Addressing Needs to Achieve High-accuracy Lunar Calibration

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Why develop high-accuracy lunar calibration?

Competing interests:

- Expectations for Earth observing sensors to measure climate-related observables
  - e.g. NASA's Earth System Observatory
  - requires unprecedented sensor accuracy and stability on orbit
- Movement of future Earth observing satellite programs toward constellations of smallsats
  - e.g. Landsat Next
  - potentially provided by the commercial sector
  - requires sensor calibration inter-consistency

To meet both these objectives together suggests a critical requirement for a reliable, common calibration reference available to all the satellite sensors

The Moon can provide this

Other capabilities enabled:

- transfer of pre-launch calibration to on-orbit operations
- additional opportunities for lunar views; reduced time to converge on calibration
- inter-calibration to benchmark sensors such as CLARREO PF, TRUTHS
- bridging a gap in an otherwise continuous observation record

The radiometric Moon

- continuously changing brightness
- mottled appearance, distribution of albedo (maria and highlands)
- non-Lambertian surface reflectance
- exceptional surface stability: invariant at 10^{-8} per year (Kieffer, 1997)

A model is used to predict the brightness for any Moon observations taken from low Earth orbit. The model constitutes the lunar calibration reference.

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Achieving high-accuracy lunar calibration follows two tracks:
Addressing both is needed

Improving the lunar reference (model)

- Specifications of the Moon's radiometric behavior — variations associated with:
  - obs geometry: phase angle & librations
  - spectral content
- Requires new measurement datasets

Improving lunar measurements from sensors

- Spatial sampling of the Moon disk
  - properties of Moon scans
  - spatial characteristics of sensor elements
- Evaluating uncertainties associated with each contributing factor

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Addressing Lunar Modeling Needs — the Absolute Scale

A lunar radiometric reference has potential sub-percent absolute uncertainty

- with SI traceability — talk by Steve Brown later in this session

The *current* USGS ROLO model for spectral irradiance: 5−10% uncertainty

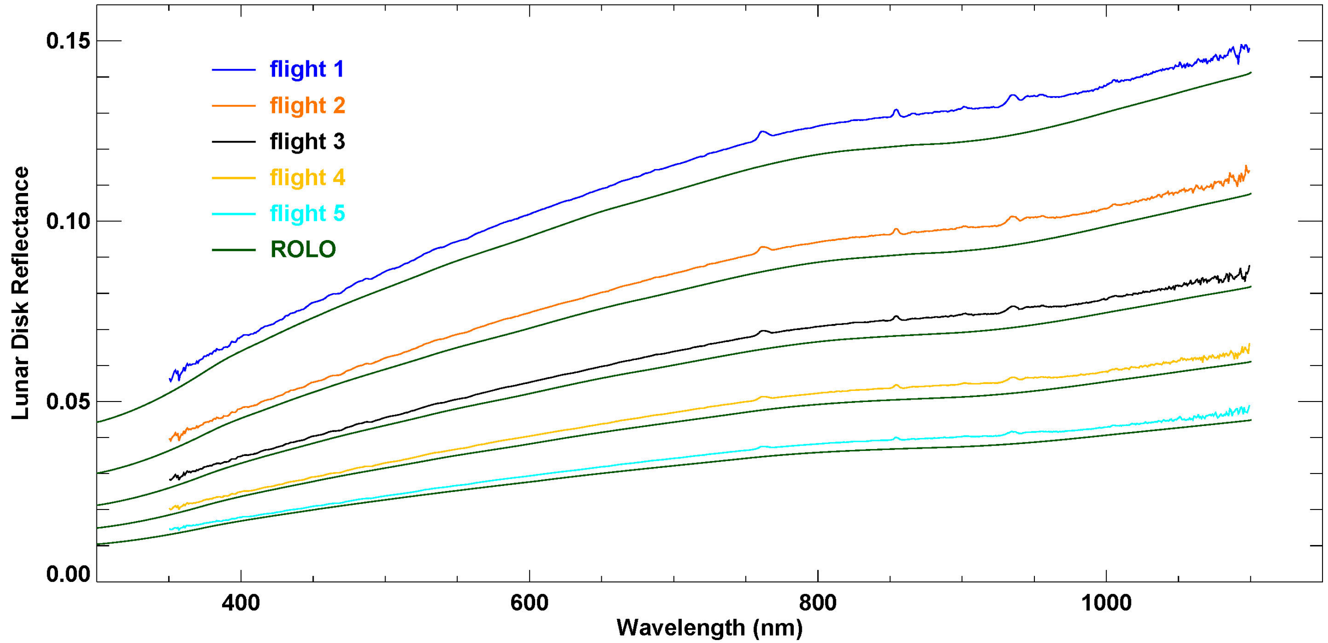
- recognized low bias, determined by comparison to other measurements

