# ARCSTONE: Calibration of Lunar Spectral Reflectance from Space

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5 – Goddard Space Flight Center, Greenbelt, MD
6 – Quartus Engineering, San Diego, CA
7 – Blue Canyon Technologies, Inc., Boulder, CO

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SBIR programs: Phase-I & Phase-II

# ARCSTONE: Team and Contributions

## NASA LaRC

Mission concept & science
Project management *
Engineering coordination
Instrument electronics
Flight and ground software
Mechanical, Thermal & Structural
Environmental testing
* SSAI: sub-contract management

## LASP
Laboratory for Atmospheric and Space Physics

Instrument concept
Component characterization
Radiometric calibration
Error budget

## NASA GSFC

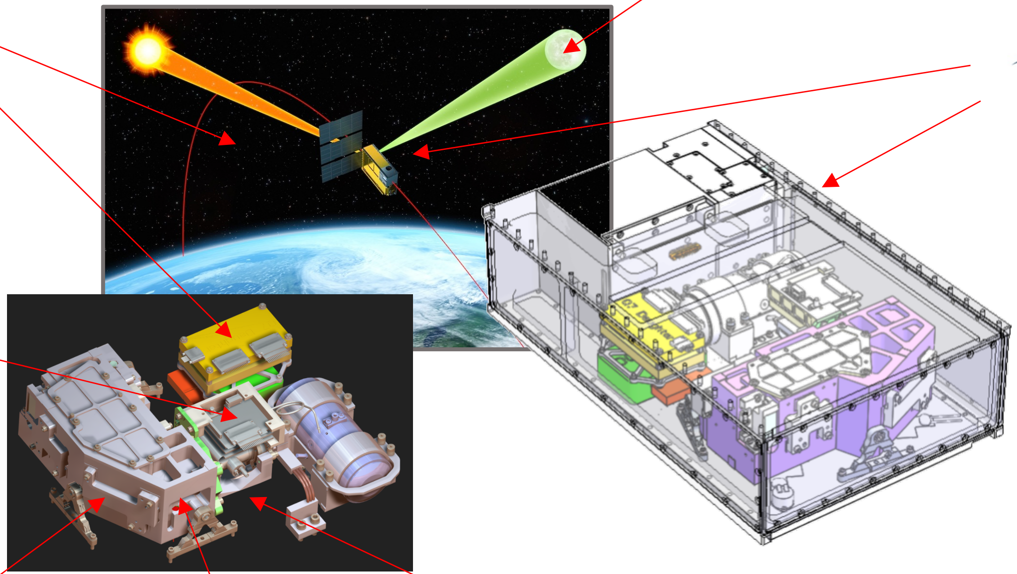
Optical black coating

## USGS

Lunar calibration approach (ROLO)

## BLUE CANYON TECHNOLOGIES

6U CubeSat Bus



## RESONON

Instrument concept
Instrument design
Radiometric modeling
Fabrication
Assembly & alignment
Functional testing

## QUARTUS ENGINEERING

Instrument Analysis (STOP, RV, TE)
Input to instrument design
Flexures design

ARCSTONE TEAM:

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

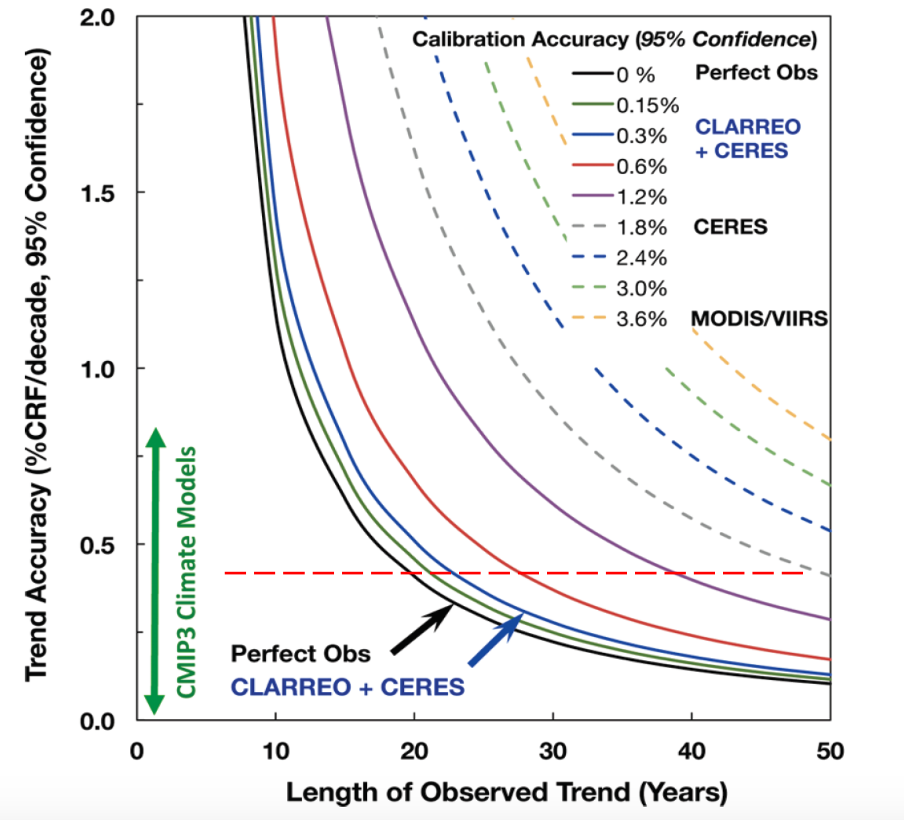
# ARCSTONE: Relevance to NRC Decadal Survey 2017

**Inputs to the NRC DS 2017:**

*1. Lukashin et al., "Accurate Inter-Calibration of Spaceborne Reflected Solar Sensors," input to NRC Decadal Survey, 2017.*

*2. Stone et al., "Redeveloping the Lunar Reflectance as a High-accuracy Absolute Reference for On-orbit Radiometric Calibration," input to NRC Decadal Survey, 2017.*

- **Information content from a measurement is function of measurement uncertainty**
- **Accuracy is a key instrument performance parameter**
- **High absolute accuracy is required to mitigate gaps in observation long-term records: e.g. MODIS/VIIRS, SeaWIFS/PACE, CERES/Libera.**




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).
*Weilicki et al., BAMS, 2013.*

# Moon: Accurate Source for Calibration On-orbit

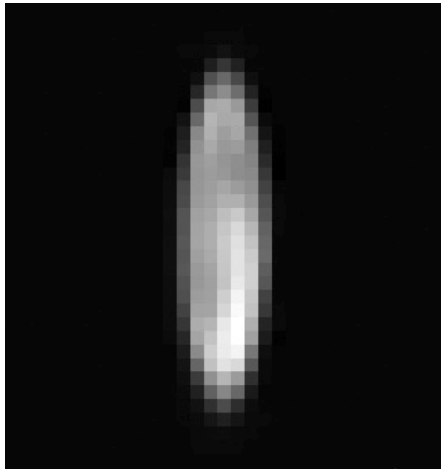
## Calibration reference: Empirical model of Lunar Spectral Irradiance (entire disk)


