# ARCSTONE: Calibration of Lunar Spectral Reflectance from Space

## ESTO InVEST-20-001

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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

# ARCSTONE InVEST Objectives

**Long-term Objective:**

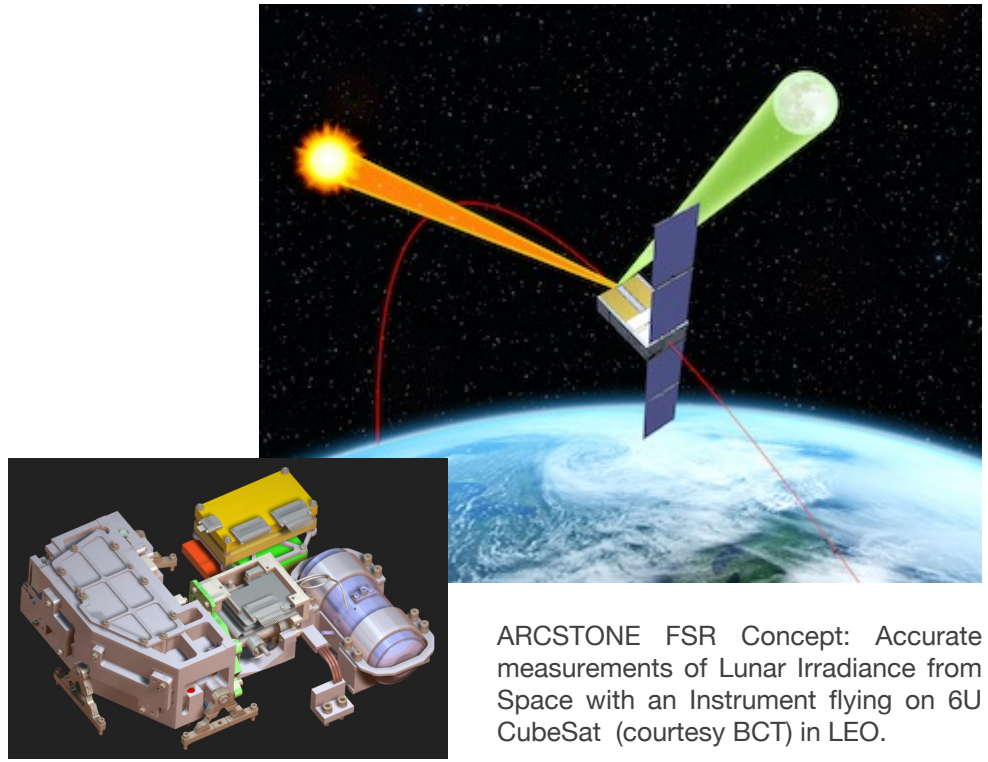
- *To enable on-orbit high-accuracy absolute calibration for the past, current, and future reflected solar sensors* in LEO and GEO by providing lunar spectral irradiance as function of satellite viewing geometry and specified wavelength.

**InVEST Baseline 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.*

**InVEST Success Criteria:**

- *To demonstrate high-accuracy measurements of lunar spectral reflectance, < 1.0% (k=1), by building a flight instrument, integrating payload with 6U CubeSat, operating it in LEO for 3 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.

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

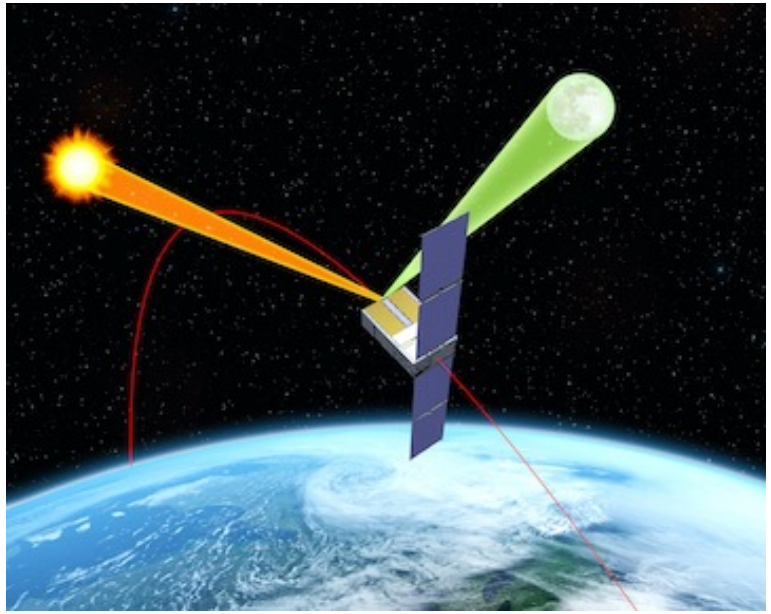
# ARCSTONE InVEST Project Outline

## 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 spectral irradiance for calibration daily
- 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 500 altitude, 6 months flight time
- Launch by SpaceX (Falcon-9 / Transporter-14), June 2025

