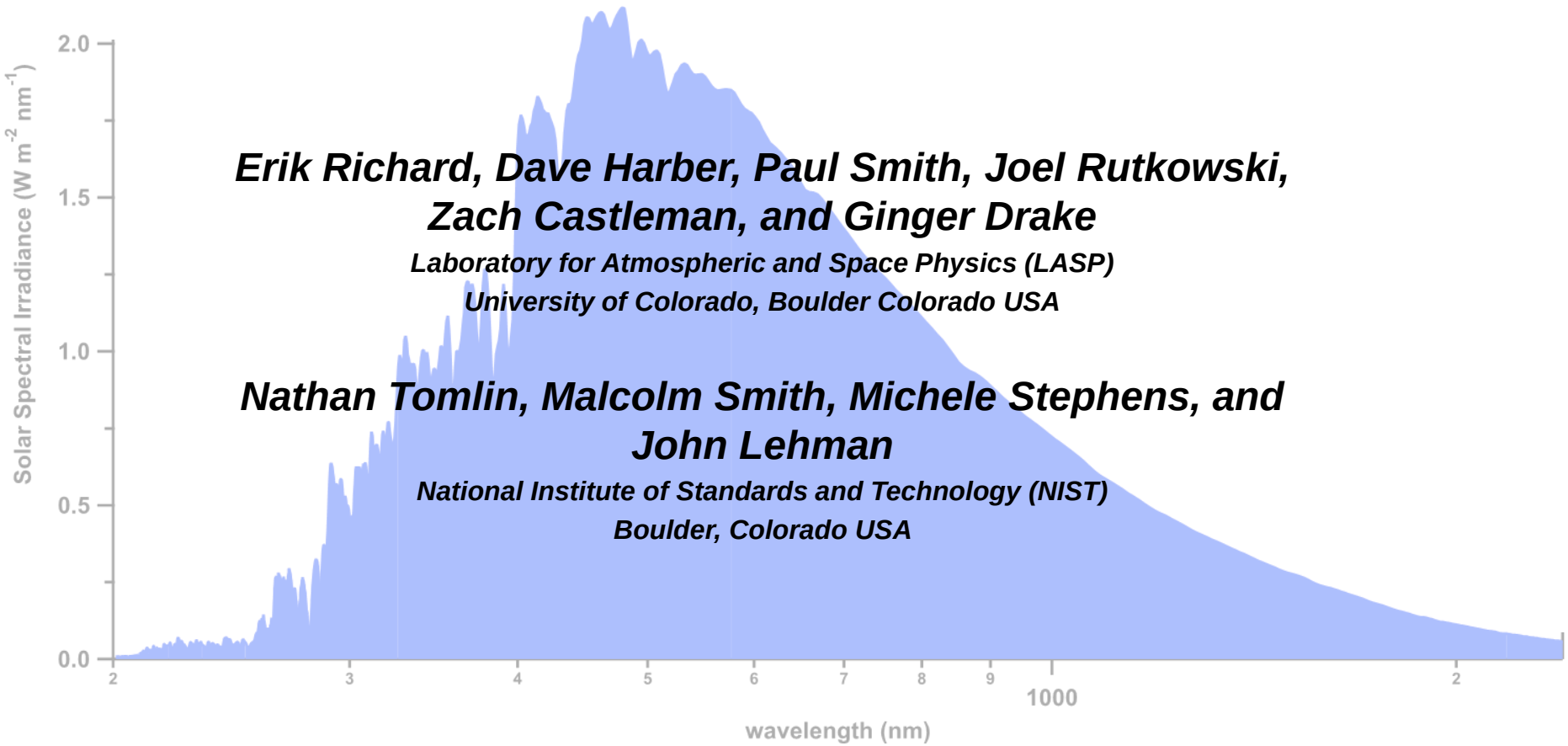
A Compact Solar Spectral Irradiance Monitor for Future Small Satellite and CubeSat Science Opportunities



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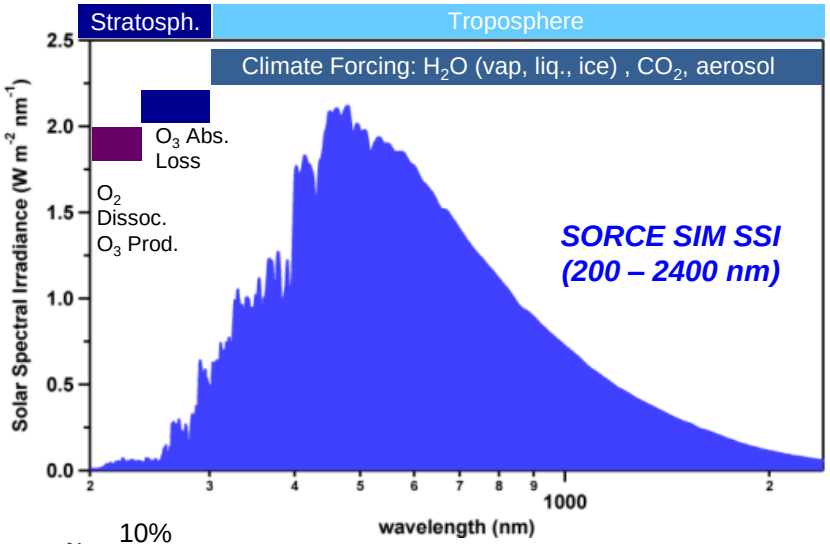
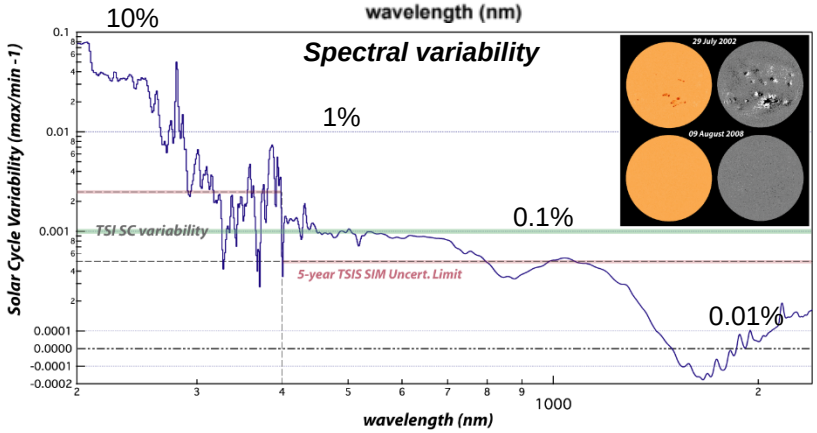
Solar Spectral Irradiance

