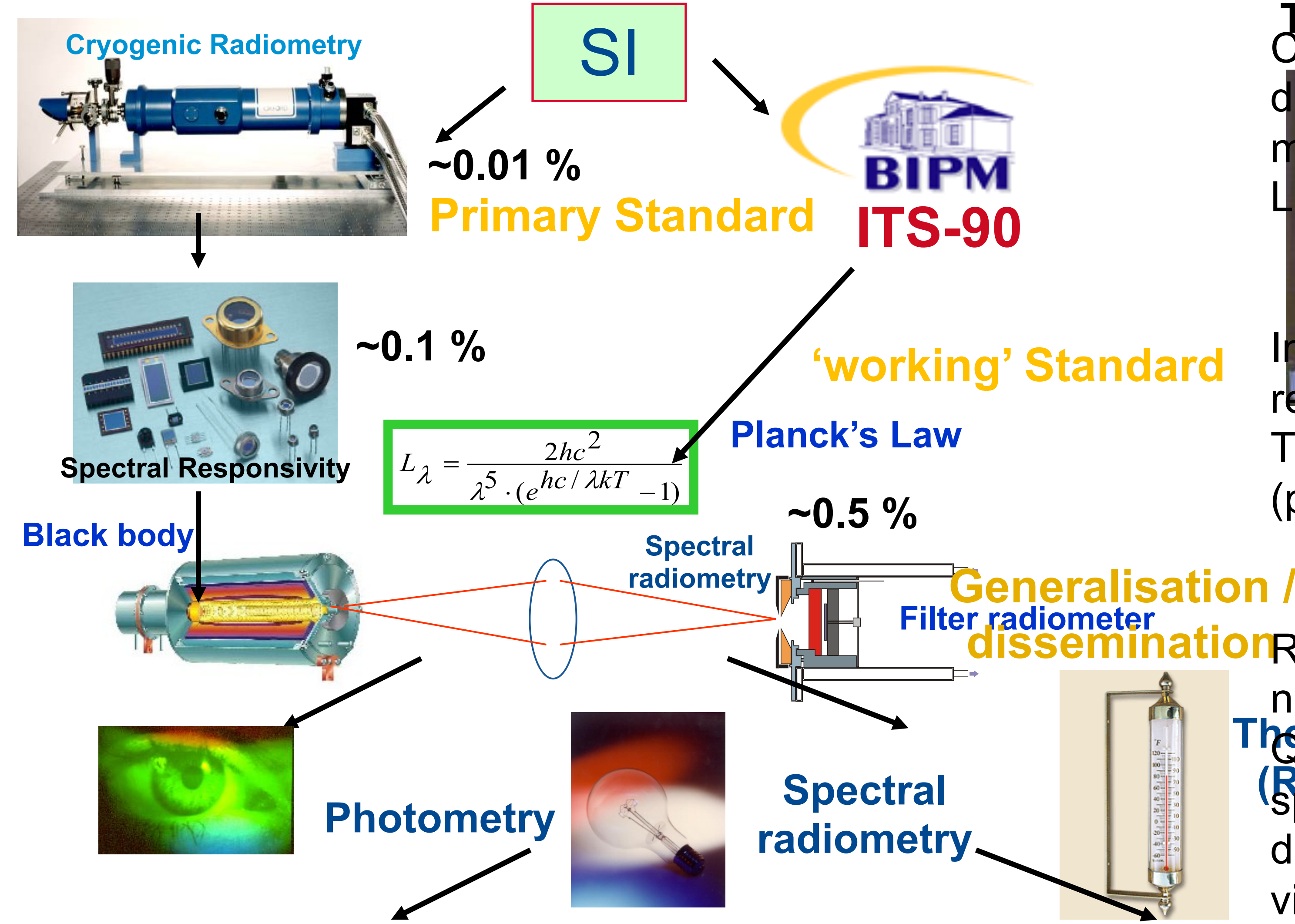
- **Bin to 250 m = ~X5 gain**
  Ocean = 500 @420 nm

- **Cross-Cal/special targets increase dwell time ~ X3**
- **Ocean = 1500 @420 nm**

DATA RATE

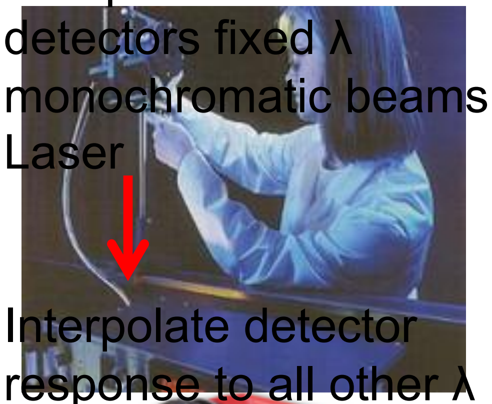
Optimised (land/ocean requirements) data transmission (single station) 4500 Gb /day

Optical Radiometric Traceability



Terrestrial instruments

Comparison to other detectors fixed λ monochromatic beams i.e. Laser



Interpolate detector response to all other λ

Then use monochromator (prism/grating)

Real world measurements need

Quasi monochromatic – spectral band defined detector with defined viewing geometry