Setting the absolute scale for lunar irradiance requires new, high-accuracy measurements

Measurements being acquired now

- airborne Lunar Spectral Irradiance (air-LUSI) — Kevin Turpie talk later
    - flights in March 2022, Nov. 2019 →
- Calibrated aerosol photometers
    - LIME project, Tenerife (ESA)
    - AERONET, Mauna Loa (US)

Lunar disk reflectances - air-LUSI measured and ROLO computed



Addressing Lunar Modeling Needs — the Absolute Scale

Upcoming measurements for setting the lunar irradiance absolute scale

ARCSTONE — cubesat-based lunar disk reflectance

- anticipated launch: 3Q 2024
- talks by Trevor Jackson and Greg Kopp later in this session

NIST Lunar Spectral Irradiance at Mauna Loa Observatory (MLO-LUSI)

- instrumentation installed, functional testing completed, remote operation working
- full robotic operation anticipated within ~6 months

Measurements of opportunity by orbiting climate observatory sensors

CLARREO Pathfinder

- scheduled launch to ISS: December 2023

TRUTHS

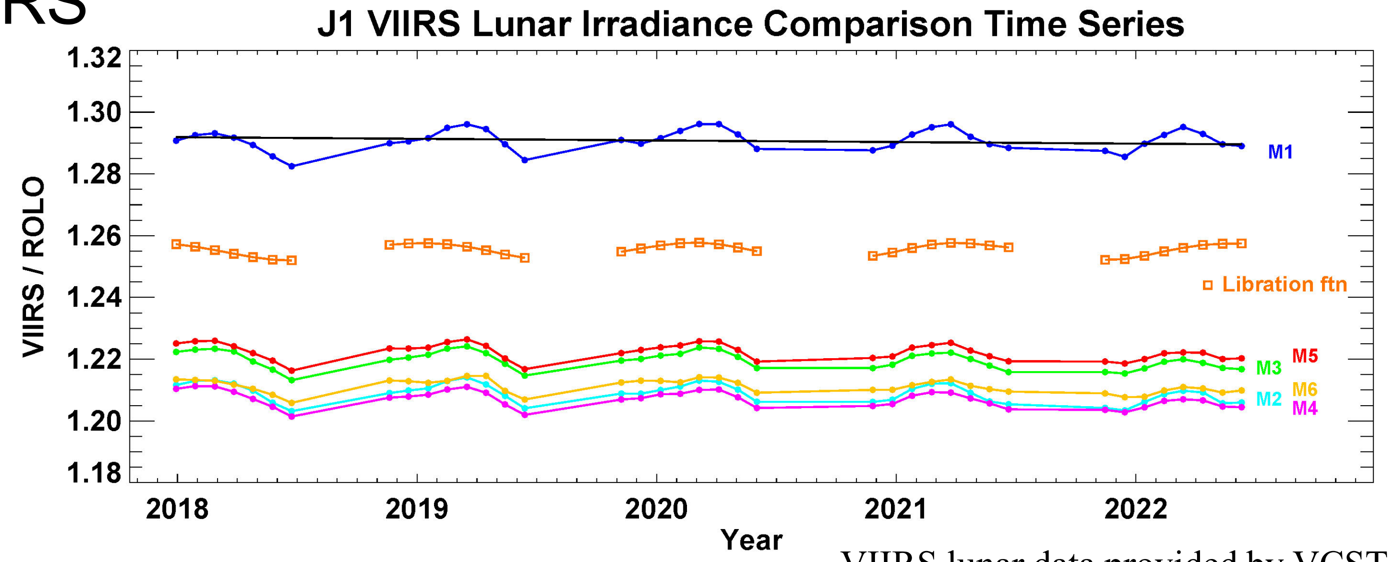
- anticipated launch timeframe: 2026-2028

