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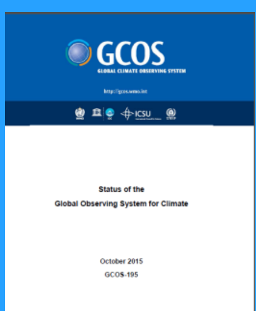
Centre for EO Instrumentation

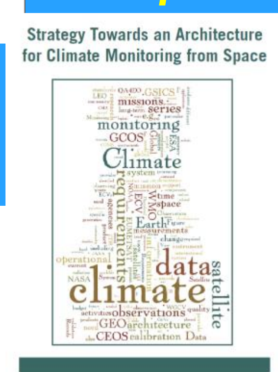
TRUTHS (Traceable Radiometry Underpinning Terrestrial and Helio-Studies): Establishing a climate & calibration hyperspectral observing system in space '*A new paradigm for Earth observation*'

Nigel Fox
(on behalf of TRUTHS 'CEOI' team)



195 (2015)

"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



CEOS/CGMS/WMO (2013)

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

TRUTHS: What is it? A small satellite mission, to enable 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

Through global measurements:

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 km swath + multi-angle	0.3
Total Solar Irradiance (TSI)	0.2 – 35	NA	NA	>500	Daily	0.02
Solar/Lunar Spectral Irradiance (SSI)	~0.30 - 2.4	1 to 10	NA	>300	Daily	0.3

- **Provision of '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**

Focus on Needs of ECV's

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
Cloud optical thickness			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/spatial coverage) yes	yes yes
Ocean Colour	Carbon cycle	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

Centre for EO Instrumentation

Has enabled:

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- Mission concept to be optimised (e.g.7 motions to 2) and key technologies to be designed, prototyped, de-risked to TRL 5/6 and address ESA review questions

  - Mission Req Doc
  - On-board calibration system (disruptive element)
    - Upgrade of space cooler
    - V2 of CSAR ‘primary standard’
    - Vac breadboard of flight representative Cal system
  - Design and performance modelling of imager
  - Platform accommodation (ConOps) (Airbus & SSTL)
    - Sat / ISS
    - Thermal, Mass, Power, Data

Hyperspectral (~300 -2350 nm) imager and its Simplification (Dan Lobb)

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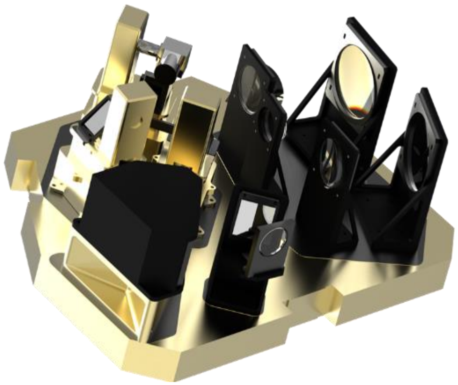
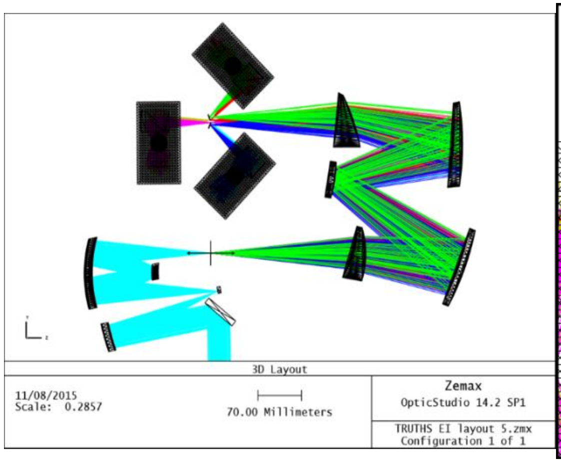
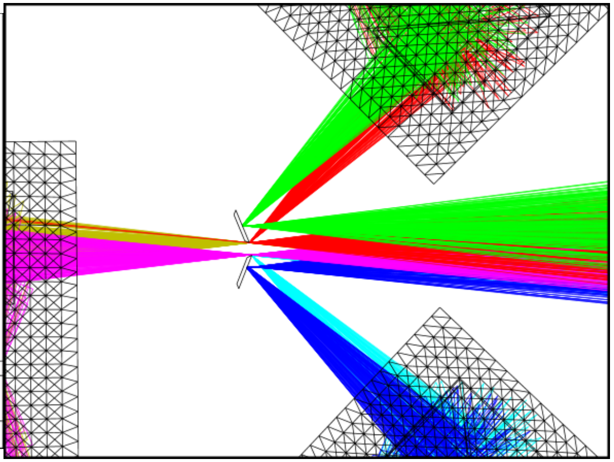
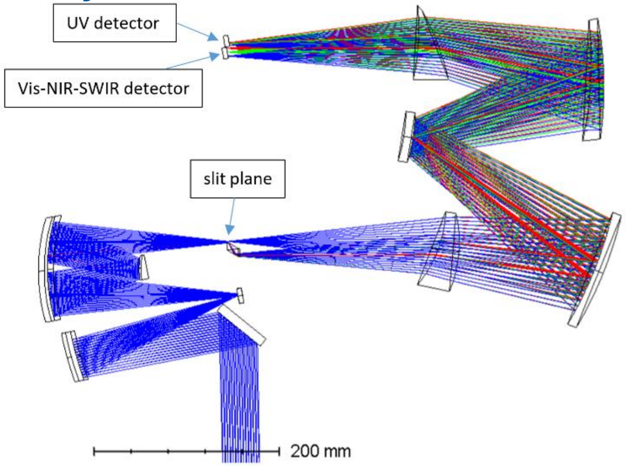
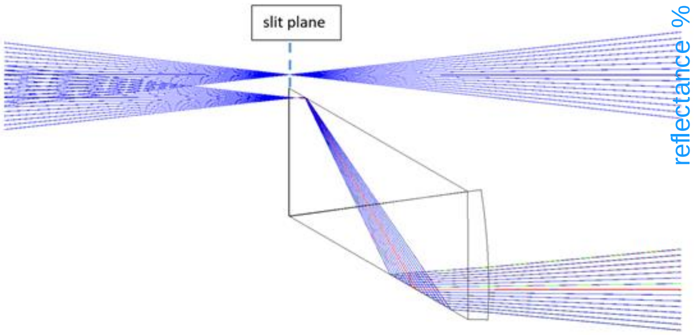




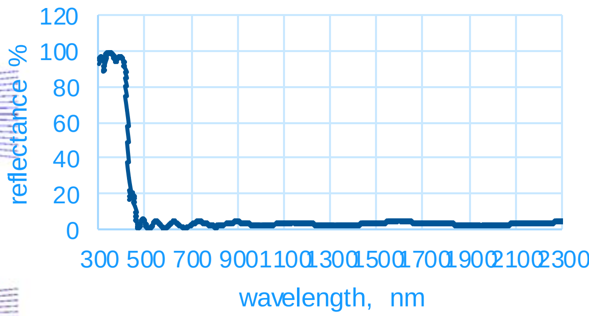


Original Baseline used single spectrometer but split to 3 detectors via a relay system – concern over detector number and knife edge mirrors for beam separation





UV-reflecting mirror



Sofradir wide spectral range CMT detector allows a 2 detector design also channel separation at ~ 420 nm reducing criticality of coregistration and Si detector design

Imager performance

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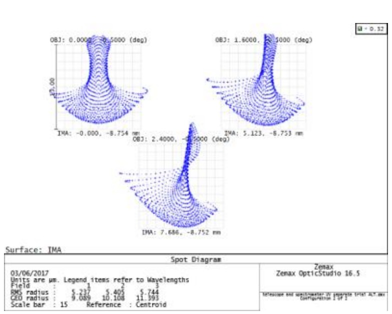
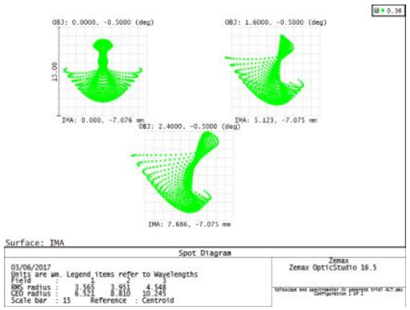
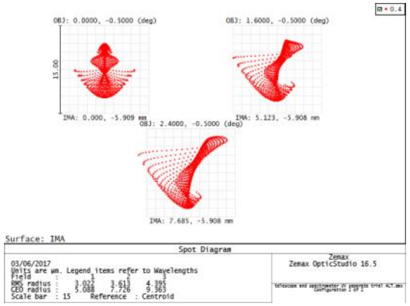
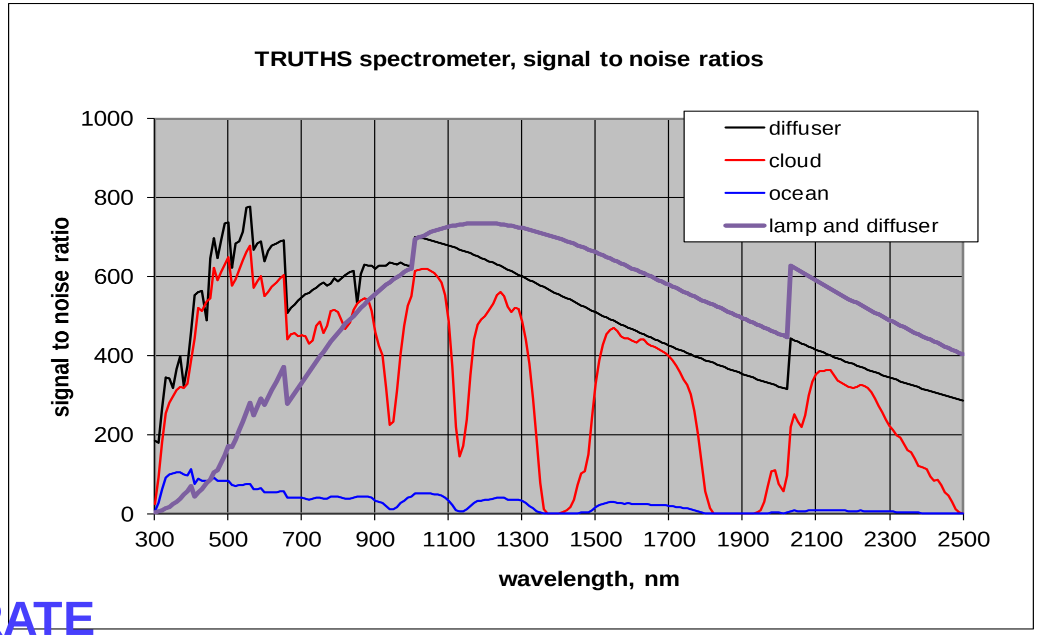






Boxes 0.015 mm Sq



Imager performance for 18 ms sample (50 m) can gain significantly by 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

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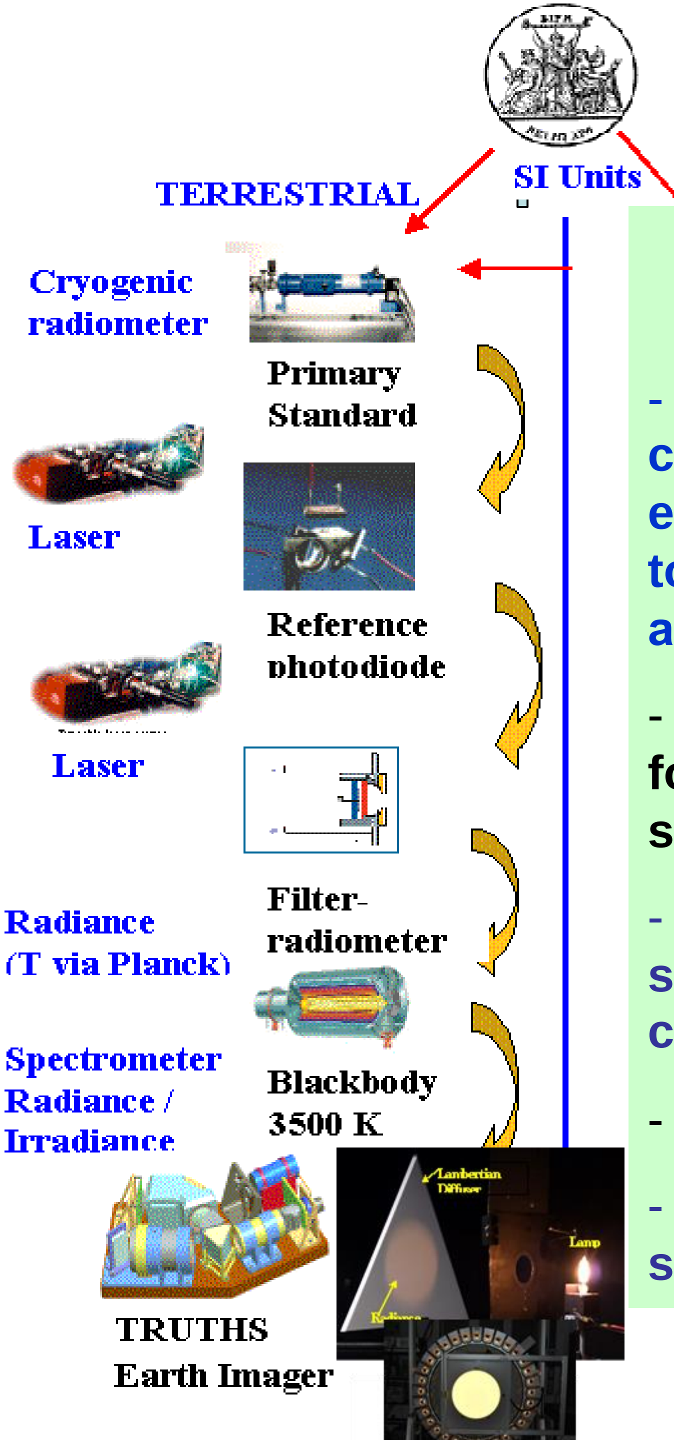

Traceability Strategy:

- 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

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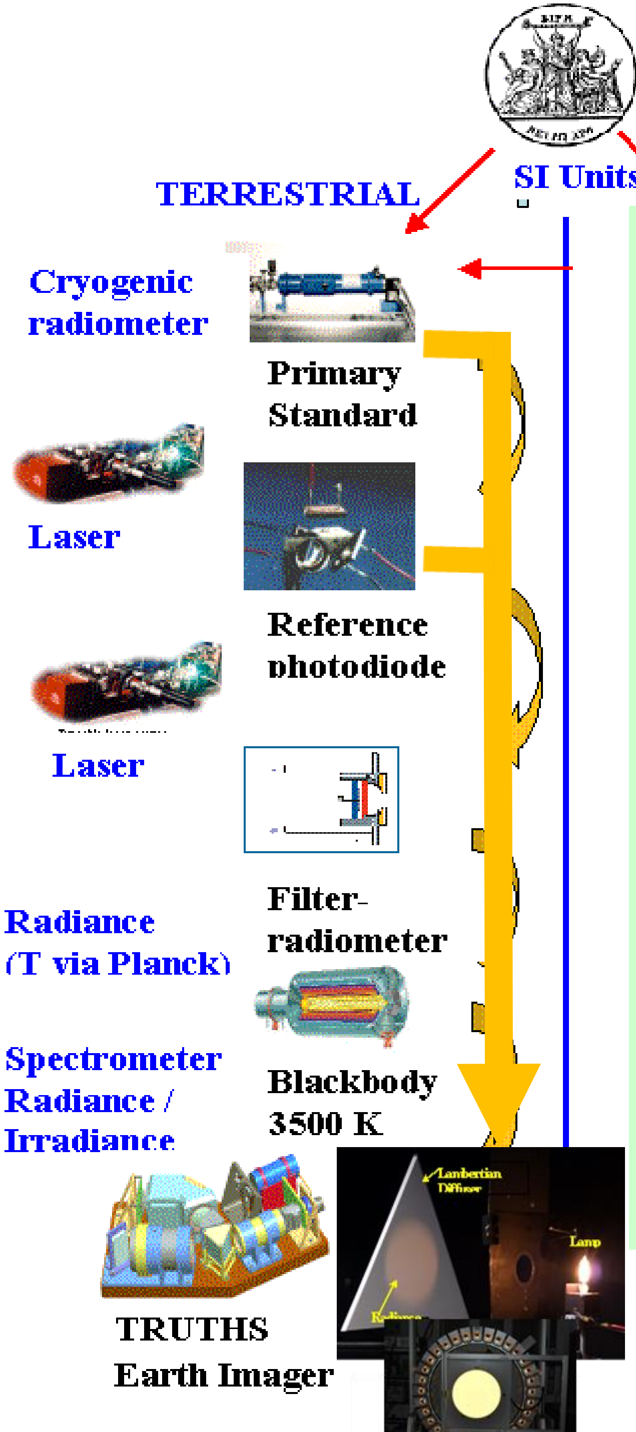
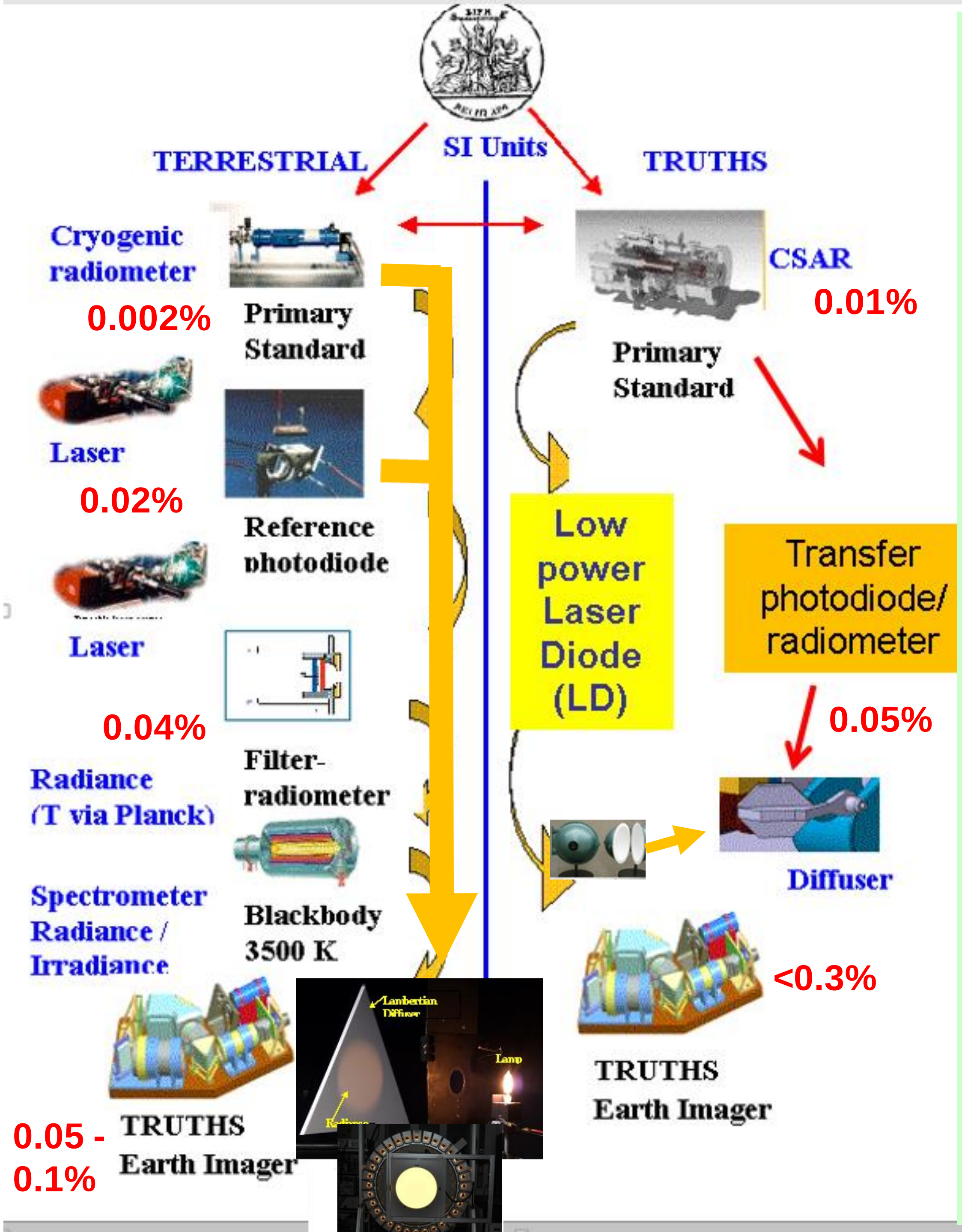


Traceability Strategy:

- 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
-



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

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

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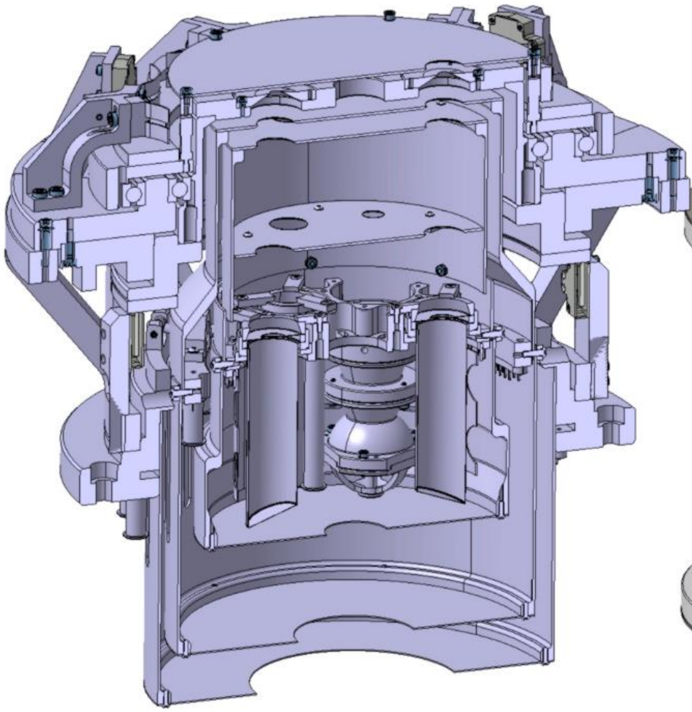
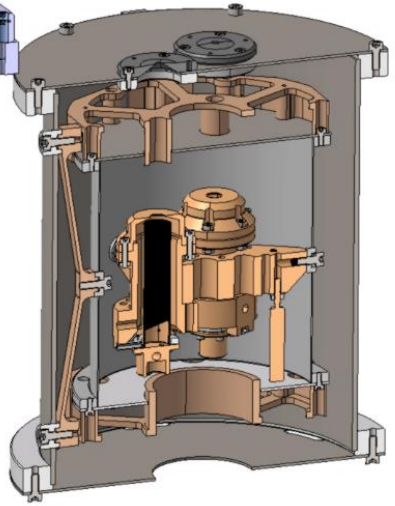
CSAR V1 @ Davos

- **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

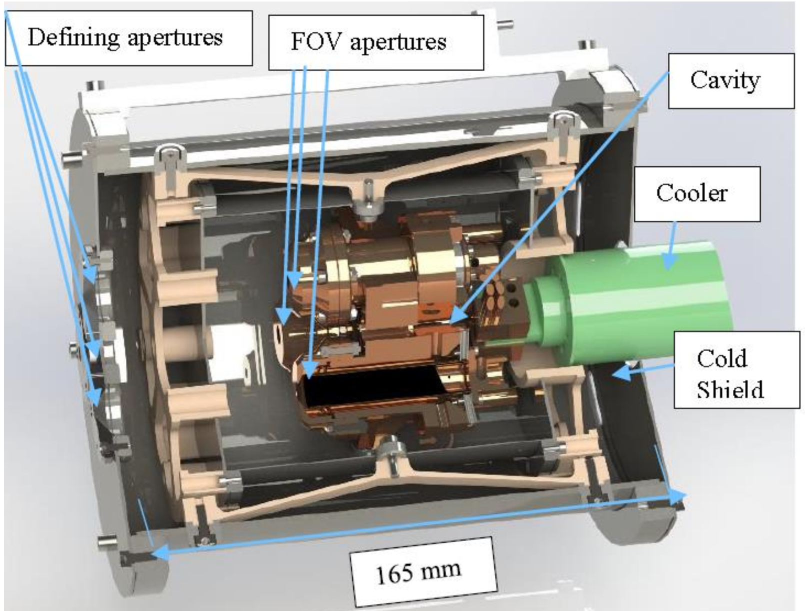


CSAR V1

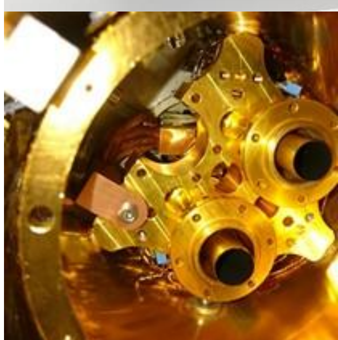


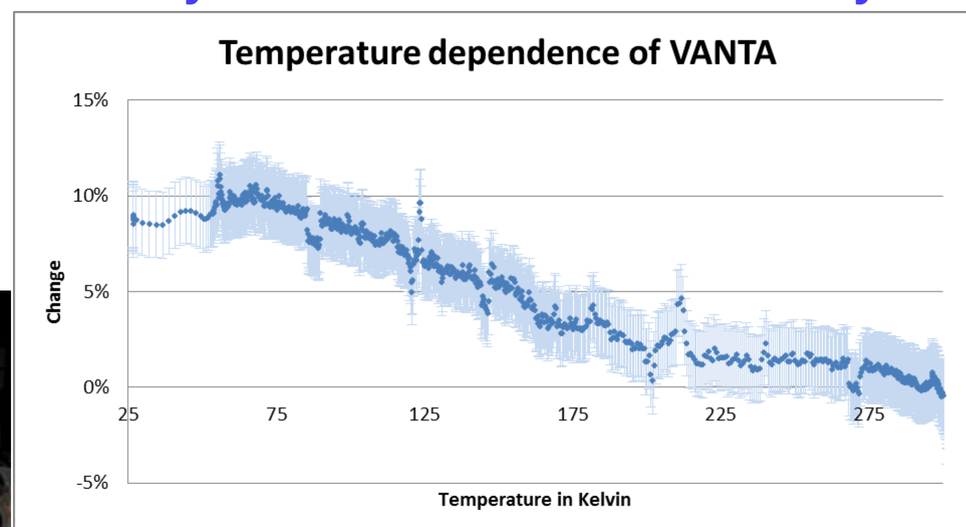
Space optimised CSAR V2

CSAR V-2: Space engineering model



- 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**

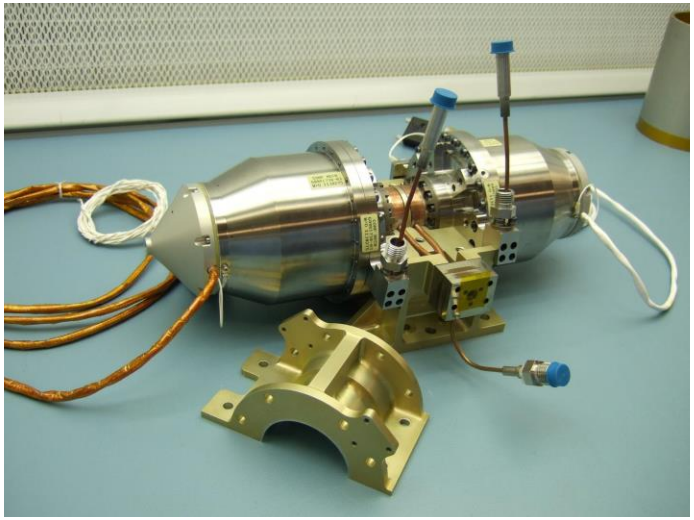




Reflectance changes <13% 300K to 25K
<3 ppm for cavity

High Performance Stirling Cooler Rebuild and Optimisation

- Airbus HPSC initially developed as ESA project for space applications
- Development of Astrium 50-80K cooler (>1M hours of in-orbit heritage), high level of common parts
- During initial build compressors had high stiction, possibly reducing performance
- 50 K cold tip temperature with 1 W heat load original