CSIM
Compact Spectral Irradiance Monitor





Global Energy Budget Contributions

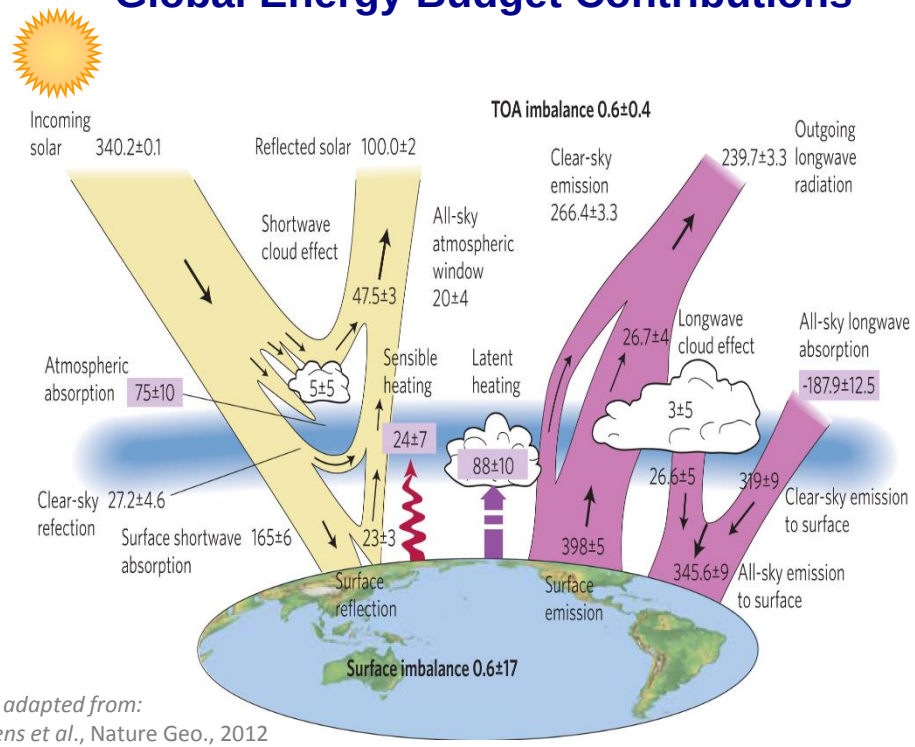


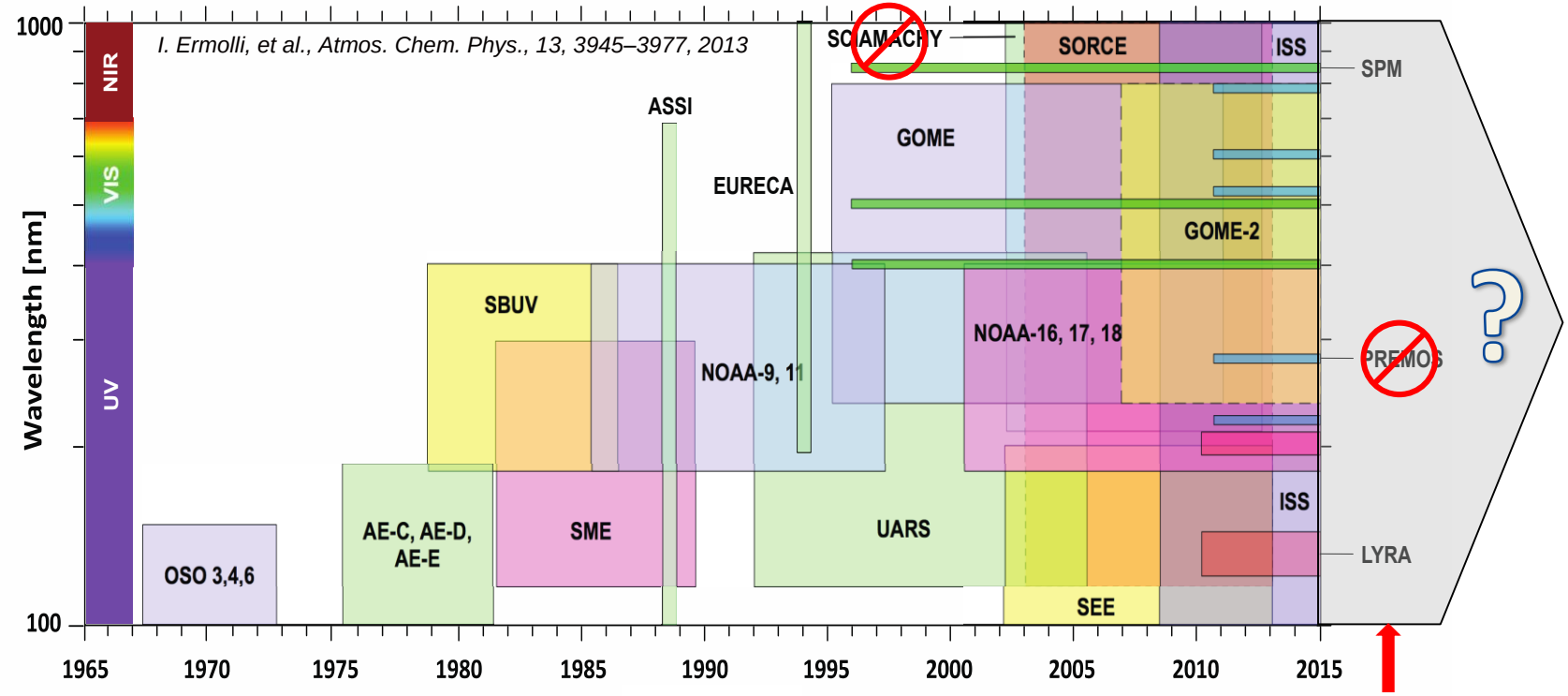
Figure adapted from: Stephens et al., Nature Geo., 2012

The measurement of SSI is vital for understanding how solar variability impacts climate and for validating climate model sensitivity to <u>spectrally varying</u> solar forcing

"Acquire SSI and TSI time series of measurements of sufficient length, consistency, and <u>continuity</u> to determine climate variability and change"

Climate Data Records from Environmental Satellites: Interim Report (2004)

SSI Measurement Continuity



Note: For several of the instruments SSI is not their primary product, therefore calibration and long-term stability corrections not well quantified

Measurement continuity relates to both <u>temporal</u> AND <u>spectral</u> coverage

- *Are there alternatives that can be implemented without sacrificing quality?*
- *Can short duration - overlap missions provide the necessary ties?*
- *Is the data quality adequate for Earth-climate research?*

Present SSI Measurement Requirements

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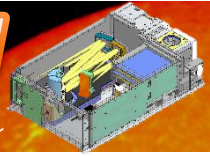

SSI Measurement Requirements		
Specification	**Requirement**	**Justification**
Irradiance Range Limits	10^{-4}-10^{1} $Wm^{-2}nm^{-1}$	Full scale bounds on SSI
Spectral Range (continuous)	200-2400 nm	Nearly full spectrum: 96% TSI
✓ Measurement Uncertainty* (k=1) (SI-traceable in irradiance)	0.2% (Absolute)	Climate modeling input Radiation budget solar attribution
Measurement Repeatability	100 ppm (Relative)	Precision Std. dev. of repeated measurements
Long-term stability** ≤400 nm >400 nm	 500 ppm/yr 100 ppm/yr	Solar cycle variability UV:10%-0.1% (Chromospheric) Vis-IR: ≤0.1% (Photospheric)
Spectral Resolution Limits ≤ 280 nm > 280 nm – 400 nm > 400 nm	 2 nm 5 nm 45 nm	Solar spectral variability Strong wavelength dependence in UV Broader wavelength dependence in Vis-IR

**Long-term correctable stability limits represent 10-25% of total expected variability

***Absolute Uncertainties (evolution):**

SORCE SIM 2-8% → **TSIS SIM 0.2%** → **CSIM 0.2%**

Achieving an Accurate SSI Observation

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Compact Spectral Irradiance Monitor

- ✓ ***GOAL #1*** *– Place the instrument on orbit with the best possible calibration (SI-units) and characterization*
- ✓ ***GOAL #2*** *– Determine on-orbit changes in instrument responsivity, correct solar data* ***(with documented uncertainties)***
- ✗ TBD ***GOAL #3*** *– Establish a solar irradiance EDR that can be reliably compared to future observations*

LASP Spectral Radiometry Facility (SRF)

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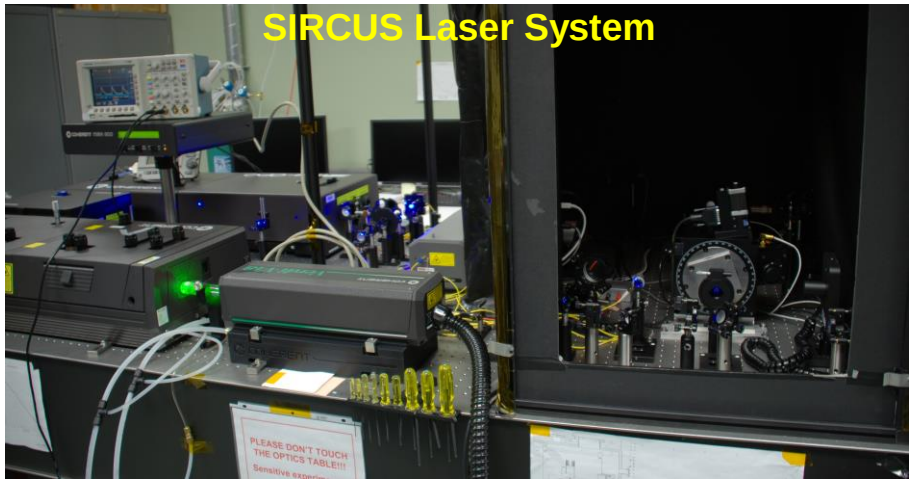

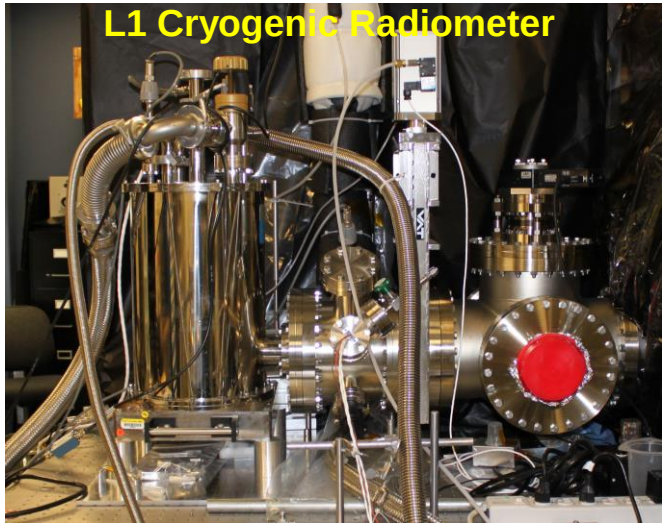

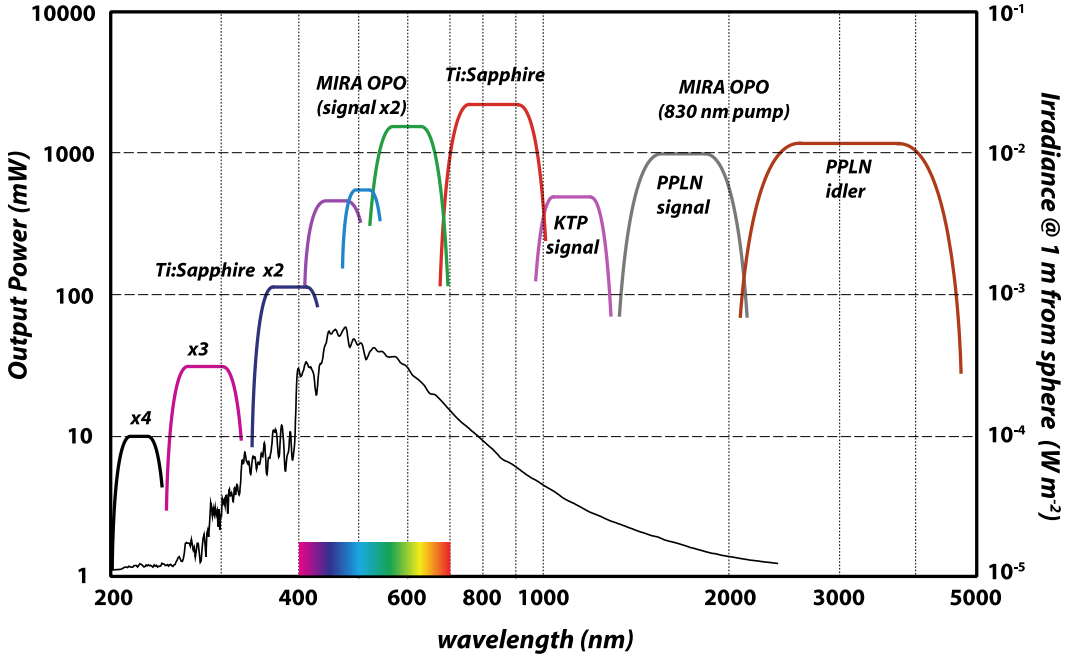

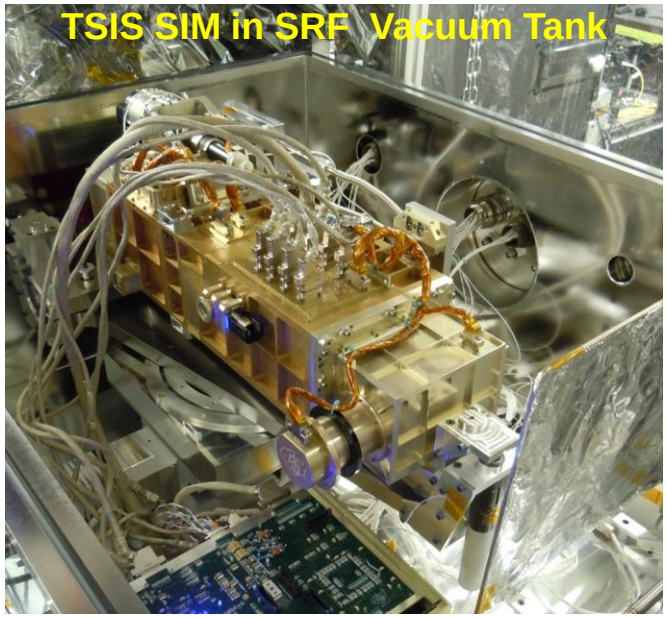

Full Spectrum Irradiance Validation (Absolute)

