ARCSTONE: Calibration of Lunar Spectral Reflectance from Space

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Co-Investigators:

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

NASA LARC & GSFC

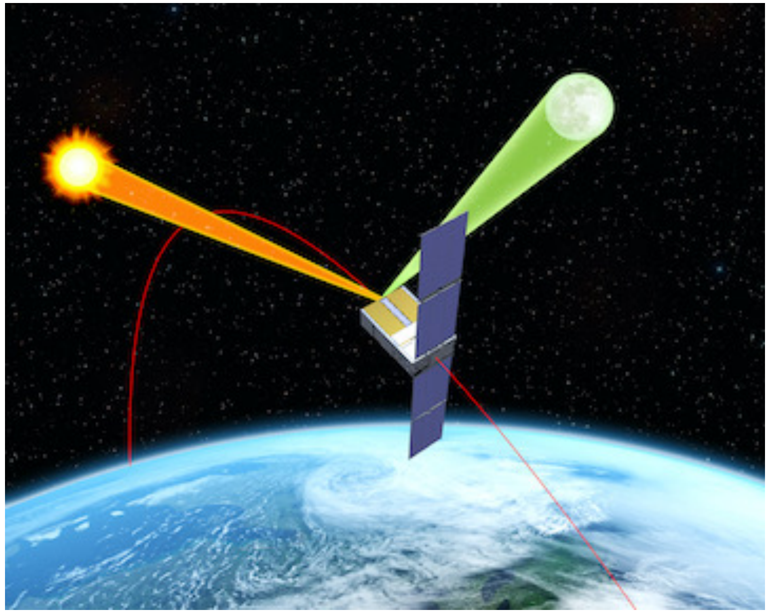
ARCSTONE InVEST: Technology Demonstration in Space

Key Parameters:

- Data to collect: Lunar spectral irradiance every 12 hours
  For Lunar Phase Angles < 90° (2 weeks out 4) required
  For Lunar Phase Angles < 135° (3 weeks out of 4) desired
- Data to collect: solar signal for calibration (entire disk)
- Combined uncertainty of lunar reflectance < 0.5% (k=1)
- Spectrometer with single-pixel field-of-view about 0.7°
- Spectral range from 350 nm to 2300 nm, spectral sampling at 4 nm
- Sun synchronous orbit at ~550 altitude, 6 months flight time
- Launch by CSLI

Key Technologies to Enable the Concept:

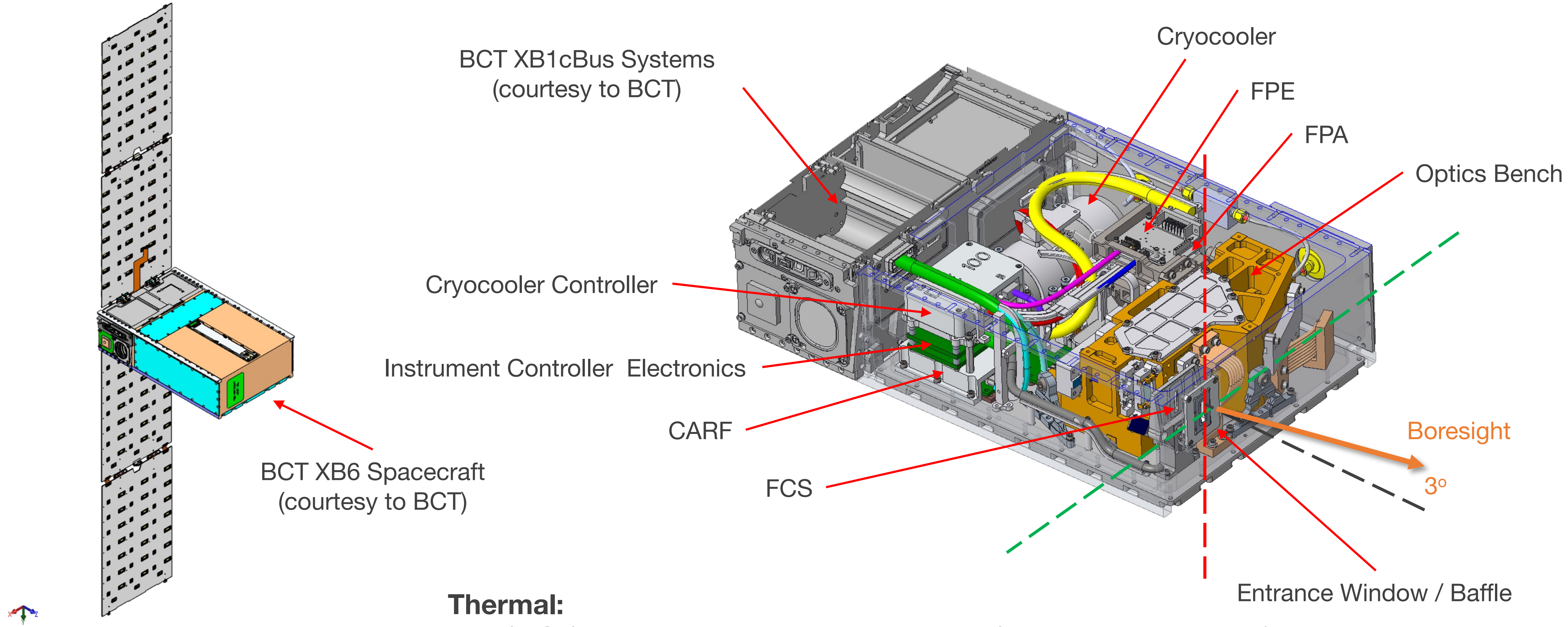
- Approach to orbital calibration via referencing Sun (TSIS measurements):
  Demonstration of lunar and solar measurements with *the same optical path using integration time to reduce solar signal*
- Pointing ability of spacecraft now permits obtaining required measurements *with instrument integrated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

