4th Joint GSICS/IVOS
Lunar Calibration Workshop
Darmstadt, Germany

Instrument Monitoring Using
Lunar Calibration > LEO > 3h
6 Dec 2023 11:25-11:50 AM CEST

OCO-2 Lunar Calibration

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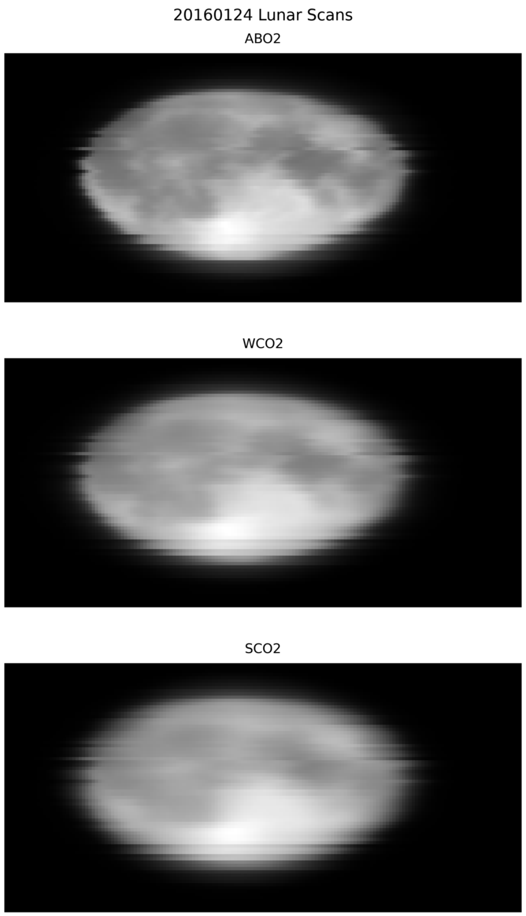
Outline

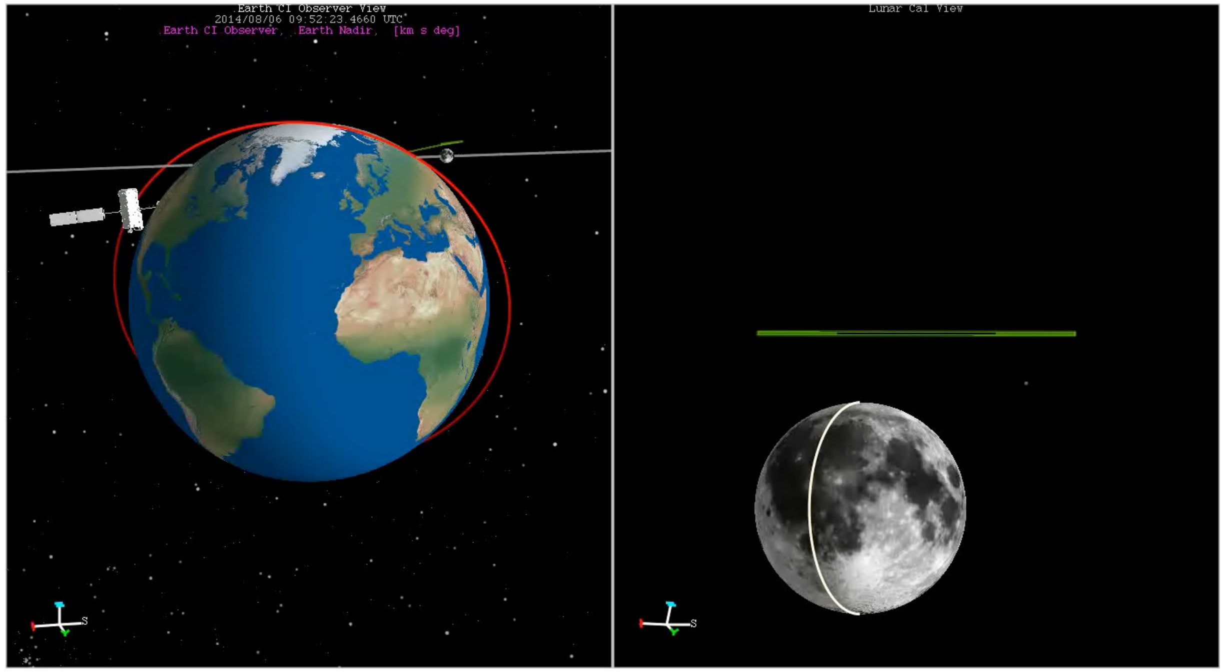
- OCO-2 Lunar Observations
- Computing Illumination/Viewing Geometry Variables & Lunar Irradiances
- ROLO Results
- ROLO+POL Model & Results
- Lunar Orbiting Carbon Observatory (LOCO) Model & Results
- Degree of Linear Polarization (DOLP)
- Conclusions



Seht ihr den Mond dort stehen? –
Er ist nur halb zu sehen,
Und ist doch rund und schön!
So sind wohl manche Sachen,
Die wir getrost belachen,
Weil unsre Augen sie nicht sehn.
-Matthias Claudius (1740-1815)