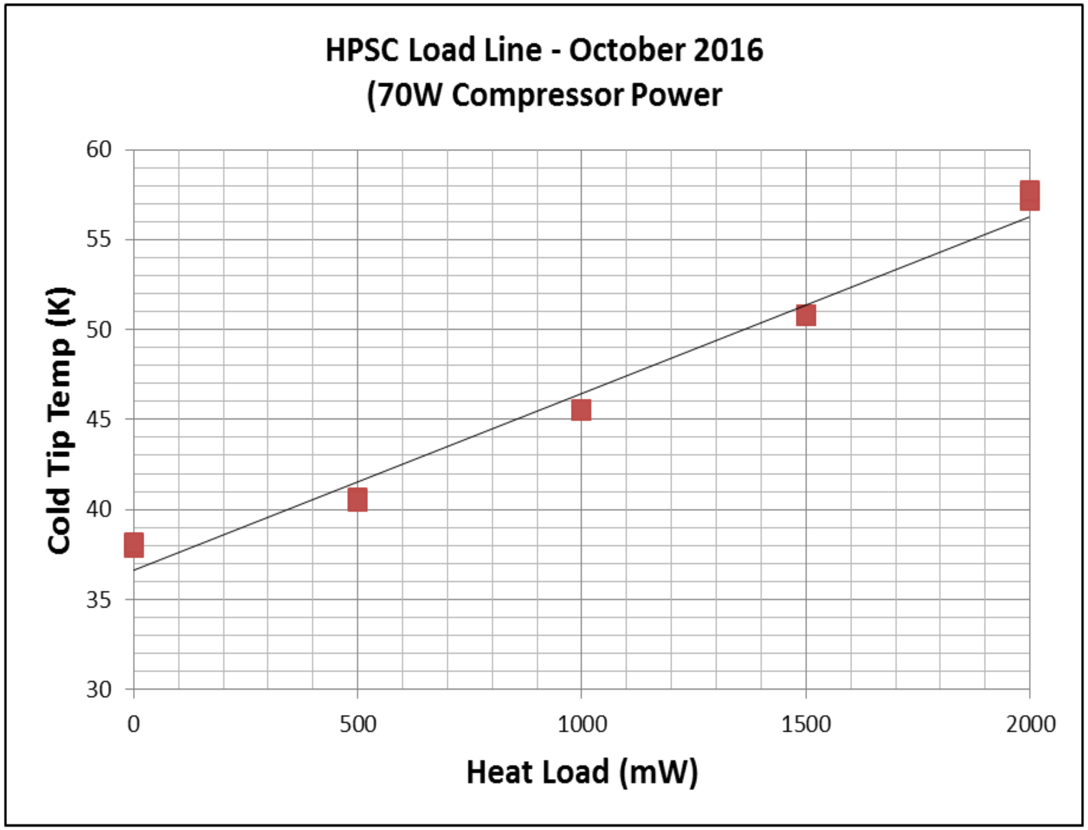
Rebuild aim:

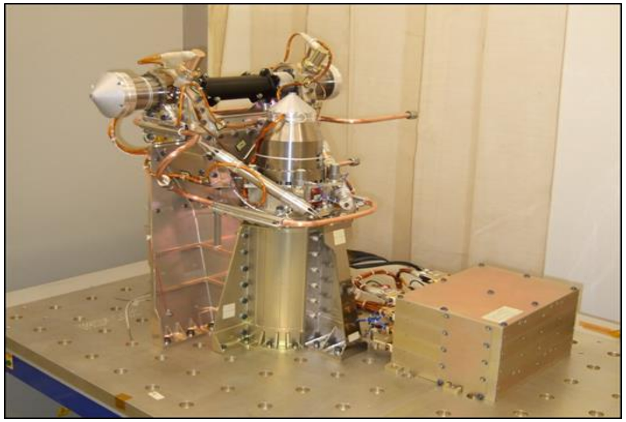
- Reduce stiction
- Optimize operating parameters
- Ideal: 30 K @ 1 W

Cooler Baseline Performance

Post Initial-optimisation results

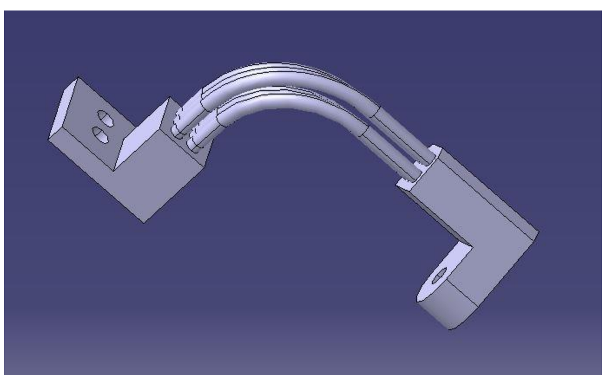
- HPSC has undergone initial optimisation including:
  - *Adjustment of fill pressure*
  - *Calibrated thermometry*
  - *Optimised compressor/displacer phase*
- Yields an optimised cold tip temperature of 45.5 K cold tip temp at 1000mW (@ 20C room temp.)
- Currently yielding a ~5K optimised improvement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





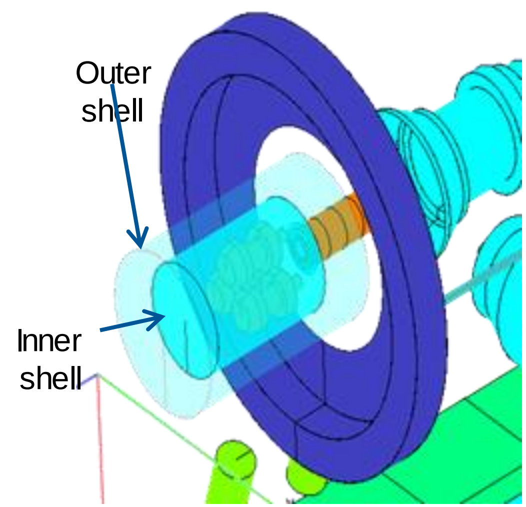
CSAR Design Tradeoffs

- Initial design at 30 K: sensitivity 0.0004%, time constant 15 s
  - Unlikely HPSC will achieve 30 K operating temperature given heat load of CSAR
- Increase in operating temperature results in decreased sensitivity and increased time constant
  - Trade-off: further sacrifice sensitivity (within requirement of 0.01%) for decrease in time constant
- Two options considered for trade-off
  - Alternative (more conductive) material for heatlink
  - Active cavity configuration



Space worthy heat link HPSC to CSAR

Thermal analysis and optimisation of CSAR and cryostat



Active Cavity Stabilization

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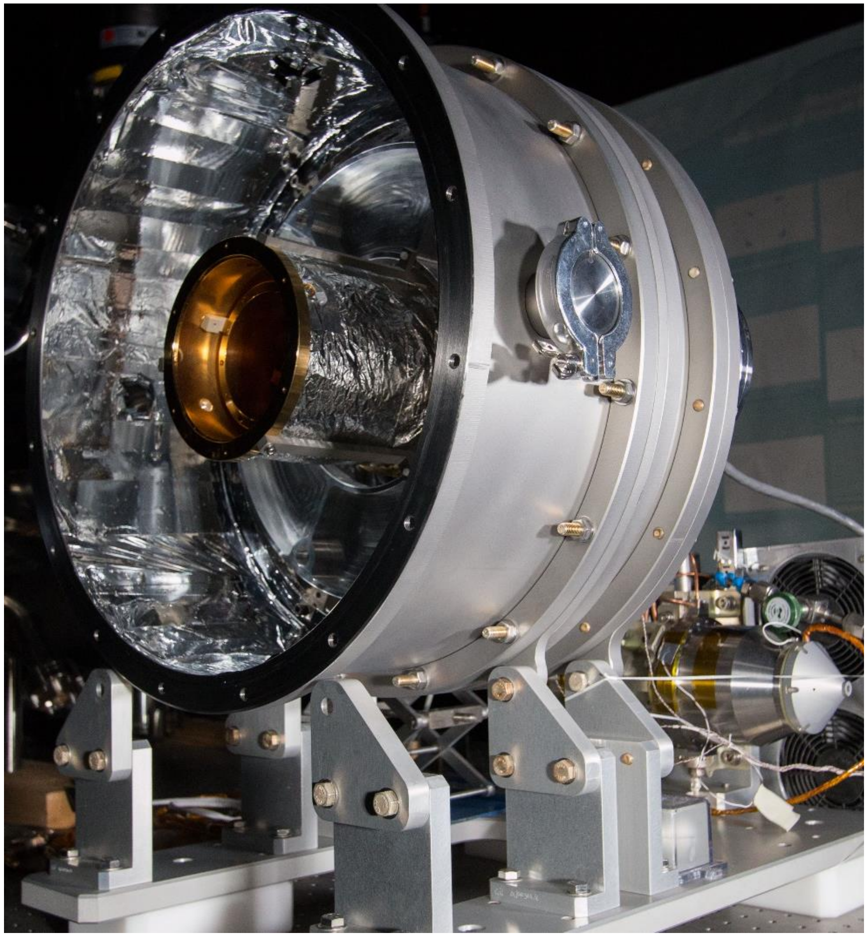
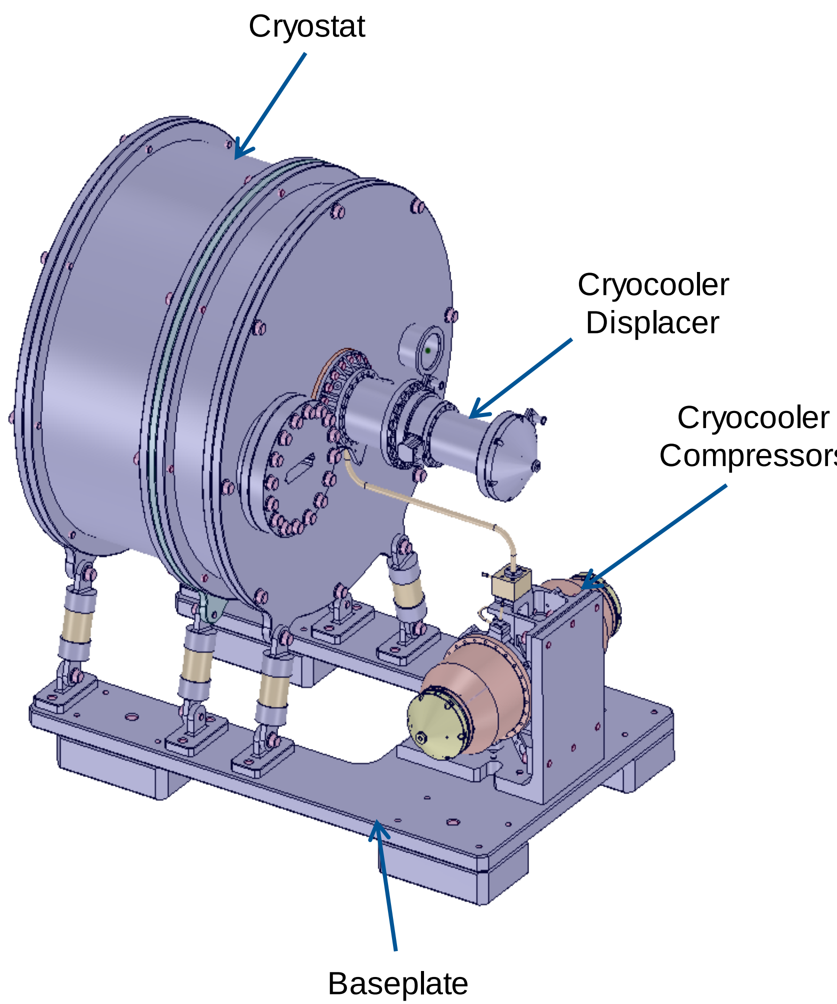
Excursion	0.2% Stability	Time	σ (% of ΔR)	N	Uncertainty	Total time
1%	± 1.36 Ω	26.0 s	0.044	20	0.006%	36.0 s
3%	± 4.09 Ω	28.5 s	0.048	20	0.007%	38.5 s
5%	± 6.82 Ω	28.0 s	0.059	20	0.009%	38.0 s

- Input power may be significantly 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: 0.02% worst case (laser)
- Total uncertainty for calibration system 0.057%