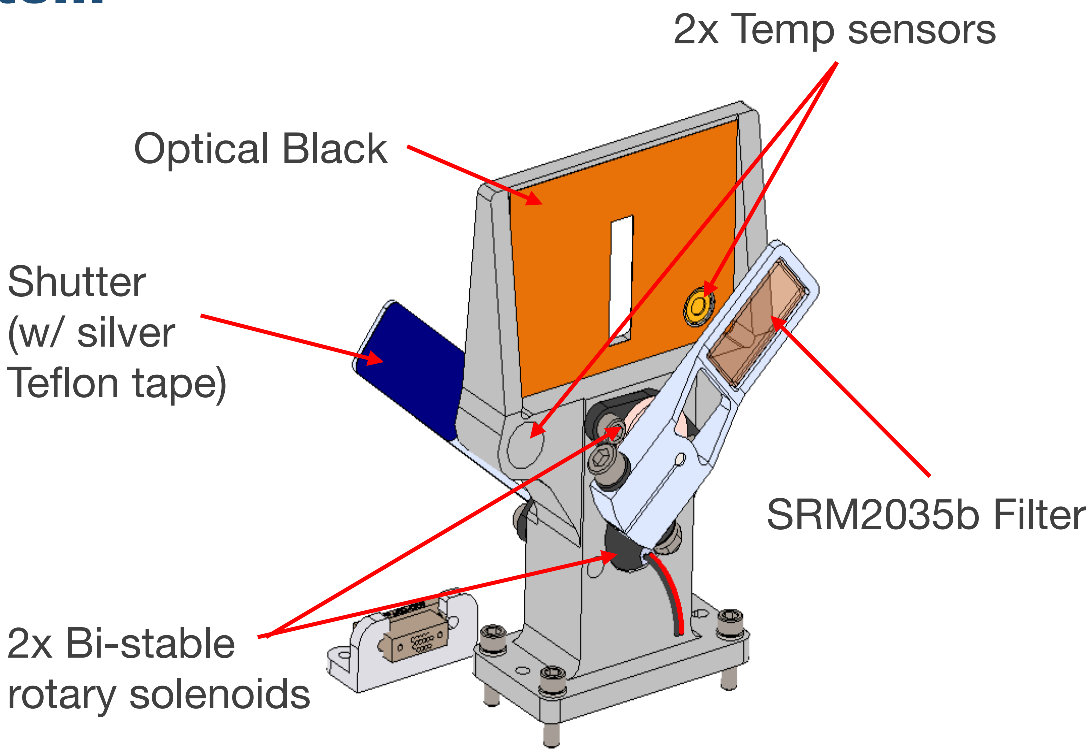


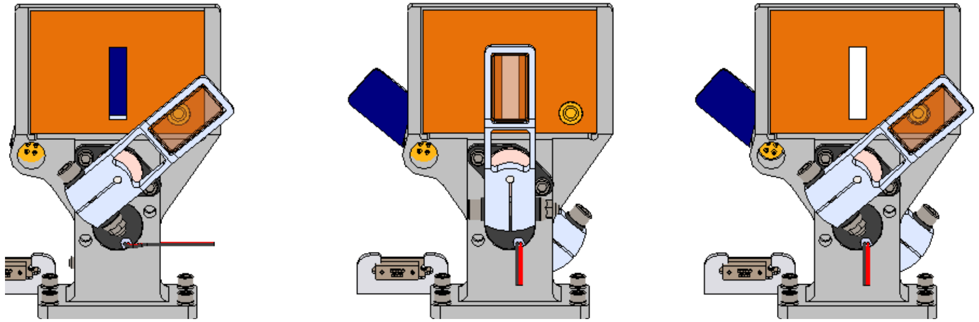
Thermal:

- FPA (MCT) operational temperature is 140K (inside vacuum dewar)
- Optical bench operational temperature is -3°C (current approach -- heaters)

ARCSTONE InVEST: Flight Calibration System

- SRM2035B filter used for on-orbit spectral calibration.
- Shutter used for "dark frames" before & after each solar and lunar data collection.
- Temperature sensors for filter and shutter used to detect position of each, in addition to temperature measurement.
- LASP is responsible for design, drawing release, fabrication, assembly, and sub-assembly testing.
- Optical-black coated aperture panel reduces stray light.





Dark, Filter, and Open positions (L to R).