How OCO-2 Observes the Moon

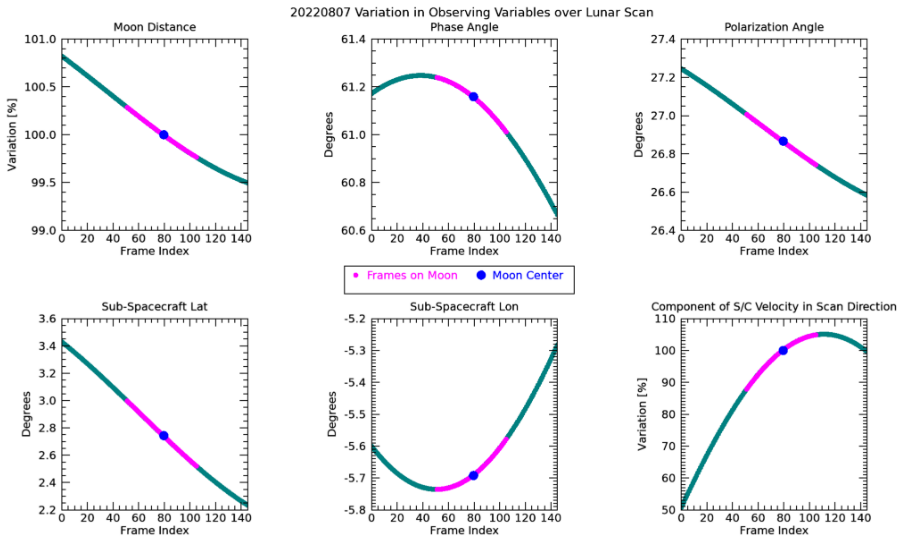
- OCO-2 slews to & stares at fixed point in inertial space
- Orbital motion sweeps instrument FOV across the Moon
- OCO-2 slews back to nadir



Implications of OCO-2 Lunar Observing Strategy

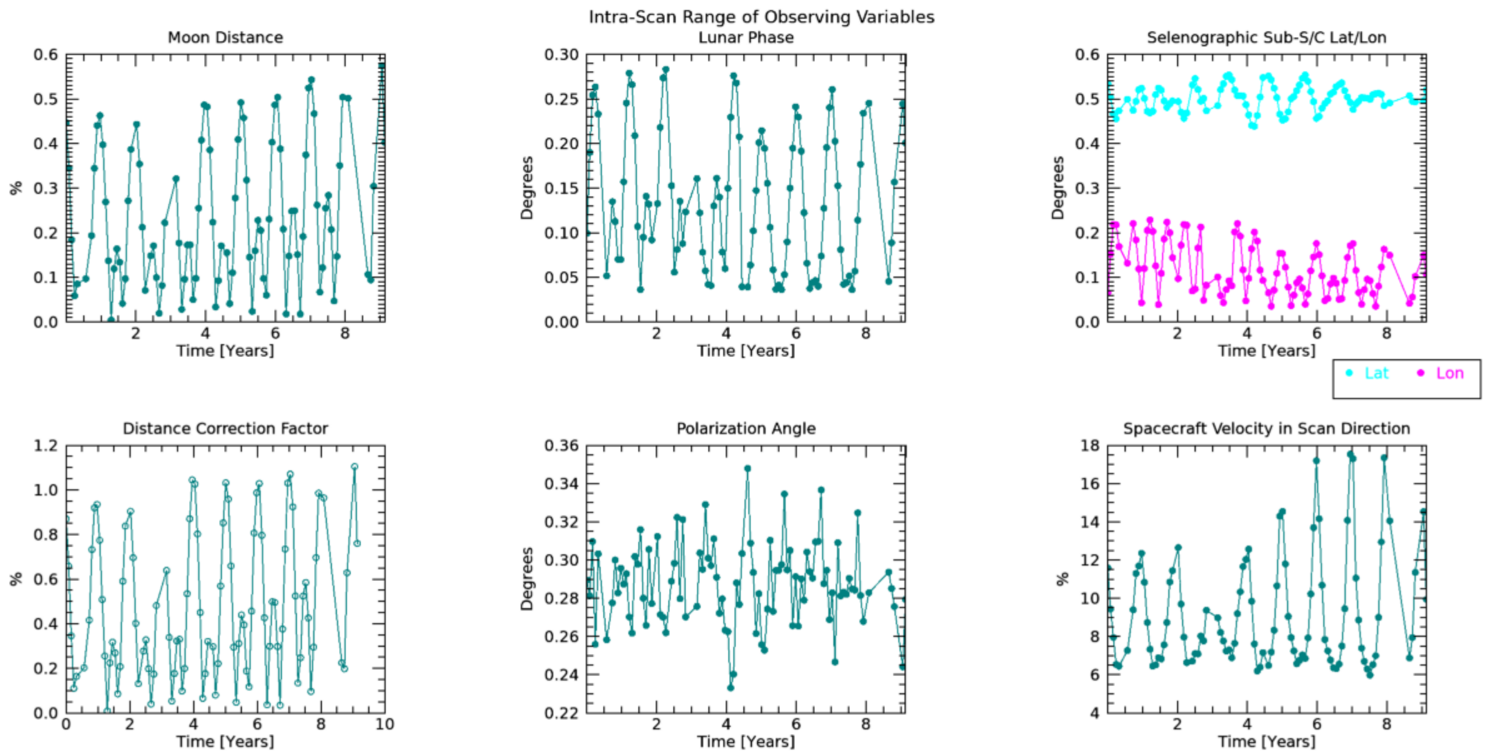
Time-Varying Quantities Complicate Data Analysis

- Scan time on Moon: 7 ½ to 9 minutes
- Distance traveled by OCO-2 during that interval: ~3,000-4,000 km
- Viewing geometry & scan rate change continuously over a scan
- Data acquisition is not continuous
  - Only every 28th 1/3 sec frame is read out in the single pixel mode usually used for lunar cals
  - 47-57 frames on the Moon per scan
- Moon is undersampled by a factor of ~2x in the scan direction

