# Further Development of Lunar Calibration Observation Requirements for the CLARREO Reflected Solar Instrument


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CLARREO Science Definition Team Meeting

Lawrence Berkeley National Laboratory

28–30 April 2015

# Overview of the task

The CLARREO operations plan includes periodic observations of the Moon for on-orbit calibration functions.

In April 2015, USGS Lunar Calibration was added to the CLARREO Science Definition Team to advance development of observational requirements for acquisition of lunar measurements by the reflected solar (RS) instrument

- to fill in details of the lunar data acquisition procedures
- to assure the highest accuracy for RS lunar irradiance measurements
- to leverage the experience and tools developed by USGS

This involves coordination with the RS instrument and flight ops teams

- to merge targeting capabilities (e.g. slew rates, field of regard) with constraints on the observability of the Moon
- to optimize acquisition parameters (e.g. exposure times)

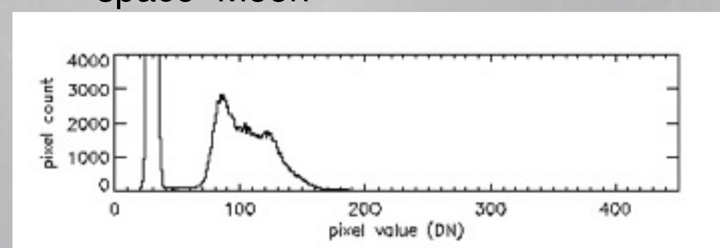
# Introduction to lunar calibration

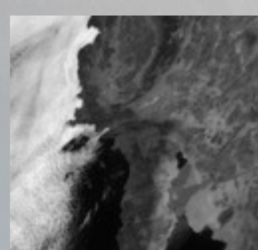
The Moon is a diffuse solar reflector with exceptional stability.

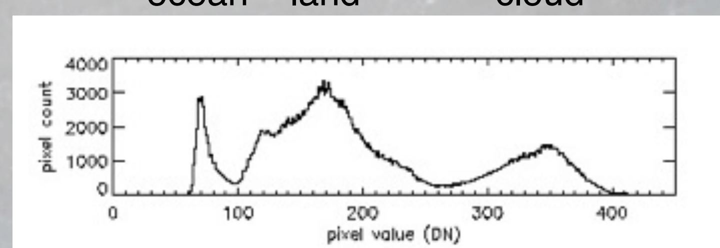
- Advantages:
  - — available to instruments in all Earth orbits
  - — no atmosphere between the source and the sensor
  - — spatially-extended source with brightness similar to Earth scenes:

Identical-size sub-images extracted from geostationary full-Earth scan

GOES−12
visible channel
30 Aug 2004
17:45:15





# Introduction to lunar calibration

- Disadvantages:
  - — limited dynamic range: maximum reflectance ~0.2
  - — spacecraft in Low Earth Orbit (LEO) must maneuver to view the Moon with nadir-viewing optics
  - — continuously varying brightness, e.g. phase, distance to the Sun
  - — non-Lambertian reflectance

To use the Moon as a radiometric reference requires a capability to predict its brightness for any illumination and view geometry which corresponds to lunar observations acquired by instruments.

The solution: a geometry-based analytic model for the intensity of moonlight — the ROLO model.

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# Lunar Calibration Development

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, 20cm 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

ROLO telescopes zenith-pointed at dusk

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# USGS Lunar Model Development

Efforts at USGS have focused primarily on modeling the spatially integrated lunar spectral irradiance.

- Gives s/n advantage from summing many radiance pixels
- Adds complication by including dependence on lunar librations

Actual model development and operation is done in terms of the lunar disk-equivalent reflectance $A$

- Uses the advantage of the smooth lunar reflectance spectrum
- Avoids complications due to the solar spectral structure

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# Lunar Model Development (2)

Empirical formulation, a function of only the geometric variables phase ($g$) and libration ($\varphi,\theta,\Phi$):

$$\ln A_k = \sum_{i=0}^{3} a_{ik} g^i + \sum_{j=1}^{3} b_{jk} \Phi^{2j-1} + c_1\phi + c_2\theta + c_3\Phi\phi + c_4\Phi\theta$$

$$+ d_{1k} e^{-g/p_1} + d_{2k} e^{-g/p_2} + d_{3k} \cos((g - p_3)/p_4)$$

$g$ = phase angle
$\phi$ = observer selenographic longitude
$\theta$ = observer selenographic latitude
$\Phi$ = selenographic longitude of the Sun

- Designed to minimize residuals from fitting ROLO data
- Coefficients derived by fitting ~1200 observations in 32 bands
- mean fit residual ≈0.0096 → a measure of model precision

