ARCSTONE: Calibration of Lunar Spectral Reflectance from Space

ESTO InVEST-20-001

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4 – Blue Canyon Technologies, Inc., Boulder, CO
5 – USGS, Flagstaff, AZ

Moon: Accurate Source for Calibration On-orbit

For a small investment → a cost saving, enabling, and permanent solution

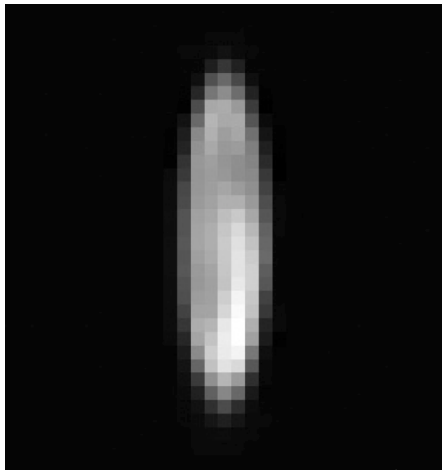
Calibration reference: Empirical model of Lunar Spectral Irradiance (entire disk)

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

- **Accuracy of current Lunar Model (ROLO): 5 – 10%**

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**

ARCSTONE Objectives

Long-term Objective:

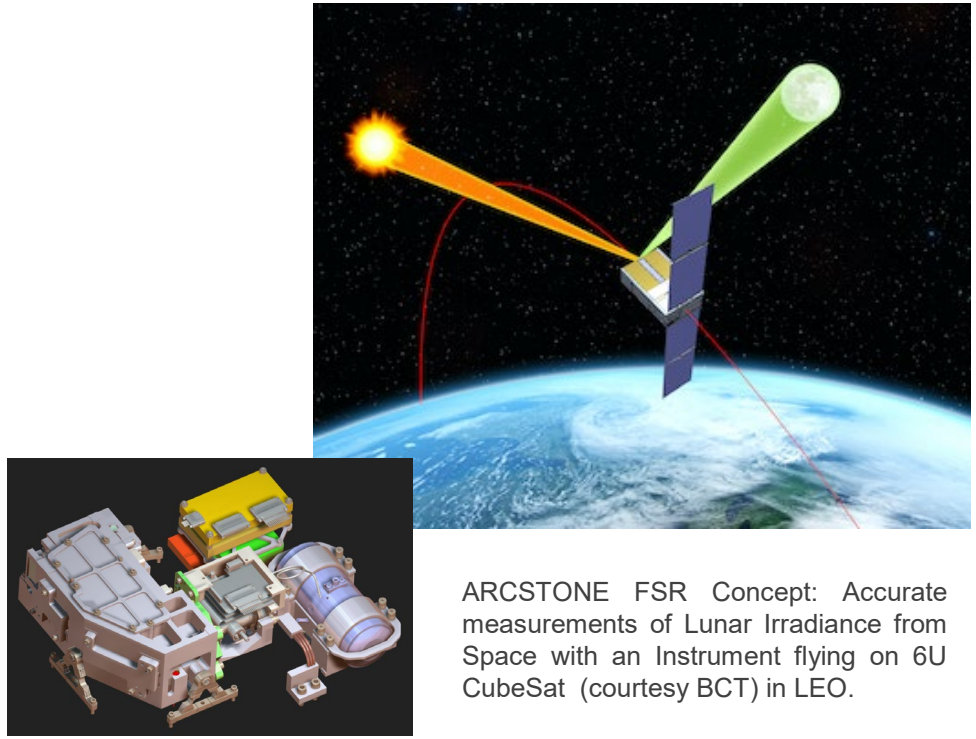
- *To enable on-orbit high-accuracy absolute calibration for the past, current, and future reflected solar sensors* in LEO and GEO by providing lunar spectral irradiance as function of satellite viewing geometry and specified wavelength.

