Lunar Observations Planning for CLARREO

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CLARREO SDT 2016 Spring Meeting
University of Michigan
10 – 12 May 2016

CLARREO RS Observations of the Moon

Nominal use of Moon views: verification of on-orbit calibration

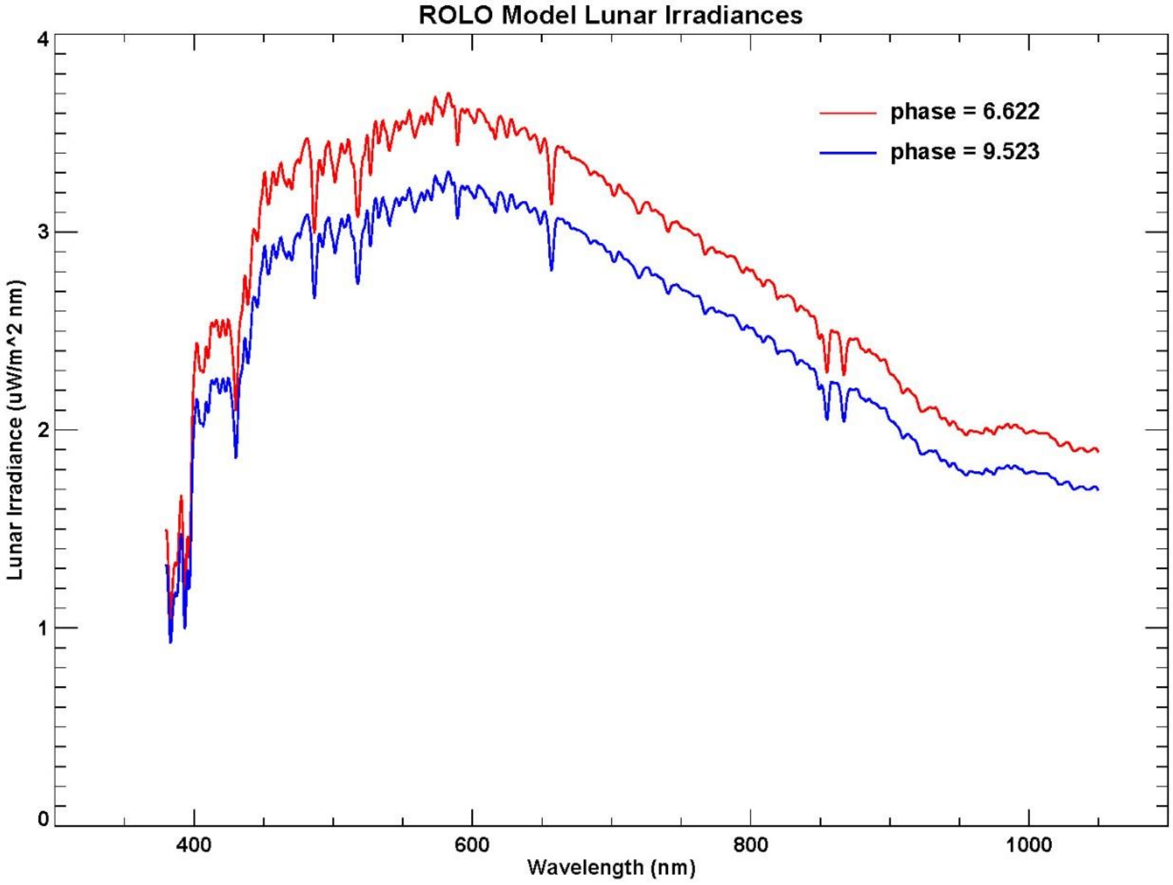
- The calibration reference for the RS instrument is the Sun, and the solar input requires attenuation
- Lunar radiance is reflected sunlight; no attenuation needed
- Solar / lunar measurement ratio quantifies attenuator performance
- This technique is feasible due to the temporal invariance of the lunar reflectance, $\sim 10^{-8}$ per year

CLARREO calibration plan calls for viewing the Moon monthly, at 5°–9° phase angle

- The variation in lunar irradiance over this range is more than 10%, wavelength-dependent (next slide)
- RS lunar measurements will require normalizing, done using a predictive reference such as the USGS ROLO model

Example of ROLO model-generated lunar irradiance spectra

- Phase angles 6.6° and 9.5° (~9 hours separation)



Radiometric Modeling of the Moon

The USGS lunar irradiance model was built empirically from an extensive set of characterization measurements of the Moon collected by the Robotic Lunar Observatory (ROLO).