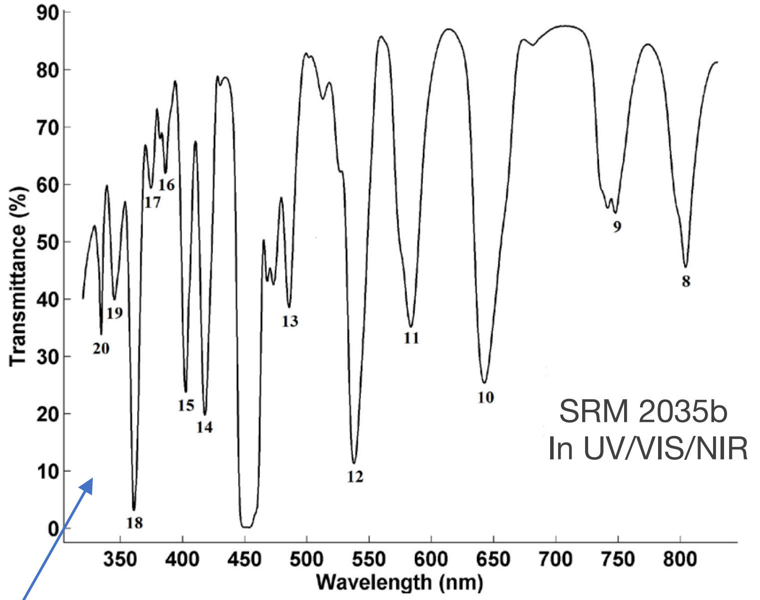
ARCSTONE InVEST: In-Orbit Spectral Calibration

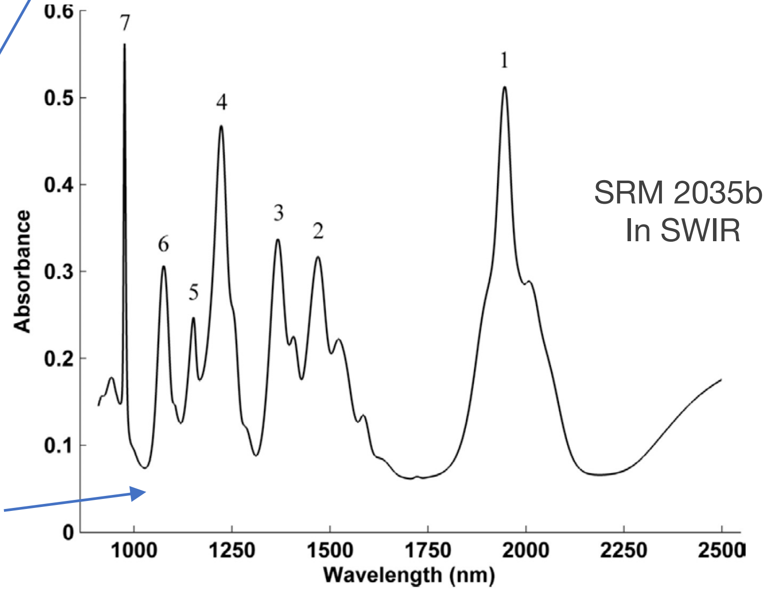
Spectral Calibration:

- Sun or Moon views with NIST filter (SRM 2035b) in FCS position
- Preformed in ”lunar” and “solar” thermal regimes
- Included into Moon and Sun observation sequences

- Space heritage (Japan on ISS)
- Demonstrated with ARCSTONE UVVNIR prototype

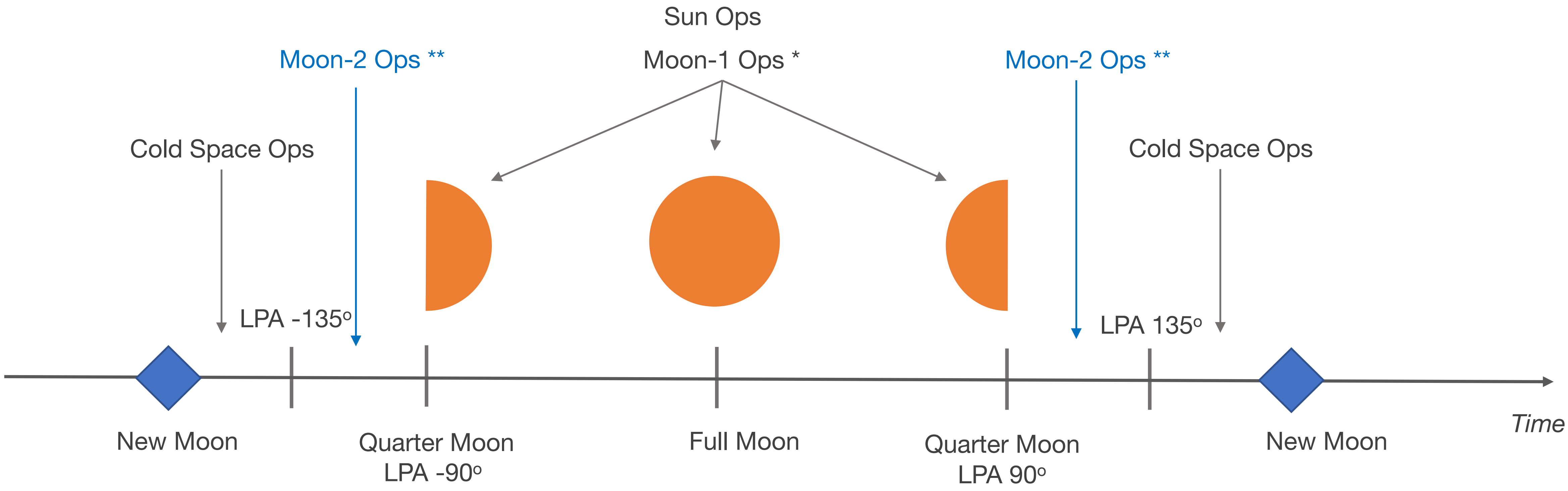
- Approach: take measurements of Sun and Moon with and without SRM 2035b filter, take ratio and analyze spectral features.





