The Compact SIM (CSIM) and Compact TIM (CTIM) Instruments

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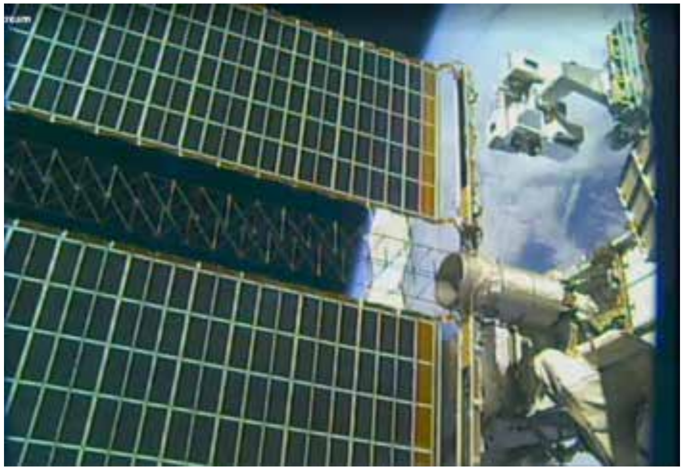
Latest TSI and SSI Instrument: TSIS SIM and TIM on ISS

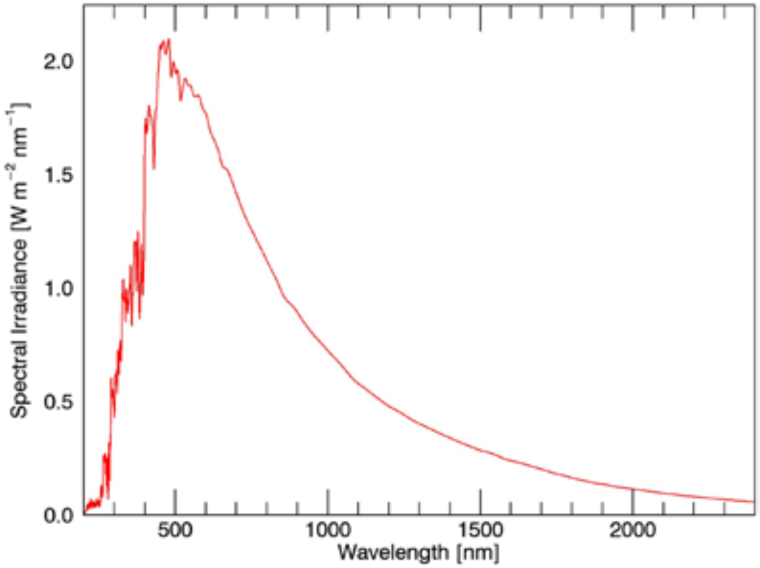
Integrated TSIS System

Falcon 9 Launch
December 15, 2017

TSIS Installation on ISS
December 30, 2017



Preliminary TSIS SIM Spectrum

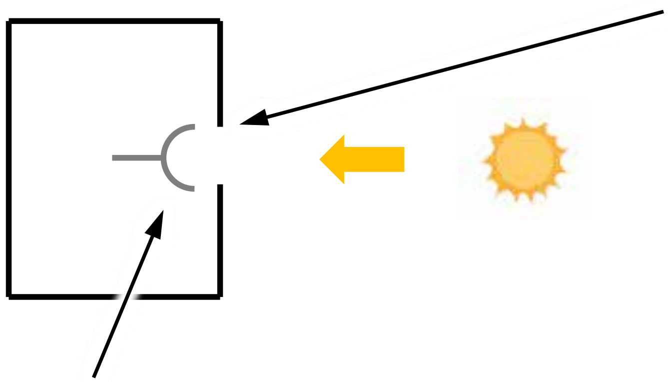


Started designing and building TSIS instruments 10 years ago based on SORCE instrument design, ~20 years old now

Total Solar Irradiance (TSI) Measurement

Total Solar Irradiance [W m^{-2}]

- Very wide wavelength acceptance: 100 nm – 50 microns
- High radiometric accuracy: 100 ppm
- Very stable: 10 ppm/year
- Power level: 25-70 mW



Precision Aperture [m^2]

- Very clean edge
- Measured aperture area

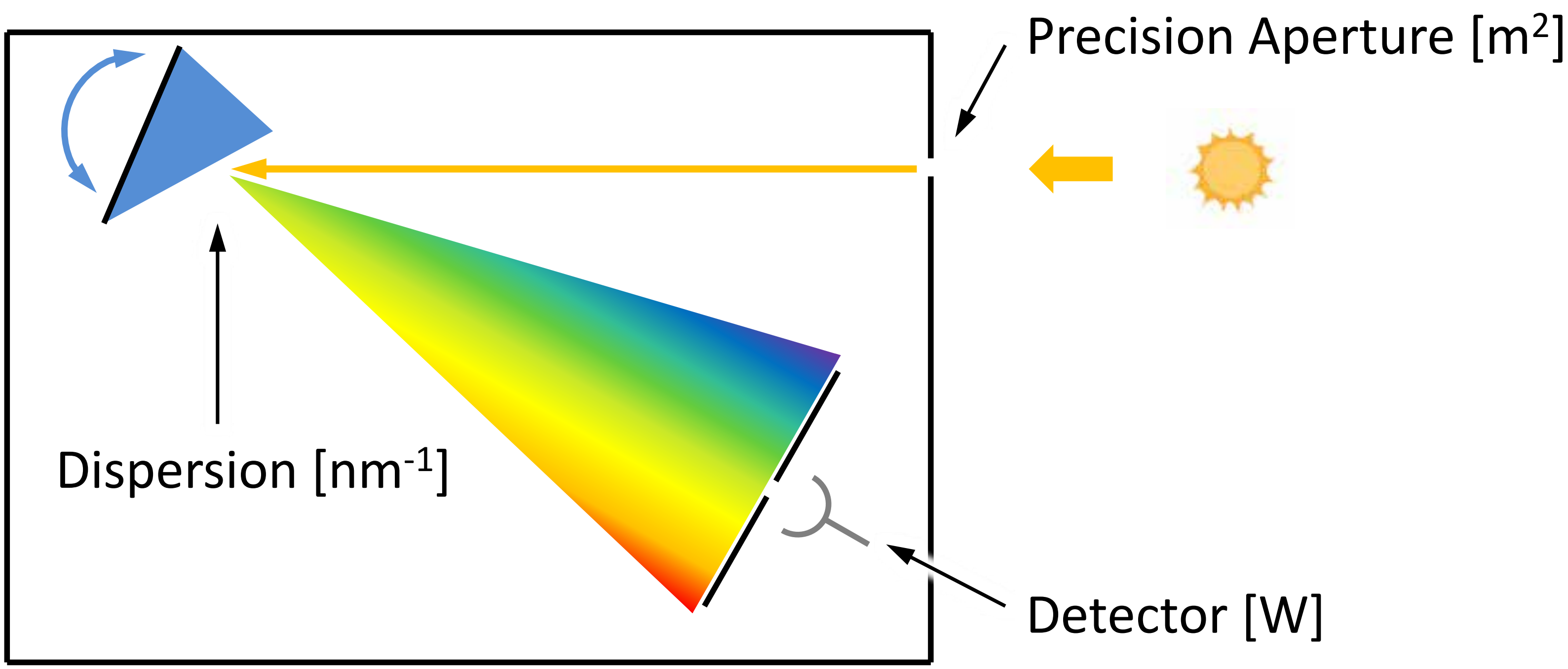
Detector [W]

- Bolometer (thermal) detector
- Good: Broadband absorption: 100 nm – 50 microns
- Good: Very stable
- Bad: Typically much less sensitive than quantum detectors (photodiodes, CCDs, etc)

Spectral Solar Irradiance (SSI) Measurement

Spectral Solar Irradiance [W m^{-2} nm^{-1}]

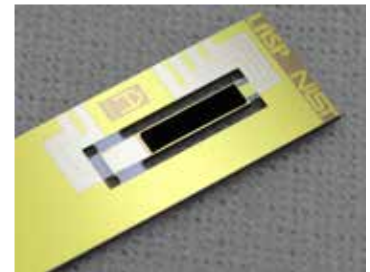
- Add a monochromator
- Cover the bulk of solar output: 200-2400 nm
- Low spectral resolution: 1-30 nm FWHM
- High radiometric accuracy: 2000 ppm
- Very stable: 100 ppm/year
- Power Levels: 10 nW-40 μW



Next Generation Instruments

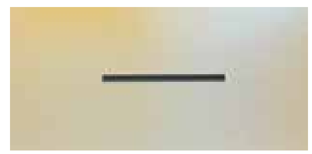
Key Next-Generation Technologies

Silicon Bolometers



- Silicon-Based Bolometers
  - Developed/fabricated by NIST Boulder
  - Vertically aligned carbon nanotubes
  - Integrated heater