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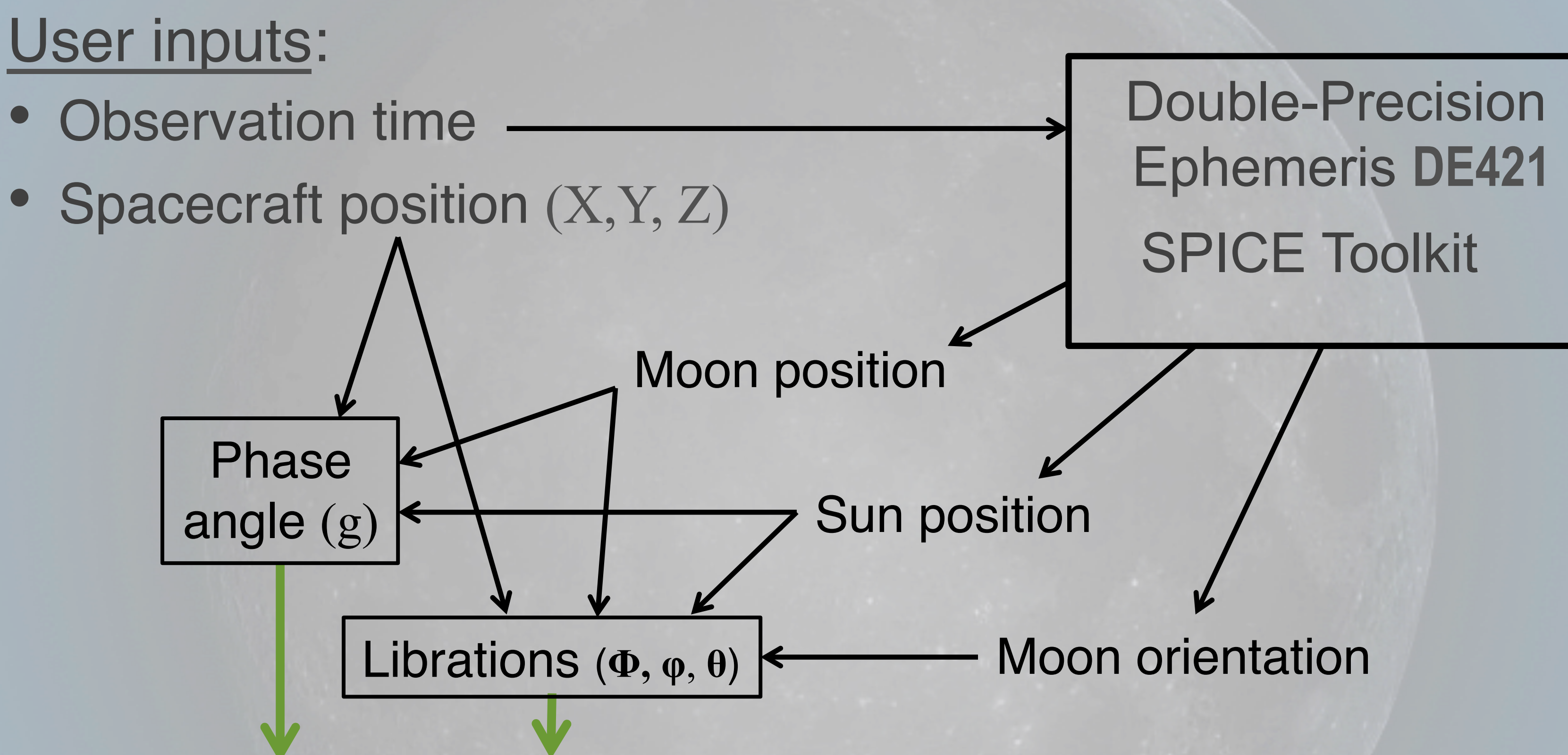
# Lunar Model Operation — Inputs Processing




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

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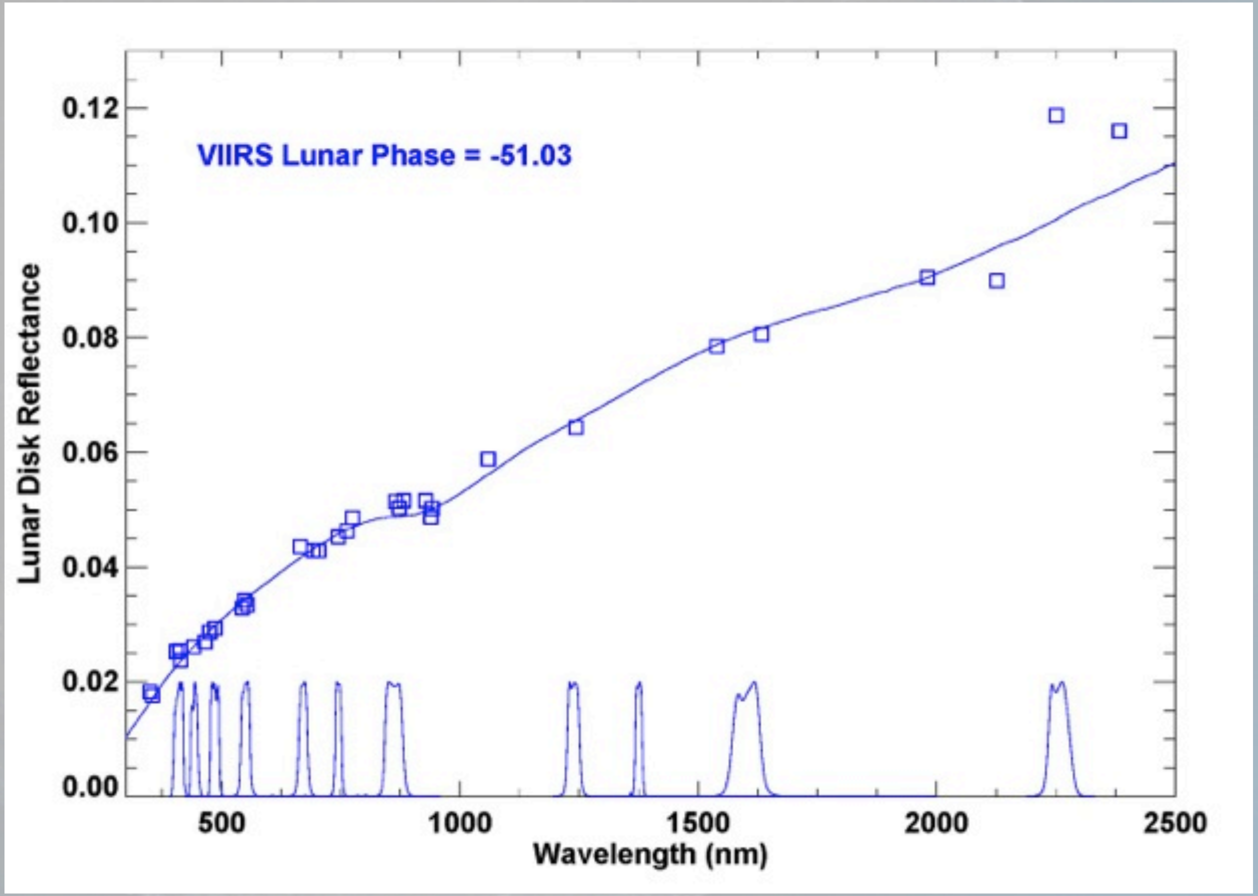
# Lunar Model Operation — Outputs Processing

Computing the model equation gives the lunar disk reflectance ($A_k$) at the 32 ROLO wavelengths. A representative lunar reflectance spectrum is then fitted to these $A_k$ values:

Symbols □ are $A_k$ from the lunar model computation

Solid line is the reference lunar reflectance spectrum, fitted to the $A_k$ values.



