Lunar research activities at CMA

Xiuqing (Scott) HU

GSICS Annual Meeting 2024,
11-15 March 2024, Darmstadt, Germany

Outline

- Ground-based Lunar Measurement
- Space-borne Lunar Observation
- Data processing and Primary Results
- AI black-box Lunar Model development
- Path Forward

1. CMA Lunar Measurement in Lijiang Observatory

CMA Groound-based Lunar observation Keep Ongoning Since 2015 in Lijiang Observatory and More and more Lunar instruments were involved

Lunar Measurement Station in Lijiang Observatory

3 Lunar spectrometer imagers

(1) VisNIR Ground-based Lunar Imaging Spectrometer (GLIS) (2015.12-Now)

(2) ShortWave Infared Lunar Oberved Infared Spectrometer (LOIS) (2020.12-Now)

(3) VNIR LeSIRB-Lunar and Earth Spectral Imager Radiometry Benchmark (2019.12-Now)

GLIS (400-1000nm)

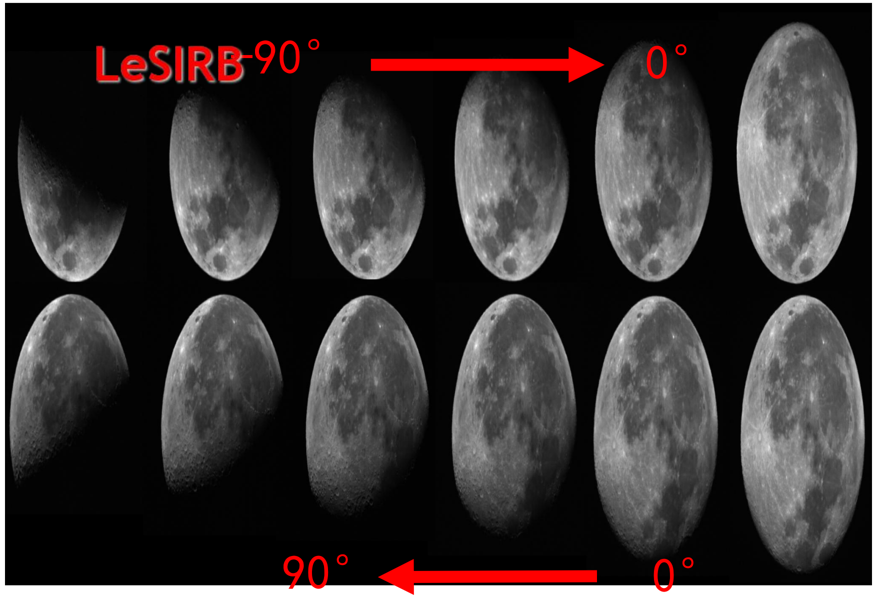
LeSIRB (400-1000nm)

FY-3G/HAOC Prototype Modified

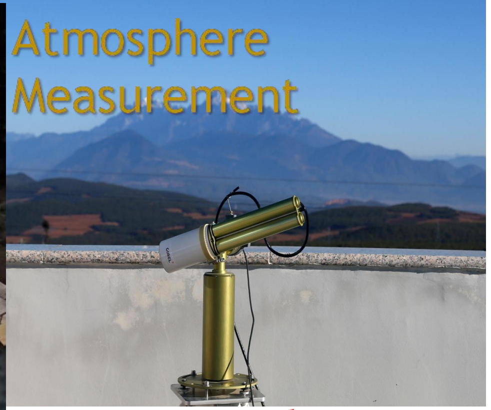
- LOIS（1000nm-2400nm）

LOIS

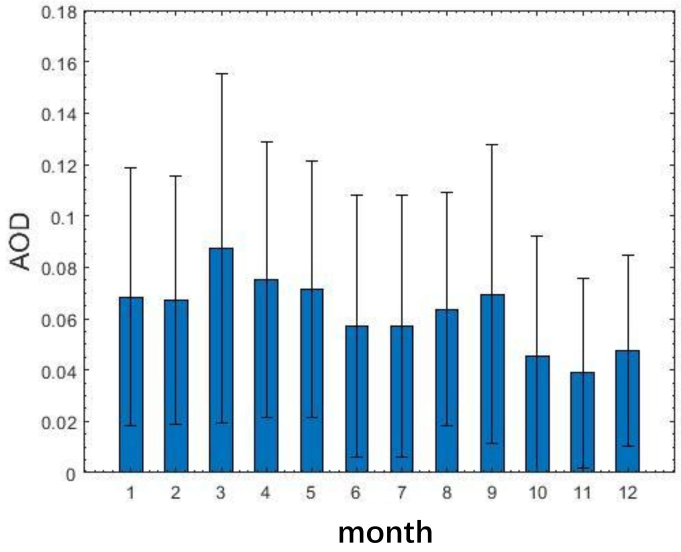
Lunar and Ancillary Observation--CMA
Instrument Calibration and Traceability--NIM