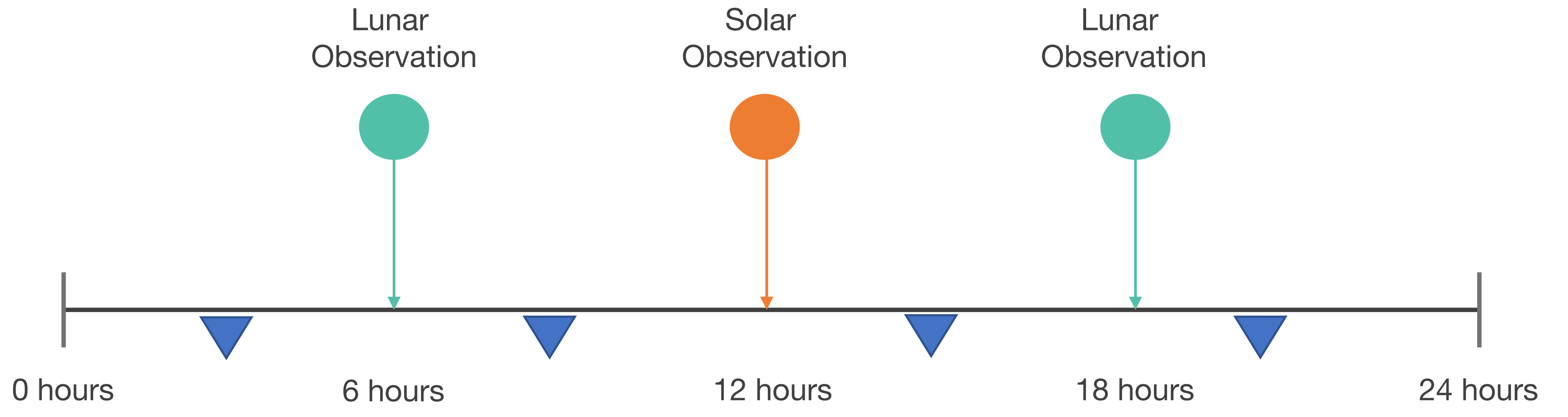
NIST Standard: 0.1 nm accuracy

MITL: Month In the Life (lunar month from new Moon → next new Moon)



* *Moon-1 Ops: requirement*
** *Moon-2 Ops: goal*

ARCSTONE InVEST: Day In The Life (DITL) for Nominal Required Operations



= Downlink / Uplink

Lunar Observation Sequence:
- Dark Frames
- Lunar measurements
- Spectral Calibration
- Int. time = 16 sec
- Detector temp. at 140K

Solar Observation Sequence:
- Dark Frames
- Solar measurements
- Spectral Calibration
- Int. time = 40 micro sec
- Detector Temp. at 140K

- The timing of lunar and solar observations has margin: +/- 1 hour
- Safe operations mode due to Space Radiation hazard overrides all modes

ARCSTONE InVEST: Data Products

Product	Contents	Level	Rate / Day
Bus data	Bus time-ordered telemetry	Level-0	210 MB
Instrument Engineering Data	Instrument engineering time-ordered telemetry	Level-0	5 MB
Calibration Data	Sun, dark, cold, spectral calibration time-ordered telemetry	Level-0	60 MB
Lunar Data	Moon time-ordered telemetry	Level-0	15 MB
Lunar Measurements	Calibrated lunar spectral reflectance and irradiance	Level-1	40 MB

- ARCSTONE Level-1 data product will include:
  (1) Lunar spectral reflectance
  (2) Lunar spectral irradiance

- Data Analysis and Validation:
  - Focus on measurement uncertainty for lunar reflectance and irradiance
  - Lunar modeling for data validation

ARCSTONE InVEST: Project Status & Timeline

- The ARCSTONE InVEST project started in August 2021
- Launch by CSLI into SSO with 550 km altitude
- Flight time 6 months, includes data analysis and validation
- Payload Analysis and Accommodation Review (PAR, CDR-like) in June 2022
- Fabrication Phase kick-off in August 2022 ← Currently in Fabrication Phase
- Payload Pre-Assembly Review (PPAR) on March 1, 2023
- Payload assembly: Spring/Summer 2023
- System Integration: Summer 2024
- Projected launch date: Fall 2024 (not manifested, CSLI dependent)