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 design

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

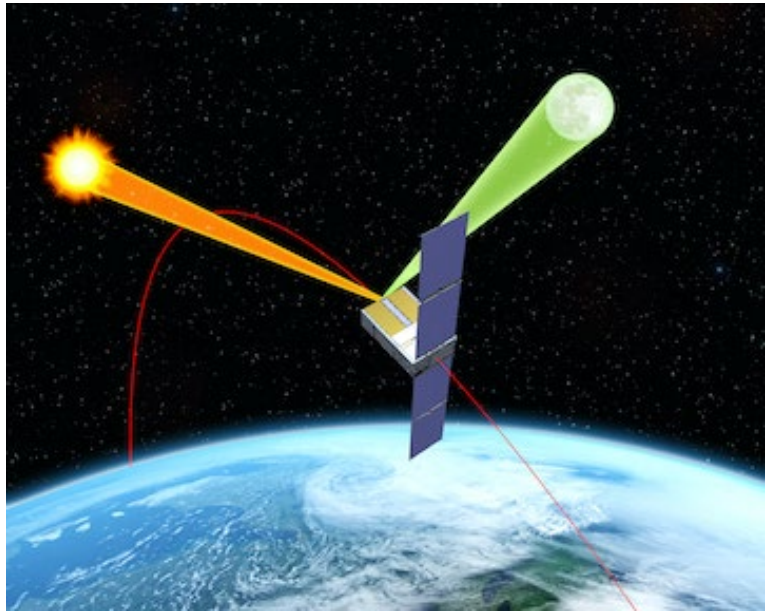
ARCSTONE InVEST Project Outline

Key Parameters:

- Data to collect: Lunar spectral reflectance every 12 hours
  - For -90° < Lunar Phase Angles < 90° (2 weeks out 4) required
  - For -135° < Lunar Phase Angles < 135° (3 weeks out of 4) demonstration
- 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, contiguous spectral sampling at 4 nm
- *Sun synchronous orbit at 500 km altitude, 6 months flight time*
- *Launch by SpaceX Falcon-9 (Transporter-14 mission), planned for 6/15/2025*
- *CubeSat deployer and LV integration by Maverick Space systems*

Key Technologies to Enable the Concept:

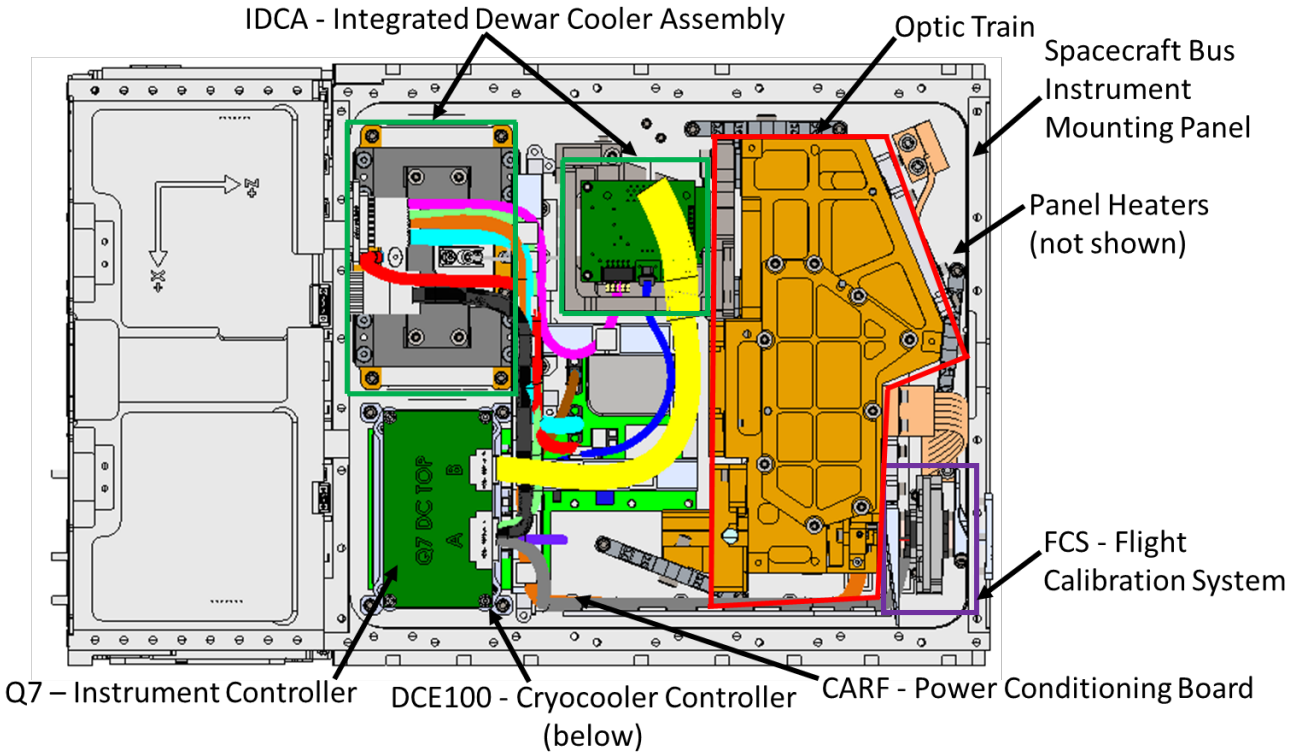
- Approach to orbital calibration via referencing Sun (TSIS measurements): Demonstration of lunar and solar measurements with *the same optical path using integration time to reduce solar signal*
- Pointing ability of spacecraft now permits obtaining required measurements *with instrument integrated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



