Technology Demonstration of TRUTHS SI-Traceable Calibration System

CEOI Emerging Technologies Workshop

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Overview of TRUTHS Mission

“Traceable Radiometry Underpinning Terrestrial- and Helio-Studies”

EO satellite mission with goals of:

- Measuring Total Solar Irradiance (TSI), Solar Spectral Irradiance (SSI) and Earth spectral radiance with unprecedented accuracy
  → Climate benchmarking
- Validating existing and future EO satellites through cross-calibration
- Uncertainty targets:
  → TSI < 0.01 %, SSI < 0.1 % and Earth spectral radiance < 0.3 %

Three main components:

- Cryogenic Solar Absolute Radiometer (CSAR)
- Hyperspectral Earth Imager (EI)
- Calibration system: calibrates EI with CSAR via transfer radiometer

Increasing Technology Readiness Level (TRL) of TRUTHS

- CSAR redesigned and integrated with upgraded space cooler

- Engineering model of calibration system tested in vacuum
  → Same scale and geometry as planned space instrument

- Transfer radiometer (TR) calibrated in situ via CSAR

- Instrument analogous to Earth imager calibrated in situ via TR

- Entire calibration carried out autonomously with simple control scheme

- Carry out reliability and feasibility assessment for 5 – 7 year mission

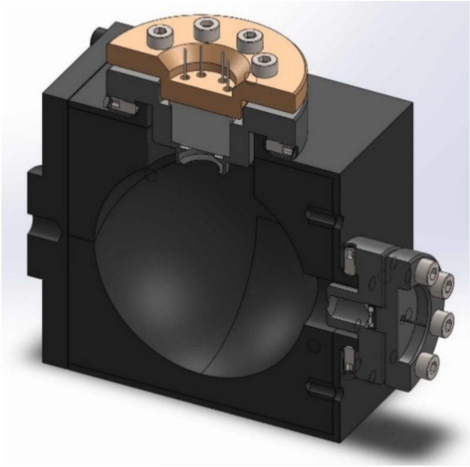
Overview of CSAR

- Provides SI traceability of Earth Imager (EI) calibration and TSI measurements as "primary standards lab in space"
- Ground-based CSAR currently based in Davos, Switzerland (future SI standard for solar irradiance)
- Recent work involved updating terrestrial design to more space appropriate design and ensuring compatibility with Airbus Defence and Space's High Performance Stirling Cooler (HPSC)
- Challenges: limited cooling power → higher operating temperature → reduced sensitivity and increased time constant

Overview of Calibration System

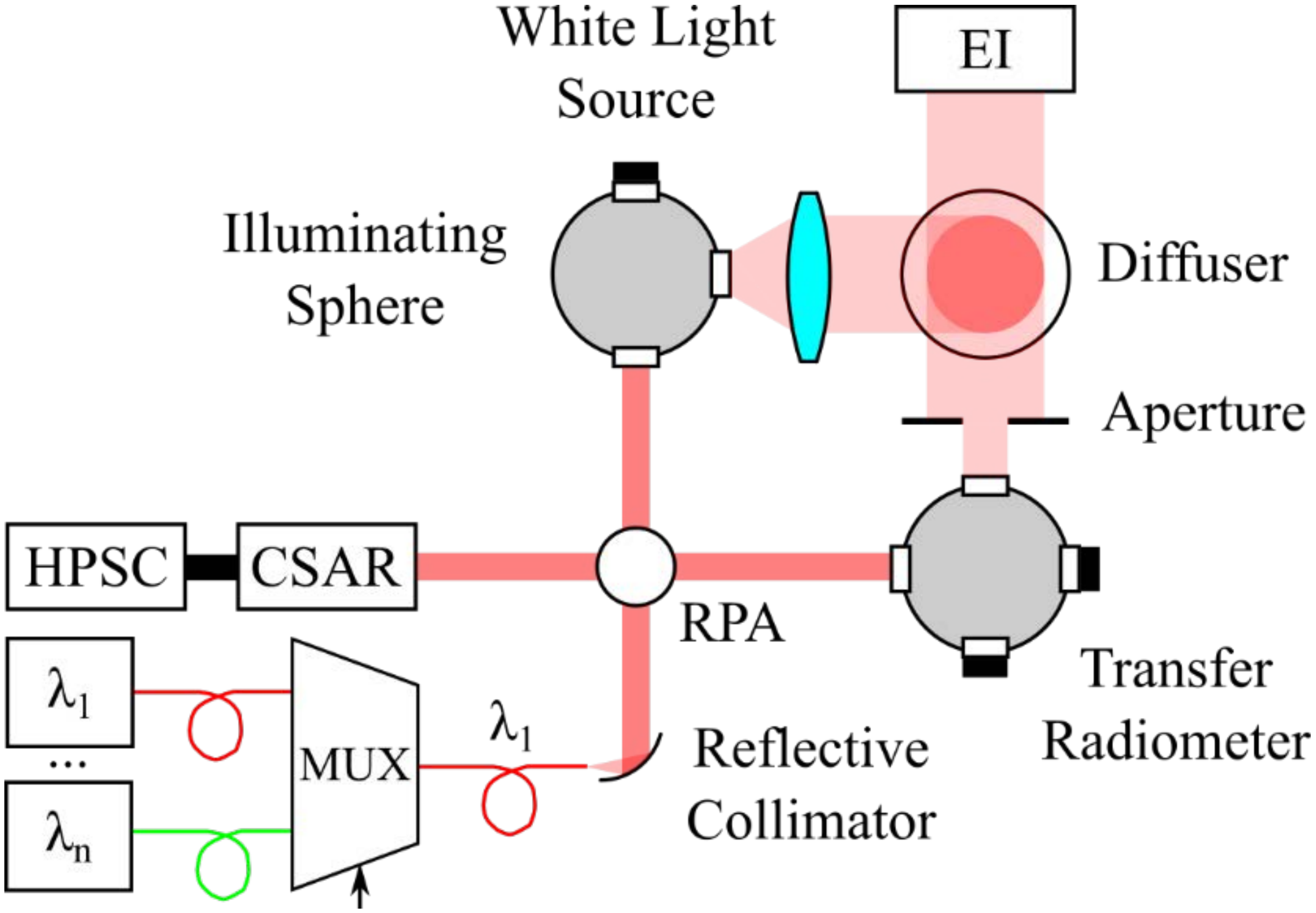
Main components of calibration system:

- Array of single-wavelength, power stabilized laser diodes
  → Range 350 nm to 2300 nm
- Beam delivery optics
  → Fibre combiner, collimator, rotating prism arm
- Transfer radiometer (calibrated with CSAR)
  → Integrating sphere with two detectors (Si and InGaAs)
  → External aperture to define radiance



- Spectralon diffuser disk and illumination optics
  → Illuminating sphere, collimating lens, steering mirrors
  → Viewable simultaneously by TR and EI

Calibration System Schematic



Calibration Chain

1. Single laser wavelength selected

2. CSAR optical power measurement

3. TR optical power calibration

4. Laser illuminates diffuser

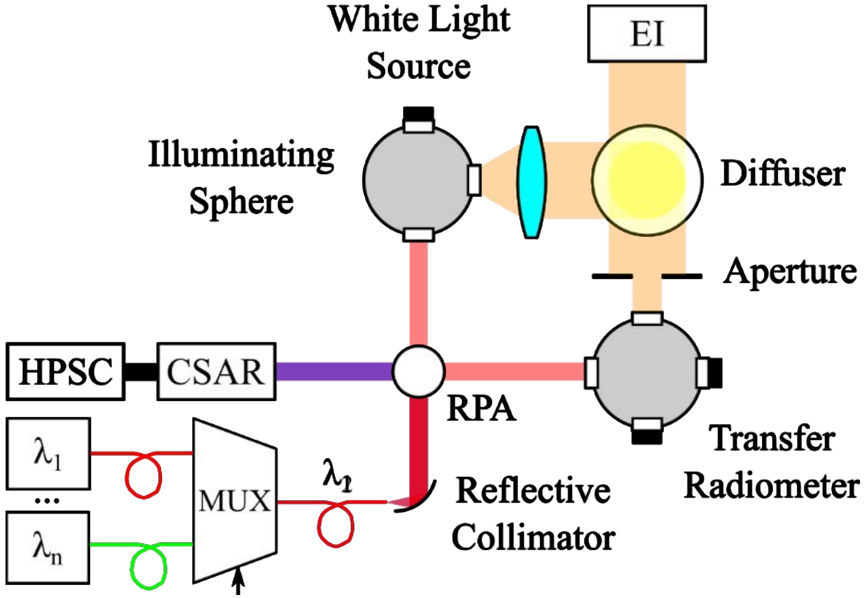
TR radiance measurement

EI spectral radiance measurement

EI spectral radiance calibration

Next laser wavelength selected

EI interpolation (white light source), views Earth analogue



Cryogenic Solar Absolute Radiometer

- Electrical substitution radiometer
  - Measure temperature T_{rad} of cavity after introduction of optical radiation, highly absorptive cavity will heat up
  - Introduce electrical current into heater attached to cavity until temperature reaches T_{rad}
  - Electrical power through heater and optical power are equivalent

- Radiometer characterized by temperature response
  - Sensitivity: temperature change after introduction of power (K/W)
  - Time constant: seconds required to reach temperature change
  - Both depend greatly on operating temperature of cavity and rest of thermal mass (reference block) and materials used

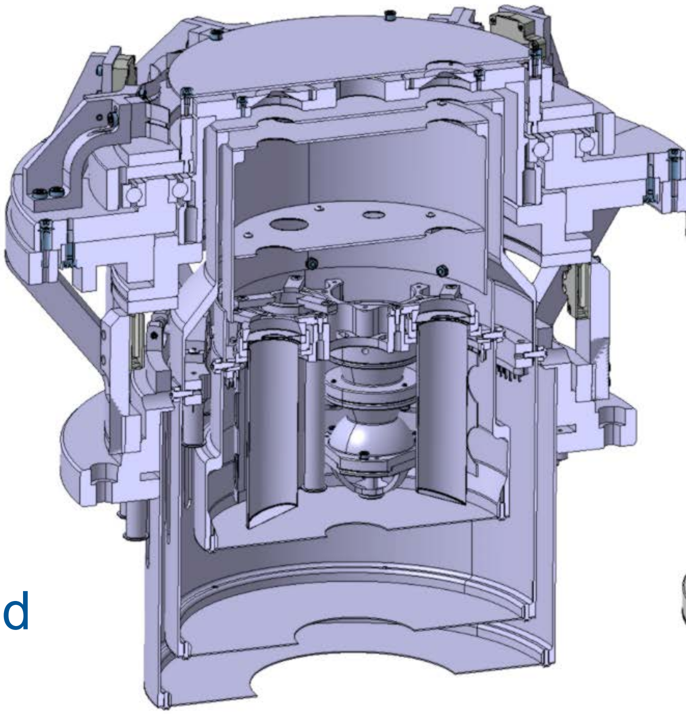
CSAR Redesign

- Redesign achieved:
  - Simplified operation
  - 3 cavities from 6
  - 1 cold stage from 2