Ion Etched Aperture



- Deep Reactive-Ion Etched Apertures
  - Fabricated by NIST Boulder

Photodiodes

- Extended InGaAs Photodiodes

FPGA

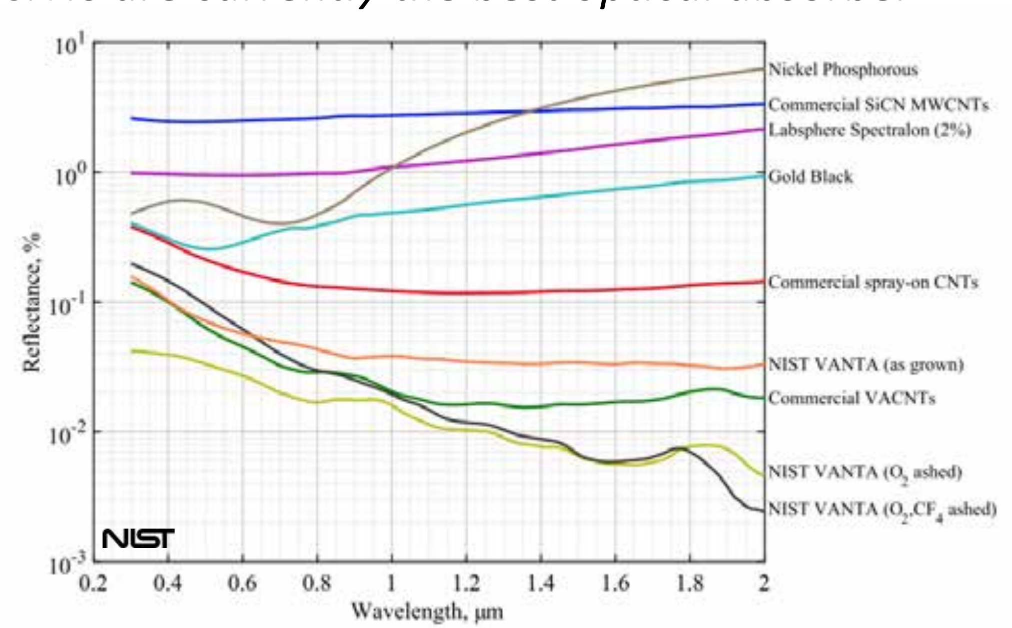
- More powerful FPGAs with embedded microprocessors

Rotary Encoder

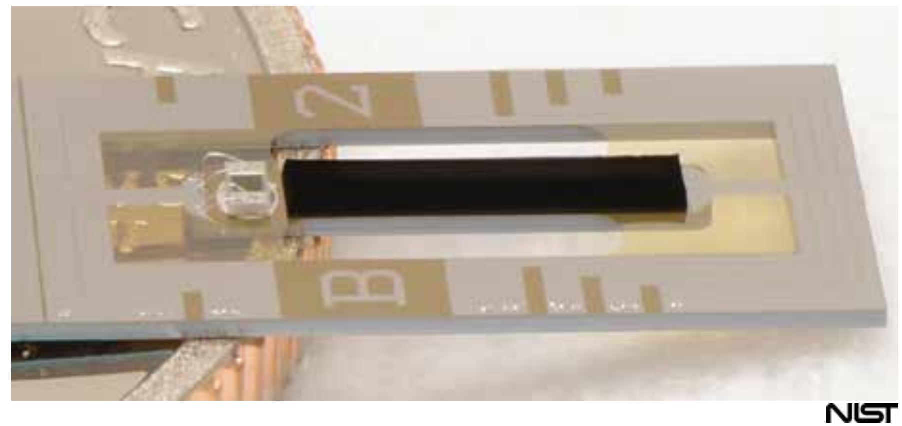
- High resolution commercial optical encoders
- Typical iterative improvements

Silicon + Vertically Aligned Carbon Nanotube (CNT) Bolometers

CNTs are currently the best optical absorber



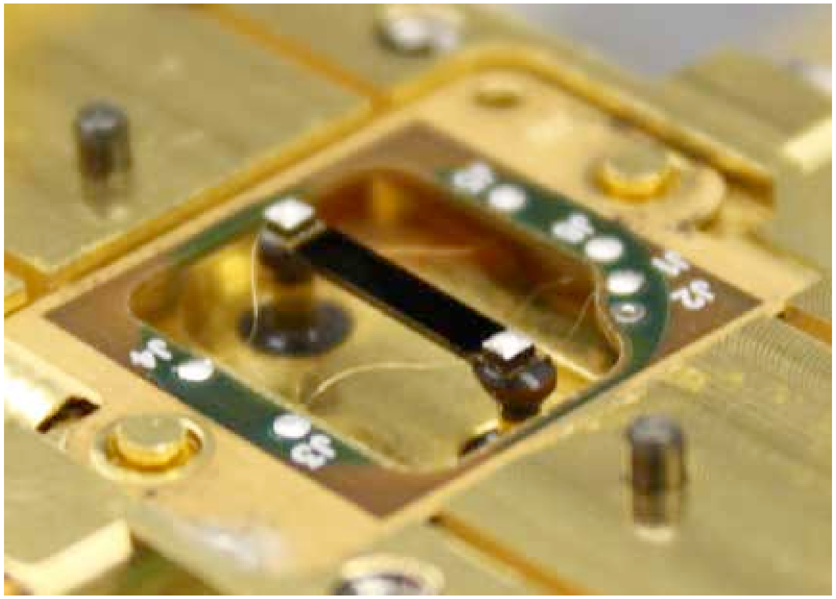
Lehman *et al.* Appl. Phys. Rev. 5, 011103 (2018)



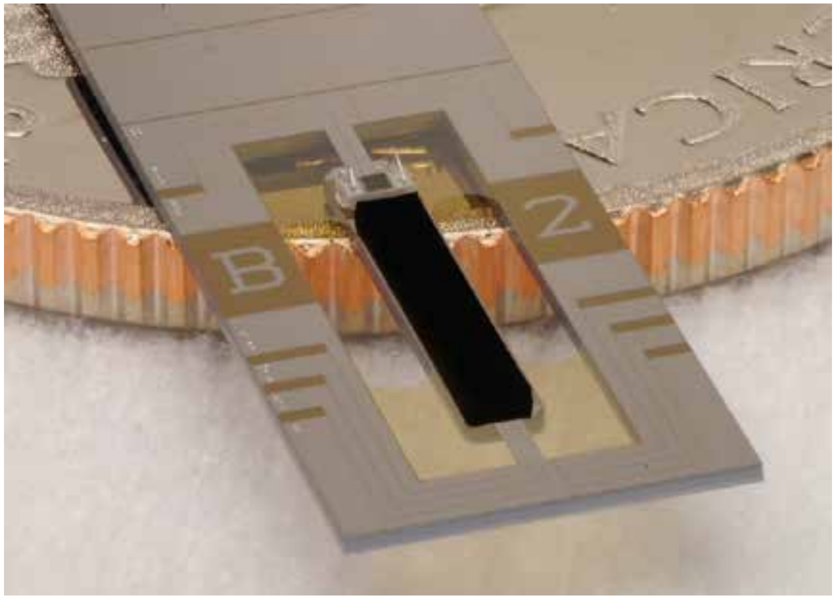
- Developed with NIST Boulder
- Silicon micro fabrication allows a nearly arbitrary 2D geometry to be fabricated with micron-level precision
- Conductive traces and integrated heaters can be fabricated on silicon
- Weak thermal links can utilize integrated thin SiN films

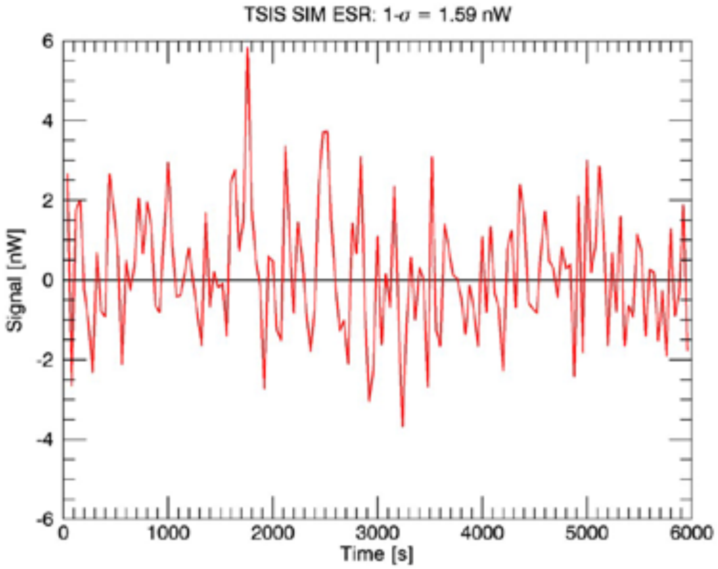
TSIS SIM vs New Silicon Bolometers

TSIS SIM Bolometer



Silicon Bolometer

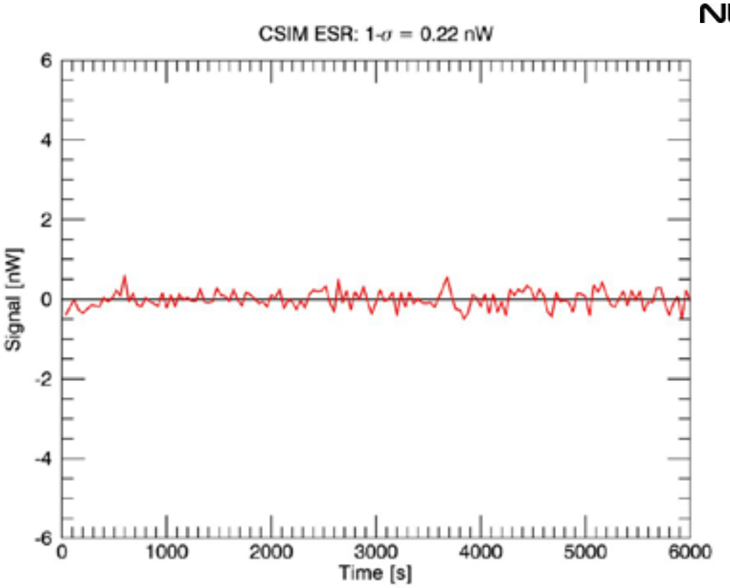




Noise-Level for
40s Integration Time

7.2x Noise Reduction

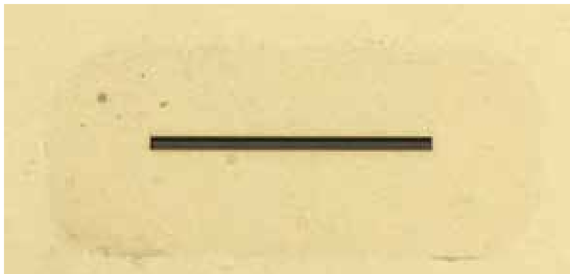
Need to 34 mins of TSIS SIM measurements to match SNR of one 40s of the new bolometer