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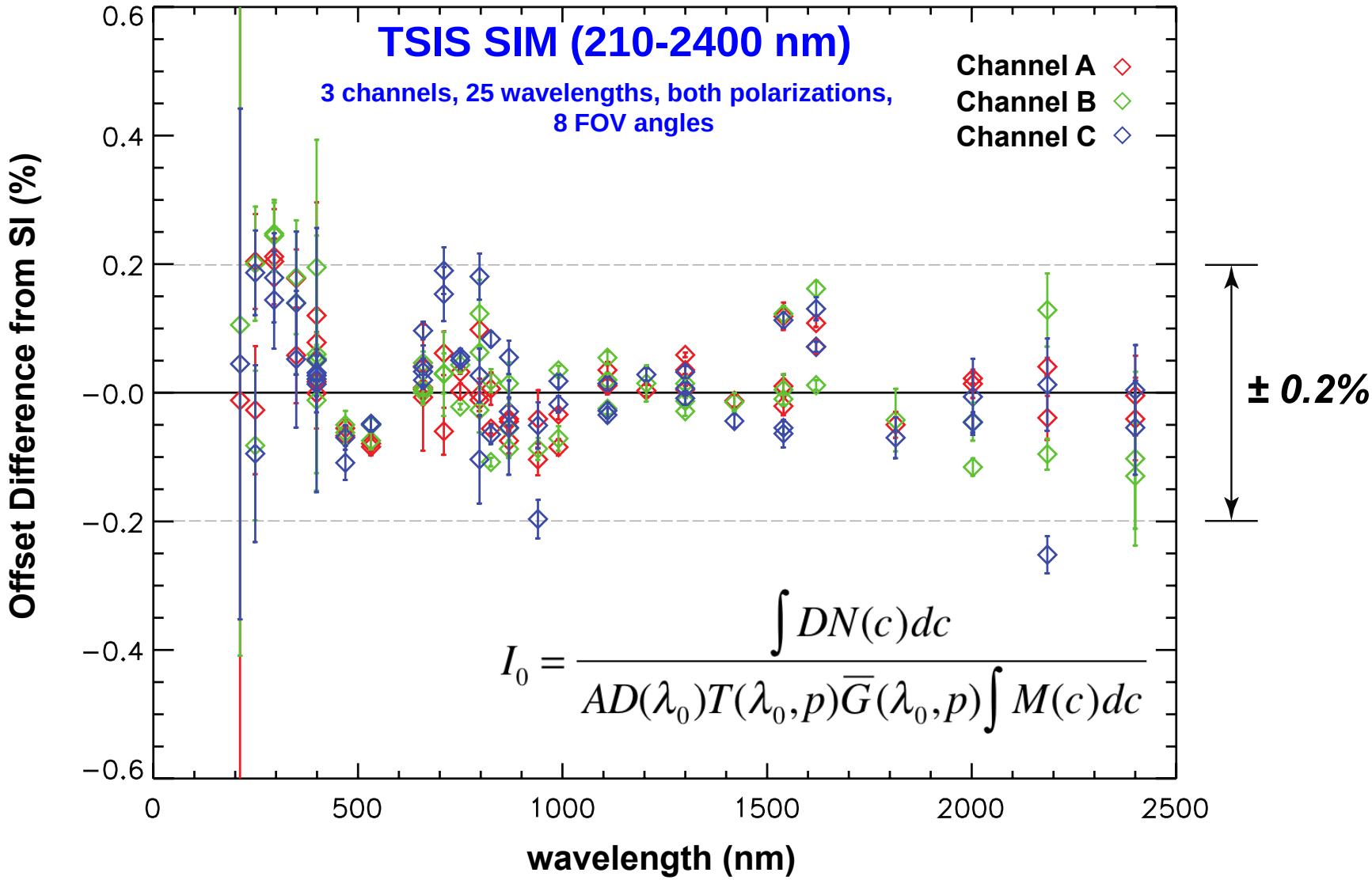
Compact Spectral Irradiance Monitor



$$I_0 = \frac{\int DN(c)dc}{AD(\lambda_0)T(\lambda_0,p)\overline{G}(\lambda_0,p)\int M(c)dc}$$

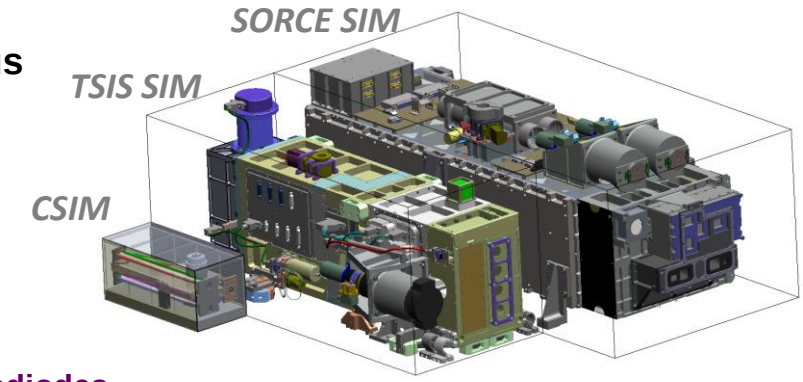
Design Evolution

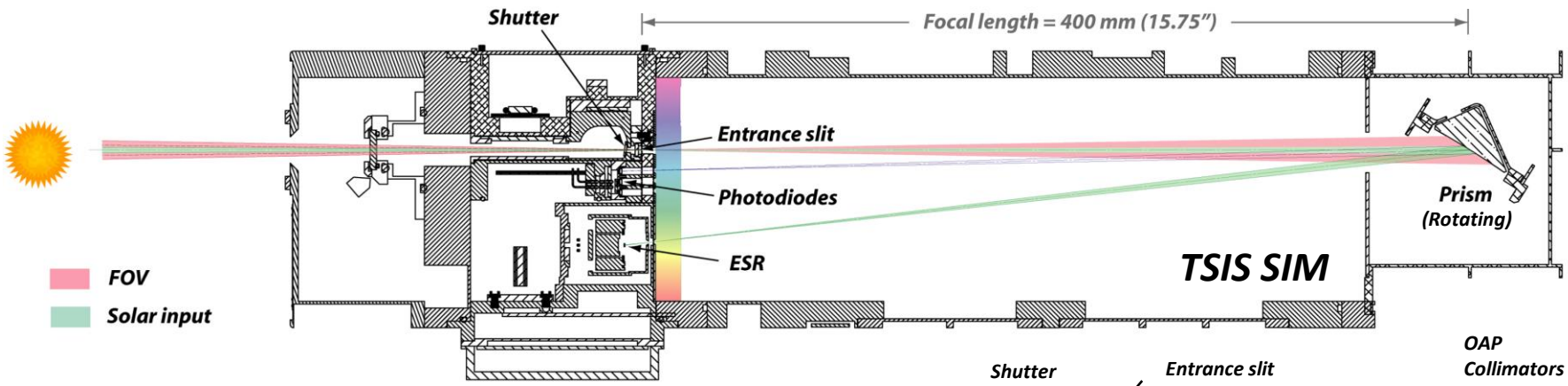
CSIM
Compact Spectral Irradiance Monitor

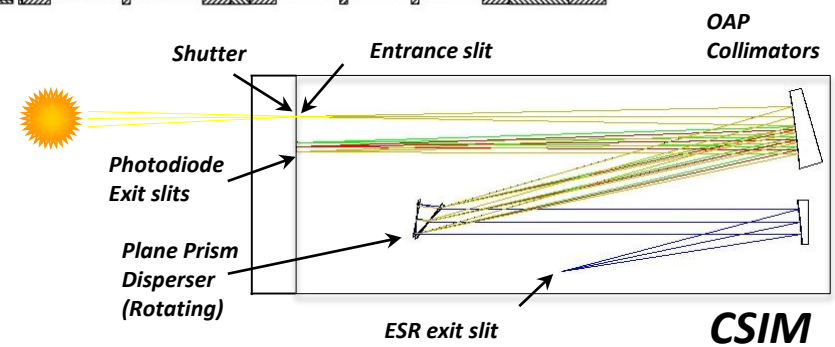
Simple light path: entrance slit-prism-exit slit-detector

Wavelength is scanned by rotating the prism (continuous spectral coverage-no *"order sorting"*)

- **Silicon (UV-Vis) and InGaAs (IR) photodiodes**
  - **High S/N and fast**
  - **Used to take two solar spectra per day**
- **Miniature electrical substitution radiometer (ESR)**
  - **Carries the absolute calibration**
  - **Provides long-term stability to calibrate the photodiodes**