AMPLE Lidar

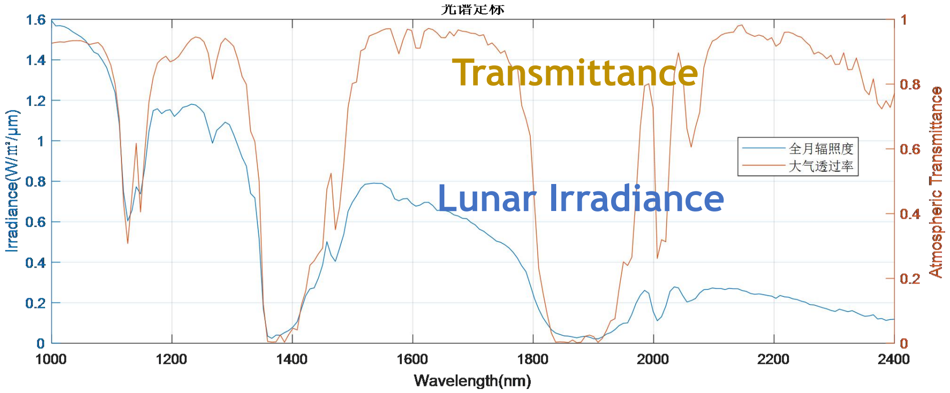


CE318T Sunphotometer



LOIS Onsite Calibration

ShortwaveIR Band Lunar Irradiance



Traceability

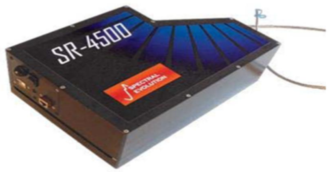
NIST

↑

1） SR4500A spectrometer

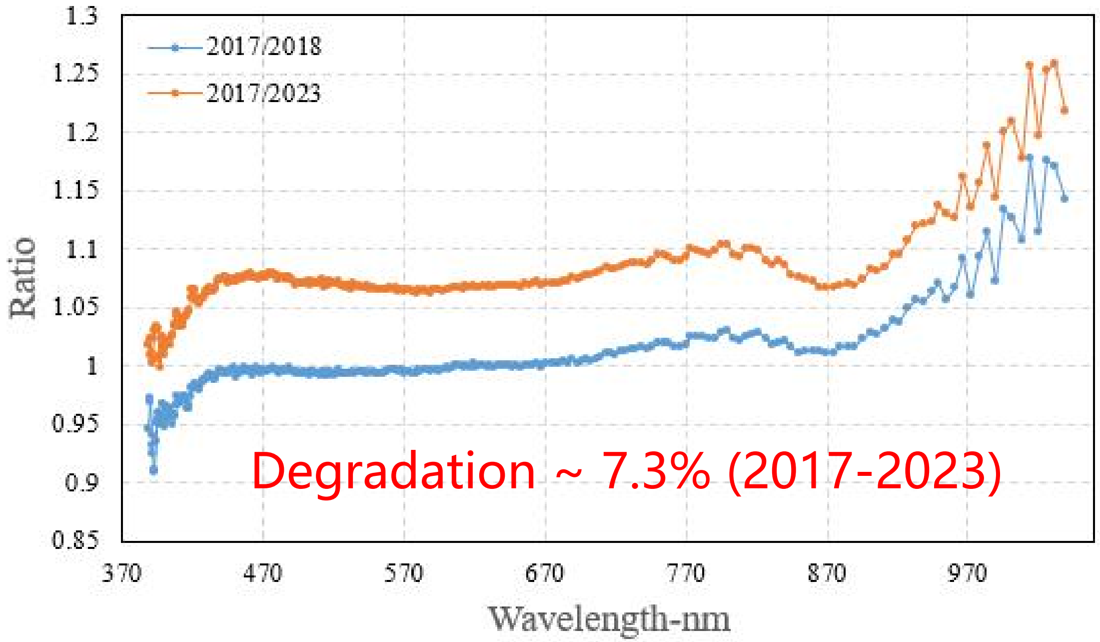
↑ Integrating sphere

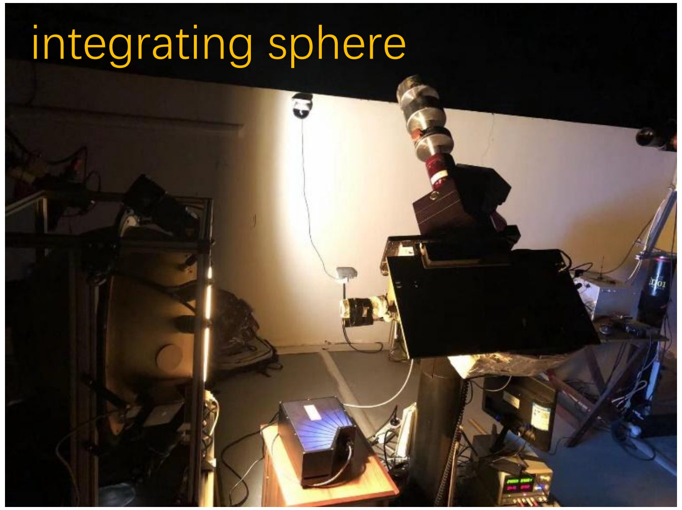
2） Lunar imaging spectrometer

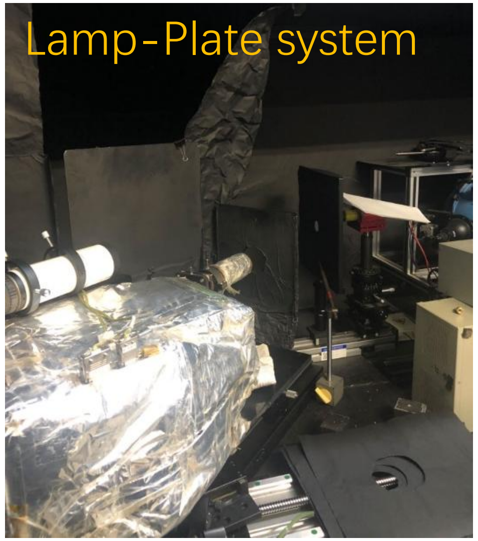


Instrument Calibration and Traceability--NIM

Date	Calibration
2017.04.10	laboratory (NIM)
2018.10.26	laboratory (NIM)
2021.05.10	on-site
2023.03.03	on-site
2023.09.14	laboratory (NIM)
2023.11.15	laboratory (NIM)