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

Contact me for more information:

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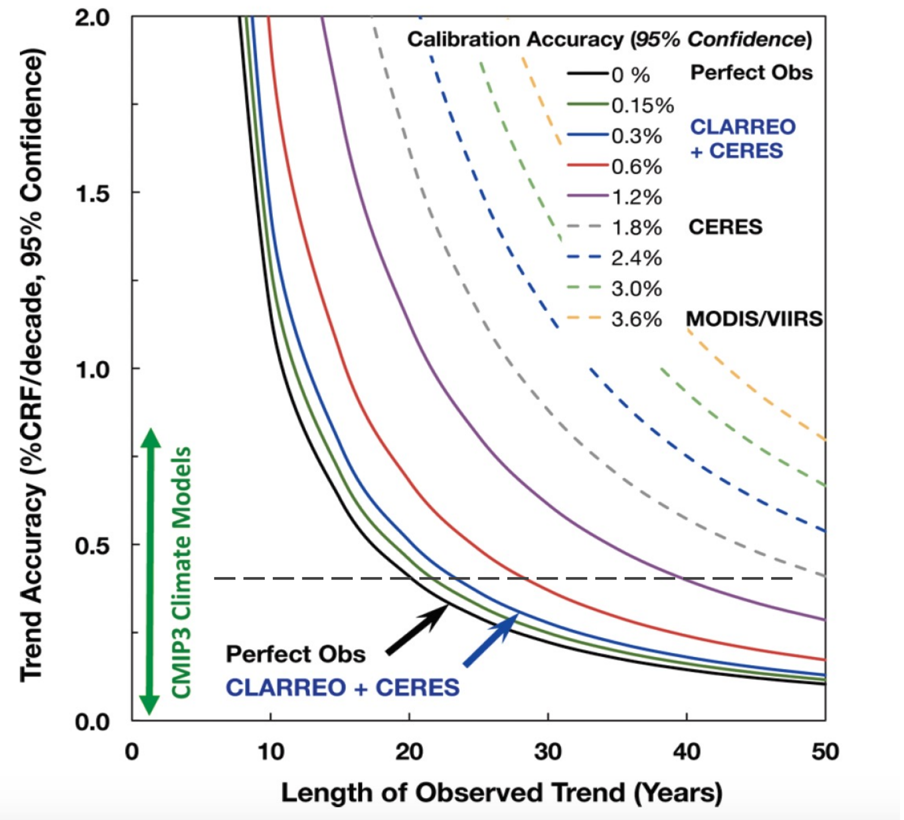
THANK YOU !

BACKUP SLIDES

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., 2022
- **High absolute accuracy is required to mitigate/bridge gaps in long-term observation records: e.g. SeaWIFS/PACE, ERB**



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).

Measurement accuracy is foundation of experimental science and its value:
- **Climate science, records, and modeling**
- **Land and ocean environmental science**

ARCSTONE Objectives

Long-term Objective:

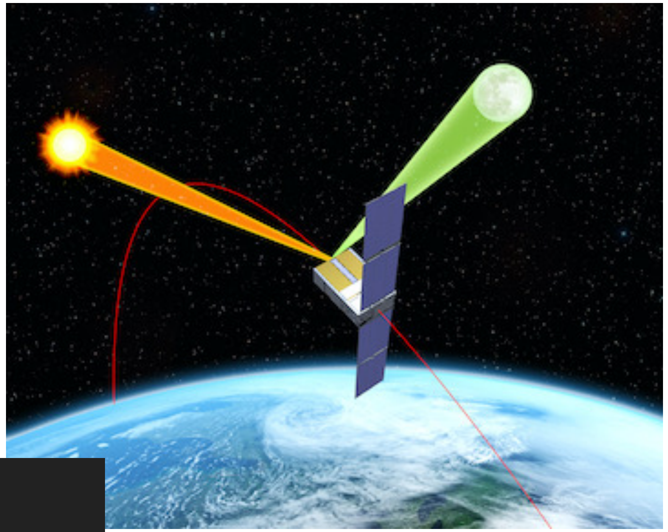
- *To enable on-orbit high-accuracy absolute calibration for the past, current, and future reflected solar sensors* in LEO and GEO by providing lunar spectral irradiance as function of satellite viewing geometry and specified wavelength.

IIP Objective (complete):

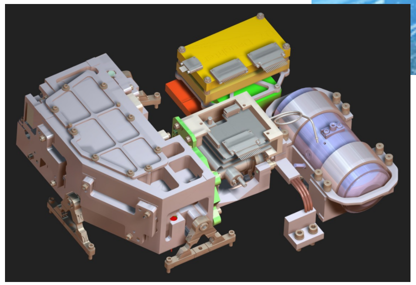
- To design, build, calibrate and validate a prototype instrument, demonstrate *form-fit-function for a 6U observatory with compliance in size, mass, power, and thermal performance*.