- Multiple years of observations are required to capture the variations in the Moon's brightness sufficiently for modeling
  - ROLO operated more than 8 years
  - multispectral imaging telescopes: 32 bands, 350 nm to 2.5µm
- Lunar irradiance measurements from ROLO were converted to disk-integrated reflectance and fitted to an analytic model form
  - lunar reflectance spectrum is smooth, removes solar spectral structure
  - empirical model formulation, designed to minimize fit residuals
  - ~1200 data points fitted for each of 32 ROLO bands
  - mean absolute residual for all bands ≈1%
    - ➢ a measure of the model's predictive precision

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CLARREO Application

Monitoring the RS solar attenuation system using the Moon requires:

- a predictive lunar reference, to account for the variations in the lunar spectral irradiance for different observations
  - due to different phase angles and librations
- knowledge of the lunar reflectance with *relative* accuracy at a similar level as the accuracy requirement for the attenuation: 0.2% ($k=1$)

This is beyond current capabilities of the USGS lunar model

- estimated uncertainty is 5–10% absolute, based on comparisons of well-calibrated instruments' measurements of the Moon
  - sample distribution size is too small (too few sensors) to quote a confidence bound
- ***But***: the model absolute error is consistent across wavelengths and observation geometries (phase angles and librations)
  - absolute offsets can be found by collecting a baseline set of lunar measurements soon after launch — a recommended best practice

Toward an Improved Lunar Reference

Current limitations are properties of the lunar model, whereas the Moon can be characterized to the accuracy limits of radiometric measurement technologies.

The kernel of the lunar irradiance reference is a specification of the spatially integrated lunar disk reflectance. Its construction requires:

- an extensive set of measurements, which form the basis for modeling
  - minimum of 3 years of acquisitions, constrained by the observability of the Moon, governed by its orbit
- formulation of a predictive expression, i.e. a reflectance model
  - analytic function(s) or a parametric form (or a combination)
  - fitted to the basis dataset, for development of coefficients
  - uncertainty due solely to model formulation and fit expected to achieve 0.5% ($k=2$)

Given the reflectance model, the irradiance reference is provided by combining with solar spectral irradiance measurements, e.g. from TSIS.

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Recent Progress

ARCSTONE mission — measuring absolute lunar spectral reflectance from space

- development based at NASA LaRC, PI: C. Lukashin
- solar and lunar spectral measurements from a 6U CubeSat in low Earth orbit (likely Sun-sync)
- level-1 and level-2 requirements drafted
- breadboard instrument has been built, initial testing done at NIST in April 2016
- **near-term goal: proposal to 2016 Instrument Incubator Program**

Support for developing a high-accuracy lunar reference has been expressed by international operational satellite agencies

- recommendations for lunar calibration delivered to CGMS by GSICS:
  - satellite instrument operators should set requirements to view the Moon
  - agencies should support proposals to re-develop the lunar standard