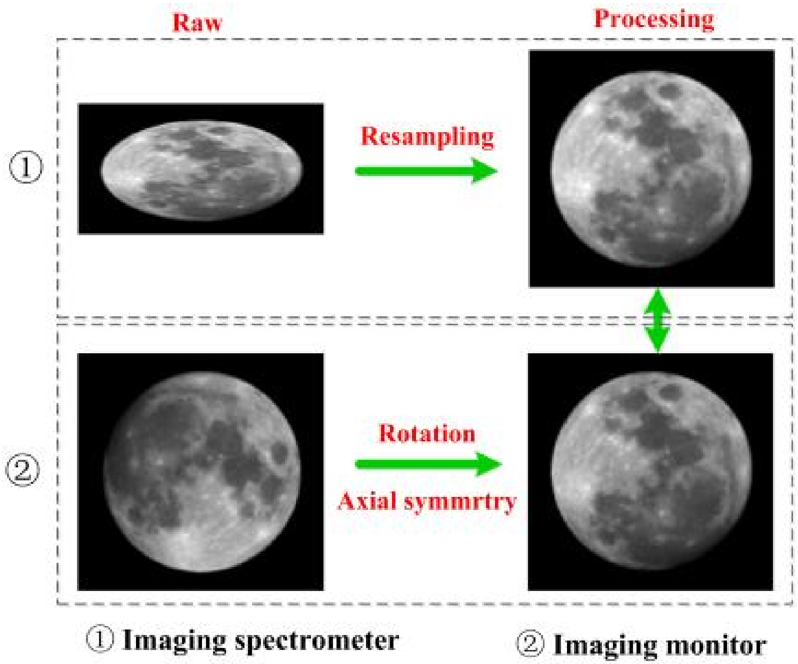


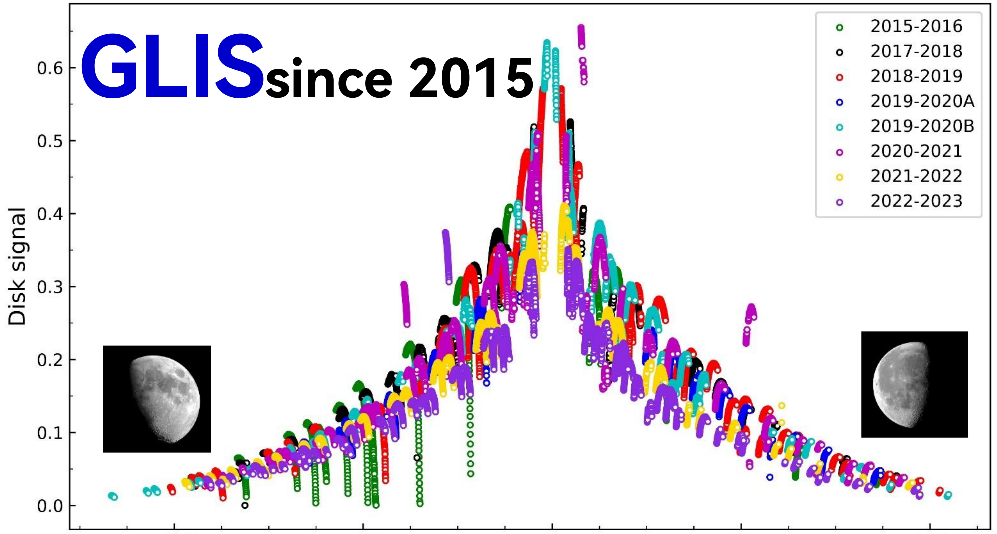


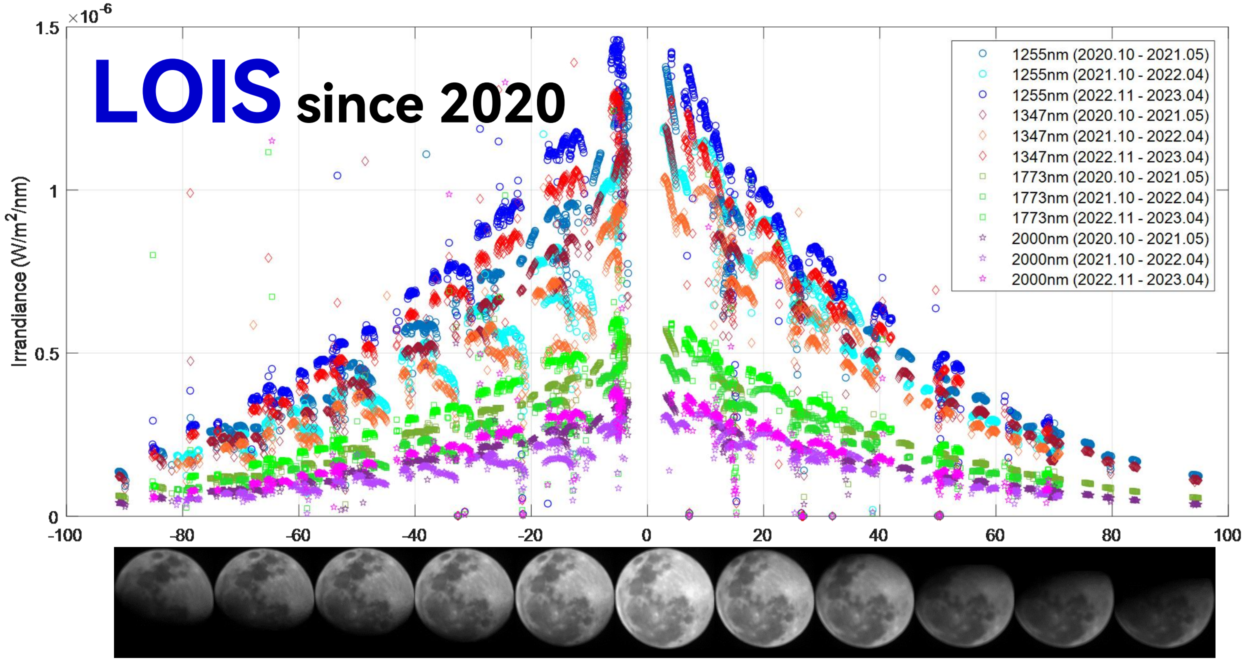
- Lamp-Plate system and low brightness integrating sphere were used for this absolute calibration with quartz-tungsten halogen lamps of known output values.
- Three NIM calibrations showed that the instrument decayed by ~7.3%.