## 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

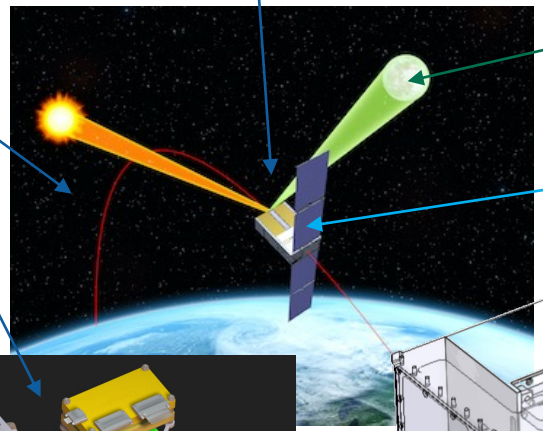
# ARCSTONE InVEST: Team & Roles

Launch manifested

## 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: SpaceX/Maverick

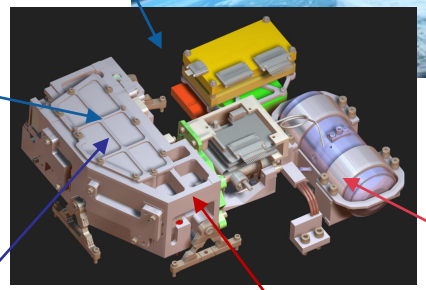


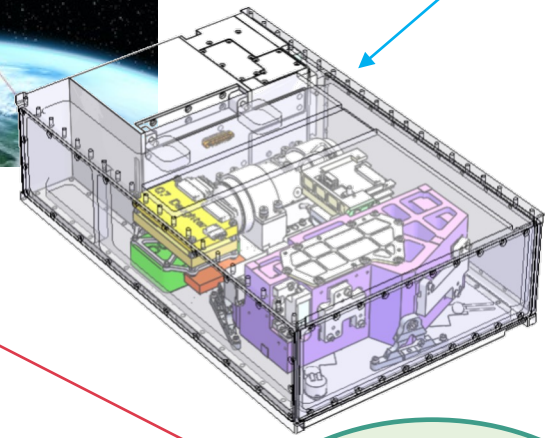
## USGS

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

Xiphos sub-contract Management
Publication

## LASP

Laboratory for Atmospheric and Space Physics

Flight Calibration System
IDCA characterization
Instrument characterization
Uncertainty budget

## RESONON

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

## quartus ENGINEERING

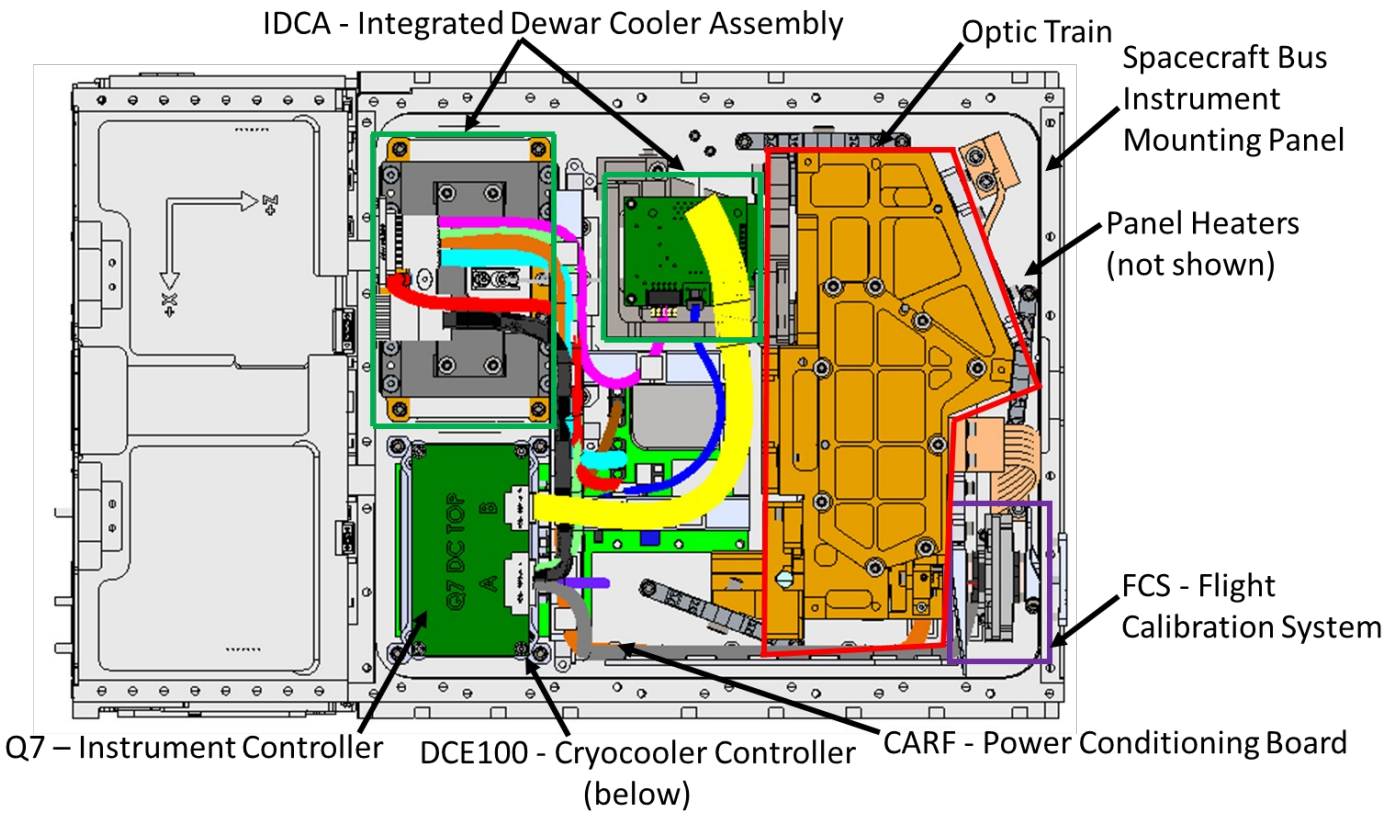
Payload Analysis
Input to payload design
Flexure design