Silicon Apertures

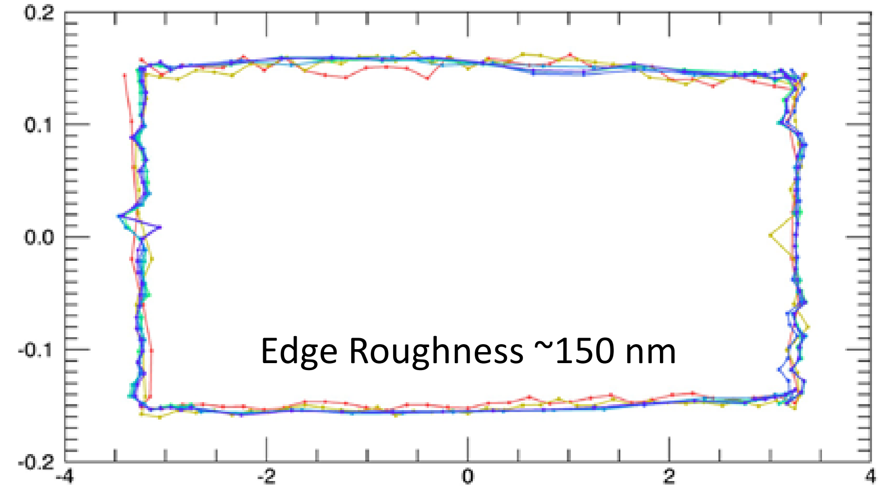
Precision aperture defines area

TSIS SIM Slit: Nickel over Brass Shadow Mask

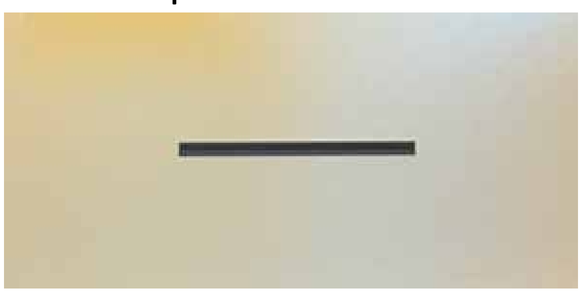


CTE = 17 ppm/C

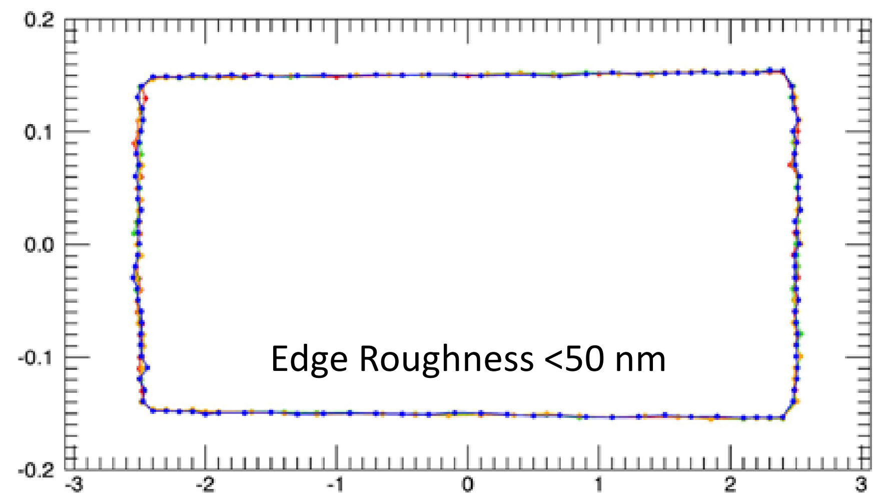
NIST Aperture Area Measurement



CSIM Slit: Aluminum on Deep Reactive-Ion Etched Silicon



CTE = 2.6 ppm/C



Silicon apertures increase instrument accuracy and stability

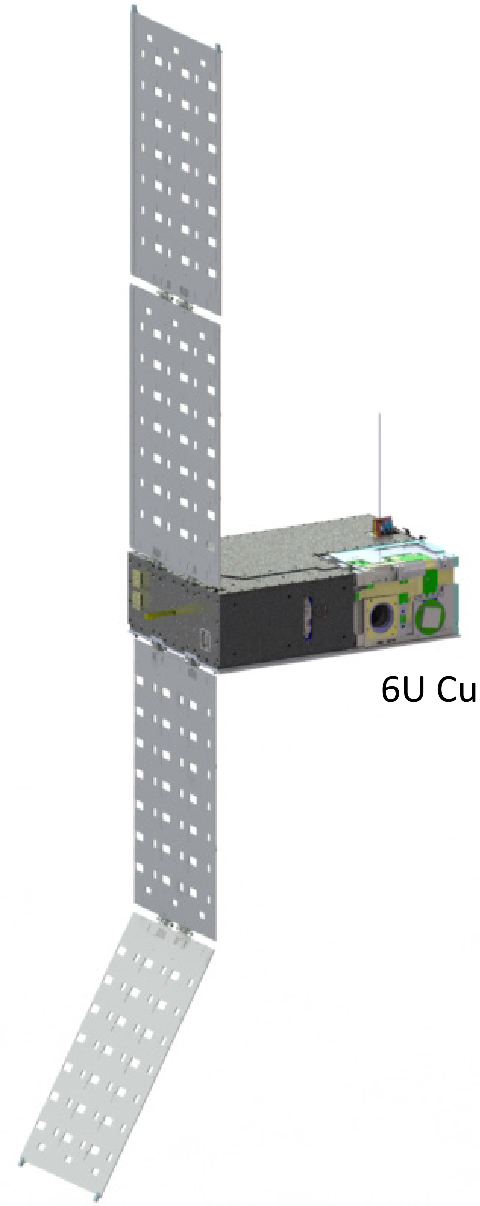
CubeSats: Promising Technology Development Platform

Larger CubeSat platforms have become common:

- 1U: 10x10x10 cm
  - Minimal capability
- 3U: 36x11x11 cm
  - Need ~1.5U for basic satellite functions
  - Allow ~1.5U for payload
  - Attitude control possible
- 6U: 36x24x12 cm
  - Allow ~4.5U for payload
  - Just becoming “standard” now
  - Maximum aperture size ~80 mm
  - Maximum unfolded optical path ~250 mm
- 12U: 36x24x23 cm
  - Future option