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 !**



Lunar image by SeaWIFS

Expected Impacts:

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

# 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 EUMATSAT as of December 2014***
- **CALCON 2019: A lot of positive discussions and feedback !**
- ***Next GSICS Lunar Calibration Workshop: Planned for November 2020 (possibly delayed)***

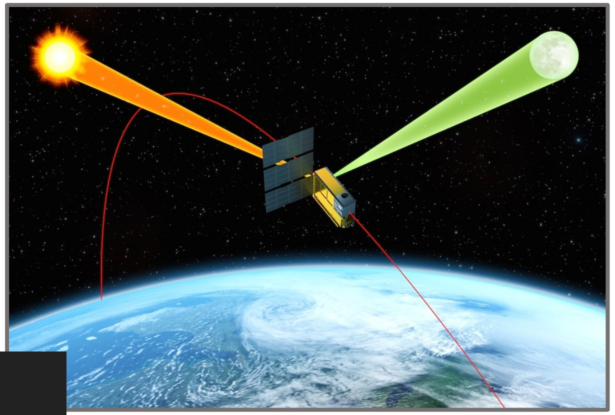
# ARCSTONE Full Spectral Range (FSR): Objectives

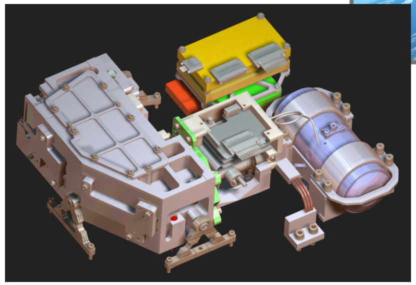
## OBJECTIVES:

- *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.

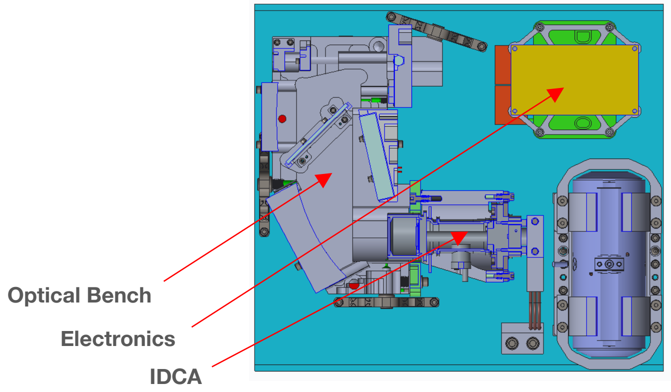
- To design, build, calibrate and validate a prototype instrument, demonstrate *form-fit-function for a 6U observatory with compliance in size, mass, power, and thermal performance*.

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





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

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

# ARCSTONE FSR Mission Concept

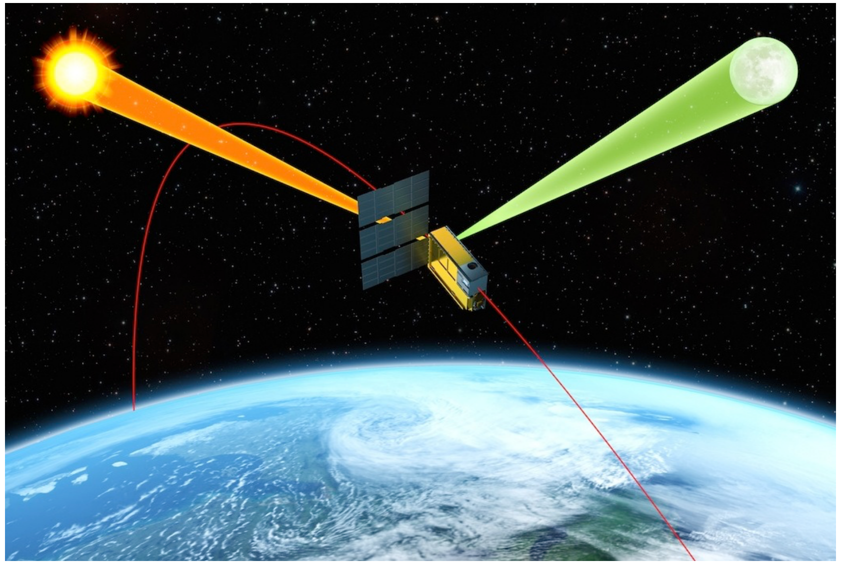
## Concept of Operations and Data Products:

- 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: Science Traceability Matrix

| ARCSTONE Goals | Earth Science Impacts | Mission Requirements | Measurement Requirements | Instrument Requirements | Data Products |
|---|---|---|---|---|---|
| Enable record accuracy for on-orbit SI-traceable calibration for reflected solar Instruments in LEO and GEO, and Planetary | Climate Benchmark and Direct Inter-Calibration | Establish calibration standard on-orbit:<br><br>Lunar spectral reflectance with accuracy < 0.5%<br><br>Sufficient sampling of lunar librations<br><br>Lunar spectral irradiance model with uncertainty < 0.7% (k=1)<br><br>On-orbit calibration against TSIS/SIM Solar Spectral Irradiance (SSI) 0.2% reference accuracy<br><br>Duration: 3 years | Calibration to Solar spectral irradiance | Single FOV spectrometers<br><br>Pointing accuracy < $0.05^{o}$ (with bus)<br><br>Size:<br>6U CubeSat payload<br><br>Payload mass < 6 kg<br><br>Payload power < 40 W<br><br>Ability to reduce solar signal: factor of a ~ $10^{5}$ | Level-1:<br><br>Calibrated high-accuracy lunar spectral reflectance |
| | LEO/GEO Imagers (e.g. VIIRS, ABI): Clouds, Aerosols, Land, Weather | | Lunar spectral irradiance with uncertainty < 0.5% | | |
| | Atm. Chemistry (e.g. GOME, TEMPO) Trace gases | | SNR < 1% in UV/VIS<br>SNR < 2% in SWIR | | |
| | Ocean Color Record: PACE & SeaWIFS | | Wavelength range: 350 nm – 2300 nm | | Level-2:<br><br>New empirical model for high-accuracy lunar spectral irradiance |
| | Sustained Land Imaging: Landsats | | Spectral sampling: < 4 nm | | |
| | SBG Calibration: VSWIR Instrument | | Lunar measurement frequency: 12 hours | | |
| | In-Situ: Aerosol OD Nighttime Obs. | | Solar measurement frequency: daily | | |