CSAR Assembly and Testing





Uncertainty of CSAR for TSI and as calibration reference

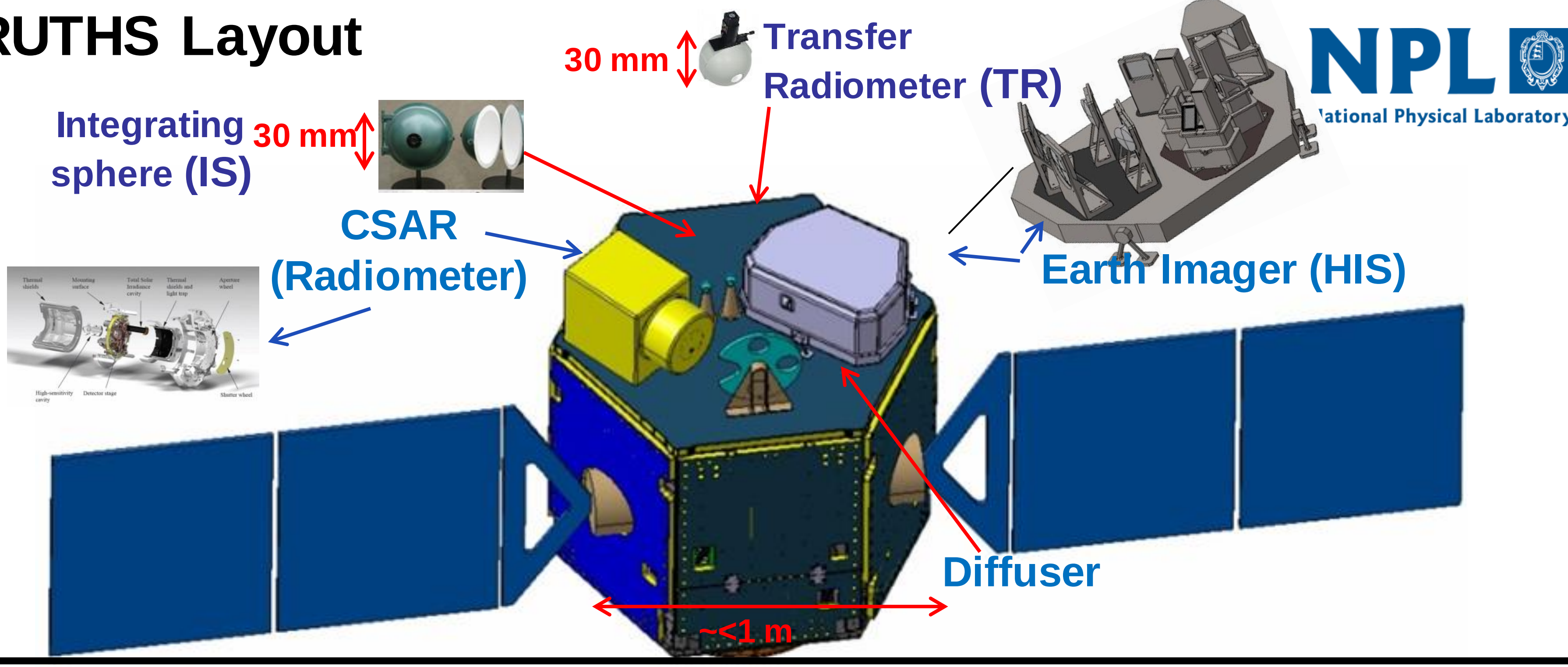
Source of uncertainty	Spectral (calibration) LD reference standard Uncertainty (*k* = 2) / %	Total Solar Irradiance Uncertainty (*k* = 2) / %
Measurement of electrical power	0.010	0.010
Area of defining aperture		0.008
Cavity absorptance	0.010	0.004
Diffraction correction		0.020
Scattered light	0.004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

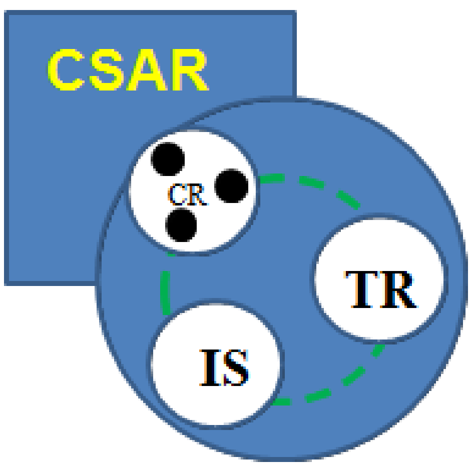
What is TRUTHS?

- **A hyper-spectral imager (320 – 2350 nm) (HIS)**

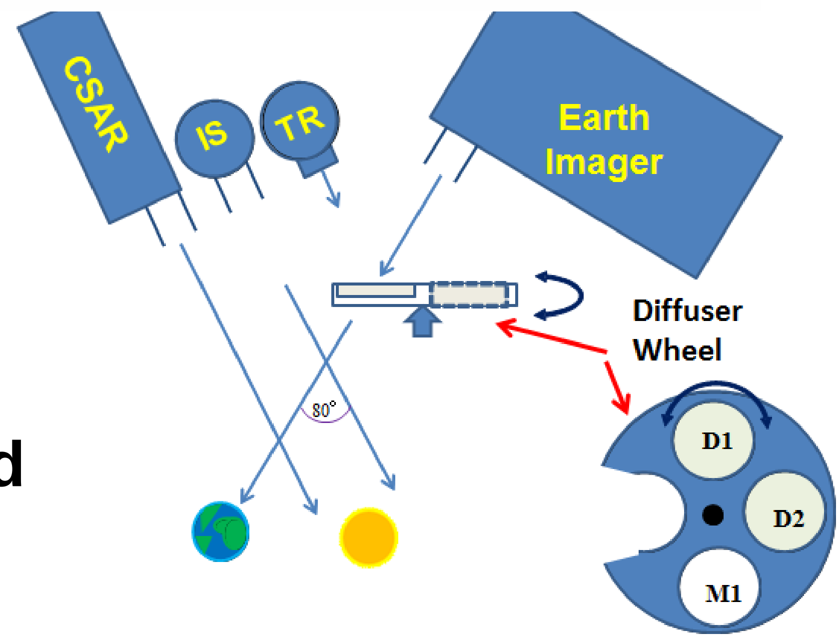
- **A Disruptive on-board Calibration system**
  - Primary standard (CSAR) (to measure power of on-board light source)
  - Light source (monochromatic) (multiple)
  - Means to move light source between CSAR and HIS
  - Means to illuminate HIS with light source

TRUTHS Layout





TRUTHS Layout simplified



TRUTHS Calibration system: including on-board laser suite

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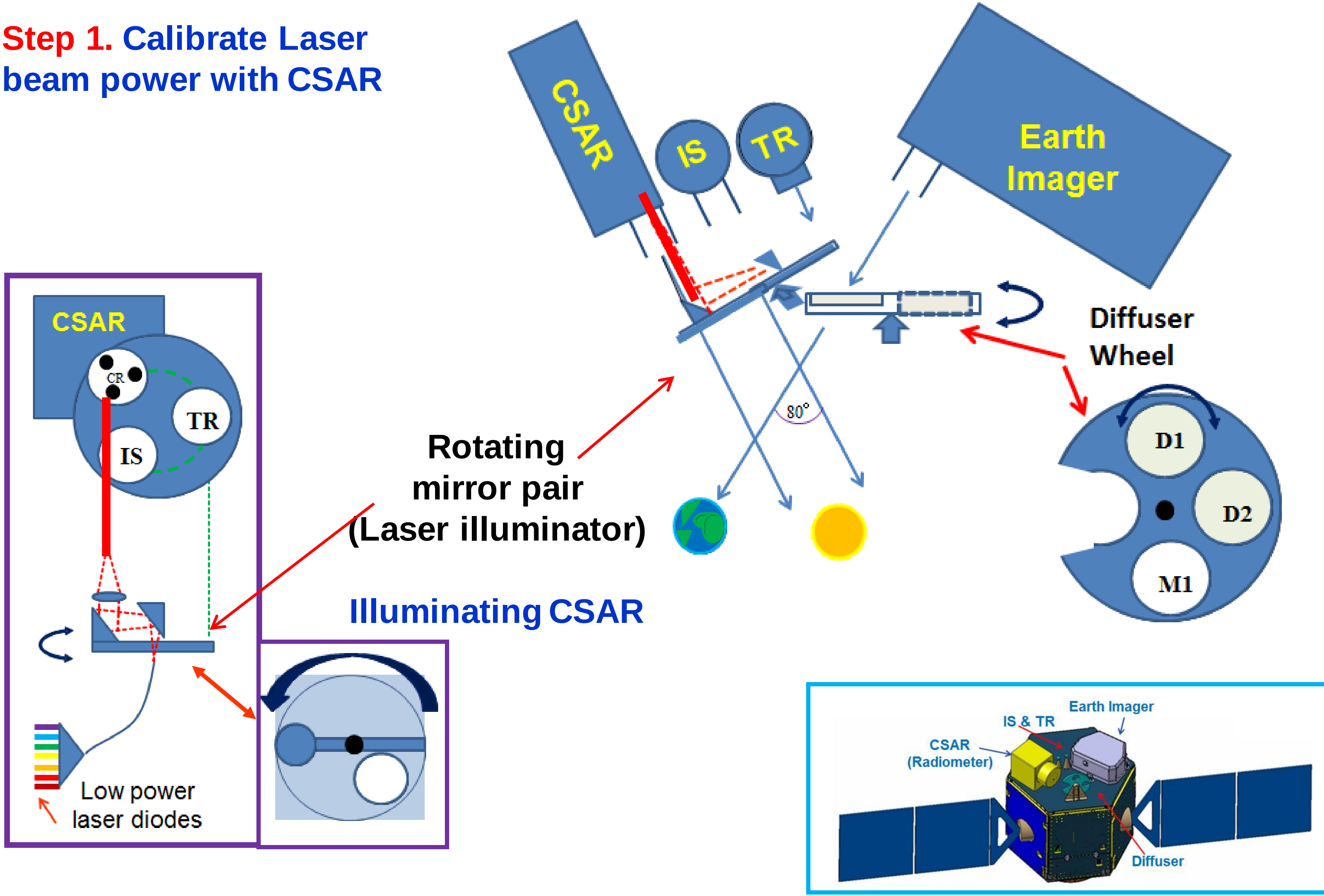
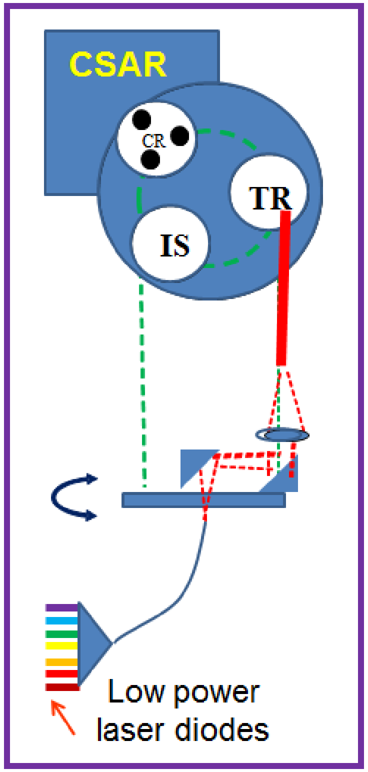
Step 1. Calibrate Laser beam power with CSAR



TRUTHS Calibration system:

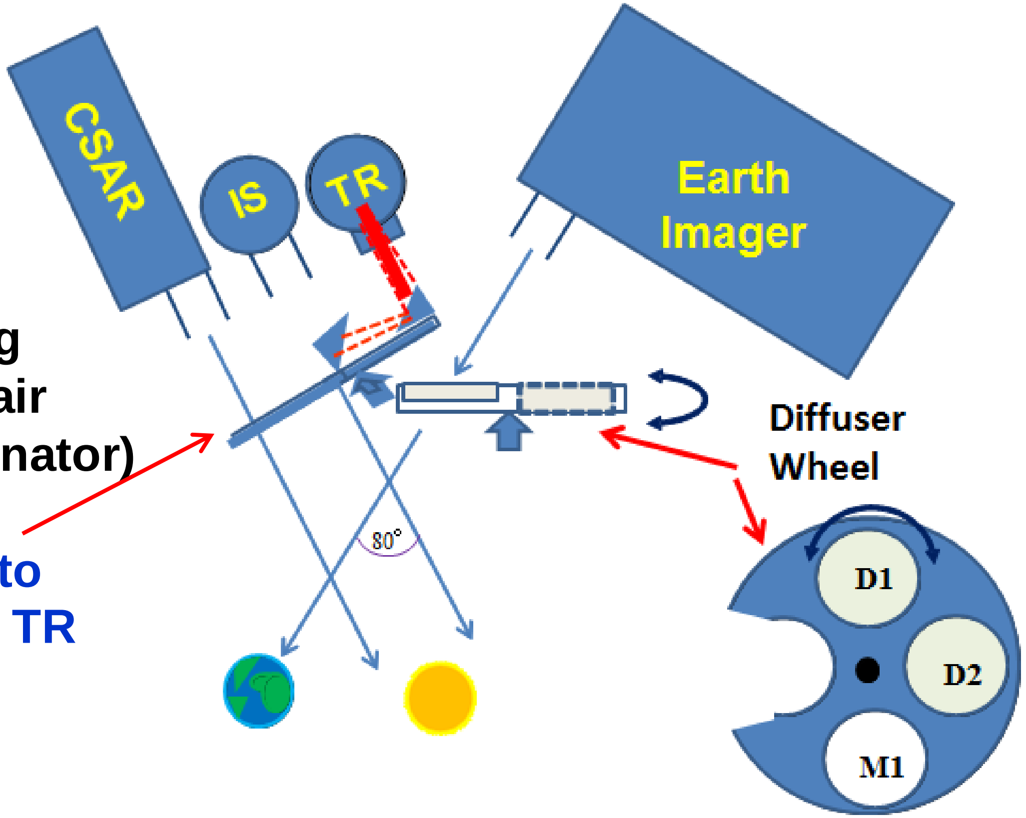
Step 2. Calibrate Transfer Radiometer (TR) using laser beam (power measured by CSAR)

(underfills entrance apertures (define FOV for radiance) of TR)



Rotating mirror pair (Laser illuminator)

Rotates to illuminate TR



TRUTHS Calibration system:

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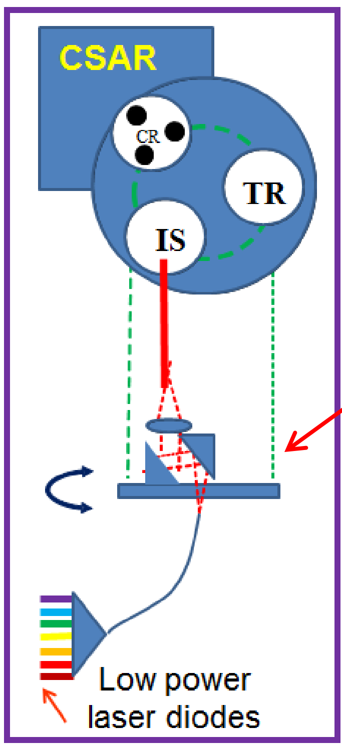
Step 3. Laser illuminates full aperture of imager via IS and diffuser.