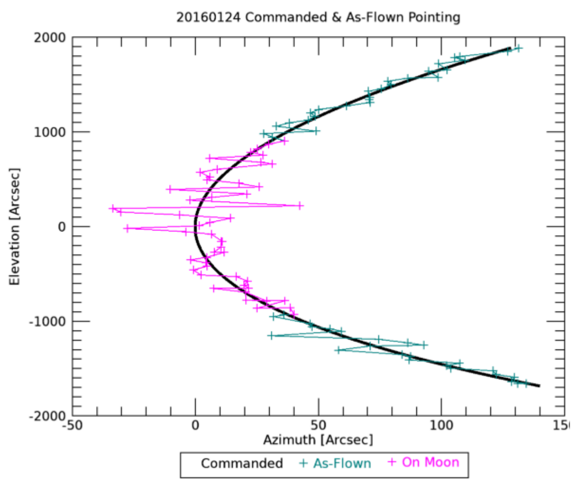


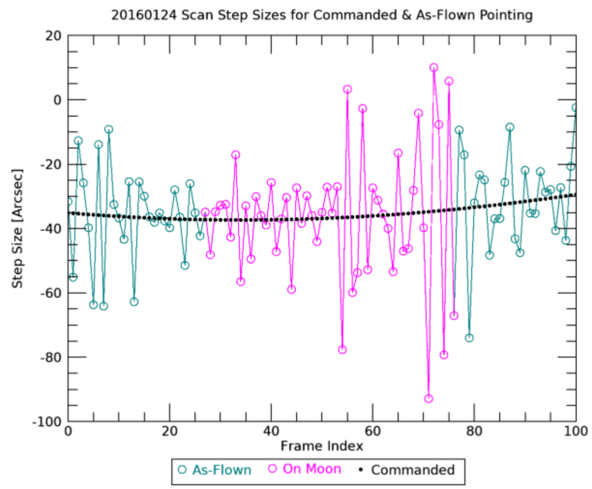
OCO-2 lunar observations do not provide a "snapshot" of the Moon.

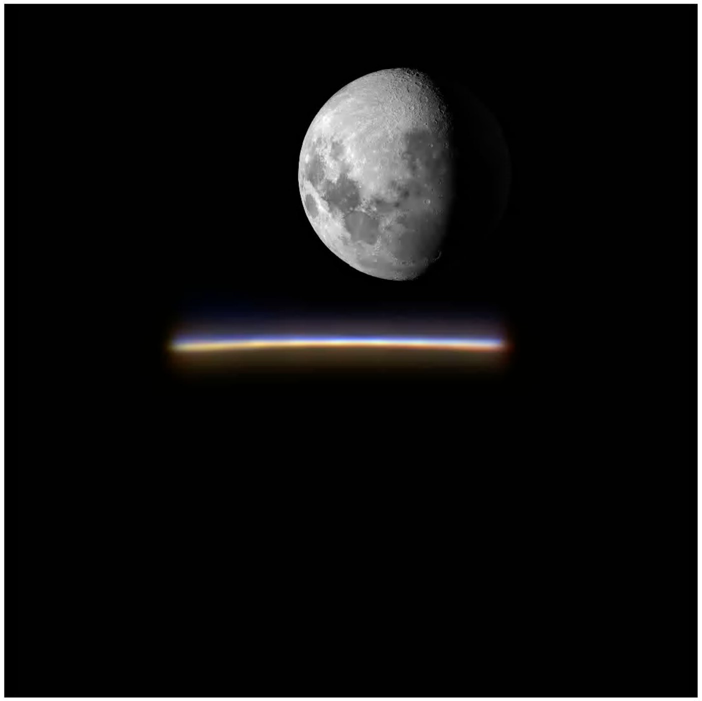
Seasonal Effects on Intra-Scan Variations



Pointing Jitter Complicates the Analysis Further





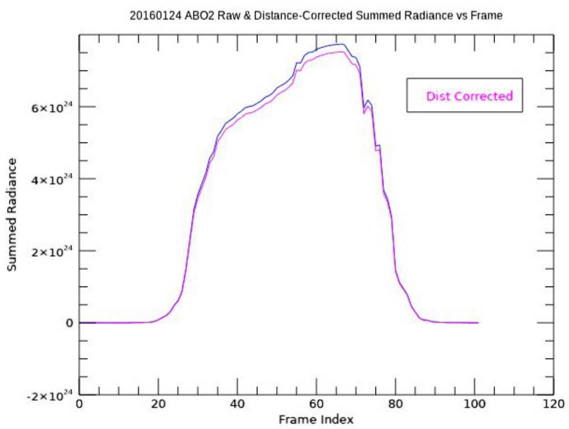


For multiple reasons, OCO-2 observations of the Moon do not sample the lunar disk uniformly.

Illumination/Viewing Geometry Variables

What Values To Use for Them When They Aren't Constant over a Scan?

- Variable: Spacecraft-Moon distance
- Intra-scan variation: up to ~0.5%
- Solution: Apply R^2 radiance distance correction on a frame-by-frame basis



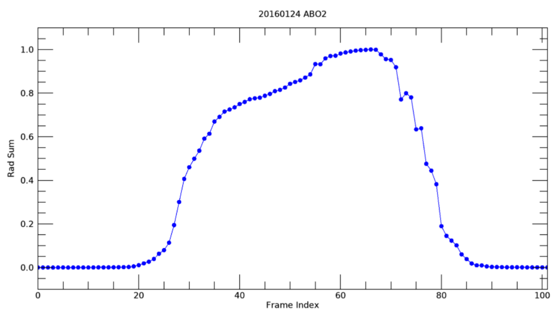
- Variables: Phase angle, selenographic sub-S/C lat/lon & polarization angle
- Intra-scan variation: up to ~0.5°, ~0.2° & ~0.3°, respectively
- Solution: Compute radiance-sum-weighted averages as follows:

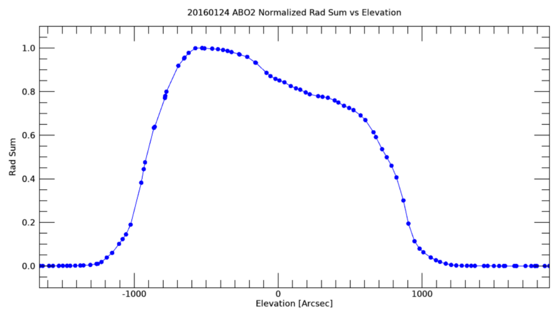
$$\psi_{wt\ ave} = \frac{\sum_{j=0}^{nframes} \sum_{i=0}^{npix} L_{i,j}\, \psi_j}{\sum_{j=0}^{nframes} \sum_{i=0}^{npix} L_{i,j}}$$

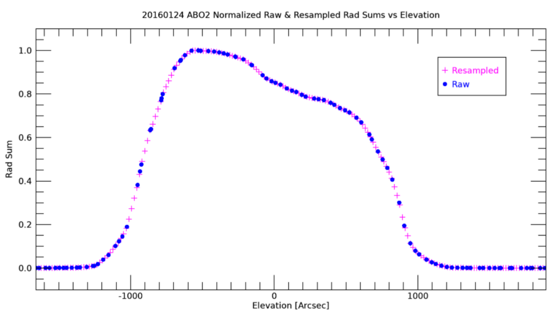
Correcting Observed Lunar Irradiances

How to Calculate Undersampling When Scan Velocity is Ill-Defined?