# Lunar Model Operation — Post-Processing

The fitted lunar reflectance spectrum is convolved with the instrument band spectral response functions and the solar spectrum to give the lunar irradiance ($E_M$) at the sensor band wavelengths:

$$E_M = \frac{\Omega_M}{\pi} \frac{\int A_{fit}(\lambda)\, E_{Sun}(\lambda)\, S(\lambda)\, d\lambda}{\int S(\lambda)\, d\lambda}$$

$A_{fit}$ = lunar reflectance spectrum
$E_{Sun}$ = Solar spectral irradiance
$S$ = spectral response function
$\Omega_M = 6.418 \times 10^{-5}$ sterad

The model computations ($A_{fit}$) and $\Omega_M$ are for standard Sun–Moon and Moon–Observer distances of 1 AU and 384400 km

Apply distance corrections:

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

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

# Engaging with the 2014 CLARREO SDT report

Report specifications regarding using the Moon:

- Lunar observations acquired once per month at 5°–10° phase angle, for on-orbit sensor stability monitoring
  - restricting the phase angle is not a requirement for lunar calibration, and this restricted range may conflict with other constraints, e.g. viewing the Moon in eclipse portions of the orbit
- The Moon is used to verify performance of the solar attenuators
  - an extremely important component of the CLARREO RS calibration strategy; perhaps warrants reviewing the frequency of Moon acquisitions
  - the accuracy of this check is directly tied to the accuracy of the lunar reference reflectance (presumably the ROLO lunar model)
- Moon views are integral to testing of the RS prototype instruments
- The SDT report indicates (correctly) that future improvements to the lunar radiometric reference can be applied to past Moon acquisitions
  - CLARREO observations, or any other sensor that has viewed the Moon
  - the CLARREO mission potentially can advance this development…

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# Potential for using CLARREO Moon acquisitions in developing a new lunar radiometric reference

Presuming the RS instrument meets the mission absolute accuracy requirement of 0.3% ($k=2$), then its Moon acquisitions are highly accurate measurements of the absolute lunar disk reflectance. An extended series of such measurements can form the basis for a revised lunar irradiance model.

- A feasibility study in the current USGS work plan
- The need for updating the ROLO model has been shown by lunar calibration analyses of some recent missions (e.g. NPP-VIIRS)
- For a measurement database to be useful for constructing an irradiance model, the critical need is sufficient coverage of phase angles and lunar librations
  - these coverages are constrained by orbital mechanics of the Moon
  - a minimum of 3 years of regular, frequent observations are required to trace a sufficiently full path through the geometric parameter space

# Example lunar observation geometry sampling for 90° polar orbit

- Simulation run for CLARREO polar orbit design: repeat cycle of 60.8 days (6 repeats per year) in 903 orbits
  - start time: 2018 Sept. 23 01:54:00 (Autumnal equinox)
  - duration: 3 years
- Two acquisitions per day, ~12 hours apart, alternating North and South pole crossings
- Expanded coverage of phase angle, up to 135 degrees
  - accessible from a space-based platform (not possible for ground-based)
  - would support lunar calibrations 3 weeks of each month (vs. currently 2)

Visualizations of lunar libration coverage: sub-satellite longitude and latitude in the Moon-centered coordinate system

- this simulation shows good libration coverage in 3 years, although not simultaneously with phase

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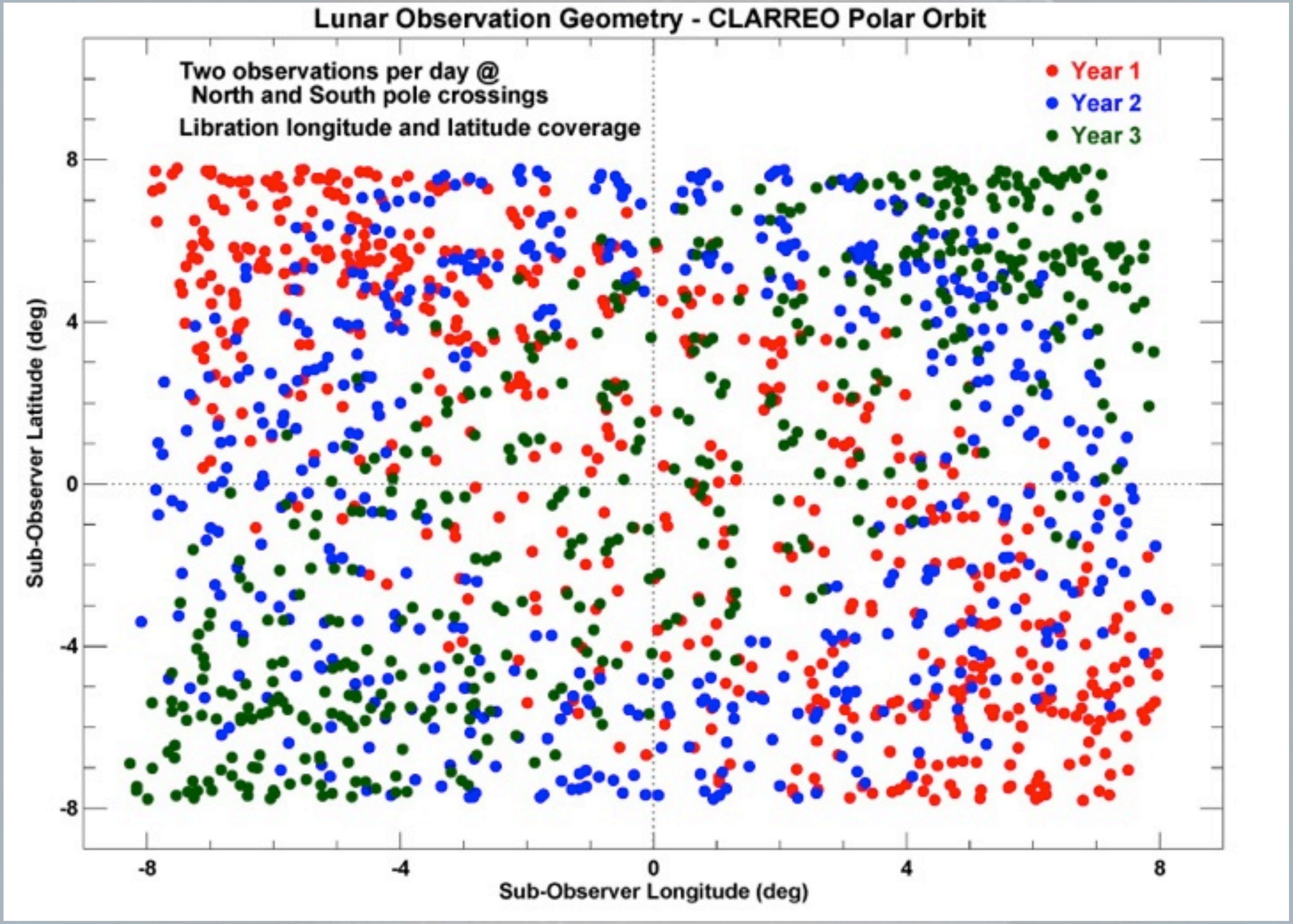
# Libration coverage for CLARREO 90° polar orbit