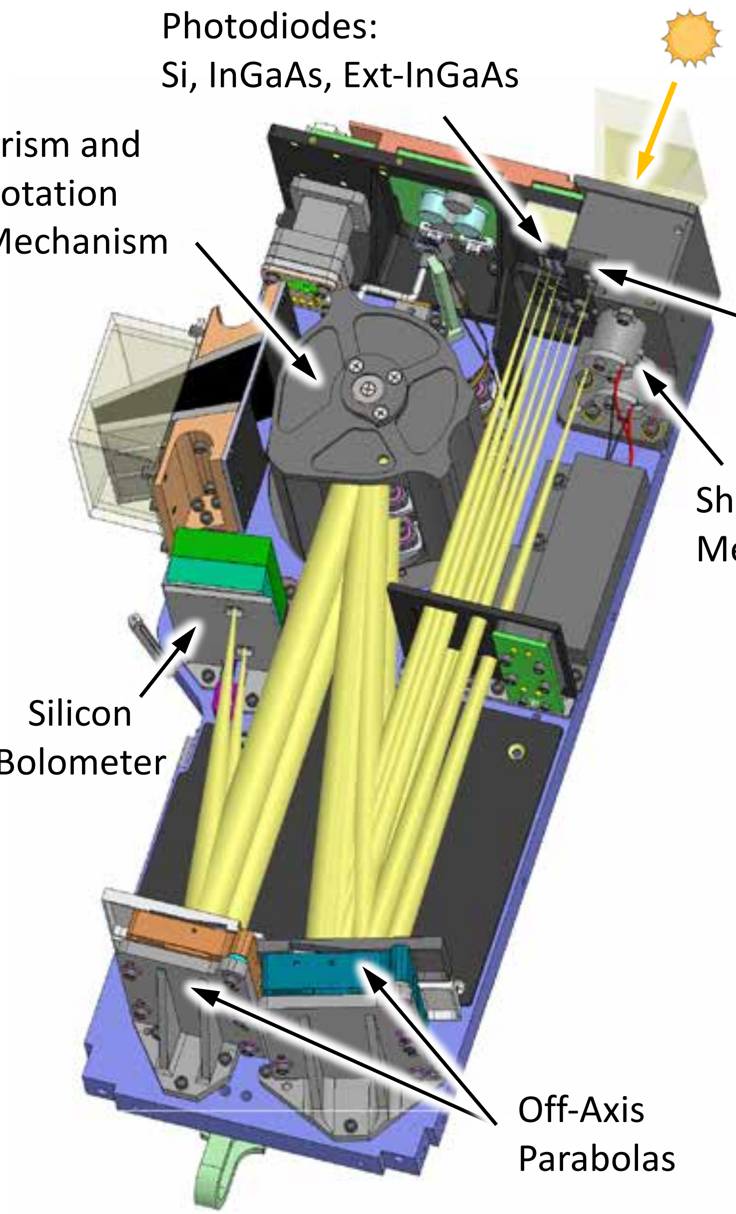
TSIS TIM Aperture: 8 mm Diameter

TSIS SIM Aperture: 6.5 mm x 0.165 mm



6U CubeSat

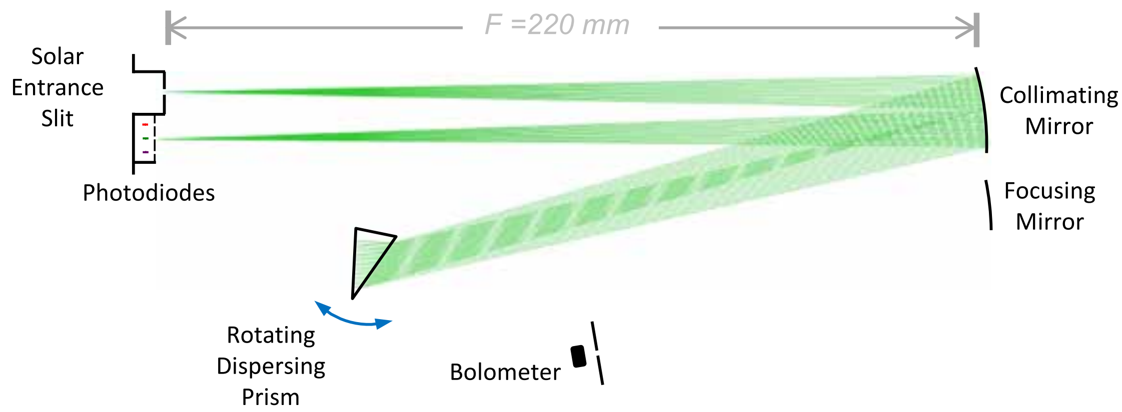
CSIM Instrument



- "Squeeze" SIM TSIS SIM design to 6U
  - TSIS SIM Focal Length = 400 mm
  - CSIM Focal Length = 220 mm
  - Scaled down down SIM by 45%
  - Factor of 2-3 decrease in signal
- Designed to meet most TSIS SIM capabilities
  - Two, rather than three, redundant channels
  - Less reliability and reduced long-term stability
- Acquires 200-2400 nm solar spectrum every 12 hours
  - Can cover entire spectrum with photodiodes
- Bolometric detector calibrates photodiodes once a month
- Secondary channel used on monthly cadence to track exposure-related degradation of primary channel

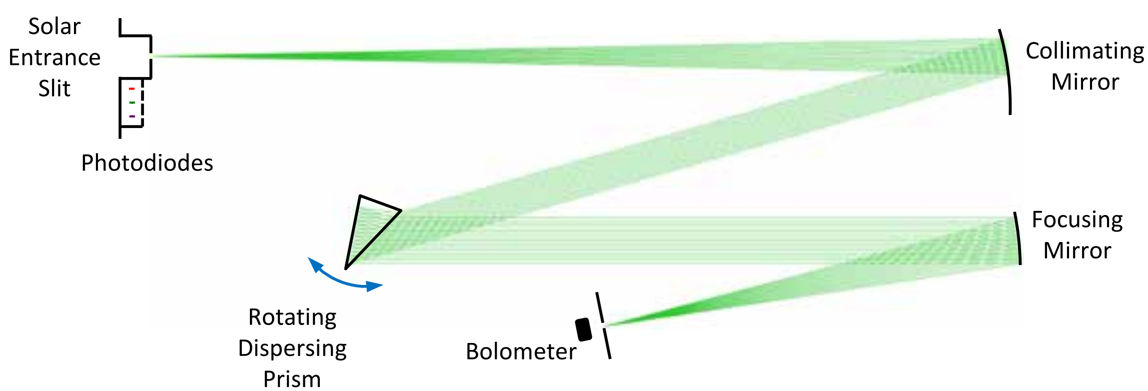
CSIM Instrument: Optical Layout

Photodiode scan mode: Fast, high SNR detectors
Full spectrum (200-2400nm) in < 30 minutes

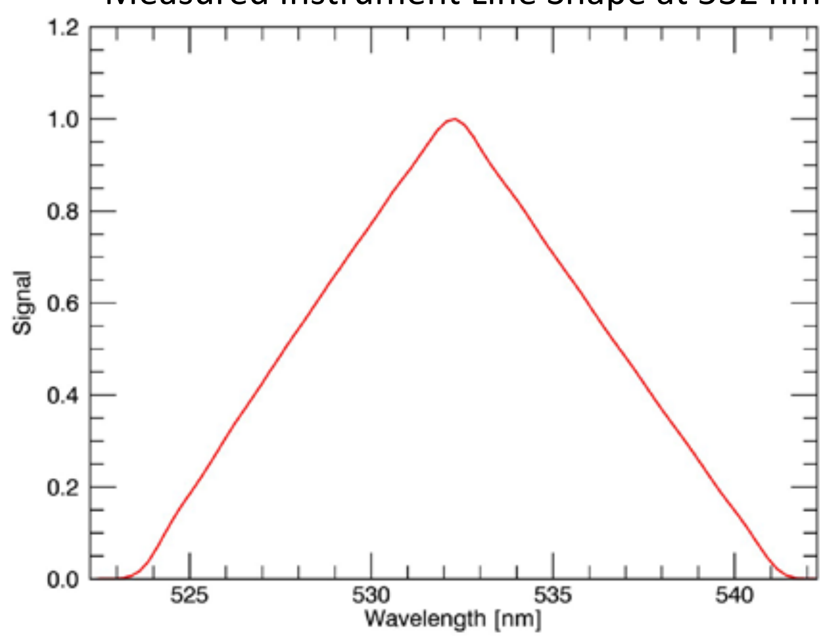


- "Step and Stare" with the prism to take a spectra
- 0.5 seconds per point with photodiodes
  - Full Spectrum in ~25 minutes
- 10-50 Seconds per point with ESR
  - Full range in ~14 orbits

ESR scan mode: Slow, robust absolute detector
Photodiode channel irradiance calibration, degradation tracking



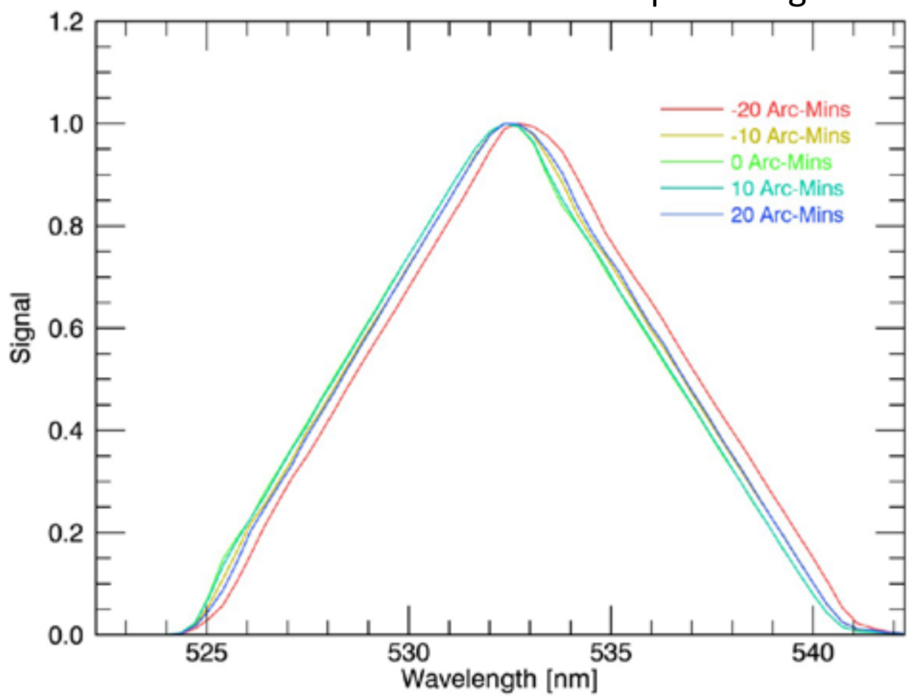
Measured Instrument Line Shape at 532 nm



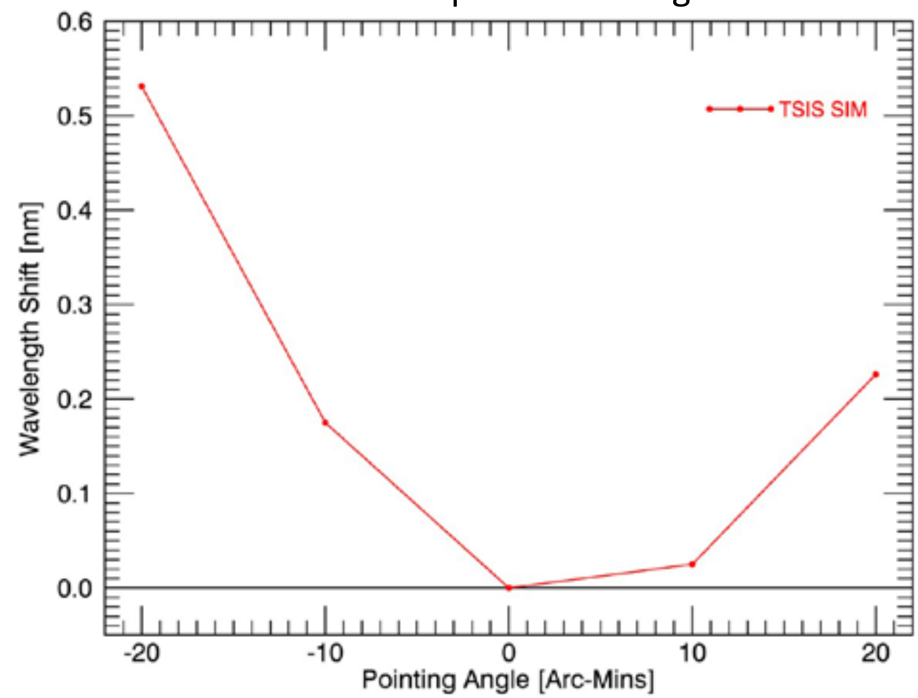
TSIS SIM Optical Performance

- TSIS SIM uses a single optical element to disperse and reimage the light
- Significant coma: Wavelength shift for off-axis light