- Initial approach: Use average scan velocities → seasonal variations remain
- Improved approach: Use time-dependent scan velocities based on commanded pointing → effects of pointing jitter remain
- Current approach: resample radiance sum profile by interpolating on regular grid in elevation space
  - Very simple
  - Dispenses with explicit undersampling factor
  - Has benefit of reducing effect of pointing jitter

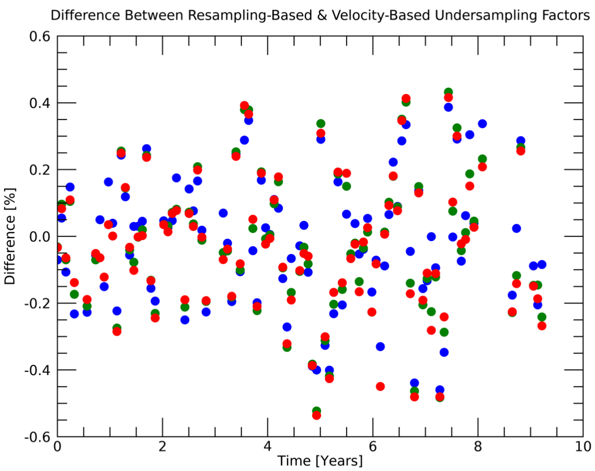


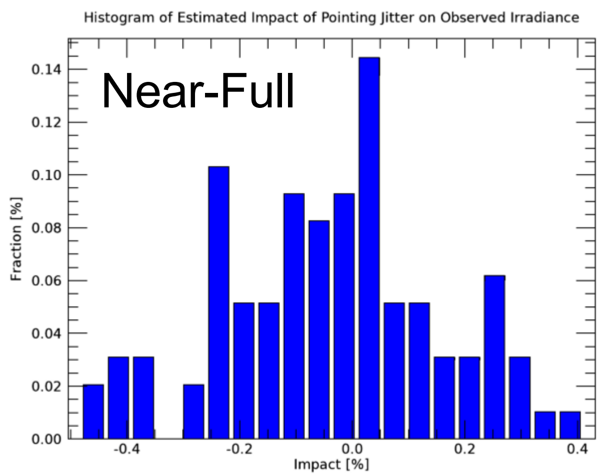


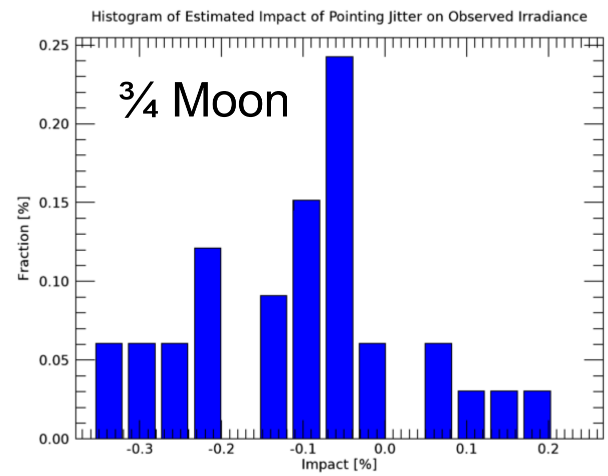


Impact of Pointing Jitter on Observed Irradiance

