Recent Developments Toward a High-accuracy Lunar Reference Standard for Reflected Solar Wavelengths

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Workshop on An SI-Traceable Space-based Climate Observing System
National Physical Laboratory, Teddington, UK
10 September 2019

Use of the Moon by a SITSCOS

SITSCOS mission accuracy requirements for Earth measurements demand special consideration of on-orbit sensor calibration.

The current most reliable system for lunar calibration is ROLO (USGS)

- uncertainties in the ROLO model limit its use for absolute calibration
  - currently ROLO outputs cannot meet requirements for an absolute reference for space-based climate observations
  - these uncertainties reflect a limitation of the ROLO model — the Moon itself has exceptional capabilities as a radiometric reference
- several active projects have objectives to make new, high-accuracy lunar radiometric measurements
  - ultimately will enable redeveloping the lunar calibration reference with improved absolute accuracy

Use of the Moon by a SITSCOS

What is the role of lunar calibration for a space-based climate observing system ?

A backup validation check for sensor performance on orbit ?

Use the Moon as a common reference for inter-calibration ?

Target the Moon for benchmark measurements, to improve the reference ?

Use of the Moon by a SITSCOS

What is the role of lunar calibration for a space-based climate observing system ?

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Target the Moon for benchmark measurements, to improve the reference ?

Best practices would suggest all of the above.

Outline

- Brief overview of the Moon as a radiometric reference
  - the lunar reference manifest as an analytic model
  - ROLO development and usage
- Considerations for new lunar measurement database
  - high absolute accuracy with SI traceability
  - geometric specification of the Moon's changing brightness (phase, librations)
  - spectral specification
  - polarization of moonlight
- Capabilities enabled by a high accuracy lunar reference
- 3 current NASA efforts that will acquire high-accuracy lunar measurements

The Moon as a radiometric reference

At reflected solar wavelengths, the Moon acts as a solar diffuser which has exceptionally stable reflectance, $<10^{-8}$ per year.

But the Moon's apparent brightness is continuously changing. To use it as a calibration reference requires the capability to predict its brightness for any lunar observations made by an instrument.

This is accomplished using an analytic model, which can be queried for the Sun-Moon-Observer geometry of the instrument's Moon observations.

The inherent stability of the lunar surface means:

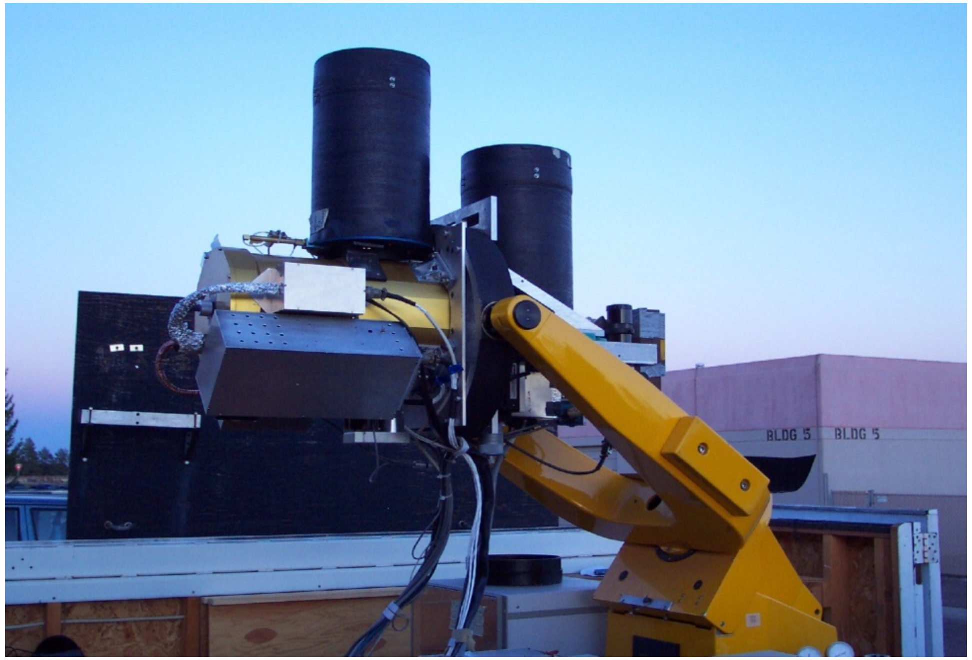
- the changing lunar brightness is periodic and predictable
  - enables radiometric and reflectance modeling
- a lunar reflectance model is valid for any time
  - including past Moon observations
  - enables cross-calibration without simultaneous observations

The lunar radiometric reference — ROLO development

To build a predictive lunar model requires collecting an extensive set of measurements. ROLO is a dedicated lunar observation facility:

- Located on USGS Flagstaff campus, 2143m altitude
- Twin telescopes, 20cm dia. primary mirrors, Ritchey-Crétien optics
  - 23 VNIR bands, 350−950 nm
  - 9 SWIR bands, 950−2450 nm
- Imaging systems — measure radiance
- Operated more than 8 years
- >110,000 Moon images
  - lunar phases from First Quarter to Last Quarter
- >10^6 Star images
  - used for atmospheric corrections

ROLO telescopes zenith-pointed at dusk



The lunar radiometric reference — ROLO development

Research and development at USGS determined that the most useful quantity for radiometric calibration is spatially integrated spectral irradiance.