## ANALYTICAL MECHANICS ASSOCIATES

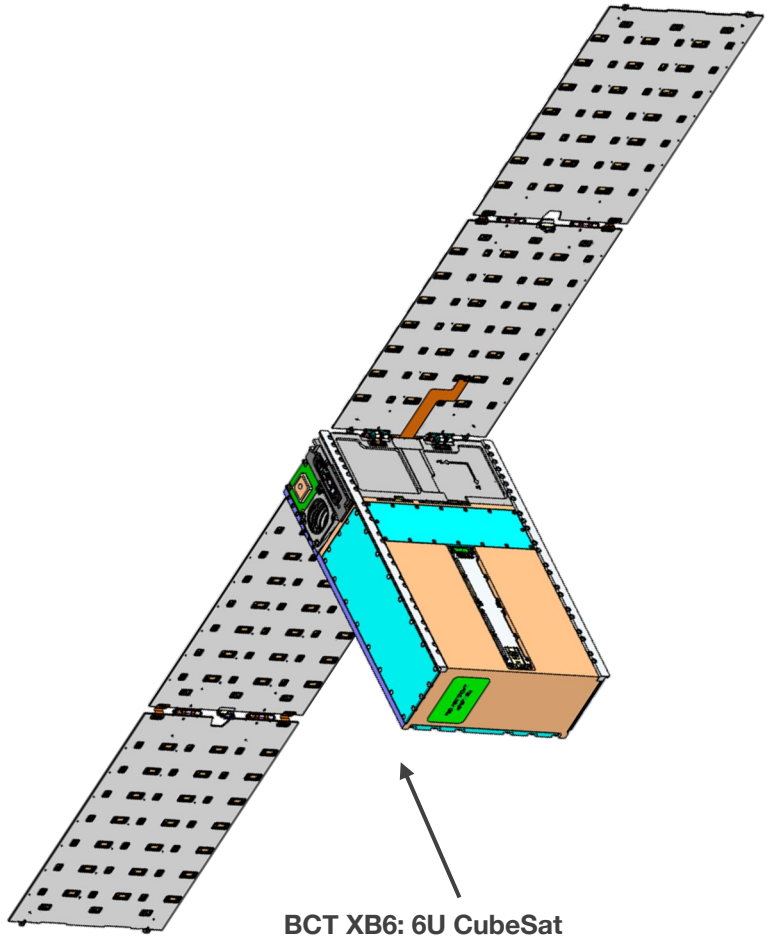
SMCE Cloud support
SPS development

Tasks completed

# ARCSTONE: Space Segment




**ARCSTONE payload integrated into 4U space**



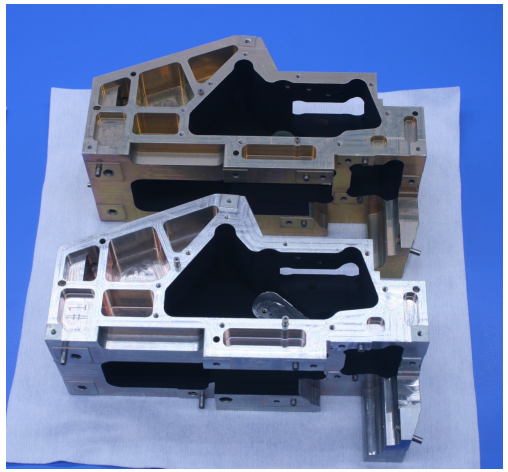
**BCT XB6: 6U CubeSat**
Courtesy of Blue Canyon Technologies (BCT)

- Detector operating temperature = 149°K
- Optics bench operating temperature = -3°C

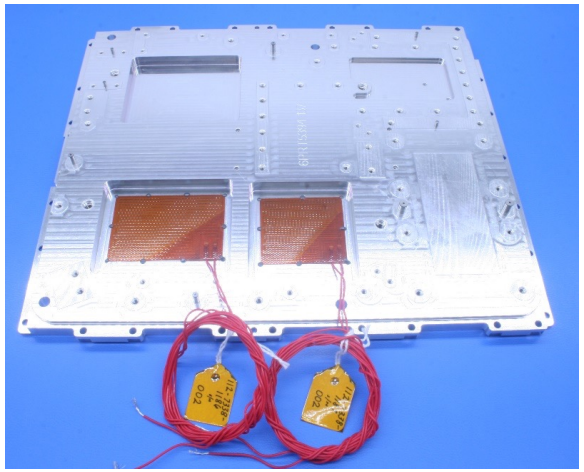
# ARCSTONE InVEST: Optomechanical Status

- **Mechanical:**
  Payload mechanical components 100% fabricated
  Minor GSE components in fabrication