Addressing Lunar Modeling Needs — Accounting for Lunar Librations

Example: JPSS-1/NOAA-20 VIIRS

lunar comparison time series →

- quasi-annual oscillations, correlated among bands (M1-M6 shown)
- analysis suggests also correlated with librations, but another influence is present



VIIRS lunar data provided by VCST

Alternative approach to model libration specification: MapLib

Implemented in SLIM by H. Kieffer — J. Appl. Rem. Sens. (2022) doi: 10.1117/1.JRS.16.038502

- based on albedo maps derived from lunar orbiting imager data
- near-normal incidence and emission angles, different from Moon observations from Earth
- applied to the J1/N20 VIIRS series above, analysis ongoing

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Addressing Lunar Modeling Needs — Reformulating the ROLO Model

Objective: a reduced uncertainty lunar reference, traceable to SI standards

Incorporating air-LUSI measurements is key, but air-LUSI acquisitions alone do not have sufficient observation geometry coverage to build a new model

The ROLO dataset is still useful as a basis for modeling

- extensive phase and libration coverage
- self-consistent calibration (against stars)
- ongoing USGS effort toward reprocessing — collaboration with EROS

Other lunar modeling efforts in the community:

➢ H. Kieffer — SLIM
  - ROLO dataset, plus 11 other ground- and space-based measurement sources

➢ ESA — LIME
  - nighttime aerosol photometer measurements from Teide peak, Tenerife

➢ GSICS activity: comparison of model outputs generated from a common set of inputs

Addressing Sensor Measurement Needs — Irradiance from Images

Objective: to determine the cause(s) of offsets in instrument lunar irradiance measurements compared to lunar model results

- These often exceed the known bias in the ROLO model
- Given a refined, high accuracy lunar reference, measurement errors need to be examined

Irradiance measurement equation:

$$\boldsymbol{E}_{\text{meas}} = \Omega_{\text{p}} \sum_{i}^{N} \frac{1}{\eta_i} \boldsymbol{L}_i$$

- each factor carries an uncertainty →

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

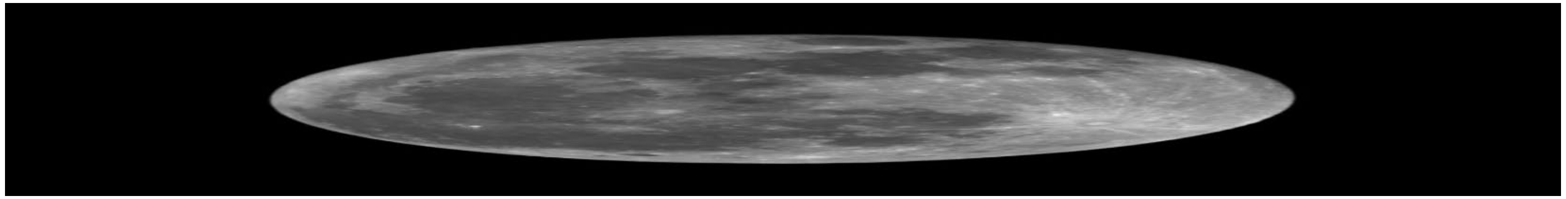
The sensor radiometric calibration applies only to the pixel radiance term $\boldsymbol{L}_i$

- *calibration uncertainty does not equate to uncertainty in irradiance measurements*
- obtaining accurate measurements requires attention to all components of this equation