- increases signal-to-noise by summing multiple radiance measurements (pixels)
- eliminates the need for co-registration of images with the reference (model)

The ROLO model that generates lunar spectral irradiance was developed and operates in terms of disk-equivalent reflectance:

$$\ln A_k = \sum_{i=0}^{3} a_{ik} g^i + \sum_{j=1}^{3} b_{jk} \Phi^{2j-1} + c_1\phi + c_2\theta + c_3\Phi\phi + c_4\Phi\theta$$
$$+ d_{1k} e^{-g/p_1} + d_{2k} e^{-g/p_2} + d_{3k} \cos((g - p_3)/p_4)$$

  - a function of only the photometric geometry variables of phase angle g and librations as selenographic sub-observer longitude θ and latitude φ and sub-solar longitude Φ

The lunar radiometric reference — ROLO development

The fundamental model outputs (A_k) at 32 ROLO bands are fitted with a lunar reflectance spectrum, which is then convolved with the instrument band spectral response functions and the solar spectrum to give the lunar irradiance (E_M) at the sensor band wavelengths:

$$E_\mathrm{M} = \frac{\Omega_\mathrm{M}}{\pi} \frac{\int A_\mathrm{fit}(\lambda)\, E_\mathrm{Sun}(\lambda)\, S(\lambda)\, d\lambda}{\int S(\lambda)\, d\lambda}$$

A_fit = lunar reflectance spectrum
E_Sun = Solar spectral irradiance
S = spectral response function
$\Omega_\mathrm{M} = 6.418 \times 10^{-5}$ sterad

NOTE: this step must use the same solar spectral model as was used for conversion of the ROLO basis data to reflectance

The model computations (A_fit) and Ω_M are for standard Sun-Moon and Moon-observer distances of 1 AU and 384400 km

Apply distance corrections:

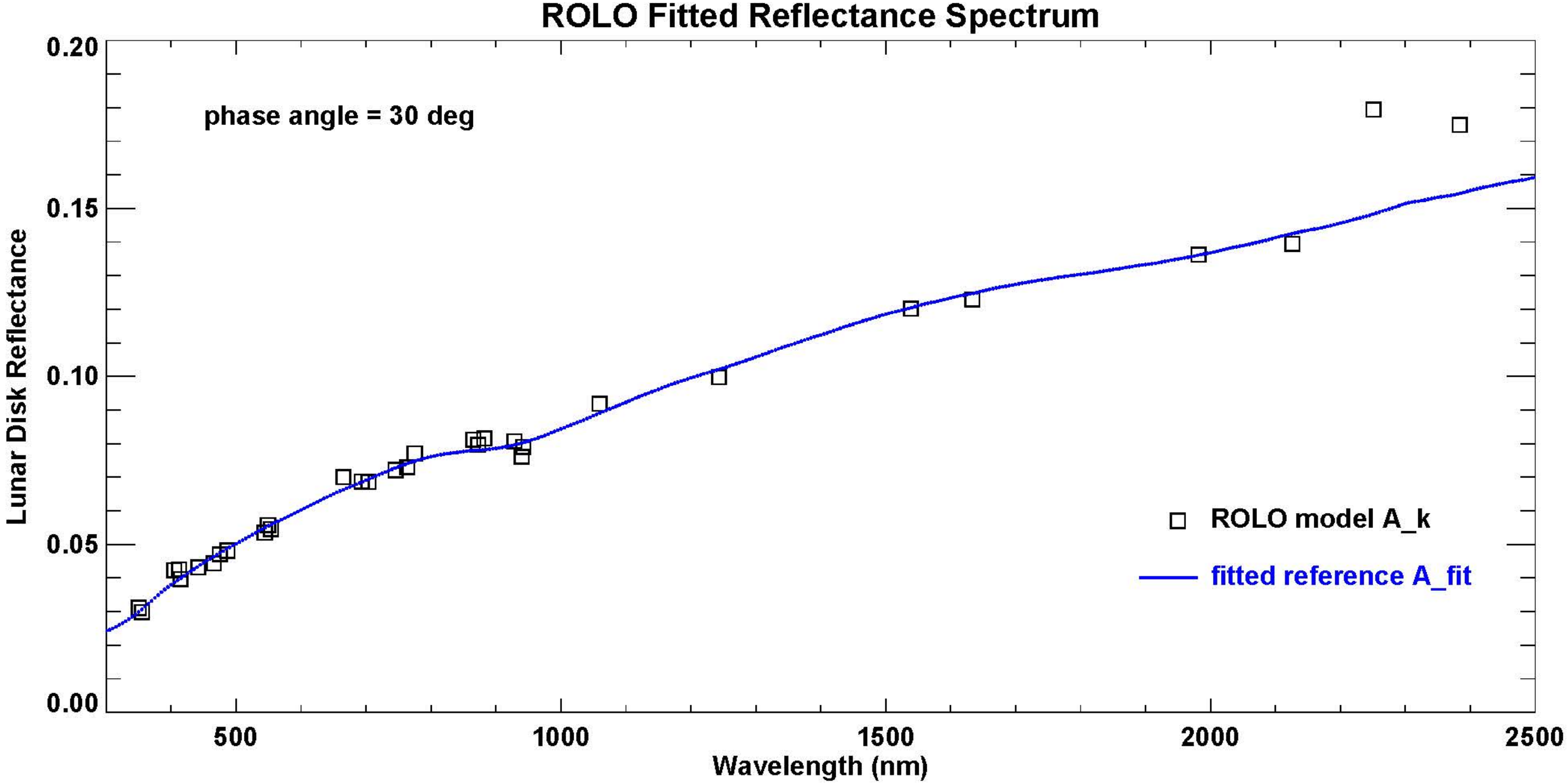
$$E'_\mathrm{M} = E_\mathrm{M} \left(\frac{1\ \mathrm{AU}}{d_\mathrm{Sun-Moon}} \right)^2 \left(\frac{384\,400\ \mathrm{km}}{d_\mathrm{Moon-Obs}} \right)^2$$

