air-LUSI

airborne LUunar Spectral Irradiance Mission

Presented by Kevin Turpie
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MODIS/VIIRS Science Team Meeting
Silver Spring, Maryland
Limitations of the Current System

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 *may be* ~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 WGCV 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).

Based on Tom Stone, CEOS WGCV IVOS-29 Meeting 15 Mar 2017
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.
air-LUSI Team

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Dana Defibaugh (NIST)
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Marc Mogavero (Hawk)
Ron Bettini (Hawk)
Gene Eplee (SAIC/GSFC 616.2)
Approach

- **IRIS - IR**radiance Instrument **S**ubsystem: 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 **T**elescope **M**ount Instrument **S**ubsystem 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.
ER-2 Basic Configuration

Specifications

<table>
<thead>
<tr>
<th>Component</th>
<th>Volume</th>
<th>Weight</th>
<th>Electrical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nose</td>
<td>47.8 ft³ (1.35 m³)</td>
<td>700 lbs (317 kg)***</td>
<td>50A @ 115VAC/400Hz, 70A @ 28VDC</td>
</tr>
<tr>
<td>Q-Bay</td>
<td>64.6 ft³ (1.83 m³)</td>
<td>1000 lbs (454 kg)***</td>
<td>100A @ 115VAC/400Hz, 140A @ 28VDC</td>
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<tr>
<td>Right Wing Pod</td>
<td>86.0 ft³ (2.43 m³)</td>
<td>650 lbs (294 kg)</td>
<td>50A @ 115VAC/400Hz, 80A @ 28VDC</td>
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<tr>
<td>System 20 Pod</td>
<td>0.74 ft³ (0.02 m³)</td>
<td>45 lbs (20.4 kg)</td>
<td>30A @ 115VAC/400Hz, 30A @ 28VDC</td>
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<tr>
<td>Centerline Pod</td>
<td>14.0 ft³ (0.40 m³)</td>
<td>350 lbs (159 kg)</td>
<td>Electrical Shared with Q-Bay</td>
</tr>
</tbody>
</table>

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

*** - Max combined Q-Bay and Nose payload cannot exceed 1300 lbs
IRradiance Instrument Subsystem
(IRIS)
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
First Moonlight
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.
- Pressure and temperature remain stable during engineering flights.

CAS 140 Spectrometer
Autonomic Robotic TElescope Mount Instrument Subsystem (ARTEMIS)
ARTEMIS – How do we control the telescope and track the Moon?

CC → Actuators → Telescope → TC
ARTEMIS – Expected Range of Motion

- Expected range of motion:
  - Elevation of Moon: 46° to 88°
  - Azimuth: ±15°
    - Based on unrestricted field of regard
    - Restricted by window geometry and telescope dimensions
ARTEMIS – Expected Range of Motion

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IRIS telescope view out the wing pod view port while situated on ARTEMIS.
Aug 1 flight lines
Aug 2 flight lines
The air-LUSI situation room.
SUMMARY

- Integration and testing of IRIS, ARTEMIS, and HERA were successful.
- Integration of the air-LUSI system onto the ER-2 aircraft was successful.
- HERA heaters performed as designed.
- ARTEMIS locked onto and tracked the Moon to within about 0.1°.
- IRIS instrument enclosure held pressure and temperature steady.
- IRIS telescope and instrument collected lunar irradiance with high SNR and sensitivity to the lunar spectrum.
- Calibration processing must be done to get geophysical values and uncertainties.
- Engineering data will be analyzed to check out systems and identify possible improvements.
- Planning and preparations will begin for next flight in the November / December time frame.
THANK YOU
BACKUP SLIDES
Entire data set for Engineering Flight 2 (Aug 2)
## Initial Top-Level Calibration 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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<tr>
<td>Calibration Source (E)</td>
<td>0.313</td>
<td>0.241</td>
<td>0.213</td>
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<tr>
<td>Telescope Calibration (R)</td>
<td>0.462</td>
<td>0.365</td>
<td>0.329</td>
<td>0.330</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>
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
LUNAR OBSERVATIONS FROM SPACE

- 58 Moon obs by SNPP VIIRS
- 6 by J1/N20 VIIRS
- 522 by Terra MODIS (inc. serendipitous obs)
- 377 by Aqua MODIS
- 64 by Landsat 8 OLI
- 26 Hyperion spectral images of the Moon have been processed to irradiance.
- Several thousand from geostationary imagers
- 1.7 million by the Planet Labs fleet.
- Others: EPIC, CERES, SCIAMACHY, PROBA-V, OCO-2, GOSAT, and PLIEADES
- HiRISE did lunar cal obs from orbit around Mars.
## Remote Sensing Activities: Spaceborne Imaging Spectrometers