Radiometric traceability for EO sensor

SI

Cryogenic Radiometry

~0.01 %

BIPM

ITS-90

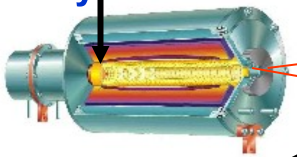
Spectral Responsivity

~0.1 %

$$L_\lambda = \frac{2hc^2}{\lambda^5 \cdot (e^{hc/\lambda kT} - 1)}$$

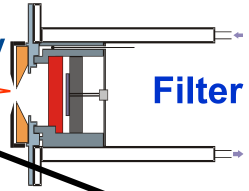
Planck's Law

Black body



~0.5 %

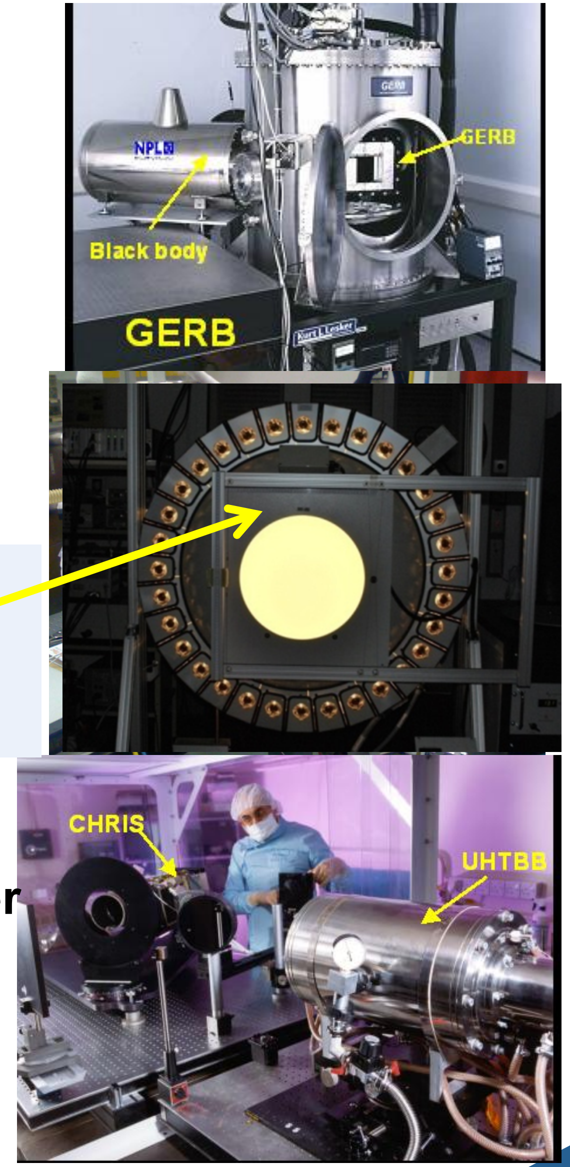
Spectral radiometry

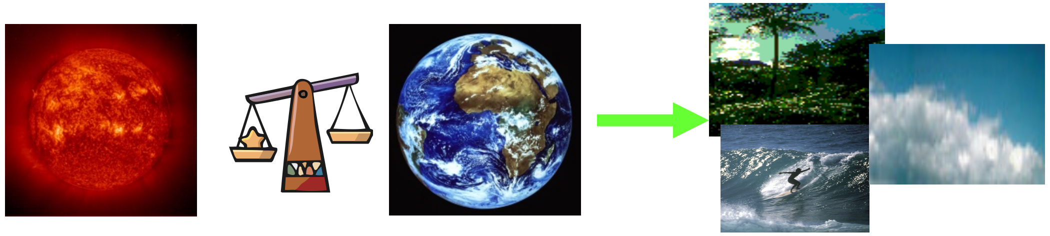


Filter radiometry

Transfer spectro-radiometer

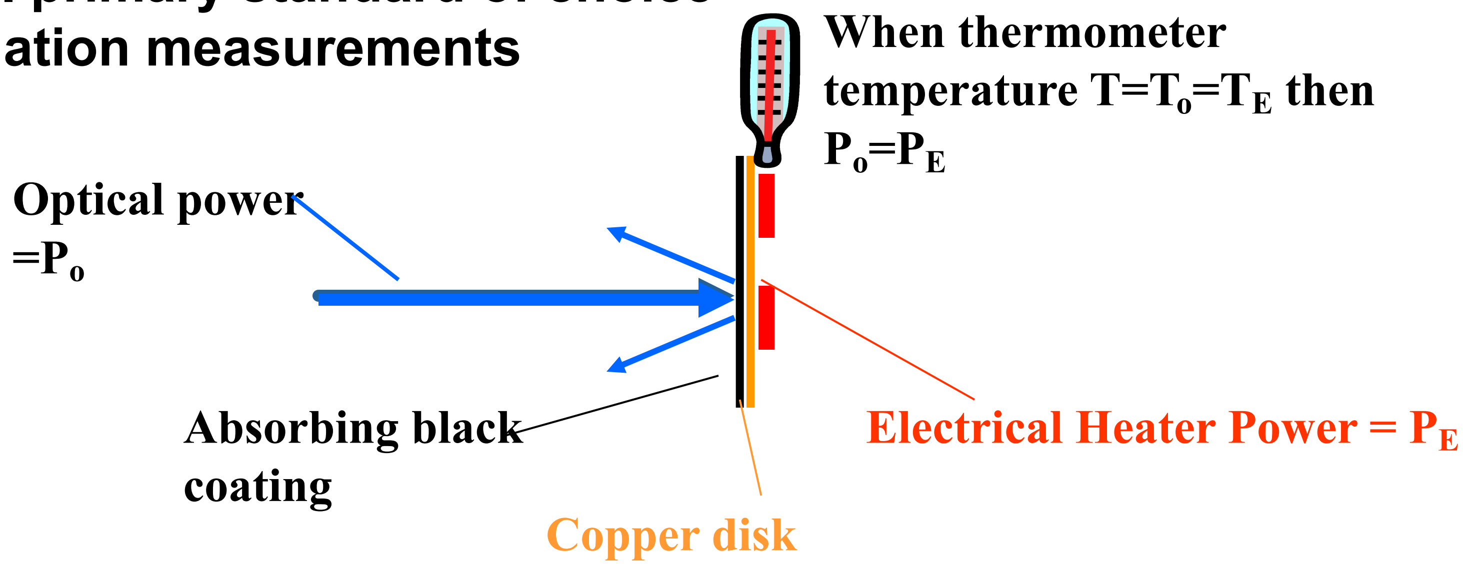
Space Instruments

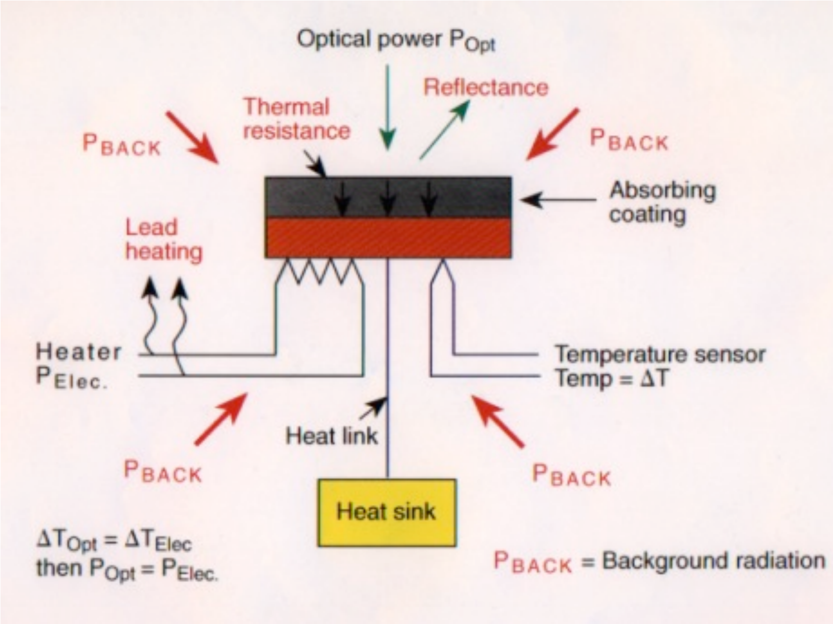




(IR)Radiances achievable but challenging !

Electrical Substitution Radiometry: A 100 yr old technology - SI primary standard of choice for optical radiation measurements



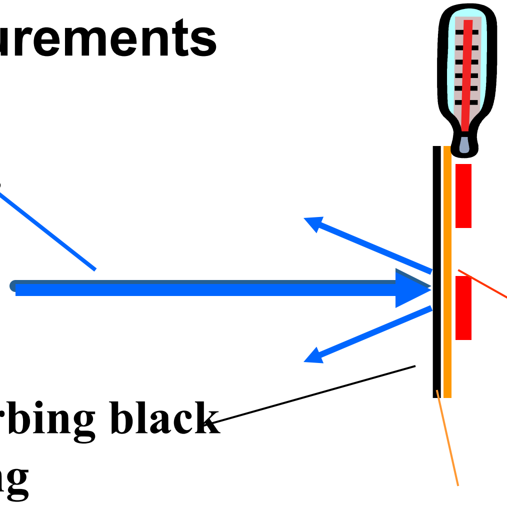


Main Sources of Uncertainty

- Surface Reflectance
- Lead (Joule) heating
- Background Temperature/radiation changes
- Electrical/optical non-equivalence

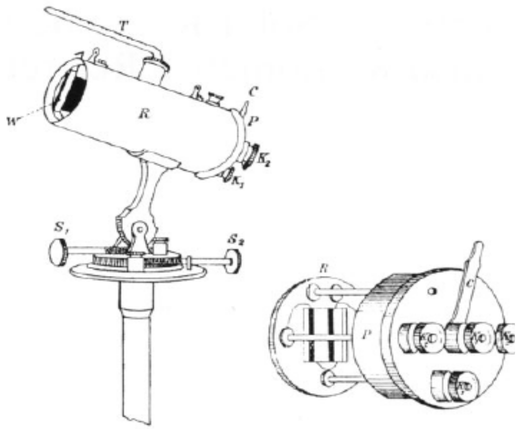
- Typical overall uncertainty ~0.1-0.3%

Electrical Substitution Radiometry: A 100 yr old technology - SI primary standard of choice for optical radiation measurements

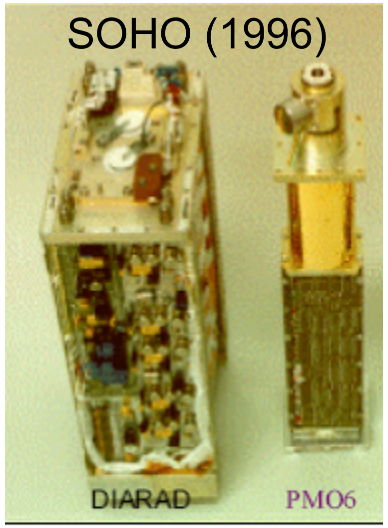


Callendar radio balance

(1910)



Ångström compensation pyroheliometer (1893)