- **Optical:**
  Payload optical components 100% fabricated

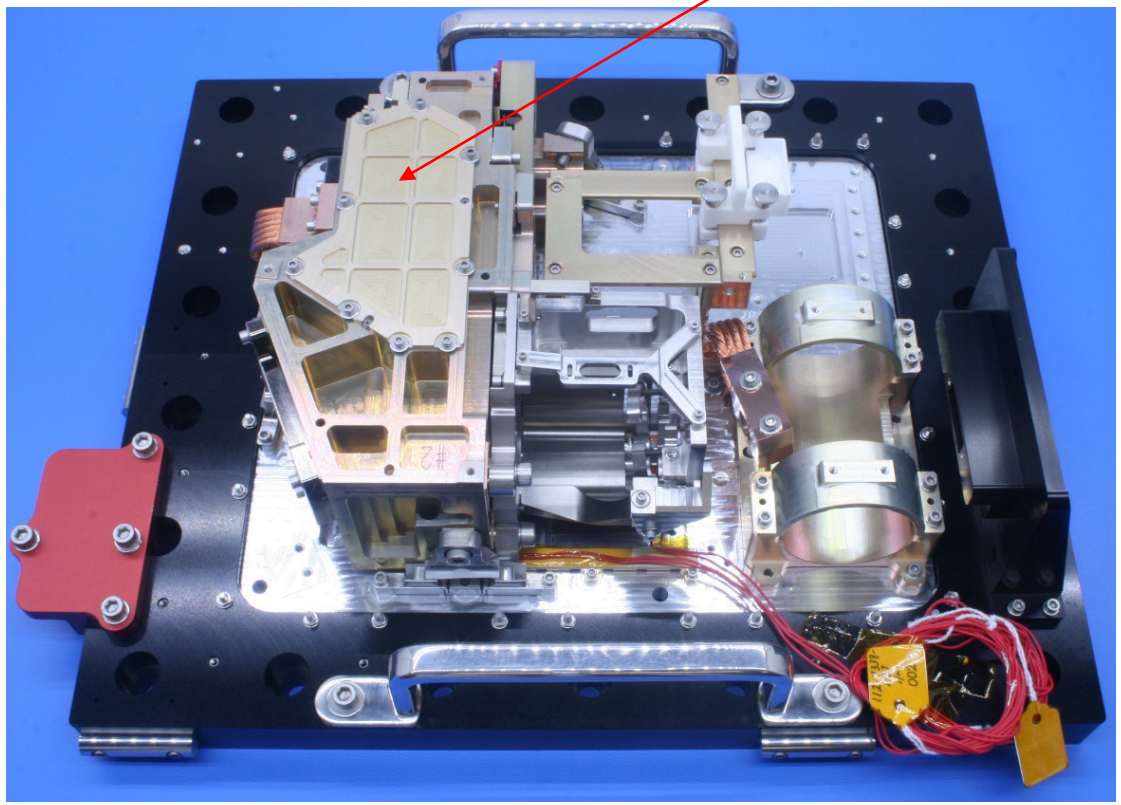


Optics Bench



+Y Bus Panel with installed payload heaters

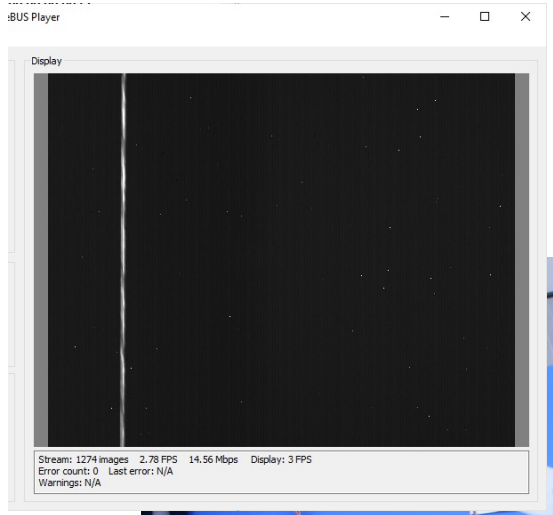
All optics installed inside of optics bench