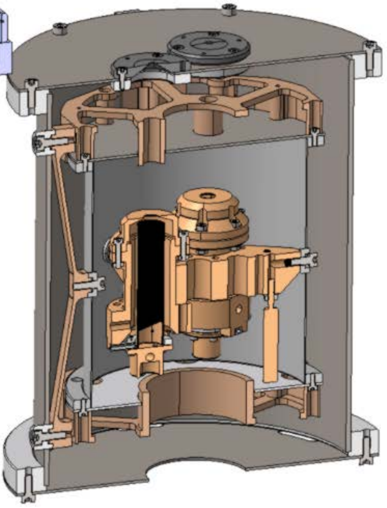
- Decreased mass, volume
  - 9.6 kg to 3.8 kg

- Reduced heat load
  - 1 W to 0.5 W estimated

- Increased absorptivity
  - VANTA black coating



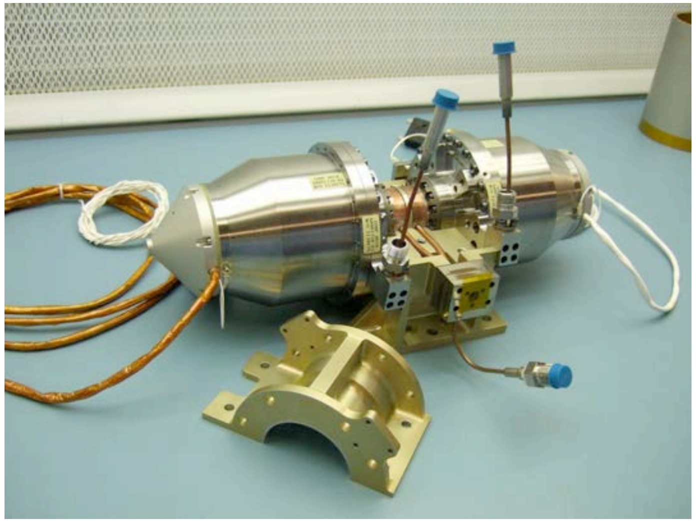
Terrestrial CSAR



Space CSAR

High Performance Stirling Cooler Rebuild and Optimisation

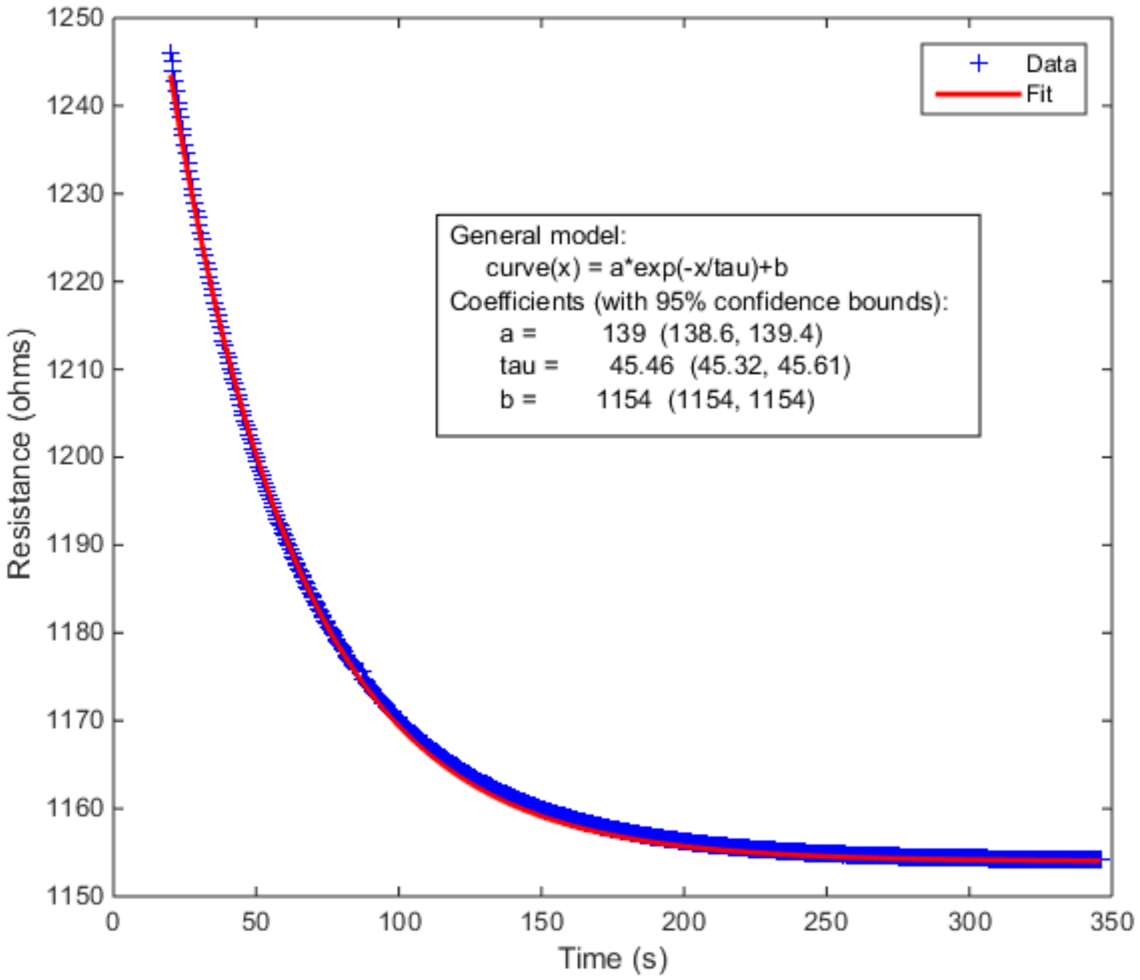
- Airbus HPSC initially developed as ESA project for space applications
- Development of Astrium 50-80K cooler (>1M hours of in-orbit heritage), high level of common parts
- During initial build compressors had high stiction, possibly reducing performance
- 50 K cold tip temperature with 1 W heat load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