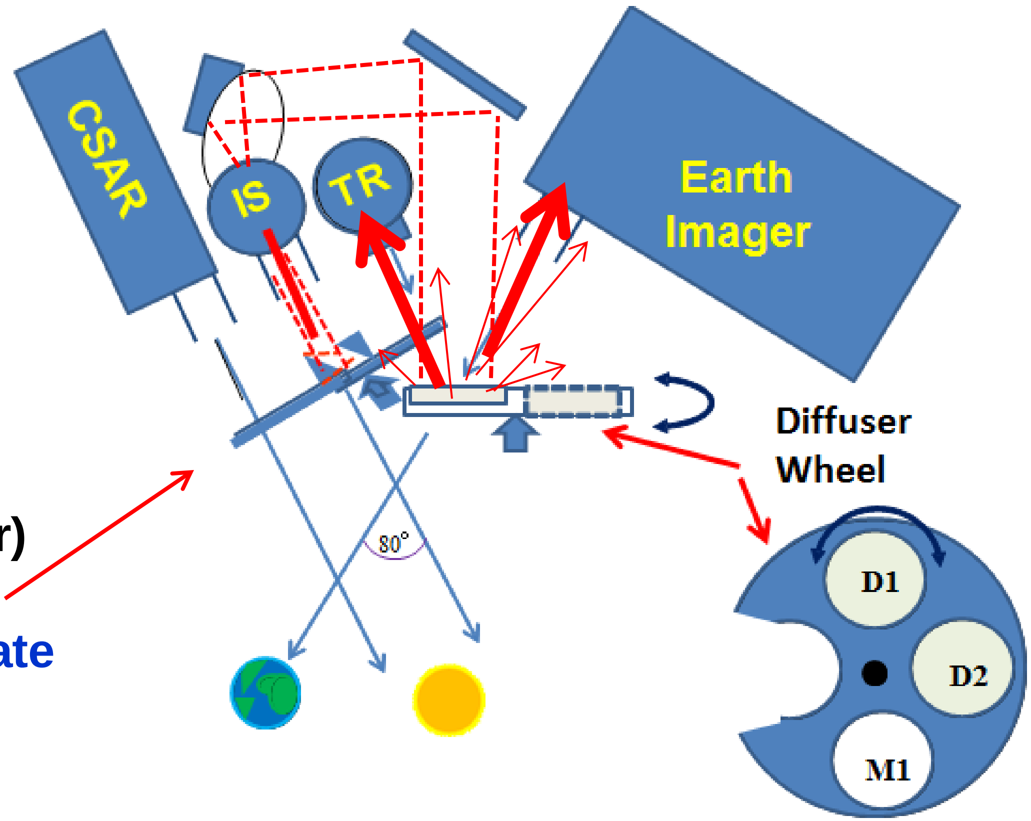
Absolute Radiance level from Diffuser measured by now calibrated TR (overfilling FOV limiting apertures of TR)



Rotating mirror pair (Laser illuminator)

Rotates to illuminate IS & thus diffuser

Scattered 'lambertian' radiation then viewed by Imager and TR at same angle

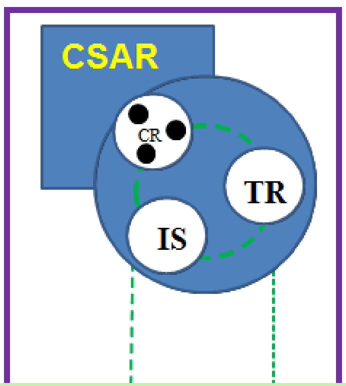


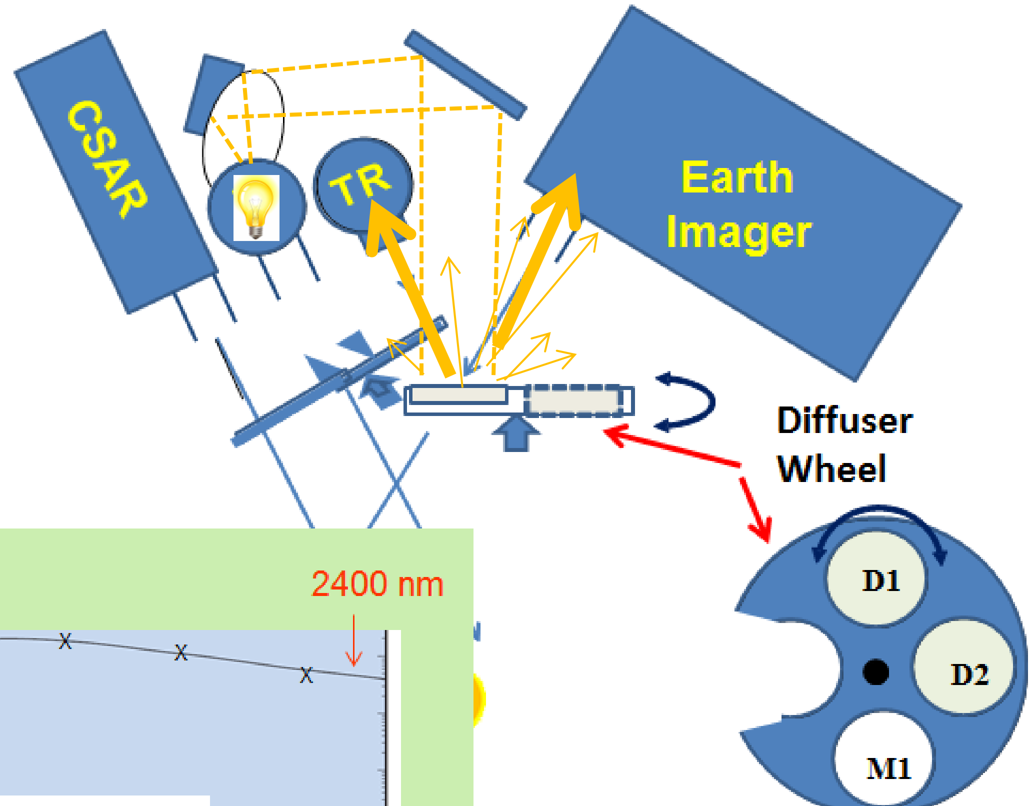
Note two diffusers for redundancy & reduced exposure/degradation. Mirror for higher illumination levels

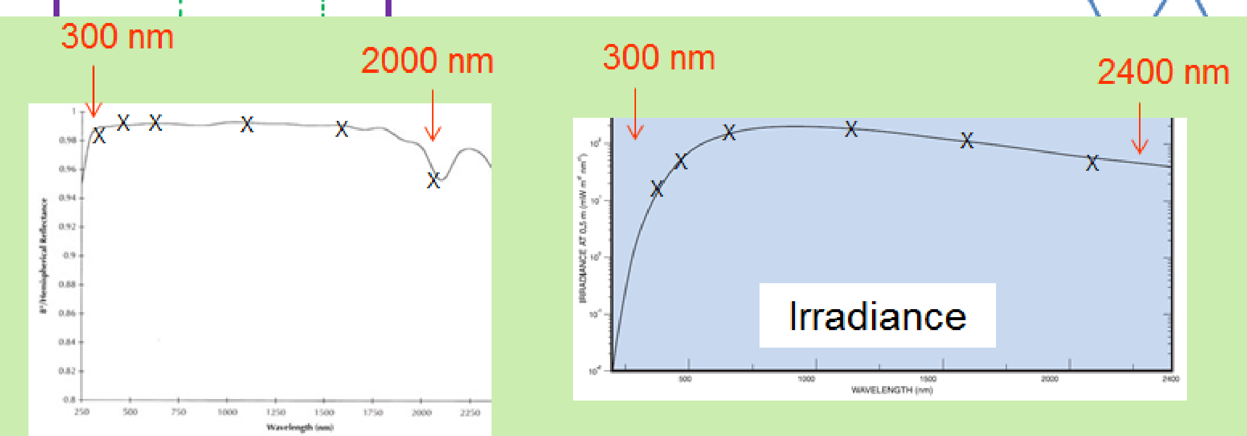
TRUTHS Calibration system:

Step 4. **Laser Off Lamp (white light) illuminates IS and full aperture of imager via IS and diffuser.**

Only Relative spectral shape is needed
Absolute level and small spectrally smooth degradation changes anchored by laser measurements





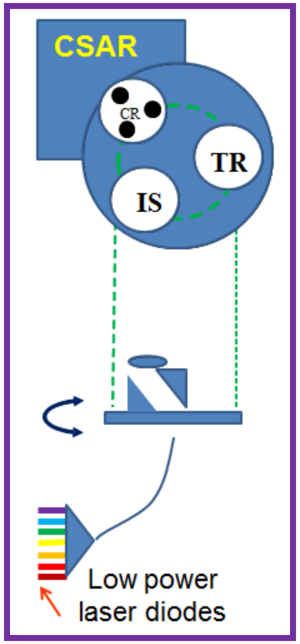


TRUTHS Observations:

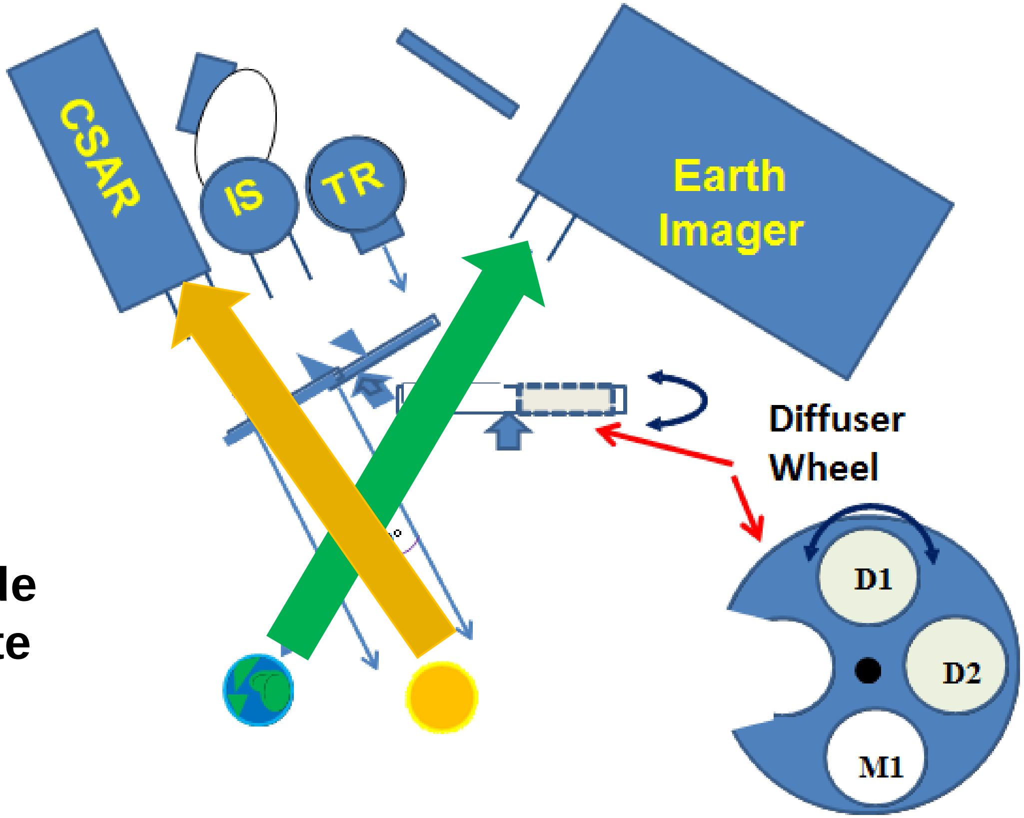
Step 5 Diffuser wheel rotates to allow imager to view the Earth

Absolute spectral radiance measurements now possible using calibrated Imager

CSAR also able to measure total solar irradiance by platform movement



TRUTHS in observation mode collecting climate data

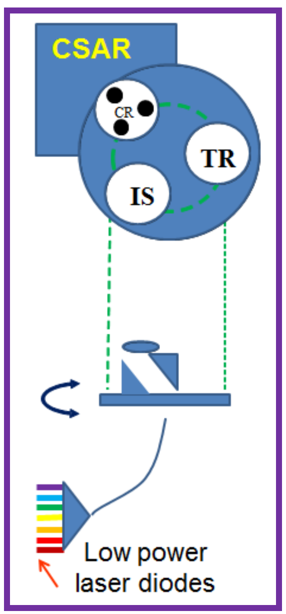


TRUTHS Measuring Solar spectral Irradiance:

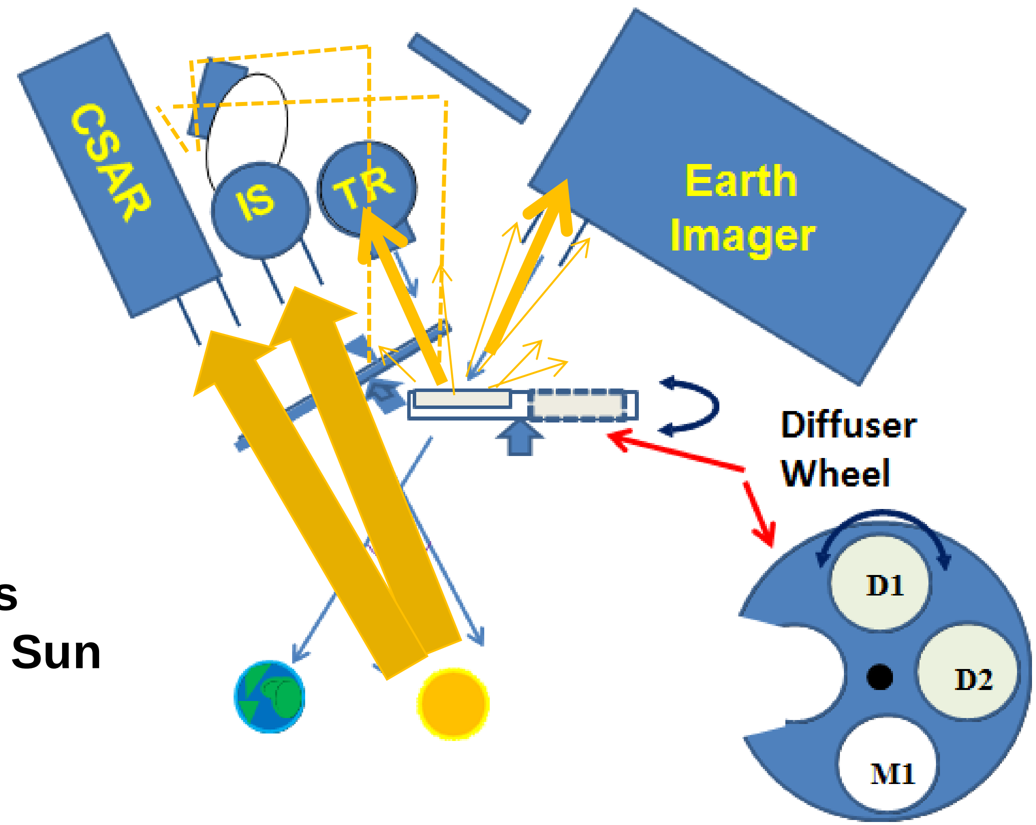
Step 6. Laser illumination (mirror) system rotated to allow Sun to illuminate entrance aperture (defined) of IS

Light path from IS same as for laser and lamp on to diffuser and Imager.