Resampling vs Time-Dependent Oversampling Correction



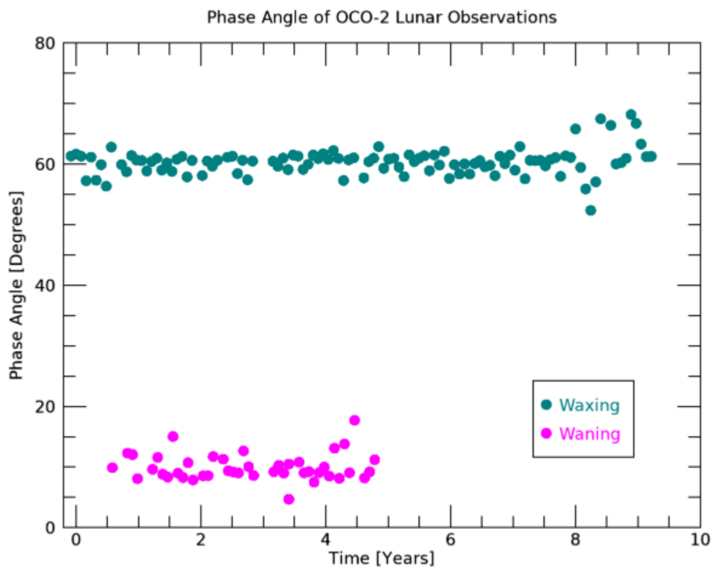


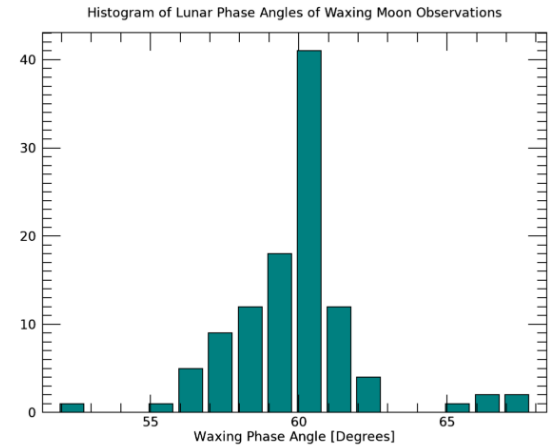


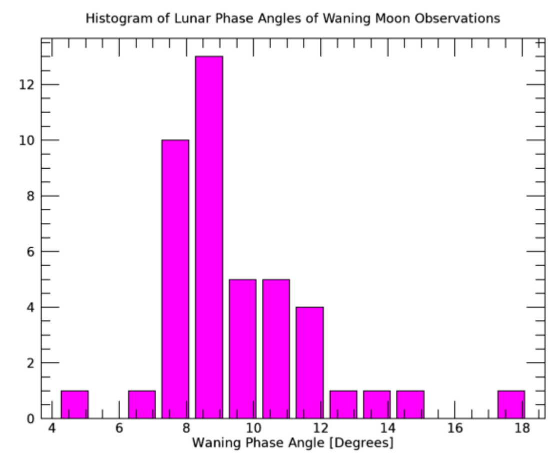
Impact is similar but not identical across bands.

Impact is smaller for near full Moon lunar cals.

Lunar Cal Time Series



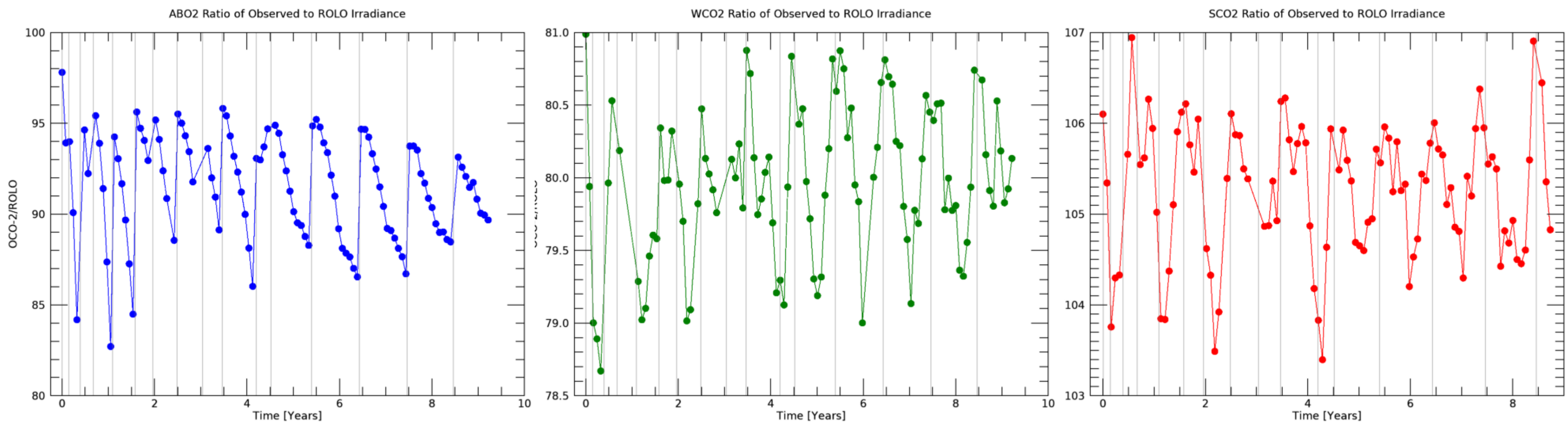




- ~108 waxing ¾ Moon lunar cals (2014-Present)
- ~43 waning near-full lunar cals (2014-2019)

ROLO Model Results

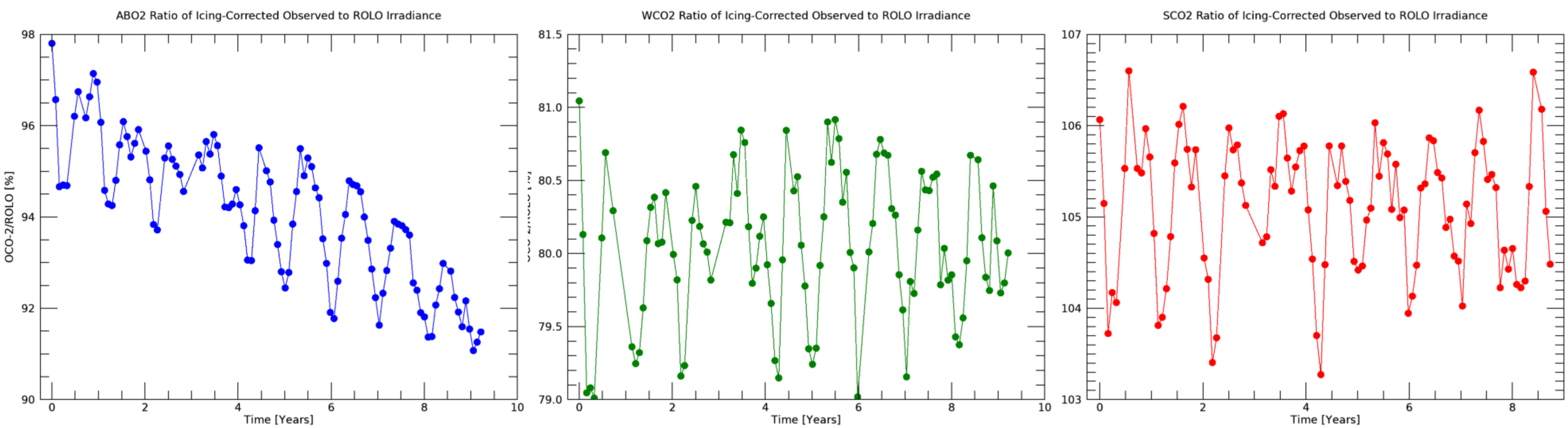
Waxing ¾ Moon



A-Band radiometric response is dominated by the effects of icing.