# 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 |

* Requirements are captured in a Mission Requirements Document

* * Threshold Values considered as success criteria

Reference for radiometric requirements (ROLO, T. Stone):
Lunar Phase Angle = 75°;
Irradiance = 0.6 (micro W / $m^2$ nm)
Wavelength = 500 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

# 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

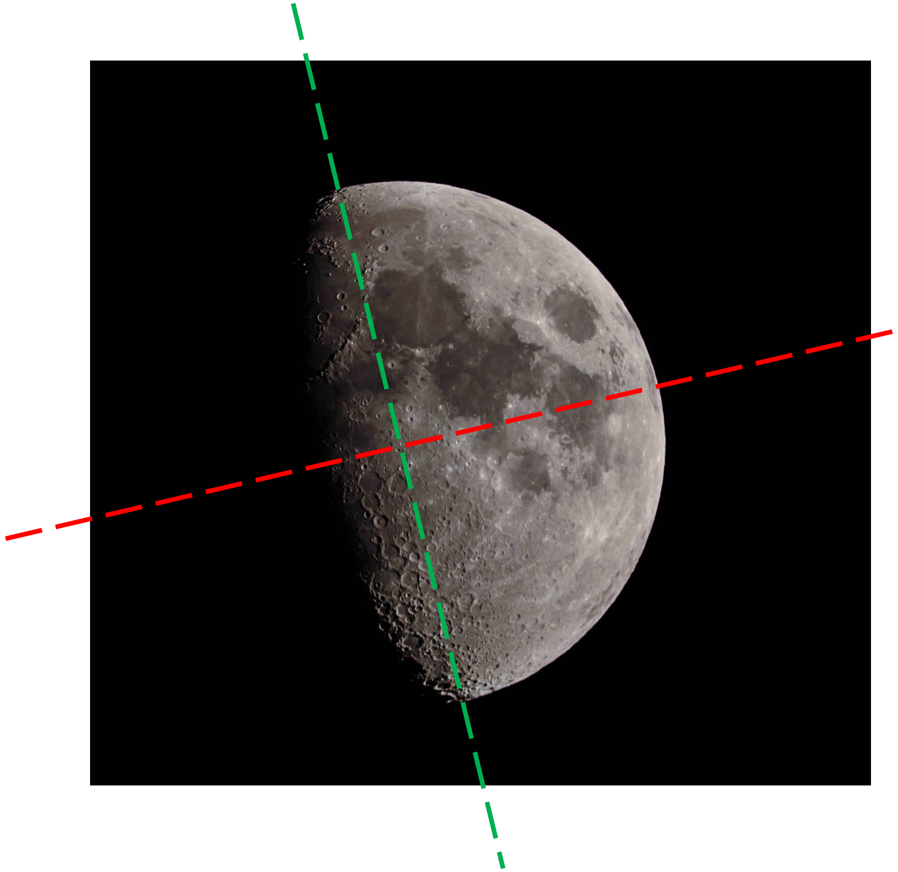
**Point at the center of Moon disk and track, time to settle**

**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]:**

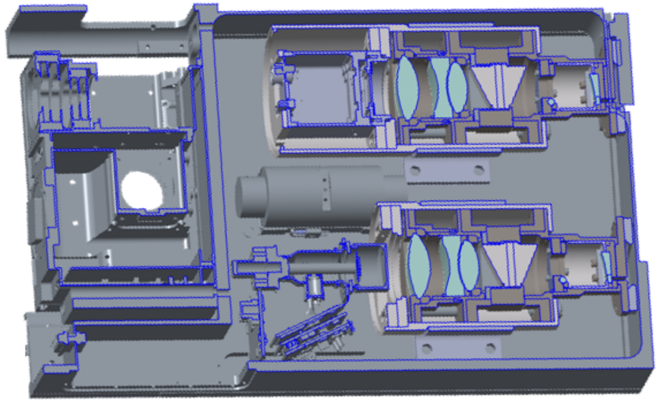
- +/- 0.002° pointing accuracy (1 sigma), 3 axes, 2 trackers
- Tracking stability 1 arcsecond per second, 3 axes, 2 trackers

**Two instrument alignment modes:**

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

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

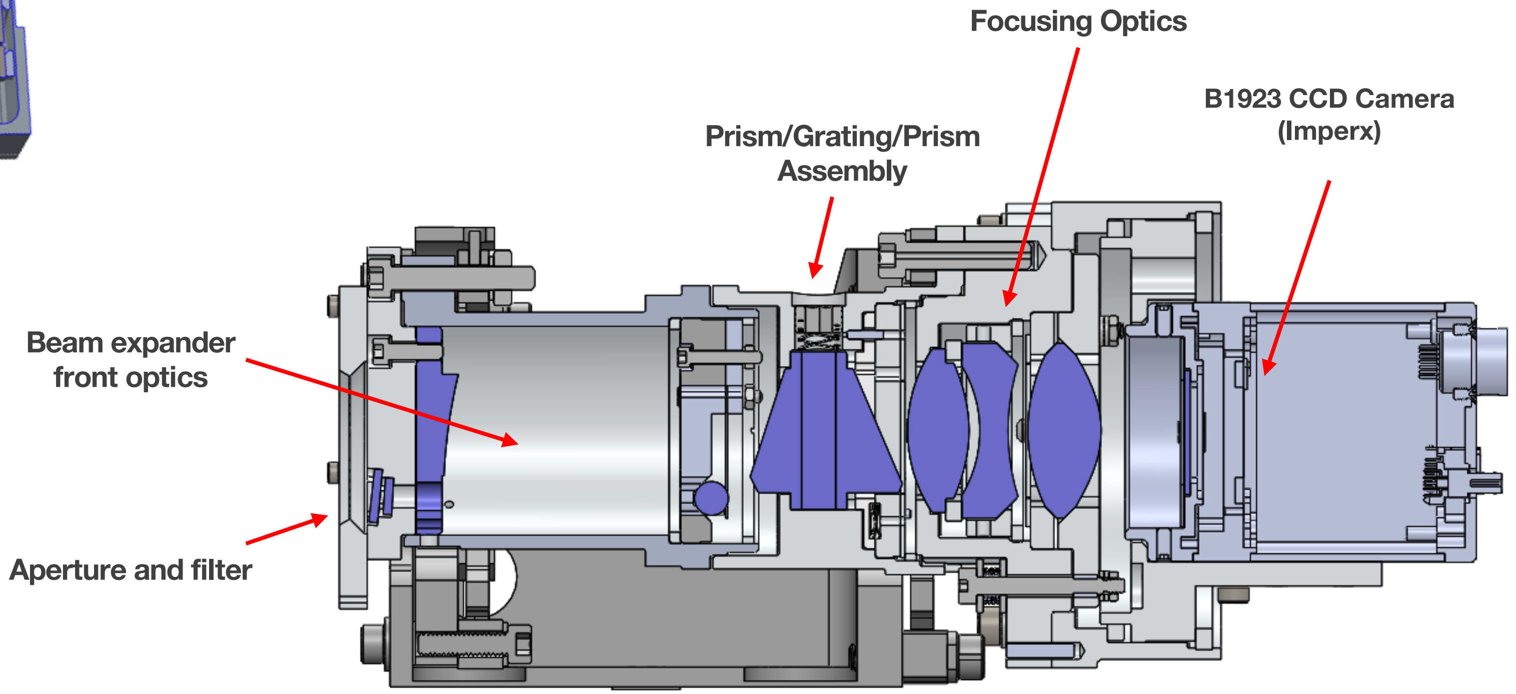
# ARCSTONE: Prototype Observatory and Instrument Design



