ARCSTONE: Calibration of Lunar Spectral Reflectance from Space

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

Funded by
NASA ESTO: IIP-QRS-16-0018
NASA SBIR programs: Phase-I & Phase-II

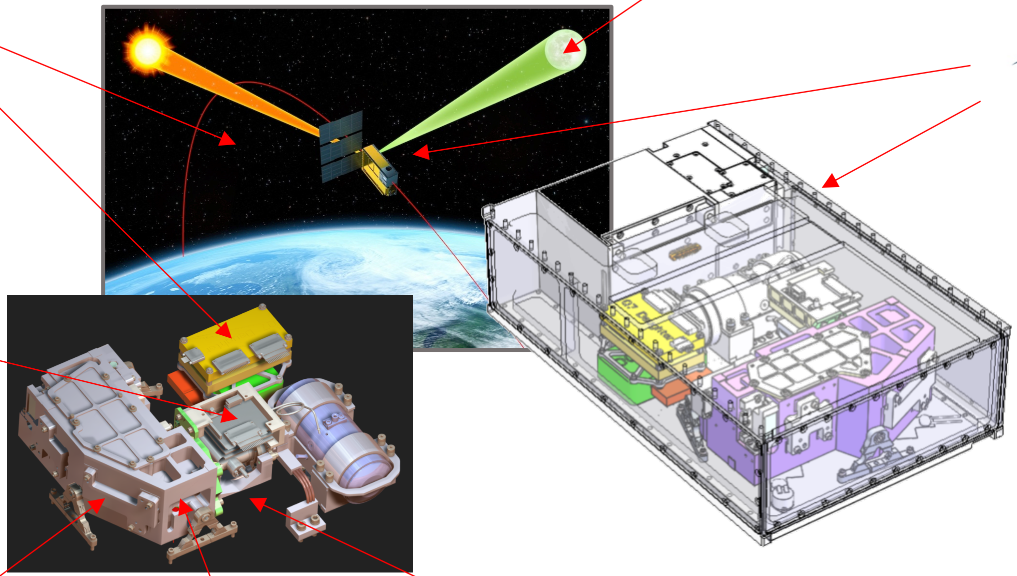
Team and Contributions

NASA LaRC

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

USGS

Lunar calibration approach (ROLO)



BLUE CANYON TECHNOLOGIES

6U CubeSat Bus

LASP

Laboratory for Atmospheric and Space Physics

Instrument concept
Component characterization
Radiometric calibration
Error budget

ARCSTONE TEAM:

- NATIONWIDE COLLABORATION
- Collaboration with NIST & UMBC:
  MLO- and Air-LUSI lunar measurements

NASA GSFC

Optical black coating

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

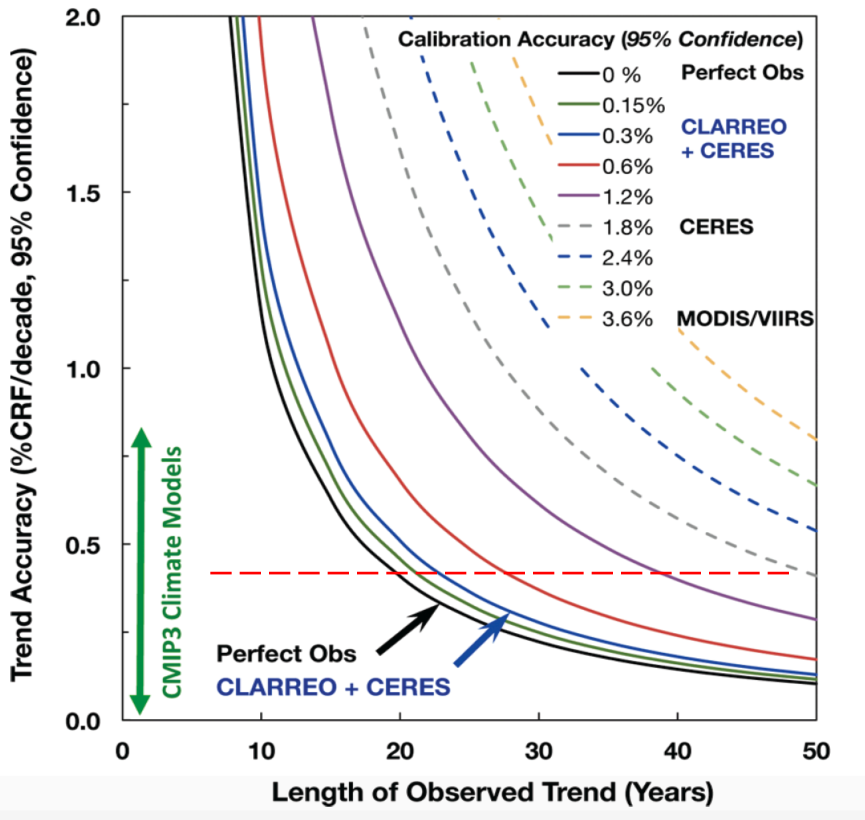
Relevance to NRC Decadal Survey 2017

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

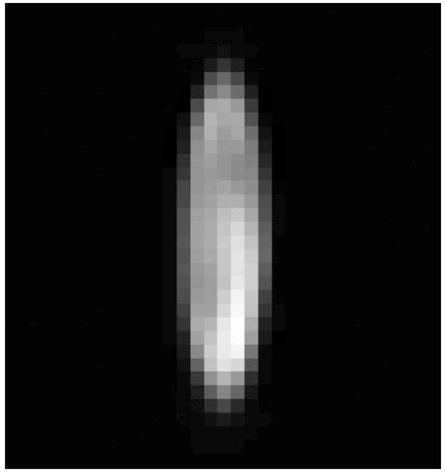
Calibration reference: Empirical model of Lunar Spectral Irradiance (entire disk)

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 !



