



ARCSTONE: Calibration of Lunar Spectral Reflectance from Space

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4 – Goddard Space Flight Center, Greenbelt, MD

5 – Quartus Engineering, San Diego, CA

6 – Blue Canyon Technologies, Inc., Boulder, CO

7 – USGS, Flagstaff, AZ

Funded by ESTO: IIP-QRS-16-0018

SBIR programs: Phase-I, Phase-II, Phase-E



ARCSTONE Team: Nationwide Collaboration



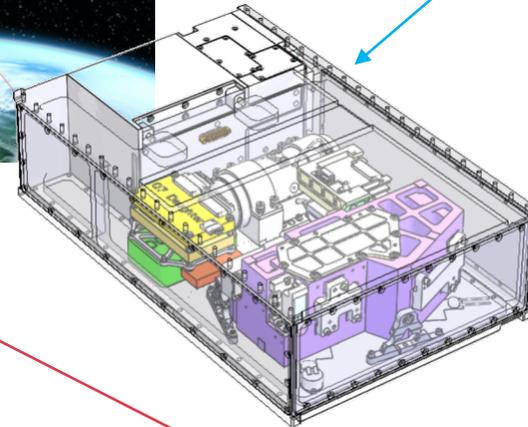
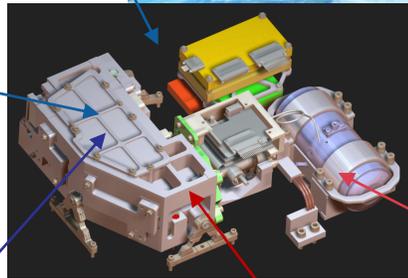
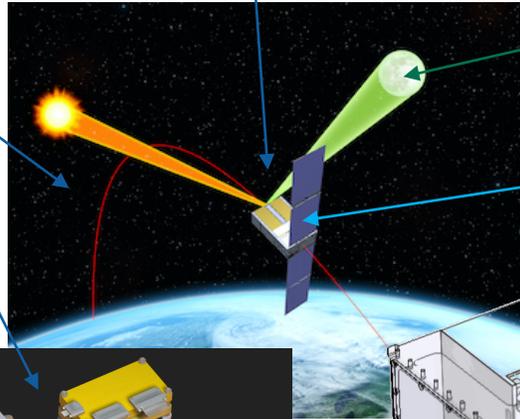
Project management
 Engineering coordination
 Instrument electronics
 Flight and ground software
 Mechanical, Thermal & Structural
 Instrument I&T
 Science and data products
 Operations
 Outreach



Lunar calibration
 approach and
 validation analysis



6U CubeSat Bus:
 Mechanical
 Power/Electric
 Electronics/Data
 Avionics
 System I&T
 Operations



Optical black coating



IDCA characterization
 Instrument calibration
 Uncertainty budget



Instrument design
 Radiometric modeling
 Instrument fabrication
 Instrument assembly
 Functional testing



Payload Analysis
 Input to payload design
 Flexures design

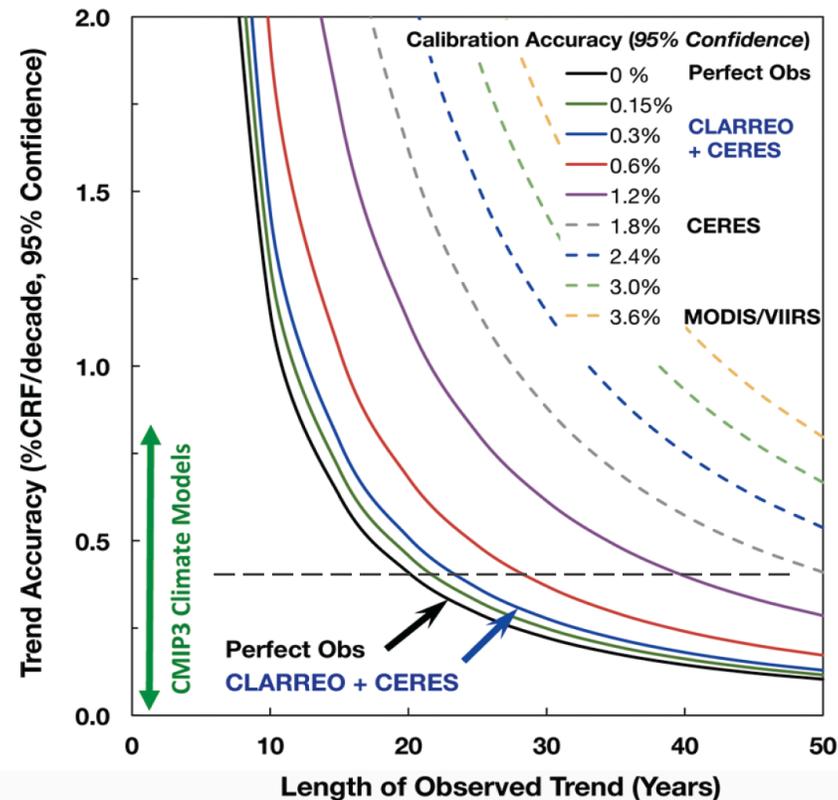
- ARCSTONE TEAM:**
- **NATIONWIDE COLLABORATION of EXPERTS !**
 - **Collaboration with NIST & UMBC:**
Ground and Airborne lunar measurements

Relevance of Radiometric Accuracy

- **Climate benchmarking in VSWIR and IR**
Weilicki et al., BAMS, 2013
- **Cloud Retrievals long-term record (similar results)**
Shea et al., J. Clim., 2017
- **Improved information content from a measurement is function of measurement uncertainty**
Shea et al., in publication, 2020
- **High absolute accuracy is required to mitigate/bridge gaps in long-term observation records: e.g. SeaWIFS/PACE, ERB**

Measurement accuracy is foundation of experimental science and its value:

- **Climate science, records, and modeling**
- **Land and ocean environmental science**



Relationship of measurement accuracy in reflected solar on both climate trend accuracy in Cloud Radiative Forcing (CRF) (Y-axis) as well as the time to detect trends (X-axis).