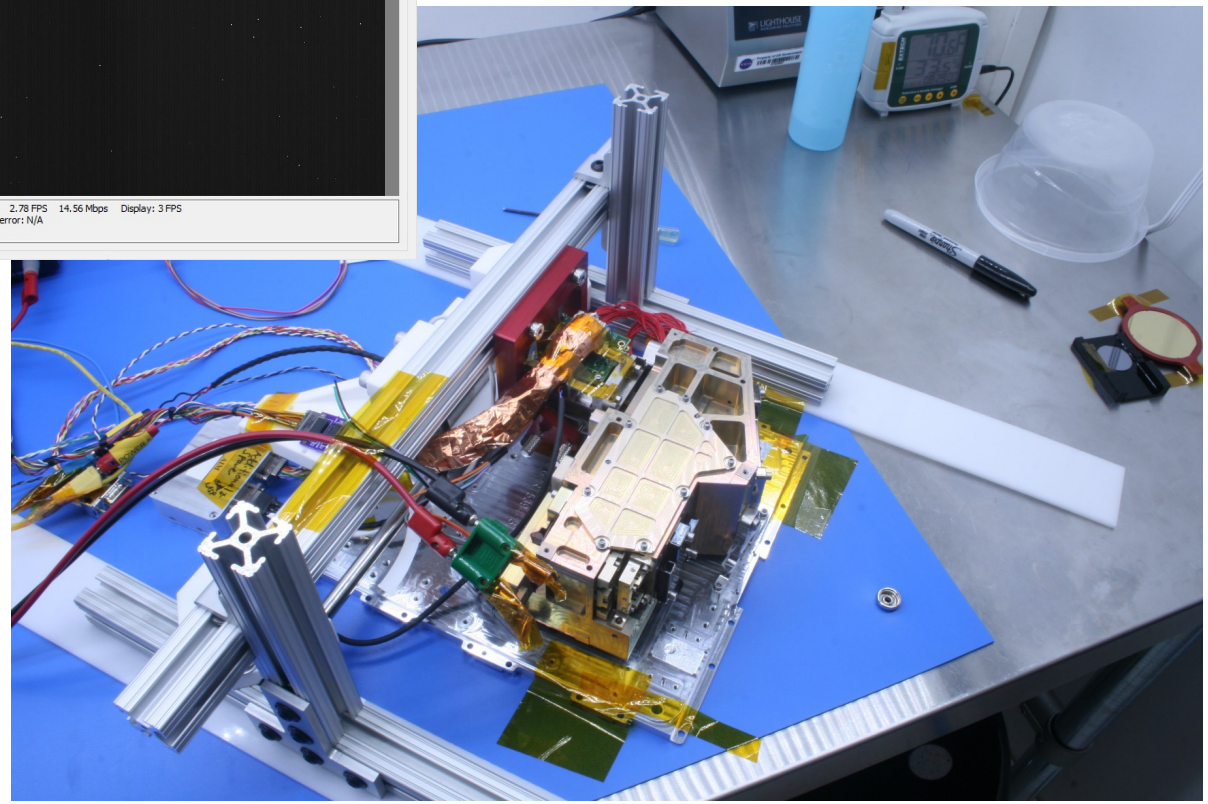


ARCSTONE Payload partial test-fit assembly at Resonon

# ARCSTONE InVEST: Payload at Opt.-Mechanical Assembly

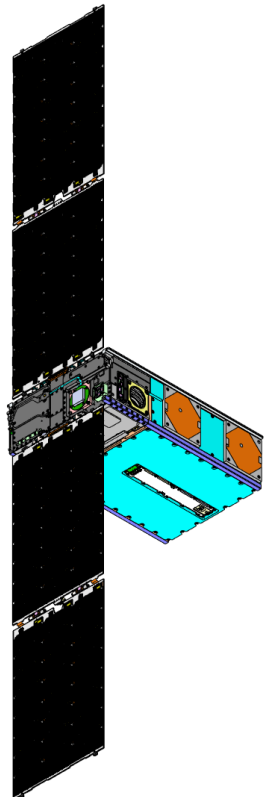
- IDCA “Gantry” supports camera and cryocooler while focus shims are installed/removed.
- Functional check with 633nm laser
- Issue with the Primary Flight IDCA (detector temp sensor signal drop out) - Being repaired…
- Using Spare IDCA for flight - Assessing impacts…



# ARCSTONE: Ground Segment

**Spacecraft**



**Ground Station Network (KSAT)**

**GSN**

- Stations 2
- Scheduling
- Antenna commanding
- Data demodulation
- Temporary data storage

Commands, Schedule requests

Telemetry, Mission data, Schedule confirmations

**Mission Operations Center (MOC)**

**BCT**

BLUE CANYON TECHNOLOGIES

- Contact scheduling
- SV Command & Control
- Health and Status monitoring
- Anomaly resolution

Tasking

Mission data

**Payload Operations Center (POC)**
**Science Planing System (SPS)**
**Science Data System (SDS)**

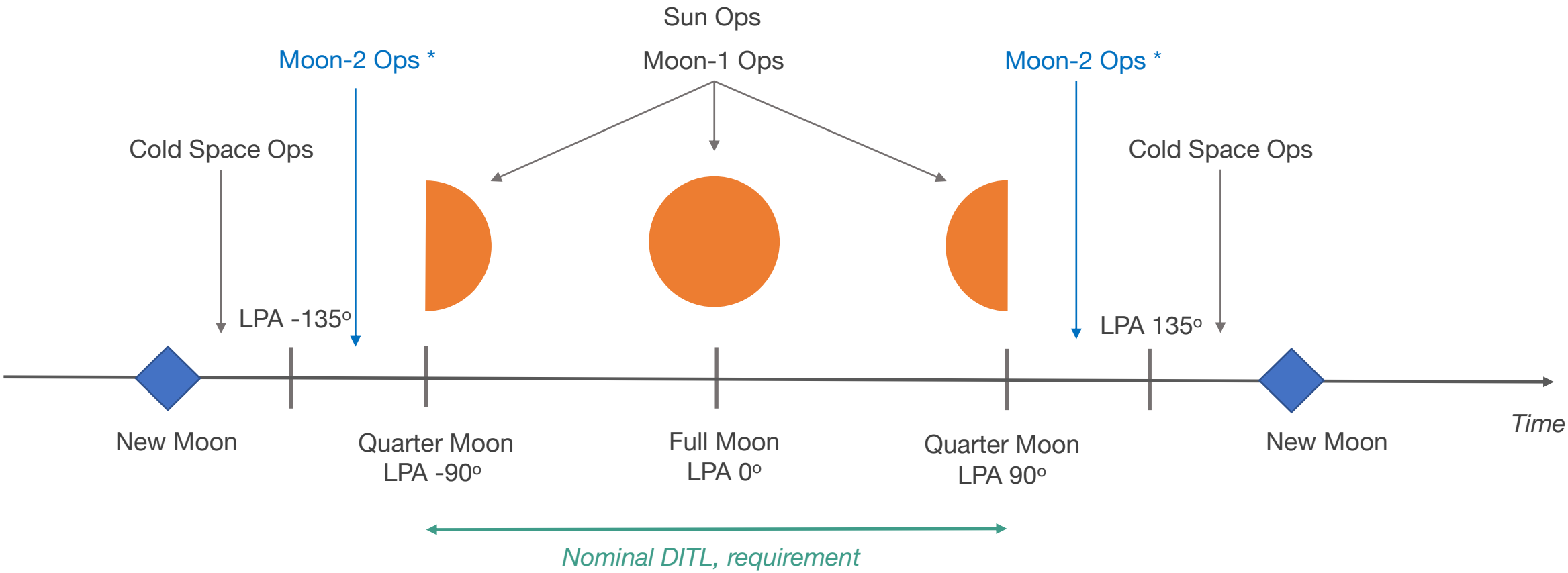
**ARCSTONE Data Systems AWS/SMCE**

- Algorithm dev.
- Mission data processing
- Payload Monitoring
- Payload long-term trending
- Event prediction
- Payload Schedule