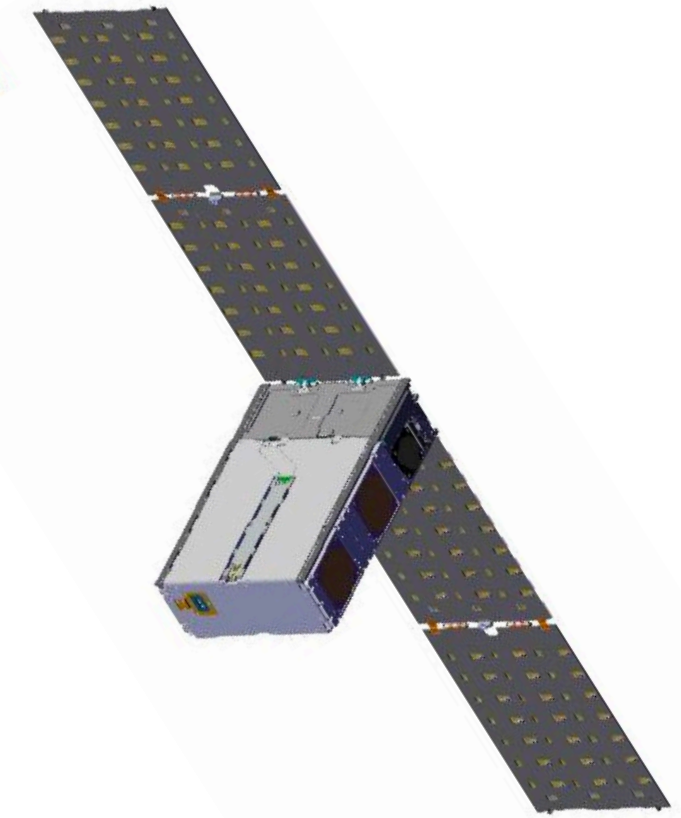
6U CubeSat Spacecraft Bus:
courtesy of Blue Canyon Technologies (BCT)

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

ARCSTONE: Space Segment Design



ARCSTONE payload integrated into 4U space



BCT XB6: 6U CubeSat
Courtesy of Blue Canyon Technologies (BCT)