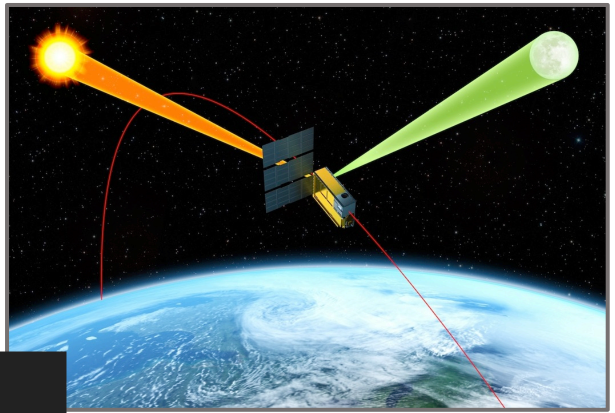
Lunar image by SeaWIFS

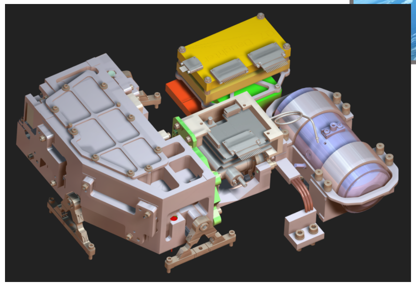
Expected Impacts:
- Quality of data products
- Long-term consistency
- Handling data gaps
- Reduces instrument size, mass, power
- Reduce complexity
- Accurate CubeSat sensors

Objectives

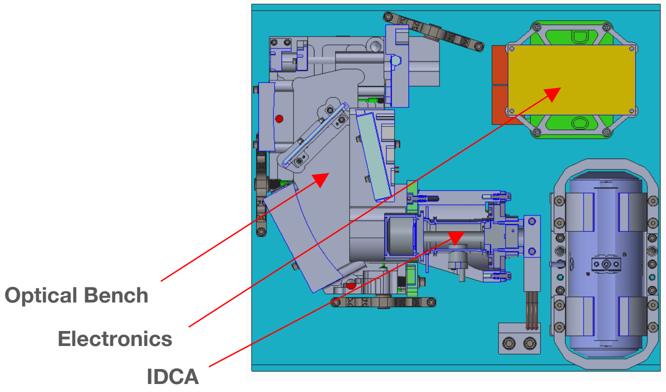
- *To enable on-orbit high-accuracy absolute calibration for the past, current, and future reflected solar sensors* in LEO and GEO* by providing lunar spectral irradiance as function of satellite viewing geometry and specified wavelength.
- To design, build, calibrate and validate a prototype instrument, 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

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

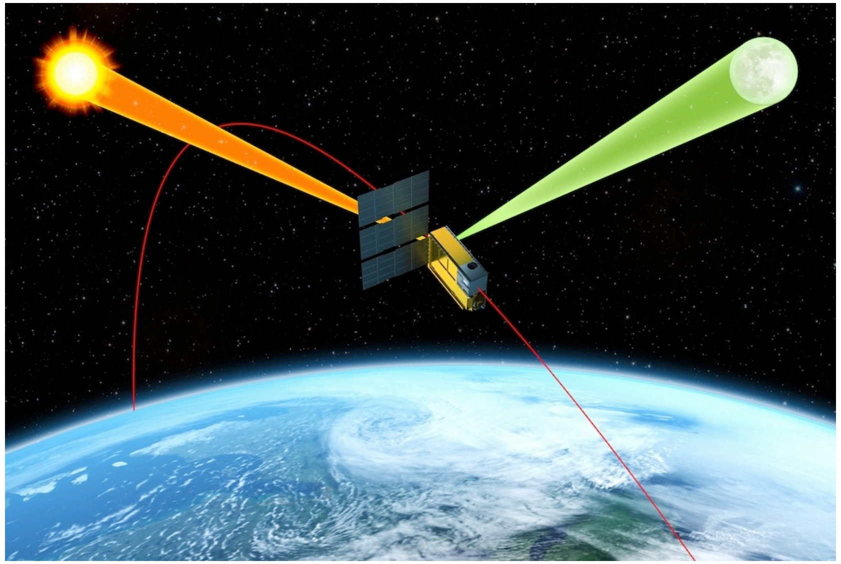
Mission Concept

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^{o} (no scanning !)
- Sun synchronous orbit at 500 – 600 km altitude
- Spectral range from 350 nm to 2300 nm, spectral sampling at 4 nm

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^{o} (1-sigma) in 3 axis
Stability 1 arc-sec over 1 sec

Mission 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

* 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

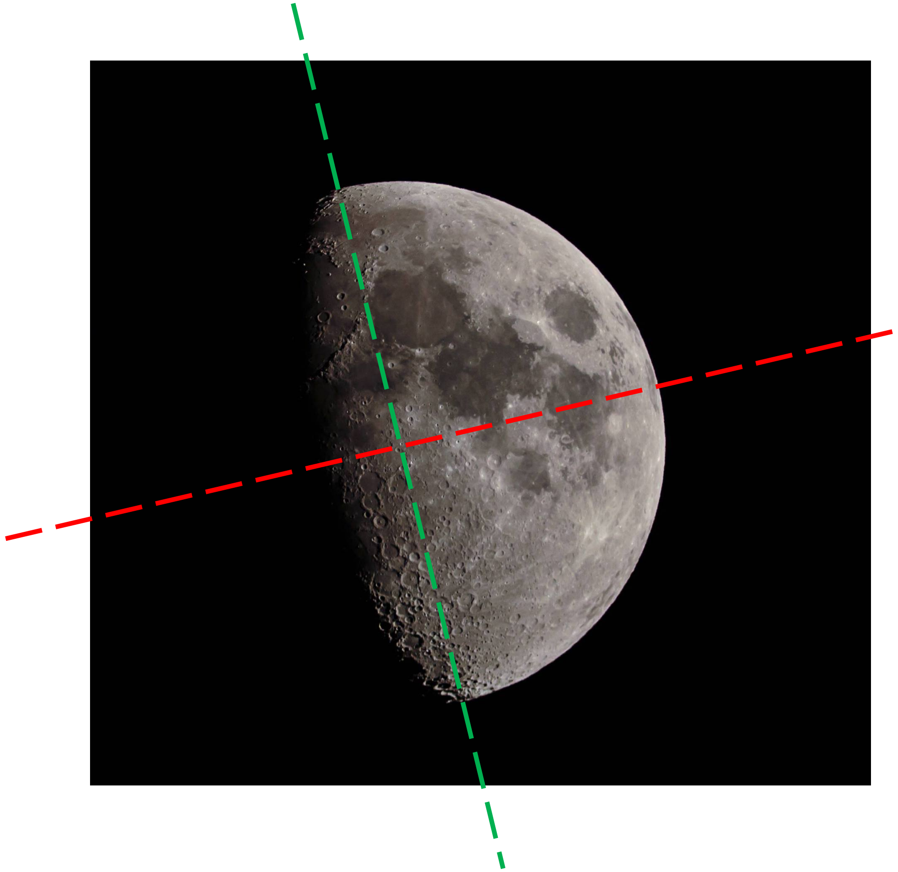
Point at the center of Moon disk and track, time to settle