RF
TCP/IP

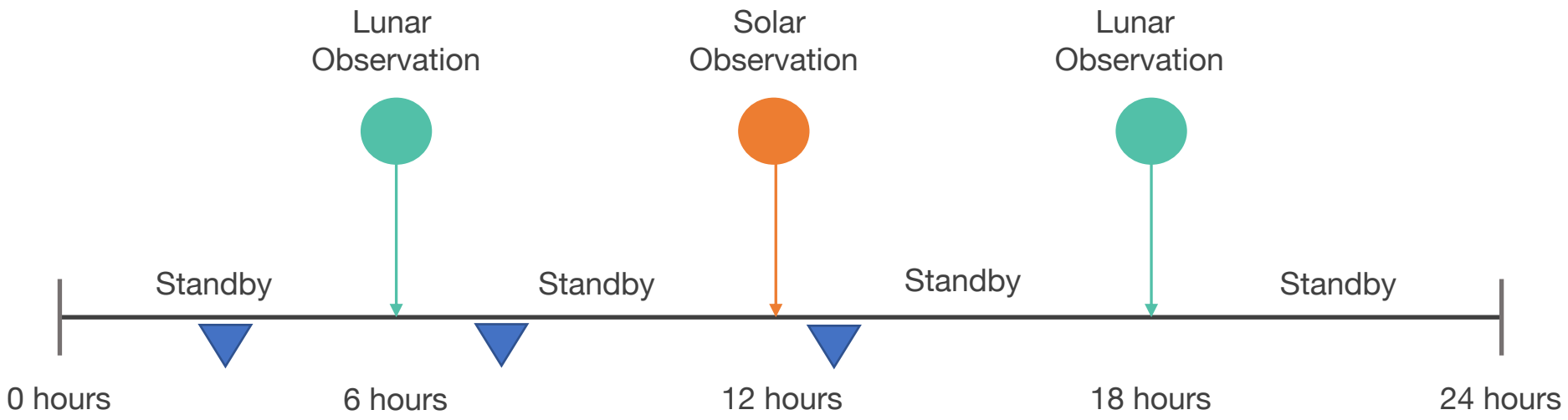
**BCT XB6: 6U CubeSat**
Courtesy of Blue Canyon Technologies (BCT)

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




* *Moon-2 Ops: demonstration, not requirement (demonstration)*

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



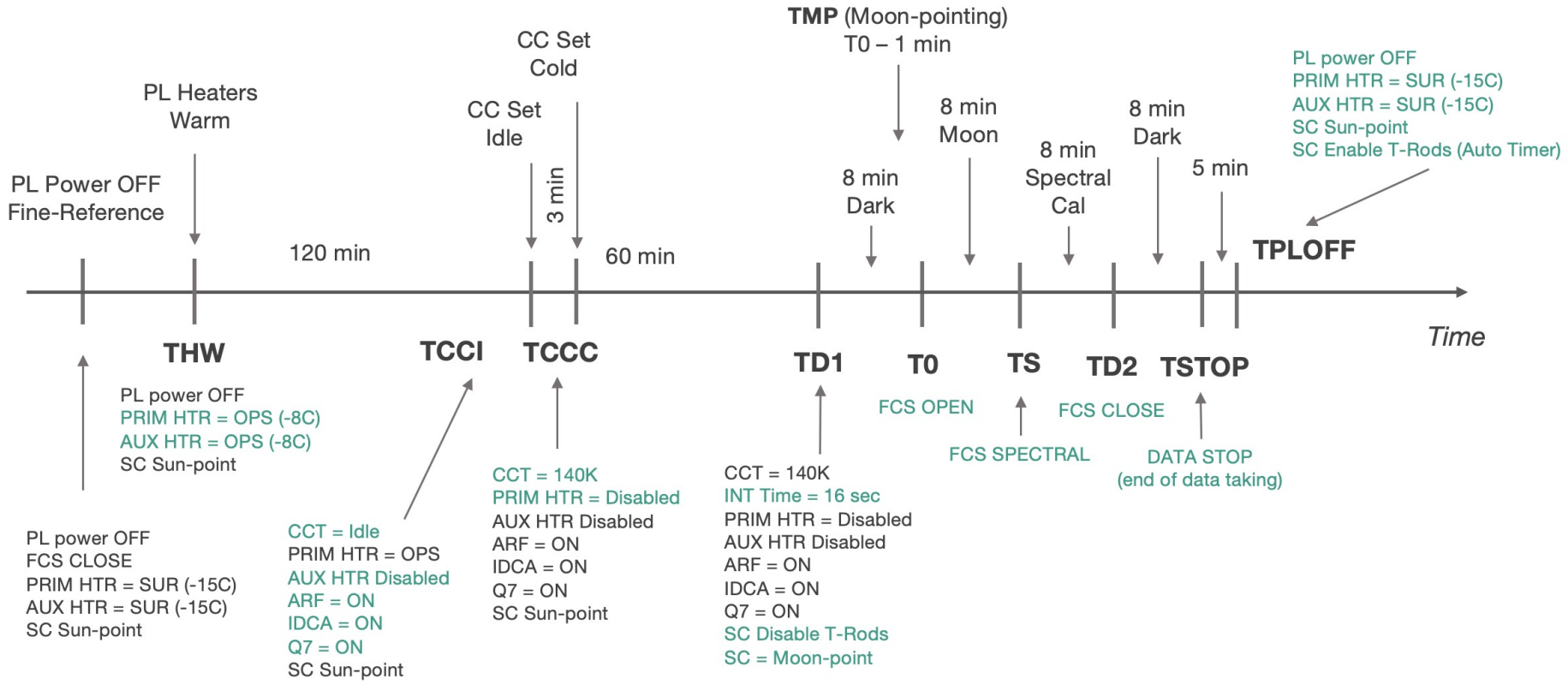

▼ = Downlink / Uplink

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 (PL power OFF) due to Space Radiation hazard overrides all modes
- Downlink/Uplink during Payload Standby mode