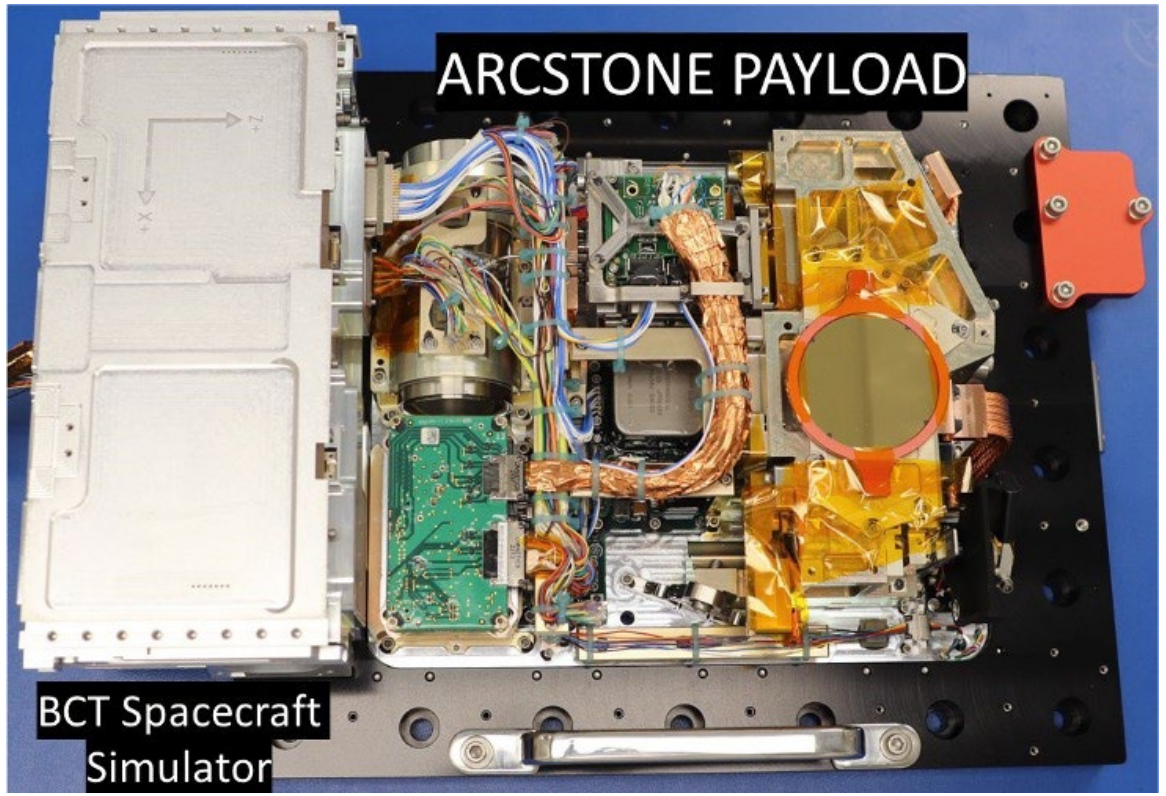
- Detector operating temperature = 140°K
- Optics bench operating temperature = -3°C

ARCSTONE InVEST: Payload Status / Fab & Assembly

- **Payload fabrication completed:**
  - Resonon (optics, metallic parts)
  - NASA GSFC (black paint)
  - Creare (ARF board)
  - Xiphos (Q7 and Interface boards)
  - LASP (Flight Calibration System)
  - NASA LaRC (harnesses)

- **Payload optomechanical assembly and alignment completed (Resonon):**
  - Optomechanical assembly and alignment testing
  - Electronics and cabling assembly
  - Functional testing of fully assembled payload

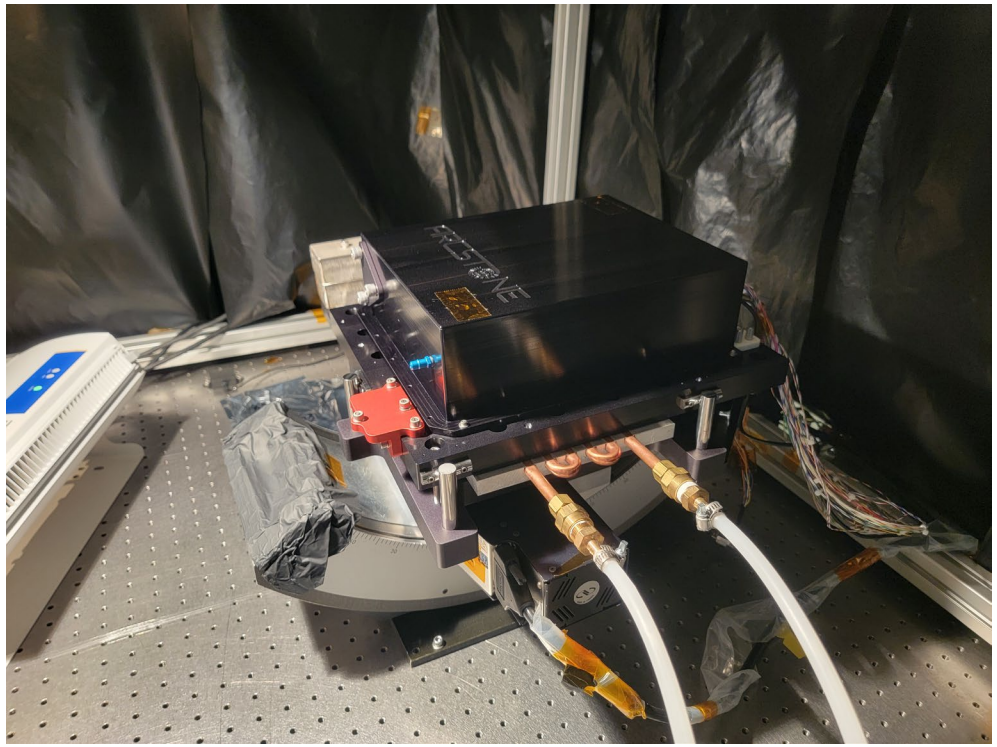
- **Payload electronics and cabling assembly completed (NASA LaRC):**
  - All flight electronics and harnessing
  - Automated Payload Functional testing