The final output E'_M is the lunar spectral irradiance present at the instrument location at the time of the observation, in each sensor spectral band.

The lunar radiometric reference — ROLO development

Example of fitting the reference lunar reflectance spectrum

reference is mixture of RELAB spectra for Apollo returned samples 62231 (soil, 95%) and 67455 (breccia, 5%)



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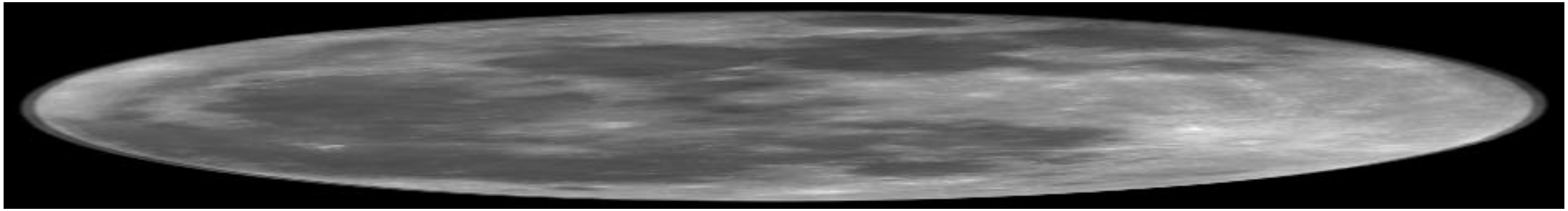
Example of using lunar calibration — Landsat 8 OLI

- Lunar images built up from scan lines
  - spacecraft rotation and detector sampling rates give ~8.25x oversampling



Landsat 8 OLI Moon image acquired 27 March 2013

- Irradiance is measured by summing image radiance pixels:

$$E_{\text{meas}} = \frac{\Omega_{\text{p}}}{\eta} \sum_{i}^{N} L_i$$

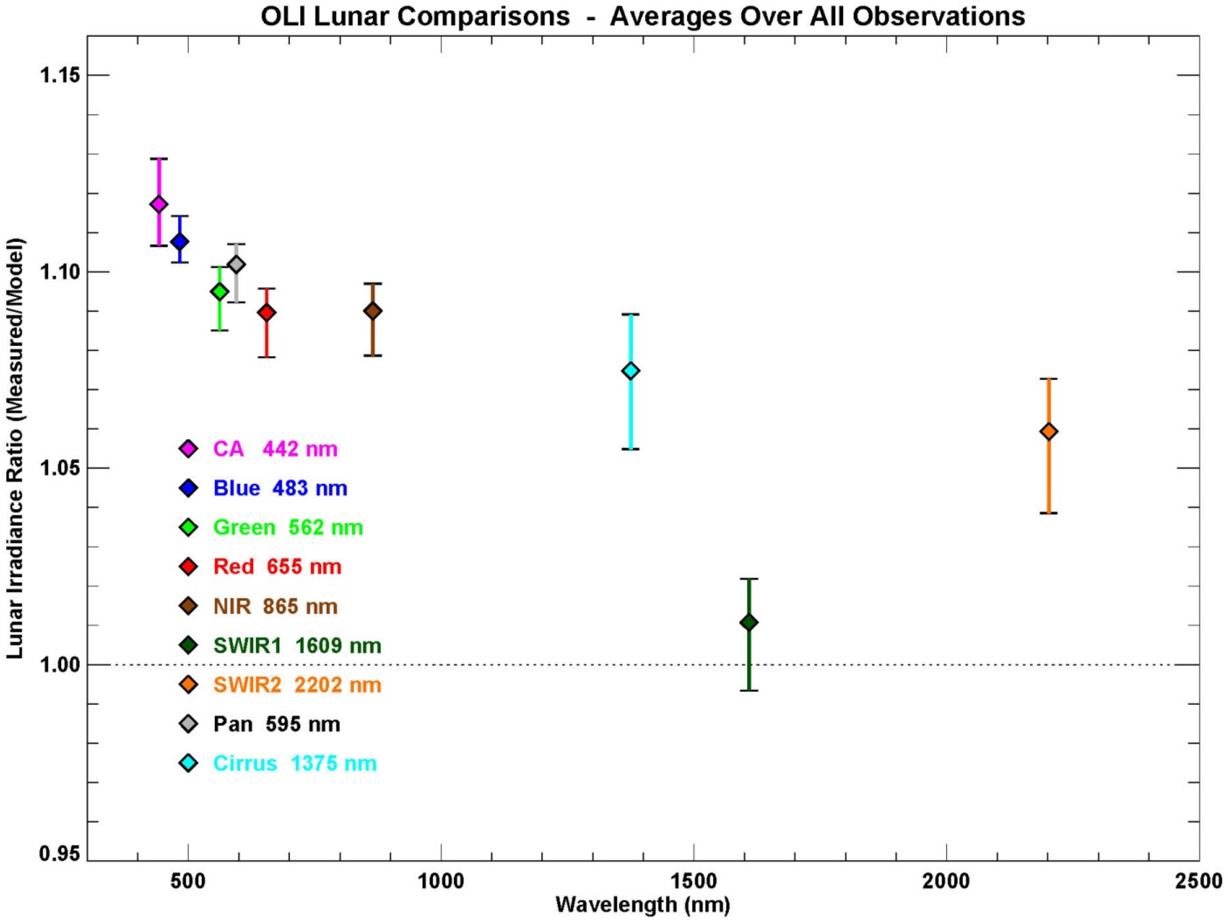
Ω_{p} = pixel IFOV (solid angle)
η = oversampling factor
L_i = pixel radiance
N = # of pixels on Moon