Moon: Accurate Source for Calibration On-orbit

Calibration reference: Empirical model of Lunar Spectral Irradiance (entire disk)



Reflectance of Lunar surface stable to $< 10^{-8}$ / year

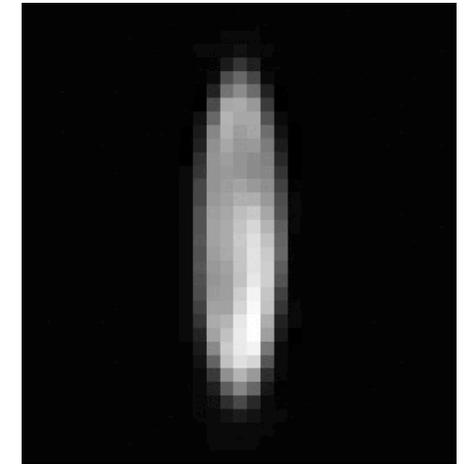
- Accuracy of current Lunar Model (ROLO): 5 – 10%
- SeaWiFS gain stability: 0.13% (k=1) over 12 years

EOS On-Orbit Calibration Need:

Absolute accurate spectral irradiance for all lunar phase and libration states !

Expected Impacts:

- Quality of data products
- Long-term consistency
- Handling data gaps
- Reduces instrument size, mass, power
- Reduce complexity
- Accurate CubeSat sensors



Lunar image by SeaWiFS



Applications of the Lunar Calibration Approach (satellite operators worldwide !)

Team	Satellite	Sensor	G/L	Dates	Number of obs	Phase angle range (°)
CMA	FY-3C	MERSI	LEO	2013-2014	9	[43,57]
CMA	FY-2D	VISSR	GEO	2007-2014		
CMA	FY-2E	VISSR	GEO	2010-2014		
CMA	FY-2F	VISSR	GEO	2012-2014		
JMA	MTSAT-2	IMAGER	GEO	2010-2013	62	[-138,147]
JMA	GMS5	VISSR	GEO	1995-2003	50	[-94,96]
JMA	Himawari-8	AHI	GEO	2014-	-	
EUMETSAT	MSG1	SEVIRI	GEO	2003-2014	380/43	[-150,152]
EUMETSAT	MSG2	SEVIRI	GEO	2006-2014	312/54	[-147,150]
EUMETSAT	MSG3	SEVIRI	GEO	2013-2014	45/7	[-144,143]
EUMETSAT	MET7	MVIRI	GEO	1998-2014	128	[-147,144]
CNES	Pleiades-1A	PHR	LEO	2012	10	[+/-40]
CNES	Pleiades-1B	PHR	LEO	2013-2014	10	[+/-40]
NASA-MODIS	Terra	MODIS	LEO	2000-2014	136	[54,56]
NASA-MODIS	Aqua	MODIS	LEO	2002-2014	117	[-54,-56]
NASA-VIIRS	NPP	VIIRS	LEO	2012-2014	20	[50,52]
NASA-OBPG	SeaStar	SeaWiFS	LEO	1997-2010	204	(<10, [27-66])
NASA/USGS	Landsat-8	OLI	LEO	2013-2014	3	[-7]
NASA	OCO-2	OCO	LEO	2014		
NOAA-STAR	NPP	VIIRS	LEO	2011-2014	19	[-52,-50]
NOAA	GOES-10	IMAGER	GEO	1998-2006	33	[-66, 81]
NOAA	GOES-11	IMAGER	GEO	2006-2007	10	[-62, 57]
NOAA	GOES-12	IMAGER	GEO	2003-2010	49	[-83, 66]
NOAA	GOES-13	IMAGER	GEO	2006	11	
NOAA	GOES-15	IMAGER	GEO	2012-2013	28	[-52, 69]
VITO	Proba-V	VGT-P	LEO	2013-2014	25	[-7]
KMA	COMS	MI	GEO	2010-2014	60	
AIST	Terra	ASTER	LEO	1999-2014	1	-27.7
ISRO	OceanSat2	OCM-2	LEO	2009-2014	2	
ISRO	INSAT-3D	IMAGER	GEO	2013-2014	2	

*From GSICS Lunar Calibration Workshop,
December 2014, EUMETSAT.*

- Instruments with lunar calibration capabilities participating in the GSICS GIRO program
- *List includes sensors with lunar observations submitted to the database at EUMETSAT as of December 2014*
- CALCON 2019: A lot of positive discussions and feedback !
- *Next GSICS Lunar Calibration Workshop: Planned for November 2020 (possibly delayed)*



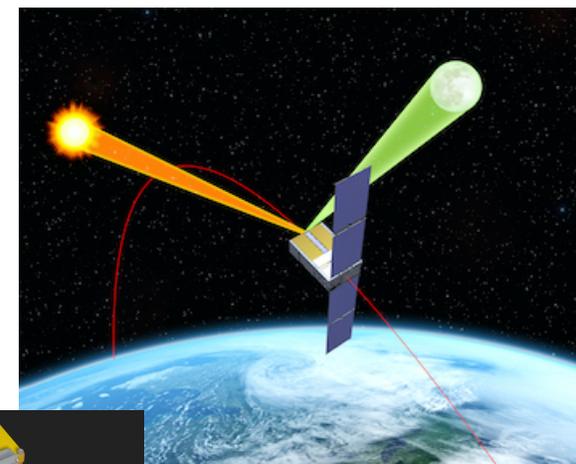
ARCSTONE IIP Objectives

OBJECTIVES:

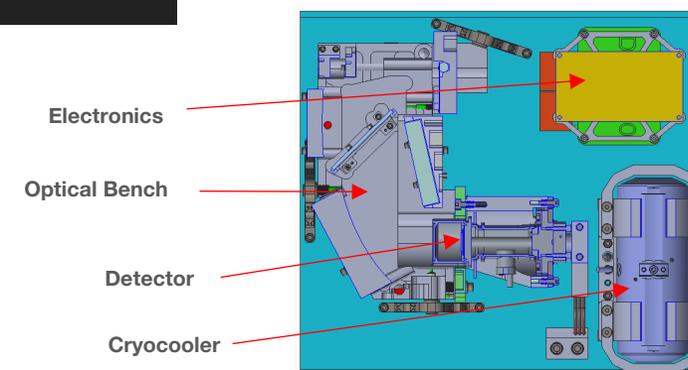
- To enable on-orbit high-accuracy absolute calibration for the past, current, and future reflected solar sensors in LEO and GEO* by providing lunar spectral irradiance as function of satellite viewing geometry and specified wavelength.
- To design, build, calibrate and validate a prototype instrument, demonstrate *form-fit-function for a 6U observatory with compliance in size, mass, power, and thermal performance.*

* Planetary instruments: OSIRIS Rex Camera suite [Golish et al., 2020]

TRL_{current} = 4 TRL_{out} = 5



ARCSTONE FSR Concept: Accurate measurements of Lunar Irradiance from Space with an Instrument flying on 6U CubeSat (courtesy BCT) in LEO.