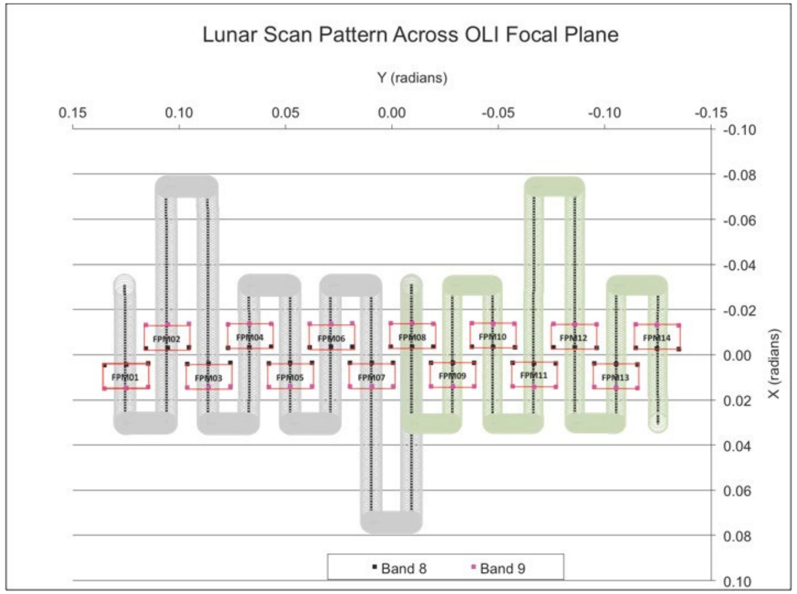
Spatial sampling of the Moon with a line-scanning sensor

Example: Landsat OLI

- pushbroom sensor
- 14 focal plane modules
- 30 m GSD, Moon diameter ≈250 pixels across-track
- Moon scans acquired using target-synced pitch maneuvers
- raster pattern to scan the Moon thru all 14 FPMs in two orbits
- slew rate for ~8x oversampling



OLI image acquired 2013-03-27 19:26:28



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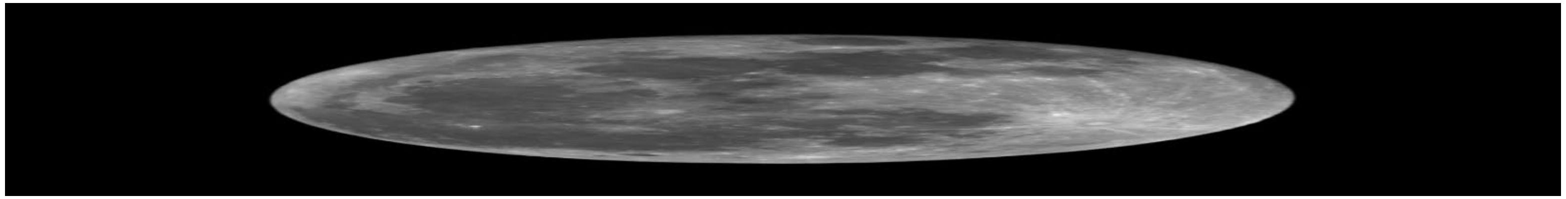

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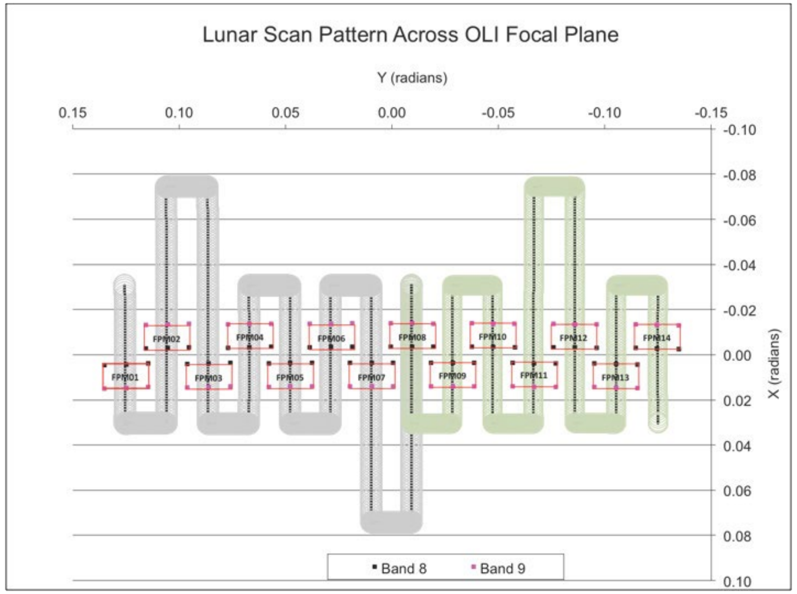