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]:

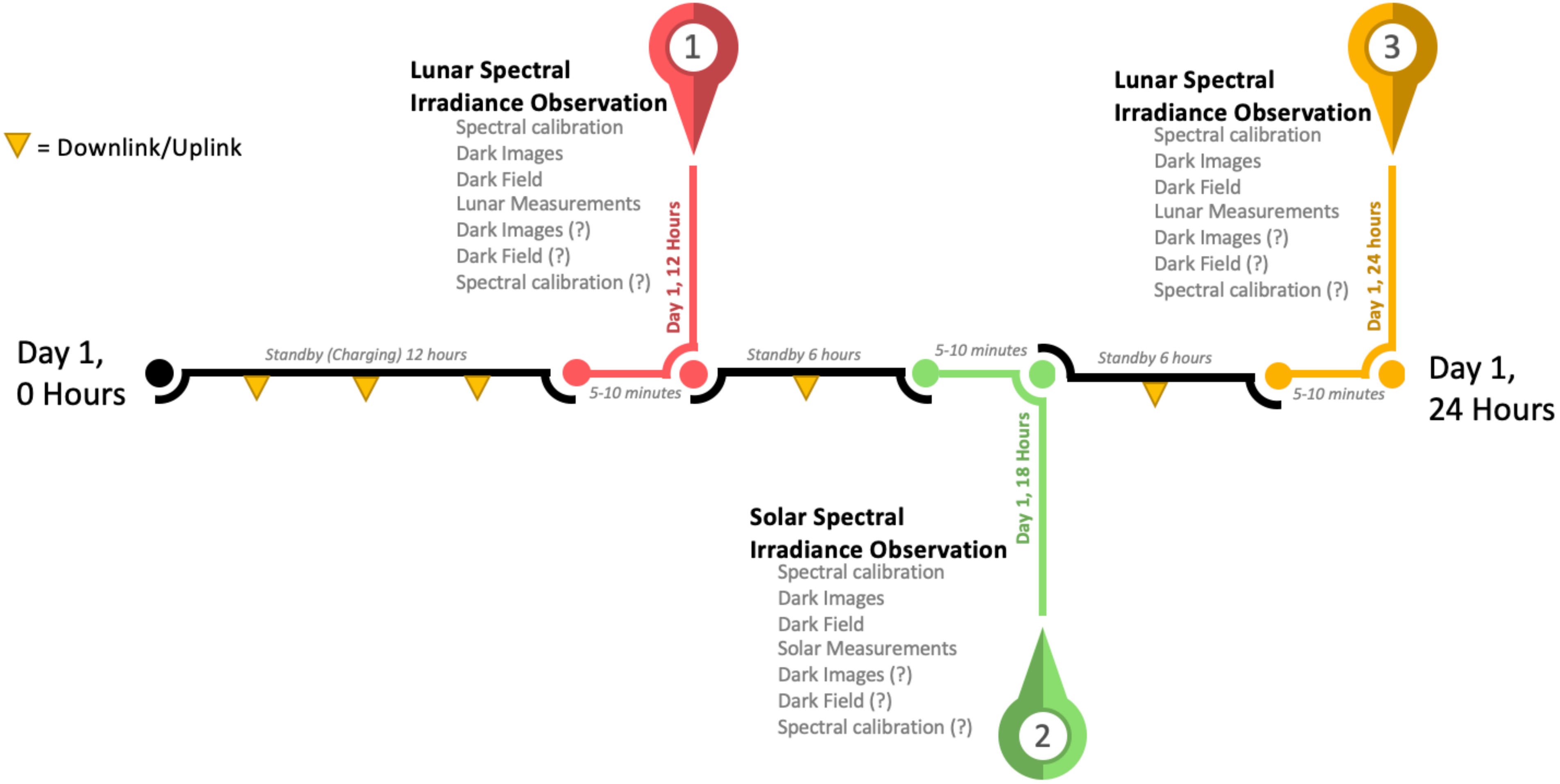
- +/- 0.002º pointing accuracy (1 sigma), 3 axes, 2 trackers
- Tracking stability 1 arcsecond per second, 3 axes, 2 trackers

Two instrument alignment modes:

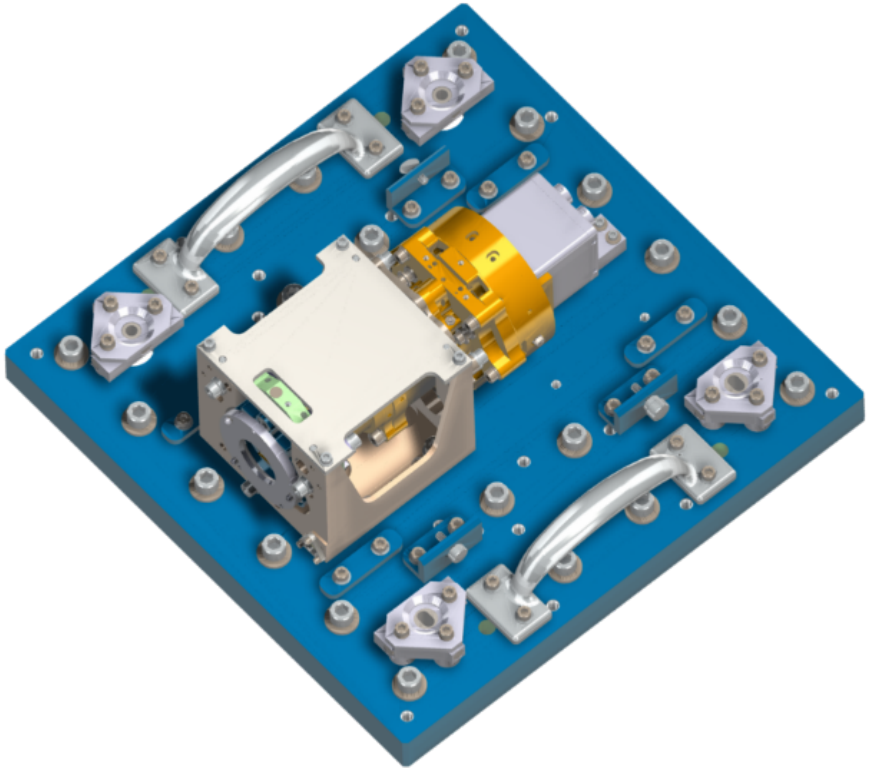
- Orthogonal to A-M-S plane
- Parallel to A-M-S plane