NSMC NCSW

2. GLIS and LOIS Moon Dataset

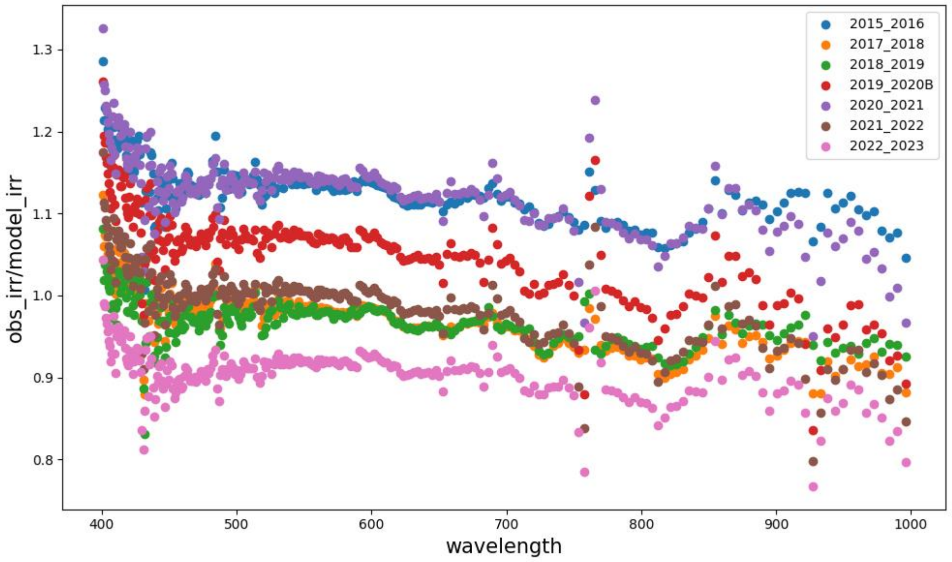


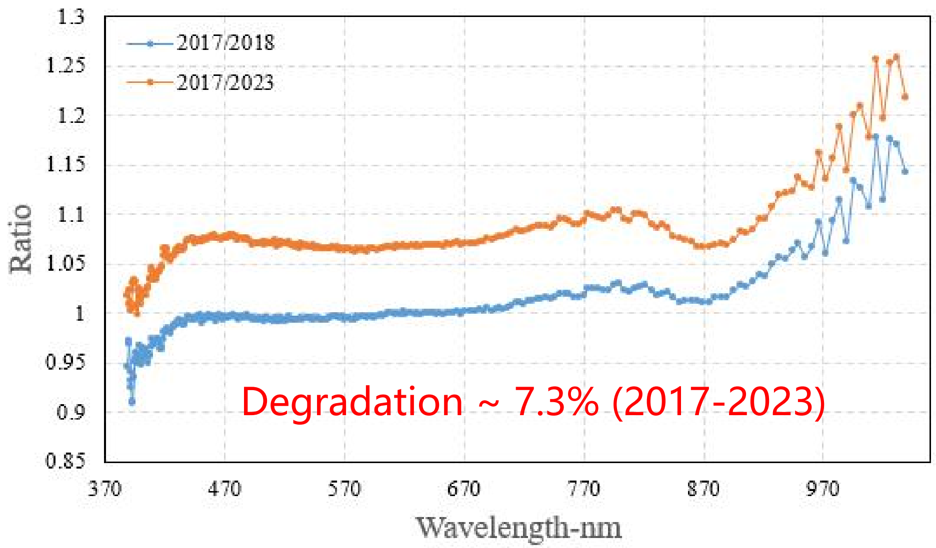


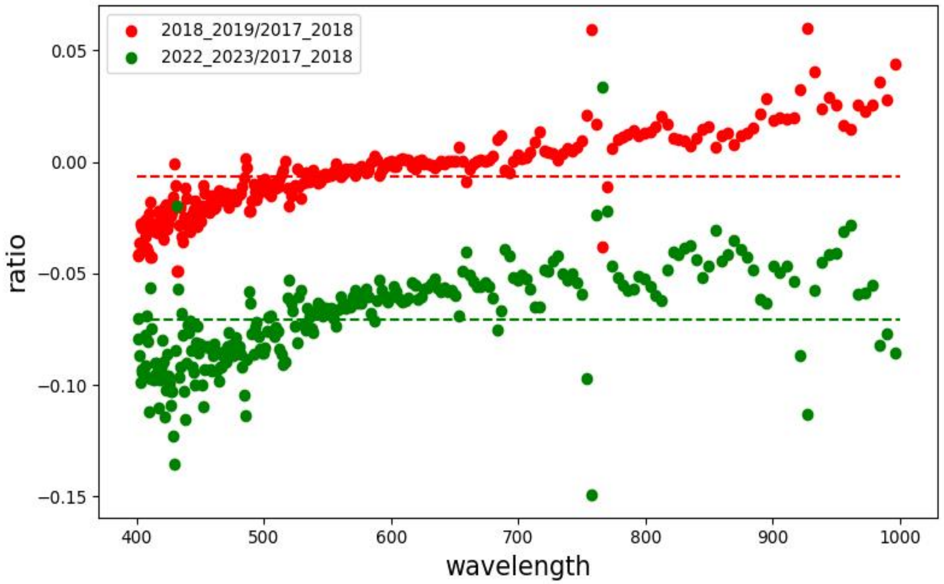


LOIS has acquired 177 days of observations in 22 months since 2020, 4304 views of the Moon were collectedValid data have 3647 views
The validity rate is 84.74%

2.1 GLIS comparsion with GIRO







(1) These individual observation cycles integrate the data for the minimum zenith angle on all valid observation days, using the same calibration;

(2) The trend of the data is generally consistent with the results of the three calibrations, with the green line in the right panel reflects a ~7% reduction in precision of the latest observations relative to the previous ones;

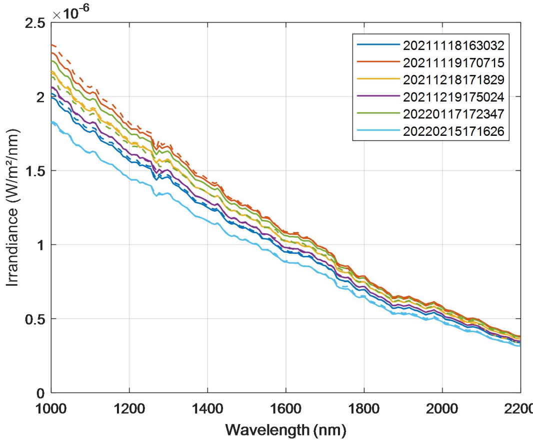
(3) Some of the trends in the above figure are not consistent with theory and may have something to do with instrument maintenance during the observing cycle, especially telescope cleaning;