Apply Landsat geolocation capabilities to Moon scans

- OLI sensor is fixed to the spacecraft bus
- interpolate s/c attitude telemetry (50 Hz) to scan frame sampling (236 Hz) to compute line of sight (LOS) vectors for each pixel
- matching LOS to the Moon's size and position in inertial space can specify which pixels intercepted the Moon

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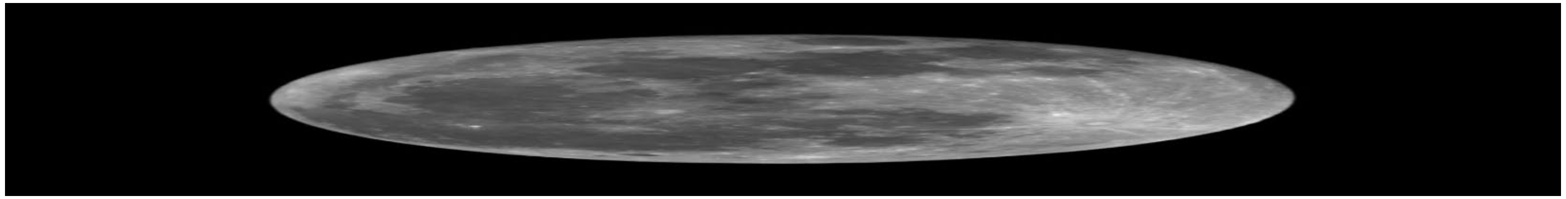

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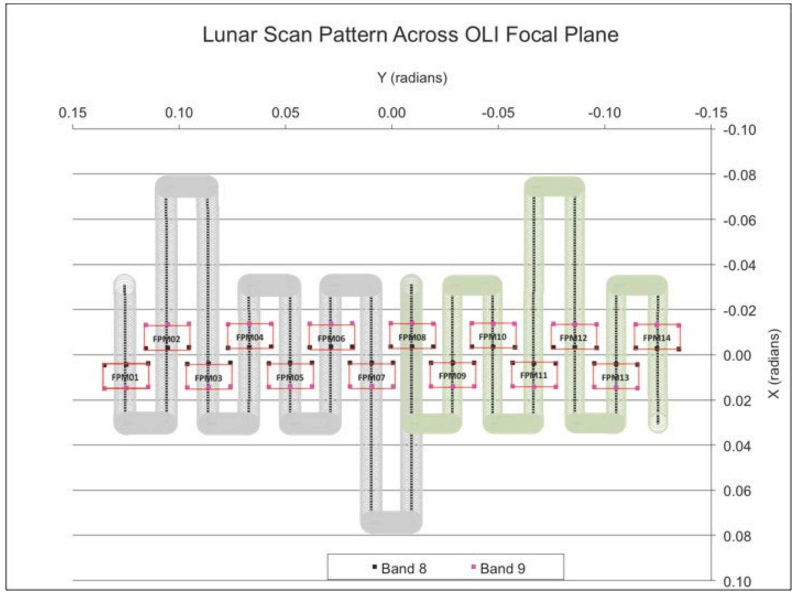

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← allows to compute oversampling directly!