Cubesat 6U bus:
Courtesy of Blue Canyon Technologies

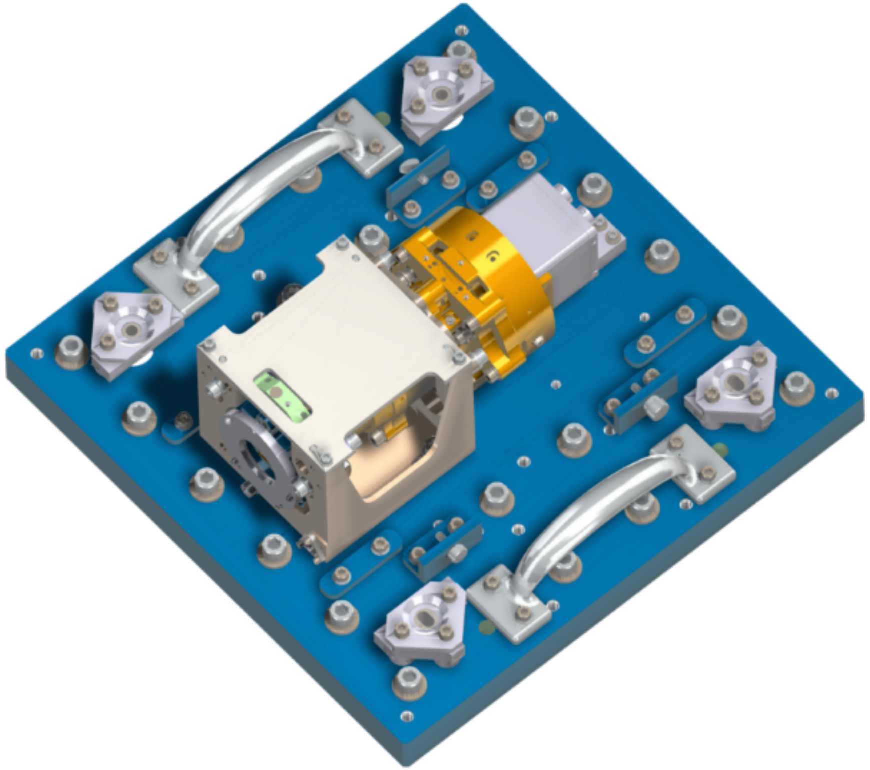
Preliminary System Design:

- 2 instruments in UVVNIR and SWIR
- Accommodated in 6U CubeSat bus

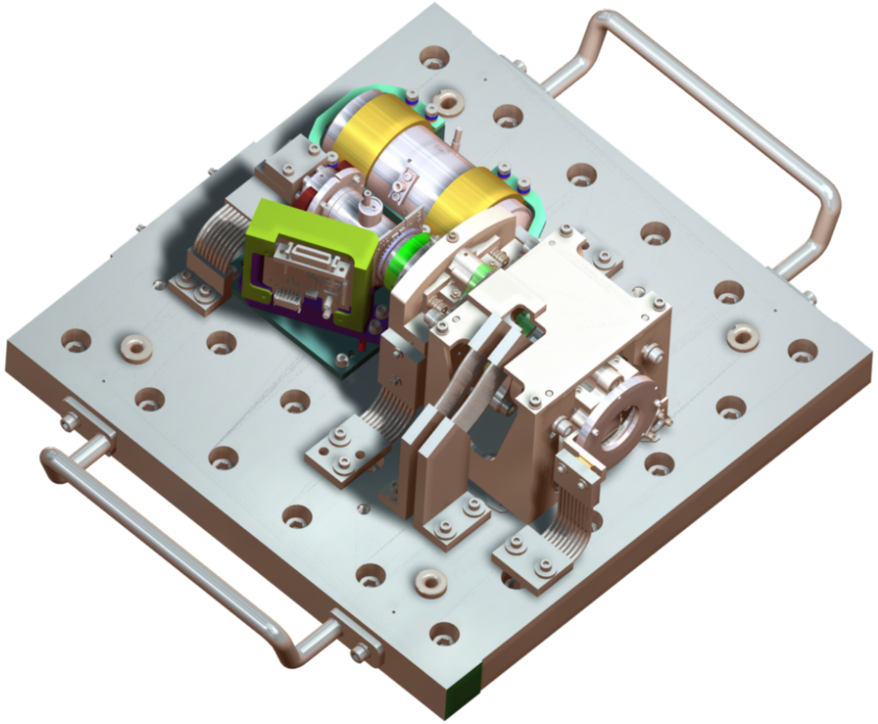



Prototype of ARCSTONE UVVNIR Instrument

# ARCSTONE IIP: Prototype Instruments Design

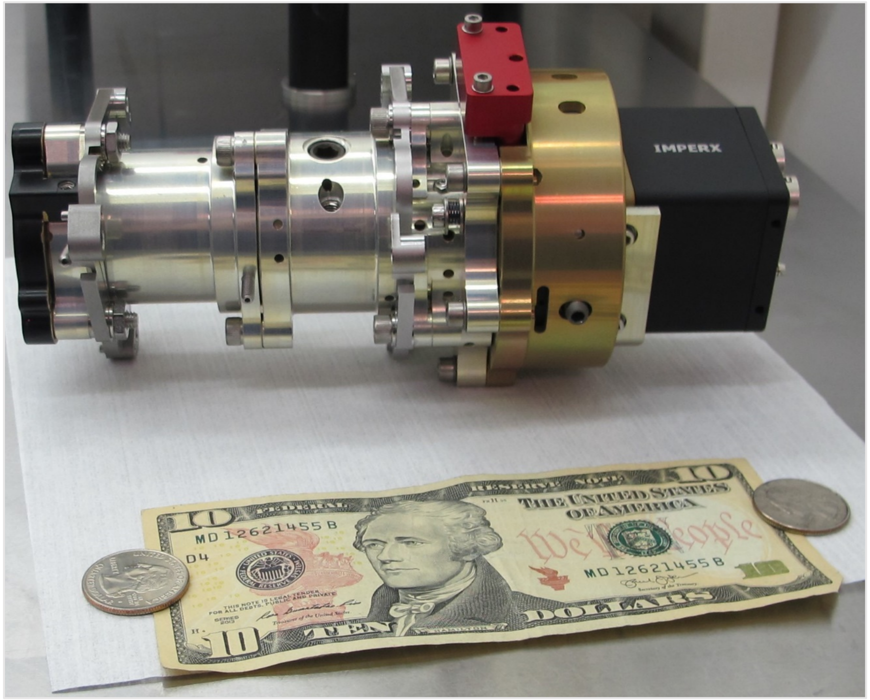


**UVVNIR Spectrometer** – Ultraviolet Visible Near Infrared 350 – 900 nm
Transmission Grating Spectrometer
Uncooled FPA (CCD) and Optic Train