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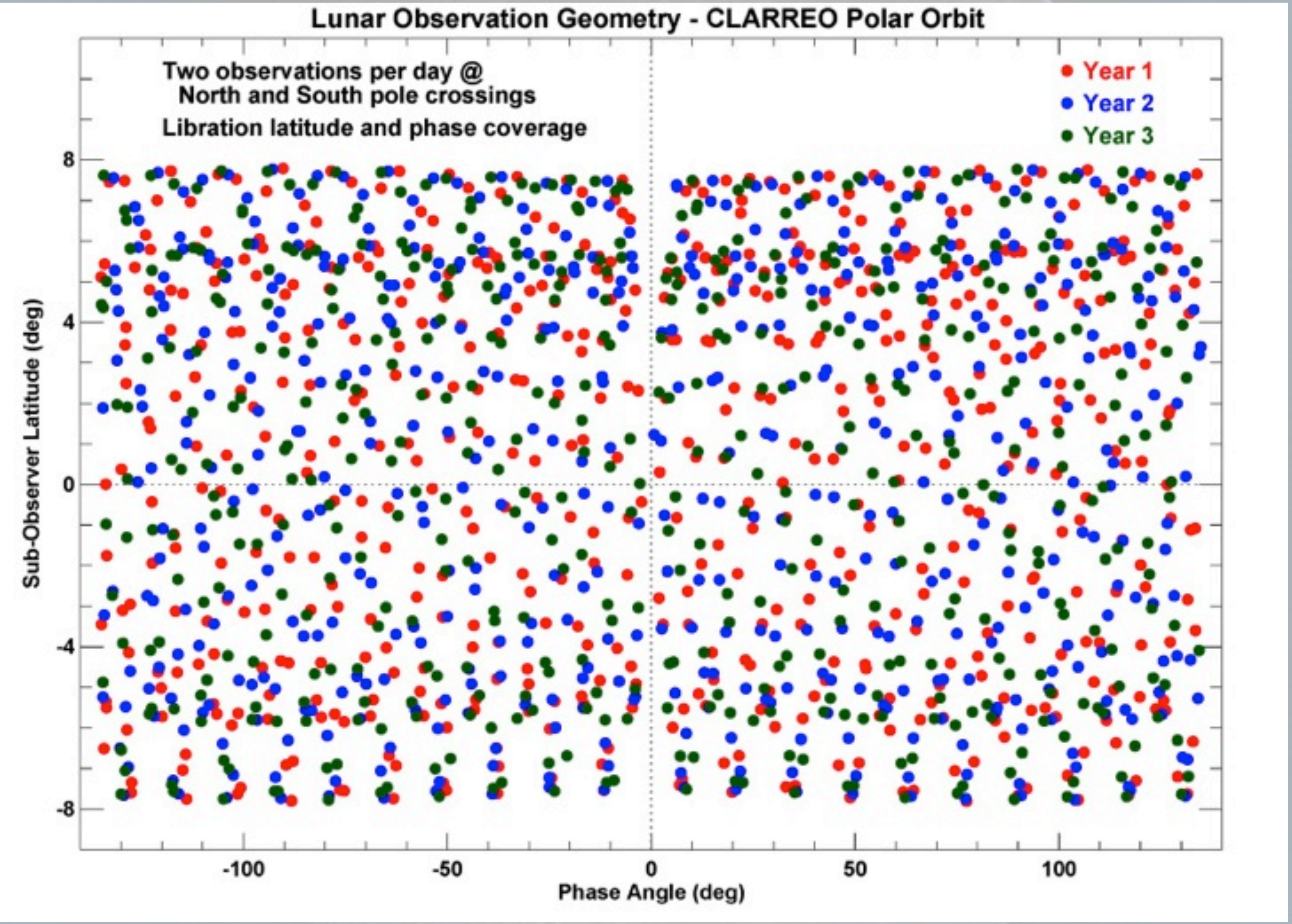
# Libration and phase coverage for 90° polar orbit