Imager, diffuser, IS light path calibrated by laser/lamp allowing Solar spectral irradiance to be determined



For solar measurements satellite points to Sun



Calibration System Schematic Reminder

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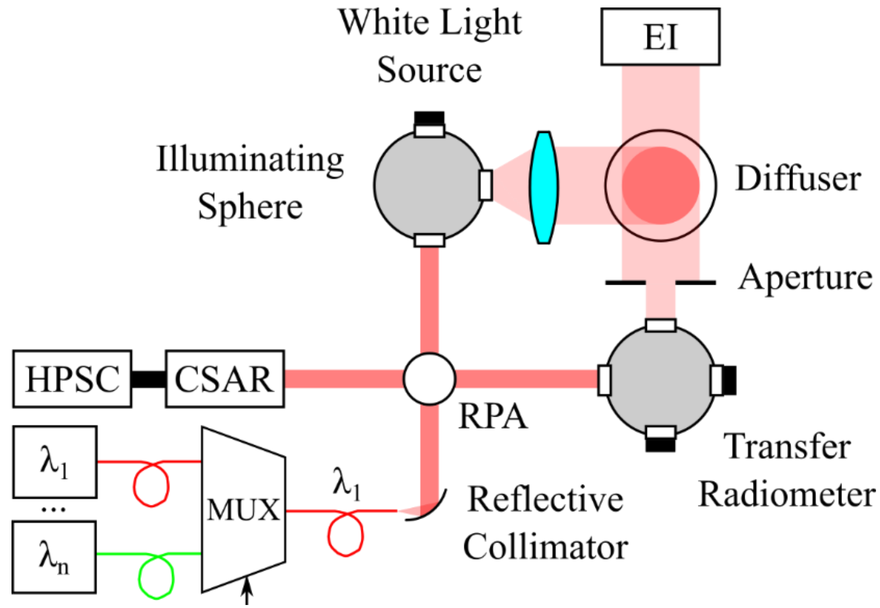
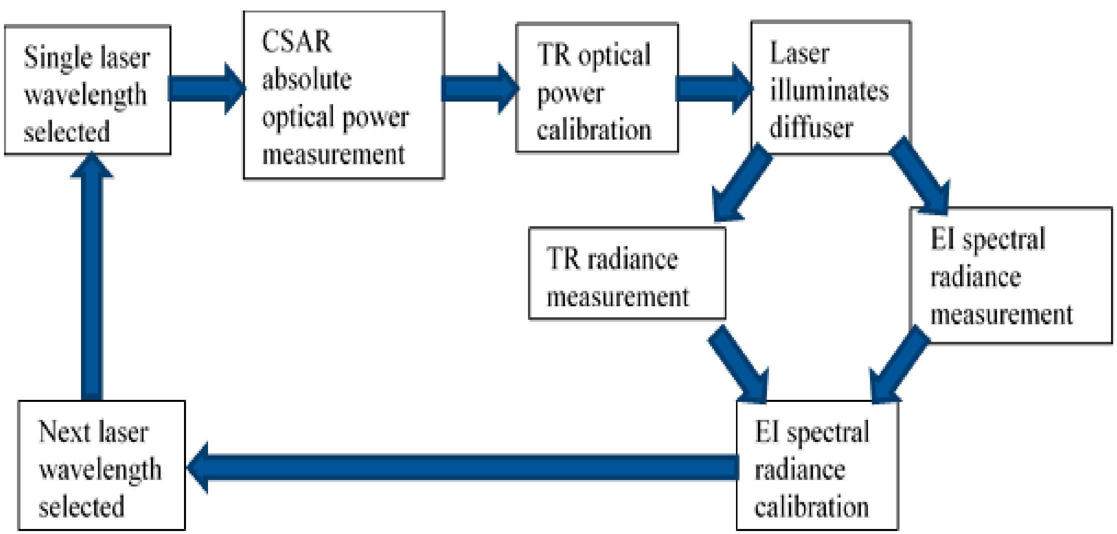
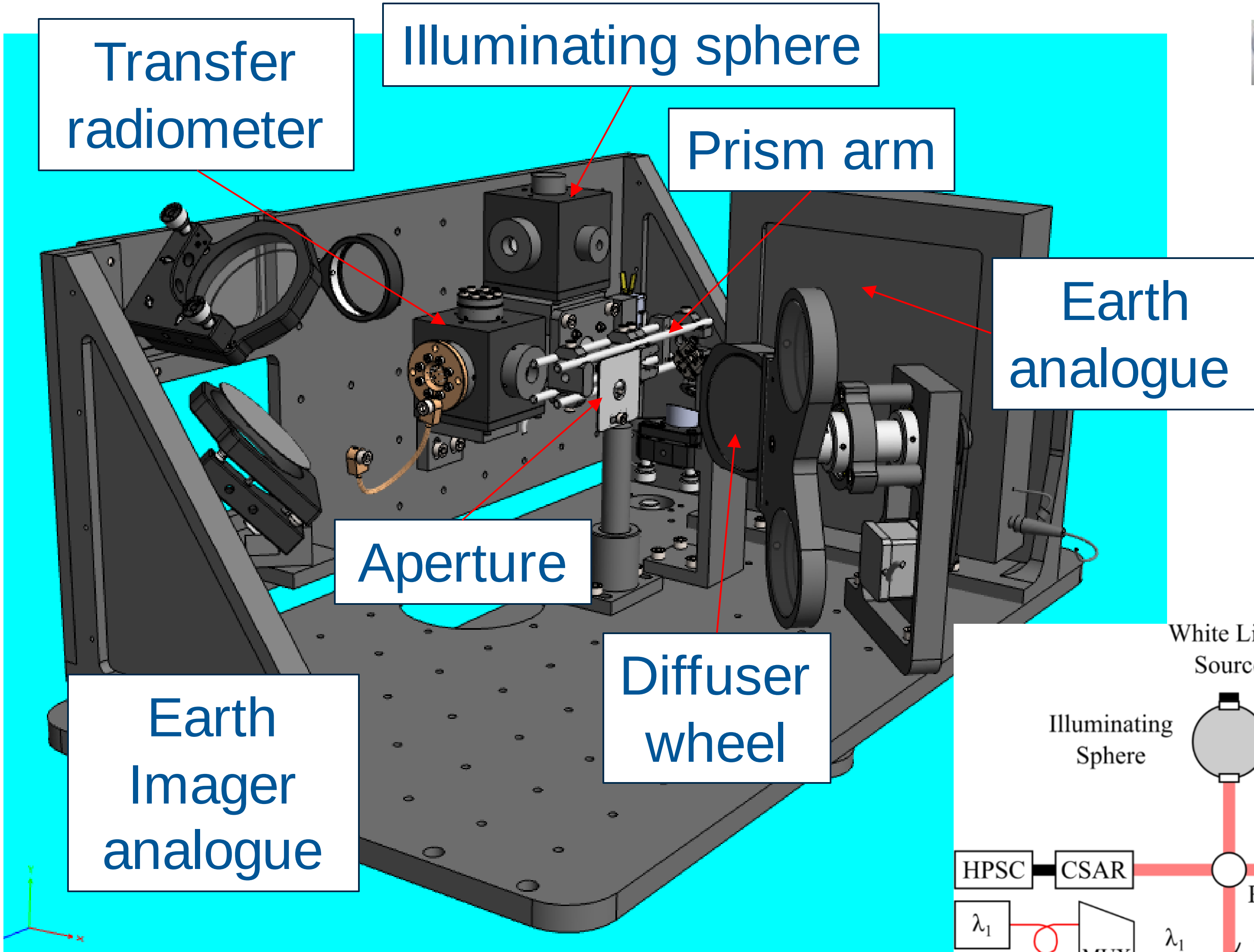
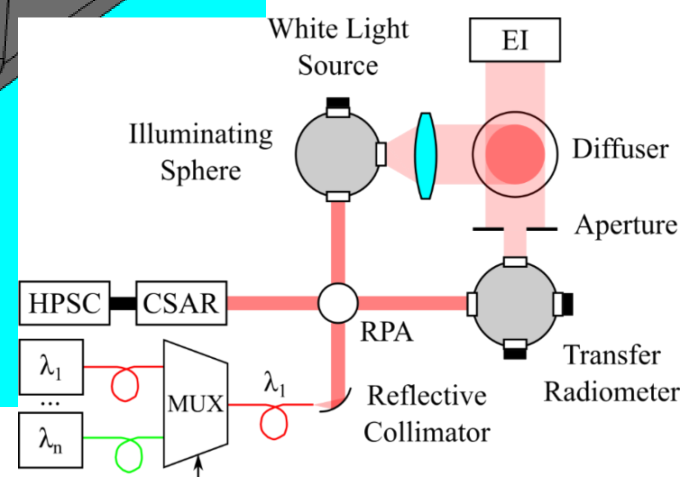