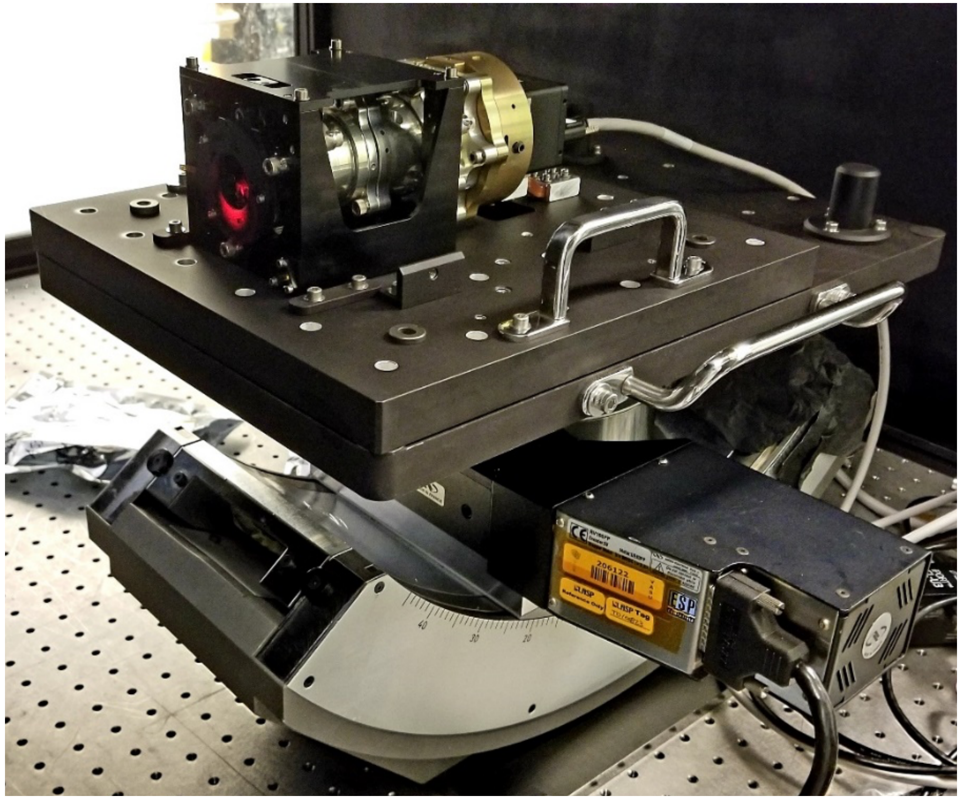
**SWIR Spectrometer** – Short Wave Infrared 880 – 2300 nm
Transmission Grating Spectrometer
Cooled FPA (MCT) and Optic Train

# ARCSTONE IIP: Fabricated and Characterized UVVNIR Instrument



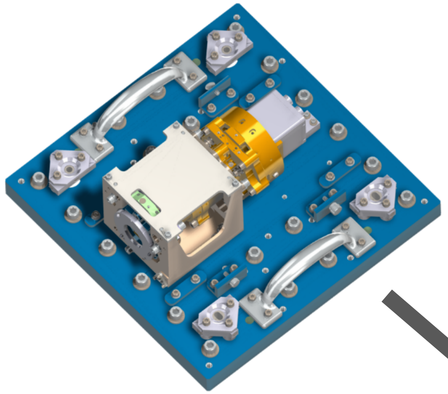

UVVNIR Instrument:
- CCD characterized & env. tested
- Assembly /Alignment completed

UVVNIR Instrument:
- Characterization at LASP completed
- Uncertainty budget in development

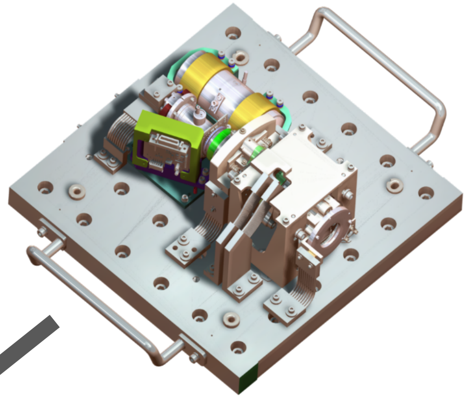


# ARCSTONE: Full Spectral Range (FSR) Instrument

2017 – 2019 work

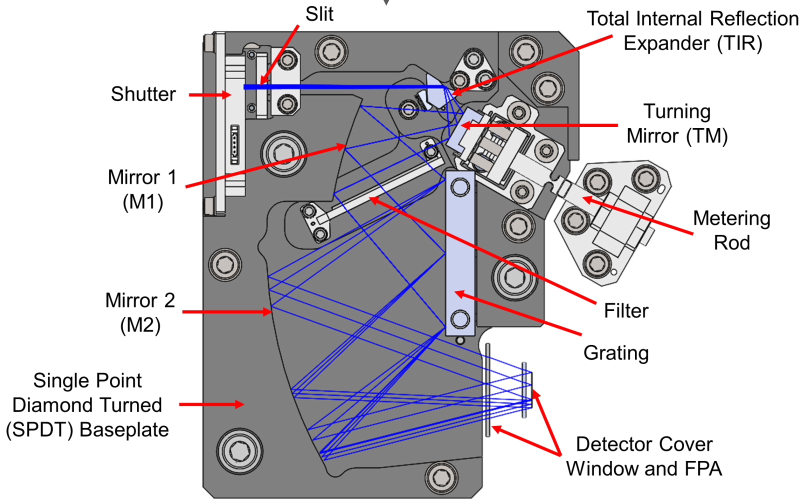


Ultraviolet Visible Near Infrared (UVVNIR)