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

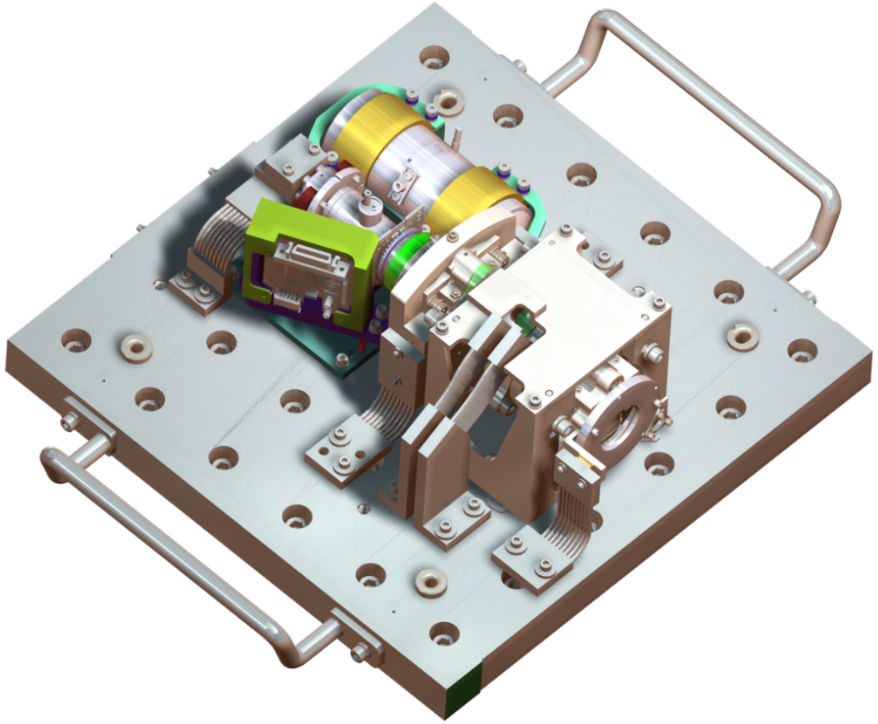
CONOPS: Day in Life



Prototype Instruments Design

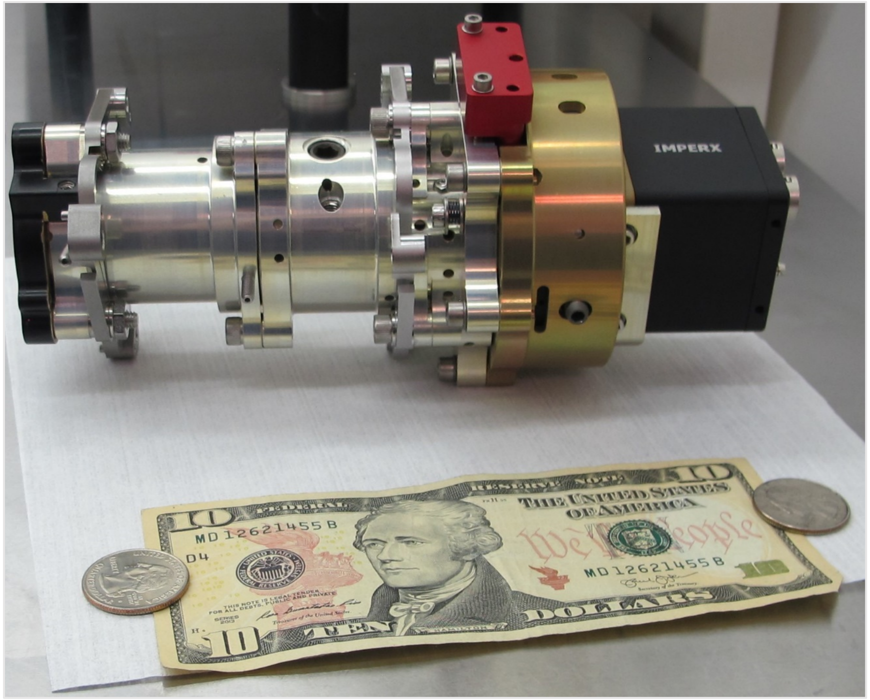


UVVNIR Spectrometer – Ultraviolet Visible Near Infrared 350 – 900 nm
Transmission Grating Spectrometer
Uncooled FPA (CCD) and Optic Train



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

Fabricated and Characterized UVVNIR Instrument

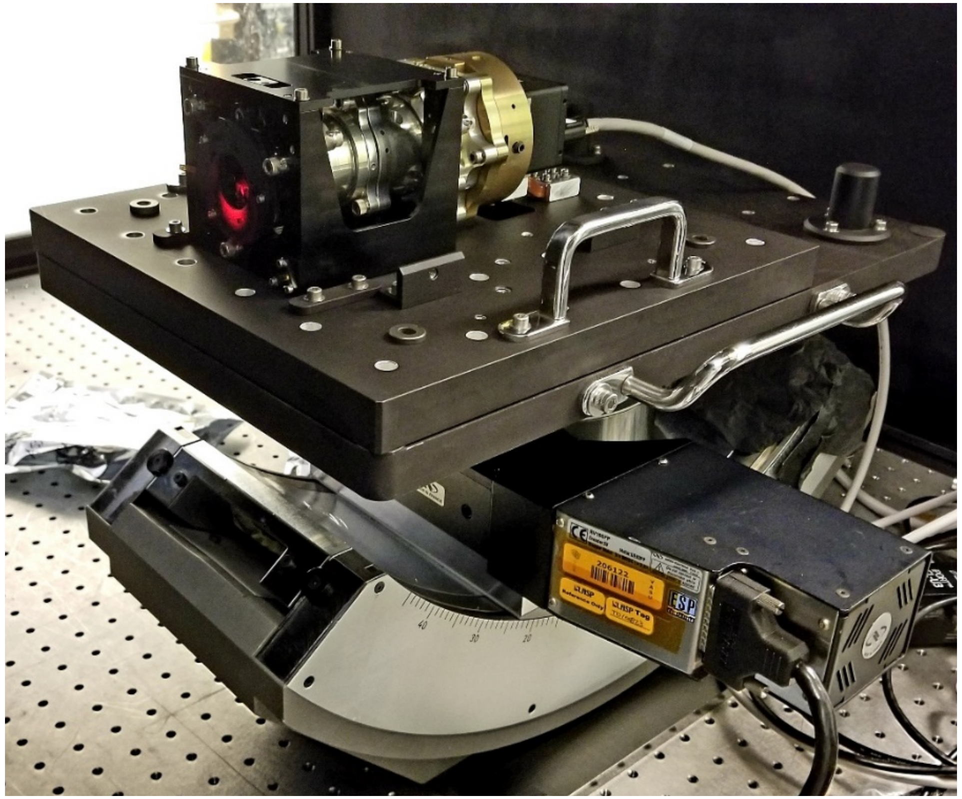


UVVNIR Instrument:

- CCD characterized & env. tested
- Assembly /Alignment completed

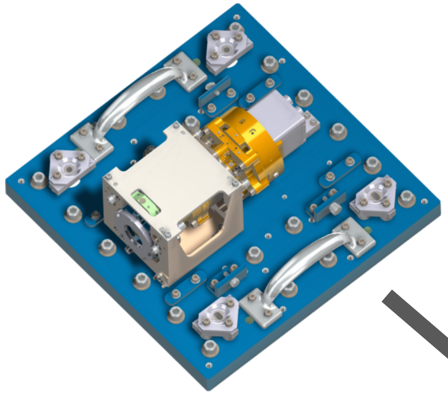
UVVNIR Instrument:

- Characterization at LASP completed
- Uncertainty budget in development

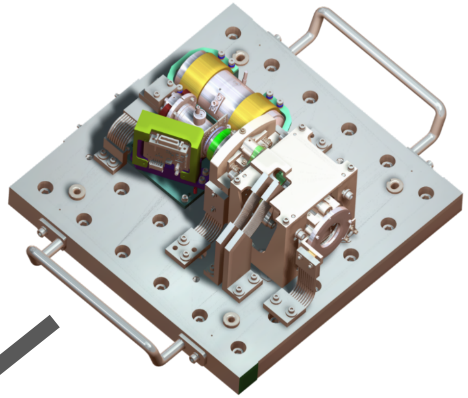


Full Spectral Range Instrument

2017 – 2019 work

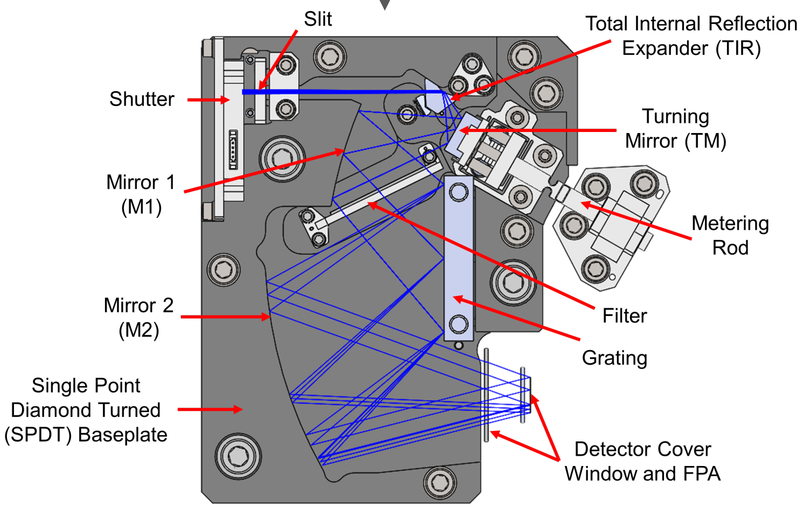


Ultraviolet Visible Near Infrared (UVVNIR)



Short Wave Infrared (SWIR)

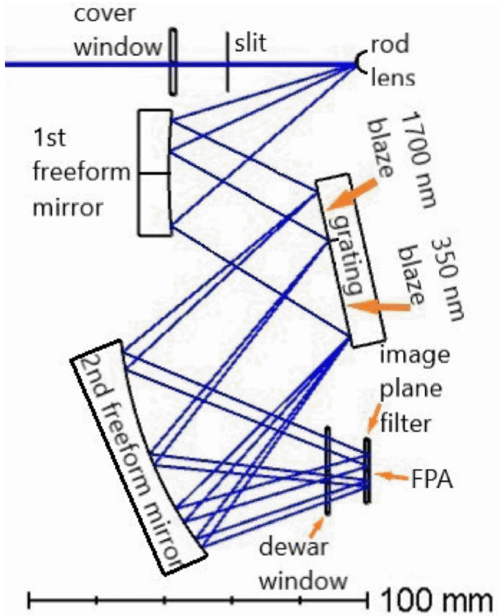
2019 – 2021 work

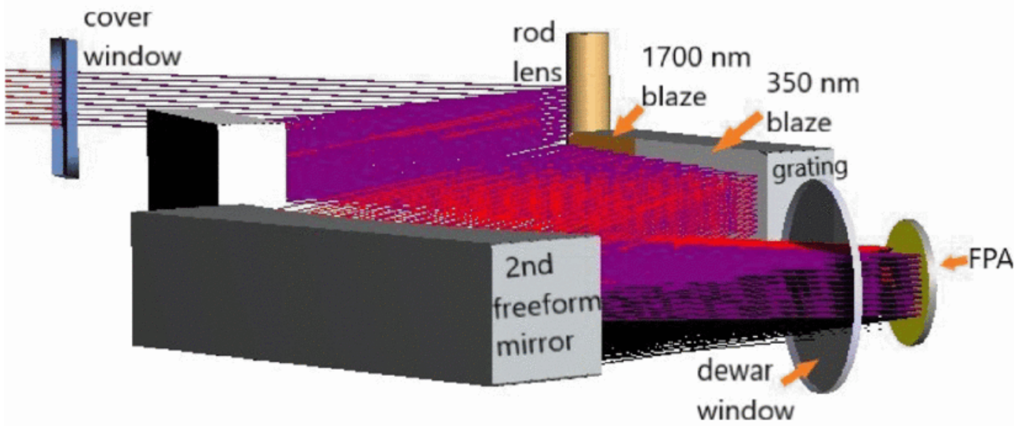


Single channel system:

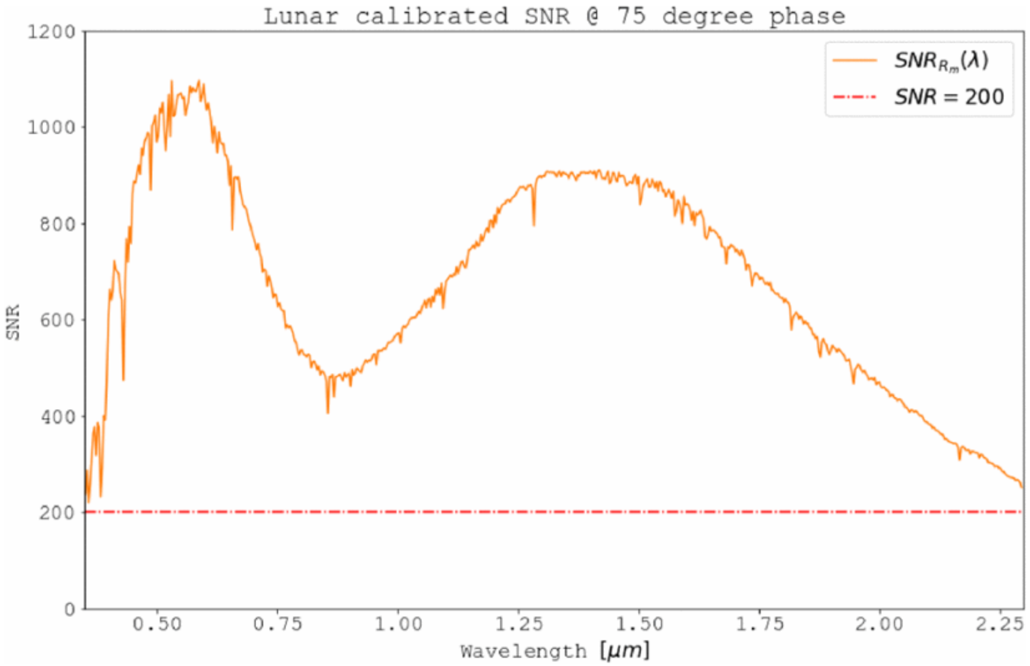
- ***Thinned MCT detector***
- ***350 – 2300 nm wavelength range***

Full Spectral Range Instrument Design



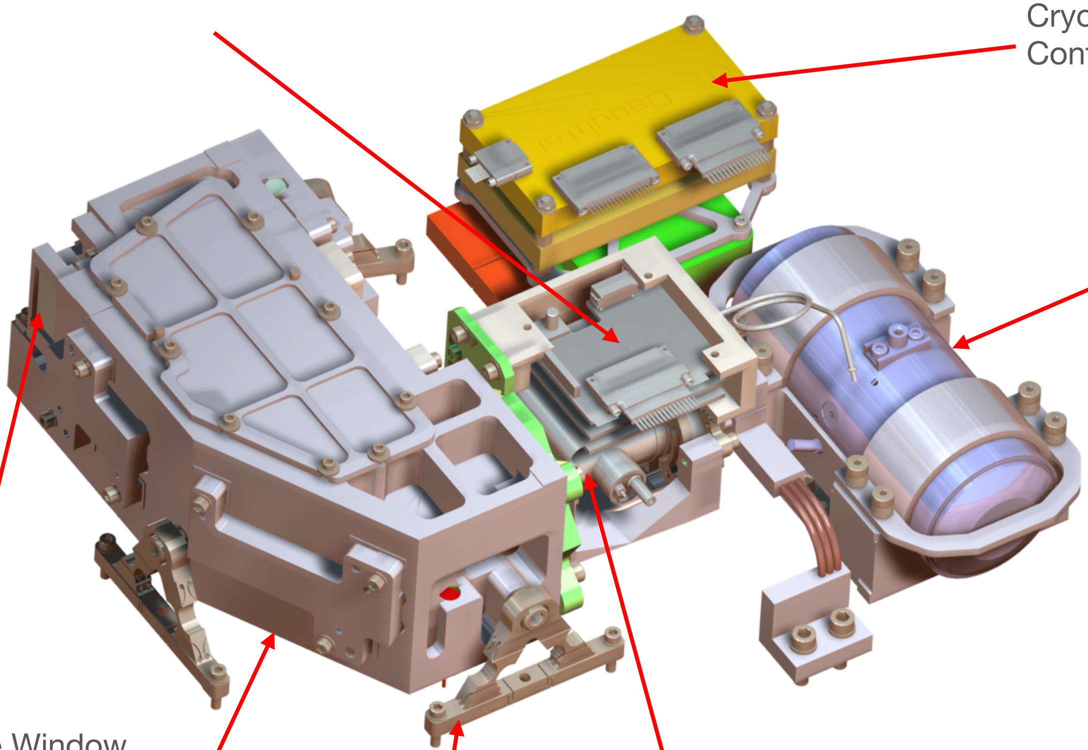


Raytrace and optics design of the ARCSTONE FSR reflective spectrograph with 350 – 2300 nm passband.



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

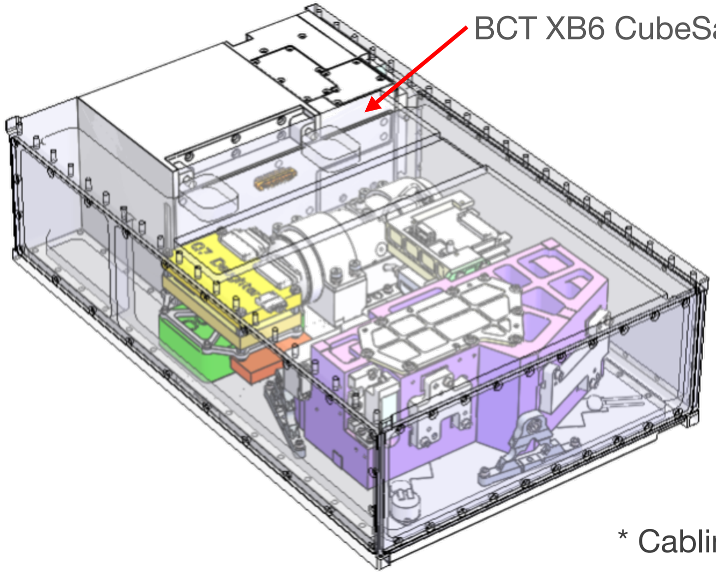
Instrument in Fabrication



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*)