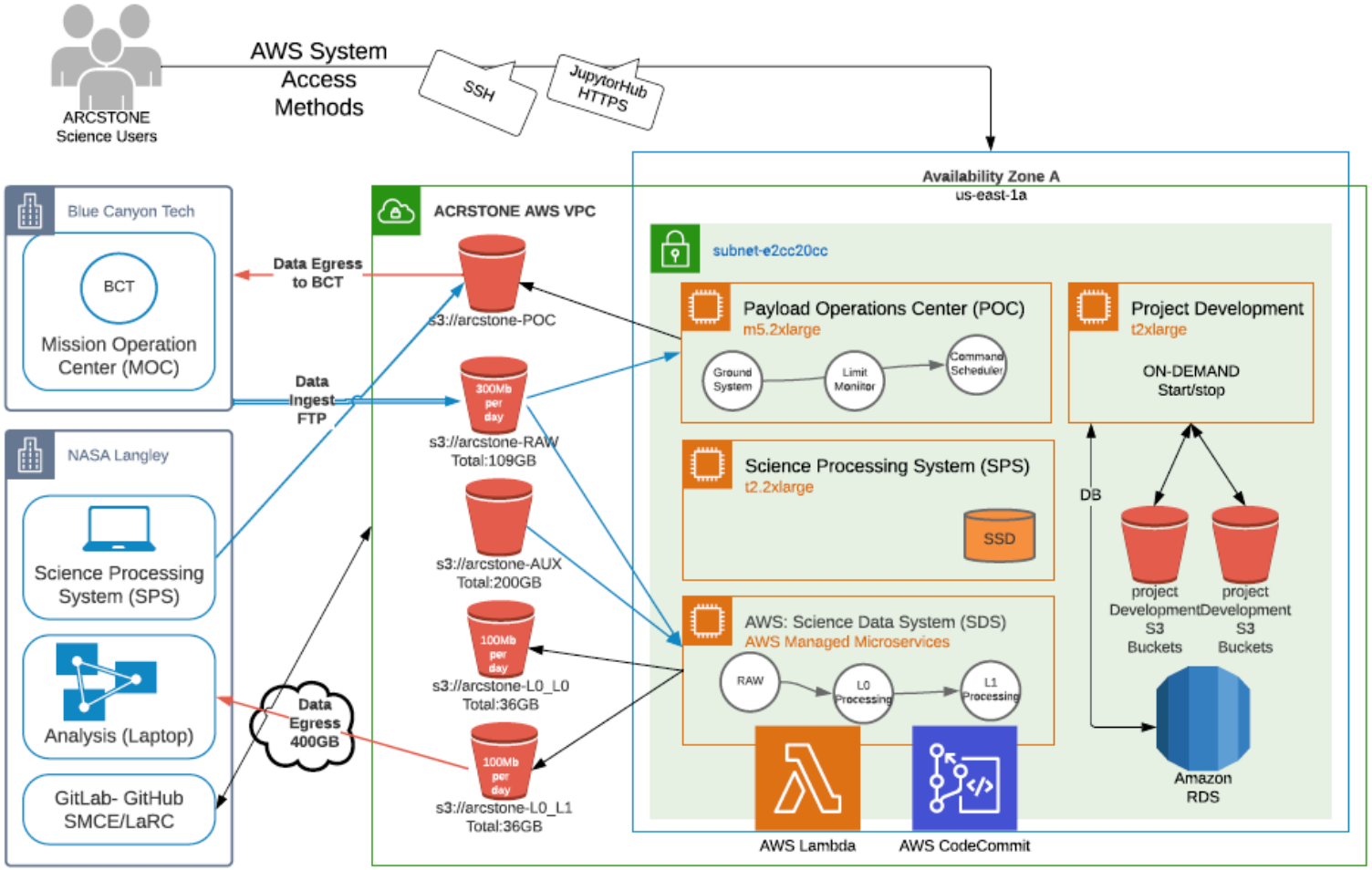
# ARCSTONE InVEST: Operations for Lunar Observations




**ARCSTONE Operations Sequence for Lunar Observations**

- **Conops status:**
  - DITL developed for nominal operations (Moon, Sun, Cold Space)
  - CONOPS update for Spare IDCA (on going)
- **RF License status:**
  - Submitted to Stage-4 Operational Certification (middle of July 2023)

# ARCSTONE InVEST: Science Systems




ARCSTONE data systems architecture in AWS Commercial and Gov Cloud

- **ATBD / data flow diagrams drafted**
- **Ground data systems prototyped:**
  - Science Prediction System (SPS)
  - Science Data System (SDS) at SMCE
  - Data tier at SMCE
  - Payload Operations Center (POC)