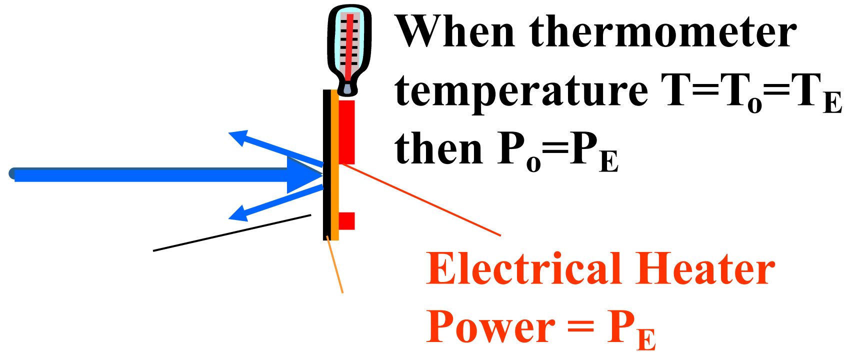


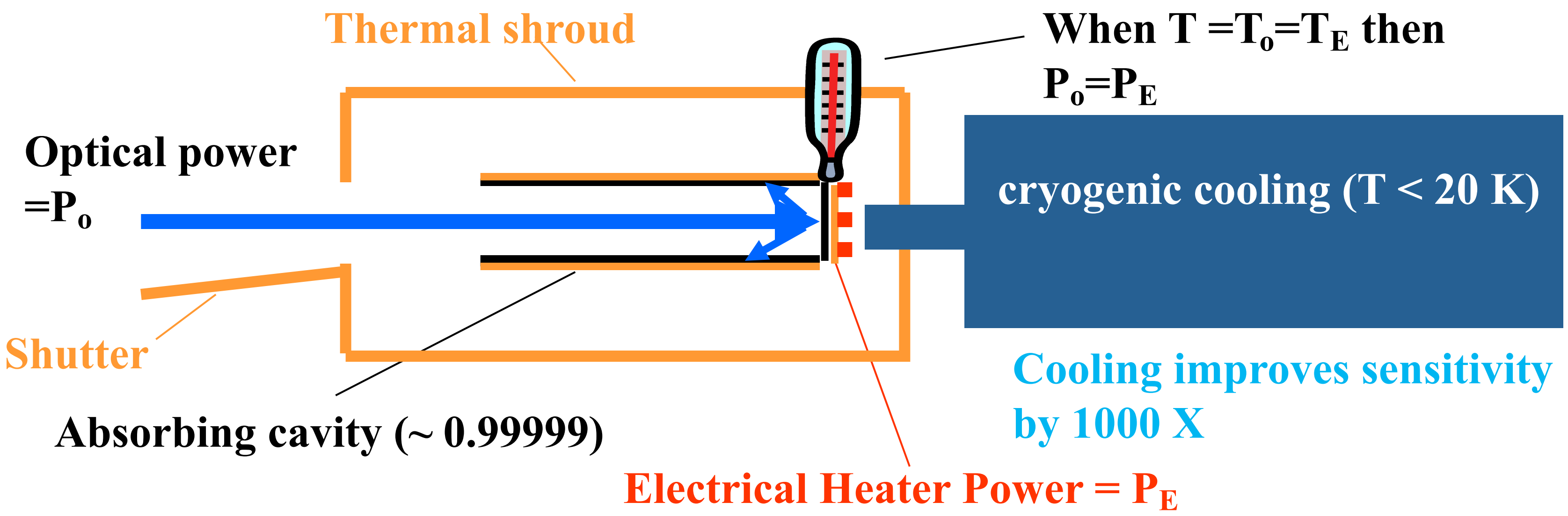
Total Solar Irradiance from Space (1975)

Electrical Substitution Radiometry: A 100 yr old technology - SI primary standard of choice

Benefits of Cryogenic operation

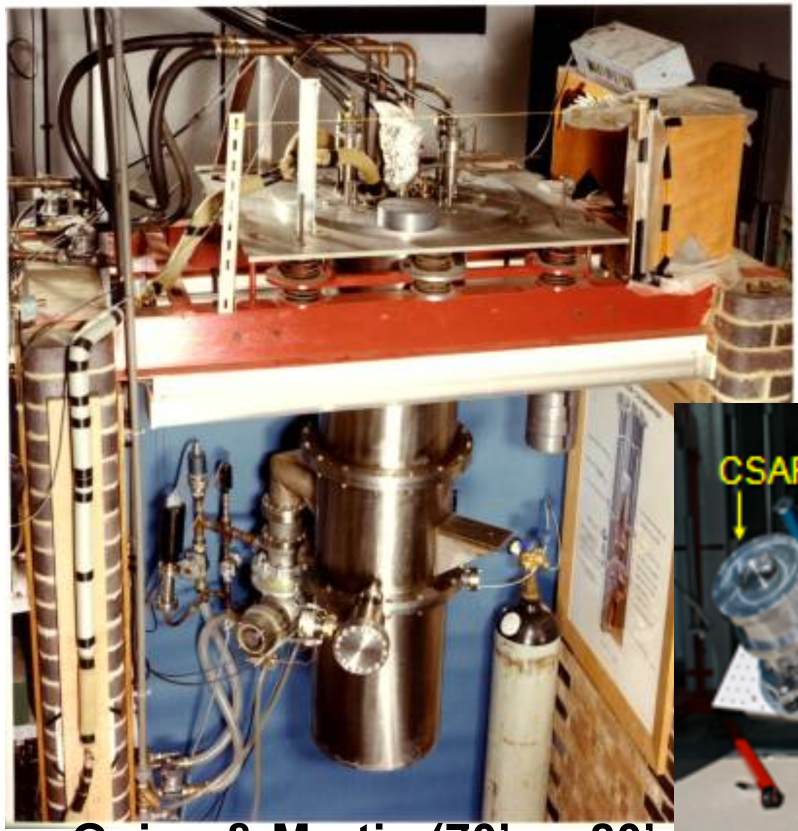
- Super-conducting leads
- High thermal diffusivity
  - Reduced non-equivalence
  - Large cavity – high absorptance
- Low radiative coupling
- Achievable Uncertainty ~ <0.002 %





Principle of Cryogenic radiometry

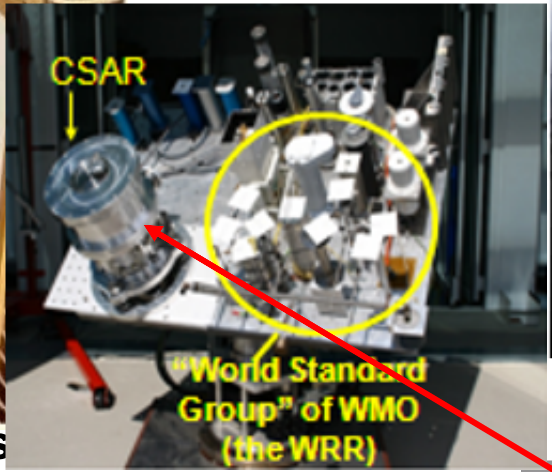
History of Cryogenic Radiometers - NPL



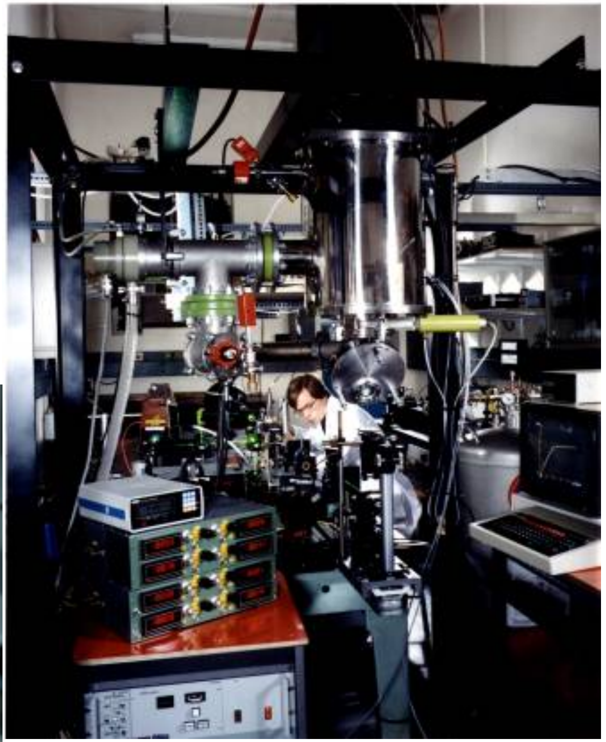
Quinn & Martin (70's – 80's)
(Designed for σ & T)

Liquid Helium

~2 – 5 K



(2015) Terrestrial Solar irradiance std for WMO

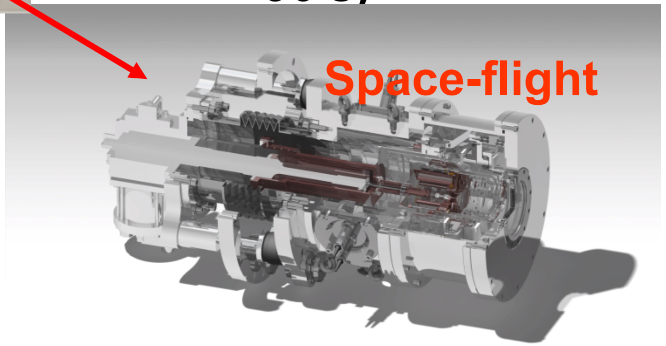


Martin, Fox, Key (80's – 90's)

Fox, Martin, Haycock (90's –)

Mechanically cooled

~10 – 20 K



CSAR v1

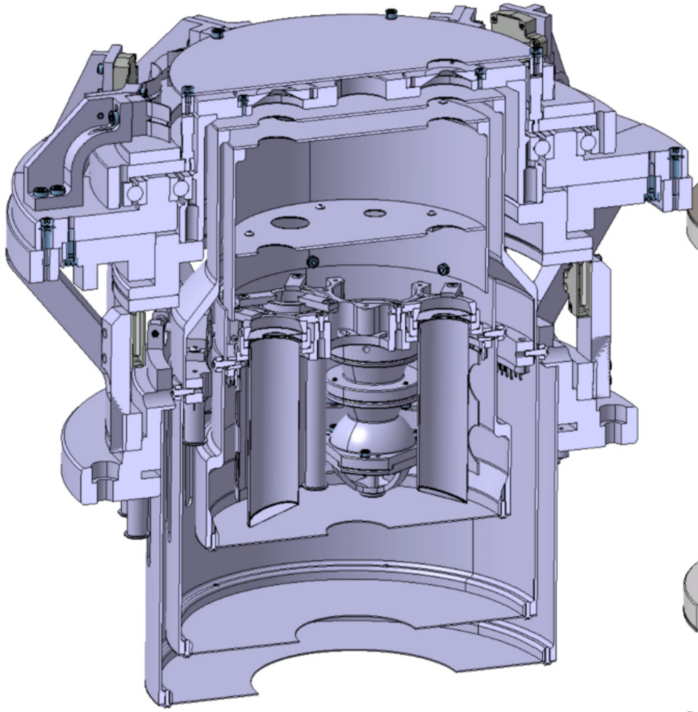
Winkler, Fox, Usadi, Finsterle, Fehlman, Blattner (10's –)