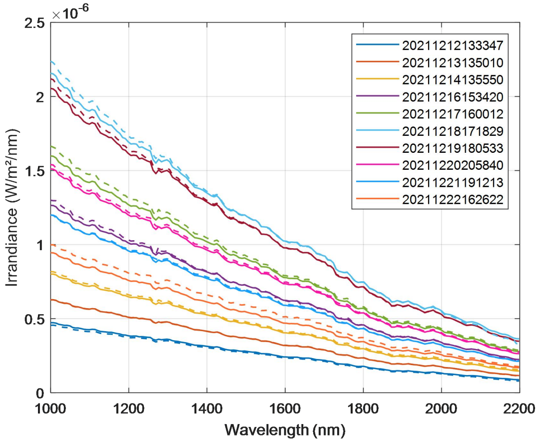
2.2 LOIS Dataset with GIRO

Six data with similar phase angles in different months were selected for dataset 1, and ten data with different monthly phase angles within a month were selected for dataset 2.

$$P_n = G_n / L_n \qquad STD = \sqrt{\frac{\sum_{n=1}^{N}(P_n - \overline{P_n})}{N-1}} \qquad RSD = \frac{STD}{\overline{P}} * 100\%$$

$$\overline{D} = \frac{1}{K}\sum_{i=1}^{K}\left|\frac{L_i - G_i}{G_i}\right| \qquad u = \sqrt{\frac{\sum_{n=1}^{N}\overline{D_n}^2}{N}}$$





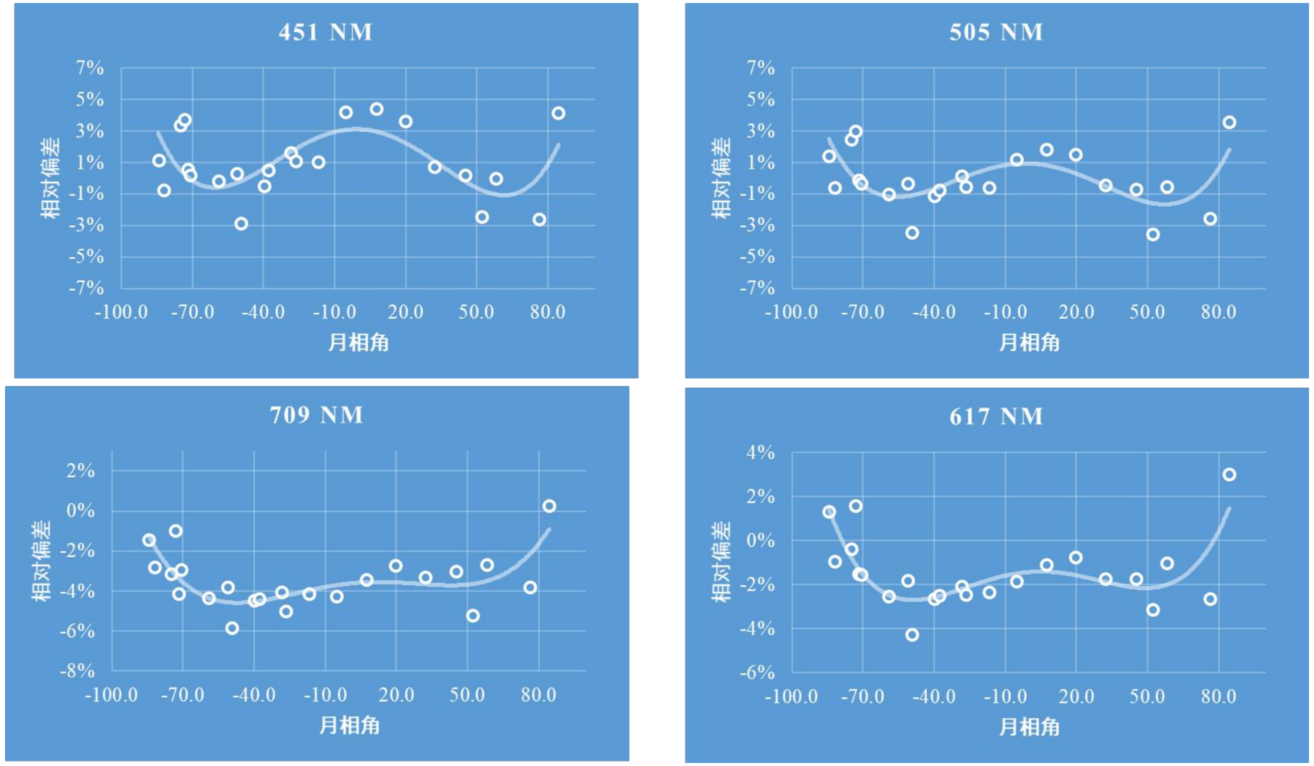
The curve colors in the figure correspond to time, the dashed line is the spectrometer observation, and the solid line is the corresponding GIRO model value..

Dataset 1	Phase angle/°	Zenith angle/°	P/%	RSD/%	u/%
2021-11-18	-7.58	10.58	0.66	1.92	1.59
2021-11-19	3.70	7.16	1.23		
2021-12-18	-5.46	5.84	0.91		
2021-12-19	6.56	1.63	0.26		
2022-01-17	-5.07	1.62	3.37		
2022-02-15	-5.21	7.74	0.88		

Dataset 2	Phase angle/°	Zenith angle/°	P/%	RSD/%	u/%
2021-12-12	-72.76	31.71	3.59	2.83	1.93
2021-12-13	-61.23	24.04	0.31		
2021-12-14	-49.95	16.92	2.97		
2021-12-16	-27.44	8.42	1.07		
2021-12-17	-16.42	4.33	2.55		
2021-12-18	-5.46	5.85	1.62		
2021-12-19	6.62	4.90	0.81		
2021-12-20	18.15	31.60	1.55		
2021-12-21	28.78	3.48	0.79		
2021-12-22	39.21	50.61	1.07		