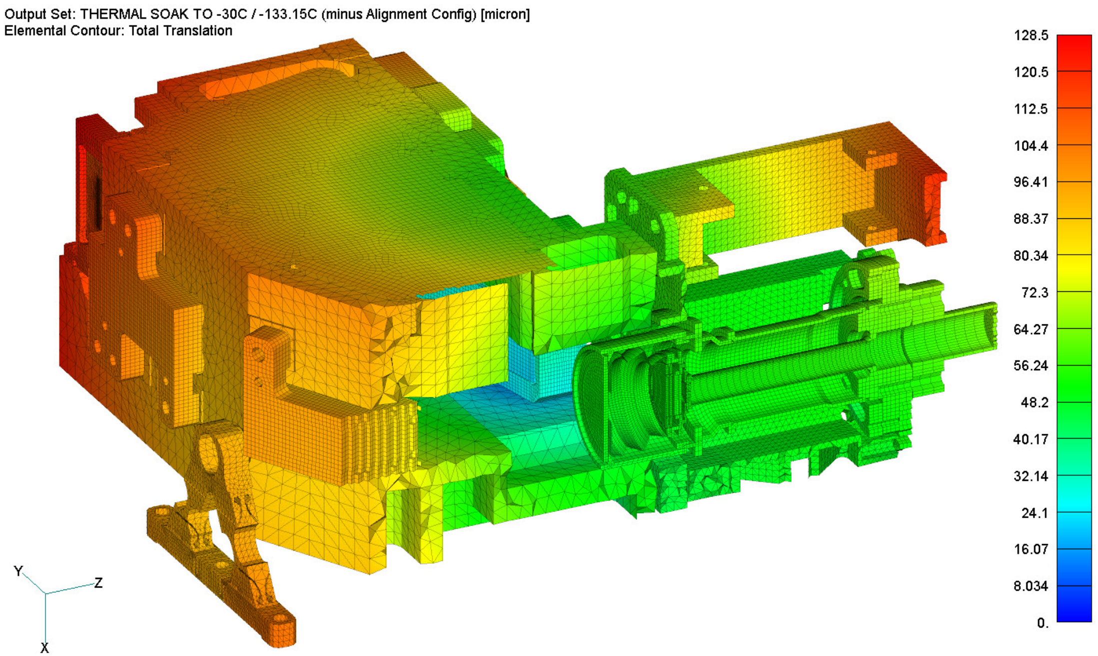
Power (all worst cases):
Science Mode: 23.83 W (*118 W peak allowable*)
TX Mode: 34.07 W
Stand By Mode: 15.5 W



* Cabling is not shown

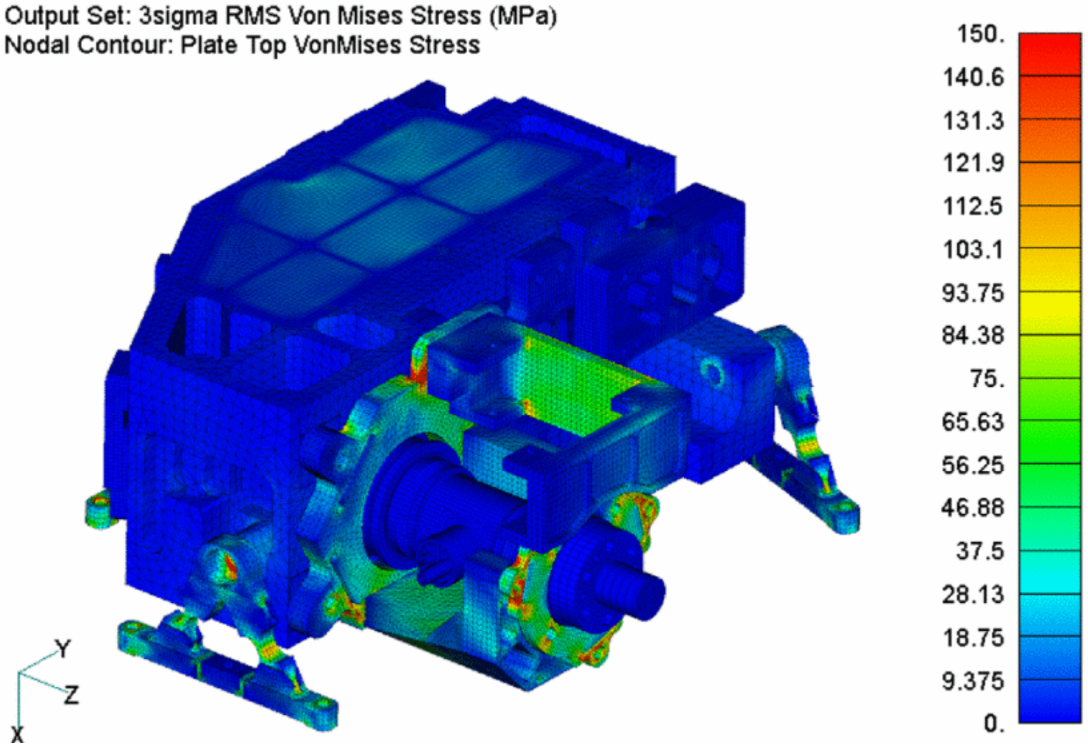
Instrument Design Analysis

Performed Analysis:
STOP, Thermoelastic, Random Vibe

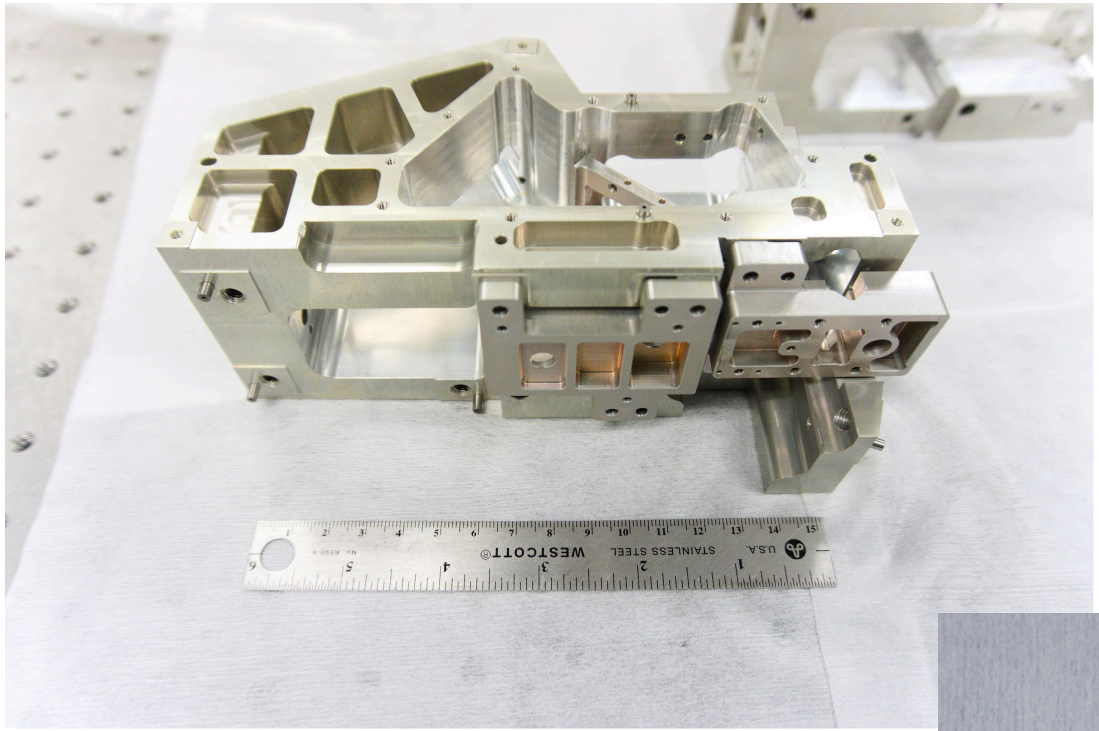


Optic bench displacements [microns] at –30°c.
Cutaway shows interior of camera dewar/cold finger.