Rebuild aim:

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

CSAR Cavity Performance



General model:
curve(x) = a*exp(-x/tau)+b
Coefficients (with 95% confidence bounds):
a = 139 (138.6, 139.4)
tau = 45.46 (45.32, 45.61)
b = 1154 (1154, 1154)

T = 25 K
P = 10 mW

Expected:

Time constant 11 s
Sensitivity 0.5 K

Actual:

Time constant 45 s
Sensitivity 2 K

CSAR Design Tradeoffs

- Initial design at 30 K: sensitivity 0.0004%, time constant 15 s
  - Unlikely HPSC would achieve 30 K operating temperature given heat load of CSAR

- Increase in operating temperature results in decreased sensitivity and increased time constant
  - Trade-off: 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

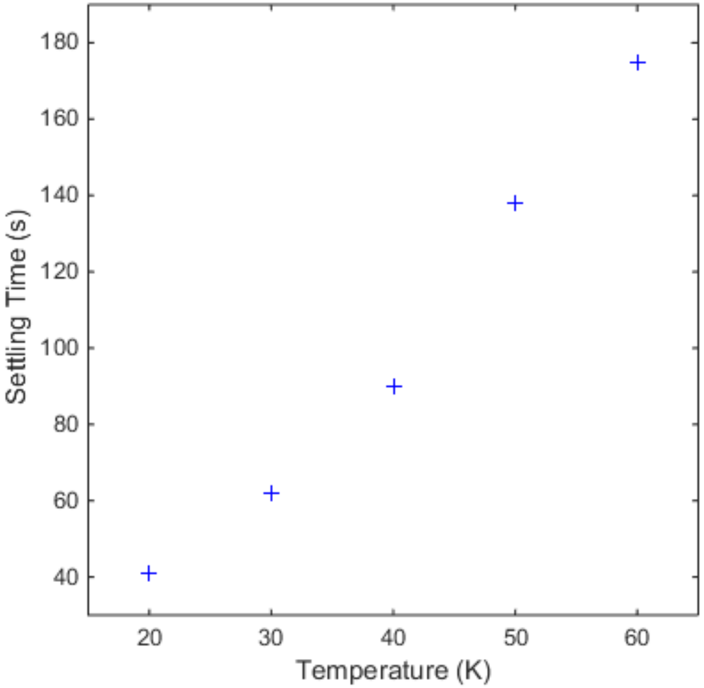
Active Cavity Configuration

- Cavity temperature actively maintained with PID loop 15 mW above zero-input power temperature (power expected from TSI measurement)

- Electrical power through cavity heater measured before and after optical radiation introduced to cavity:

  $$P_{dark} – P_{light} = P_{optical}$$

- Significantly faster than passive method, but some loss of accuracy
  - No longer just cavity sensitivity; noise of PID loop, current source resolution etc.