Icing-Corrected ROLO Model Results

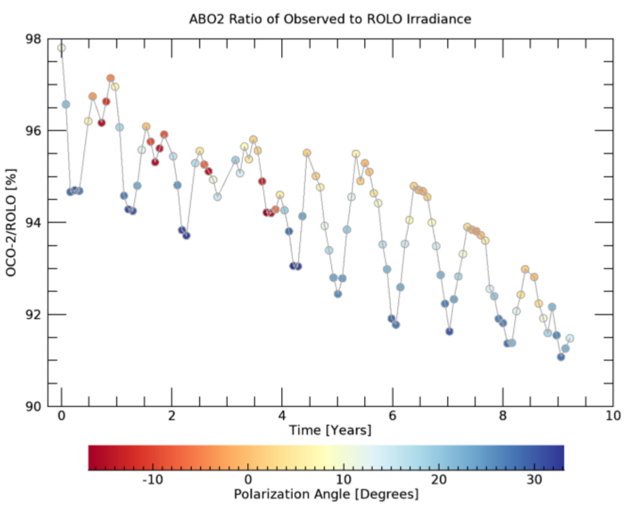
Icing Correction Derived Independently, from Solar Cal Data

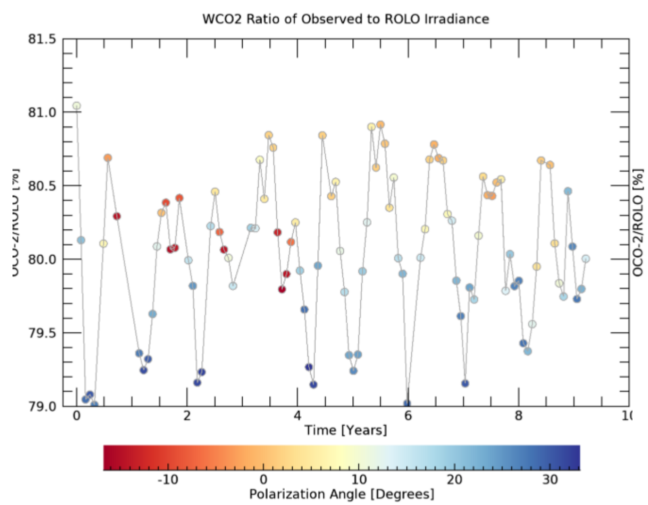


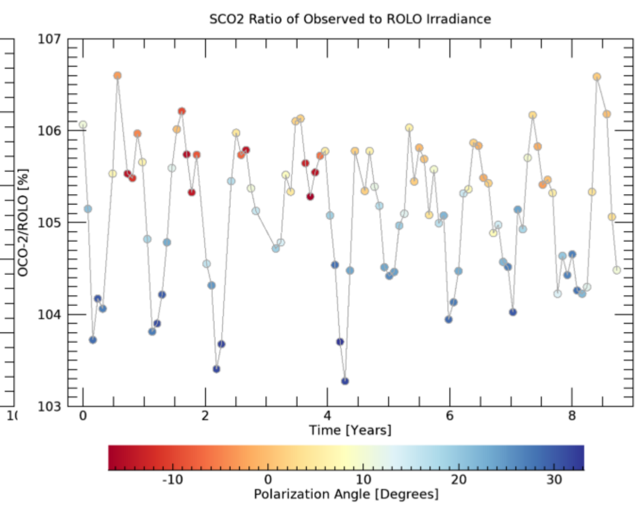
Time series are characterized by pronounced seasonal oscillations.

ROLO Model Results

A Closer Look







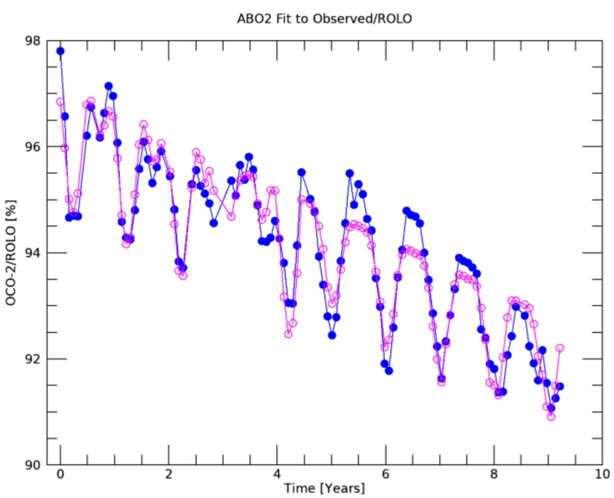
Oscillations in irradiance ratios correlate with polarization angle.