2.3 lunar observation from LeSIRB

FY-3G/HAOC Prototype Modified since 2019



Radiometric calibration

1) Laboratory traceability: Standard lamp+diffuse system

2) Laboratory calibration: Integrating sphere+SR4500A

Atmospheric Correction

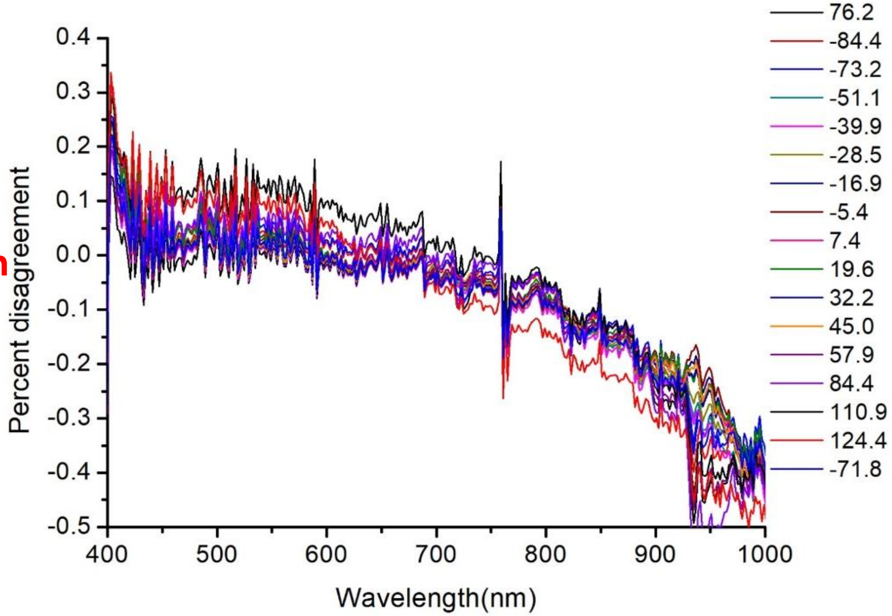
1) CE318+Modtran 4.3

Model comparison

1) Relative comparison

2) Absolute comparison

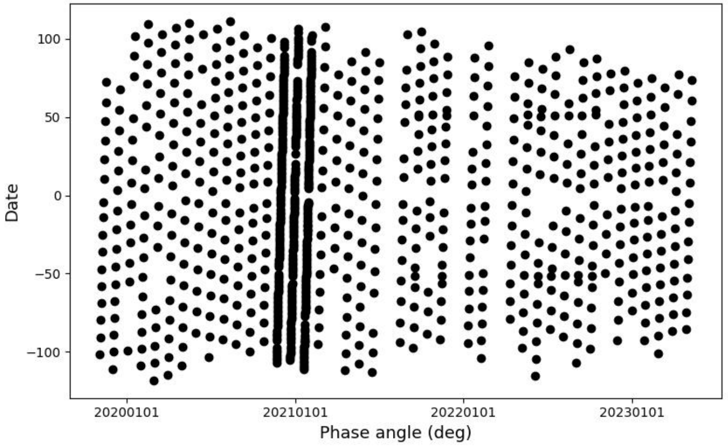
$$p = \frac{I_{instrument} - I_{model}}{I_{instrument}}$$

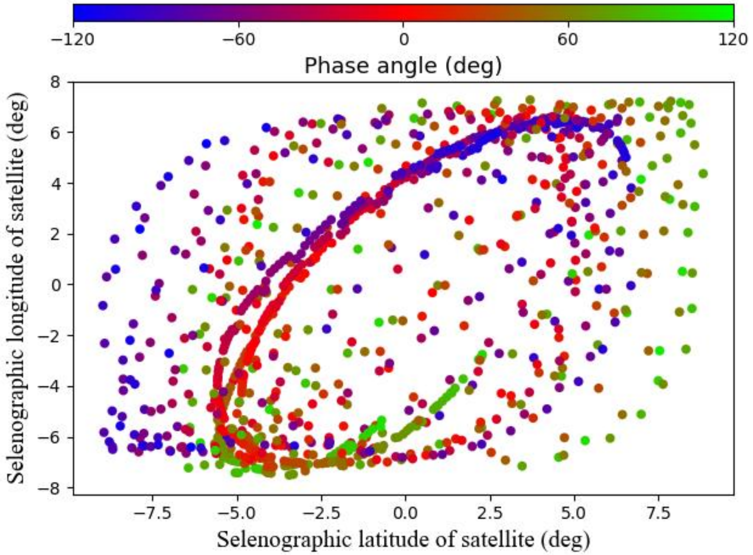


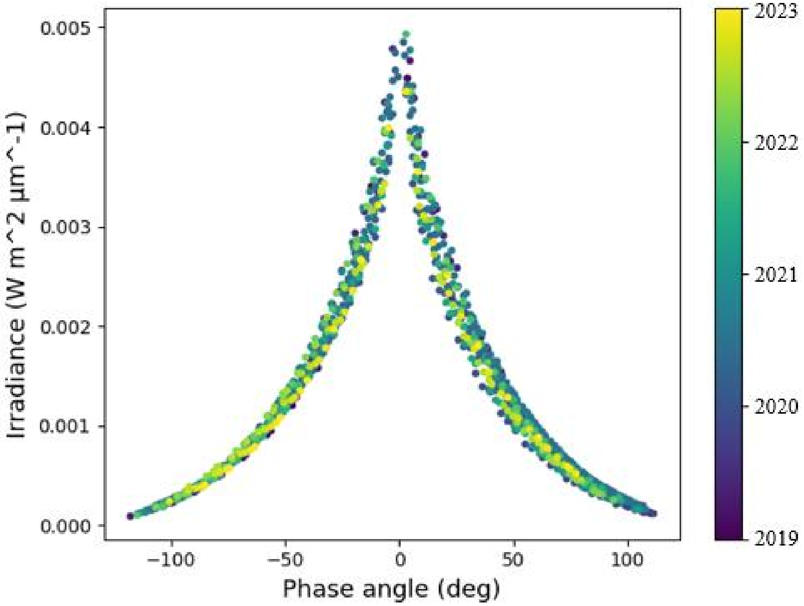
3. 1 JiLin-1 Small Satellite--Collaboration with CMA

Conducted Space-borne Lunar Imaging (19 bands in Visible to NIR)

JiLin-1 Lunar observation (41 months since April, 2019)







(1) The Jilin-1 commercial small satellite has high maneuver ability and spatial resolution (~ 3.5 km on the Moon).

(2) Starting in 2020, the Moon is observed at the appropriate time in each lunation.

- For calibration purposes
- Exploring the possibilities of radiance calibration

(3) Also made observations of three intensive lunar phases to attempt to discover the phase angle sensitivity of the model.