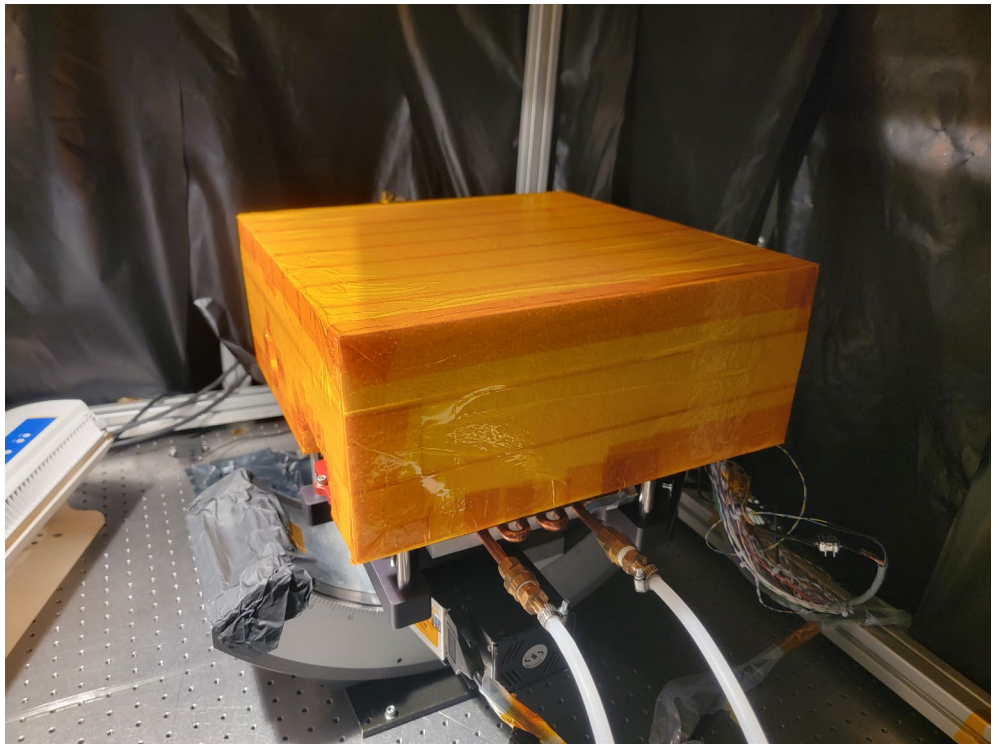
ARCSTONE Payload and BCT Bus EDU: fully assembled and functionally tested at LaRC laboratory

ARCSTONE InVEST: Payload Status / Characterization

- **Instrument Characterization in Progress:**
  - Objective is to meet the uncertainty requirements



ARCSTONE Payload setup at LASP “black room”



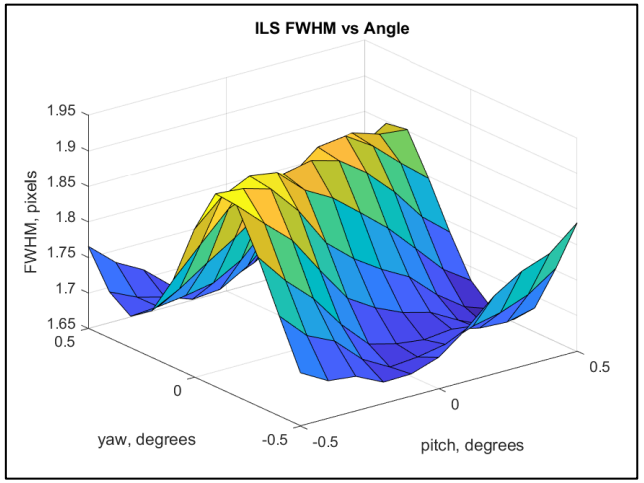
ARCSTONE Payload setup at LASP “black room”: insulated