CSAR Assembly and Testing

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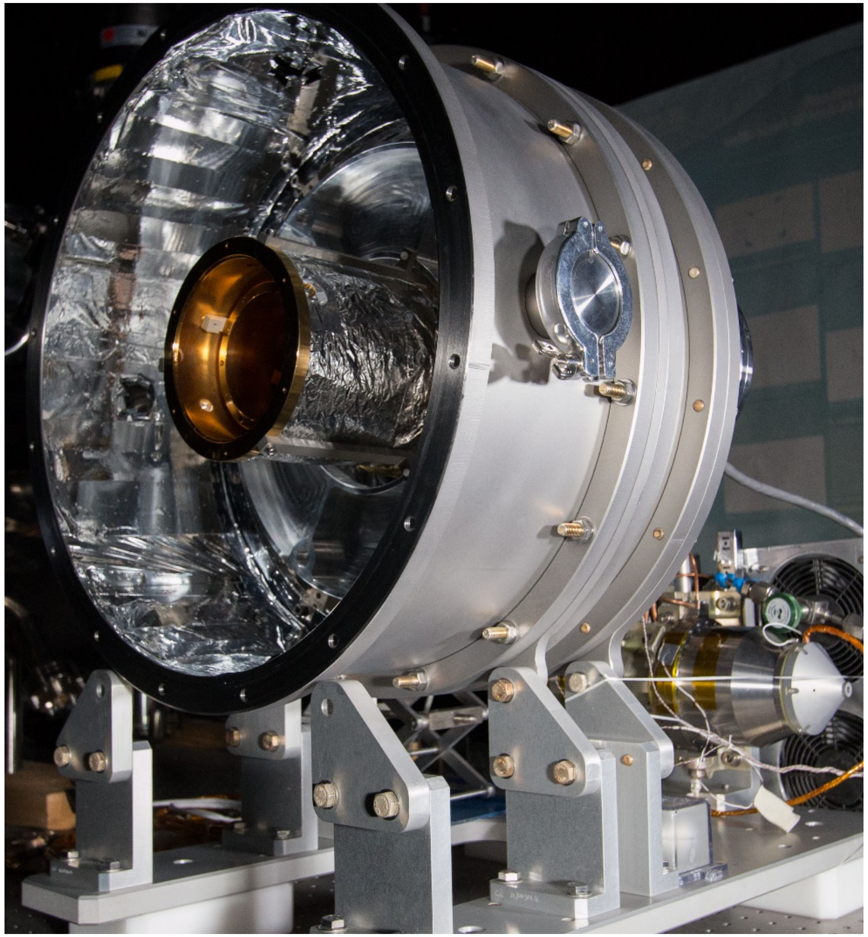
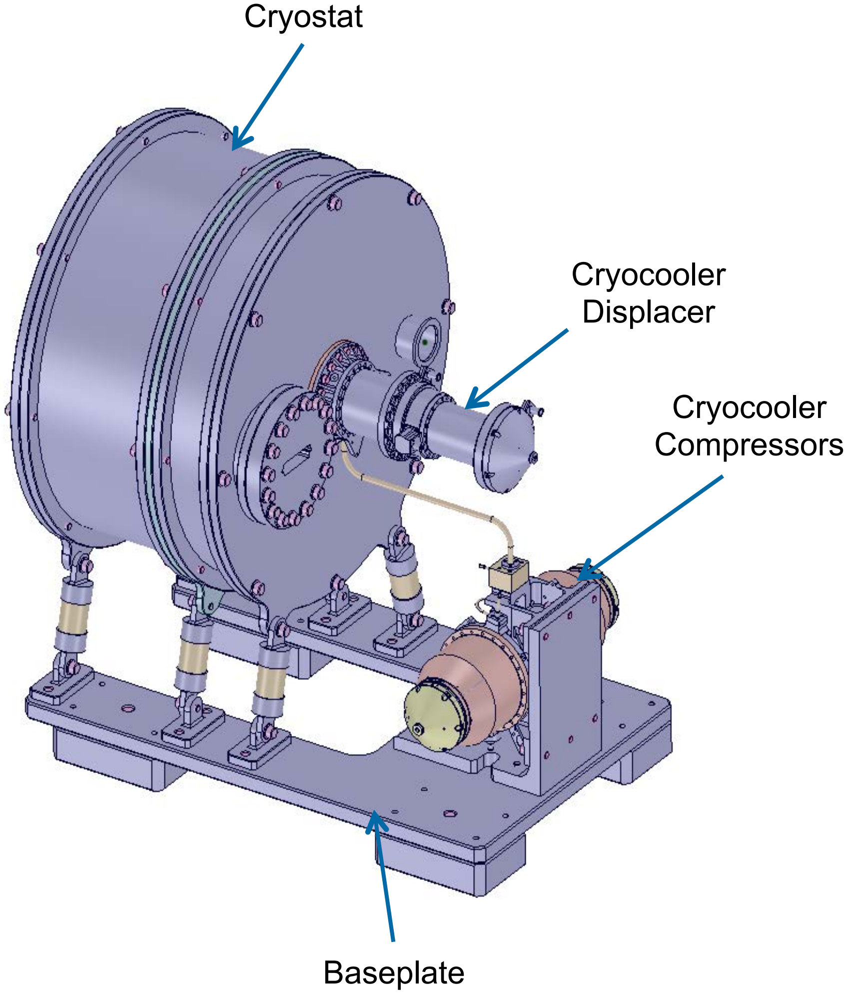