- ★The accuracy of lunar irradiance measurements from images depends on careful evaluation of several imaging parameters:
  - net radiance: subtraction of the dark background
  - actual detector spatial response (IFOV, different from GSD)
  - oversampling <u>of the Moon disk</u> (different from slew/sampling ratio)

Example of using lunar calibration — Landsat 8 OLI

Lunar calibration analysis: comparing irradiances measured from images against corresponding model-generated reference values

- results presented as ratios of measured/ROLO irradiances
- symbols show mean values and range (“error bars”) over a set of 224 observations
- differences range from 6% to 13% (except 1.6 µm band)
  - exceeds the known uncertainty in ROLO model outputs
  - leads to not using the Moon for absolute calibration



Advancing development of the lunar reference

The uncertainties in ROLO model outputs reflect the lunar irradiance measurements taken from the ROLO image dataset. The two largest error sources are:

- atmospheric correction, derived from star observations
  - stellar extinction measurements were limited to 2.0 airmass
- calibration against Vega
  - uncertainty in Vega absolute irradiance
  - ROLO measurements of Vega, require atmospheric correction

The Moon's absolute brightness potentially can be known to the accuracy limits of field measurements.

- a practical limit for lunar spectral irradiance may be ~0.5% ($k=2$) absolute

To achieve this requires collecting a new lunar measurement database

Requirements for a new lunar measurement database

- Primary consideration: absolute accuracy
  - with SI traceability, to primary optical power standards
  - at least some measurements acquired from above the atmosphere, to eliminate (or greatly reduce) uncertainty due to atmospheric corrections
- Radiometric and geometric specification of the lunar irradiance
  - requires sufficient sampling the parameter space of phase angles and lunar librations
  - the geometries available for viewing are constrained by the Moon's tilted orbit
  - minimum three years of acquisitions required
- Spectral specification
  - the lunar reflectance spectrum is dependent on phase angle and on terrain type
  - different observation geometries sample different distributions of terrains
  - requires advanced lunar modeling to capture the different spectral compositions

Requirements for a new lunar measurement database

- Polarization specification
  - moonlight is slightly polarized, up to ~13%
    - varies widely with phase angle
    - dependent on wavelength and lunar terrain type (thus librations)
  - an inherent property of the Moon, thus a supplemental part of a lunar reference
  - effects are instrument-dependent, tied to the sensor's polarization sensitivity
  - requires developing a polarization model separate from the radiometric one
    - built from a dataset of full-disk polarization measurements, spectrally resolved and spanning the full range of phase angles

Capabilities enabled by a high accuracy lunar reference

- Calibration to the same reference standard for all sensors that have viewed the Moon
  - can remove cross-sensor biases; facilitates inter-operability of datasets
- Back-calibration of data archives that contain lunar images
  - Moon observations acquired in the past are valid forever. An updated lunar model can be applied to irradiance measurements made at any time.
  - example: geostationary meteorological imagers
    - the Moon is captured in the off-Earth regions of a rectangular FOR
    - potential consistent EO records extending back decades in time
- Ability to bridge a gap in otherwise continuous Earth observation records
  - given views of the (invariant) Moon by instruments operating before and after the gap
  - the accuracy of the bridge calibration depends on the accuracy of the lunar reference
- Transfer of pre-launch calibration to on-orbit operations