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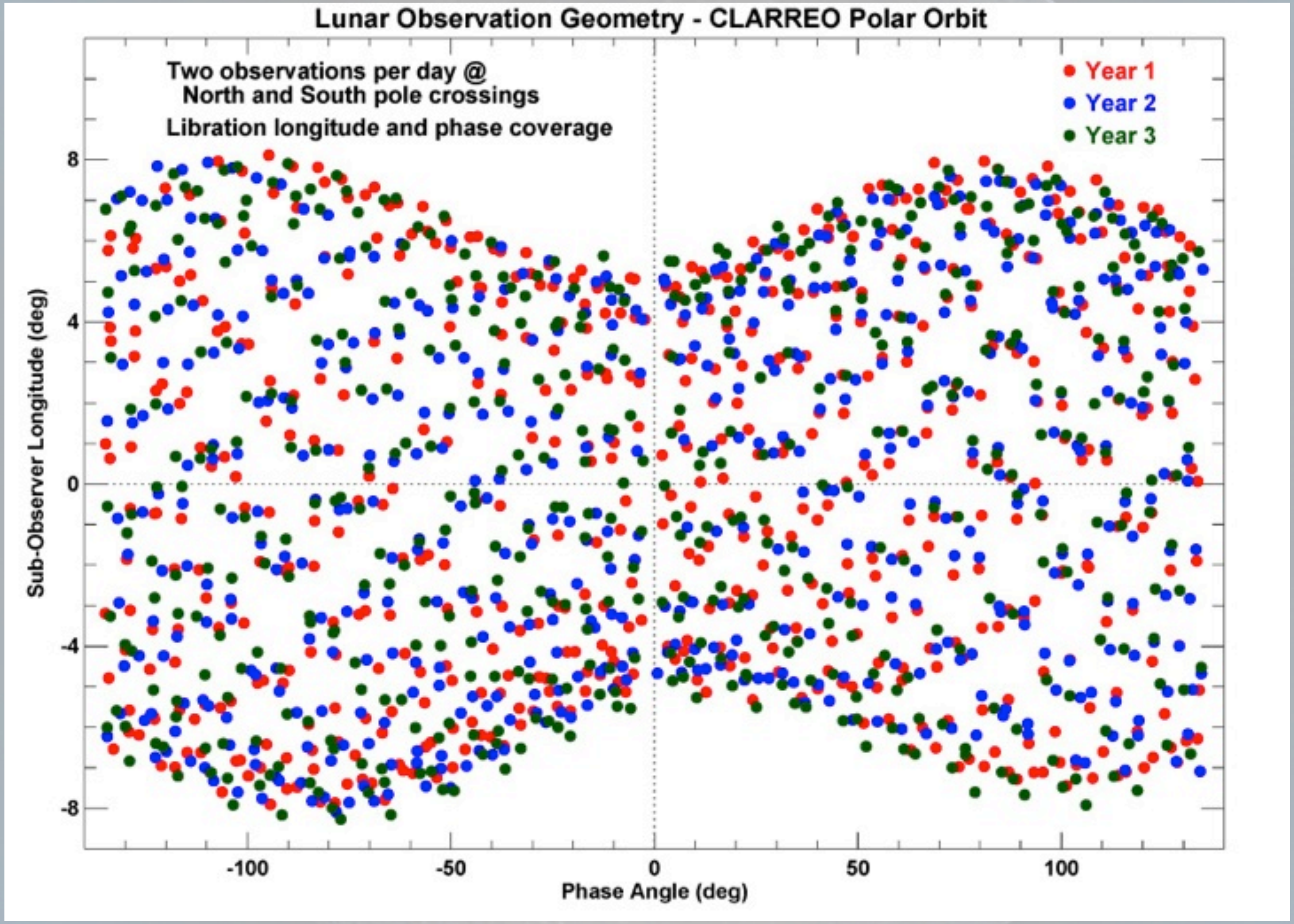

# Beyond the current Science Definition: Reference Inter-calibration using the Moon

The Moon is an ultra-stable reflectance target. Through application of the lunar model, it can be used as a calibration transfer standard.

- CLARREO RS will view the Moon, and thus represents the reference instrument for this technique
  - other instruments with lunar observations: NPP-VIIRS, MODIS (both), Landsat-8 OLI, all geostationary imagers, more…
- Lunar inter-calibration does not require simultaneous views
  - the differences due to geometry are accounted for by the lunar model
  - if restriction to a small range of phase angles is enforced, it argues for expanding the CLARREO Moon acquisitions as described above
- Spectral response differences between instruments are accounted for inherently by the lunar calibration system
  - overcomes an identified "major challenge" for reference inter-calibration
- GSICS is moving toward declaring the Moon as the RS reference std

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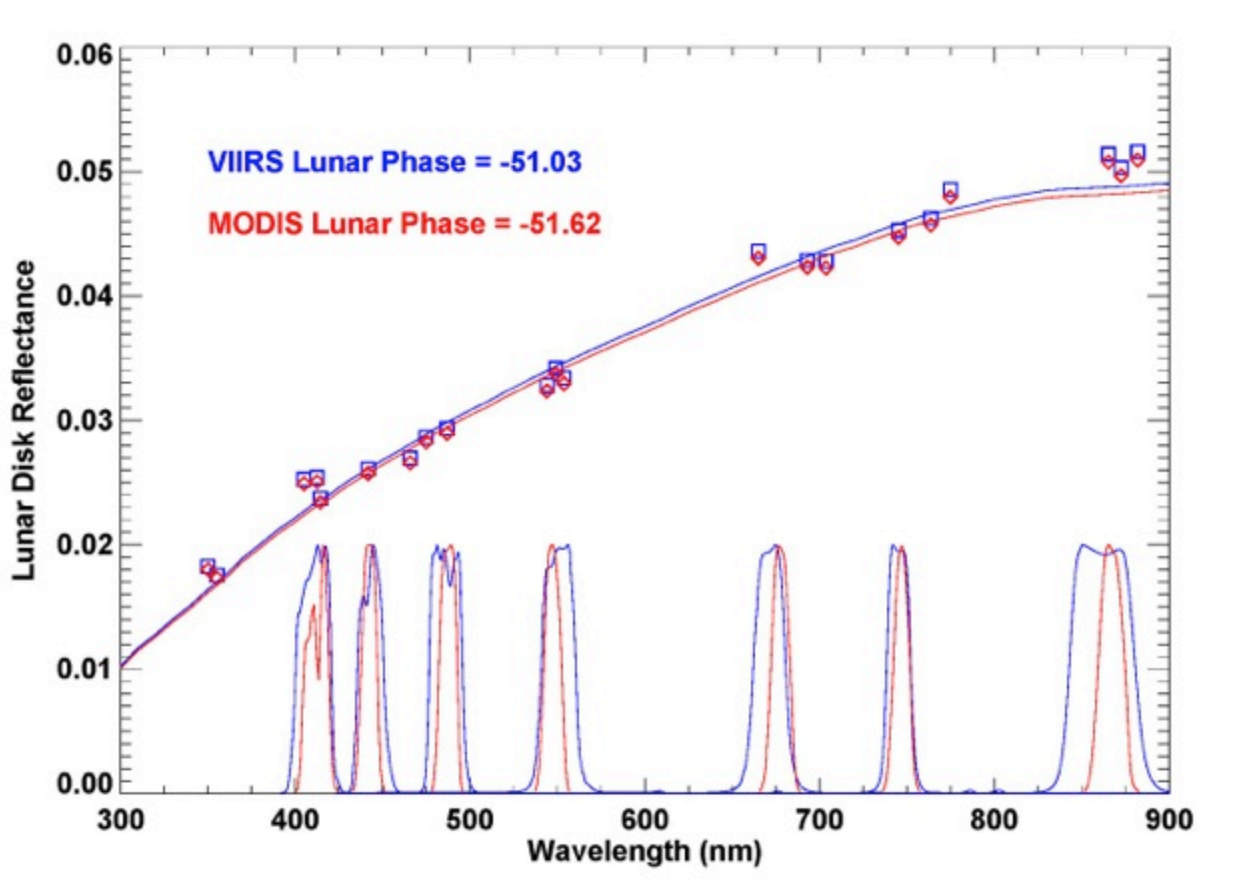
# Lunar cross-comparison: MODIS and VIIRS