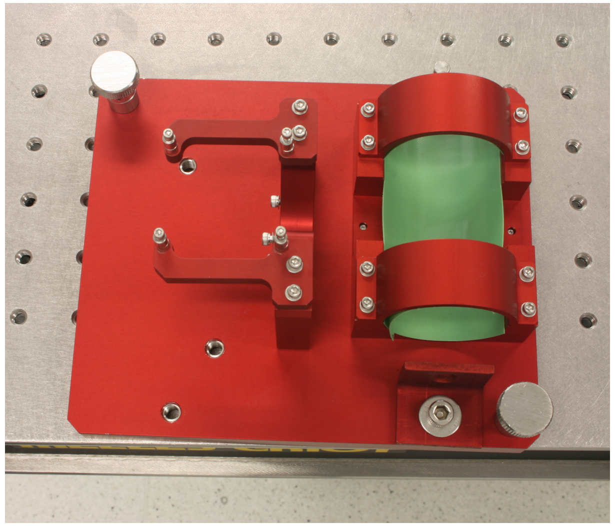
Optic bench random vibration analysis.



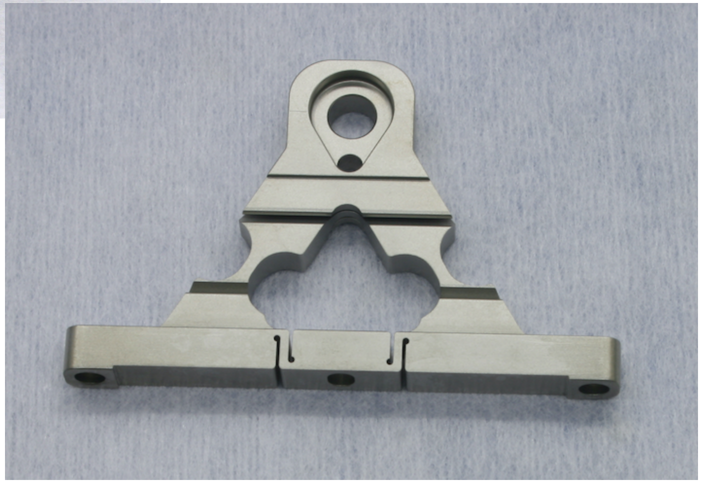
Fabrication (complete in November 2020)



Optics bench acceptance assembly
These parts are at GSFC for optical black coating



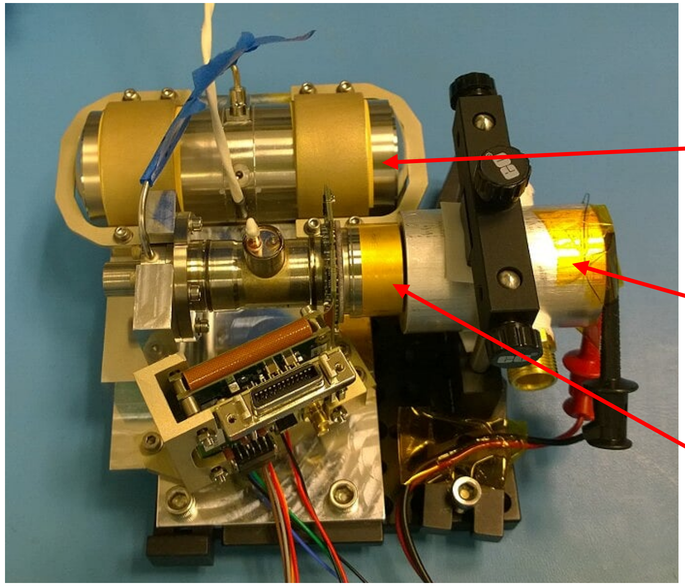
FSR IDCA mount for testing and characterization



Mount Flexure

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)

Status and Next Steps

Status:

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

Next Steps:

- Characterize FSR IDCA (February 2021)
- Assemble FSR instrument (March 2021)
- Calibrate FSR instrument (June 2021)
- Field-test FSR instrument with Sun and Moon (TRL5, July 2021)
- Submit NASA InVEST proposal in FY21

Testing ARCSTONE field equipment at NASA LaRC

Lunar Calibration Approach and ARCSTONE

Recent Publications:

- *Please contact me for more information*
  Email: constantine.lukashin-1@nasa.gov

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

NESC Academy Webcast on ARCSTONE available online at

https://mediaex-server.larc.nasa.gov/Academy/Play/ed1d00768a15486096edf4dac6d8cc7b1d

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

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ARCSTONE

Achieving Instrument High Accuracy In-Orbit

One of the most challenging tasks in remote sensing from space is achieving required instrument calibration accuracy on-orbit. The Moon is considered to be an excellent exoatmospheric calibration source. However, the current accuracy of the Moon as an absolute reference is limited to 5 - 10%, and this level of accuracy is inadequate to meet the challenging objective of Earth Science observations. ARCSTONE is a mission concept that provides a solution to this challenge. An orbiting spectrometer flying on a small satellite in low Earth orbit will provide lunar spectral reflectance with accuracy sufficient to establish an SI-traceable absolute lunar calibration standard for past, current, and future Earth weather and climate sensors.

LEARN MORE

The ARCSTONE observatory is shown in low Earth orbit with the spectrometer viewing the Sun and Moon. The spacecraft rotates in order to view the Moon or the Sun.

"The Moon is available to all Earth-orbiting spacecraft at least once per month, and can be used to tie together the sensor radiance scales of all instruments participating in lunar calibration without requiring near-simultaneous observations."

– HUGH KIEFFER & TOM STONE

THANK YOU !