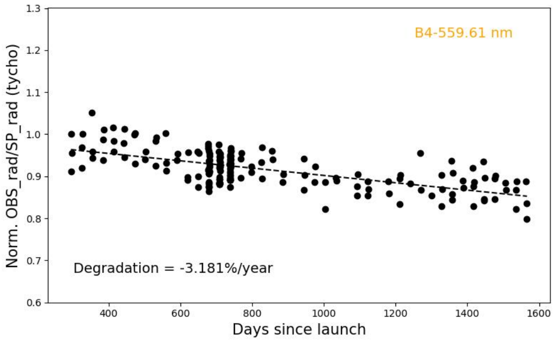
	Band	Ground sampling distance (m)	Radiometric resolution (bits)
Panchromatic	B0	5	12
Multispectral	B1-B6	5	12
	B7-B12	10	14
	B13-B19	20	16

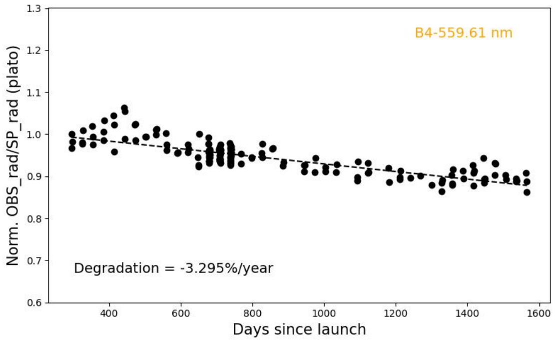
Jilin-1 Results with GIRO irradiance

- Visible channel performance of PMS monitored using lunar data from November 2019 to March 2023
- Degradation in two bands, B3 and B4, was observed using GIRO simulations
  - The irradiance comparison trend for band 4 is in good agreement with the radiance comparison