Measured Instrument Line Shape vs Angle

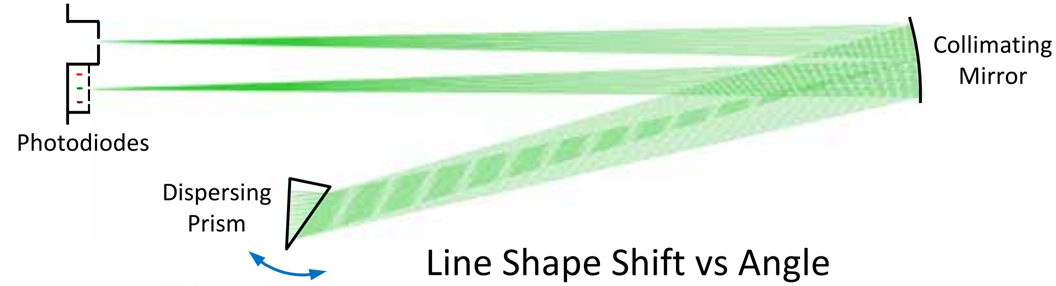


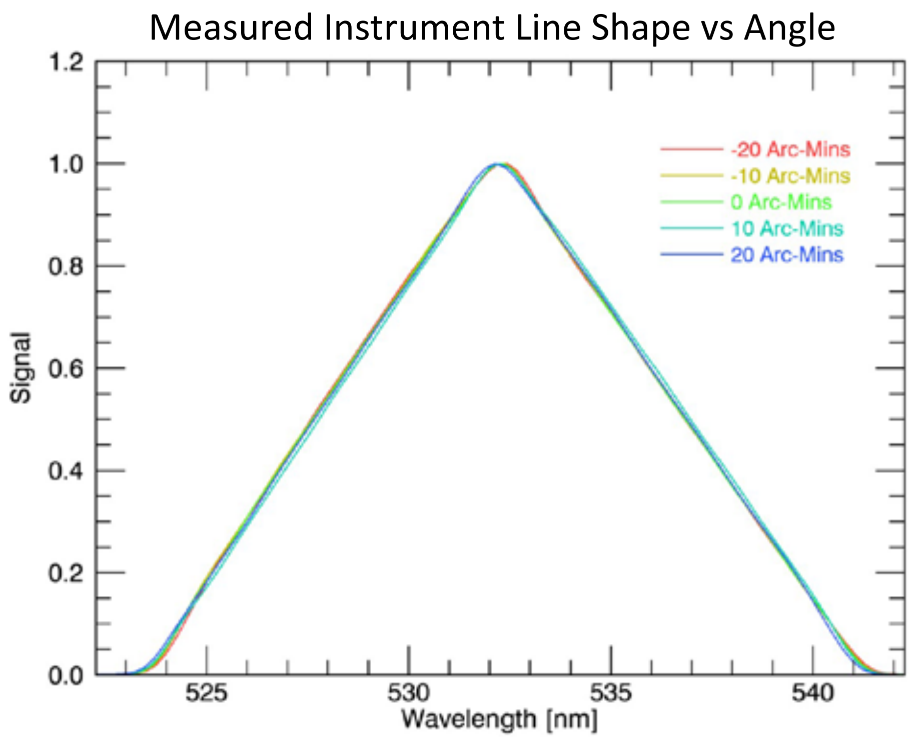
Line Shape Shift vs Angle

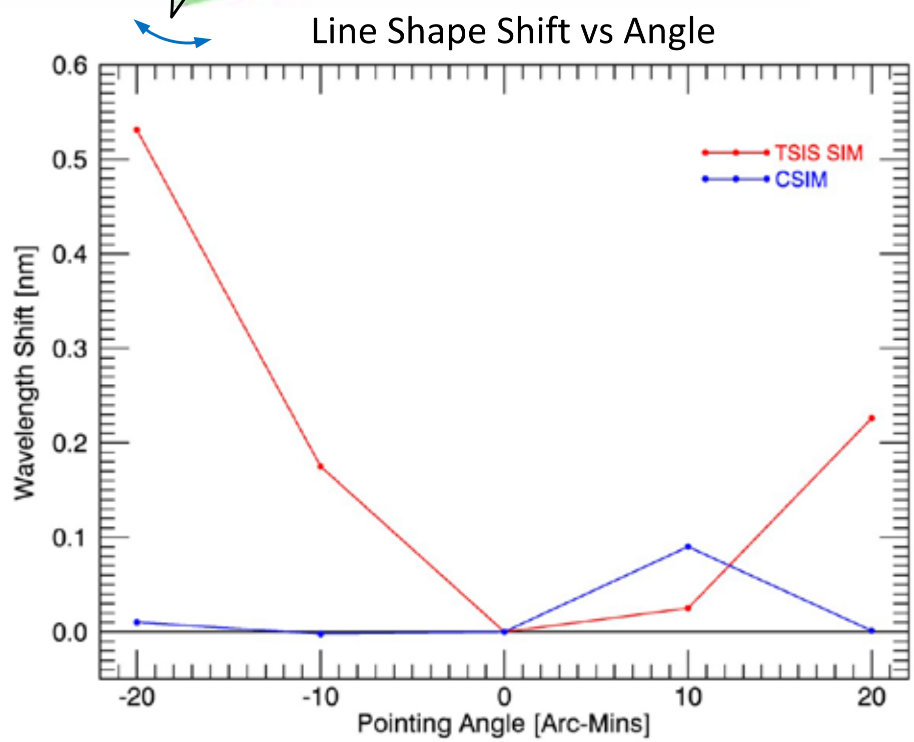


CSIM Optical Performance

- CSIM uses separate reimaging and dispersing elements
- Better off-axis performance
- Optical performance limited by collimating mirror figure



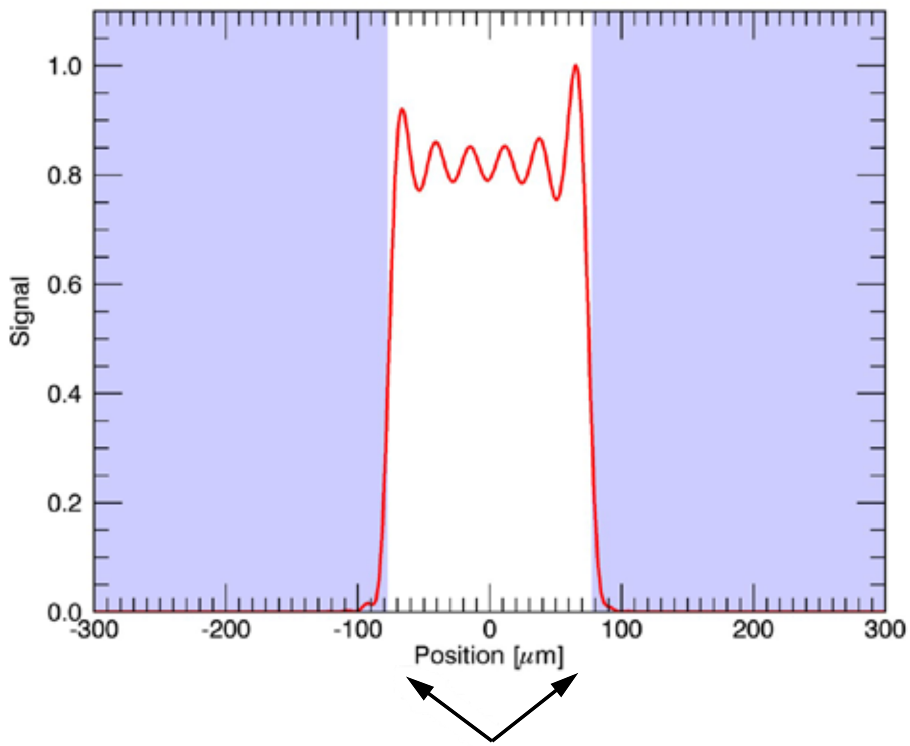




CSIM Photodiode Instrument Line Shape

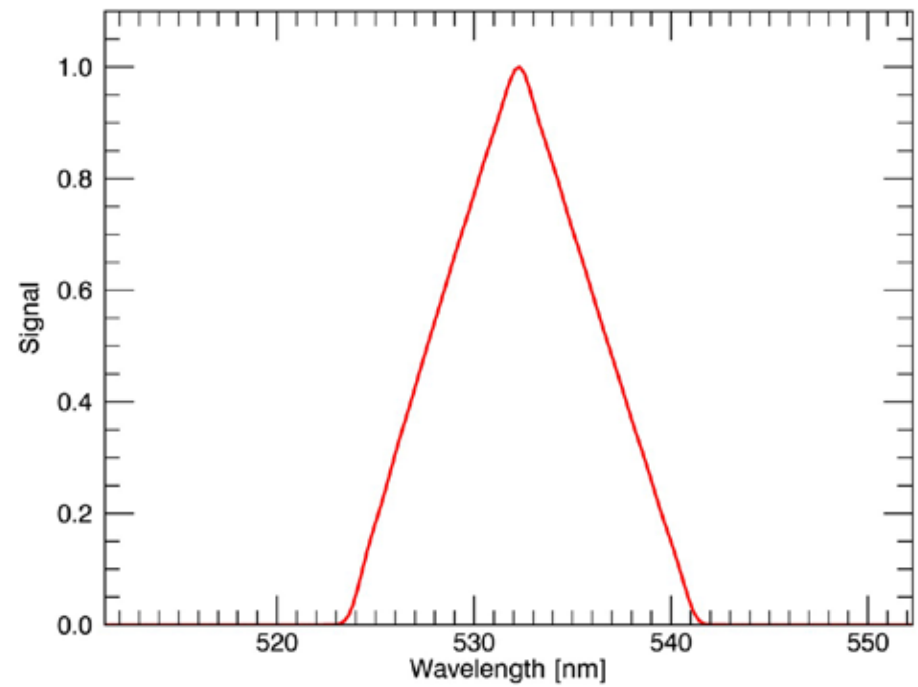
- Photodiode Exit Slit Width = Slide Image Width
- Optimized for spectral resolution