CSAR Re-design

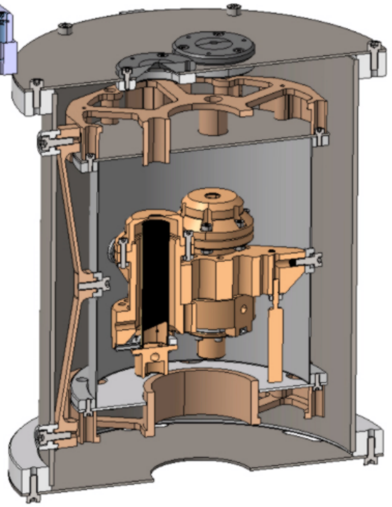
- Compares heating effect of optical power with Electrical power
- Cryogenic cooling 100X improvement in uncertainty
- 30 yr heritage (NPL concept)
- Primary standard at most NMIs

CSAR V1 @ Davos

- **Redesign achieved:**
  - Simplified operation
  - 3 cavities from 6
  - 1 cold stage from 2
- **Decreased mass, volume**
  - 9.6 kg to 3.8 kg
- **Reduced heat load**
  - 1 W to 0.5 W estimated
- **Increased absorptivity**
  - VANTA CNT black coating

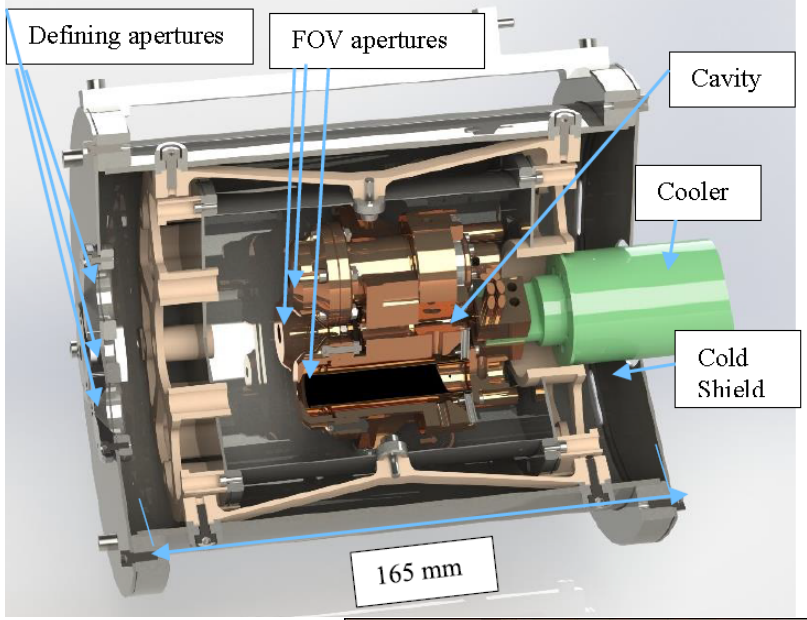


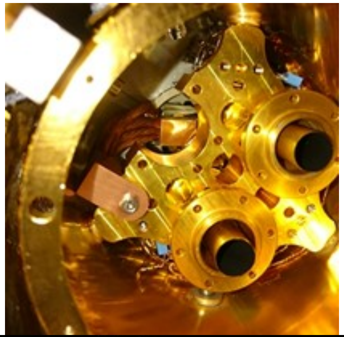
CSAR V1

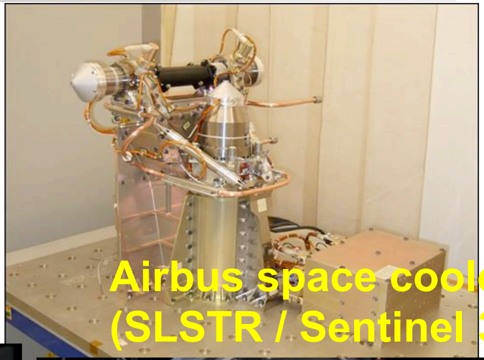


Space optimised CSAR V2

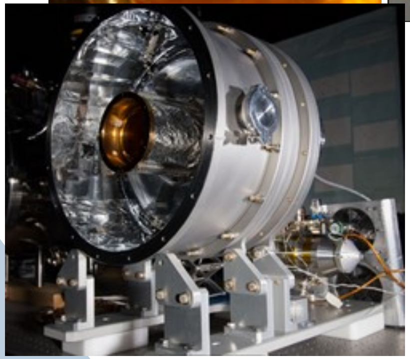
CSAR V-2: Space engineering model

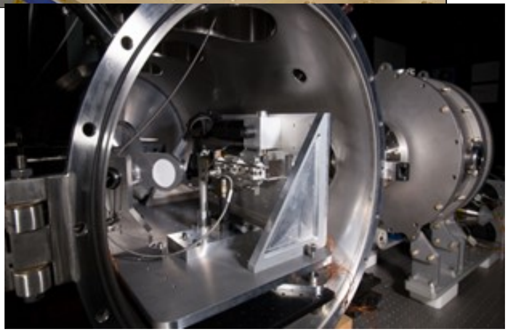




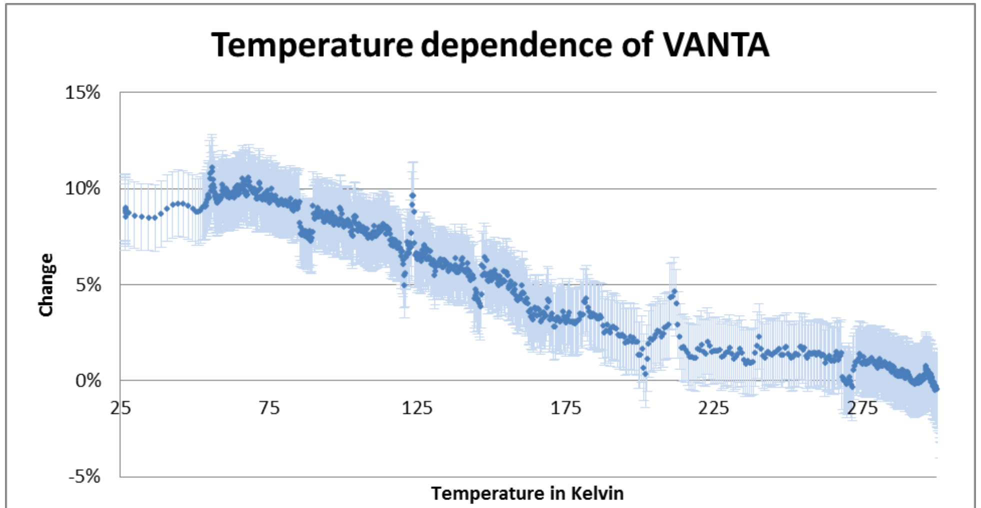


Airbus space cooler (SLSTR / Sentinel 3)



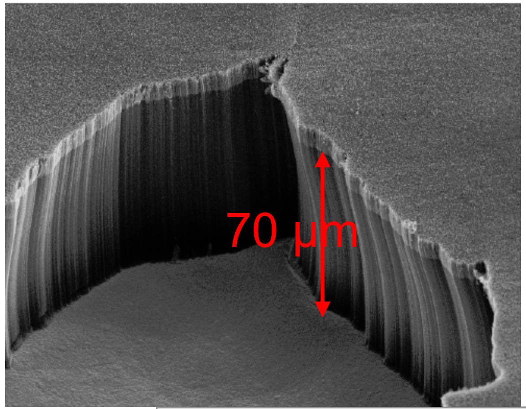


- Electrical Substitution Radiometer
- Coupled to Airbus space cooler
  1 W lift @ 45 K (upgrade)
- Mass = 25 Kg inc cooler
- Power = 150 W
- 3 cavities ~ 0.99998
- τ ~ 30 s
- CNT (VANTA) black
- Operates with full performance @~65K
- **Measures Total Solar Irradiance (TSI)**
- **Primary standard for on-board Cal system**