Progress of ARCSTONE FSR instrument Design

ARCSTONE Mission Concept

Concept of Operations and Data Products:

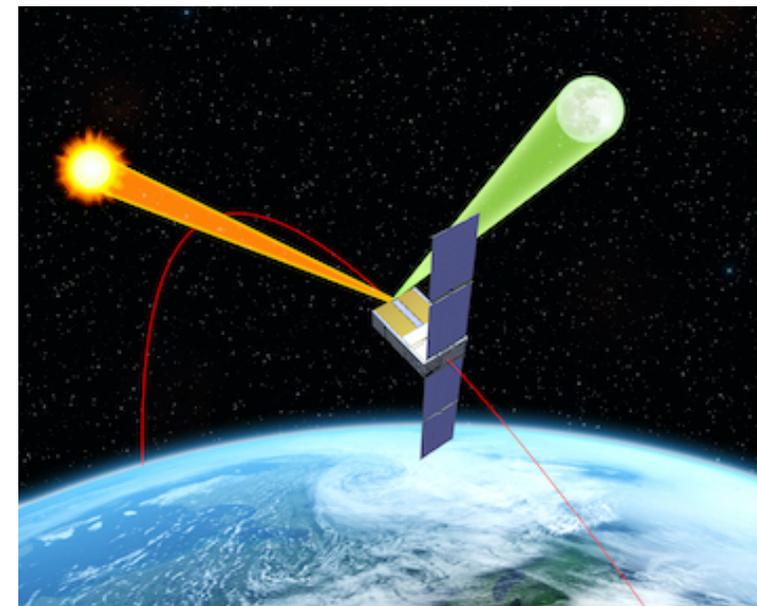
- Data to collect: Lunar spectral irradiance every 12 hours, 10 minutes
- Data to collect: Solar spectral irradiance for calibration (daily)
- Combined uncertainty < 0.5% (k=1)
- Spectrometer with single-pixel field-of-view about 0.7° (no scanning !)
- Sun synchronous orbit at 500 – 600 km altitude
- Spectral range from 350 nm to 2300 nm, spectral sampling at 4 nm

1 year: Improvement of current Lunar Calibration Model (factor of 2 – 4);

3+ years: New Lunar Irradiance Model, improved accuracy level (factor of 10).

Key Technologies to Enable the Concept:

- Approach to orbital calibration via referencing Sun (TSIS measurements):
 Demonstration of lunar and solar measurements with *the same optical path using integration time to reduce solar signal -- Major Innovation !*
- Pointing ability of spacecraft now permits obtaining required measurements *with instrument integrated into spacecraft.*



6U CubeSat Spacecraft Bus:
 courtesy of Blue Canyon Technologies (BCT)

BCT 6U XB6 Spacecraft pointing:
 Accuracy 0.002° (1-sigma) in 3 axis
 Stability 1 arc-sec over 1 sec



ARCSTONE Mission: Key Performance Parameters

Key Parameters	Threshold Value	Goal Value
Accuracy (reflectance)	1.0% (k=1)	0.5% (k=1)
Stability	< 0.15% (k=1) per decade	< 0.1% (k=1) per decade
Orbit	Sun-synch orbit	Sun-synch orbit
Time on-Orbit	1 year	3 years
Frequency of sampling	24 hours	12 hours
Instrument pointing	< 0.2° combined	< 0.1° combined
Spectral Range	380 nm – 900 nm	350 nm – 2300 nm
Spectral Sampling	8 nm	4 nm

ARCSTONE MISSION CONOPS:

1. Lunar spectral irradiance observations:

- Every 12 hours
- Close to polar locations
- Multiple measurements within 5– 10 minutes to improve SNR

2. Solar Spectral Irradiance observations (solar calibration):

- Multiple measurements to get required SNR
- This is radiometric calibration to the TSIS reference

3. Dark images:

- Multiple measurements with closed shutter
- Before every lunar and solar observations

4. Dark field (to calibrate instrument thermal background):

- Multiple measurements of dark space

5. Field-of-view sensitivity characterization:

- Calibration of instruments alignment

6. Spectral calibration:

- On-board spectral calibration

7. Spacecraft pointing calibration and other checks:

- Defined by the BCT for calibration of spacecraft functions

8. Stand by mode:

- Mode between observations

9. Data Downlink Mode

10. On-board data processing mode (if required)

11. Safe Mode (if required)

* 6U CubeSat Accommodation Study is complete

* Threshold Values considered as success criteria

Reference for radiometric requirements (ROLO, T. Stone):

Lunar Phase Angle = 75°;

Irradiance = 0.6 (micro W / m² nm)

Wavelength = 500 nm

Lunar Observation Sequence

- Every 12 hours
- Close to polar locations in-orbit
- Predicted with ground Science Prediction System (SPS) weekly

Point close to the Moon (TBD), time to settle

Dark field (to calibrate instrument thermal background):

- Multiple measurements of dark space with shutter closed and open

Point at the center of Moon disk and track, time to settle

Dark images:

- Multiple measurements (e.g. 10) with closed shutter

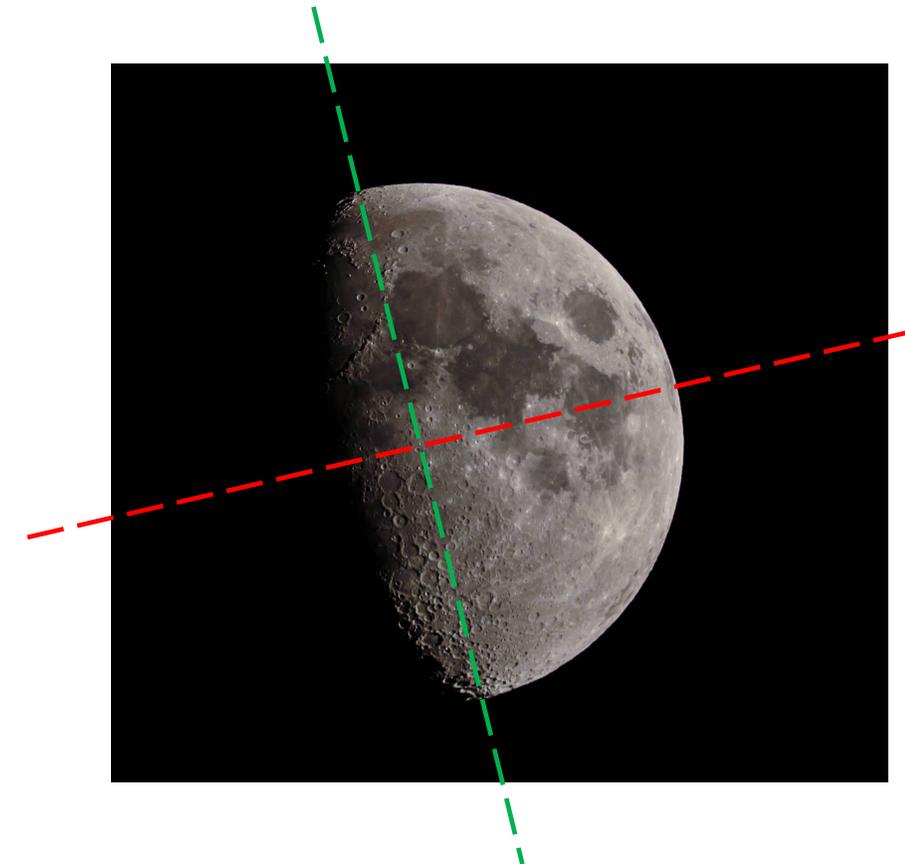
Lunar spectral irradiance observations:

- 16 seconds integration time for a single measurement
- Multiple measurements (e.g. 10) within 5 minutes to get required SNR

ARCSTONE requires accurate pointing/tracking !

BCT XB6 pointing *uncertainties* [public information]:

- +/- 0.002° pointing accuracy (1 sigma), 3 axes, 2 trackers
- Tracking stability 1 arcsecond per second, 3 axes, 2 trackers

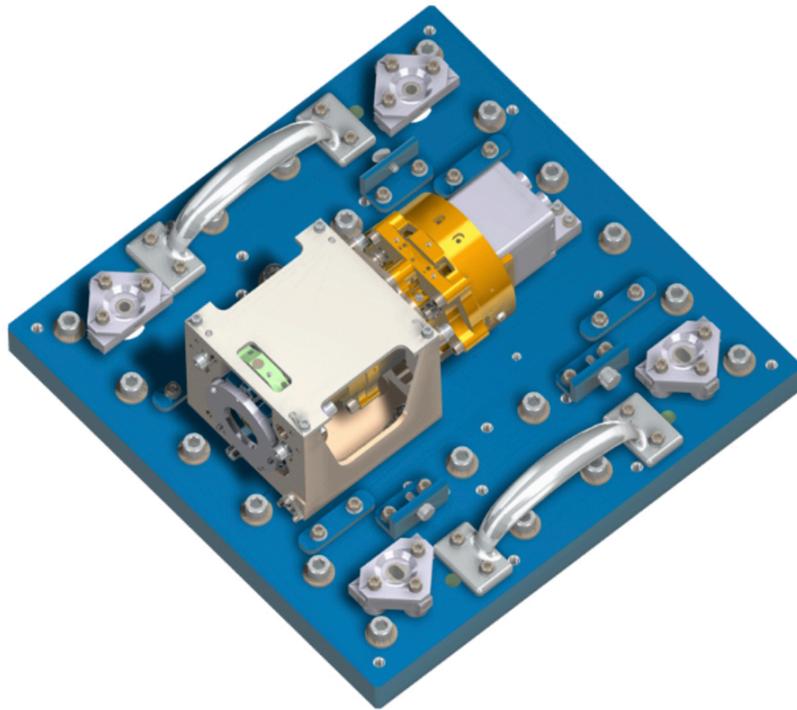


Two instrument alignment modes:

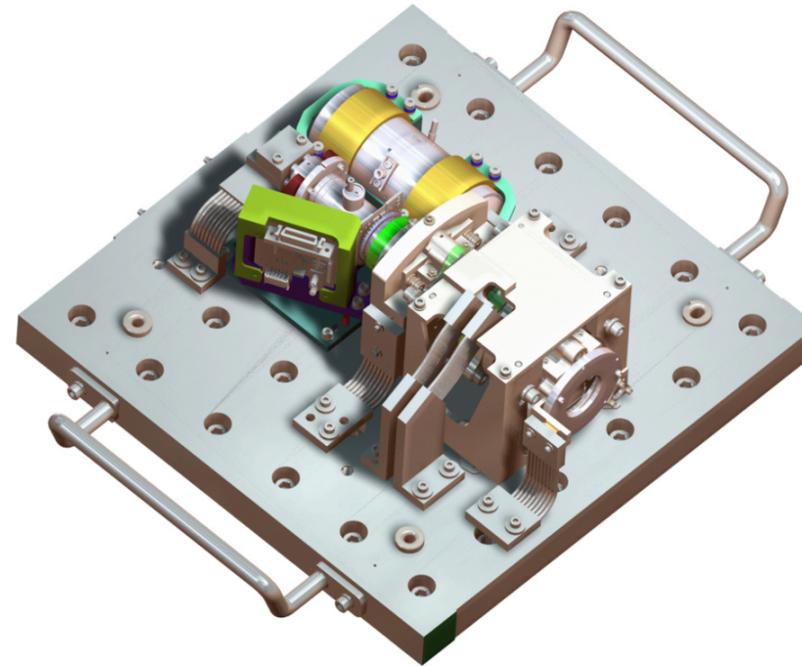
- Orthogonal to A-M-S plane
- **Parallel to A-M-S plane**