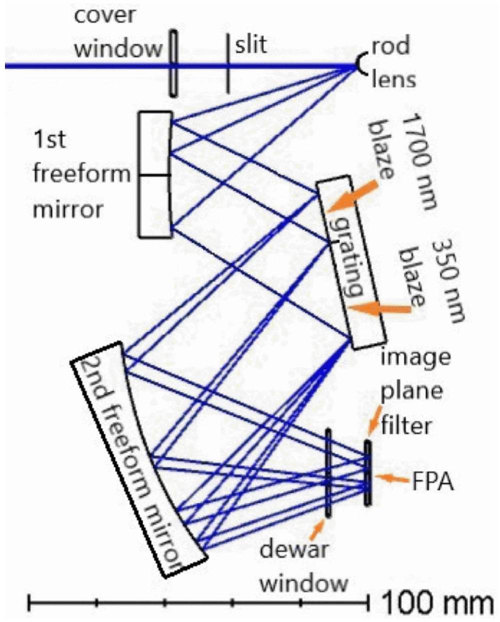
Short Wave Infrared (SWIR)

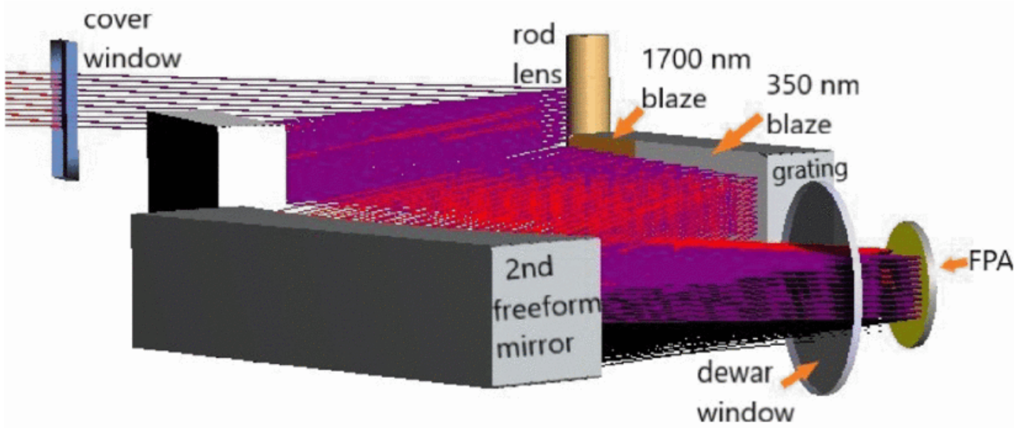
2019 – 2021 work



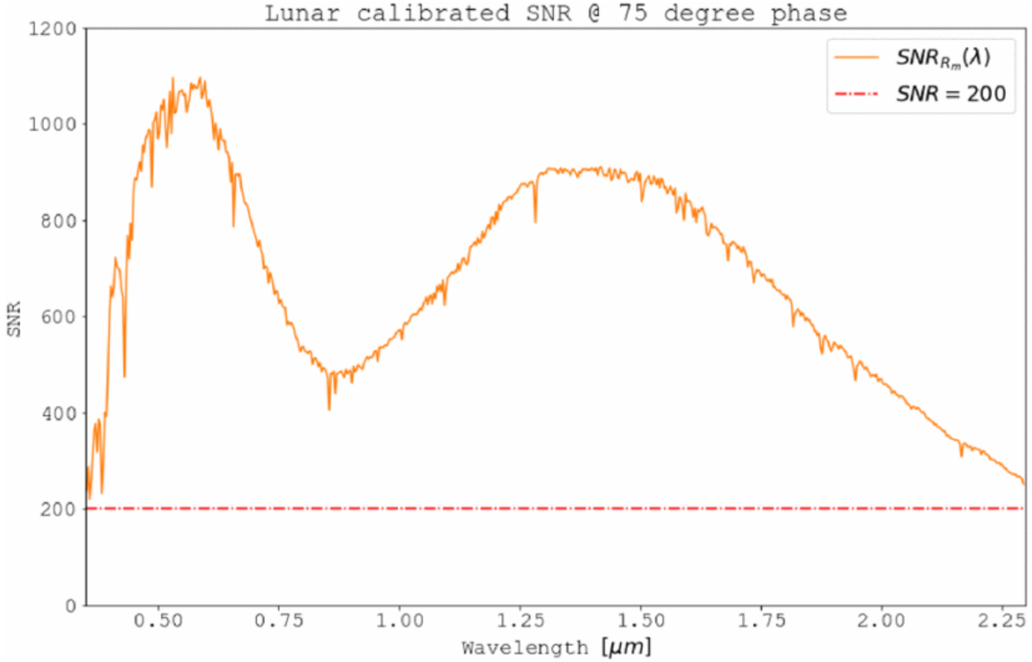

** Single channel system*
*Thinned MCT detector covers 350 – 2300 nm wavelength range*

# ARCSTONE: Full Spectral Range (FSR) Instrument



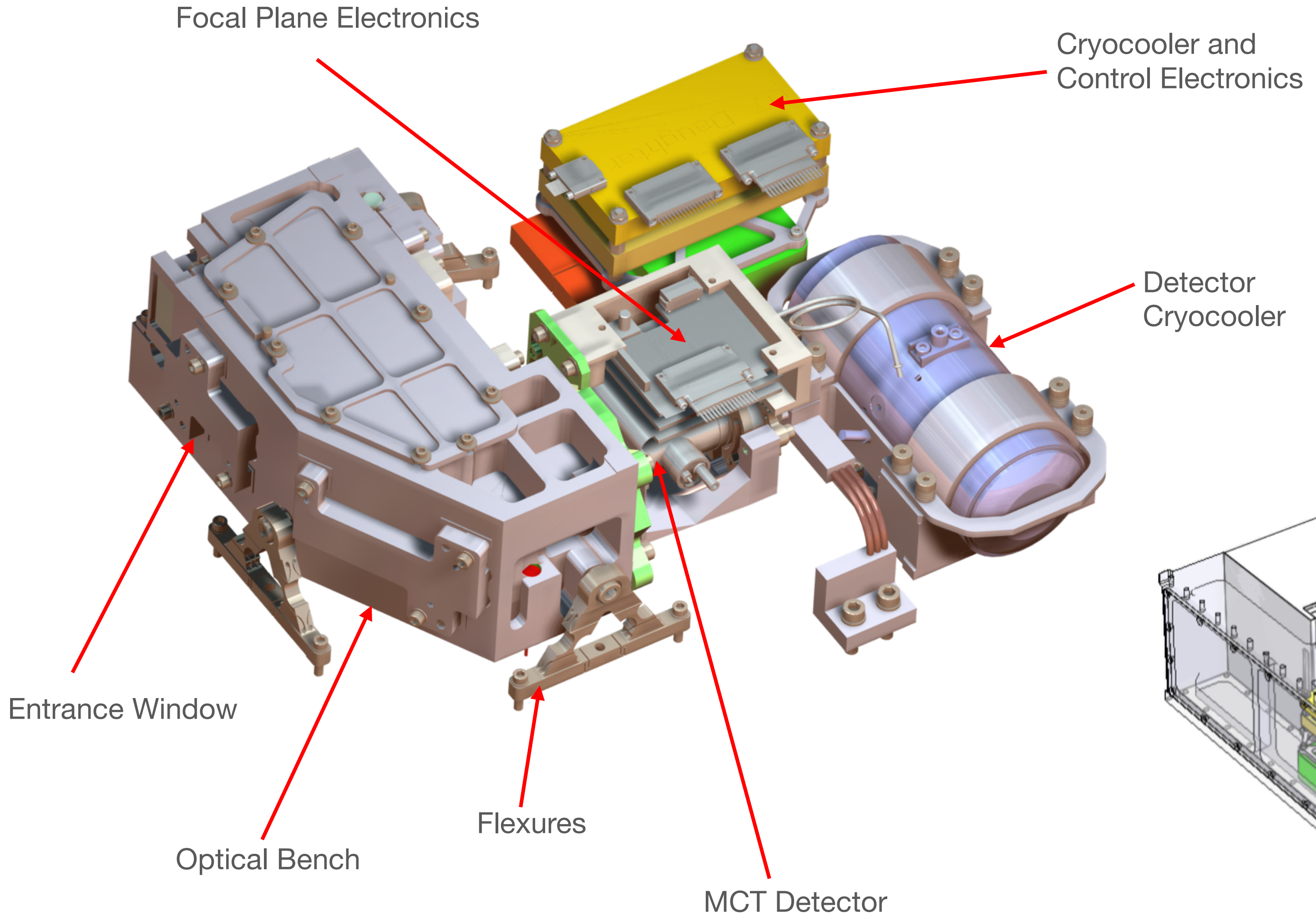




Raytrace and optics design of the ARCSTONE FSR reflective spectrograph with 350 – 2300 nm passband.