| | Observation date | Phase angle | Sub-solar longitude | Sub-solar latitude | Sub-satellite longitude | Sub-satellite latitude |
|---|---|---|---|---|---|---|
| NPP-VIIRS | 2014-02-10 | −51.03 | 55.32 | 1.488 | 4.328 | 5.159 |
| MODIS-Aqua | 2002-10-16 | −51.62 | 56.55 | 1.171 | 5.024 | 5.774 |

Seven MODIS ocean color bands coincide with VIIRS bands M1–M7.

The similar geometry of the observations means the lunar disk reflectance spectra are nearly the same.

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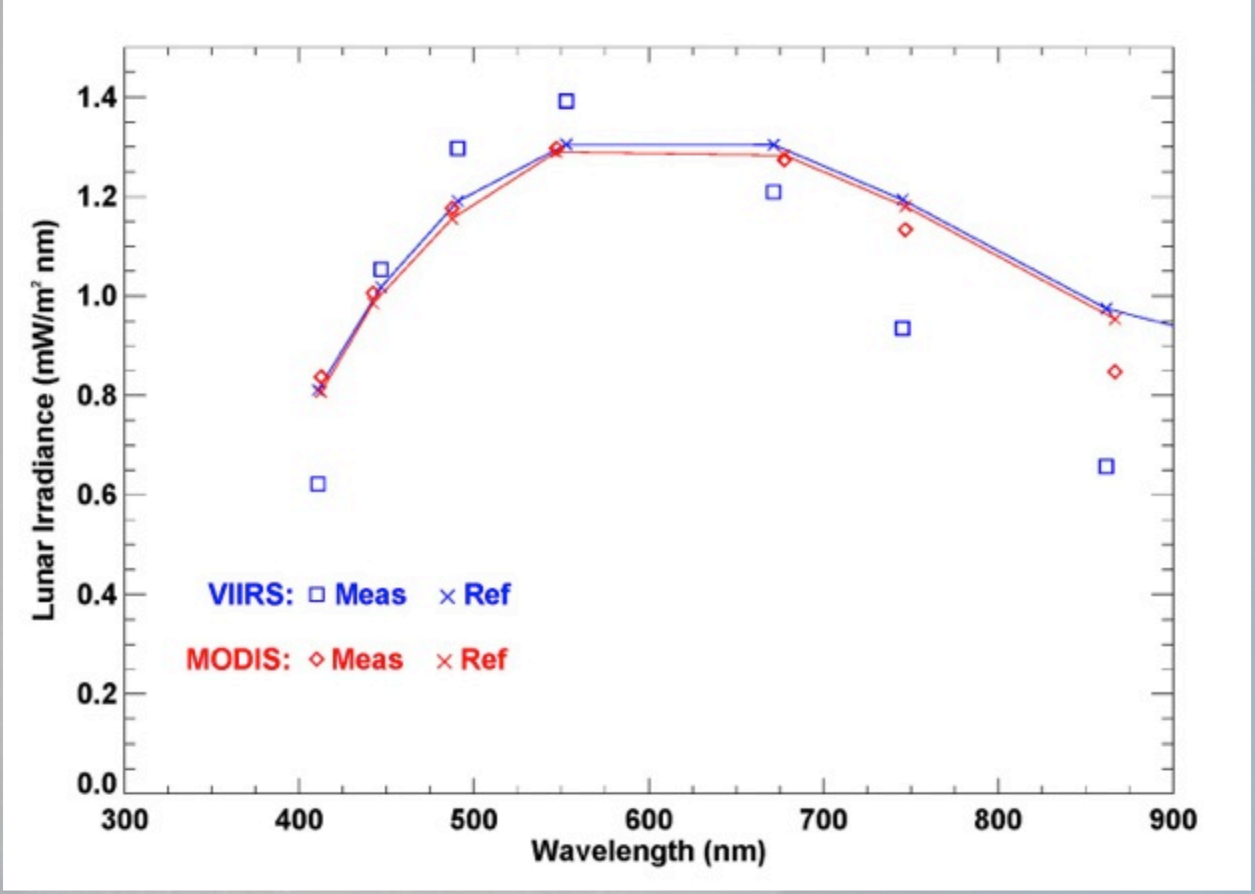
# Lunar irradiance cross-comparison

MODIS and VIIRS Moon observations with similar geometry, but more than 11 years apart

☐ and ◊ symbols are lunar irradiance measurements from VIIRS and MODIS images.

The reference lunar irradiance is nearly the same for both instruments.

There are notable differences in sensor response to the similar lunar source.