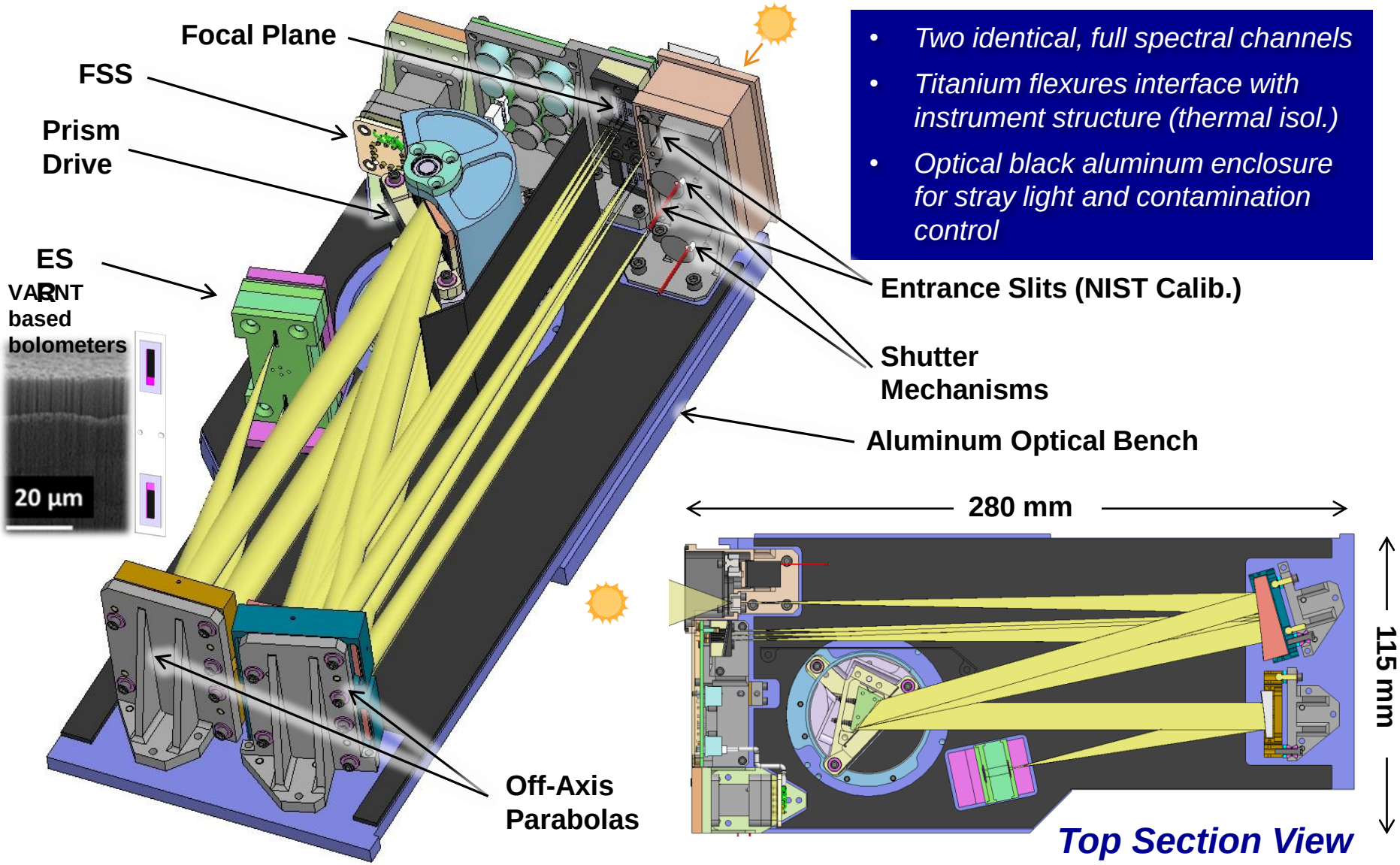


Measurement Equation (Units: $Wm^{-2}nm^{-1}$)

$$\mathcal{E}_\lambda(\lambda_s) = \frac{\mathcal{P}_{\mathrm{ESR}}(\lambda_s)}{A_{slit} \cdot \int \alpha_\lambda \cdot T_\lambda \cdot \phi_\lambda \cdot S(\lambda, \lambda_s)\, d\lambda}$$

Compact SIM – Dual channel SSI

CSIM
Compact Spectral Irradiance Monitor

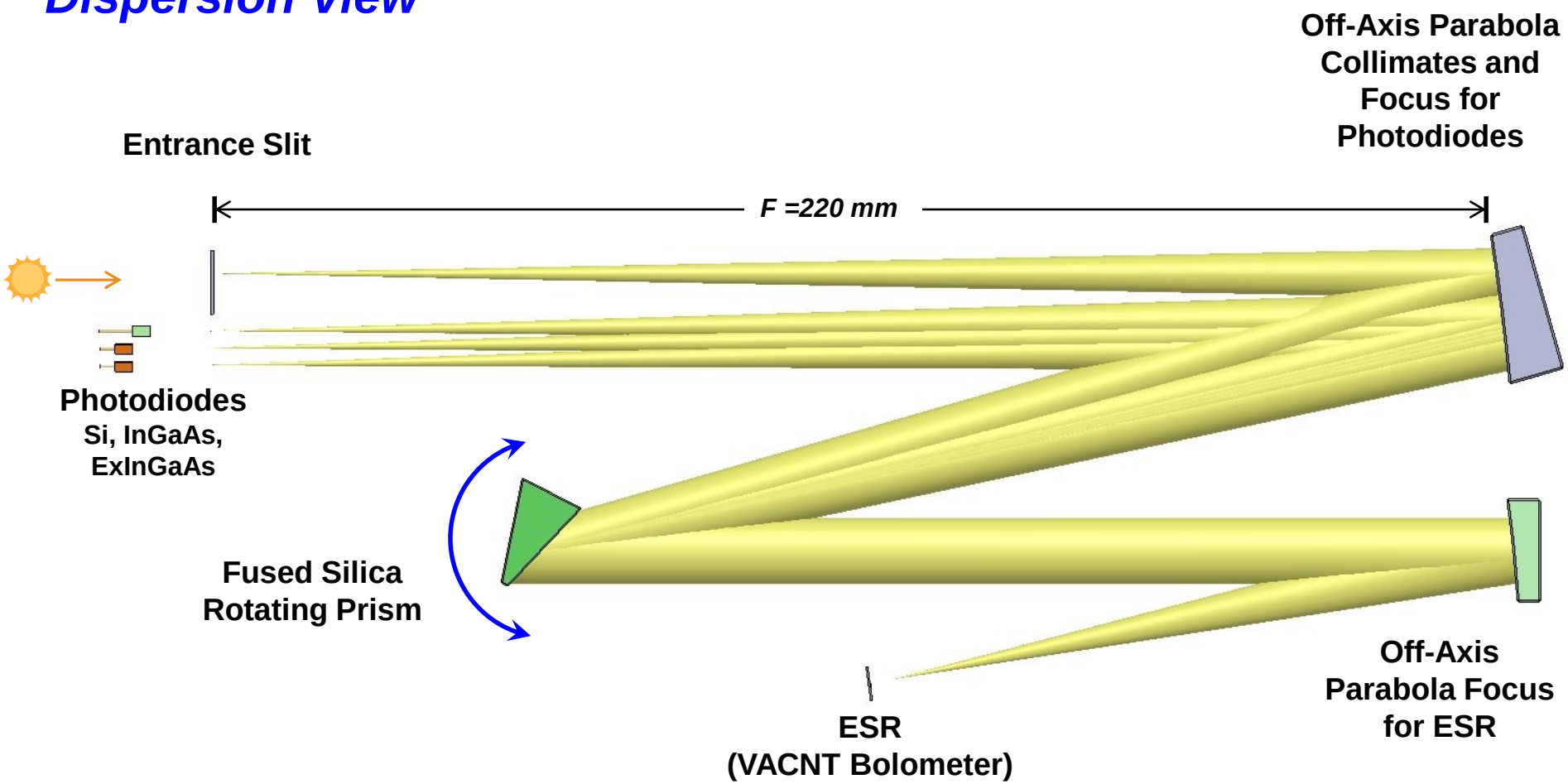


- *Two identical, full spectral channels*
- *Titanium flexures interface with instrument structure (thermal isol.)*
- *Optical black aluminum enclosure for stray light and contamination control*

CSIM Optical Overview

CSIM
Compact Spectral Irradiance Monitor

Dispersion View

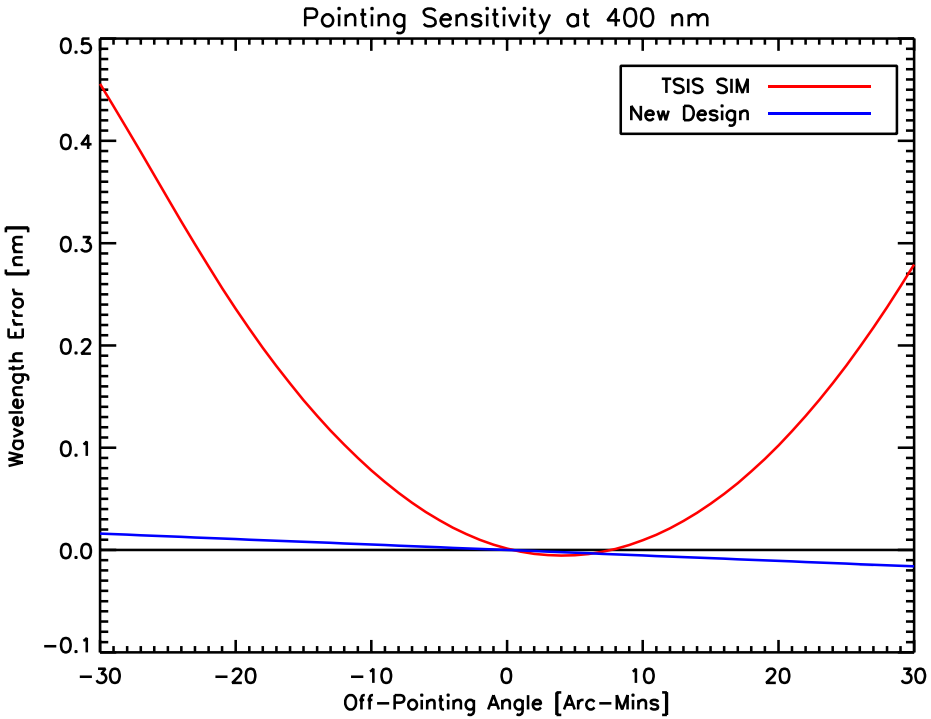


CSIM incorporates two identical channels, stacked on top of each other, to permit tracking of exposure-induced degradation

