air-LUSI Team

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Limitations of the RObotic Lunar Observatory (ROLO) Model

Although the ROLO model is the most precise and reliable lunar radiometric reference available, it typically is not used for absolute calibration. 

Why not?

Uncertainty in the model absolute scale is ~5-10%  
– originates with the ROLO telescope empirical dataset  
– the main source of error is the atmospheric correction

The current absolute accuracy limitation is solely with the lunar model.

The Moon potentially can provide an absolute calibration reference with total uncertainty under 1% (k=2)

To achieve a high-accuracy, SI-traceable absolute lunar calibration reference requires acquisition of a new measurement database.

From Tom Stone, CEOS WGCW IVOS-29 Meeting 15 Mar 2017
“ground” LUSI

NIST ground-based Lunar Spectral Irradiance (LUSI) project

• non-imaging optical system, COTS spectrometer: 390–1040 nm
• on-site calibration reference: 30 cm integrating sphere “artificial Moon”
• Mt. Hopkins, AZ: two nights in Nov. 2012 with good viewing conditions (out of three years).
  - atmospheric correction by Langley analysis of the lunar data
  - combined total uncertainty under 1% ($k=1$) from 400 nm to 1000 nm
• Current status: NIST staff is budgeted for setup at Mauna Loa, Hawaii (3397 m alt).
air-LUSI Objectives

• **Fly** the ground-based LUSI system above 90% of the Earth's atmosphere on an ER-2 aircraft to measure lunar spectral irradiance ultimately to an unprecedented level of accuracy (<0.3% k=1 uncertainty).

• **Provide a capability** to operationally acquire SI-traceable extraterrestrial lunar spectral irradiance over a broad range of viewing angles, lunar phases, and libration angles.
ER-2 Basic Configuration

### Specifications

<table>
<thead>
<tr>
<th>Crew:</th>
<th>One Pilot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length:</td>
<td>62 feet, 1 inch</td>
</tr>
<tr>
<td>Wingspan:</td>
<td>103 feet, 4 inches</td>
</tr>
<tr>
<td>Engine:</td>
<td>One General Electric F-118-101 engine</td>
</tr>
<tr>
<td>Altitude:</td>
<td>Above 70,000 feet</td>
</tr>
<tr>
<td>Range:</td>
<td>Over 6000 nautical miles, subject to pilot duty time limitations</td>
</tr>
<tr>
<td>Duration:</td>
<td>Over 10 hours</td>
</tr>
<tr>
<td>Cruise Speed:</td>
<td>~400 knots above 65,000 feet altitude (~210 Meters/sec)</td>
</tr>
</tbody>
</table>

**4. RIGHT WING POD**
- 86.0ft³ (2.43m³)
- 650lbs (294 kg)
- 50A @ 115VAC/400Hz
- 80A @ 28VDC

**5. SYSTEM 20 POD**
- 0.74ft³ (0.02m³)
- 45 lbs (20.4 kg)
- 30A @ 115VAC/400Hz
- 30A @ 28VDC

**6. CENTERLINE POD**
- 14.0ft³ (0.40m³)
- 350lbs (159 kg)
- Electrical Shared with Q-Bay

**2. Q-BAY**
- 64.6ft³ (1.83m³)
- 1000lbs (454 kg)***
- 100A @ 115VAC/400Hz
- 140A @ 28VDC

**3. LEFT WING POD**
- 86.0ft³ (2.43m³)
- 650lbs (294 kg)
- 50A @ 115VAC/400Hz
- 80A @ 28VDC

**1. NOSE**
- 47.8ft³ (1.35m³)
- 700lbs (317 kg)***
- 50A @ 115VAC/400Hz
- 70A @ 28VDC

*** - Max combined Q-Bay and Nose payload cannot exceed 1300lbs
**Approach**

- **IRIS - IR**radiance **Instrument Subsystem**: non-imaging telescope with integrating sphere feeding light via fiber optics to a spectrograph. An on-board validation source also sends light to the spectrograph via fiber optics.

- **ARTEMIS - Autonomous, Robotic TEllecope Moun**t **Instument Subsystem** keeps telescope fixed on the Moon to within less than 0.1°.