# ARCSTONE: Planned Data Products

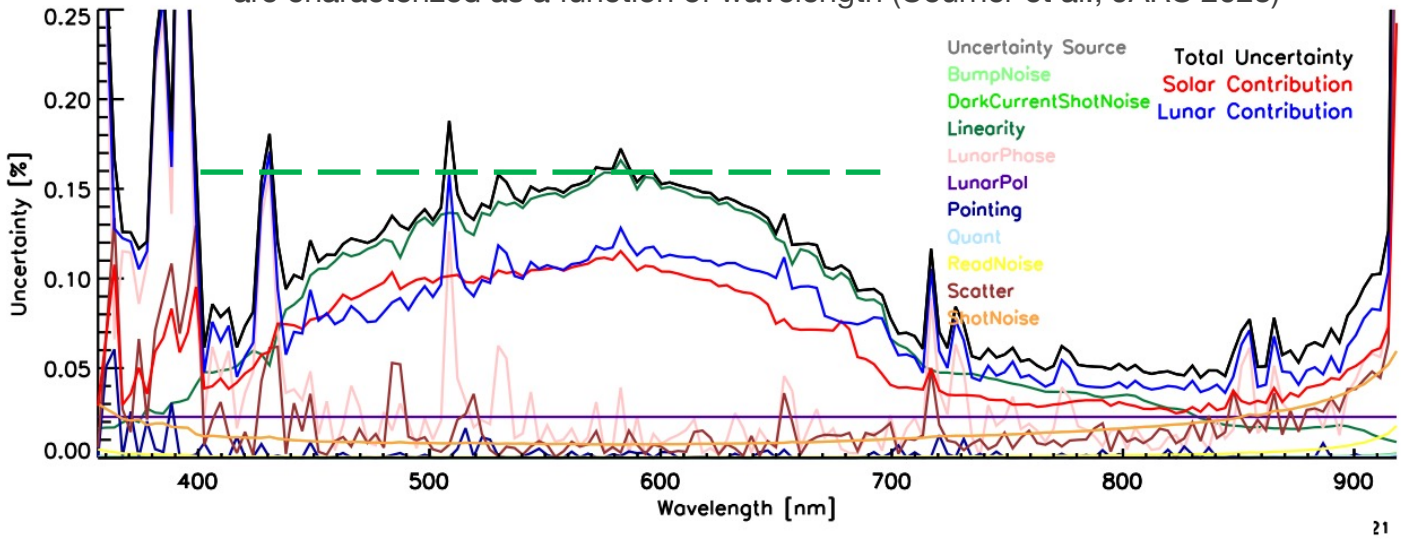
| Product | Contents | Level | Rate / Day |
|---|---|---|---|
| Bus data | Bus time-ordered telemetry | Level-0 | 210 MB |
| Instrument Engineering Data | Instrument engineering time-ordered telemetry | Level-0 | 5 MB |
| Calibration Data | Sun, dark, cold, spectral calibration time-ordered telemetry | 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 |

- ATBD for Level-1 data product
- Uncertainty analysis and budget developed for instrument prototype
- 2 approaches: rationing spectrometer and absolute calibration to TSIS-1/SSI

# ARCSTONE InVEST: Project status

- Funded by the NASA ESTO InVEST program
- Technology demonstration
- Class E mission
- Under NPR 7120.8 (R&D)
- Payload design → complete
- Payload fabrication → complete
- Bus fabrication & I&T → complete (in storage)
- Payload assembly in progress…

UVVNIR Prototype: Reflectance uncertainties from several contributing effects are characterized as a function of wavelength (Courrier et al., JARS 2023)




- Manifested launch by CSLI: SpaceX/Maverick Transporter-14 mission (Falcon-9)
  - Launch in June 2025 (window from May to August 2025)
  - Launch site: Vandenberg SFB, CA
  - SSO orbit at 500 km altitude
  - 97.4° inclination

# ARCSTONE: Recent Publications

**1.** Stone, T.C., H. Kieffer, C. Lukashin, K. Turpie,
"The Moon as a Climate-Quality Radiometric Calibration Reference," *Rem. Sens.,12*, 1837, 2020
Available online at https://www.mdpi.com/2072-4292/12/11/1837

**2.** 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

**3.** NESC Academy Webcast on ARCSTONE (C. Lukashin & Team) available online at
https://mediaex-server.larc.nasa.gov/Academy/Play/ed1d00768a15486096edf4dac6d8cc7b1d

**4.** Courrier H., R. Swanson, C. Lukashin, C. Buleri, J. Carvo, M. Cooney, W. Davis, A. Halterman, A. Hoskins, T. Jackson, M. Kehoe, G. Kopp, T. Nguyen, N. Ryan, C. Roithmayr, P. Smith, M. Stebbins, T. Stone, C. Young, "Calibration of lunar spectral reflectance from space. Prototype instrument concept, analysis, and results," JARS, November 2023. Available online at https://doi.org/10.1117/1.JRS.17.044508

# ARCSTONE: 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:

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

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

- Currently ARCSTONE is at TRL 5+ (2023)
- Complete ARCSTONE InVEST project and achieve TRL 7 (2025)
- Initial release Level-1 data product with uncertainty budget analysis (2026)
- Extension of lunar model to SW broadband applications (NIP, PI: Cindy Young)
- Input to the the NASA Decadal Survey for Earth Science (expected in 2027):
  - Part of EOE as Cal/Cal component (Landsat Next, SBG next, Ocean/Land missions, etc.)
  - Part of international Cal/Val component
- Full 3-year mission (NASA EV or DS)
- Integration into new Lunar Calibration models
- Online lunar calibration service