InVEST Objective:

- *To demonstrate high-accuracy measurements of lunar spectral reflectance, < 0.5% (k=1), by building a flight instrument, integrating payload with 6U CubeSat, operating it in LEO for 6 months, validation and data analysis.*



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



ARCSTONE payload concept in 2019

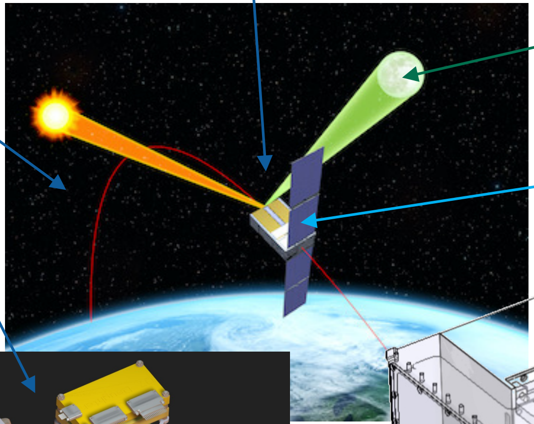
$TRL_{current}$ = 5 (IIP) TRL_{out} = 7 (InVEST)

ARCSTONE InVEST: Team

LaRC

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

CubeSat Launch Initiative



USGS

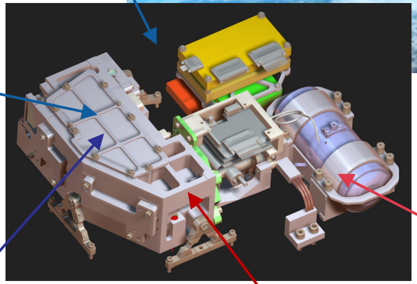
Lunar calibration
approach and
validation analysis

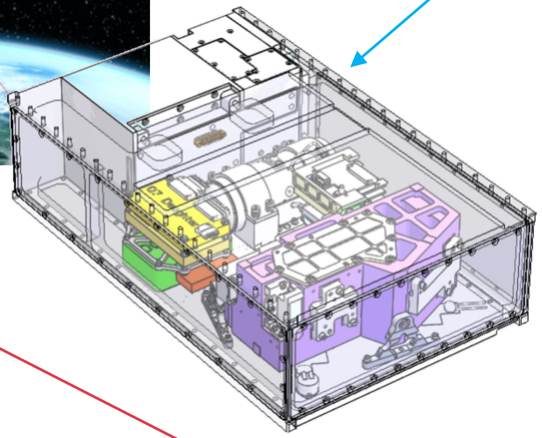
BLUE CANYON TECHNOLOGIES

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

GSFC

Optical black coating





SSAI

AWS Cloud Architecture
Science Planning System
Sub-contracts Management

LASP

Laboratory for Atmospheric and Space Physics

Flight Calibration System
IDCA characterization
Instrument calibration
Uncertainty budget
FCS (3-position shutter)

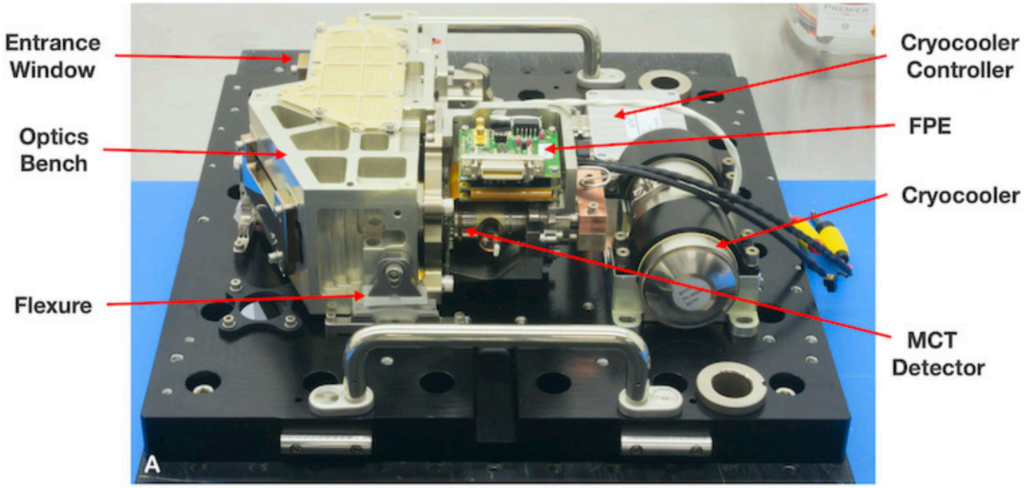
RESONON

Opto-mechanical design
Radiometric modeling
Instrument fabrication
Instrument assembly
Functional testing