Modeled signal-to-noise ratio of the ARCSTONE calibrated lunar reflectance.

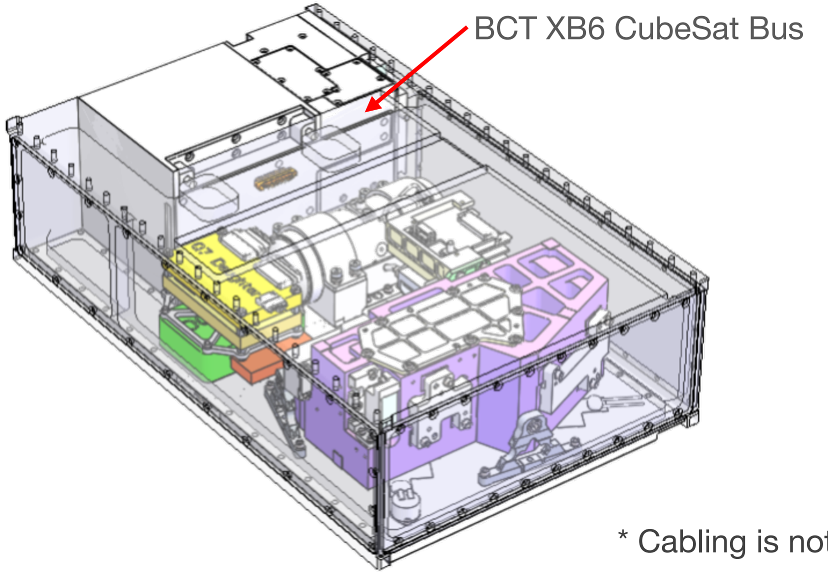
# ARCSTONE FSR: Instrument in Fabrication




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

**Mass:**
4.13 kg (*6 kg payload allowable*)

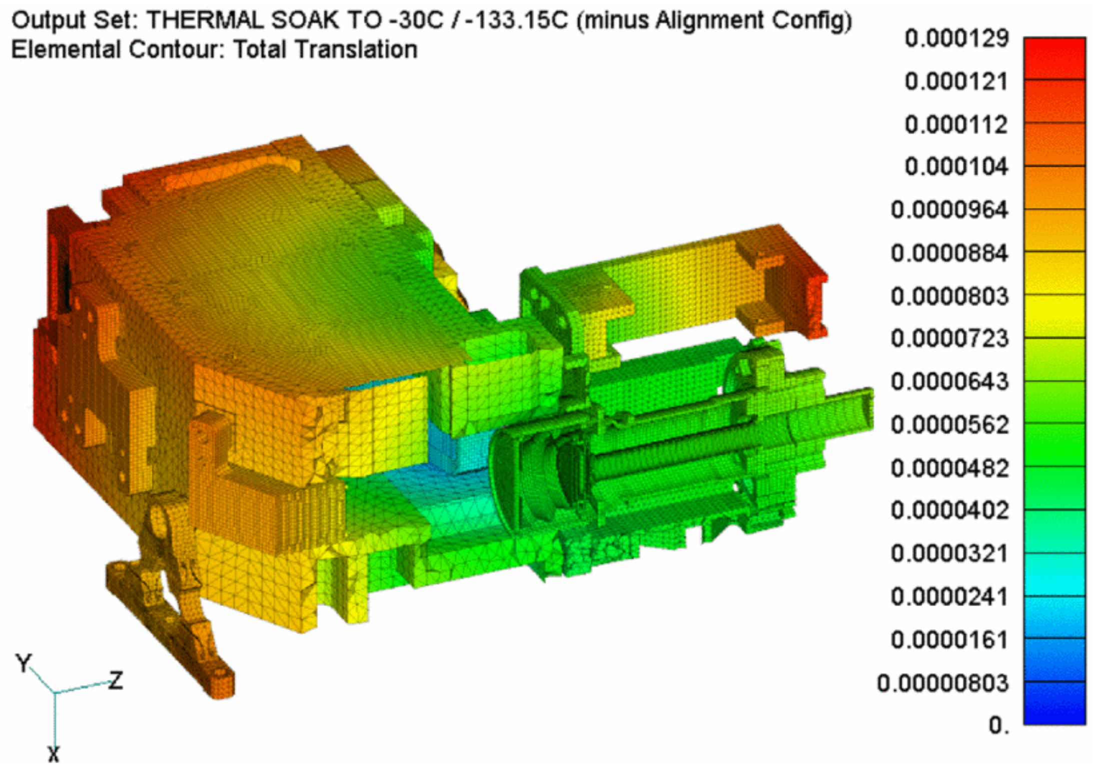
**Power (all worst cases):**
Science Mode: 23.83 W (*118 W peak allowable*)
TX Mode: 34.07 W
Stand By Mode: 15.5 W