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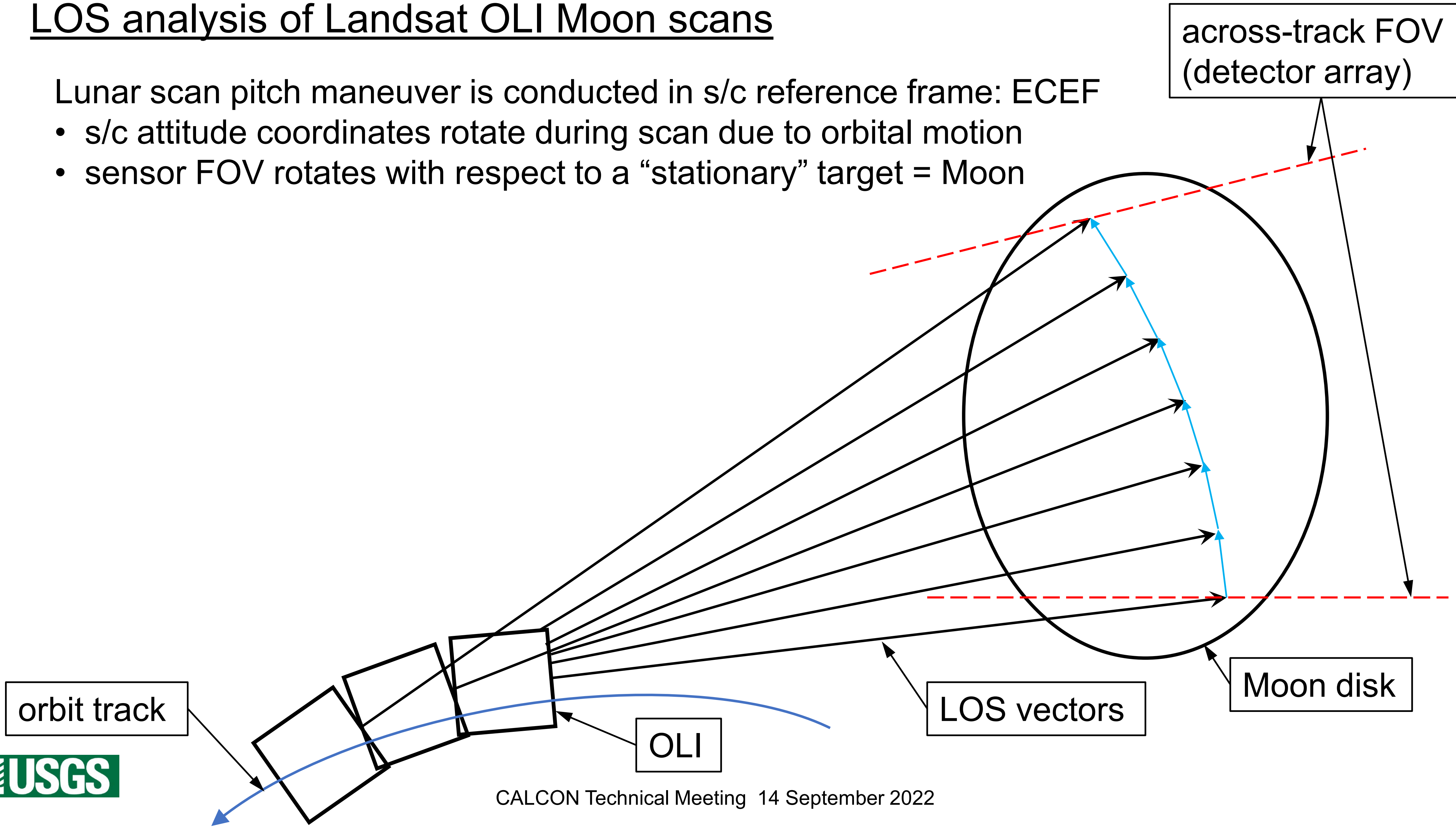
LOS analysis of Landsat OLI Moon scans

Lunar scan pitch maneuver is conducted in s/c reference frame: ECEF
- s/c attitude coordinates rotate during scan due to orbital motion
- sensor FOV rotates with respect to a “stationary” target = Moon