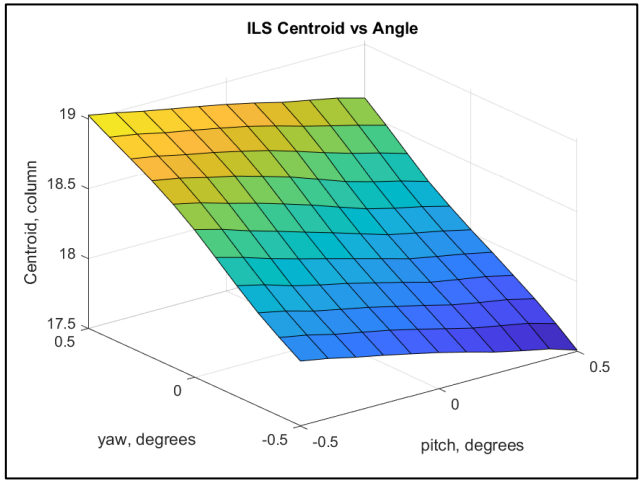
ARCSTONE InVEST: Payload Status / Characterization

- **Planned Characterization Activities:**
  - Boresight (Field of View/Vignetting) [complete]
  - Thermal Background (Dark) Signal [complete]
  - Instrument Line Shape (ILS) vs. Temperature [complete]
  - Stray Light and Scatter [complete]
  - Dispersion [complete]
  - ILS vs. Angle vs. Wavelength [in-progress]
  - Polarization Sensitivity [in-progress]

- **Planned completion by mid-June 2024**

ILS vs Angle – 408nm

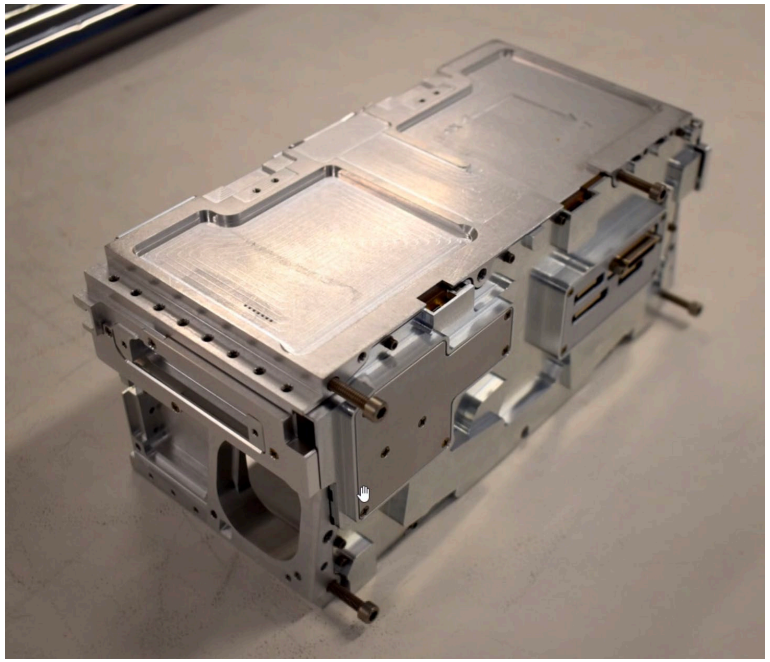




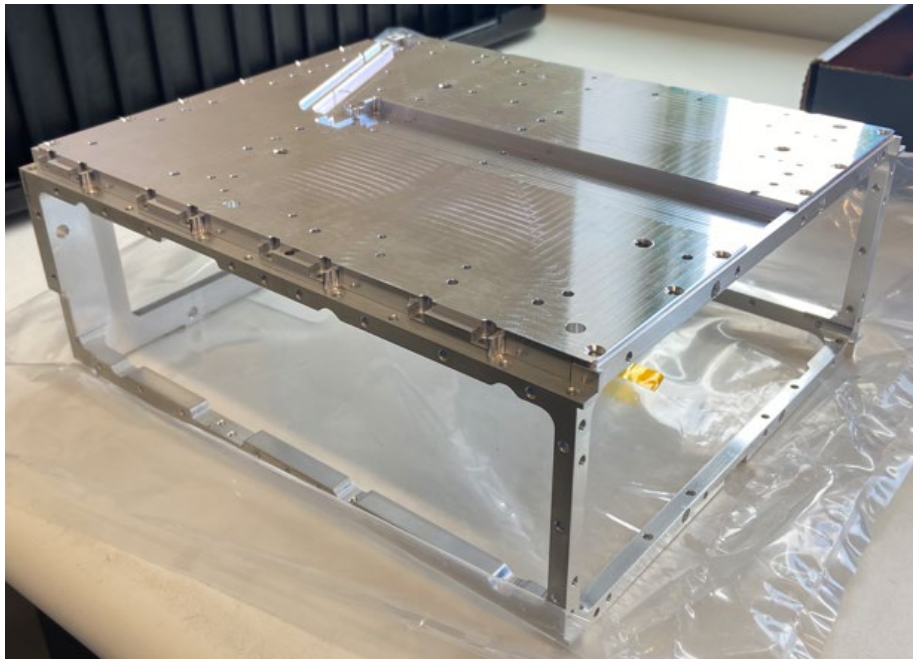
ARCSTONE InVEST: BCT Bus Status / Fab and Assembly