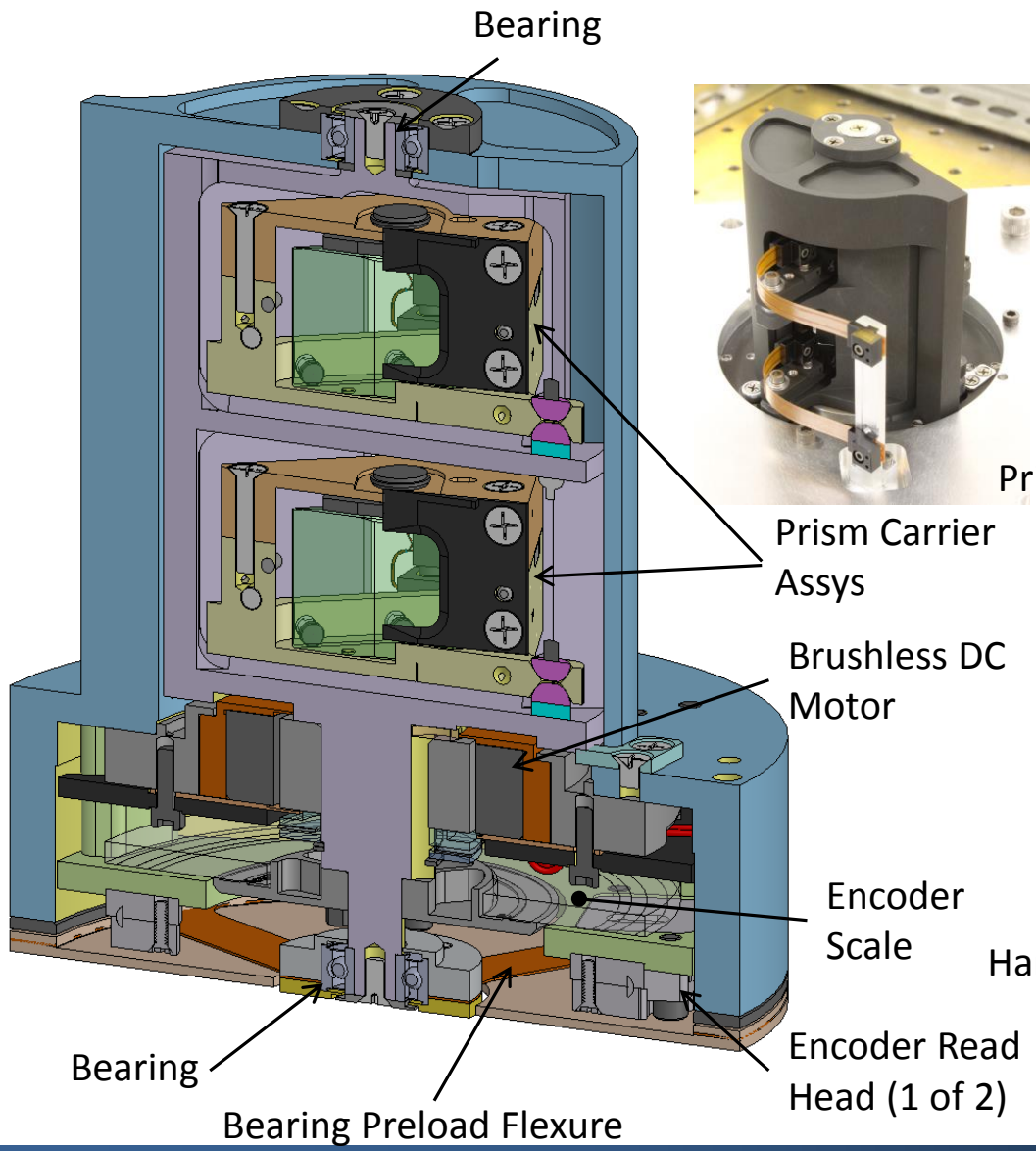
CSIM Design Attributes

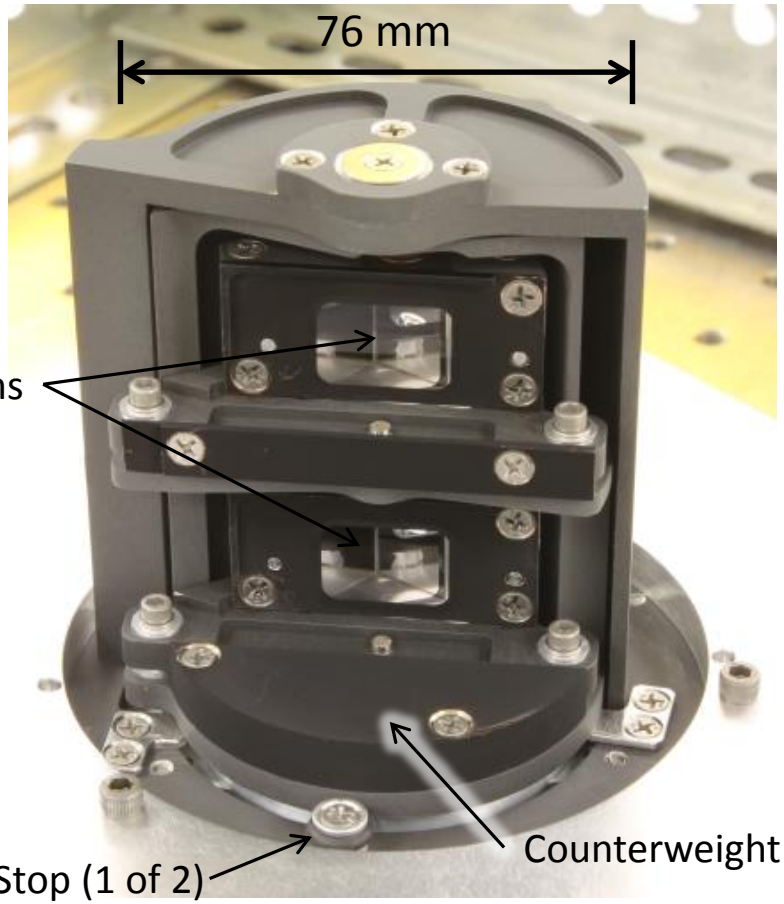
CSIM
Compact Spectral Irradiance Monitor

- ***Reduced pointing sensitivity***
- ***Increased FOV***
- ***Improved encoder design***
- ***Improved stray light rejection***
- ***Simplified configuration with improved manufacturability***
- ***Reduced size***
- ***Modular design***



CSIM Prism Rotation Drive





Actual CSIM Prism Drive
(mounted to GSE plate)

CSIM prism positional stability

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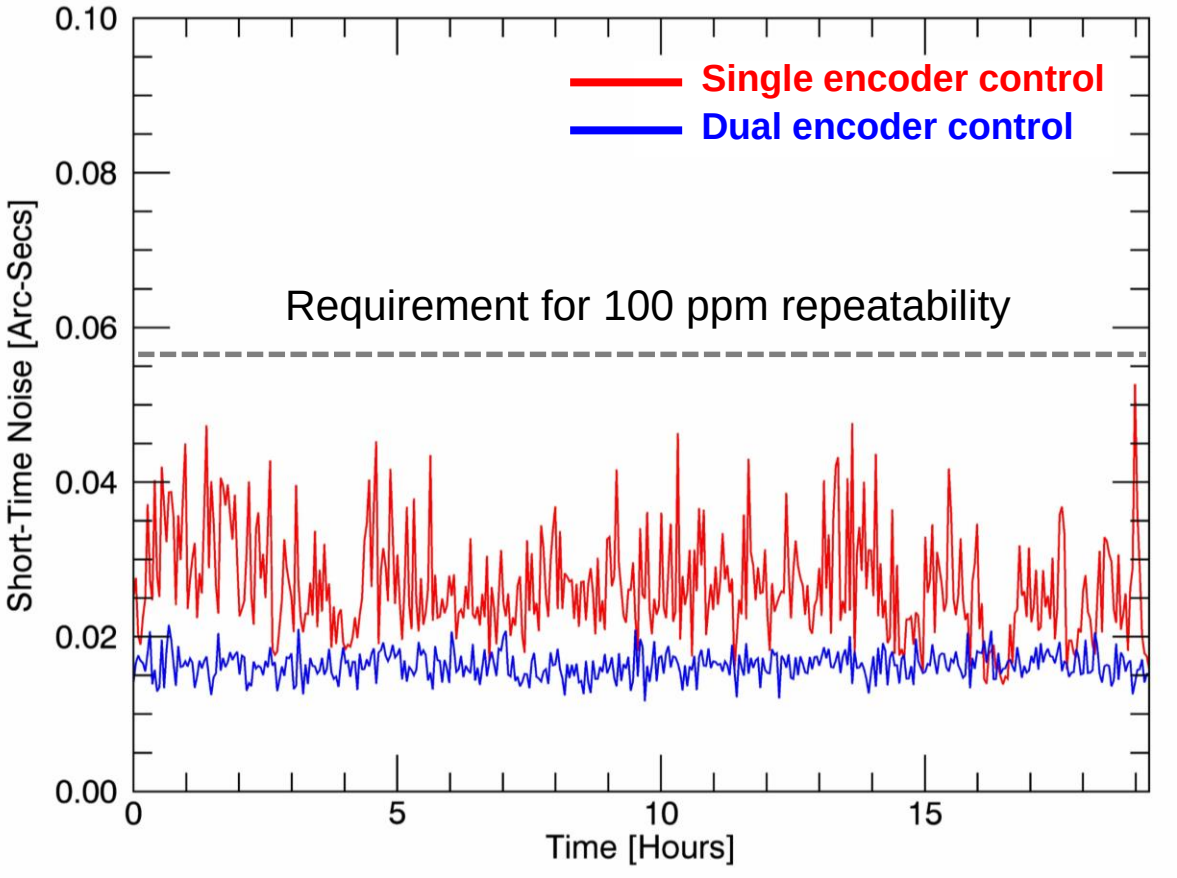
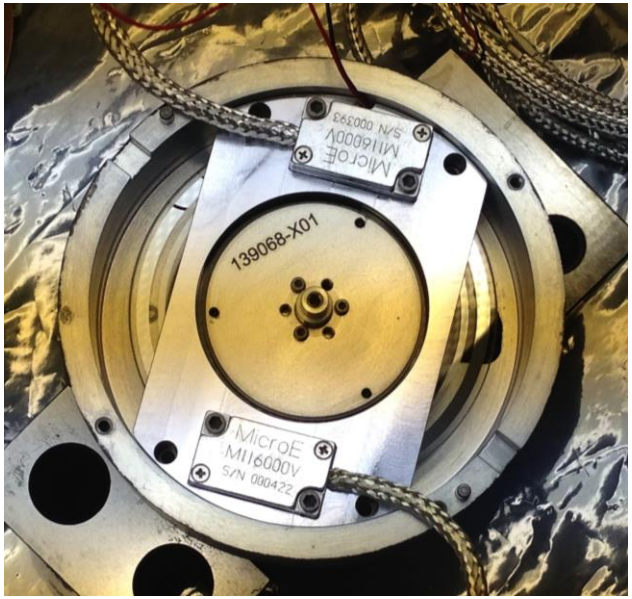
Measurement stability requires wavelength stability