New, high accuracy lunar measurements

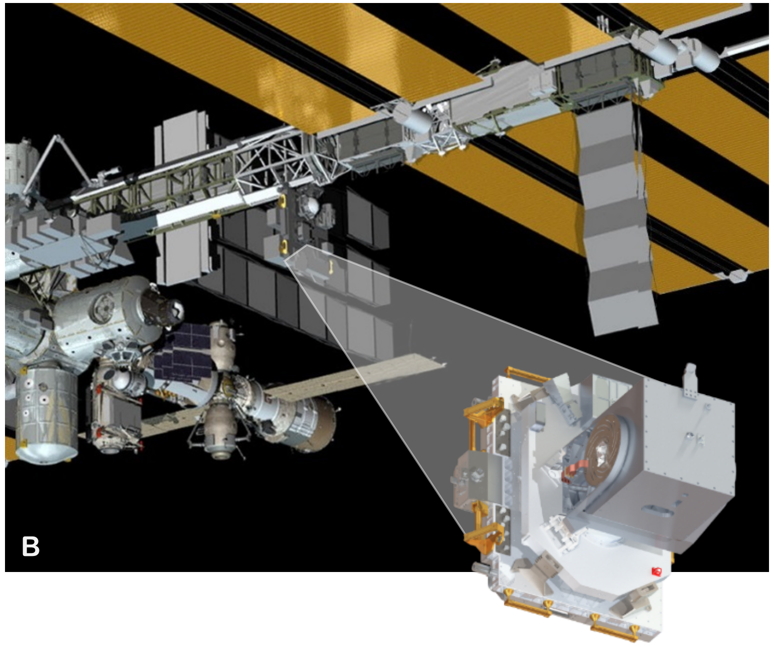
CLARREO Pathfinder (CPF)

Mission objective: to demonstrate technologies required for producing climate records from Earth observations:

1. benchmark measurements of Earth spectral reflectance with unprecedented absolute accuracy: ≤0.3% (k=1)
2. inter-calibration of space-based sensors

The current NASA-funded CPF project supports a reflective solar instrument

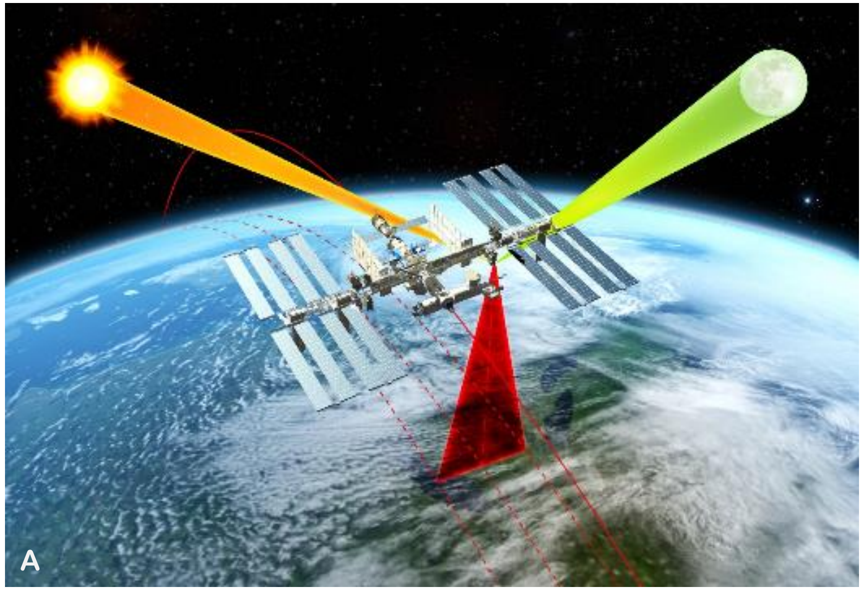
- to be hosted on the International Space Station in the 2023 timeframe
- sensor is based on the Hyperspectral Imager for Climate Science (HySICS)



New, high accuracy lunar measurements

CLARREO Pathfinder (CPF)