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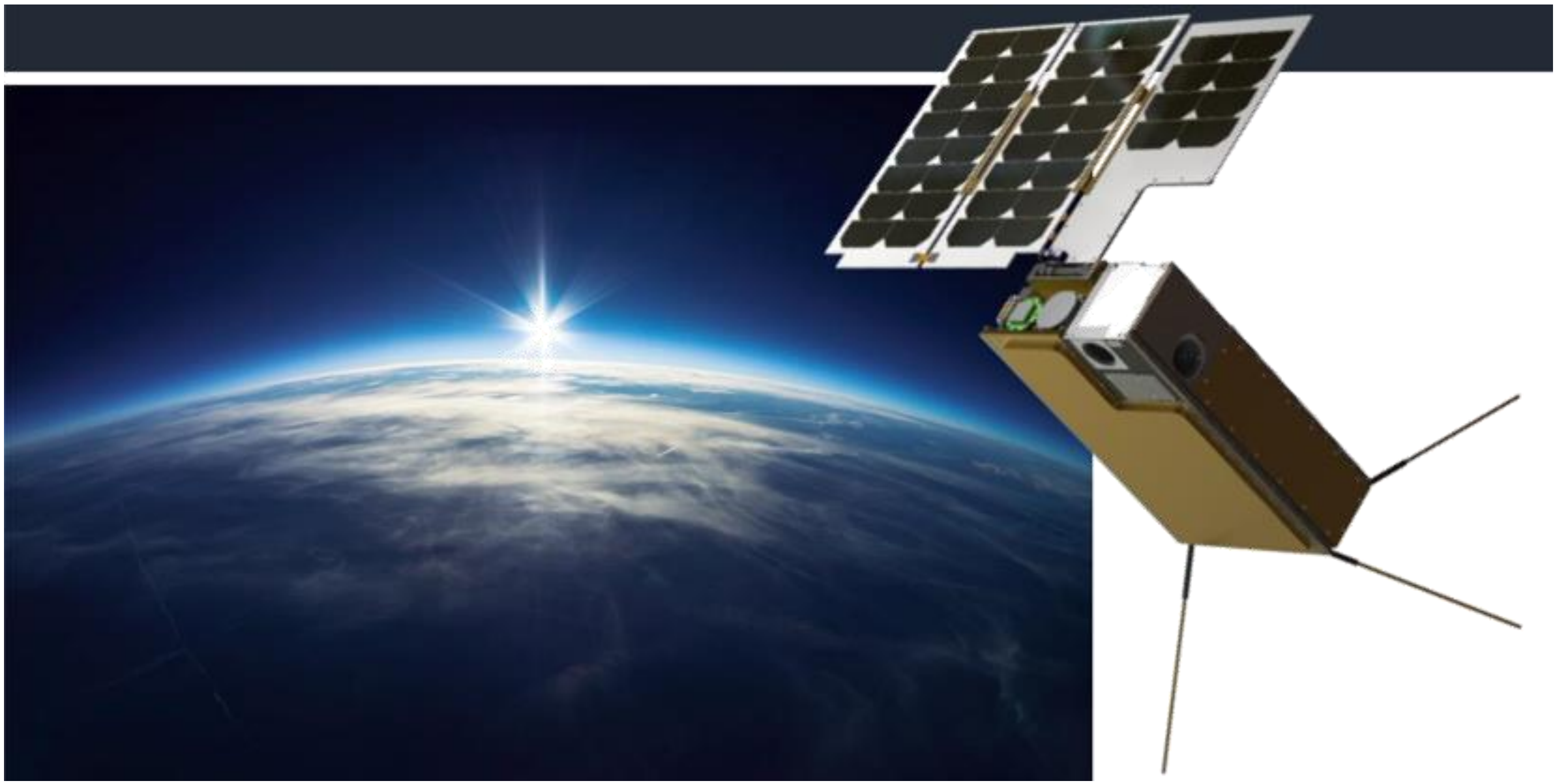
ARCSTONE

Calibration of Lunar Spectral Reflectance from Space

PI: Constantine Lukashin

Team: NASA LaRC, NASA GSFC, USGS, NIST, Resonon Inc.



ARCSTONE:
A spectrometer flying in LEO on a 6U CubeSat
Image courtesy of Blue Canyon Technologies

ARCSTONE: Key Mission Performance Parameters

Key Performance Parameters (KPP)	Threshold Value	Goal Value
Accuracy (reflectance)	1.0% (k=1)	0.5% (k=1)
Stability	< 0.15% (k=1) per decade	< 0.1% (k=1) per decade
Orbit	Sun-synch orbit	Sun-synch orbit
Time on-orbit	1 year	3 years
Frequency of sampling	24 hours	12 hours
Instrument pointing	< 0.2^{o} combined	< 0.1^{o} combined
Spectral range	380 nm – 900 nm	350 nm – 2300 nm
Spectral sampling	8 nm	4 nm
Lunar phase angle	0^{o} – 75^{o}	0^{o} – 135^{o}

Reference for radiometric requirements (ROLO, T. Stone):
Lunar Phase Angle = 75^{o}
Nominal Irradiance = 0.6 (μW / m^{2} nm)
Wavelength = 500 nm

ARCSTONE: Current Status

- ARCSTONE development is funded internally at NASA LaRC (for FY16)
- 1st ARCSTONE Team Meeting: September 2015, Hampton, VA
- Kick off ARCSTONE Engineering team: November 2015, NASA LaRC
- Level-1 and major Level-2 Requirements are drafted, work in progress
- Instrument concept by the Resonon, Inc: January, 2016
- Instrument Breadboard design by the Resonon, Inc: January 2016
- Instrument EDU/Flight design (Resonon & LaRC team): February 2016
- Initial instrument characterization testing at NIST: April 2016
- ARCSTONE mission development in parallel with instrument