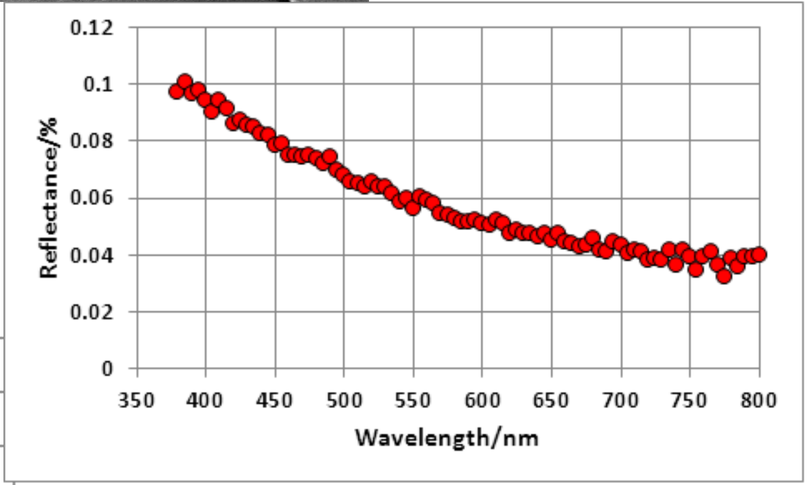


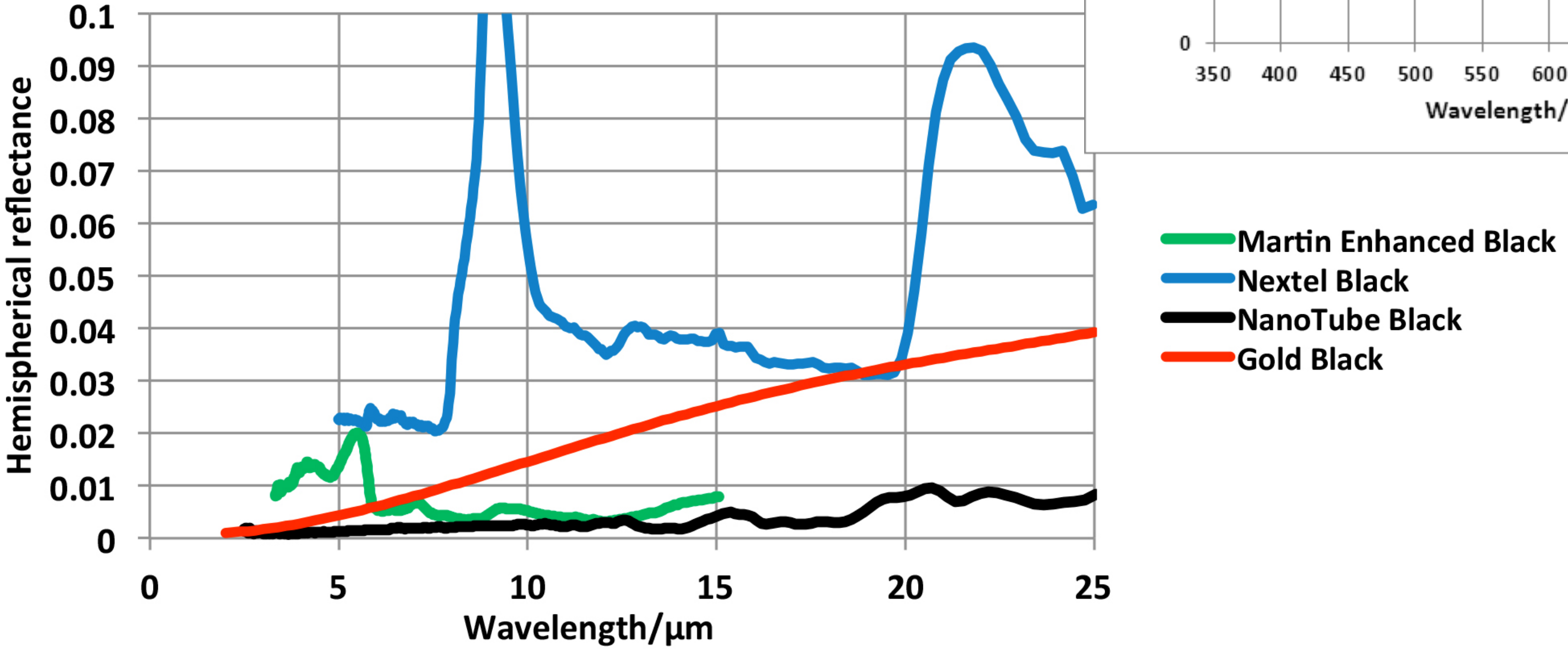
Reflectance changes <13% 300K to 25K
<3 ppm for cavity

Carbon Nano-tube black

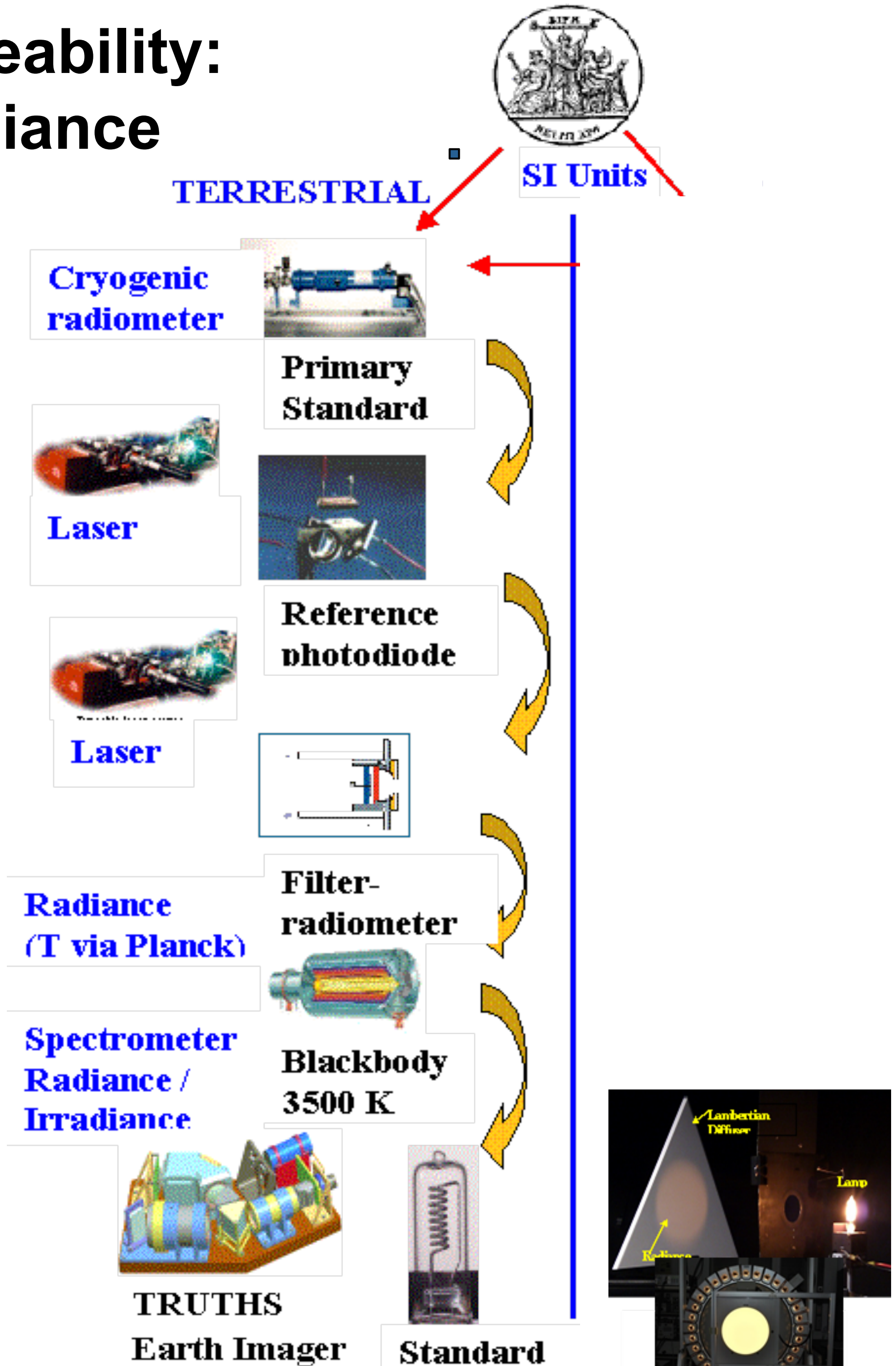


- Coating can be applied to many materials
- VERY black <1% in IR and <0.1 % in Vis
  - Suitable for Cryogenic temperatures
    - Space qualified
      - Outgassing
      - Vibration