* Cabling is not shown

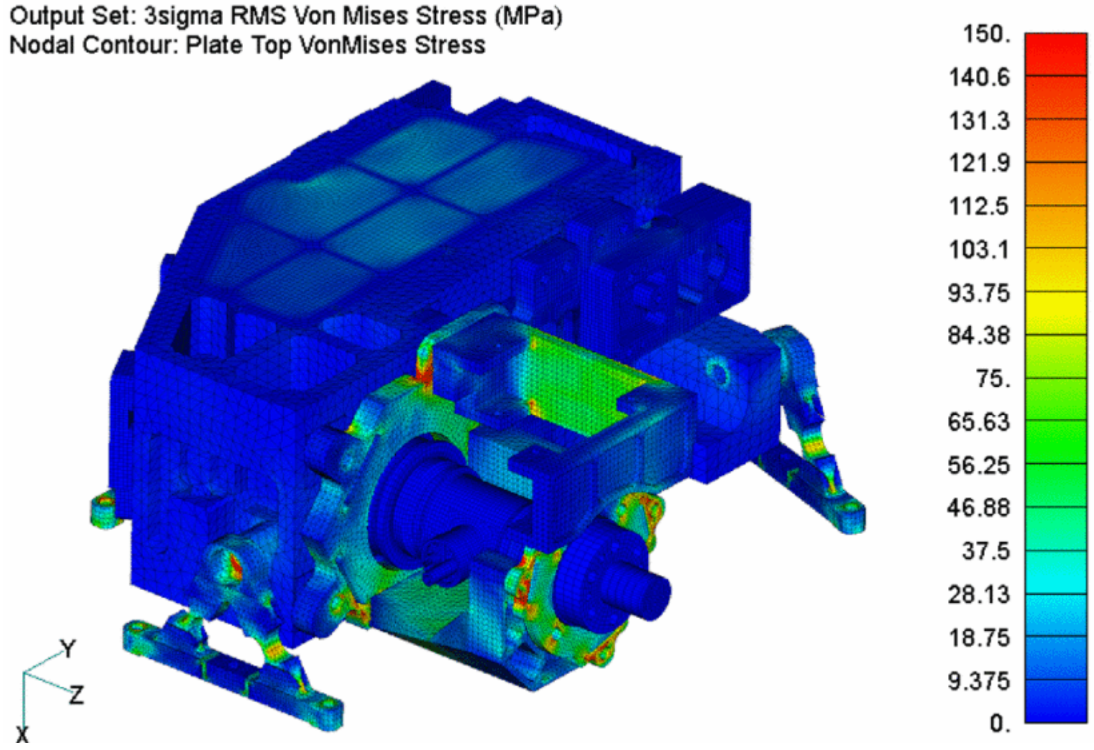
# ARCSTONE FSR Instrument Analysis

## Performed Analysis:
## STOP, Thermoelastic, Random Vibe



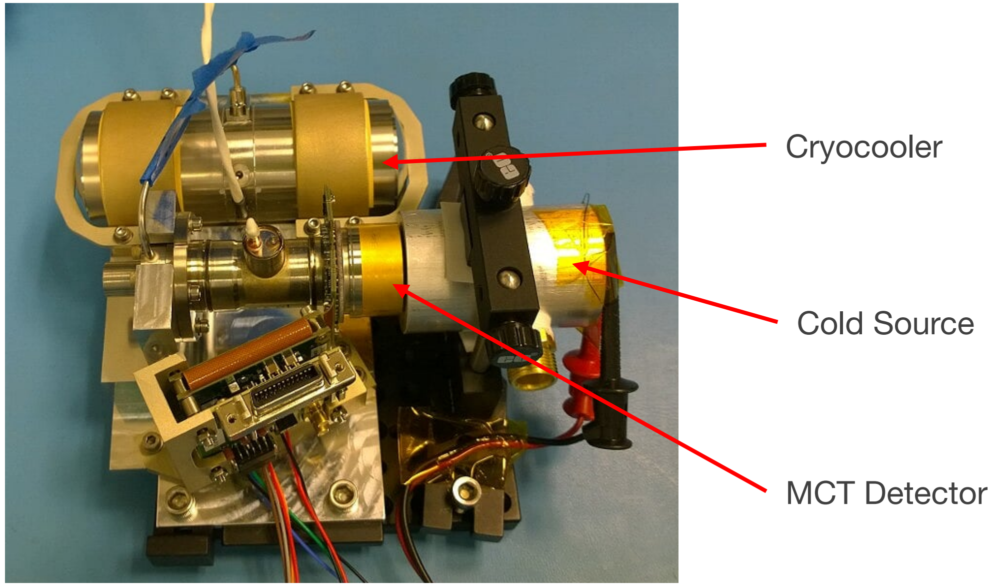

Optic bench displacements [m] at –30°c.
Cutaway shows interior of camera dewar/cold finger.

Optic bench random vibration analysis.



# ARCSTONE: SWIR IDCA Characterization

- **Sensor is uniform**
  - 745 hot/dead pixels
  - Only 2 pixels with no normal surrounding pixels
- **Vertical banding apparent in both dark and light images**
  - Eliminated through dark subtraction




Major Credits:
- IDCA selection/acceptance: Mike Cooney (NASA LaRC)
- Mechanical design: Trevor Jackson (NASA LaRC)
- IDCA characterization: Paul Smith (LASP, CU)

**Integration time from $10^{-4}$ to 3.3 seconds !**

**SWIR IDCA Characterization Conclusions:**

(1) SWIR IDCA *usable at 0.3% - 0.4% uncertainty level:*
- *Primary contributor to uncertainty is variation in the offset value between its measurements (repeatability over a few days).*
- *Offset value variation is a systematic uncertainty that cannot be mitigated through increased averaging, but may be lower during real data collecting operations, e.g. measuring offset before every lunar observation.*

(2) Camera linearity: *better than expected at 0.1% !*

(3) Initial Vibe and TVAC tests: *positive results !*

**FSR IDCA is essentially the same as SWIR IDCA (except for detector, OB filter, and integration time extended to 16 seconds)**

# ARCSTONE IIP: Status and Next Steps

## Status:

- UV-VNIR EDU instrument is complete and radiometrically calibrated
- Fabrication complete for SWIR EDU instrument (assembly is on hold)
- Breadboard VIS instrument ready for field tests
- Design and STOP analysis completed for FSR EDU instrument
- 6U CubeSat accommodation study completed
- Fabrication of FSR instrument is in progress

## Next Steps:

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

Testing ARCSTONE field equipment at NASA LaRC

# ARCSTONE: Calibration of Lunar Spectral Reflectance from Space

- *Please contact me for more information*

*Email: constantine.lukashin-1@nasa.gov*

## 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

# ARCSTONE: Calibration of Lunar Spectral Reflectance from Space

***http://arcstone.larc.nasa.gov***


# THANK YOU !