* A-M-S: ARCSTONE-Moon-Sun

ARCSTONE IIP: Prototype Instruments Design

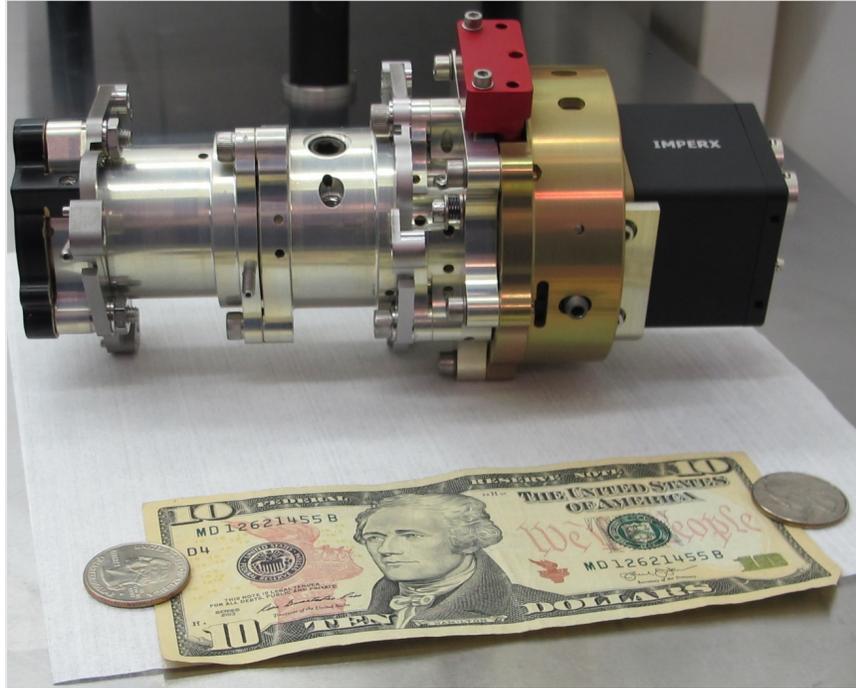


UVNIR Spectrometer – Ultraviolet Visible Near
Infrared 350 – 900 nm
Transmission Grating Spectrometer
Uncooled FPA (CCD) and Optic Train



SWIR Spectrometer – Short Wave Infrared
880 – 2300 nm
Transmission Grating Spectrometer
Cooled FPA (MCT) and Optic Train

ARCSTONE IIP: Fabricated and Characterized UVNIR Instrument



UVNIR Instrument:

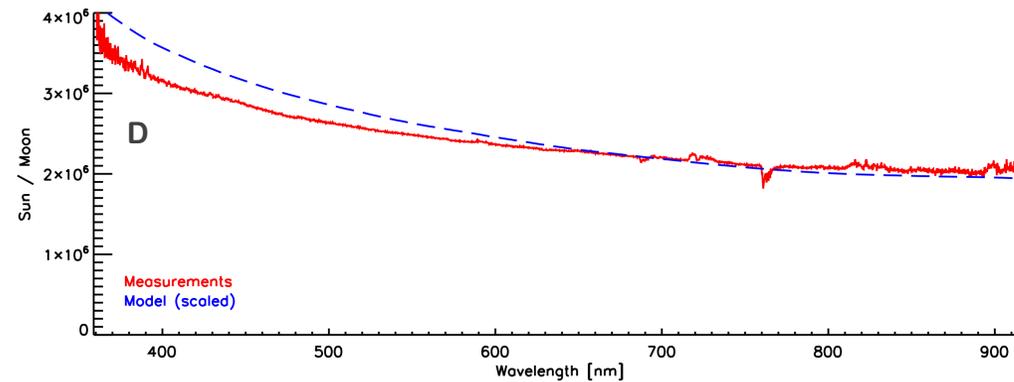
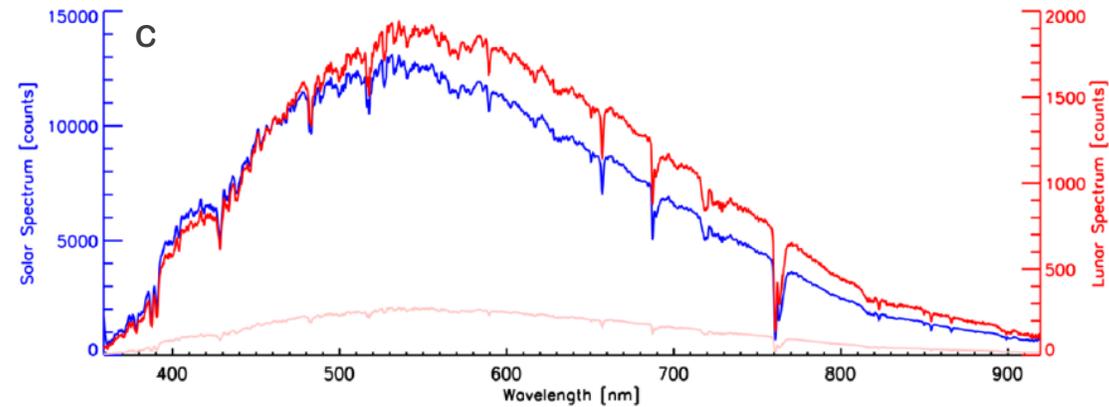
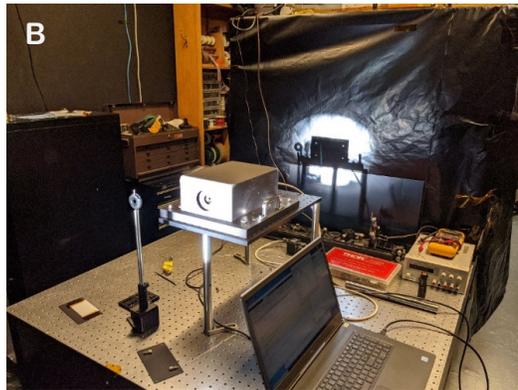
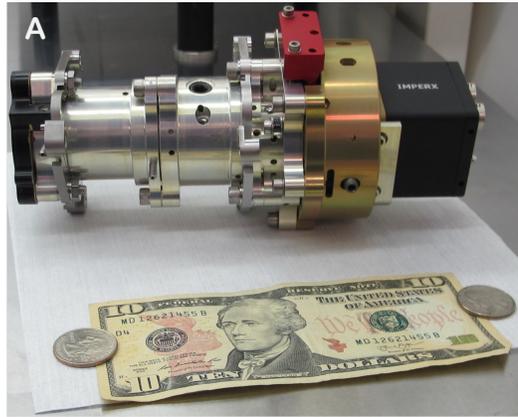
- CCD characterized & TVAC tested
- Assembly /Alignment completed