Modelled Slit Image



Exit Slit Edges

Measured Instrument Line Shape

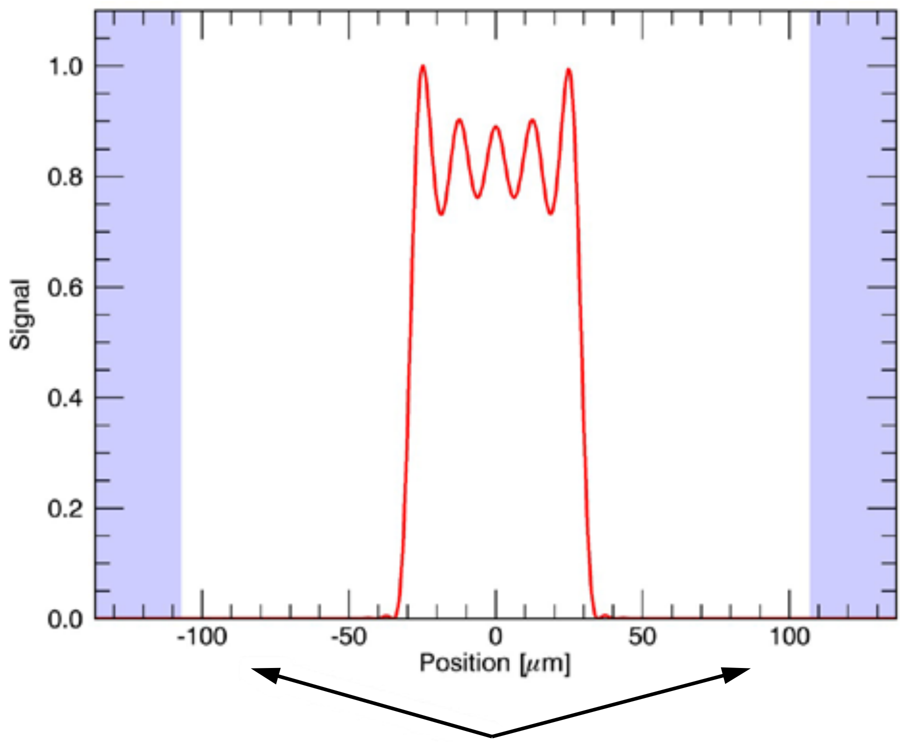


CSIM CTIM LASP NIST ESTO NASA

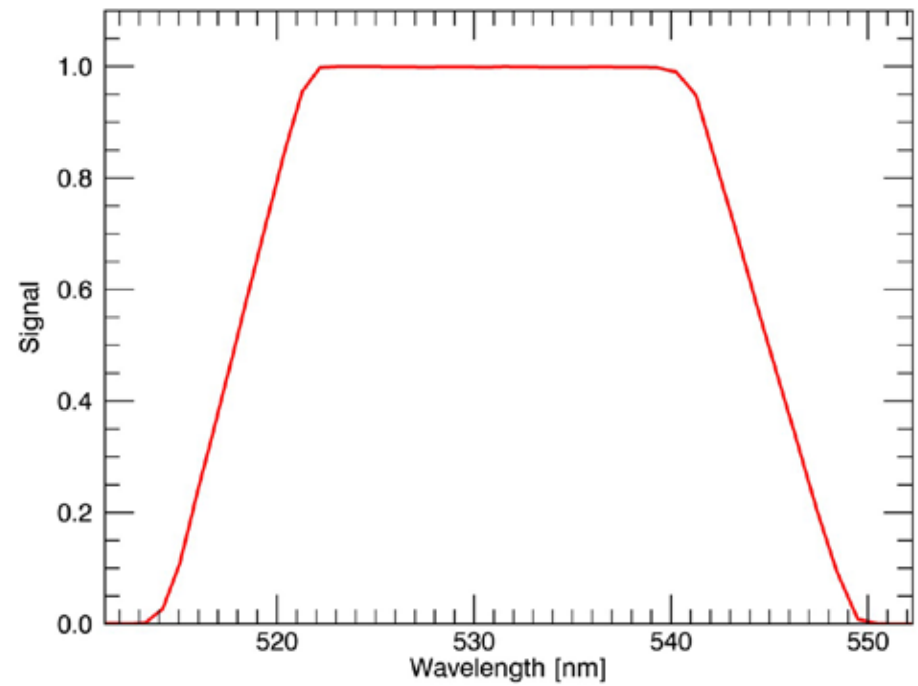
CSIM Bolometer Instrument Line Shape

- Bolometer Exit Slit Width = 3 x Slide Image Width
- Optimized for light collection: Bolometer corrects diodes
- Can measure total throughput with monochromatic light
  - *Improve radiometric calibration accuracy*

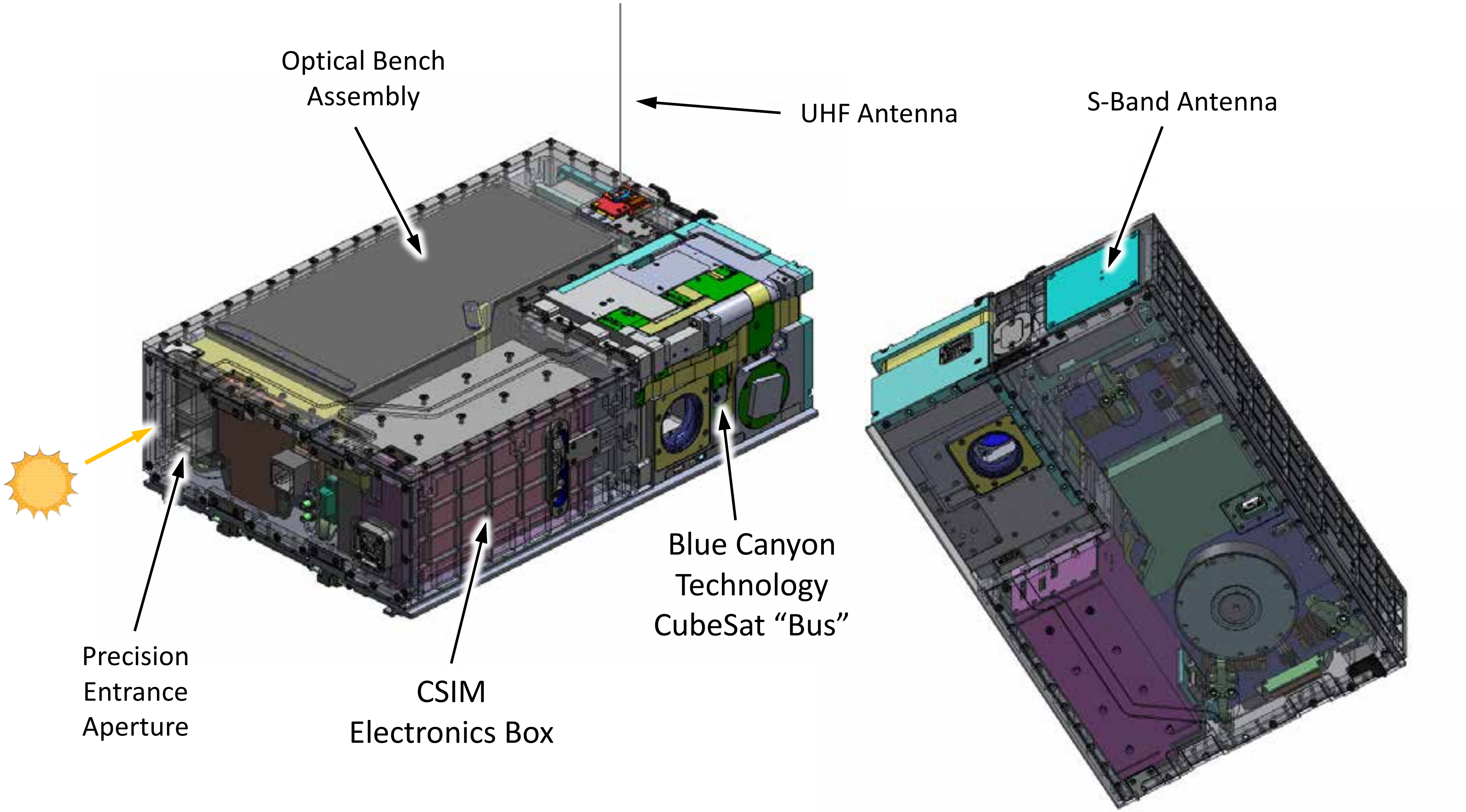
Modelled Slit Image



Measured Instrument Line Shape



CSIM CubeSat

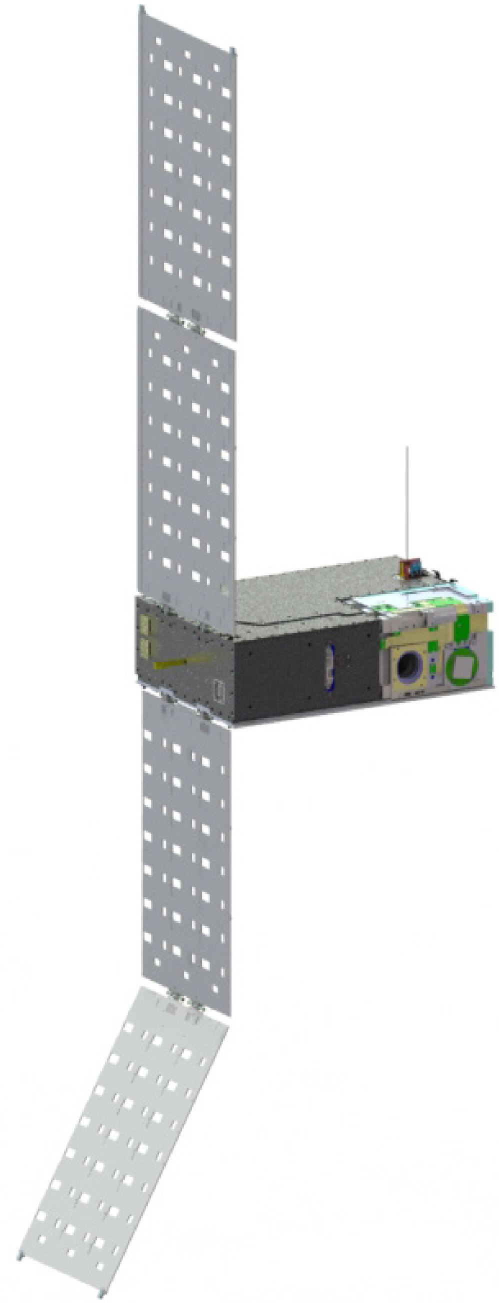


CSIM CTIM LASP NIST ESTO Earth Science Technology Office NASA

CSIM Mission

- Instrument development started in 2014
- Funded by NASA ESTO
- Calibrate like TSIS SIM
- Planned launch
  - Late 2018-Early 2019
  - 1.5 year mission
- Ground Operations
  - UHF and S-Band ground stations at LASP
  - S-Band downlink allows ~20 MB/day of data
  - Will compare absolute spectra, short-term trends, and long-term trends against TSIS SIM