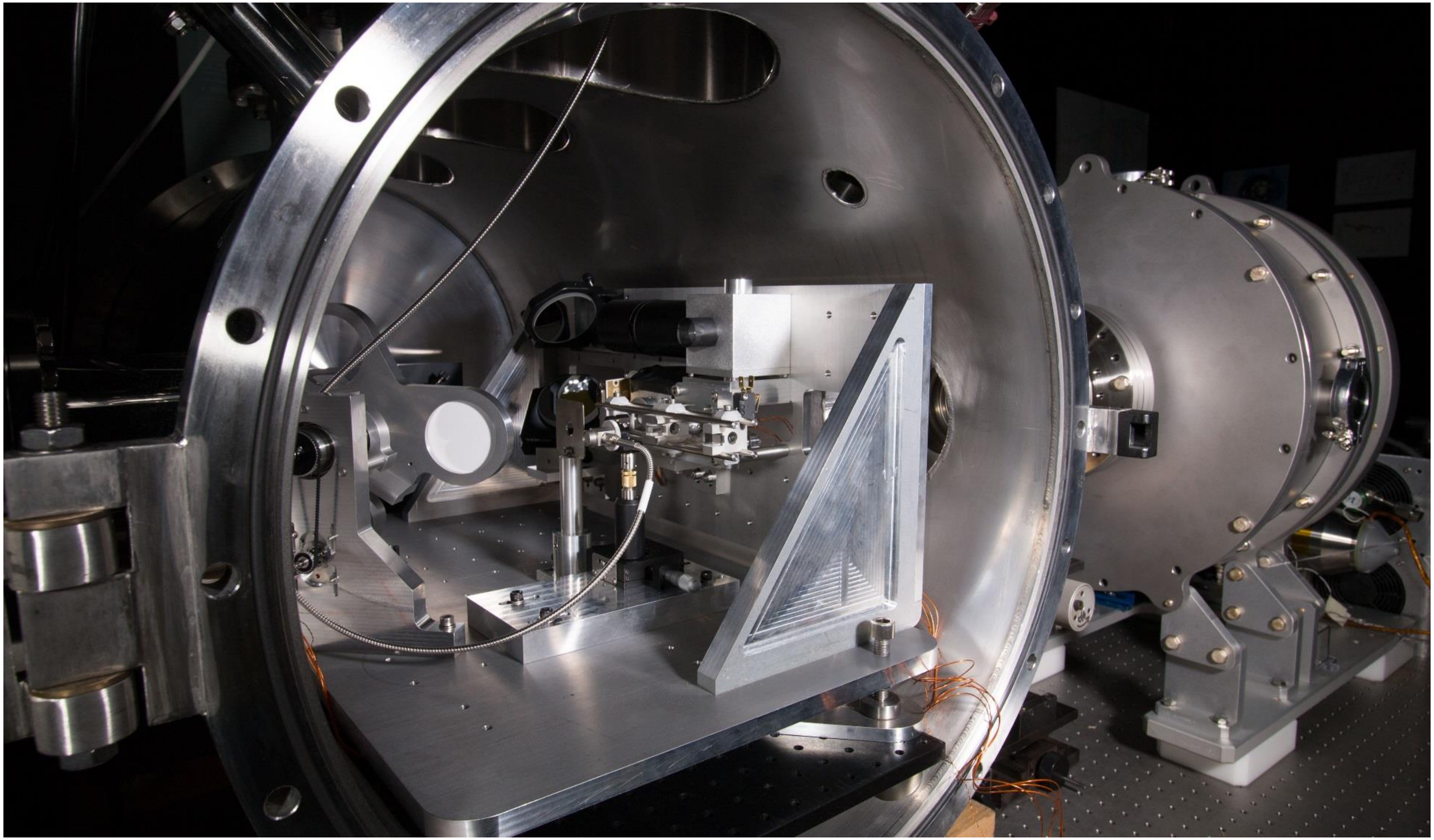
Calibration System Design



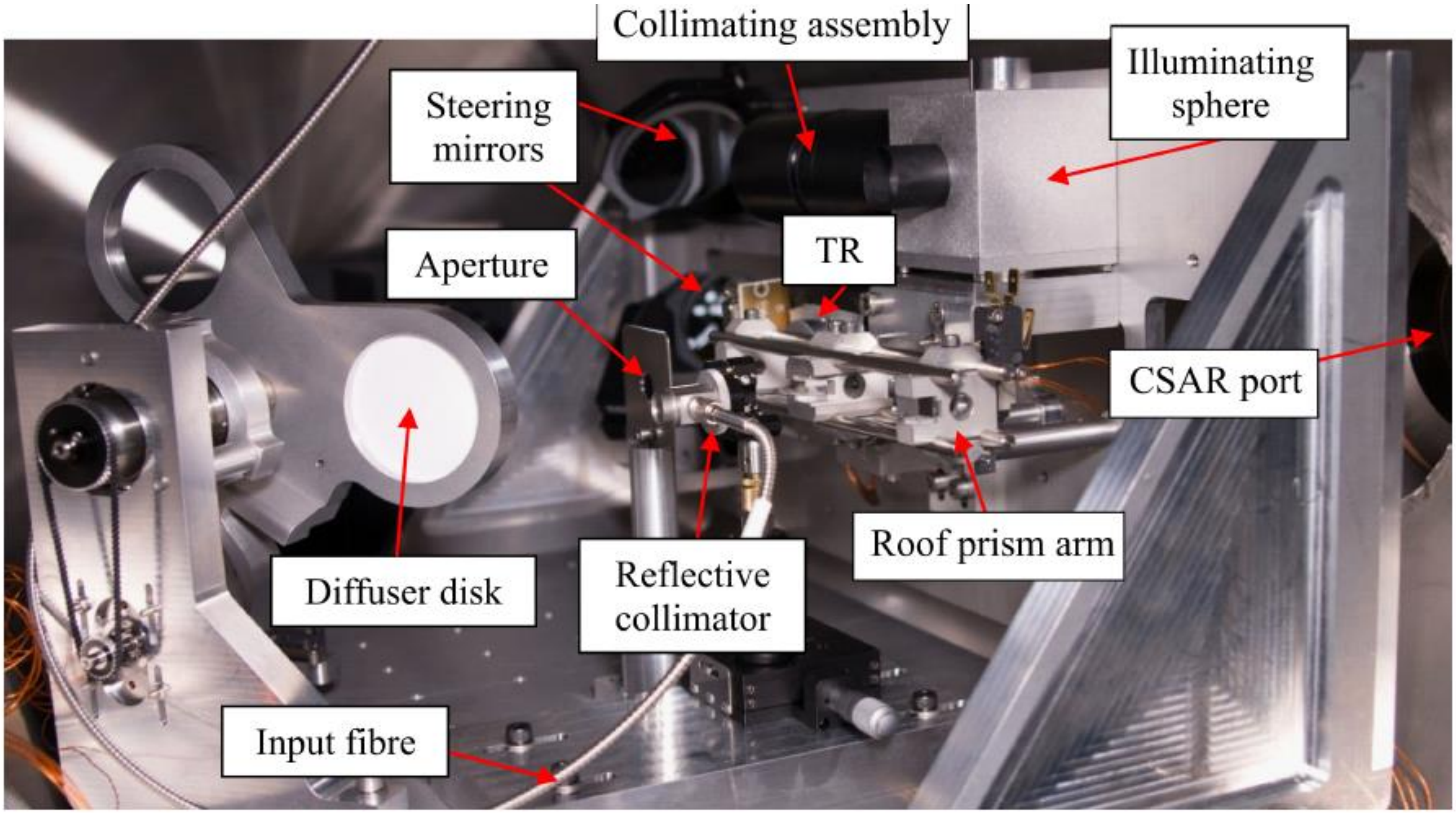


Design credit: Peter Lovelock – National Physical Laboratory

Calibration System Assembly



CSAR CAL SYSTEM

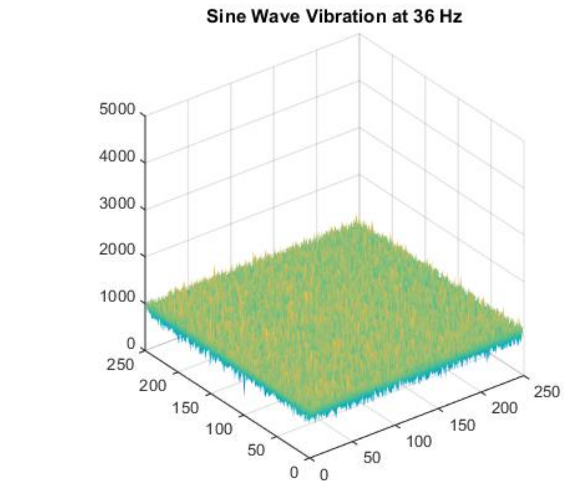


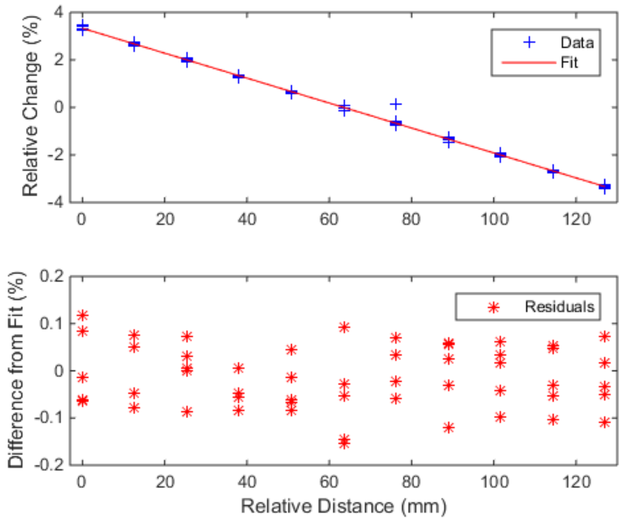
Uncertainty of Earth Imager cal

Uncertainty Source	Lab-based Uncertainty	Space-based Uncertainty
Laser diode stability	0.2 %	0.07 %
CSAR (noise)	0.06 %	Same
Prism arm	< 0.01 %	Same
Transfer radiometer	0.03 %	Same
TR aperture (radiance FOV)	0.02 %	0.02 %
Diffuser uniformity	0.2	0.2
SI Traceability (taansfer)	0.06%	Same
TOTAL	**0.30%**	**0.23 %**

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
- **Solution**: linear correction for viewing distance (within 0.3 %)





Reliability Assessment and Control Electronics Feasibility

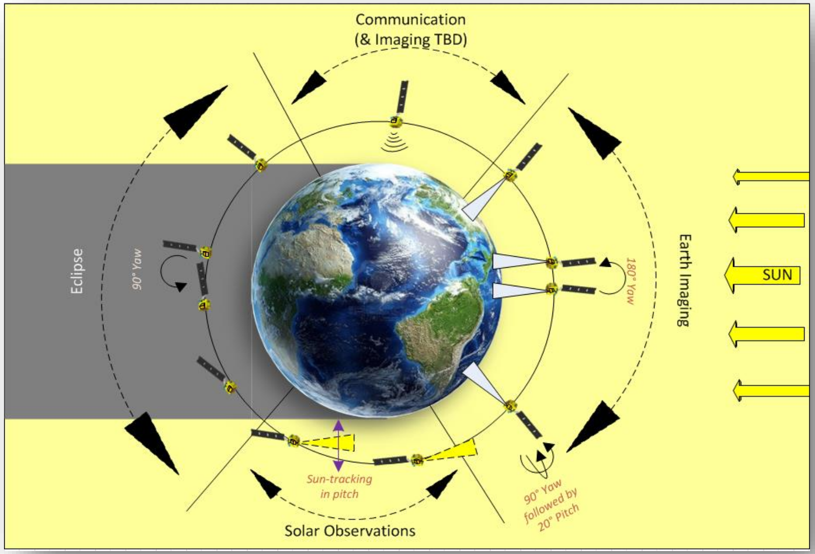
- 5 year mission: R = 0.971 (7 year 0.955)
  - No critical areas for development
  - **Considered adequate for level of complexity**
  - Dependent on failure rate model of laser diode array e.g. loss of 3 to 4 calibration wavelengths, R = 0.9997

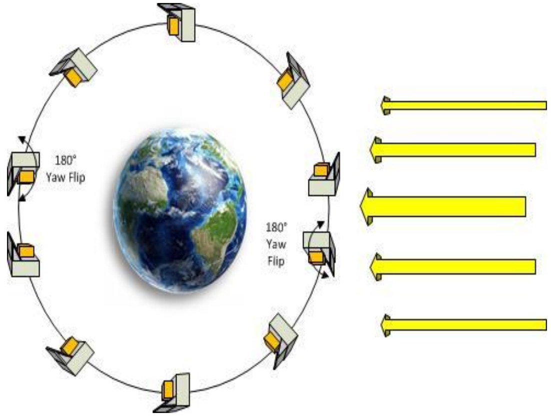
- Main reliability drivers identified:
  - Cryocooler assembly, drive electronics (R = 0.9876), displacer (R = 0.9969) and compressor (R = 0.9977) all non-redundant
  - CSAR control, on-board computer (R = 0.9939), assumes any OBC can control any of 3 CSAR cavities (fully cross strapped)
  - Transfer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

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

CONOPS: polar recessing orbit provides multiple cross-overs with sats & 2 diurnal cycles PA

- Most of the duty cycle dedicated to Earth observation through nadir viewing
- About 10 minutes per orbit are for comms
- When crossing the ecliptic plane, a yaw manoeuvre of 180 deg is required to shield the instrument from direct sunlight
- During eclipse the spacecraft performs a 90 deg yaw manoeuvre, positioning itself with the CSAR FoV aimed at the sun.
- Once out of eclipse, the solar observation phase will start, requiring spacecraft to track the sun for 10 min adjusting its pitch orientation



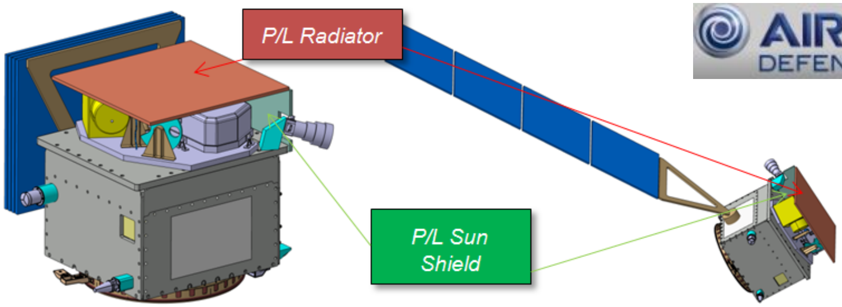


Operational Mode	12:00 O'clock Orbit
Climate benchmarking (Earth Imaging)	43%
Communication & Earth Imaging	10%
Eclipse	36%
Solar measurements	10%

Some preliminary thermal analysis on radiator and orbit effects

Spacecraft

- The AstroBus platform represents a high performance, high quality and competitive platform line covering the full range of mission needs in LEO Earth Observation
- For TRUTHS it possible to use the Astrobus-S platform with some adaptations
- The spacecraft has a payload sun shield and a dedicated payload radiator



Platform based on Astrobus-S with small adaptations

Feature	Value
Spacecraft launch Wet mass	556.2 kg (incl. system margin)
Platform mass	293.7 kg
Platform size (stowed incl. solar array)	1190 x 1190 x 1100 mm^3
Peak Power generation	928 W
Power allocation for payload	274 W
Power units	Deployable and 2DoF steerable single wing (4.5m^2) & Battery (79.5 Ah)
AOCS elements	Complete set of sensors and actuators
Propulsion	Monoprop system with 28.5 kg of propellant
Payload Data Handling and Transmission	X-band downlink of payload data up to 620 Mbps Two X-band transponders in hot redundancy One X-band dual polarisation antenna On-board mass memory: 2 Tbit

Analysis also performed for ISS

Spacecraft Mass Budget

National Physical Laboratory

AIRBUS DEFENCE & SPACE

TRUTHS			
Subsystem	**Current Best Estimate (kg)**	**Design Maturity Margin (kg)**	**Total CBE + DMM (kg)**
Data Handling Subsystem	16.9	0.8	17.8
Power Subsystem	79.2	4.0	83.2
Harness	22.0	6.6	28.6
X Band Communications Subsystem	10.6	1.2	11.8
S-Band Communications Subsystem	4.7	0.2	4.9
AOCS	40.9	2.0	42.9
Structure	70.3	6.2	76.4
Thermal Subsystem	10.3	1.0	11.4
Propulsion	16.0	0.8	16.8
PLATFORM / SERVICE MODULE TOTAL	**270.9**	**22.9**	**293.7**
PAYLOAD / PAYLOAD MODULE TOTAL	**137.0**	**27.4**	**164.4**
DRY TOTAL	**407.9**	**50.3**	**458.1**
System Mass Margin		15%	68.7
DRY TOTAL (incl. System Margin)			**526.8**
Propellant	28.50		28.5
Residuals + Uncertainty			0.8
Pressurant			0.03
WET MASS			**556.2**
Launch Vehicle Adapter	Not needed for VESPA		0.0
WET MASS incl. Launch Vehicle Adapter			**556.2**

Launch Vehicle Capability - VESPA-C Lower Berth	**700.0**
Mass Margin to Launch Vehicle Capability - Lower Berth	**143.8**

Launch Vehicle Capability - VESPA-C Upper Berth	**1400.0**
Mass Margin to Launch Vehicle Capability - Upper Berth	**843.8**