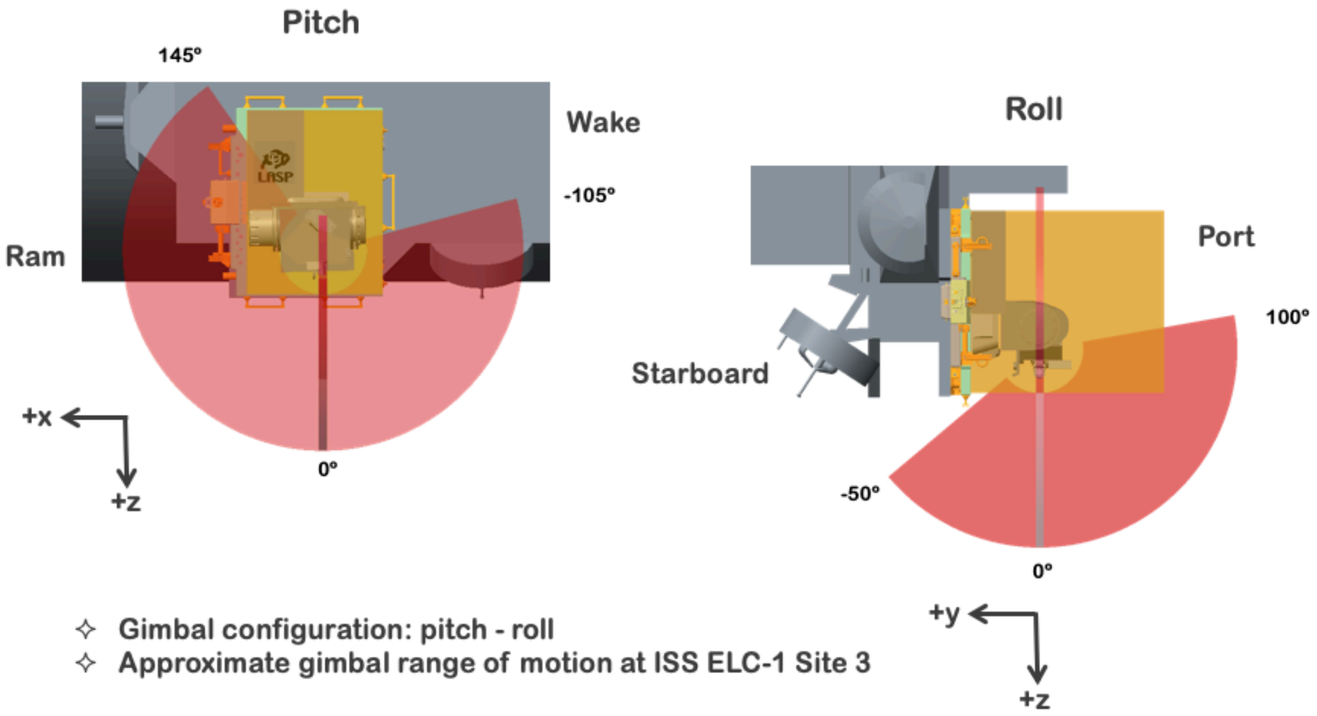
- location of the CPF payload on ISS is optimized for Earth views (nadir and inter-calibration) and Sun views (for sensor calibration)
  - mounted on ExPRESS Logistics Carrier 1, site 3
  - nominal nadir-viewing spectral imaging in pushbroom mode
- observations of the Moon are planned as measurements of opportunity
  - simulations show numerous Moon viewing opportunities will be available during the nominal one year of CPF operations
  - scheduled to cover a wide range of phase angles
- lunar spectral images will be built up from across-slit scans over the Moon, acquired using gimbal motions



New, high accuracy lunar measurements

CLARREO Pathfinder (CPF)

- the CPF instrument has a 2-axis gimbal, for roll-over-pitch pointing:
- for off-nadir across-slit scans, the slit footprint will rotate on the target (e.g. the Moon)
  - leads to differential oversampling
- processing spectral images of the Moon to lunar irradiance will require precise knowledge of:
  - pointing to the Moon
  - sampling and gimbal slew rates
  - ISS position and attitude
  - spectrometer spatial response

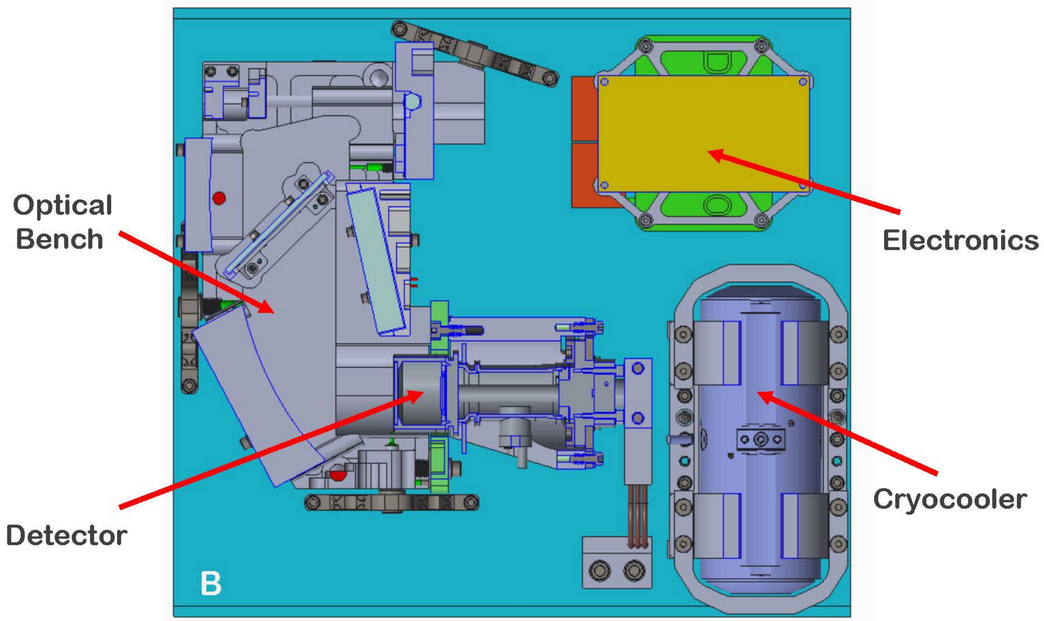


New, high accuracy lunar measurements

ARCSTONE

Mission objective: to enable using the Moon for accurate absolute calibration by collecting an extensive set of lunar spectral reflectance measurements