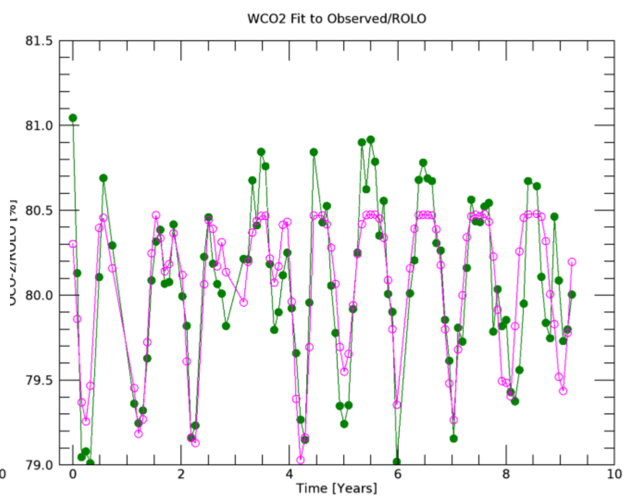
ROLO+POL Model

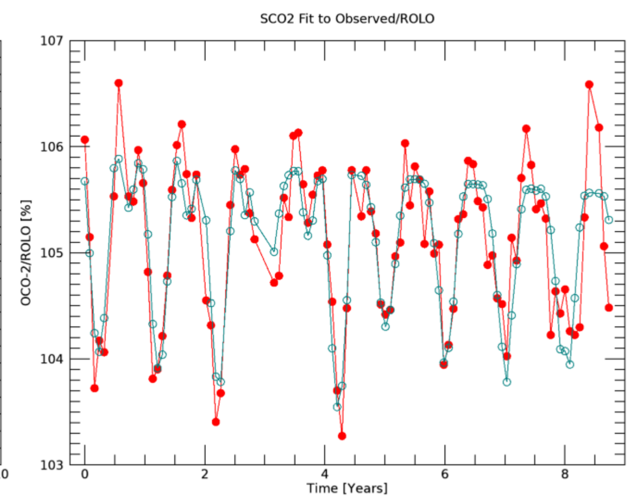
Fit to Observed/ROLO Irradiance Ratio

Attempt to fit out polarization (& time) dependence of ROLO residuals for each band using a function of the form:

$$f_{fit}(\alpha, t) = k_0 * f_{pol}(\alpha) * f_{time}(t) \qquad \text{where} \qquad f_{pol}(\alpha) = \cos^2 \alpha + k_1 \sin^2 \alpha \qquad \& \qquad f(t) = 1 - k_2 t$$

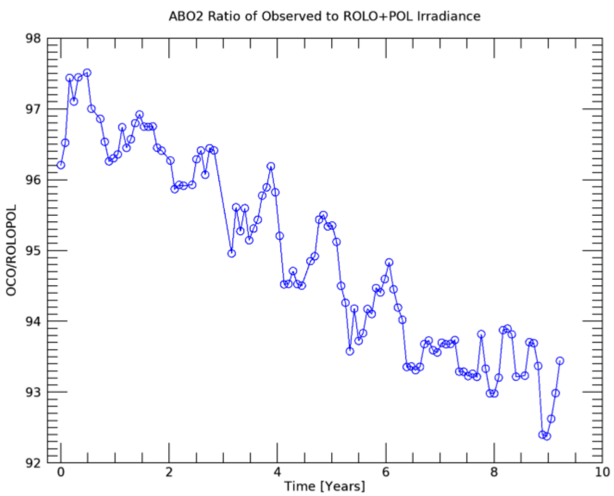


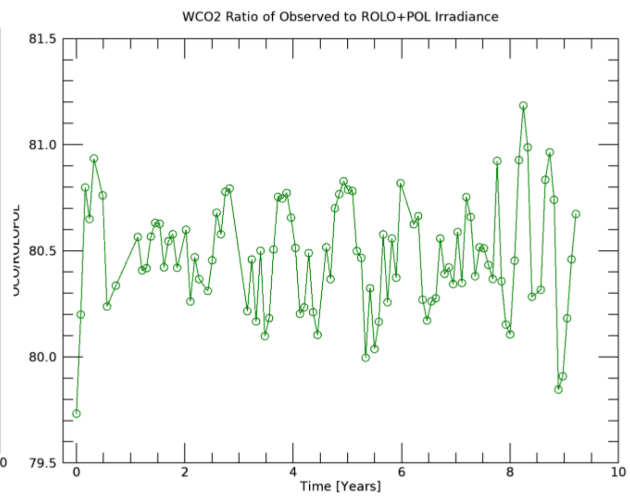


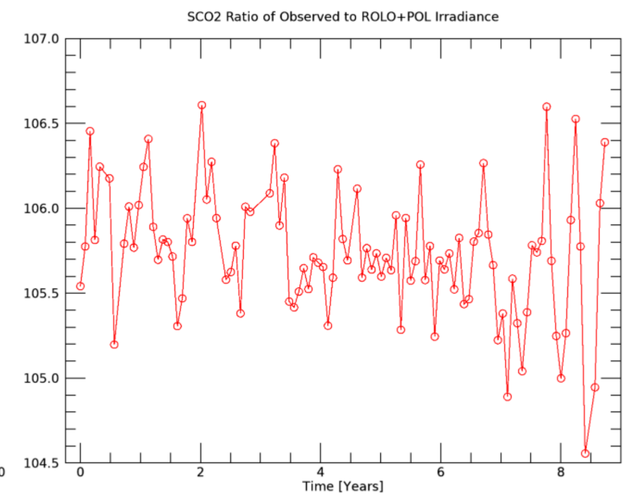


ROLO+POL Model Results

ROLO Plus Ad-Hoc Polarization Correction







Seasonal oscillations are substantially reduced but not eliminated.

Lunar Orbiting Carbon Observatory (LOCO) Model

Simplified, Linearized ROLO-Like Model with Polarization & Time Corrections

- Goal: Improved relative radiometric trending
- Parametric fit to relative observed irradiances
- Strategy: Given smallish number of observations, reduce the chances of overfitting by reducing the number of free parameters to a bare minimum
- To this end, reduce the number of variables by
  - Retaining only those that explain a significant fraction of the variation
  - Restricting the range of phase angles that are considered
  - Linearizing around mean phase angles and sub-solar longitudes

$$I(g, \Phi, \alpha, \theta, t) = k_0 * f_{phase}(g) * f_{pol}(\alpha) * f_{sol}(\Phi) * f_{libr}(\theta) * f_{degrad}(t)$$