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Orbit</th>
<th>Global?</th>
<th>&gt;1μm?</th>
<th>Status</th>
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<tbody>
<tr>
<td>HICO</td>
<td>ISS</td>
<td>No</td>
<td>No</td>
<td>Off</td>
</tr>
<tr>
<td>CHRIS/Proba</td>
<td>Polar</td>
<td>No</td>
<td>No</td>
<td>Working</td>
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<tr>
<td>Hyperion</td>
<td>Polar</td>
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<td>Yes</td>
<td>Off</td>
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<tr>
<td>EnMap</td>
<td>Polar</td>
<td>No</td>
<td>No</td>
<td>2020</td>
</tr>
<tr>
<td>DESIS</td>
<td>ISS</td>
<td>No</td>
<td>No</td>
<td>2018?</td>
</tr>
<tr>
<td>HISUI</td>
<td>ISS</td>
<td>No</td>
<td>No</td>
<td>2019?</td>
</tr>
<tr>
<td>PRISMA</td>
<td>Polar</td>
<td>No</td>
<td>No</td>
<td>2019?</td>
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<tr>
<td>COCI</td>
<td>Polar</td>
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<td>-</td>
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<tr>
<td>PACE⁺</td>
<td>Polar</td>
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<td>Yes</td>
<td>2022</td>
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<tr>
<td>GeoCAPE</td>
<td>GEO</td>
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<td>No</td>
<td>-</td>
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<tr>
<td>HyspIRI/SBG</td>
<td>Polar</td>
<td>Yes</td>
<td>Yes</td>
<td>-</td>
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<tr>
<td>Landsat 10</td>
<td>Polar</td>
<td>Yes</td>
<td>Yes</td>
<td>-</td>
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</tbody>
</table>
ROLO biases are predominantly phase dependent.
### Remote Sensing Activities:
#### Airborne Campaigns and Feasibility Studies

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Activity</th>
<th>Sensors</th>
<th>Subject of Study</th>
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<tbody>
<tr>
<td>ABC LOBO</td>
<td>Study</td>
<td>AVIRIS, PRISM</td>
<td>S. FL Watershed</td>
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<tr>
<td>CORAL</td>
<td>Campaign</td>
<td>PRISM</td>
<td>Coral Reefs</td>
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<tr>
<td>HyperMAQ</td>
<td>Study</td>
<td>?</td>
<td>Coastal/Inland Waters</td>
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<tr>
<td>HyspIRI APC: CA</td>
<td>Campaigns</td>
<td>AVIRIS-C</td>
<td>Coastal/Inland Waters</td>
</tr>
<tr>
<td>HyspIRI APC: HI</td>
<td>Campaigns</td>
<td>AVIRIS-C (+PRISM?)</td>
<td>Coral Reefs (MOBY)</td>
</tr>
<tr>
<td>C-HARRIER</td>
<td>Instrument</td>
<td>2 Line Spectrometers</td>
<td>Coastal/Inland Waters</td>
</tr>
<tr>
<td>AirShrimp</td>
<td>Instrument</td>
<td>Line Spectrometer</td>
<td>Coastal Waters</td>
</tr>
<tr>
<td>Great Lakes AC</td>
<td>Campaigns</td>
<td>Imaging Spectrometer</td>
<td>Inland Water Quality</td>
</tr>
<tr>
<td>GLiHT</td>
<td>Campaigns</td>
<td>Imaging Spectrometer</td>
<td>S. FL Mangroves</td>
</tr>
<tr>
<td>air-LUSI</td>
<td>Instrument</td>
<td>Spectrograph</td>
<td>Moon (Reference)</td>
</tr>
</tbody>
</table>
The system consists of a refracting telescope that focuses the lunar light into an integrating sphere which is fiber coupled to a spectrograph. Advantages include a low sensitivity to lunar shape and polarization and a relatively simple in-field calibration protocol. The spectrograph is extensively characterized using NIST’s SIRCUS facility.
ER-2
The air-LUSI system just prior to upload onto the ER-2.

IRIS instrument enclosure loaded into the wing pod mid-body.
ER-2 SuperPod Midbody Payload Area

Forward Midbody looking Aft

Lower Midbody looking Up and Aft
IRIS Subsystem

Major Components
- Instrument Enclosure
- Telescope
- Integrating sphere
- Spectrograph
- Fiber Bundle
- Validation source
  - LEDs
- Data Logger
- Instrument Computer
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
Top Level

- Femto amp x2
- NI-6211
- Slot for cabling
Inside Bottom of Enclosure

- Slotted upright wall
- Computer table
- QF-40 flange clamp x2
- Mil spec feed through Flange x2
ARTEMIS – Testing and Performance

- **Controlled Autonomous Tracking (CAT) Test** – testing in laboratory tracking a light spot on wall or ceiling.
- **“Pick-Up” Test** – Lunar tracking from bed of moving vehicle.
- **Engineering flights** – ARTEMIS tracked the Moon in flight to within around 0.1°.
ER-2 Aft-Body Payload Area
Removable Alignment Camera

- Use for test telescope alignment
- Stray light testing
- Aligning ARTEMIS tracking camera
TVAC Test

- Demonstrated survivability of telescope, i.e., repeatability of measurements.
- Test showed that heating system on the integrating sphere work well to stabilize its temperature.
Tunnel Test 1: Back view of the telescope on a Mount looking toward a source, white circle in the background. The white oblong ‘disks’ on the top of the telescope body are Teflon and are used during TVAC testing.

TVAC Test: View of the telescope installed in the TVAC chamber from the back. Toward the front end of the picture is the integrating sphere detector. The Teflon on the bottom of the chamber is to protect the fiber from getting too cold.