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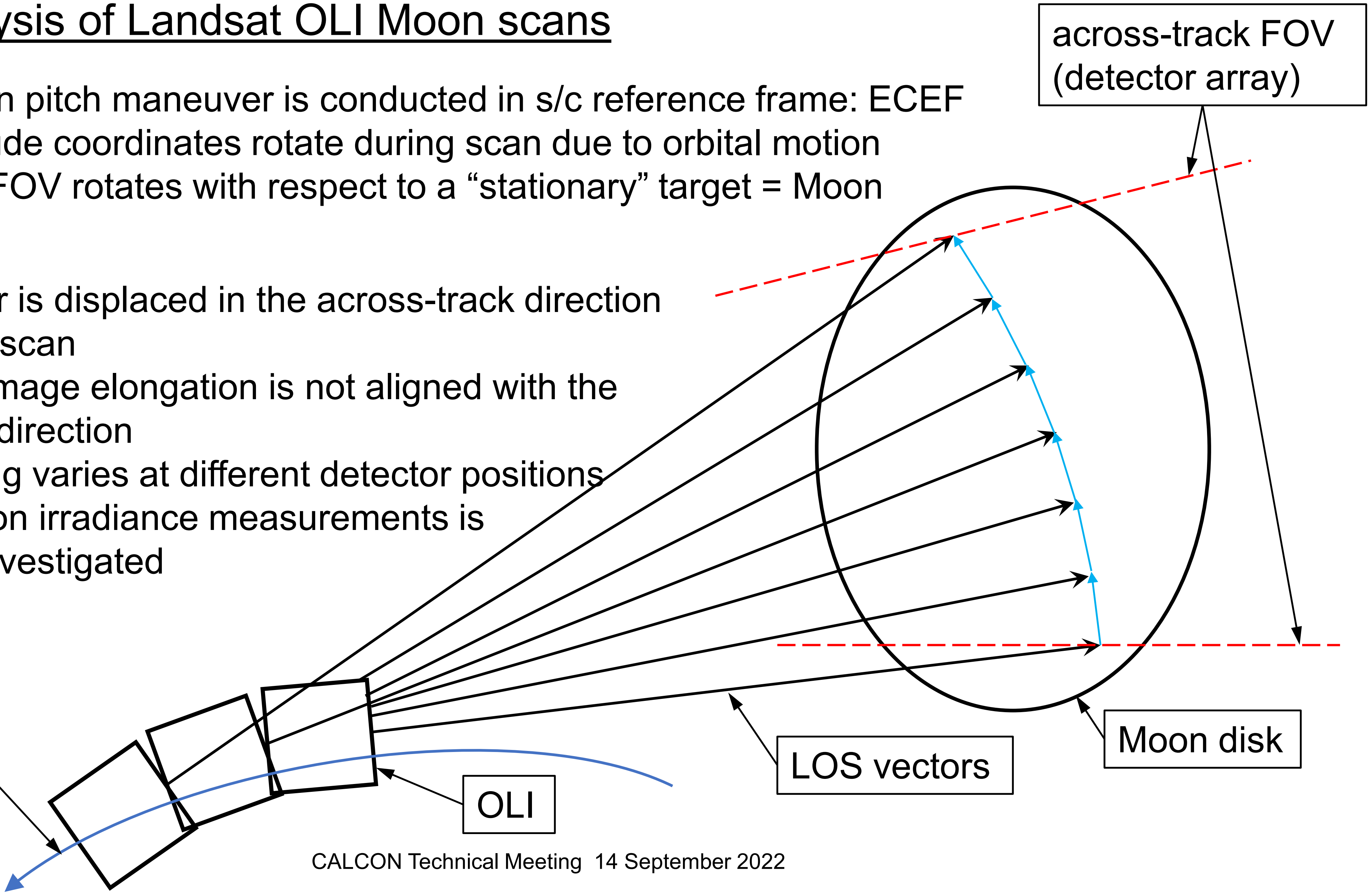
Ramifications:

- Moon center is displaced in the across-track direction through the scan
- Moon disk image elongation is not aligned with the along-track direction
- oversampling varies at different detector positions
  - impact on irradiance measurements is being investigated



Summary and Conclusions

- Lunar calibration has the potential to achieve sub-percent absolute accuracy
  - with SI traceability, given anchoring measurements
  - necessary for climate sensing by Earth observing satellites, especially constellations
- Investment is needed to improve the lunar reference
  - time and labor: scientific studies, development of methods and analytic specifications
  - to acquire additional high-accuracy, spectrally resolved lunar irradiance measurements
    - to set the absolute scale
    - with verifiable low uncertainties
    - technically feasible
- Ongoing and planned activities to acquire the needed new measurements
  - upcoming talks in this CALCON session
- Attention needed toward improving lunar measurements from sensors
  - a refined lunar reference will enable high-accuracy calibration against the Moon
  - impacts for constellation approaches to Earth observations