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

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SBIR programs: Phase-I & Phase-II
ARCSTONE: 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

NASA GSFC
Optical black coating

Instrument concept
Component characterization
Radiometric calibration
Error budget

ARCSTONE TEAM:
- NATIONWIDE COLLABORATION of EXPERTS!
- Collaboration with NIST & UMBC:
  Ground and Airborne lunar measurements

Lunar calibration approach (ROLO)

6U CubeSat Bus

Instrument Analysis (STOP, RV, TE)
Input to instrument design
Flexures design
Moon: Potentially Accurate Source for Calibration On-orbit

- Measurement accuracy is directly related to the information content of the dataset. Measurement accuracy is critical to EOS!
  Current EOS cannot handle data gaps. Need overlapping observations: CERES, MODIS/VIIRS, Landsats, PACE/SeaWIFS, etc.

Calibration reference: Lunar Spectral Irradiance (entire disk)

- SeaWiFS gain stability: 0.13% (k=1) over 12 years
- Accuracy of current Lunar Model (ROLO): 5 – 10%

On-Orbit Calibration Need:
Absolute accurate spectral irradiance for all lunar phase angles and libration states.

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

Reflectance of Lunar surface stable to < 10^-8 / year
### Applications of the Lunar Calibration Approach
(satellite operators worldwide !)

<table>
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<th>Team</th>
<th>Satellite</th>
<th>Sensor</th>
<th>G/L</th>
<th>Dates</th>
<th>Number of obs</th>
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From GSICS (Global Space-based Inter-Calibration System) Lunar Calibration Workshop, December 2014, EUMETSAT.

- Instruments with lunar calibration capabilities participating in the GSICS GIRO (GSICS implementation of the ROLO model) program
- List includes sensors with lunar observations submitted to the database at EUMATSAT as of December 2014.
- Next GSICS Lunar Calibration Workshop: November 2020, virtual (?)
ARCSTONE 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 a 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 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° (no scanning!)
- Sun synchronous orbit at 500 – 600 km altitude
- Spectral range from 350 nm to 2300 nm, spectral sampling at 4 nm

1 year: Improvement of current Lunar Calibration Model (factor of 2 – 4);
3+ years: New Lunar Irradiance Model, improved accuracy level (factor of 10).

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° (1-sigma) in 3 axis
Stability 1 arc-sec over 1 sec
## ARCSTONE Mission: Key Performance Parameters

<table>
<thead>
<tr>
<th>Key Parameters</th>
<th>Threshold Value</th>
<th>Goal Value</th>
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<tr>
<td>Accuracy (reflectance)</td>
<td>1.0% (k=1)</td>
<td>0.5% (k=1)</td>
</tr>
<tr>
<td>Stability</td>
<td>&lt; 0.15% (k=1) per decade</td>
<td>&lt; 0.1% (k=1) per decade</td>
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<td>Orbit</td>
<td>Sun-synch orbit</td>
<td>Sun-synch orbit</td>
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<tr>
<td>Time on-Orbit</td>
<td>1 year</td>
<td>3 years</td>
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<td>Frequency of sampling</td>
<td>24 hours</td>
<td>12 hours</td>
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<tr>
<td>Instrument pointing</td>
<td>&lt; 0.2° combined</td>
<td>&lt; 0.1° combined</td>
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<tr>
<td>Spectral Range</td>
<td>380 nm – 900 nm</td>
<td>350 nm – 2300 nm</td>
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<tr>
<td>Spectral Sampling</td>
<td>8 nm</td>
<td>4 nm</td>
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</table>

**Threshold Values considered as success criteria**

Reference for radiometric requirements (ROLO, T. Stone):
- Lunar Phase Angle = 75°;
- Irradiance = 0.6 (micro W / m² 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 out shutter temp):
   - 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
10. Safe Mode (if required)

* 6U CubeSat accommodation Study is completed
**ARCSTONE 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)
- Data Downlink Mode: 34.07 W
- Stand By Mode: 15.5 W

* Cabling is not shown
ARCSTONE Instrument Analysis

Optic bench random vibration analysis.

Performing Analysis: STOP, Thermoelastic, Random Vibe

Optic bench displacements [microns] at −30°C. Cutaway shows interior of camera dewar/cold finger.
ARCSTONE: SWIR IDCA (1 – 2.3 µm) 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

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 Vacuum tests: positive results!

Full Spectral Range IDCA is essentially the same as SWIR IDCA (except for detector, OB filter, and integration time extended to 16 seconds)

Major Credits:
- IDCA selection/acceptance: Mike Cooney (NASA LaRC)
- Mechanical design: Trevor Jackson (NASA LaRC)
- IDCA characterization: Paul Smith (LASP, CU)
ARCSTONE IIP: Status and Next Steps

**Status:**
- Design and STOP analysis completed for EDU instrument
- 6U CubeSat accommodation study completed
- Fabrication of instrument is in progress

**Next Steps:**
- Complete 6U CubeSat/Payload thermal study (September 2020)
- Complete fabrication of instrument (October 2020)
- Characterize Full Spectral Range IDCA (January 2021)
- Assemble instrument (February 2021)
- Calibrate instrument (May 2021)
- Field-test instrument with Sun and Moon measurements (TRL5, June 2021)

Testing ARCSTONE field equipment at NASA LaRC
ARCSTONE: Calibration of Lunar Spectral Reflectance from Space

Recent Publications:


Available online: https://ieeexplore.ieee.org/abstract/document/9172629


Available online at https://www.mdpi.com/2072-4292/12/11/1837
ARCSTONE: Calibration of Lunar Spectral Reflectance from Space

http://arcstone.larc.nasa.gov

THANK YOU!