# Conclusions

- USGS lunar calibration work for CLARREO currently at an early stage
  - objective is to derive operational requirements for the RS measurements of the Moon, to optimize the usefulness of these data
  - outcomes will provide details for the next SDT report
- Initial orbit and lunar observation simulations done for 90° polar orbit, in progress for ISS orbit
  - for ISS, field of regard constraints for JEM-EF deployment: exclusion zones for the CLARREO payload carrier, adjacent payloads, ram direction
- Feasibility study in progress for acquiring a new lunar characterization dataset for irradiance/reflectance modeling
  - initial polar orbit simulations show reasonable geometry coverage in 3 yrs
- The possibility exists to use the Moon as a transfer target for inter-calibration with CLARREO RS
  - a suitable opportunity, and a larger vision for the CLARREO mission

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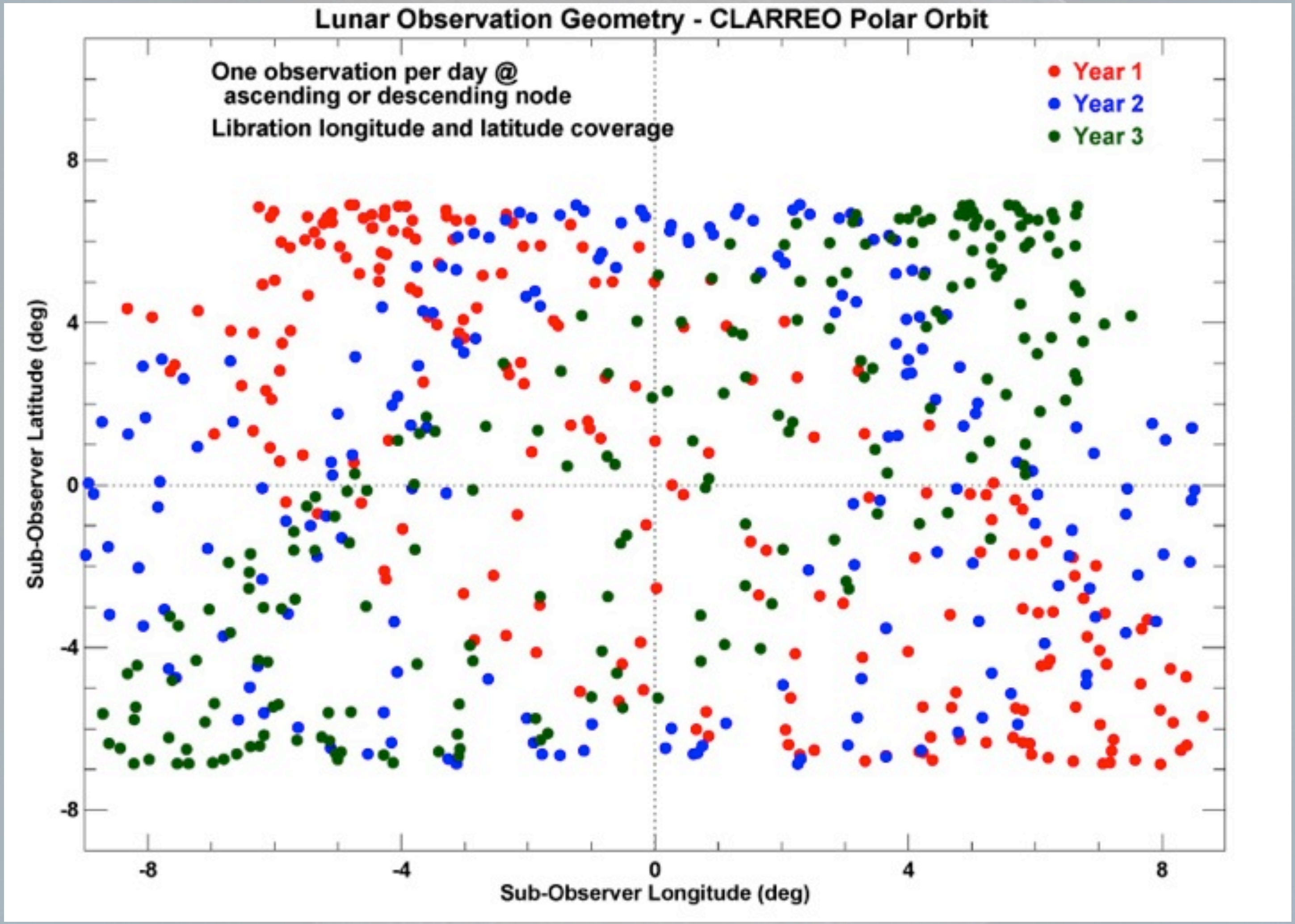
# Backup slides