- compact spectrometer on a 6U cubesat
- whole-disk measurements of the Moon and Sun using the same optical path
  - spectrally resolved, 350-2300 nm range with 4-8 nm spectral sampling
  - measurement goal is to produce lunar spectral reflectance with accuracy ≤0.5% ($k=1$)
- SI traceability is achieved by reference to solar spectral irradiance (e.g. TSIS)

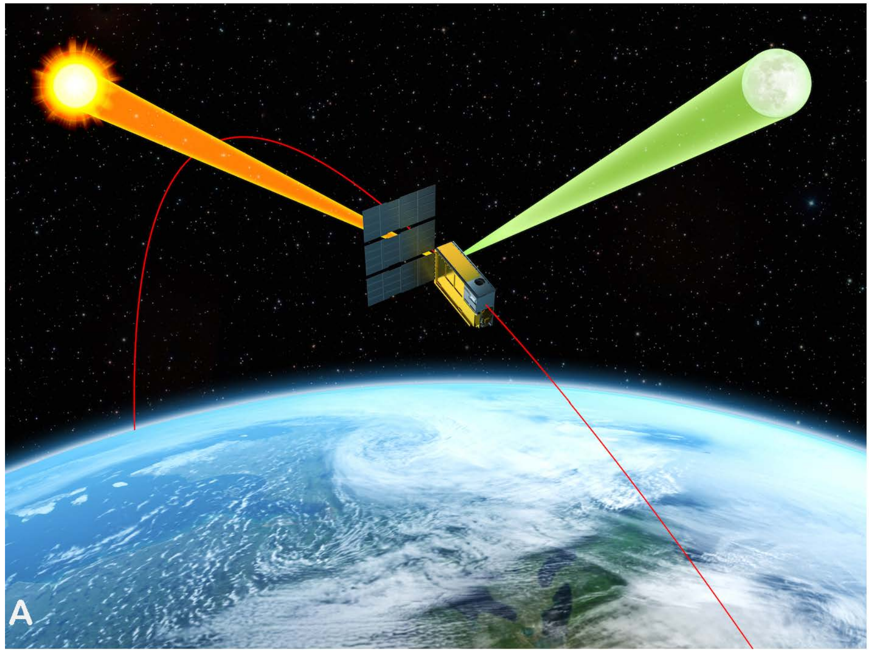


ARCSTONE instrument layout in 4U footprint

New, high accuracy lunar measurements

ARCSTONE

- planned for Sun-synchronous orbit at 550 km altitude, 3-year operational lifetime
- 12-hour Moon observation cadence
  - for sufficient phase and libration sampling
- collect phase angles up to 135°
  - to expand lunar calibration capabilities up to 3 weeks per month
- development is on track for potential space flight demonstration in the 2024 timeframe
  - supported by NASA Langley Research Center

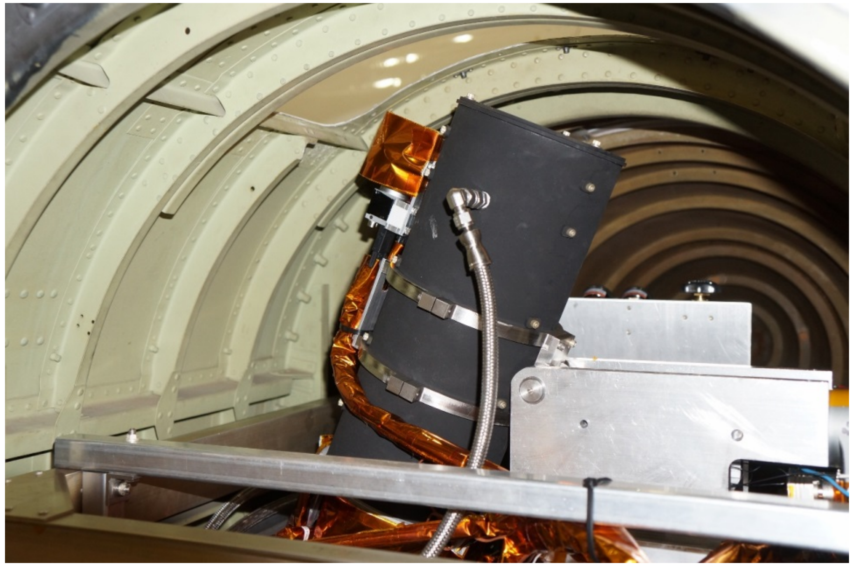


New, high accuracy lunar measurements

Airborne Lunar Spectral Irradiance (air-LUSI)

Project operational objective: to acquire high-accuracy spectral irradiance measurements of the Moon from a high-altitude aircraft