- **HERA - High-altitude ER-2 A**daptation subsystem integrates subsystems and aircraft together. HERA team manages cables, interfaces and integration with the ER-2 aircraft and develops solutions to protect components from the extreme cold and low pressure during flight or high moisture from condensation during descent.
IRradiance Instrument Subsystem
(IRIS)
IRIS Subsystem

Major Components
- Instrument Enclosure
- Telescope
- Integrating Sphere
- Spectrograph
- Fiber Bundle
- LED Validation Source
- Data Logger
- Instrument Computer
Telescope Design

**Telescope**
- Single-lens Refractor
- Carbon Fiber Tube
- Invar internal support rings and baffles

**Integrating Sphere**
- Used for collecting light
- Removable
- Improves accuracy
- Scrambles polarization
- Fiber optic ports for Spectrometer
- LED Validation Source
IRIS Instrument Enclosure – NIST in a Box

- Carved from a single block of high-grade aluminum.
- Holds spectrograph, validation source, DAQ and instrument computer.
- Temperature and pressure are maintained at sea-level.
- Formally pressure tested to 20 psig for 5 hours (18 hours in pre-check), with no measurable deformation.
Calibration Methodology

1. NIST SI-Traceable reference spectrometer is used to measure a calibration source prior to flight.
2. air-LUSI IRIS system is used to measure the calibration source prior to and after flight.
3. A validation source is observed during ascent and descent (~45 minutes each) to monitor for any changes in calibration.
## Initial Top-Level Error Budget

<table>
<thead>
<tr>
<th>Component</th>
<th>450 nm</th>
<th>550 nm</th>
<th>650 nm</th>
<th>750 nm</th>
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<tbody>
<tr>
<td>Transfer Spectrograph (R)</td>
<td>0.159</td>
<td>0.159</td>
<td>0.159</td>
<td>0.159</td>
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<td>Calibration Source (E)</td>
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<td>0.241</td>
<td>0.213</td>
<td>0.213</td>
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<td>Telescope Calibration (R)</td>
<td>0.462</td>
<td>0.365</td>
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<tr>
<td>Lunar measurement (E)</td>
<td>0.597</td>
<td>0.486</td>
<td>0.445</td>
<td>0.446</td>
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</table>
Autonomic Robotic TElescope Mount Instrument Subsystem (ARTEMIS)
ARTEMIS – How do we control the telescope and track the Moon?

CC → Actuators → Telescope → TC
ARTEMIS – Expected Performance

- Expected range of motion:
  - Elevation of Moon: 47° to 90°
  - Azimuth: ±15°
    - Restricted by window geometry and telescope dimensions

- Expected tracking accuracy
  - air-LUSI mission requirement is 0.5° or better
  - ARTEMIS personal target of 0.25° or better
    - Depends on flight path and pointing device
    - Early tests show pointing is within 0.1°
IRIS telescope was successfully fitted ARTEMIS on the first try on June 13th.
FLIGHT SCHEDULE
### Flight Schedule

#### Engineering Flights

<table>
<thead>
<tr>
<th>Flight Window</th>
<th>Date</th>
<th>Day</th>
<th>Time</th>
<th>T-Z</th>
<th>Obs Target (deg)</th>
<th>Phase (deg)</th>
<th>Duration (hr)</th>
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<tbody>
<tr>
<td>E1.1</td>
<td>1-Aug-18</td>
<td>Wed</td>
<td>4:00</td>
<td>PDT</td>
<td>2</td>
<td></td>
<td>2</td>
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<tr>
<td>E1.2</td>
<td>2-Aug-18</td>
<td>Thu</td>
<td>4:00</td>
<td>PDT</td>
<td>2</td>
<td></td>
<td>2</td>
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</tbody>
</table>

#### Demonstration Flights

<table>
<thead>
<tr>
<th>Flight Window</th>
<th>Date</th>
<th>Day</th>
<th>Time</th>
<th>T-Z</th>
<th>Obs Target (deg)</th>
<th>Phase (deg)</th>
<th>Duration (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1.1</td>
<td>26-Nov-18</td>
<td>Mon</td>
<td>2:30</td>
<td>PST</td>
<td>42</td>
<td></td>
<td>2</td>
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<tr>
<td>D1.2</td>
<td>27-Nov-18</td>
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<td>D1.3</td>
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<td>Fri</td>
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<td>PST</td>
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<td>D5.2</td>
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<td>D5.3</td>
<td>17-Mar-19</td>
<td>Sun</td>
<td>22:30</td>
<td>PST</td>
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<td>0</td>
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</table>