CSIM dual-encoder arrangement



CSIM ESR Bolometer Design

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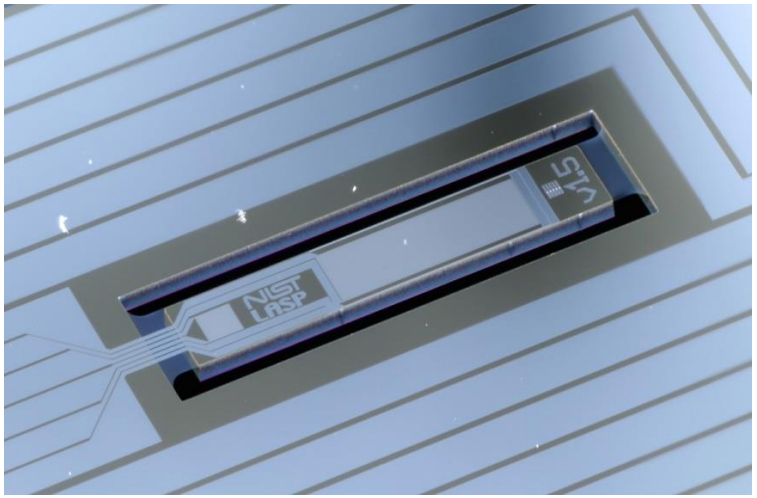
Compact Spectral Irradiance Monitor

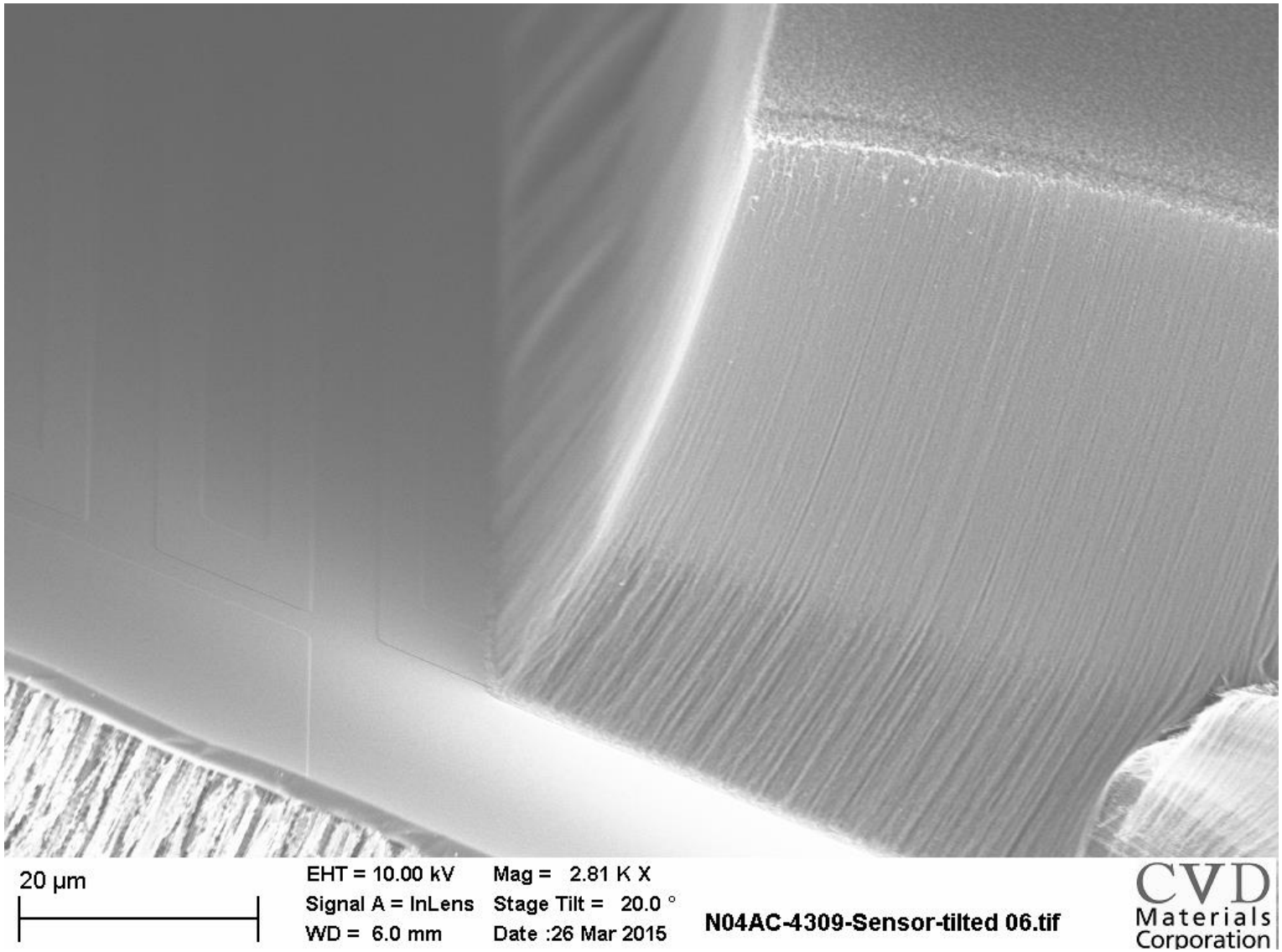
- **Vertically aligned carbon nanotubes**
  - Extremely "Black"
  - Spectrally flat
  - Large thermal conductivity
- **Silicon substrate**
- **SiN Thermal Link**
  - Low thermal conductivity
  - Low thermal mass
- **Patterned heater and leads**
- **Bonded thermistor**

Parameter	Value
Active Area	1.2 x 4.5 mm
Bolometer	1.2 x 6.3 x 0.375 mm Silicon
Thermal Link	1.2 x 0.5 x 0.002 mm Silicon Nitride
Absorber	VACNT
Thermal Link Impedance	~5500 K/W
Heat Capacity	~4.8 mJ/K

Well controlled fabrication process



Vertically Aligned Carbon Nanotubes (VACNT)



Vertically Aligned Carbon Nanotubes (VACNT)

VACNT ESR Noise Estimate

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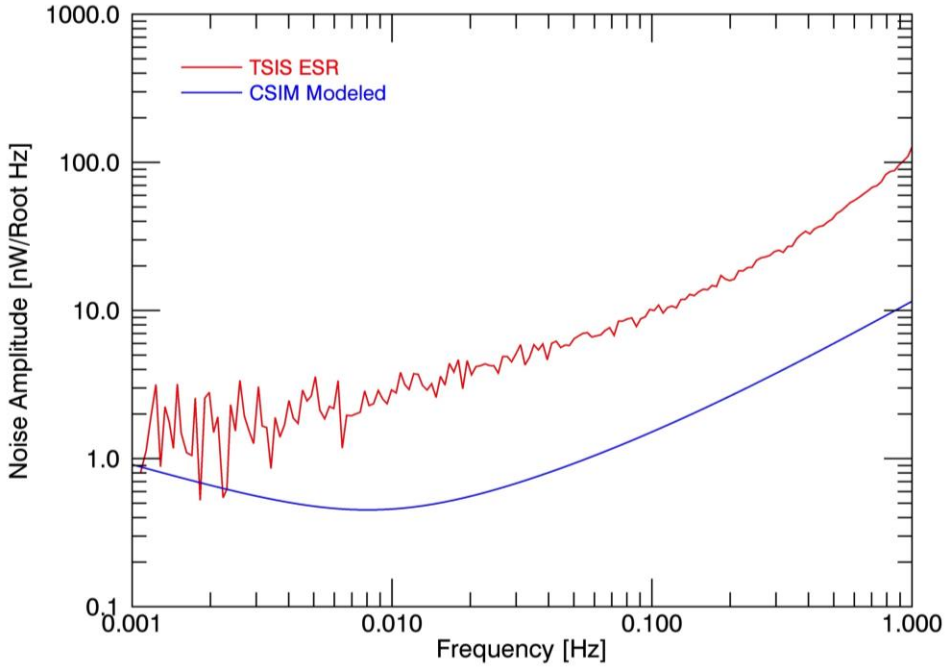
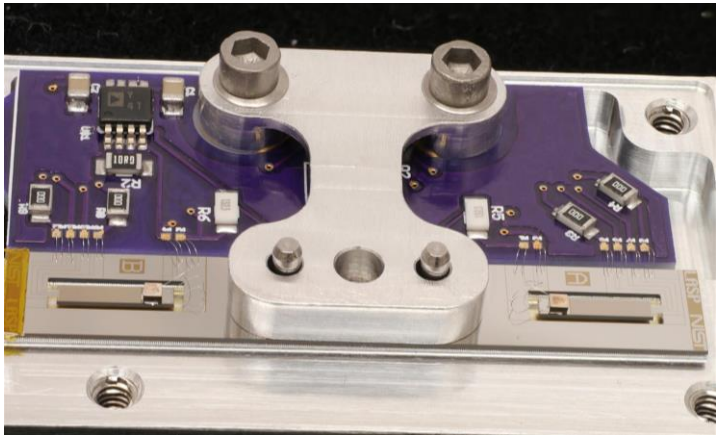
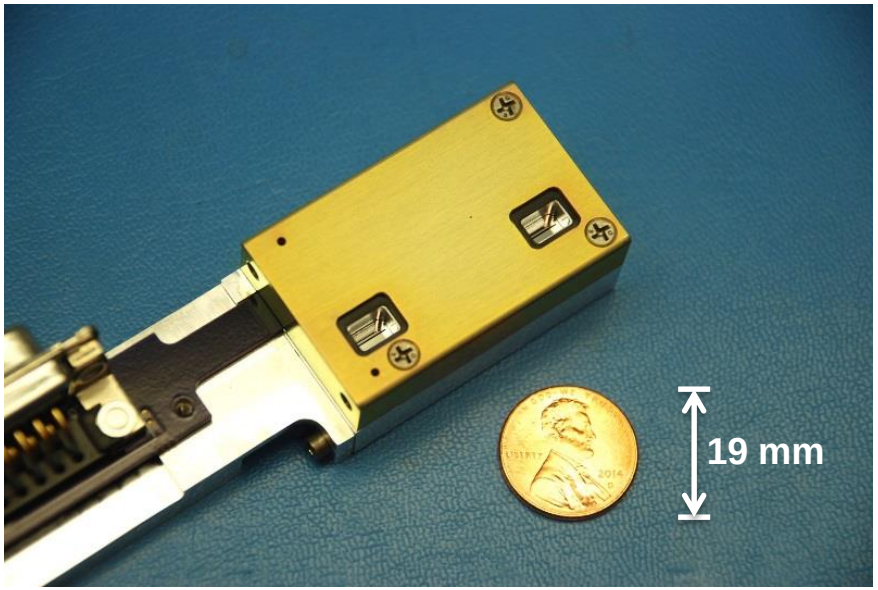
Noise spectral power density vs. frequency



Assembled Prototype ESR





Bolometer Model

- ***Measured thermal parameters***
- ***Z_0=5500 K/W, C_p=4.8 mJ/K, tau=19 s***
- ***same temperature noise as TSIS***