- observations from the NASA ER-2 platform; flies at 70,000 feet (21.6 km) altitude, above 90% of the atmosphere
- collaboration of NASA, NIST, USGS, Univ. Guelph (Canada)
- direct measurements of lunar irradiance
  - instrument is a variant of NIST ground-based LUSI
  - non-imaging telescope with small integrating sphere at the focus
  - coupled to a field spectrograph via fiber optic cable
  - wavelength range 350-1100 nm



air-LUSI telescope mounted in the ER-2 wing pod

K. Turpie

USGS NASA

New, high accuracy lunar measurements

Airborne Lunar Spectral Irradiance (air-LUSI)

- calibration against NIST sphere sources
  - pre- and post-flight irradiance calibrations
  - reference spectrograph to monitor source
  - also on-board LED validation source
- autonomous robotic tracking system
  - locks onto the Moon, compensates for aircraft motion during acquisitions
  - demonstrated capability for tracking to <0.1°
- active thermal control of critical optical components
  - including systems exposed to the ambient environment (telescope, tracking camera) and inside the pressurized wing pod section (spectrograph, LEDs, control & telemetry)

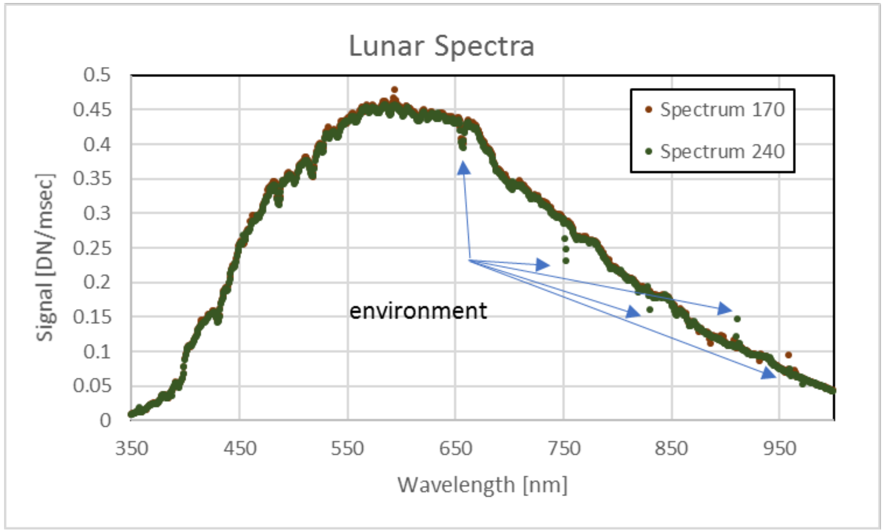
air-LUSI calibration in the aircraft hangar

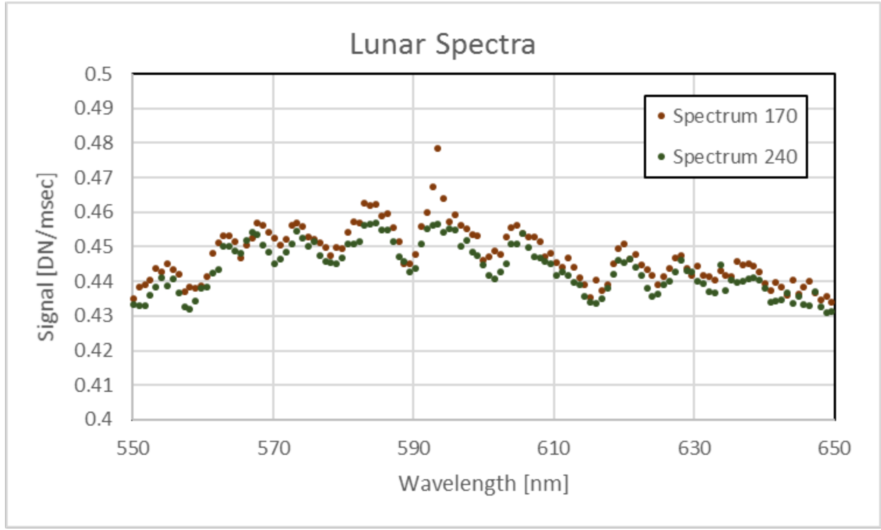
K. Turpie

New, high accuracy lunar measurements

Airborne Lunar Spectral Irradiance (air-LUSI)

- engineering/test flights were conducted August 2018





- demonstration (science) flights are scheduled for 13-17 November 2019
  - phase angles +10° to +60°; expected absolute accuracy ~1% (k=1)
- ultimate air-LUSI accuracy goal: ≤0.5% (k=1) absolute
  - ability to constrain the absolute scale of the lunar calibration reference (ROLO model)

Summary

- The Moon represents a radiometric reference with high capabilities, but its full potential as an absolute calibration standard has not yet been realized
  - ➢ The ROLO lunar irradiance model is currently the most reliable lunar reference, but it has known limitations
  - ➢ measuring absolute lunar irradiance from Moon images requires close attention to details of processing the images to measurements
- New measurements are required to improve the lunar reference
  1) high accuracy, with SI traceability
  2) with sufficient breadth and density of phase and libration coverage for modeling
  3) spectrally resolved
  4) plus a full-disk polarization database
- Several projects are currently underway to acquire high accuracy lunar irradiance measurements
  – results from the ER-2 high-altitude aircraft should be available “soon”

Thank You!