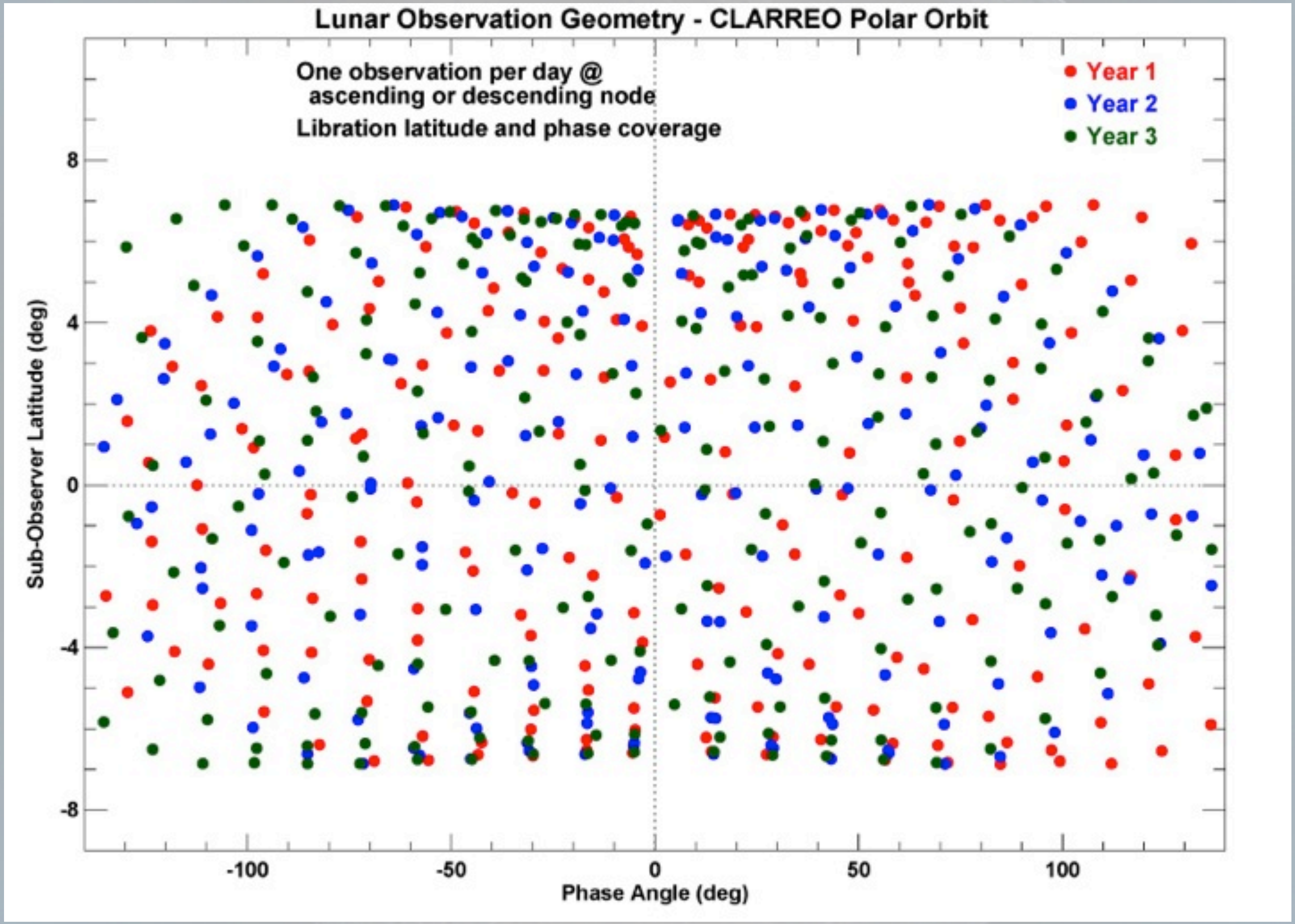
# Libration coverage for CLARREO 90° polar orbit

Simulation for one observation per day, at node crossing



# Libration and phase coverage for 90° polar orbit

Simulation for one observation per day, at node crossing

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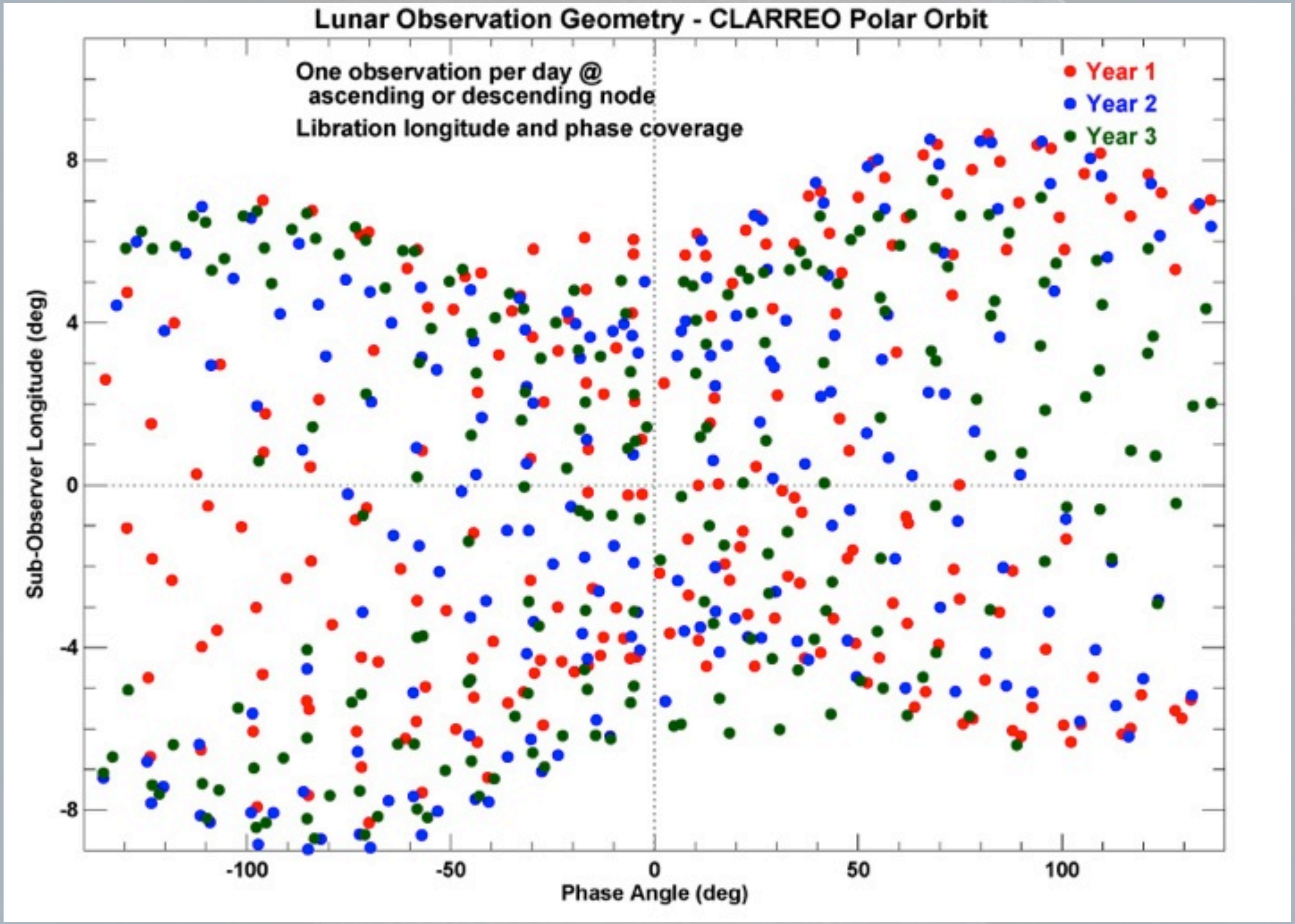


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