This mission will allow these new technologies to be tested on-orbit on a low-cost, rapid-timescale mission

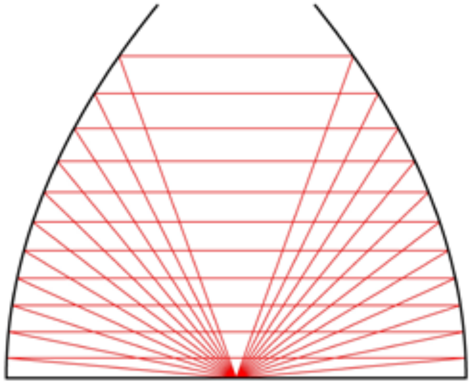


CTIM: How to make a Bolometer Cavity?

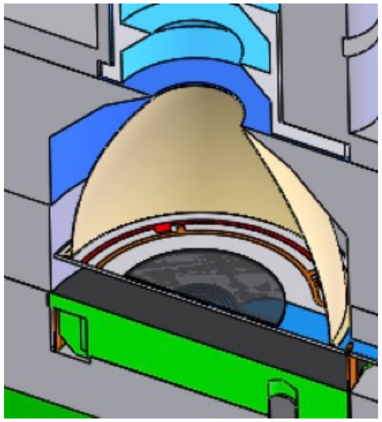
- Can we create a Silicon Bolometer for TSI?
  - Silicon fabrication is limited to flat/2D
- Cavity created with flat bolometer + reflector
  - 51 μm thick Copper, plated with Gold
  - Reflector is thermally part of the bolometer
    - Light absorbed by the reflector is measured
  - CNT + Reflector is ~10x darker than CNT only
    - <100 ppm reflectivity

TSIS TIM Bolometer Cavity

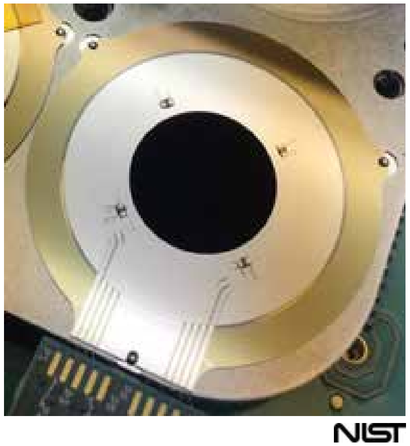
Dome Optical Raytrace



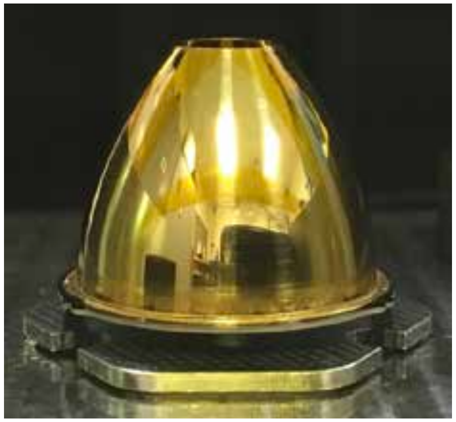
Bolometer Design



Silicon Bolometer



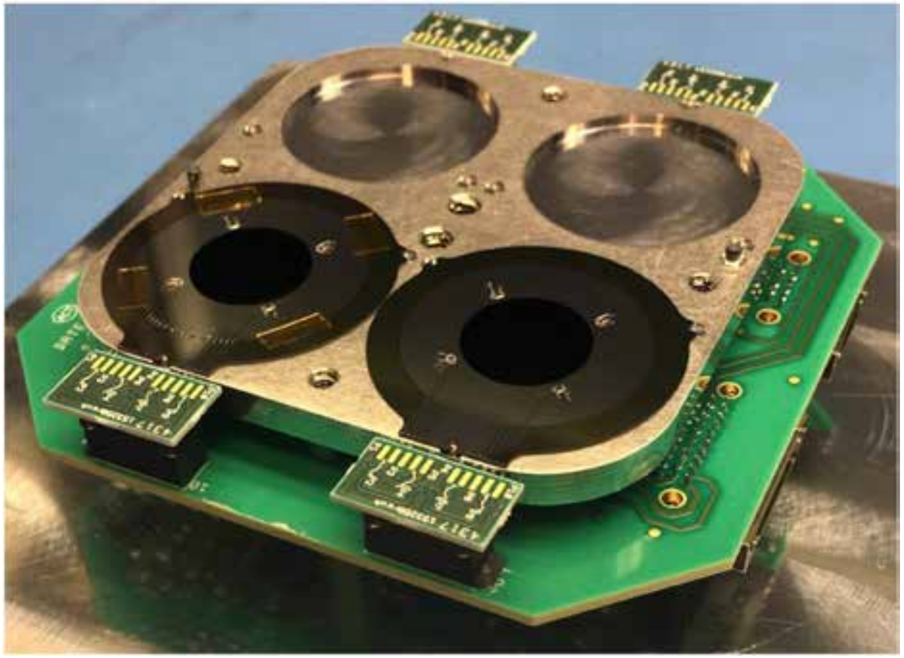
CTIM Bolometer with Dome

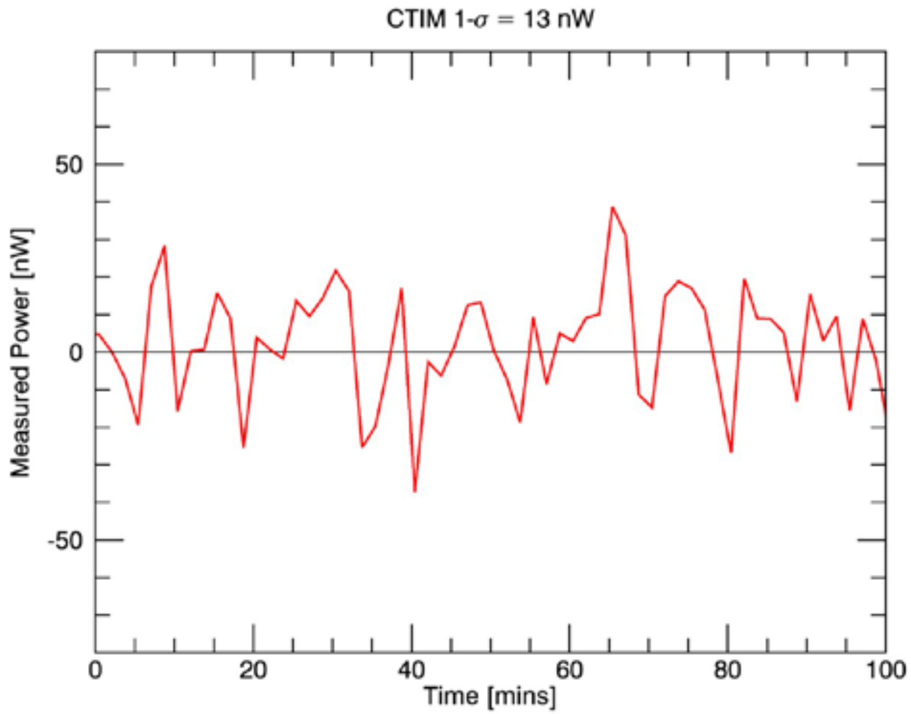


Prototype CTIM Noise Level

- Expected Power Level = 26.7 mW
  - 5 mm diameter entrance aperture
- Measured Noise Level = 13 nW
- Relative Noise Level = 0.5 ppm