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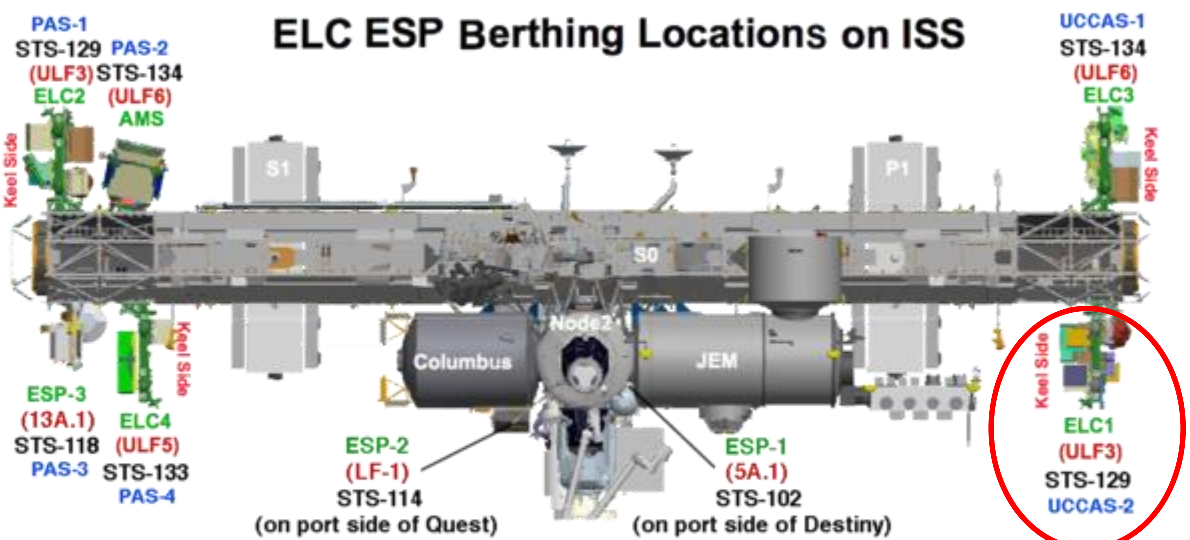
Considerations for Viewing the Moon from the ISS — CLARREO Pathfinder

Major concern: possible limitations on Moon observability

- ISS orbit inclination of 51° has very little impact
- line of sight obstructions by the ISS superstructure and solar panels could impose significant viewing limitations
  - need a view map from the perspective of the Pathfinder mount location
    - ExPRESS Logistics Carrier ELC1 (TBC?)
  - priority for placement is CLARREO primary mission: benchmark Earth measurements and reference inter-calibration
    - downward-looking slew ranges



Considerations for Viewing the Moon with an Imaging Spectrometer

Lunar irradiance measurements are taken by scanning over the Moon.

- requires constant spatial sampling across the Moon disk
  - compensation for spacecraft motion (orbit and attitude) and Moon orbit
  - best practice recommendation: oversample the disk
    - ➢ oversampling factor must be known accurately

The lunar irradiance varies along the orbit track.

- potential impact on integration times
- Sun-sync orbit simulations show 0.1% change in less than a minute
  - many dependencies, e.g. phase angle, spacecraft latitude

For 0.25 arcmin spatial sampling, the mean Moon diameter is 12 pixels

- operationally impractical to scan the entire Moon with all detectors
- measurements rely on precise detector equalization (flatfielding)
  - on-orbit flatfield measurements can use the Moon

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Alternative Uses for CLARREO Moon Observations

Presuming the CLARREO RS instrument meets target specifications for absolute accuracy, 0.3% ($k=2$), additional Moon measurements could be acquired for lunar characterization use.

- the nominal 5°–9° phase angle range is an imposed limit
  - depending on accessibility of Moon views, CLARREO could collect lunar measurements over a wide range of phase angles and librations
- an extensive collection potentially can form the basis for a revised lunar model, to develop into an on-orbit calibration reference
  - studies show at least 3 years of regular observations are needed
    - ➢ feasibility study done for CLARREO SDT in FY15, including observation simulations for 90° polar, Sun-sync and ISS orbits
    - ➢ phase and libration coverage is constrained by Moon and spacecraft orbits
  - space-based observations allow reaching higher phase angles
    - ➢ removes nighttime-only restriction, which effectively limits to 90° phase
    - ➢ acquiring up to 135° phase enables lunar calibration for 3 weeks per month

Alternative Uses for CLARREO Moon Observations

Since the Moon is a stable reflectance target, it can be used as a transfer standard for reference inter-calibration.

- near-simultaneous lunar views can be used, but still require adjustments for viewing angle differences
  - generated by lunar model computations
- a high-accuracy lunar reference enables transfer inter-calibration with no constraint for contemporaneous observations
  - a rationale for acquiring additional Moon measurements with CLARREO
- the lunar reference (model) intrinsically accounts for sensor spectral response differences between instruments
- lunar inter-calibration is a topic for a future feasibility study
  - accuracy requirements for the lunar reference
  - achievable accuracy for transfer calibrations

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Thank You!