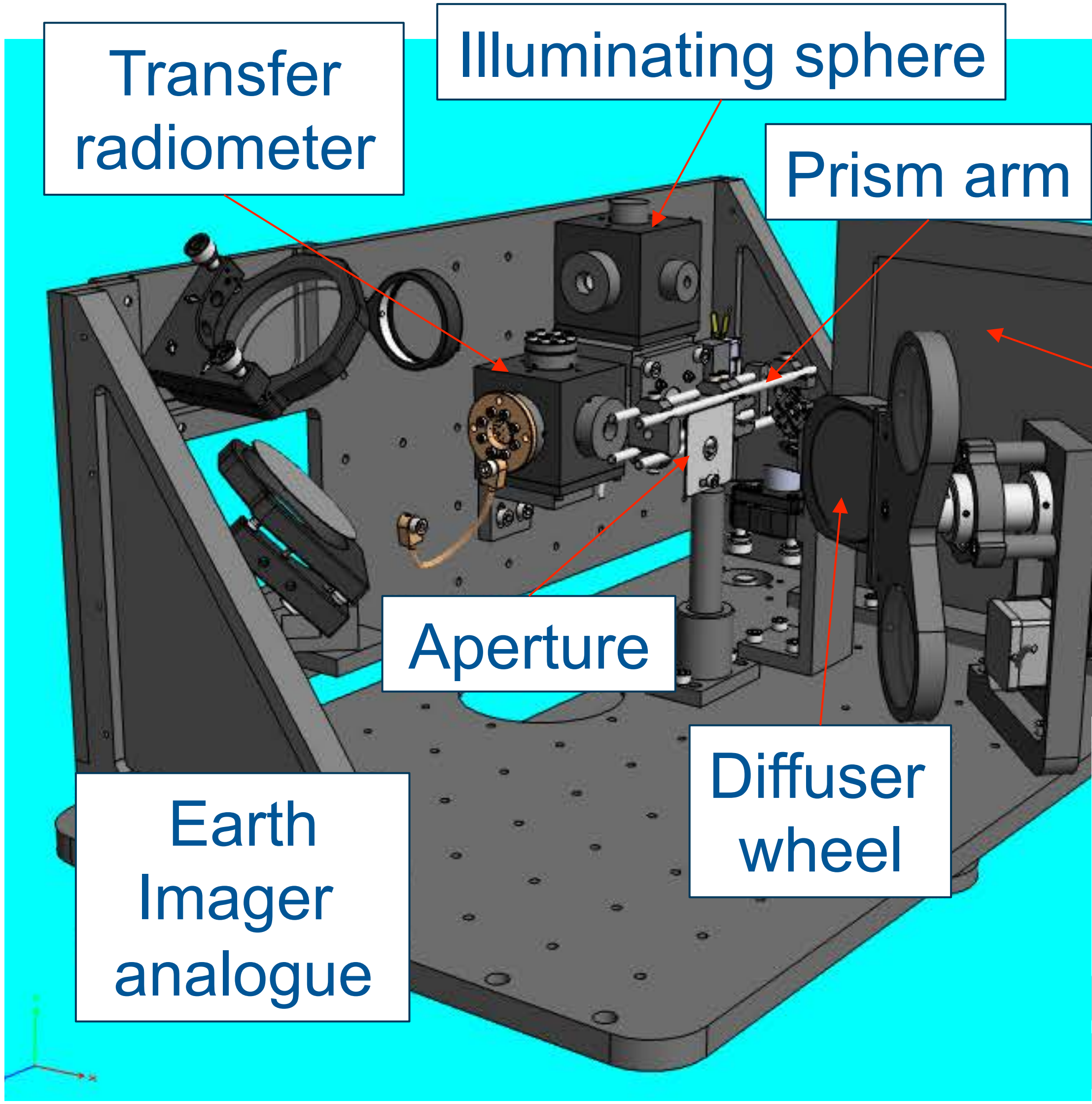


CSAR Coupled with HPSC

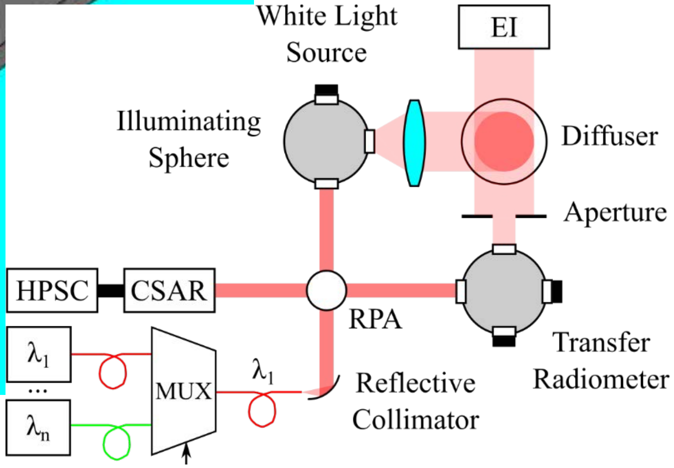
- Initial cooldown: achieved minimum reference block temperature just below 56 K with minimal optimization of cooler settings
- Base cavity temperature 60 K, sensitivity 0.09 K/mW, time constant 217 seconds
- For typical excursions from setpoint, PID loop cannot achieve 0.01% stability by itself (integration of N samples needed at 2 Hz)

Excursion	Initial time	σ	N	Uncertainty	Total time
1%	26.0 s	0.044%	20	0.006%	36.0 s
3%	28.5 s	0.048%	20	0.007%	38.5 s
5%	28.0 s	0.059%	20	**0.009%**	**38.0 s**