Prototype CTIM Detector

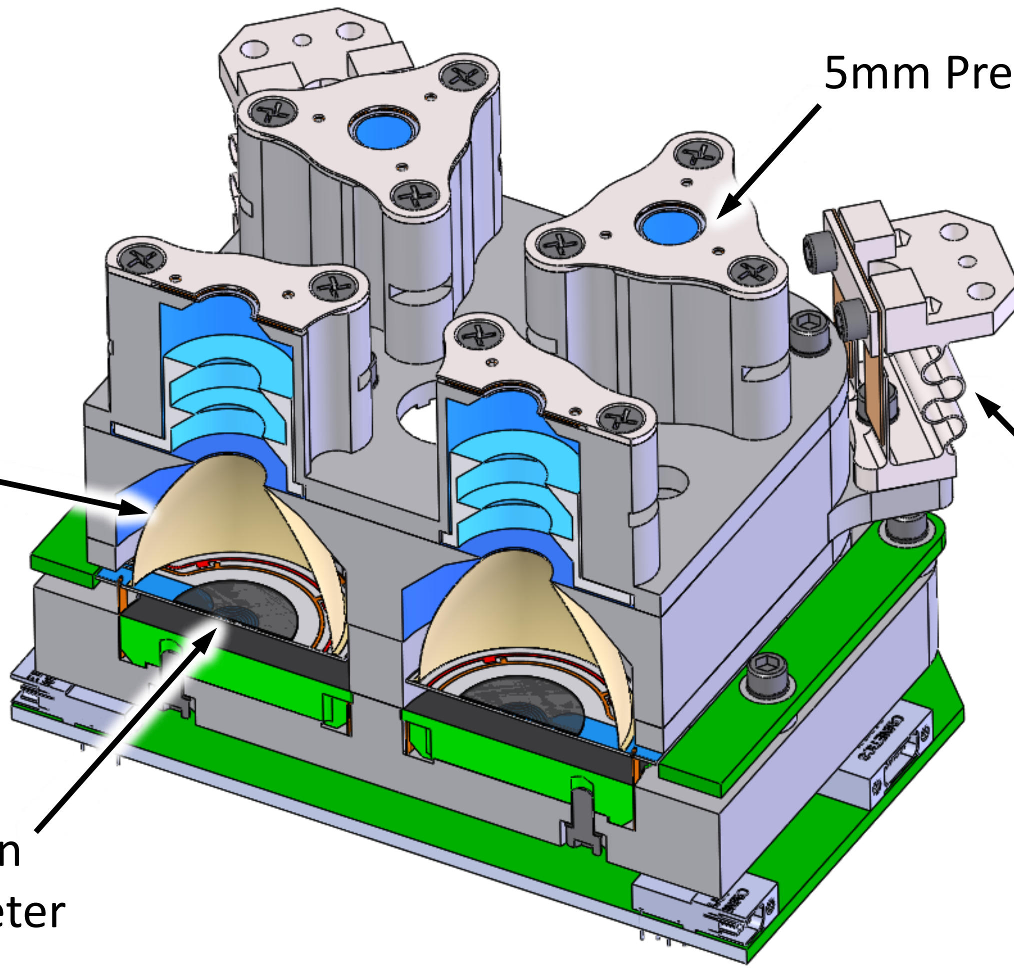




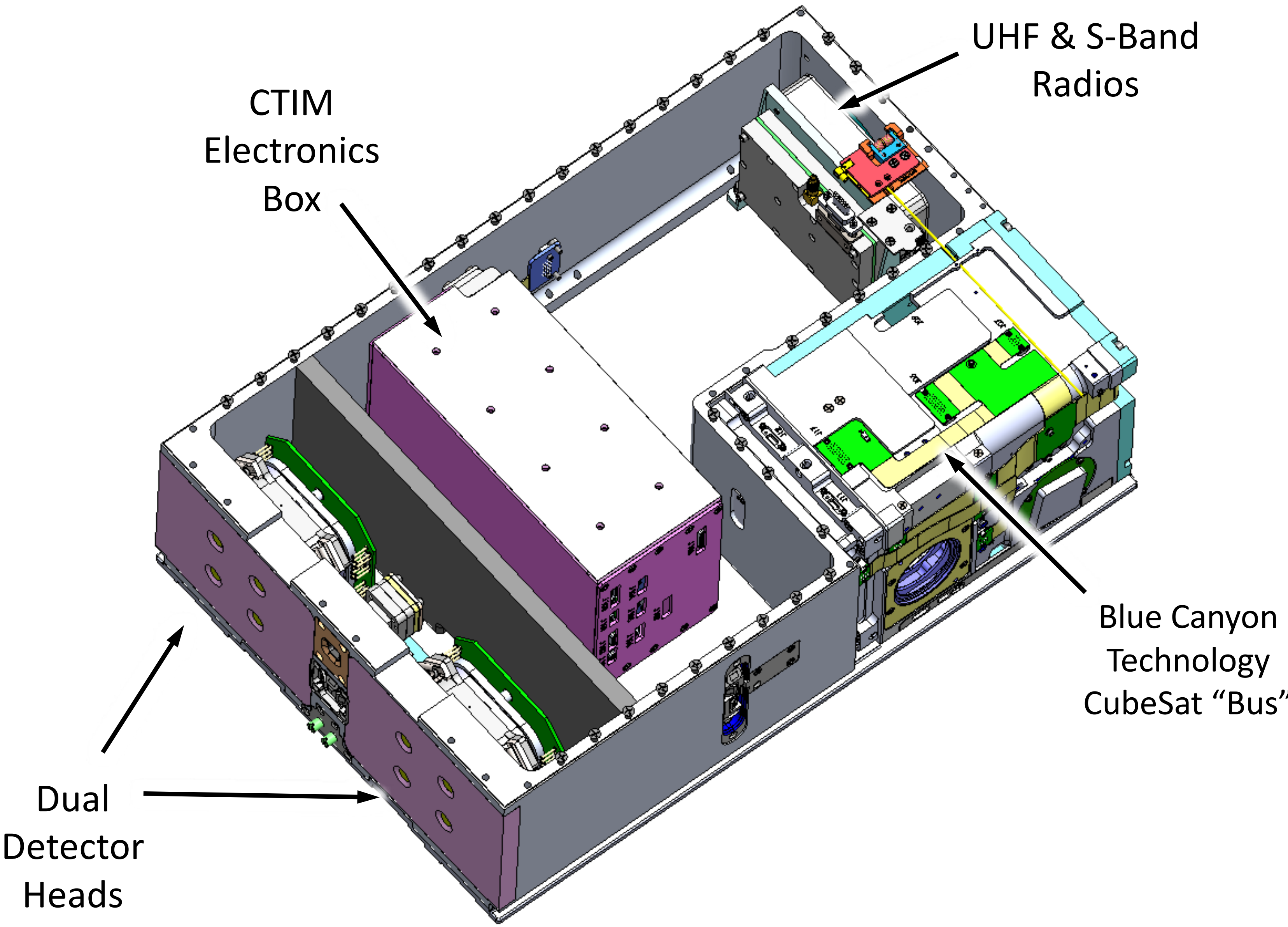
Radiometric testing of the CTIM prototype is in progress

Detector Core: Optical Path and FOV

- Circular 5 mm Ion-Etched Precision Apertures
- Four channels to permit redundant channel degradation tracking

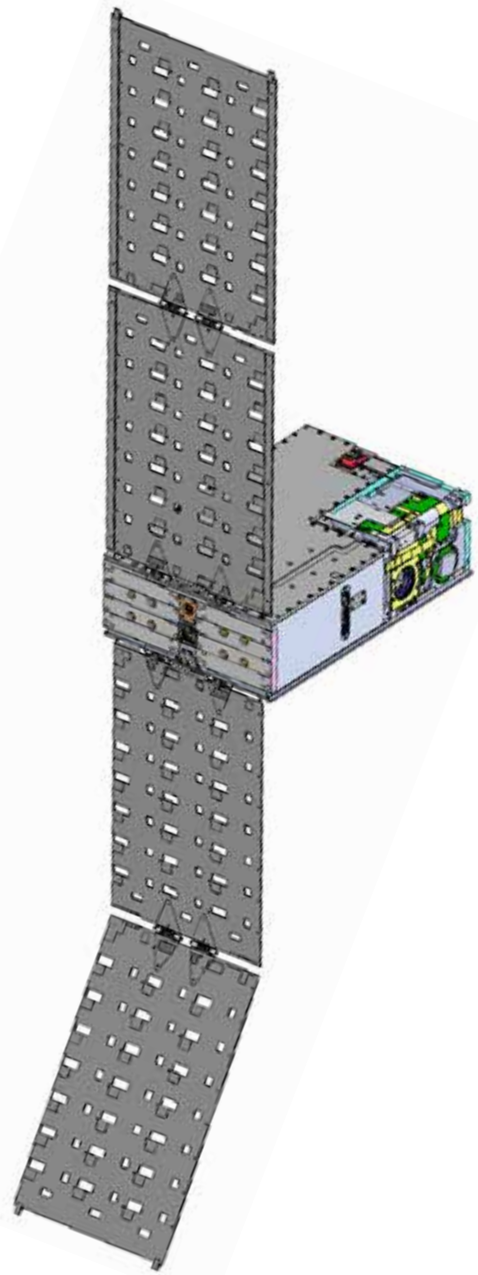


CTIM 6U CubeSat Design



CTIM Mission Concept

- TSI Bolometer Development started in 2015
- Funded by NASA ESTO
- 6U CTIM instrument concept borrows from CSIM design
- Currently developing 6U CTIM instrument
- Build, test, and environmentally qualify instrument in 2018 and 2019
- Calibrate like TSIS TIM
- Working to test CTIM on orbit in a similar mission to CSIM
- Dual detector head operation options:
  - Run parallel instruments
  - Continuous exposure

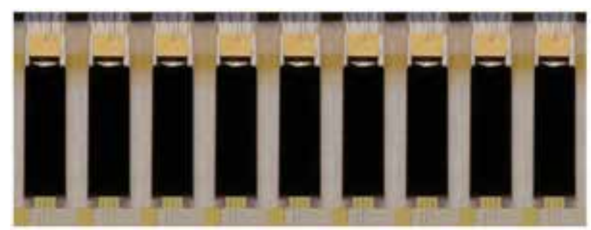


Why is this interesting? What is next?

Development of these new technologies will improve future measurements of solar irradiance

Future Possibilities

- Widen spectral wavelength coverage
  - CSIM-IR: 800 nm – 10 microns
- Faster cadence measurements
  - Current TIM TSI cadence: 6.7 minutes
  - Current SSI cadence: 12 hours
  - Possible TSI cadence: 5 seconds
- Bolometer Arrays
  - Faster cadence SSI measurements
  - Radiometric Imaging



- Continuous Coverage
  - Constellations could allow continuous TSI (and SSI) measurements