- **BCT XB6 spacecraft status:**
  - XB1 Completed and in storage from November 1, 2023
  - 6U Chassis completed

- **XB1 EDU completed in July 2023**
  - Supports flight software and CONOPS development & testing
  - Functionally tested at LaRC with fully assembled flight payload



ARCSTONE Deliverable XB1 EDU



ARCSTONE +Y Bus Panel with Chassis

ARCSTONE InVEST: Manifested Launch by SpaceX

Maverick/SpaceX Launch (managed by NASA CSLI):

- Monthly meetings with CSLI/Maverick/SpaceX

- *ICD for CubeSat deployer approved and signed:*
  - Maverick's Tab-based 6U CubeSat dispenser with isolators
  - Over 50% Reduction in gRMS Environment Transmission

- Launch by SpaceX:
  - Transporter-14 mission (Falcon-9)
  - Integrator: Maverick Space Systems
  - Readiness date: April 15, 2025
  - Expected launch date: June 15, 2025 from Vandenberg SFB, CA
  - SSO at 500 km altitude (LTAN is TBD)

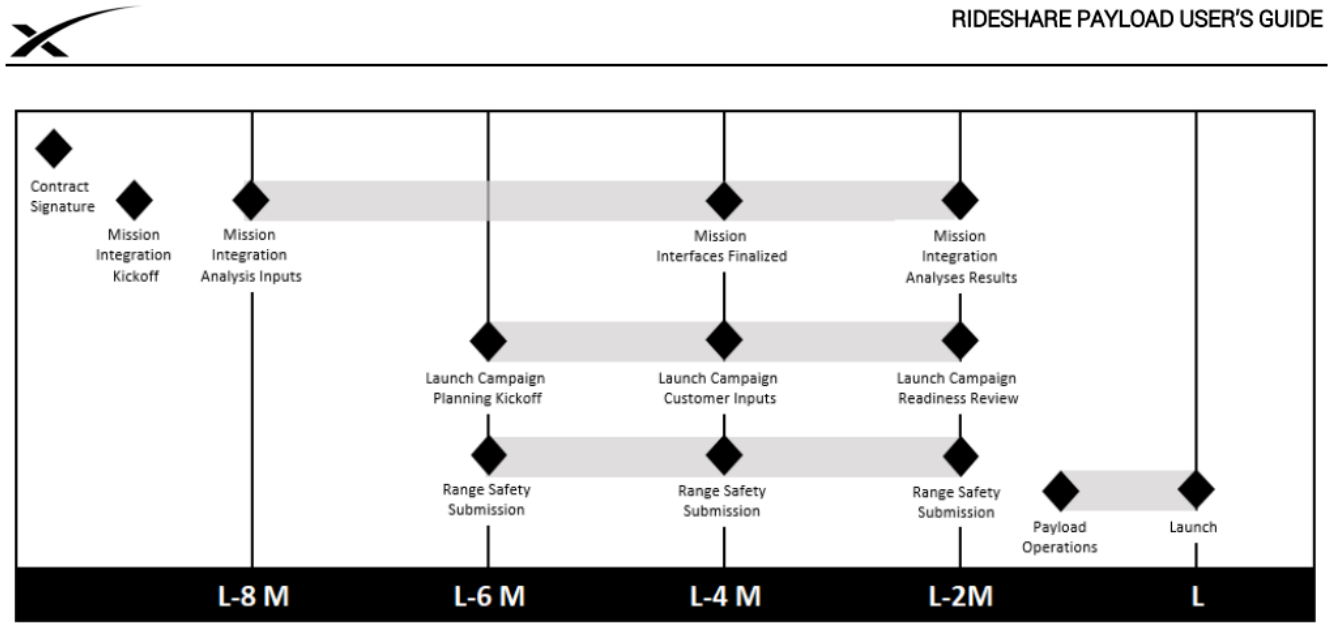
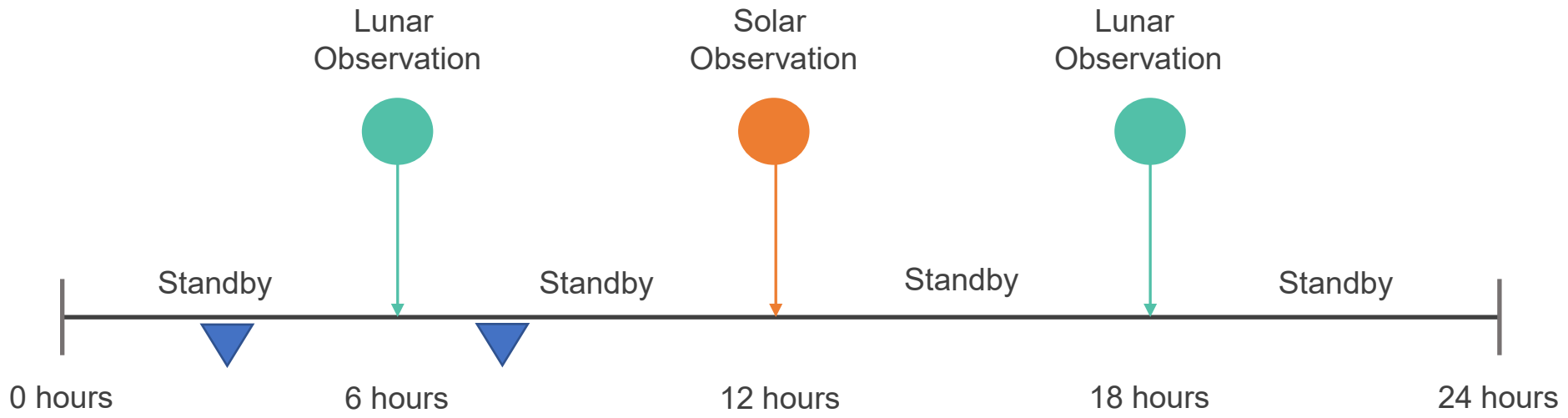


Figure 1-2: Typical Rideshare Program Schedule

ARCSTONE InVEST: Day In The Life (DITL) for Nominal Operations
Lunar Phase Angle from -0.5° to -90° and from 0.5° to 90°



▼ = Downlink / Uplink

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

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

ARCSTONE InVEST: Planned Data Products

Product	Contents	Level
Bus data	Bus time-ordered telemetry	Level-0
Instrument Engineering Data	Instrument engineering time-ordered telemetry	Level-0