Provisionsal Power study

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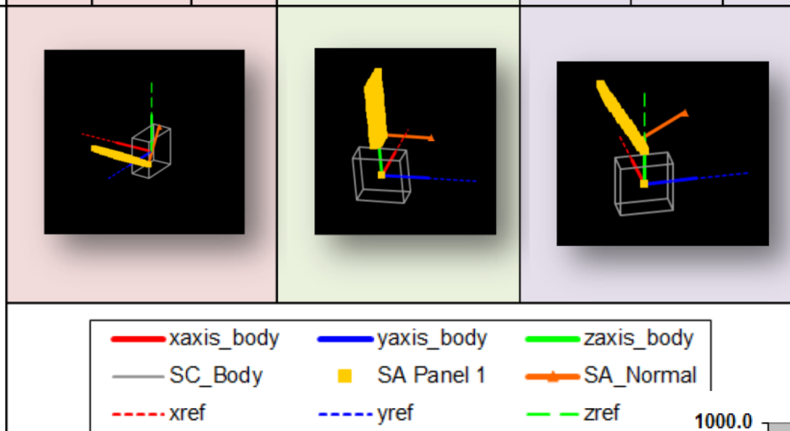
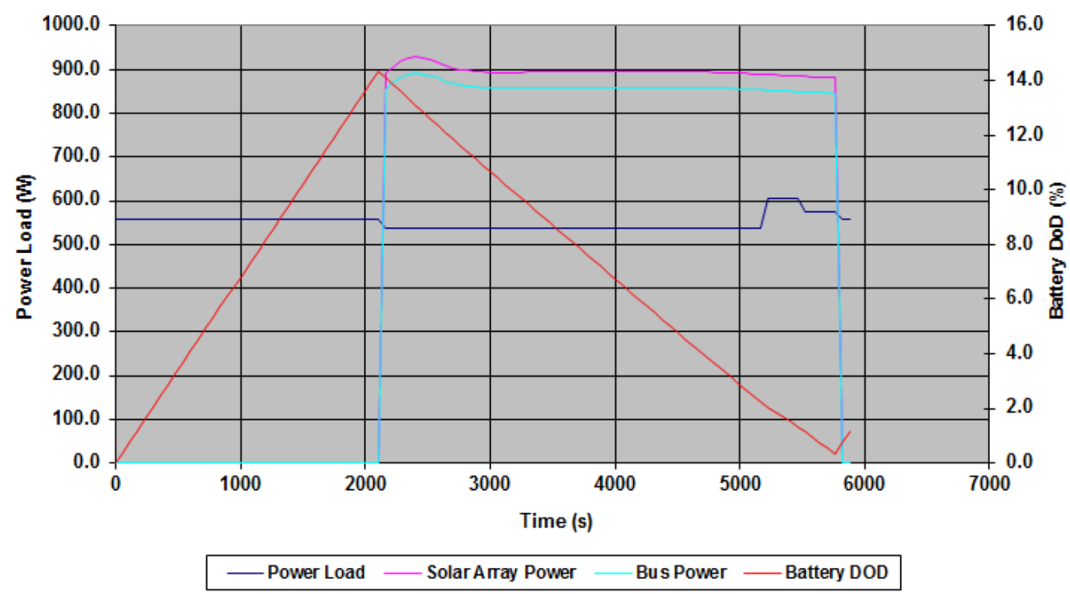
AIRBUS DEFENCE & SPACE

SA Location	Y Panel + 30Deg inclination			-Z Panel, not inclined	-Z Panel, +30 deg inclination		
Orbit [LTAN]	**12:00**	**06:00**	**18:00**	**12:00**	**12:00**	**06:00**	**18:00**
Max Power @ PCDU (W)	925	750	756	1765	1165	687	645
Required Area (m^2)	5.2	4	4.2	8.9	5.3	3.5	3.5



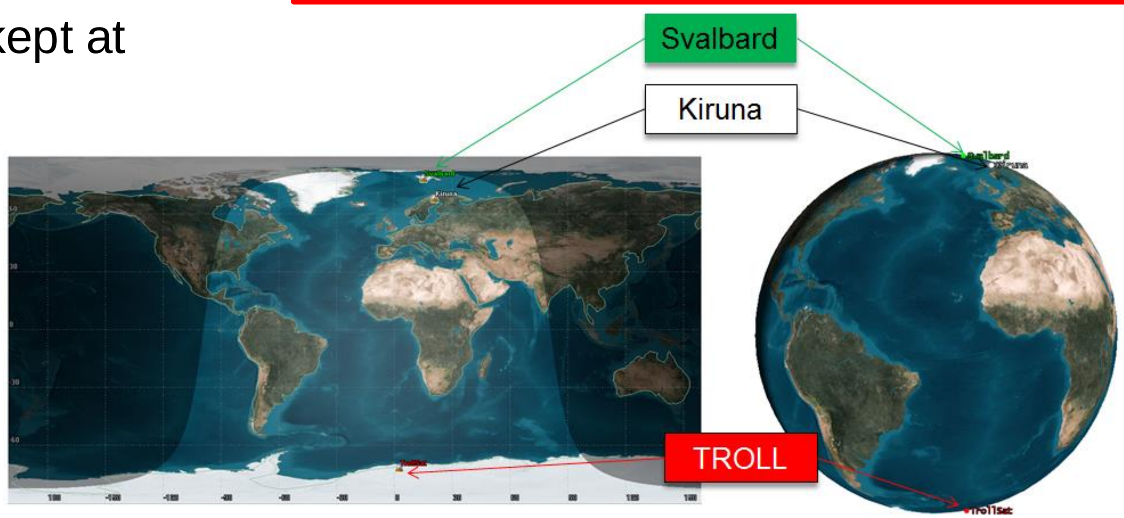
4.5 m^2 2 DoF sail adequate to maintain payload and systems for polar orbit



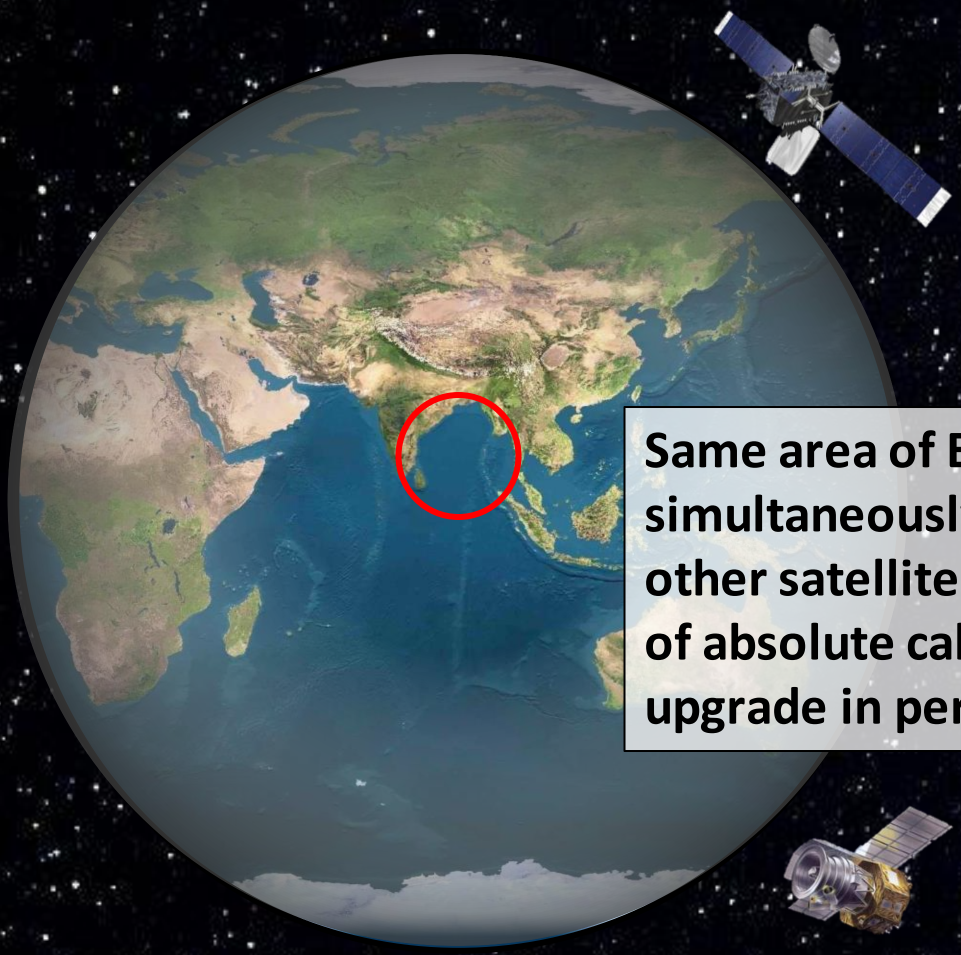
Data download

- Ground Station at high latitudes optimal for polar orbit
- Svalbard, Kiruna and Troll ideally located
- Due to the contact gaps, the required data rates with Kiruna or Troll are very high
- Svalbard is the only one without contact gaps and hence the data rate can be kept at acceptable levels

Parameter	Unit	Kiruna	Svalbard	Troll
Min Elevation	Deg	10	5	10
Daily Data	Gb/day	4415		
Orbit Period	min	96.87		
Data/orbit	Mb/orbit	2.97E+05		
Mean Contact duration	min	6.72	8.63	6.47
Max contact Gap	Orbits	5.05	0.00	3.87
Stored Data from Gaps	Mb	1.50E+06	0.00	1.15E+06
Total Data to be downlinked	Mb	1.80E+06	2.97E+05	1.45E+06
HK Data Rate	kb/s	10		
Data rate required	Mb/s	4455.57	573.42	3728.56

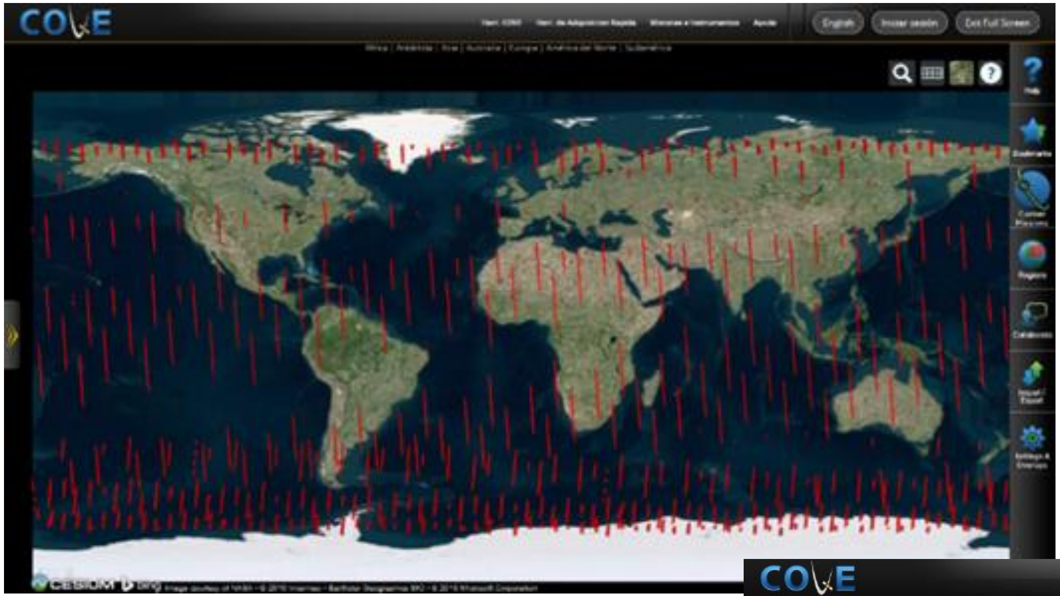


Upgrading Earth observing system for climate

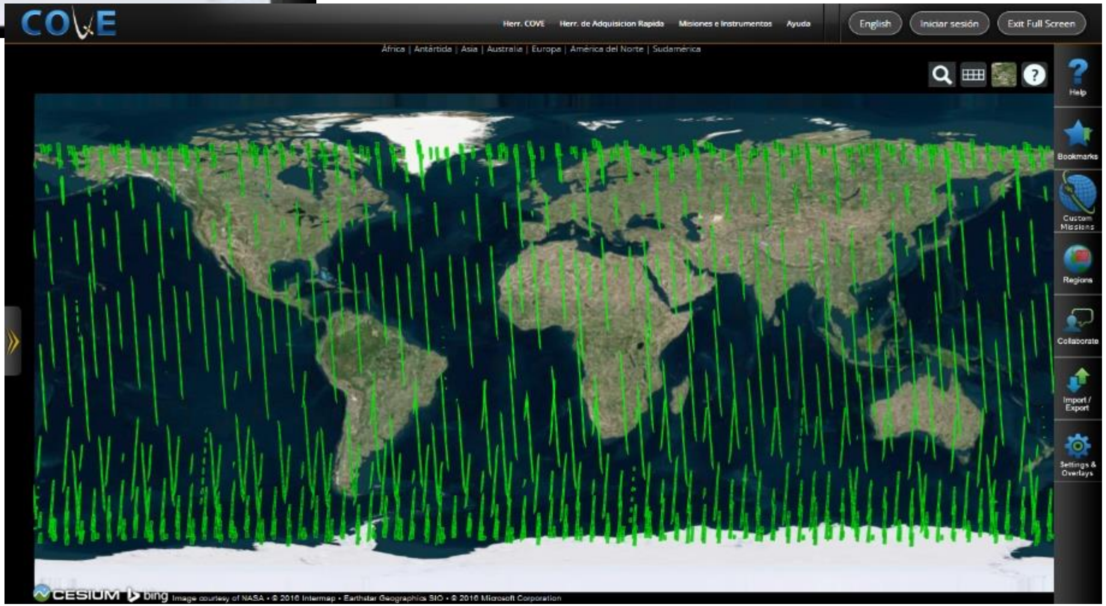


Same area of Earth viewed simultaneously by TRUTHS and other satellite enables transfer of absolute calibration and upgrade in performance

Nadir Overlaps per year (30 min window)



Sentinel 2



Sentinel 3

Uncertainty budget for TRUTHS – satellite comparisons

(single overpass – reduces for multiple overpasses)

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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 %**

Conclusion

CEOI 8 has

- **Significantly derisked and increased TRL of TRUTHS payload (TRL5-6) and mission**
- **Improved performance of Airbus HPSC (~5K)**
- **CSAR now 1/3 mass, space qualifiable, integrated and tested with HPSC meets performance needed (but can also be optimised further)**
- **Cal System as a whole shown to have performance needed under vacuum with similar scale and motions to space (can also be optimised further)**
- **Mission ConOPS evaluated and avionics shown to be compatible and achievable with smallest Airbus platform – meets mass, power, thermal and data handling in non-standard orbit**
- **Imager design simplified to a two detector system where (UV) detector no longer needs co-registration**