ARCSTONE: Calibration of Lunar Spectral Reflectance from Space

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\begin{itemize}
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  \item 2 – LASP University of Colorado, Boulder, CO
  \item 3 – Resonon Inc., Bozeman, MT
  \item 4 – Goddard Space Flight Center, Greenbelt, MD
  \item 5 – Quartus Engineering, San Diego, CA
  \item 6 – Blue Canyon Technologies, Inc., Boulder, CO
  \item 7 – USGS, Flagstaff, AZ
\end{itemize}
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 payload concept in 2019

TRL\textsubscript{current} = 5 (IIP) \hspace{1cm} TRL\textsubscript{out} = 7 (InVEST)
ARCSTONE EDU: IIP project completed in July 2021

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

ARCSTONE EDU instrument and components

ARCSTONE EDU at LASP CU-Boulder characterization facility.
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
Key Parameters:

- Data to collect: Lunar spectral irradiance every 12 hours
  For Lunar Phase Angles < 90° (2 weeks out of 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.*
**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.
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)

- **New Moon**
- **Quarter Moon**
- **Full Moon**
- **Quarter Moon**
- **New Moon**

- **Cold Space Ops**
- **Moon-1 Ops**: requirement
- **Moon-2 Ops**: goal
- **Sun Ops**

*Diagram notes:*
- LPA -135°
- LPA 90°
- LPA 135°
ARCSTONE InVEST: Day In The Life (DITL) for Nominal Required Operations

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

<table>
<thead>
<tr>
<th>Product</th>
<th>Contents</th>
<th>Level</th>
<th>Rate / Day</th>
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<tbody>
<tr>
<td>Bus data</td>
<td>Bus time-ordered telemetry</td>
<td>Level-0</td>
<td>210 MB</td>
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<tr>
<td>Instrument Engineering Data</td>
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<tr>
<td>Calibration Data</td>
<td>Sun, dark, cold, spectral calibration time-ordered telemetry</td>
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<tr>
<td>Lunar Data</td>
<td>Moon time-ordered telemetry</td>
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<tr>
<td>Lunar Measurements</td>
<td>Calibrated lunar spectral reflectance and irradiance</td>
<td>Level-1</td>
<td>40 MB</td>
</tr>
</tbody>
</table>

- 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

- 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
- 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

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

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).
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

GSFC
- Optical black coating

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

Payload Analysis
- Input to payload design
- Flexure design

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

AWS Cloud Architecture
Science Planning System
Sub-contracts Management
ARCSTONE InVEST: Payload Layout in Bus

Payload accommodated in 4U of spacecraft.
ARCSTONE: Calibration of Lunar Spectral Reflectance from Space

Recent Publications:


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Available online at https://www.mdpi.com/2072-4292/12/11/1837