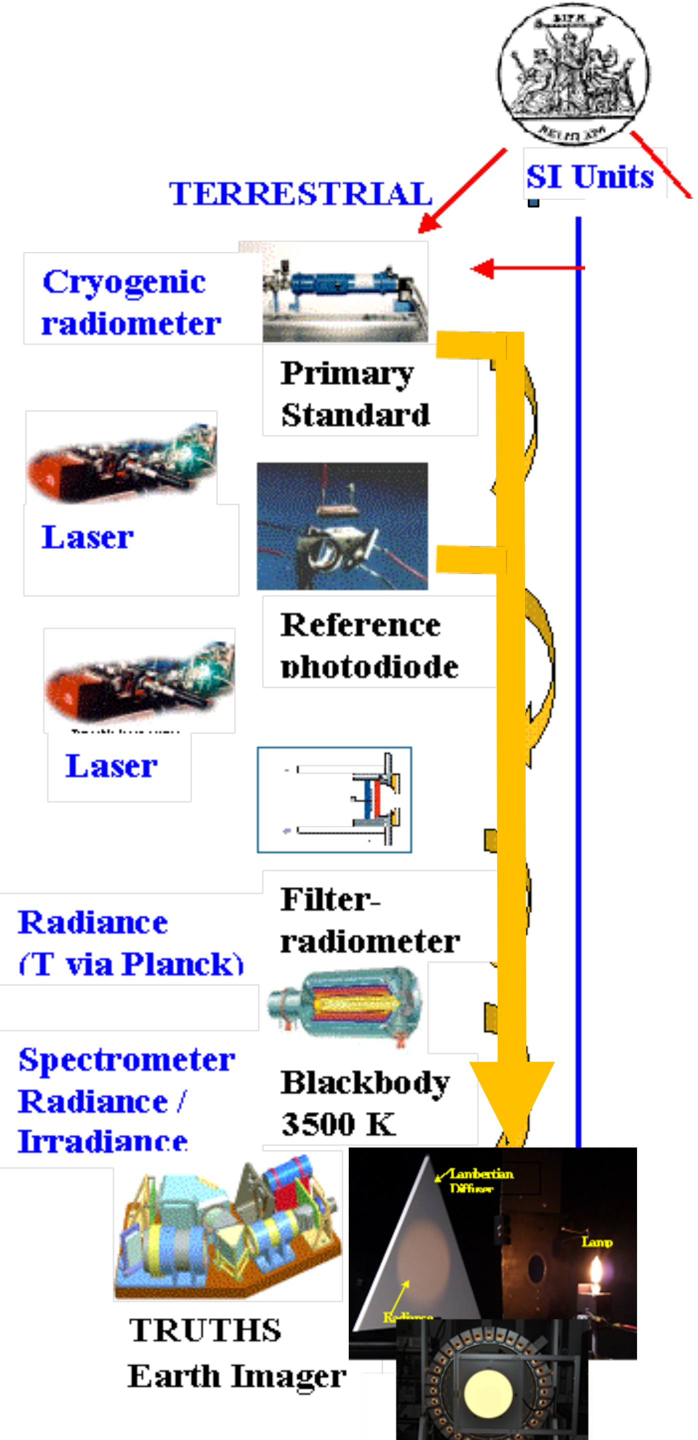


Pre-flight Traceability: Radiance/irradiance



Traceability Strategy:

- Primary reference standard is cryogenic radiometer compares heating effect of monochromatic optical power to electrical power (widely used at NMIs across the globe since 1980's)
- Solid-state transfer standard calibrated for spectral responsivity (physics allows spectral interpolation)
- 'White light' source (high T black body as solar simulator) Filter radiometer SRF calibrated using tuneable laser defines T
- Spectral radiance from Planck's law
- Compare (calibrate) incandescent lamp or similar source using spectro-radiometer



Traceability Strategy:

- Primary reference standard is cryogenic radiometer compares heating effect of monochromatic optical power to electrical power (widely used across the globe since 1980's)

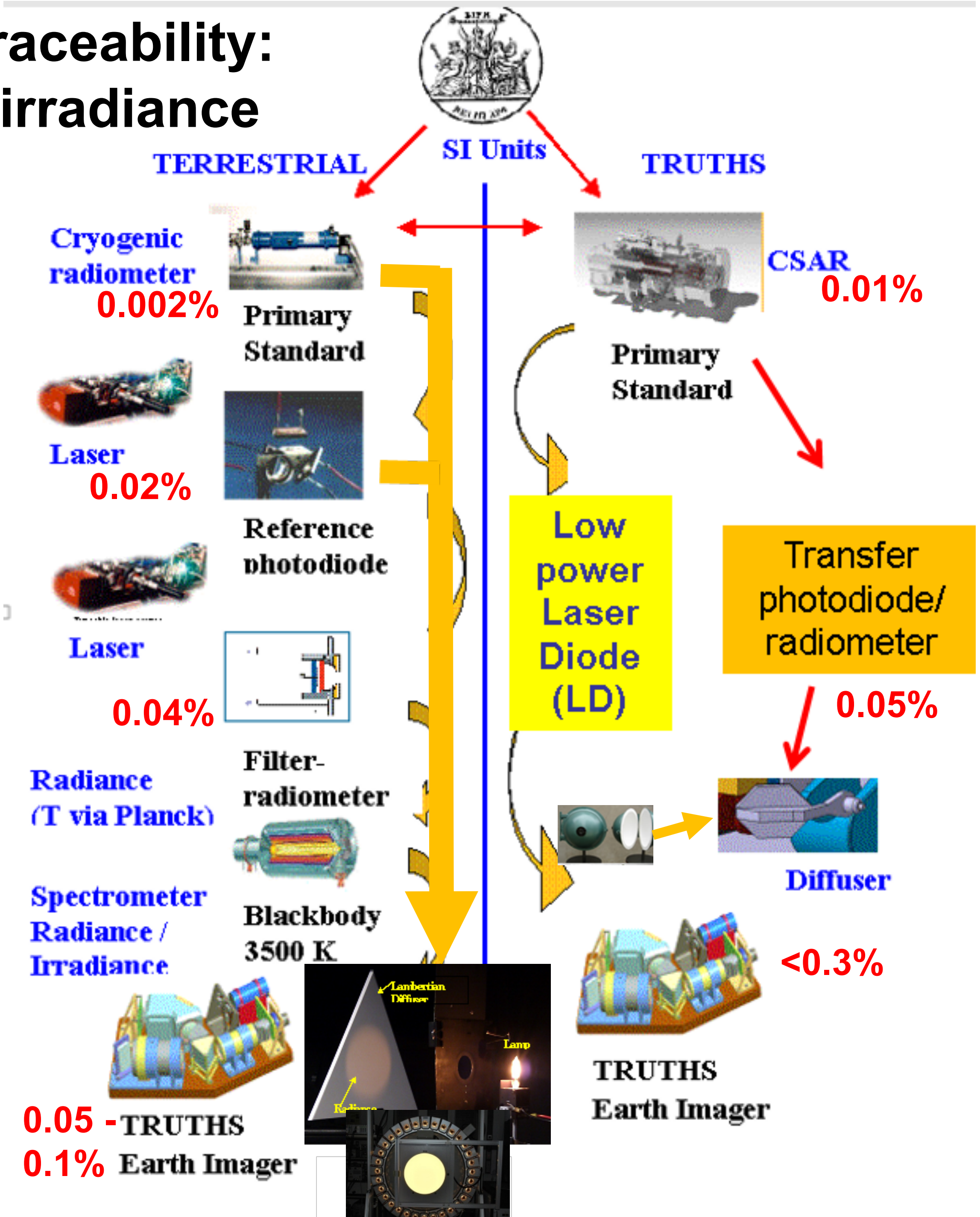
- Solid-state transfer standard calibrated for spectral responsivity (physics allows spectral interpolation)

- Direct from primary standard / spectral response to monochromatic (spectrally tuneable) radiance via laser

- Spectral radiance sphere or diffuser

-

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

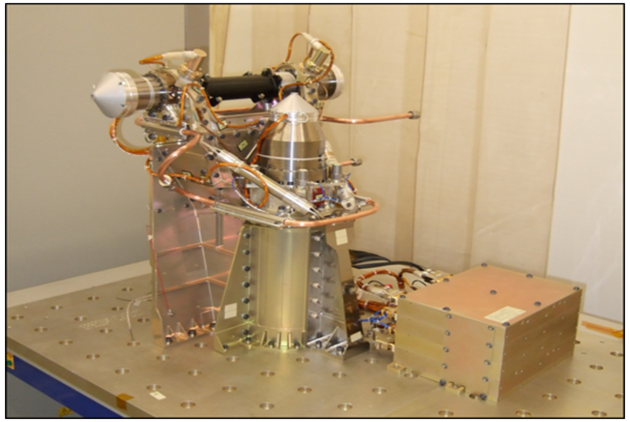
- Repeat for other λ smooth spectral shape of diffuser minimises number