Noise Level for 40s Measurement

- ***TSIS ESR ~ 1.6 nW***
- ***CSIM ESR ~ 0.24 nW***

VACNT ESR Noise Measurement

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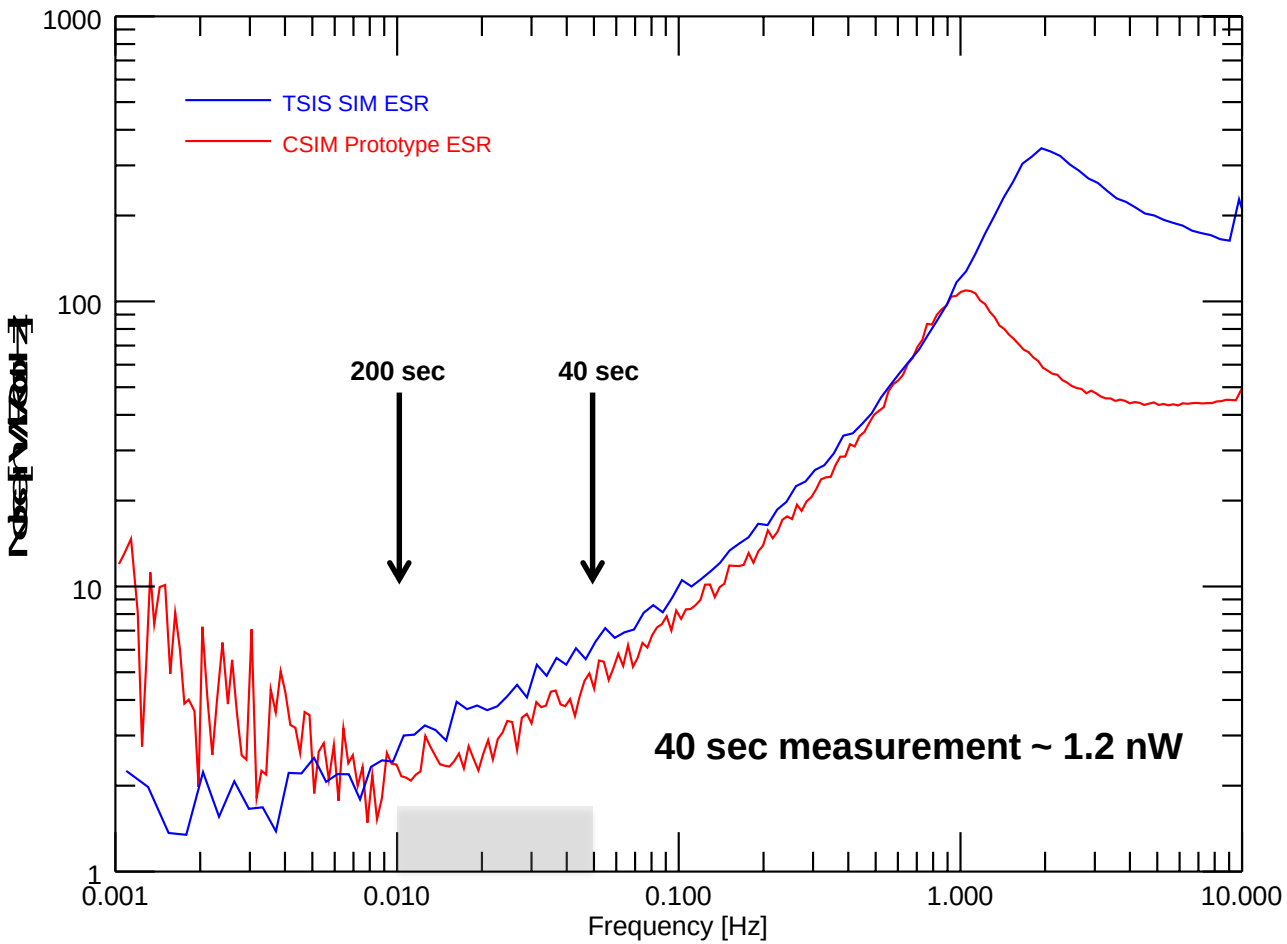
Compact Spectral Irradiance Monitor

✓ Prototype CSIM ESR meets TSIS SIM ESR performance



CSIM CubeSat Package

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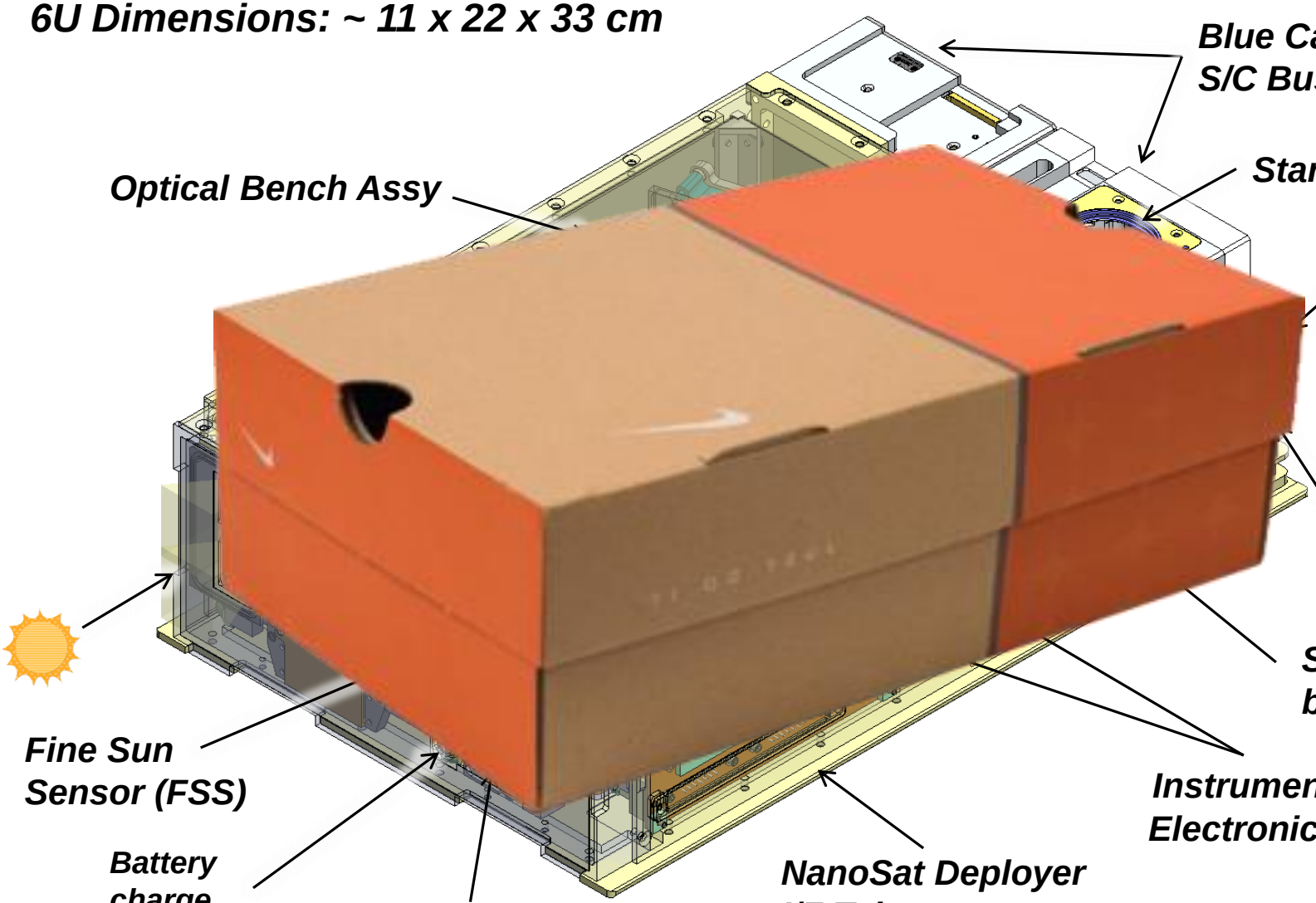
6U Dimensions: ~ 11 x 22 x 33 cm



CSIM CubeSat Overview

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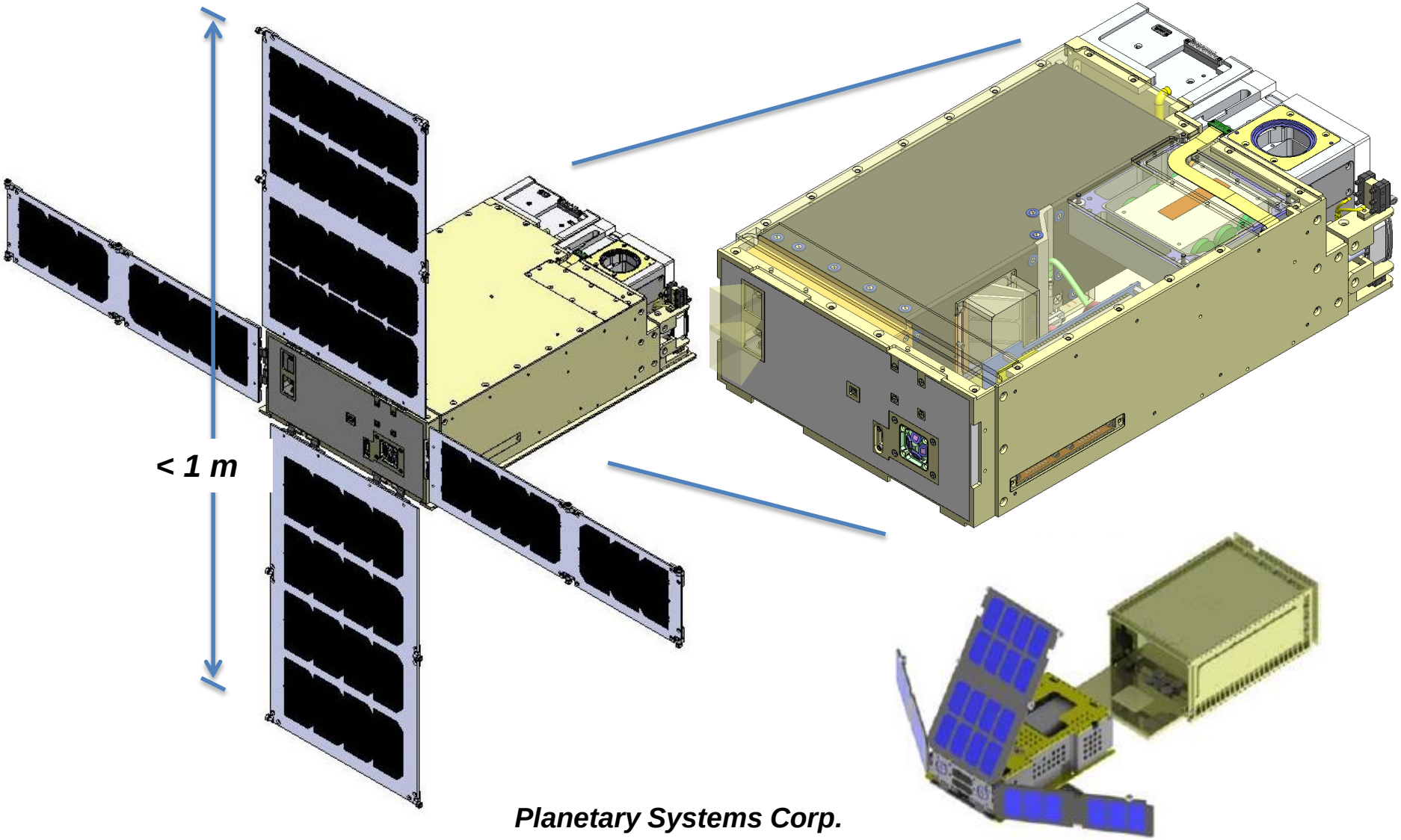