Calibration System Design

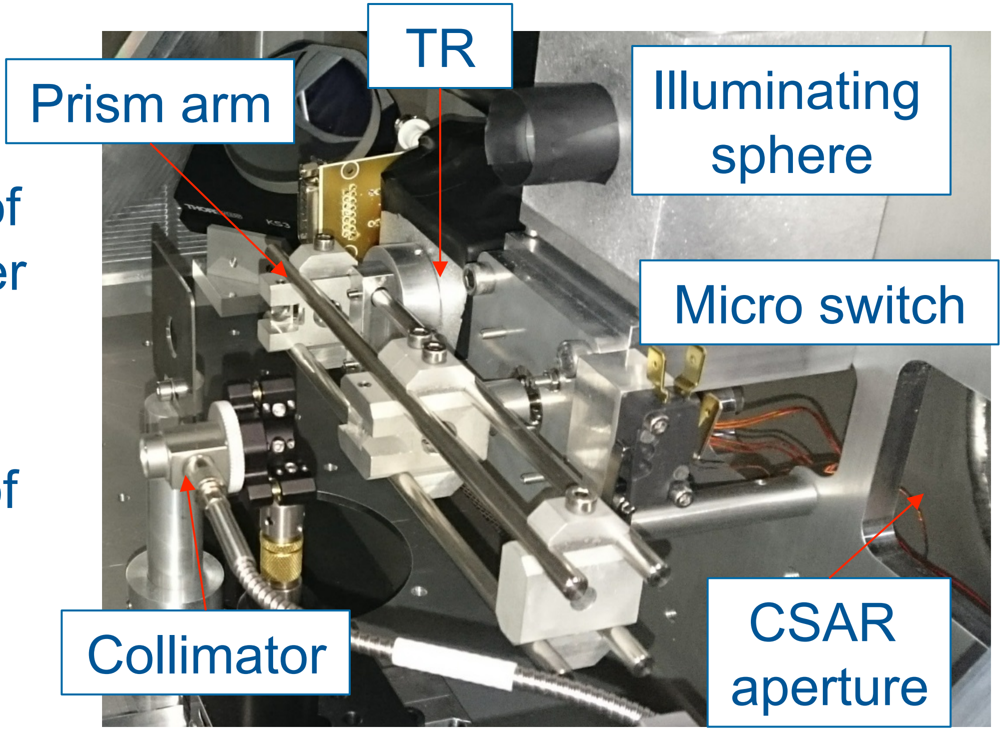


Design credit: Peter Lovelock – National Physical Laboratory

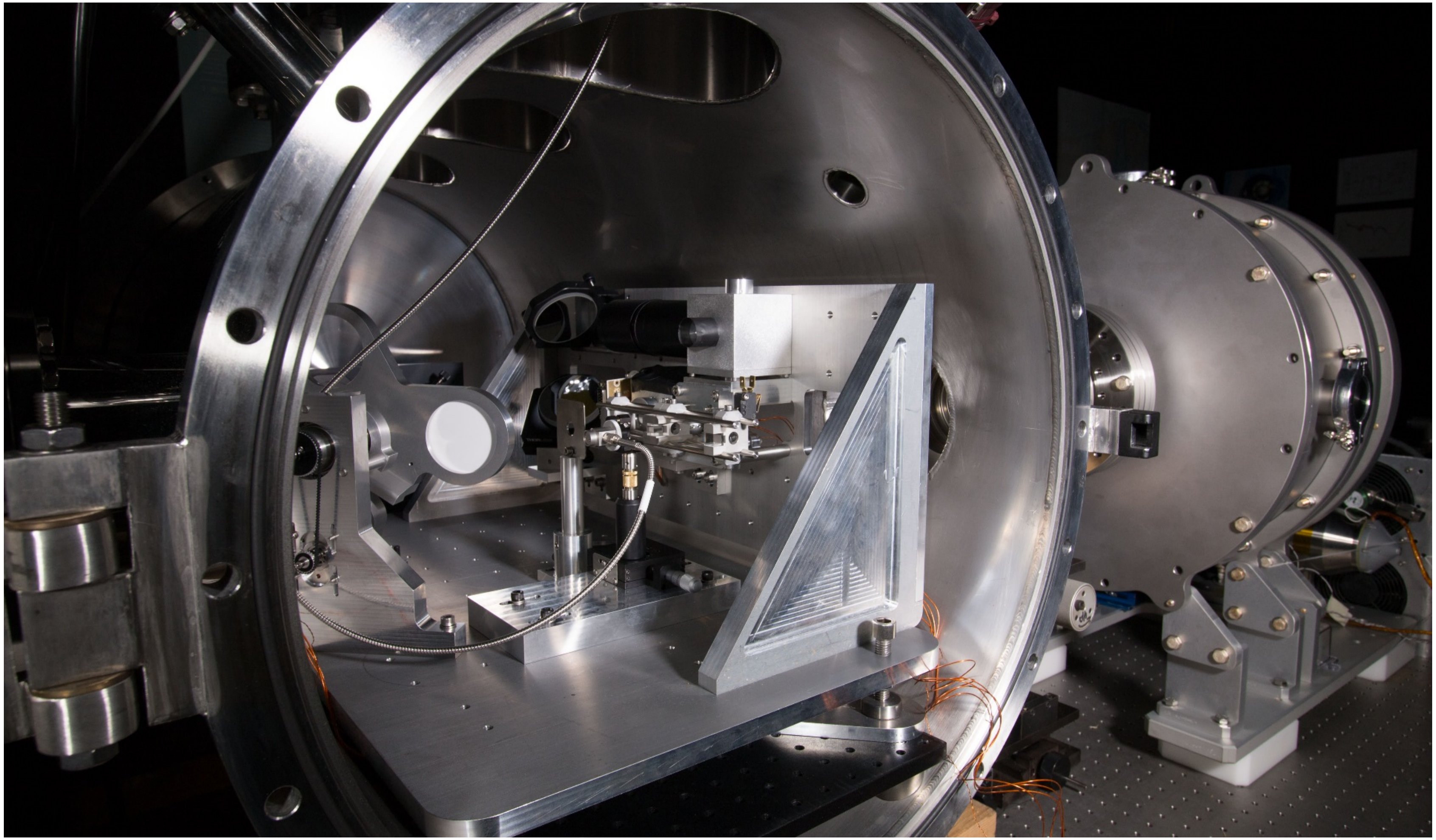


Beam Delivery Optics

- Reflective fibre collimator (broadband)
- Counter-balanced rotating roof prism arm, moved with stepper motor
- Achieved repeatable control of prism arm position directing beam into CSAR, TR or illuminating sphere
- Micro switch used to "home" prism arm position