quartus ENGINEERING

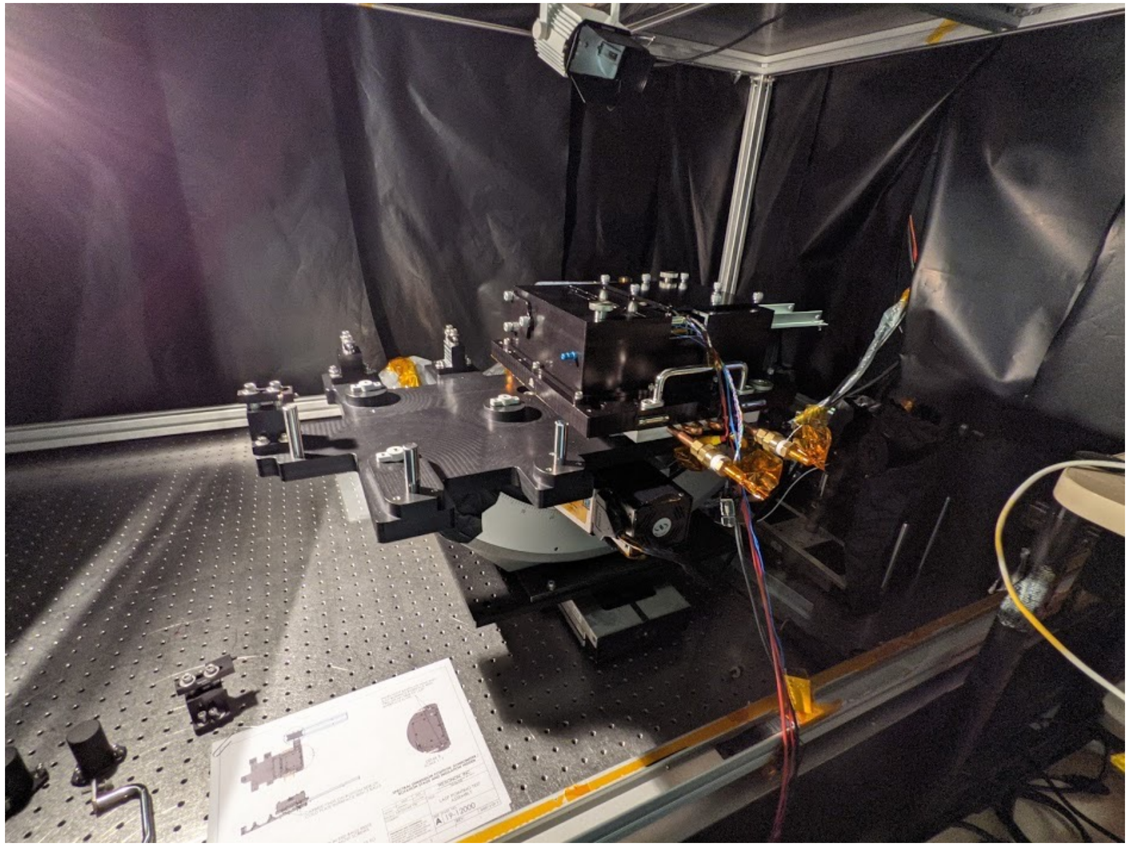
Payload Analysis
Input to payload design
Flexure design