18 = Total Flight Hours
LOOKING FORWARD

- System will continue to be integrated and tested over the next two-three weeks.
- Shipping is schedule for 13 July 2018, with arrival on 16 July 2018.
- Team mobilizes and arrives at AFRC on 16 July to begin aircraft integration work.
- Engineering flights are scheduled for data collects at 0400 PDT, Aug 1 & 2.
- Post flight analysis will be used to prep for up to two Winter flight campaigns.
- Objective of Winter campaigns are meant to demonstrate the air-LUSI capability.
THANK YOU
In Memoriam

Keith Lykke
1956 - 2016

Bob Barnes
1947 - 2015

Dennis McCarthy
1940 - 2018
As we know, instruments, especially spaceborne instruments, change over time.

So, time-dependent calibration is necessary to account for changes in measurement scale.

To measure surfaces with very low reflectivity, such as deep water, the calibration needs to be extremely low in uncertainty.
Why?

Case 1 water, Chl = 1

A small relative error in the at-sensor measurement leads to a systematic, relative error in the surface measurement that is an order of magnitude larger.
Individually or in combination these errors can affect estimates of biogeophysical parameters derived from spectral reflectance features.

For instance, changes in opposite directions in the NIR channel can cause coastal and open ocean chlorophyll $a$ to change in opposite directions.

Small drifts in calibration over time can lead to misinterpretation of geophysical observations.

Hence, we need an accurate, stable time-dependent calibration of ocean color sensors, ideally better than 0.3% (k=2).
There are various methods that support a time-dependent calibration.

A fairly reliable approach is using the Moon as a calibration reference because:

- to best of our experience, lunar reflectance has not changed more than $10^{-8}$ and
- the brightness of Moon is directly commensurate with Earth observations, as opposed the Sun, which requires potentially unstable optical components to attenuate its signal.
• Many satellite missions make lunar observations for cal/val, but there are example applications that are used to observe life in the upper layers of the open ocean:

  - SeaWiFS time-dependent calibration was entirely reliant on the Moon.
  - For Suomi NPP VIIRS, we currently use the Moon to address small spurious trends in the solar calibration system.
  - The PACE mission also intends to use lunar observations for calibration, in concert with its solar calibration system.

ROLO biases are predominantly phase dependent.

PLEIADES (CNES)

- 505 nm
- 558 nm
- 663 nm
- 844 nm
To use the Moon, we need to know two things first:

1. The spectral photometric properties of the lunar surface.
2. The effect of the viewing and illumination geometry on an observation.

With these, we can predict what a sensor should see when making an observation.

That prediction comes from a model based on empirical data and first principle calculations.

The best model available is USGS’s Robotic Lunar Observatory (ROLO) model.

ROLO provides lunar spectral irradiiance given any viewing and illumination.
DEVELOPMENT OF THE ROBOTIC LUNAR OBSERVATORY MODEL (ROLO)

Extensive characterization of the Moon using ground-based measurements acquired by a dedicated facility — the Robotic Lunar Observatory (ROLO):

- Located on USGS Flagstaff campus, 2143m altitude
- Twin telescopes, 20 cm dia.
  - 23 VNIR bands, 350–950 nm
  - 9 SWIR bands, 950–2450 nm
- Imaging systems — radiance
- > 110,000 Moon images
  - phases from eclipse to 90°
- > 900,000 star images
  - used for atmospheric transmission corrections
Removable Alignment Camera

- Use for test telescope alignment
- Stray light testing
- Aligning ARTEMIS tracking camera
Bottom Level

- SSR X 5
  - (3 pilot switches, 1 cockpit lamp, N2 solenoid)
- LED validation source
- Triple output VDC
- 24 VDC
- VAC terminal block
- Cable break out
Inside Bottom of Enclosure

- Slotted upright wall
- Computer table
- Mil spec feed through
- Flange x2
- QF-40 flange clamp x2

CAS 140 Spectrometer
DS-1000