$$f(g) = 1 + k_1(g - \bar{g})$$

$$f(\alpha) = \cos^2\alpha + \frac{1 - k_3}{1 + k_3}\sin^2\alpha$$

$$f(\Phi) = 1 + k_4(\Phi - \bar{\Phi})$$

$$f(\theta) = 1 + k_5\theta$$

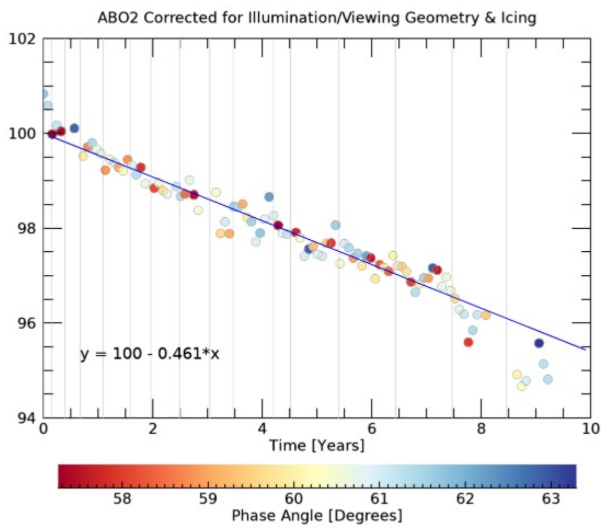
$$f(t) = 1 - k_5 t$$

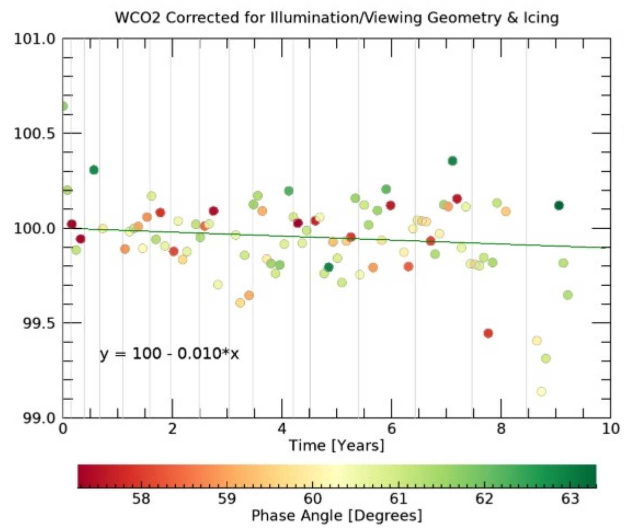
$$f(t) = 1 - k_6[1 - exp(-t/k_7)]$$

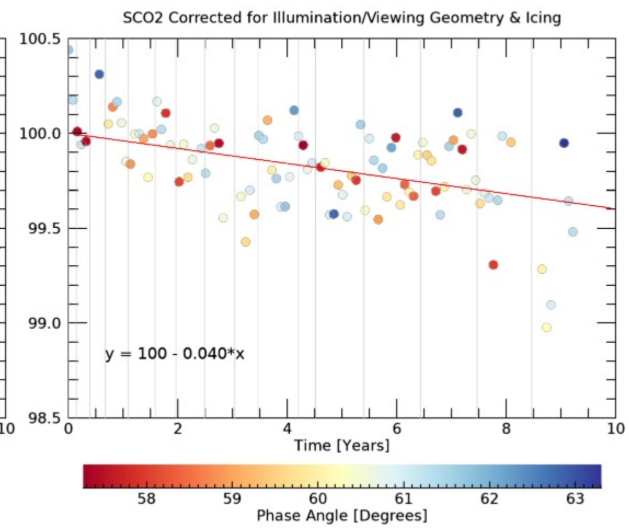
g: phase angle
α: polarization angle
Φ: selenographic sub-solar longitude
θ: selenographic sub-S/C latitude

LOCO Model Results

Waxing ¾ Moon







Degree of Linear Polarization (DOLP)

ROLO+POL vs LOCO vs Lunar Irradiance Model of ESA (LIME) Values

DOLP [%]

	ABO2 (0.76 μm)	WCO2 (1.61 μm)	SCO2 (2.06 μm)
Lunar Phase Angle: -60°			
ROLO+POL	4.9	3.1	3.6
LOCO	5.1	3.5	3.9
LIME	4.9	4.0	N/A
Lunar Phase Angle: 8°			
ROLO+POL	-1.1	-1.0	-1.1
LOCO	-1.2	-1.1	-1.2
LIME*	-1.2	-1.1	N/A

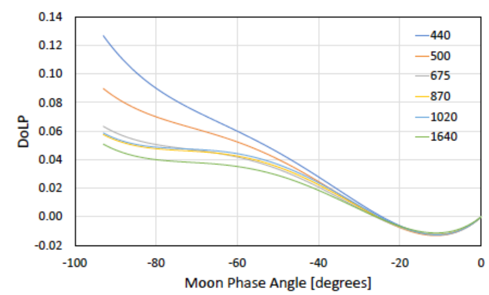
* Assumes DOLP curves are symmetric for lunar phases near 0°

Note: LIME DOLP values estimated from curves in Figure 14 of:

https://doi.org/10.5194/egusphere-2023-1539
Preprint. Discussion started: 31 July 2023

LIME: Lunar Irradiance Model of ESA, a new tool for the absolute radiometric calibration using the Moon

Carlos Toledano[1], Sarah Taylor[2], África Barreto[3], Stefan Adriaensen[4], Alberto Berjón[5,3], Agnieszka Bialek[2], Ramiro González[1], Emma Woolliams[2], and Marc Bouvet[6]



Conclusions

- Analysis of OCO-2 lunar cal data is complicated by multiple factors, including variable viewing geometry, variable scan rates, pointing jitter, icing & polarization
- Undersampling & pointing jitter corrections can be simply calculated by resampling summed radiances
- Absolute radiometric cal agreement with ROLO is reasonable for ABO2 & SCO2 bands but not for WCO2
- Effects of polarization can be reduced but not eliminated by ad-hoc polarization fits to Observed/ROLO irradiance ratios, i.e. ROLO+POL
- LOCO parametric model appears to offer improved relative radiometric trending, at least for the ABO2, the only band for which it matters much
- DOLP results agree reasonably well with those used in the LIME model

Thank you for your attention