UVNIR Instrument:

- Characterization at LASP completed
- Uncertainty budget completed

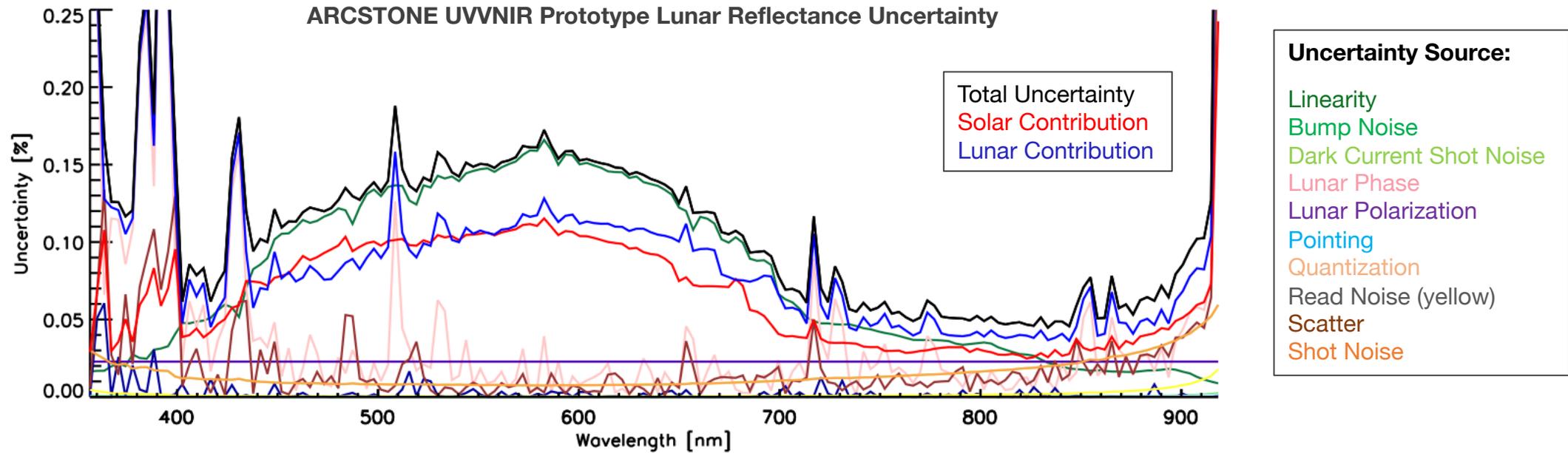


ARCSTONE UVNIR Instrument: testing with Moon and Sun



ARCSTONE UVNIR prototype: (a) assembled instrument, (b) testing in LASP's Heliostat facility for solar and lunar direct views, (c) measured solar and lunar spectra, (d) ratio of measured solar to lunar signals, demonstrated dynamic range of $> 10^6$.

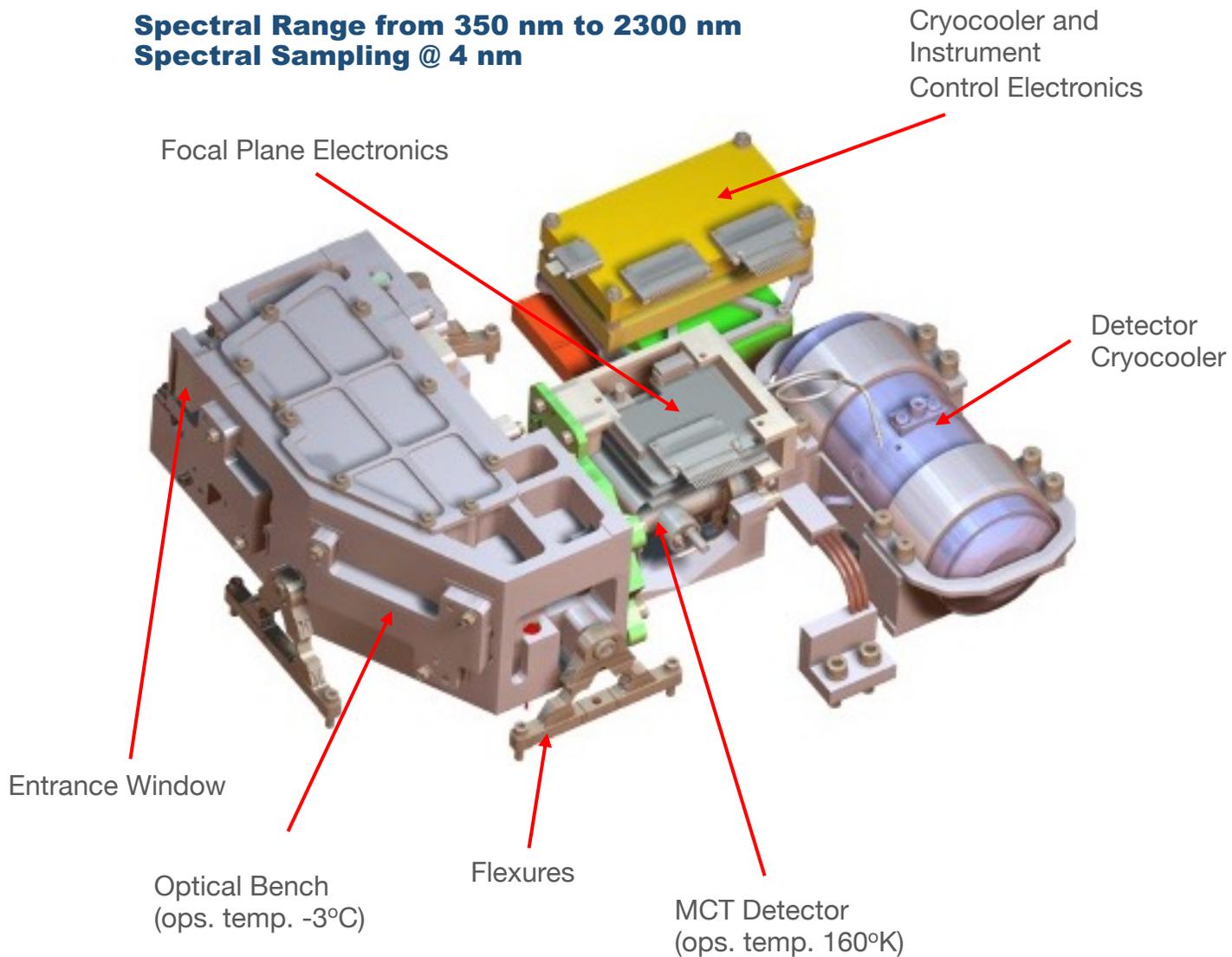
ARCSTONE UVNIR Instrument: Uncertainty Budget



Due to large dynamic range for solar signal attenuation, uncertainty contribution from linearity is dominant as expected. The net uncertainties for this prototype, $< 0.15\%$ ($k=1$), meet ARCSTONE requirements across limited spectral range of this prototype instrument.