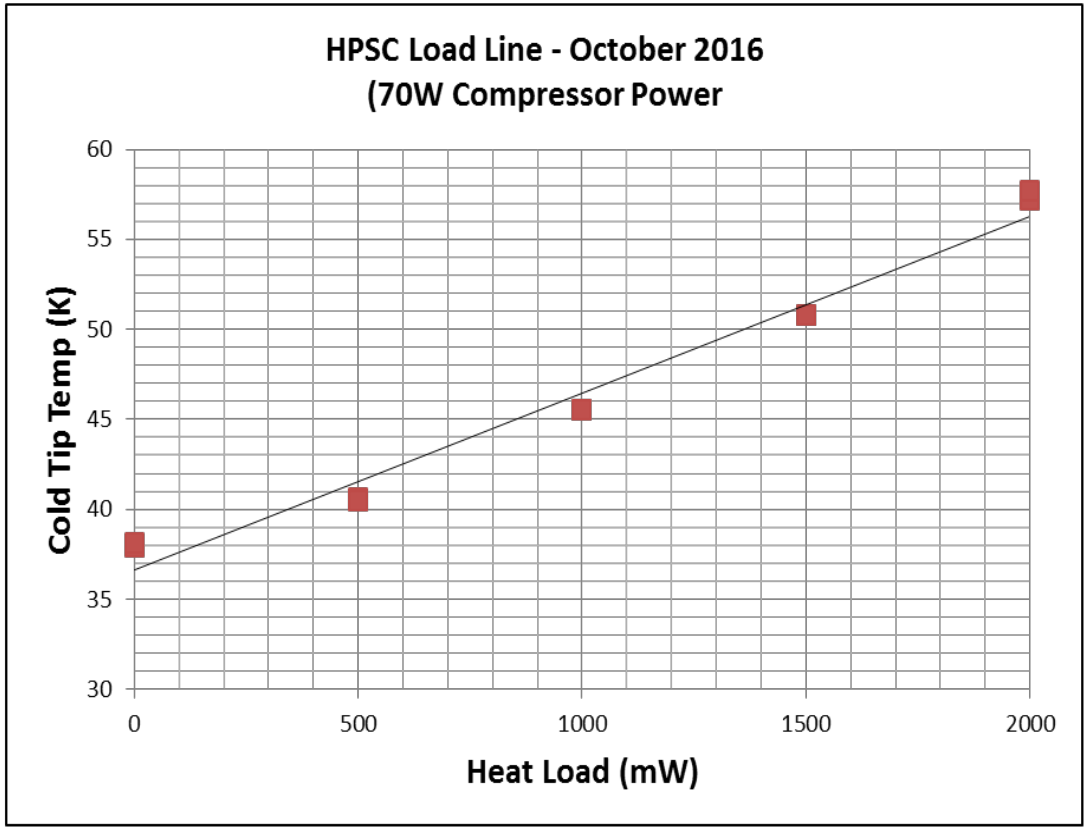
-LDs also provide λ calibration and spectral stray light check in-orbit

Cooler Baseline Performance

Post Initial-optimisation results

- HPSC has undergone initial optimisation including:
  - *Adjustment of fill pressure*
  - *Calibrated thermometry*
  - *Optimised compressor/displacer phase*
- Yields an optimised cold tip temperature of 45.5 K cold tip temp at 1000mW (@ 20C room temp.)
- Currently yielding a ~5K optimised improvement over the original 50k 1000mW baseline temperature before the project began.





HPSC cooler flying on Sentinel-3 based on long heritage of space coolers

CSAR performance stability: Active Cavity Stabilisation

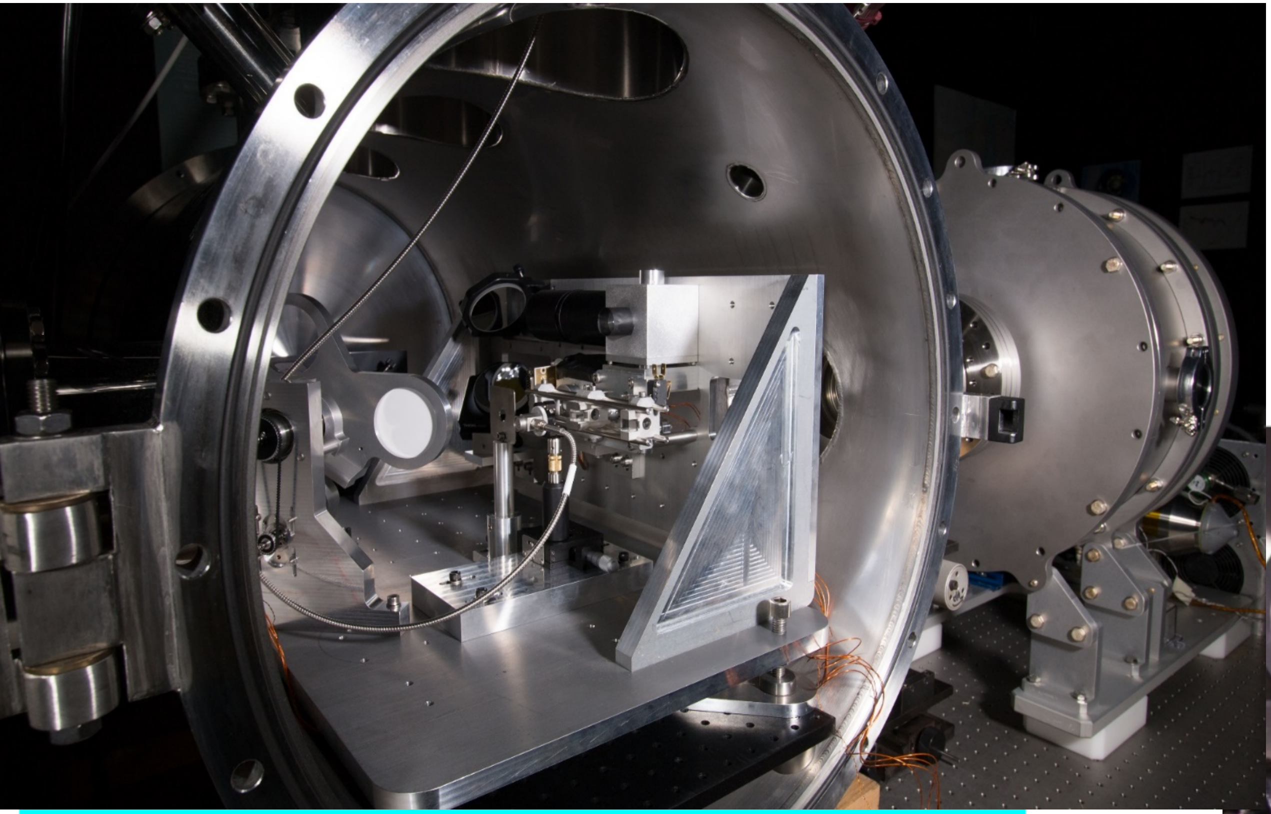
Excursion	Stability	Time	σ (% of ΔR)	N	Uncertainty	Total time
1%	± 1.36 Ω	26.0 s	0.044	20	0.006%	36.0 s
3%	± 4.09 Ω	28.5 s	0.048	20	0.007%	38.5 s
5%	± 6.82 Ω	28.0 s	0.059	20	0.009%	38.0 s

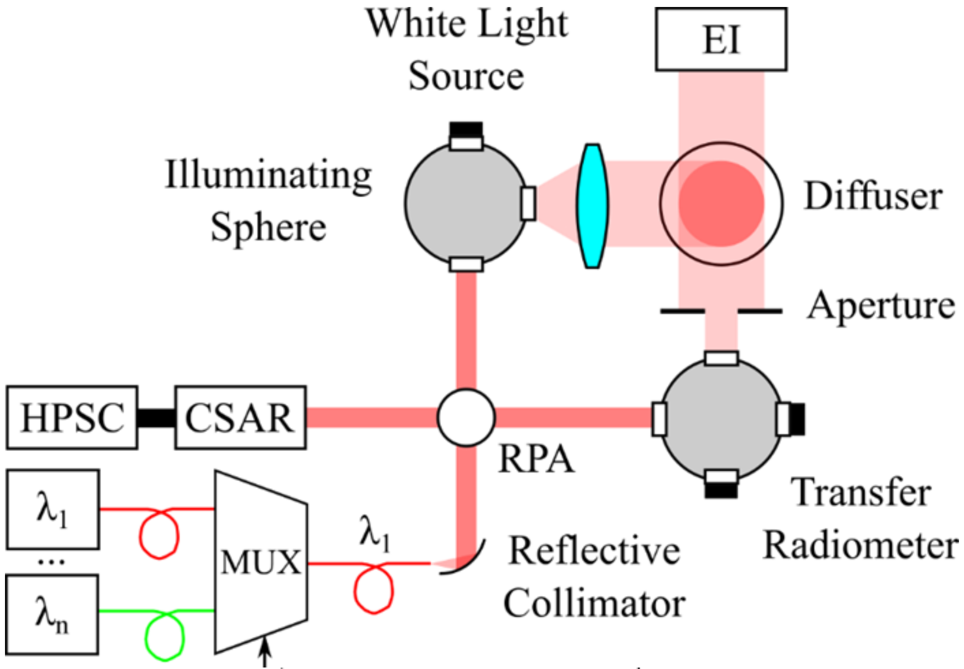
- If Input power less than 15 mW, would increase relative uncertainty but likely a smaller excursion
- Typical laser powers 1.5 mW, uncertainty becomes 0.04% for a 1% excursion (N = 20 gives 0.006%)
- Measurement of CSAR power error (systematic effects): 0.02% worst case (laser)