Calibration Data	Sun, dark, cold, spectral calibration time-ordered telemetry	Level-0
Lunar Data	Moon time-ordered telemetry	Level-0
Lunar Measurements	Calibrated lunar spectral reflectance and irradiance	Level-1

- ARCSTONE data and algorithms → ATBD for Level-0 and Level-1 data products
- Main two approaches:
  (1) ratioing spectrometer
  (2) absolute calibration to SSI (TSIS-1/2)

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

ARCSTONE InVEST: Summary and Path Forward

***Lunar Calibration* offers a cost-efficient approach to accomplish the necessary calibration accuracy, stability, and inter-consistency of multiple sensors in reflected solar (VSWIR) in LEO and GEO:**

- Collaboration with ROLO, Air LUSI, MLO LUSI, SLIM and LIME projects
- Participation in the GSICS activities

- Currently ARCSTONE is at TRL 5+ (June 2024):
  - Design completed
  - Bus and payload fabrication and assembly completed
  - Functional tests completed

- Instrument Characterization by mid-June 2024
- Payload ConOps Simulation Testing by end of July 2024
- Payload and Bus I&T by end of December 2024
- Spacecraft Delivery to LV Integrator by mid April 2025
- Launch in mid-June 2025
- Space flight for 6 months in June – December 2025
- Initial release Level-1 data product with uncertainty budget analysis (2026)

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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

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

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THANK YOU !