Planetary Systems Corp.
Canisterized Satellite Dispenser (CSD)

Summary

CSIM
Compact Spectral Irradiance Monitor

The CSIM instrument concept will mitigate potential risks associated with large mission delays – resulting in observational data gaps – by developing a cost effective, reduced-size SSI instrument.

- ***CSIM offers significant implementation flexibility for future alternative flight opportunities – hosted payloads, small sats, & CubeSats***

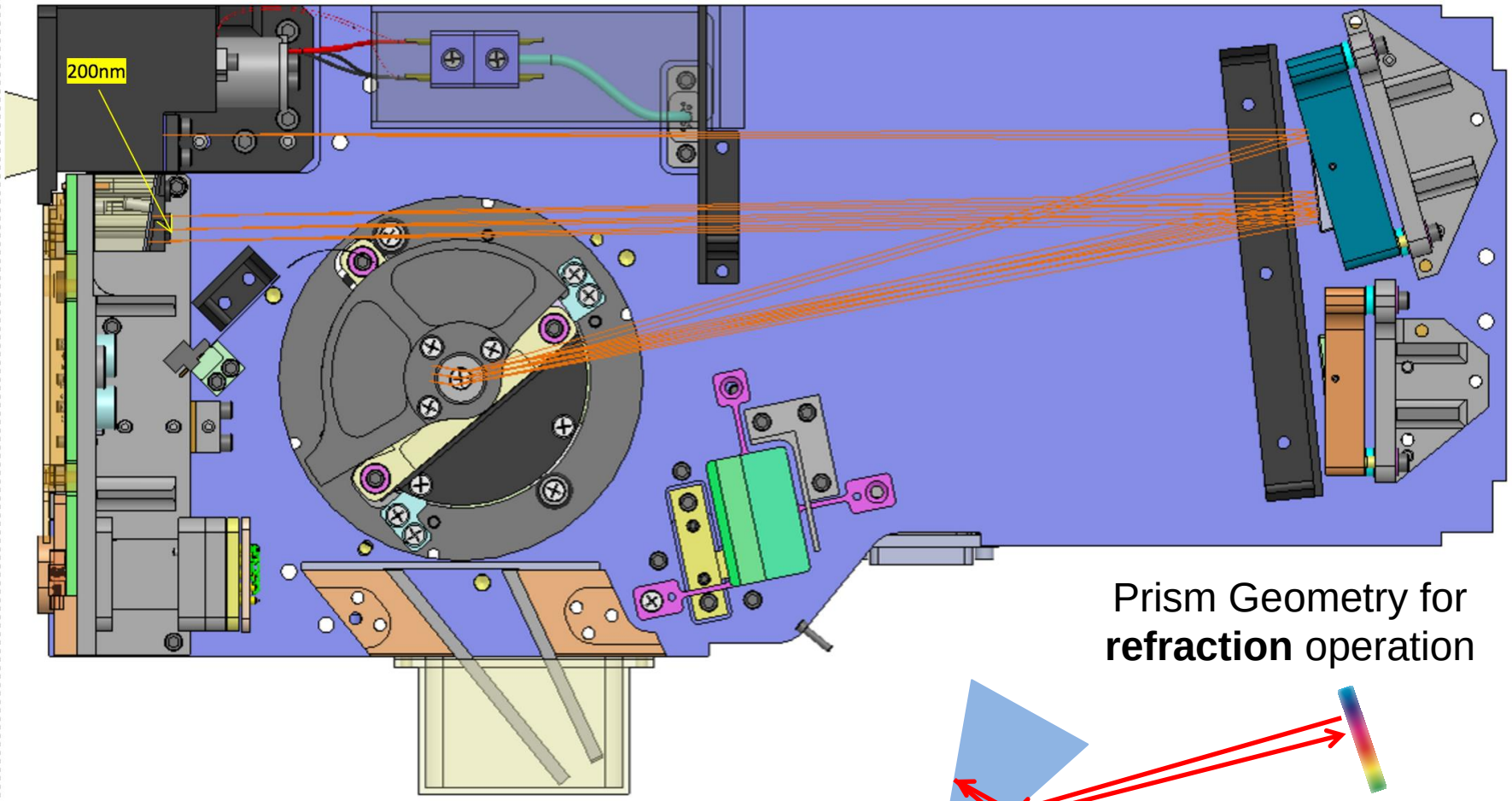
- ***CSIM will enable high priority Earth science measurements of SSI and provide an SI-traceable tie to existing and future satellite records, including the SSI record that began with SORCE (2003) and beyond TSIS (2017)***

Acknowledgements

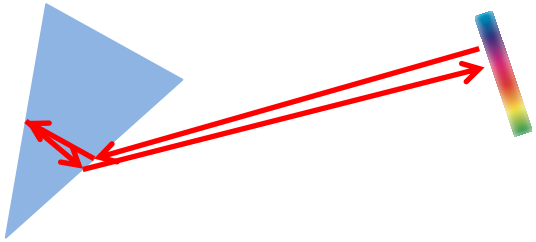
National Aeronautics and Space Administration
Earth Science Technology Office

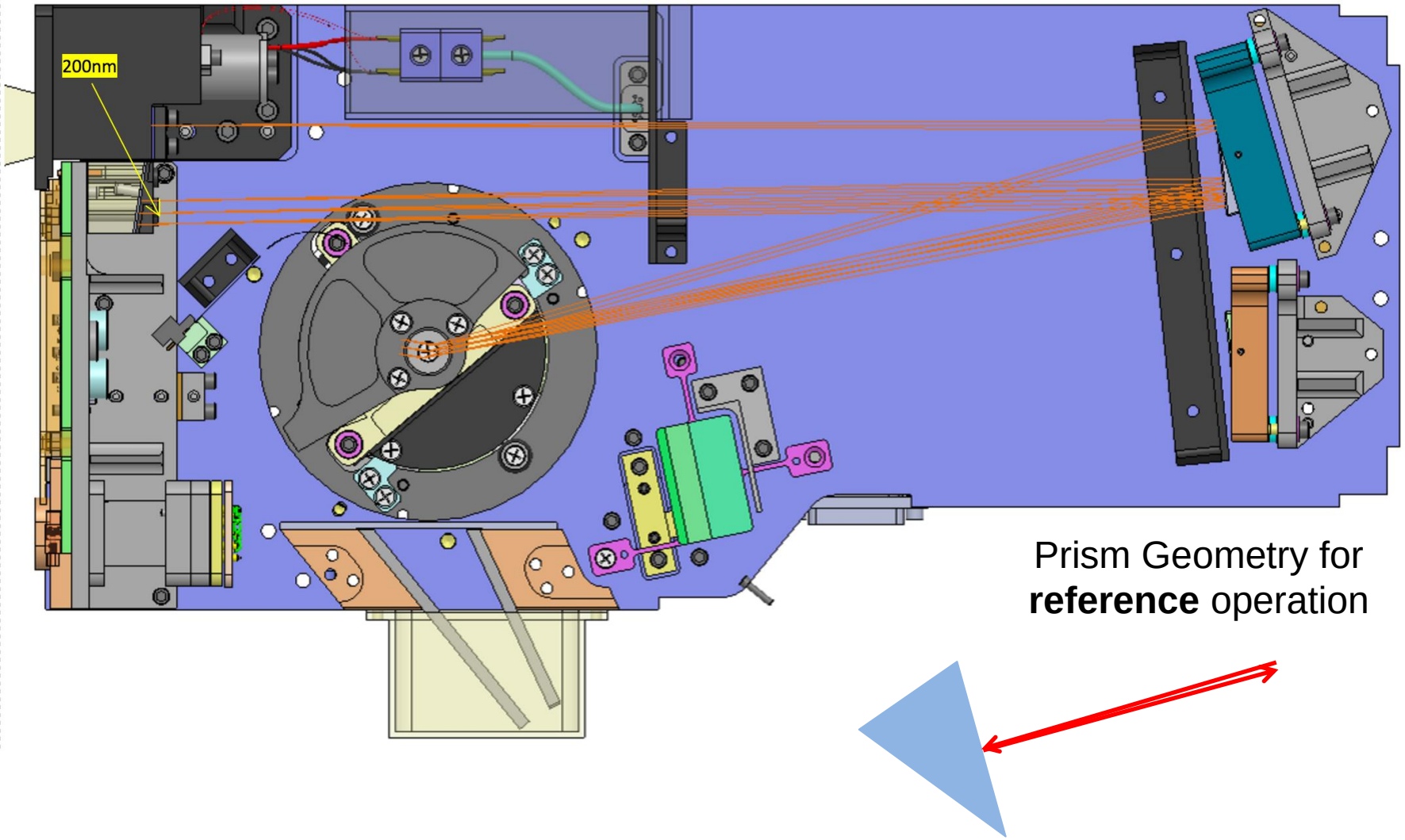
NASA Earth Science Technology Office (ESTO); IIP-13-0036

Backup Slides



Prism Geometry for **refraction** operation





Prism Geometry for **reference** operation