ARCSTONE FSR EDU

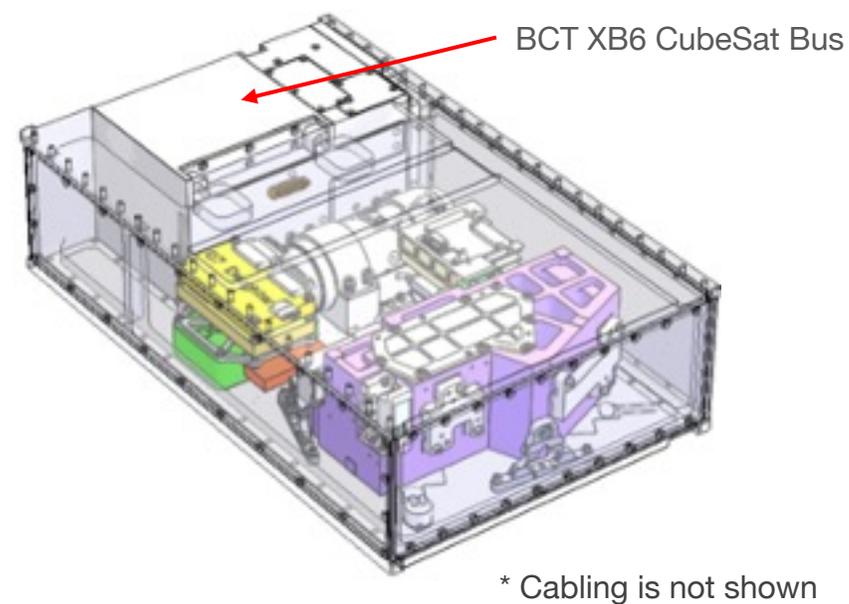
Spectral Range from 350 nm to 2300 nm
Spectral Sampling @ 4 nm



Volume:
Fits within up-to-date spacecraft bus CAD from BCT with at least 0.5mm clearance from all payload walls/features

Mass:
4.71 kg (6 kg payload allowable)

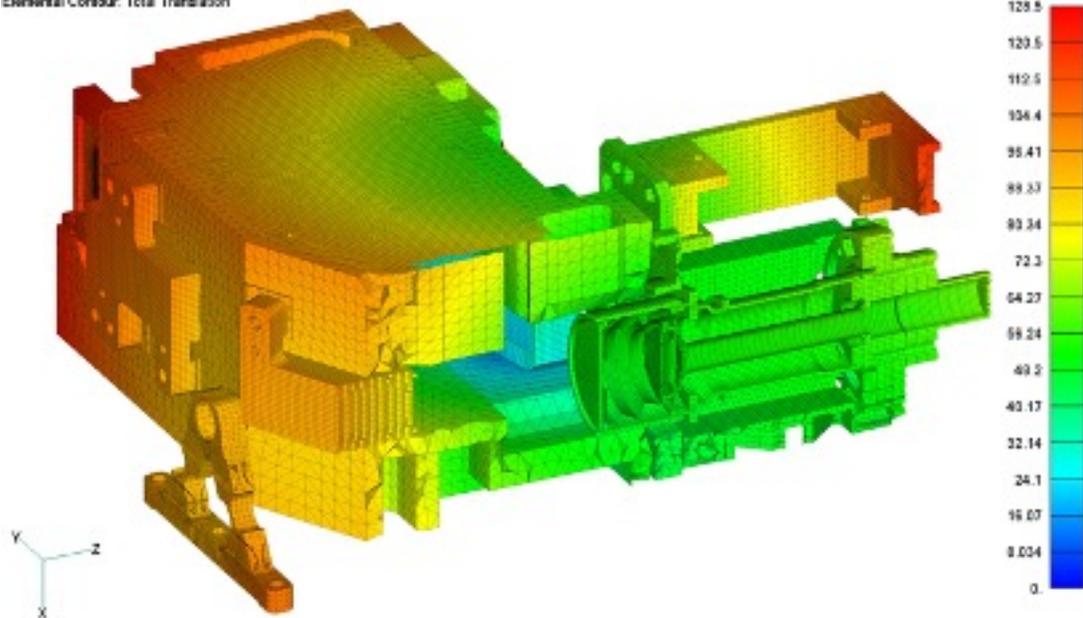
Power (118 W peak allowed):
Cryocooler in cooling phase for 2 min: 48 W
Science Mode: 23.83 W
Data Downlink Mode: 34.07 W
Stand By Mode: 15.5 W