ARCSTONE EDU: IIP project completed in July 2021



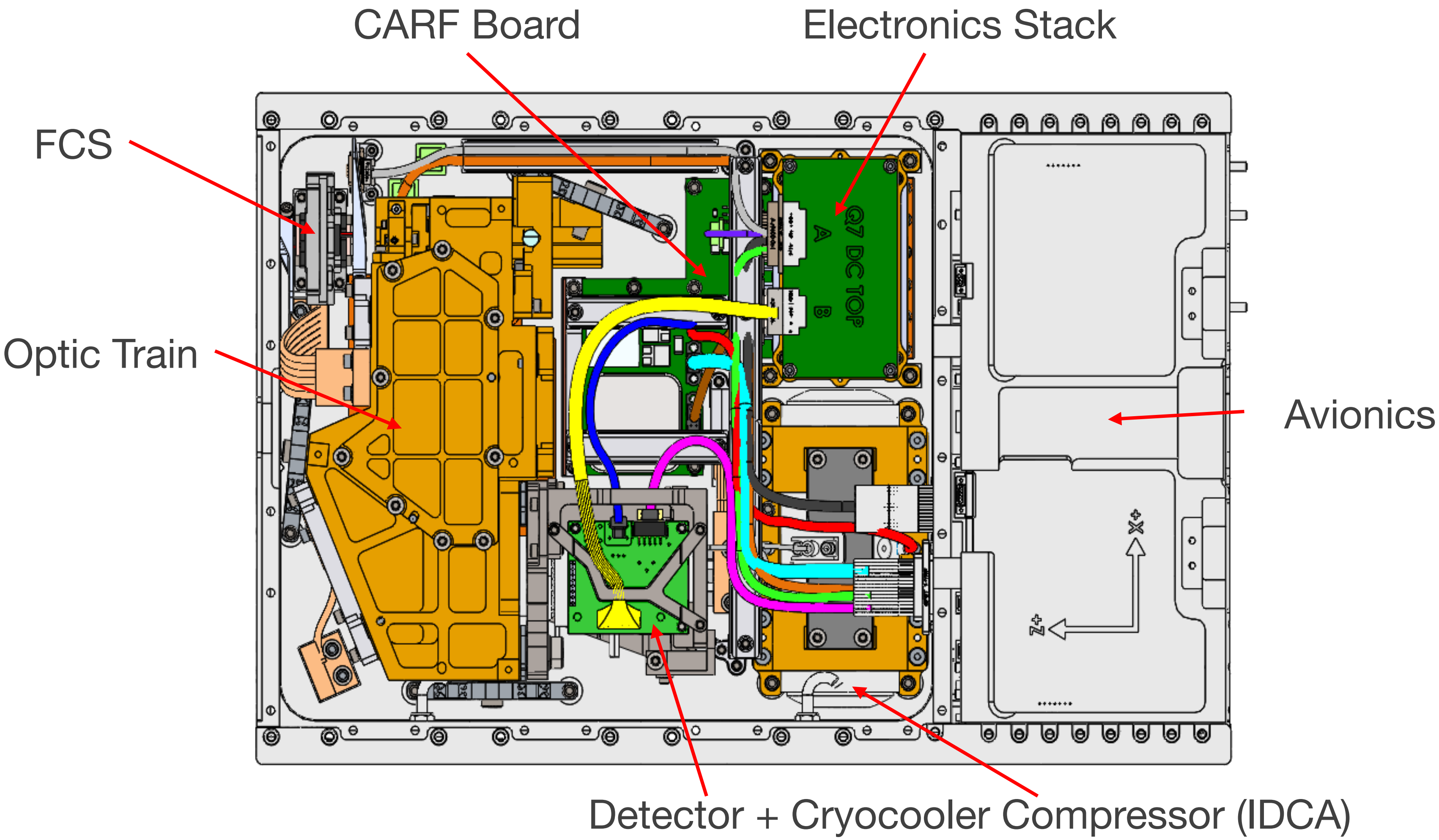
ARCSTONE EDU instrument and components

- ARCSTONE EDU assembled and aligned
- ARCSTONE EDU characterized
- Confirmation of athermal performance



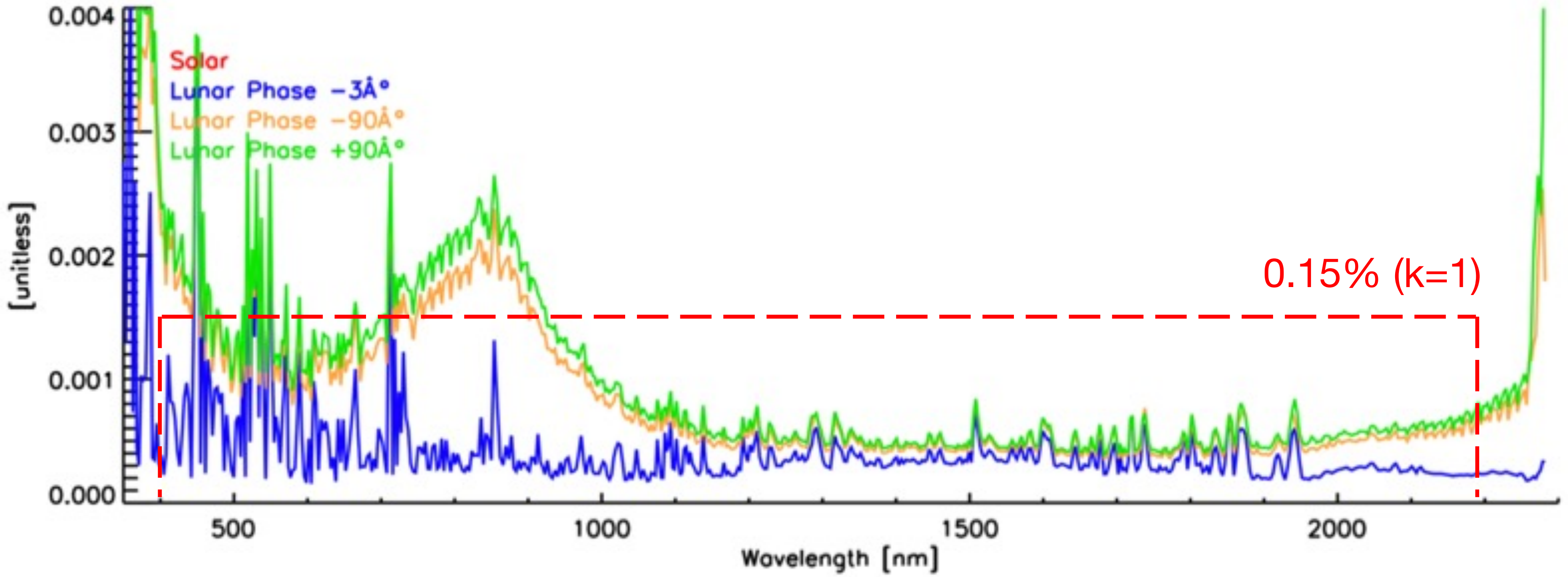
ARCSTONE EDU at LASP CU-Boulder characterization facility.

ARCSTONE InVEST: Payload Layout in Bus



Payload accommodated in 4U of spacecraft.

ARCSTONE IIP: Uncertainty Budget from Instrument EDU Results from LASP (characterization in laboratory)



- Lunar reflectance uncertainty budget for ARCSTONE EDU instrument (IIP).
- Developed by team at LASP CU-Boulder.
- *Requirement (baseline): < 0.5% (k=1) in 400 nm to 2200 nm spectral range*

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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