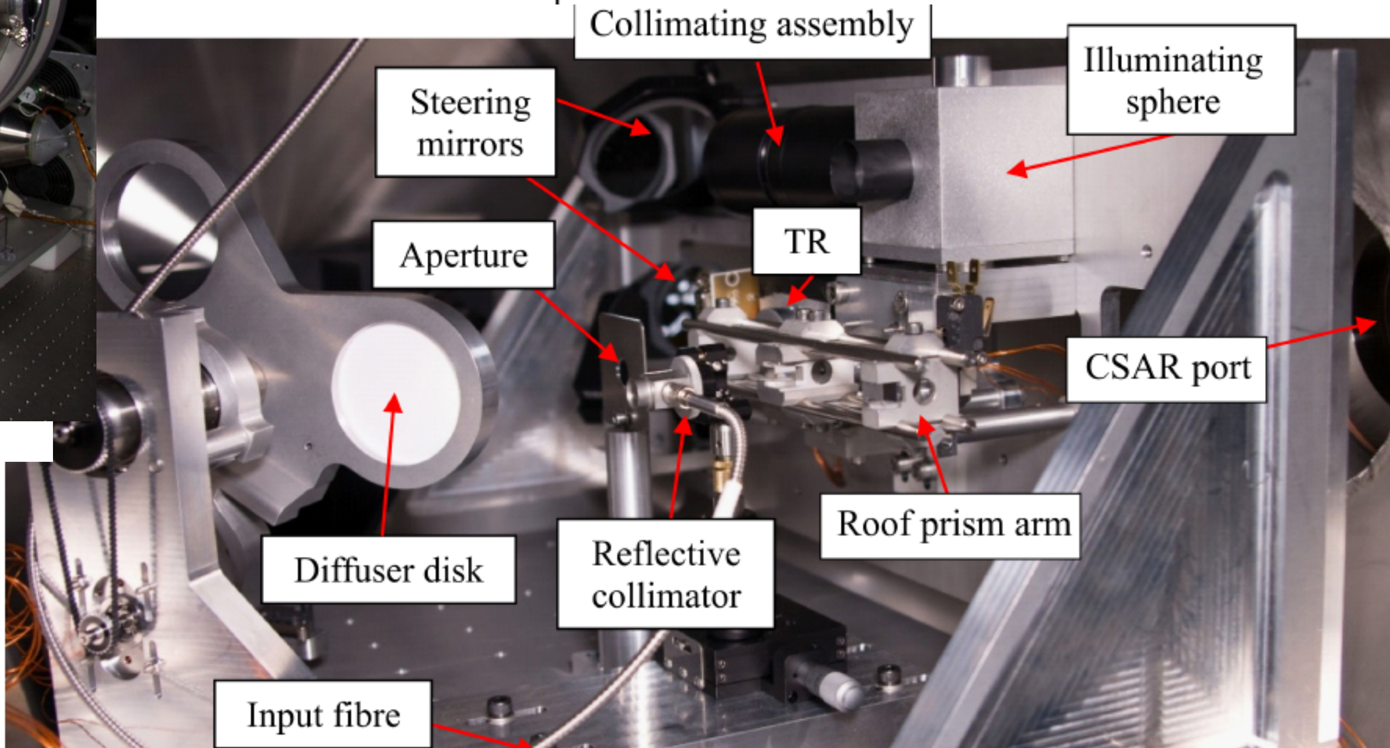
Uncertainty of CSAR for TSI and as calibration reference

Source of uncertainty	Spectral (calibration) LD reference standard Uncertainty (k = 2) / %	Total Solar Irradiance Uncertainty (k = 2) / %
Measurement of electrical power	0.010	0.010
Area of defining aperture		0.008
Cavity absorptance	0.010	0.004
Diffraction correction		0.020
Scattered light	0.004	0.004
Random noise (inc laser stab)	0.06	0.010
Total	**0.06**	**0.026**

Breadboard Calibration System

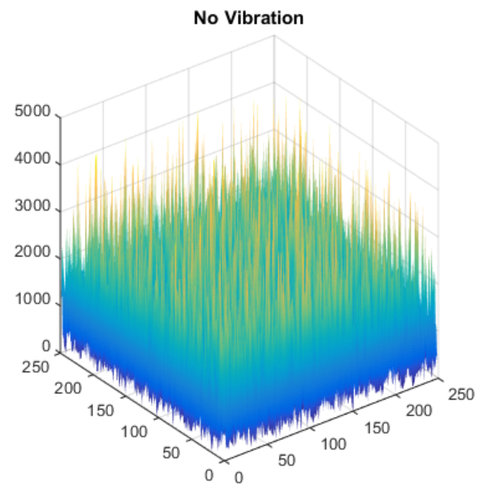


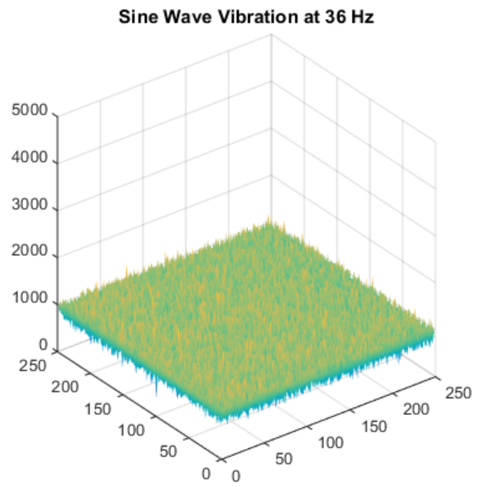




Uniformity of Diffuser Illumination: initial prototyping

- **Speckle** pattern on diffuser: potentially serious problem due to high spatial coherence of single-wavelength laser diode
- **Solution**: wrap multimode output fibre around HPSC compressor prior to collimation vibration mixes speckle, 20 % variation reduced to <1 % (currently optimising coupling and averaging) also limited by 12 bit camera on speckle facility
- **Uniformity** of radiance depends heavily on uniformity of illumination (collimation)
  Breadboard used Single fluorite lens: chromatic defocus, some higher order aberrations





Imager performance

Uncertainty Source	Lab based uncertainty	Breadboard-based Uncertainty	Space-based Uncertainty	Notes
Laser (diodes)	0.01%	0.07-0.3%	<0.07%	Space qualified, stabilized DFB lasers (lab ion laser)
CSAR / primary std	0.01%	0.06 %	<0.06 %	Worst-case scenario for laser diode power levels
Prism arm	<0.01%	< 0.01 %	< 0.01 %	Negligible
Transfer radiometer	0.02%	0.03 %	0.03 %	Voltage measurement uncertainty
External aperture	0.02%	0.02%	0.02%	Calibrated pre-flight
Traceability issues	0.01%	0.08%	0.08%	e.g. diffuser non-uniformity
HIS thermal control (1K)			0.01-0.20%	<0.05% at all wavelengths, except at extremes (<350 nm & >2200 nm)
HIS SNR			0.03%	some spatial binning for solar spectral irradiance
TOTAL	**0.04%**	**0.16-0.32%**	**0.16-0.26%**	Uncertainties added in quadrature

Reliability Assessment and Control Electronics Feasibility

- 5 year mission: R = 0.971 (7 year 0.955)
  - No critical areas for development
  - **Considered adequate for level of complexity**
  - Dependent on failure rate model of laser diode array
    e.g. loss of 3 to 4 calibration wavelengths, R = 0.9997

- Main reliability drivers identified:
  - Cryocooler assembly, drive electronics (R = 0.9876), displacer (R = 0.9969) and compressor (R = 0.9977) all non-redundant
  - CSAR control, on-board computer (R = 0.9939), assumes any OBC can control any of 3 CSAR cavities (fully cross strapped)
  - Transfer radiometer (R = 0.9985), assumed non-redundant

TRUTHS CSAR control electronics can be constructed entirely with space-qualified components, with all performance requirements met

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

Next Steps

- May 2019: ESA Member states adopted TRUTHS into its EarthWATCH program and open for ‘subscriptions’ for initial Phase A/B1 + in November Ministerial €42M (UK expected to be major funder / ESA member state partners welcome)
- September 2019: User requirements study KO
- November 2019: Program approval at ESA ministerial council Space 19+
- Q2 2020: KO of A/B1
  Pre-developments include:
  - Hyperspectral imager Qualification model
  - CSAR (qualification model)
  - Calibration system (Qualification model)
  - Raising TRL to 6
  - Sensor to Sensor Cal system prototyped
  - Metrological Uncertainty analysis (Fiduceo like)

International partnerships explored

- Nov 2022: Full funding commitment for TRUTHS implementation – transition to Phase B2/CDE
- Q4 2026 target launch TRUTHS (5-8 yrs operations) Data: Free open source
- -UK ground segment (PDGS)   Flight Opd TBD