ARCSTONE FSR Instrument Analysis

Performed Analysis for ALL instruments:
STOP, Thermoelastic, Random Vibe

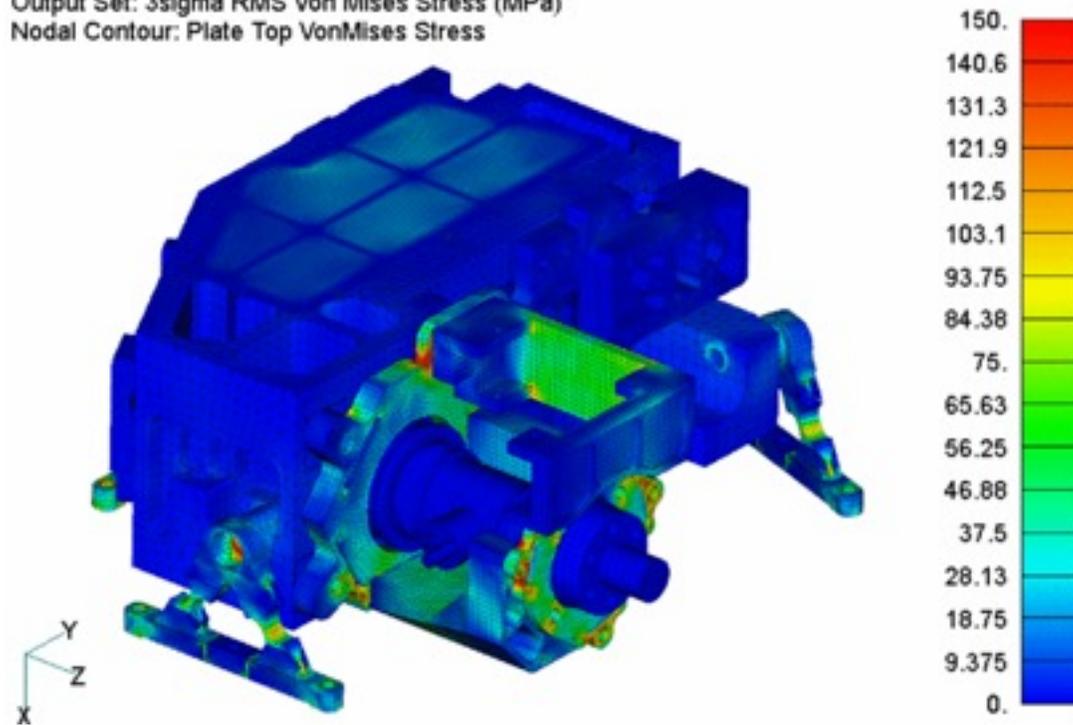
Output Set: THERMAL STOP TO -30C / -133.15C (minus Alignment Config) [micron]
Elemental Contour: Total Translation



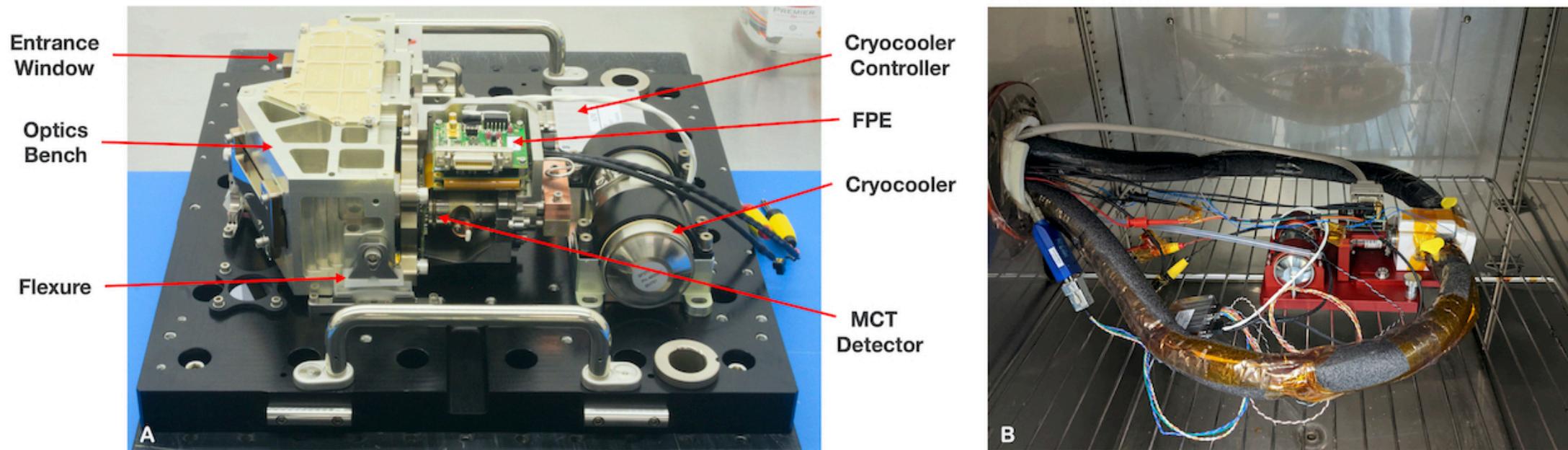
Optic bench displacements [microns] at -30°C .
Cutaway shows interior of camera dewar/cold finger.

Optic bench random vibration analysis.

Output Set: 3sigma RMS Von Mises Stress (MPa)
Nodal Contour: Plate Top VonMises Stress



ARCSTONE FSR Instrument: Status



(a) ARCSTONE EDU, assembled with a spare IDCA for performing instrument alignment
 (b) Primary IDCA being characterized for dark current, linearity, etc. using cold target



ARCSTONE: Status and Opportunities

Status:

- UV-VNIR instrument is complete and radiometrically calibrated
- Fabrication complete for SWIR instrument (assembly is on hold)
- Design and analysis completed for FSR EDU instrument
- 6U CubeSat accommodation study completed
- Fabrication of FSR instrument completed

Current Schedule:

- Complete 6U CubeSat/Payload thermal study (September 2020)
- Complete fabrication of FSR instrument (October 2020)
- Characterize FSR IDCA (April 2021)
- Assemble FSR instrument (May 2021)
- Calibrate FSR instrument (June – July 2021)
- Field-test FSR instrument with Sun and Moon (TRL5, July 2021)
- Vibe/TVAC of FSR instrument (TRL6, September 2021)

Opportunities:

- Space flight project (InVEST or mission)
- Ground use of UVVNIR prototype
- Ground use of FSR EDU
- Airborne & UAV applications

ARCSTONE: Calibration of Lunar Spectral Reflectance from Space

Recent Publications:

Swanson, R., C. Lukashin, M. Kehoe, M. Stebbins, H. Courrier, T. Jackson, M. Cooney, G. Kopp, P. Smith, C. Buleri, T. Stone, “The ARCSTONE Project to Calibrate Lunar Reflectance,” *IEEE Aerospace Proceedings*, 2020

Available online: <https://ieeexplore.ieee.org/abstract/document/9172629>

Stone, T.C., H. Kieffer, C. Lukashin, K. Turpie, “The Moon as a Climate-Quality Radiometric Calibration Reference,” *Remote Sens.*, 12, 1837, 2020

Available online at <https://www.mdpi.com/2072-4292/12/11/1837>



Website <http://arcstone.larc.nasa.gov>



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THANK YOU !