Calibration System Assembly



Coupling with HPSC

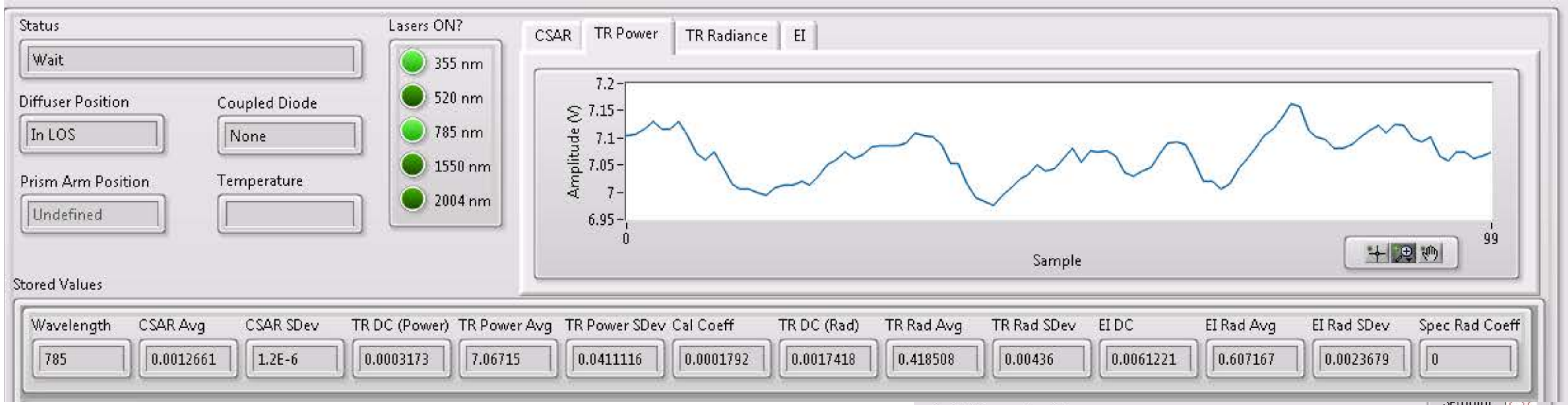
- Coupling with HPSC and CSAR was successful
  Vacuum was not ideal (10^{-4} mbar) but could improve with additional cryopumping/bakeout

- Achieved stabilized reference block temperature of 72 K with some optimization of cooler settings (4 W on displacer, 62 degrees phase, 36.4 Hz)

- Stabilized cavity at 75 K, 15 mW above RB

- Observed change in cavity power with introduction of laser radiation

End-to-End Calibration In-Situ



Status: Wait

Diffuser Position: In LOS

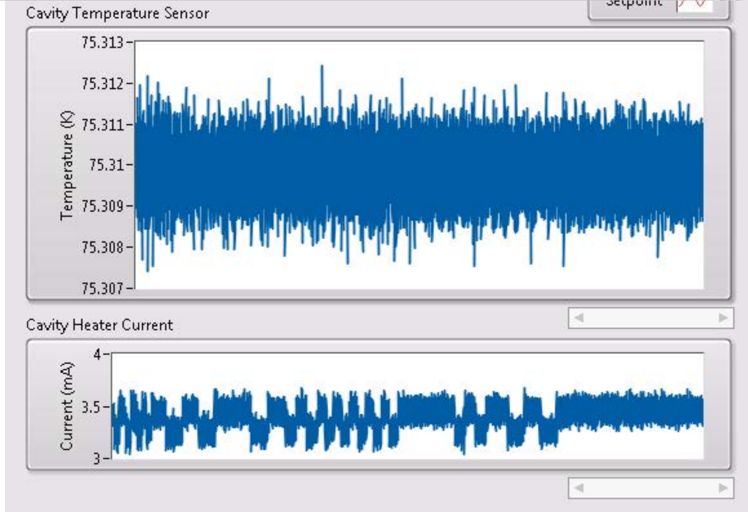
Coupled Diode: None

Prism Arm Position: Undefined

Temperature:

Stored Values

Wavelength	CSAR Avg	CSAR SDev	TR DC (Power)	TR Power Avg	TR Power SDev	Cal Coeff	TR DC (Rad)	TR Rad Avg	TR Rad SDev	EI DC	EI Rad Avg	EI Rad SDev	Spec Rad Coeff
785	0.0012661	1.2E-6	0.0003173	7.06715	0.0411116	0.0001792	0.0017418	0.418508	0.00436	0.0061221	0.607167	0.0023679	0



- P_{CSAR} = 1.266 mW ± 0.001 mW
- C = 0.179 mW/V± 0.006 mW/V
- TR radiance: 0.025 W m^{-2} sr^{-1}
- Agrees with expected radiance calculated from radiance of illuminating sphere with input power P_{CSAR}
- Signal level of EI analogue comparable

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

	Lab-based	Space-based	
Laser diodes	< 0.3%	< 0.07%	Stabilized DFB lasers
CSAR	< 0.06%	< 0.06%	
Prism arm	< 0.01%	< 0.01%	
Transfer radiometer	< 0.03%	< 0.03%	
External aperture	< 0.17%	< 0.02%	Calibrated pre-flight
Traceability	< 0.08%	< 0.08%	
	Total < 0.38%	**Total** **< 0.12%**	

Next Steps to Space Qualified Calibration System

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- Passive laser conjoiner: e.g. waveguide rod, hexagonal fibre
- Uniformity mapping of diffuser illumination and radiance
- Install white light source for EI calibration interpolation
- Improved radiation shielding of CSAR from rest of system, cryopumping/bakeout to improve vacuum
- Perform end-to-end calibration of suitable imaging spectrometer (not in vaccum)
- Incorporate flat-panel source as Earth analogue