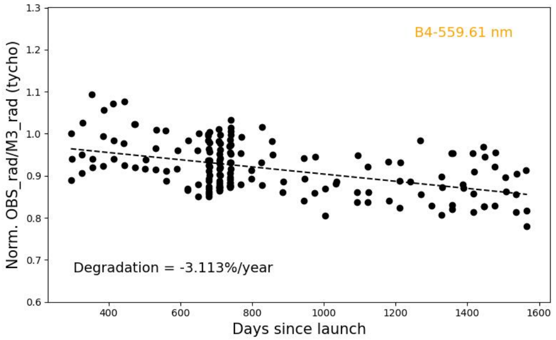
Tycho | Plato

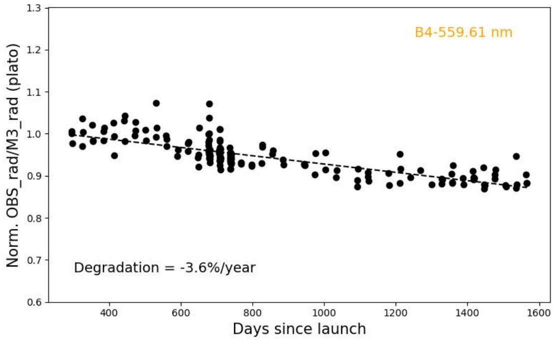
SP

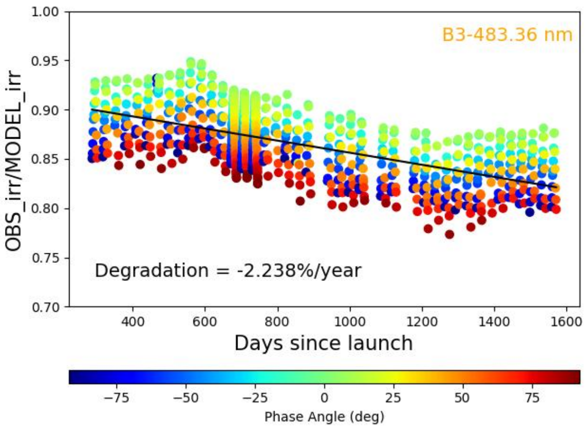


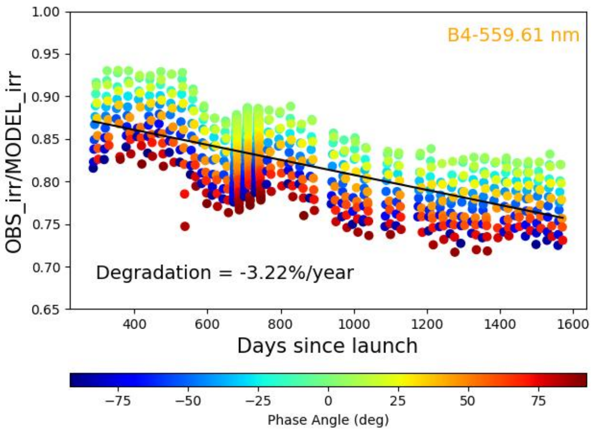


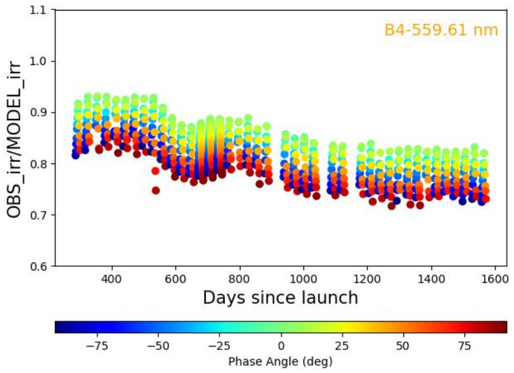
M3

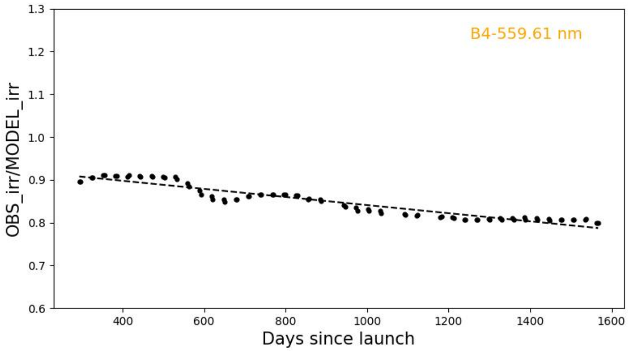






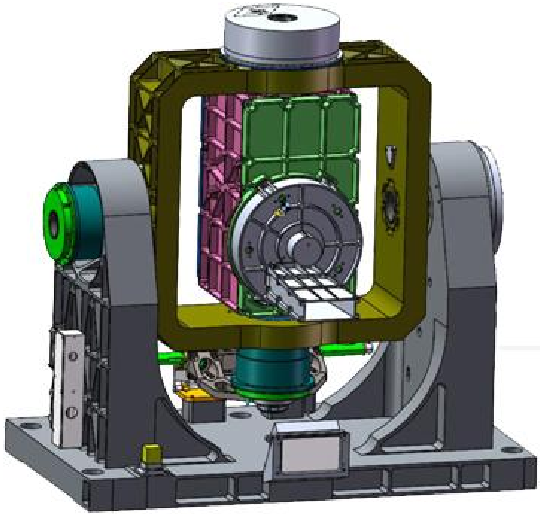






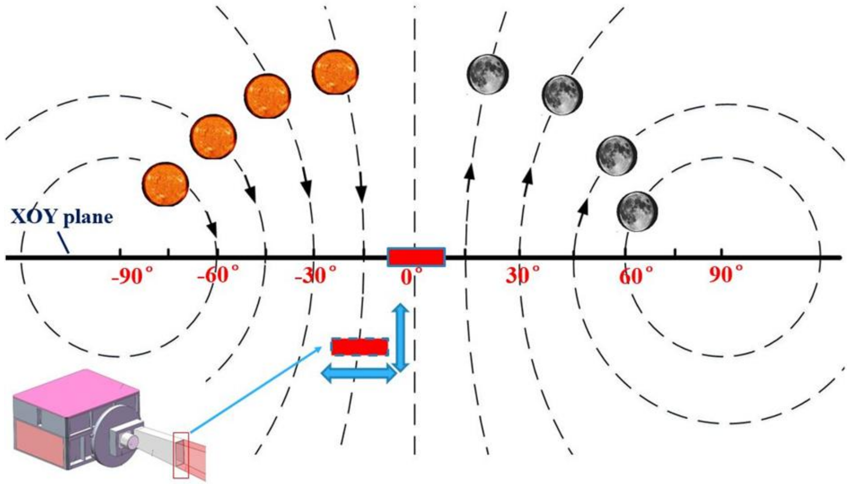
3.2 Lunar observations from FY-3G/ HAOC

FY-3G



HAOC

- ■ **Observation mode:**
  - ✓ **Scan the solar disk，the Lunar disk**
  - ✓ **Scan the solar along the slit**
  - ✓ **Scan the transmissive diffuser along the slit**
  - ✓ **Pushbroom imaging**



Lunar and solar observations

High Accuracy On-board Calibrator(HAOC)

- ➢ Push-broom imaging spectrometer；
- ➢ Spectral Images of the Earth in the Visible Near Infrared Band (400-1060nm) through Offner Grating Spectroscopy， Scan width :50km;
- ➢ Cross calibration and radiation reference transfer for Fengyun 3 series satellites.

① First validation test of solar cross calibration technology on orbit

② Transfer form high-precision radiometric calibration results to visible/near-infrared instruments on the same platform or other satellites

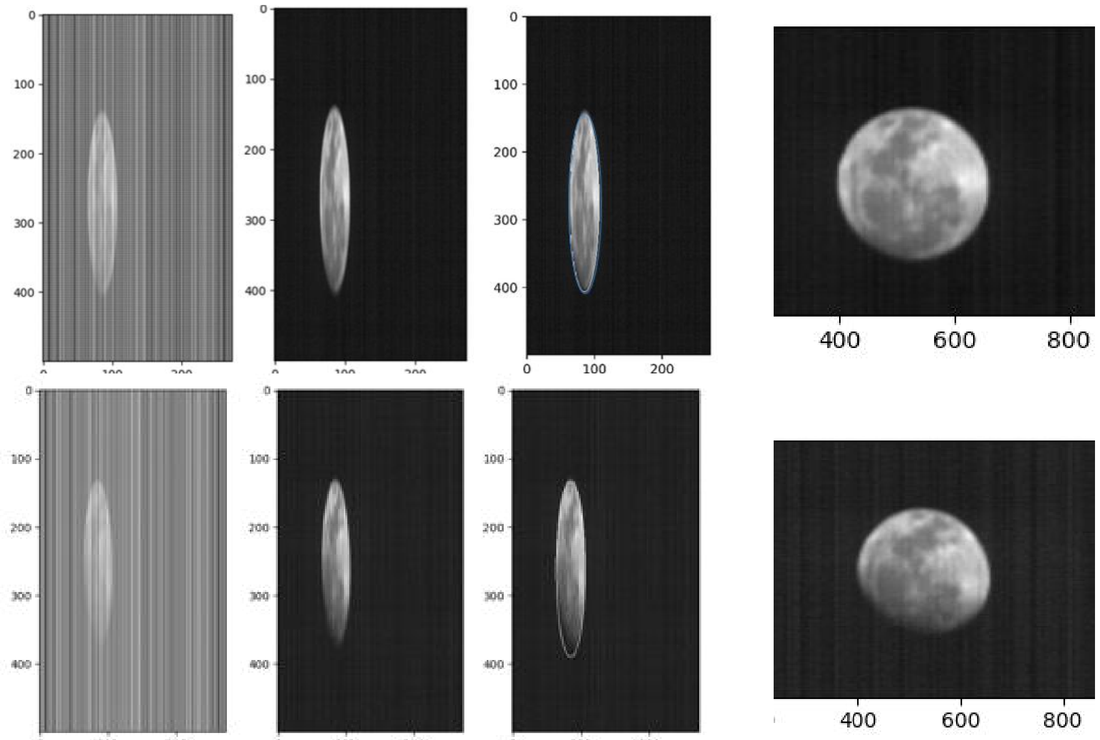
③ Establishing a unified "scale" for the measurement results of optical instruments on orbit

④ Research foundation for the fusion application of future satellite monitoring data and the establishment of climate datasets.

Lunar observations results for FY-3G/HAOC

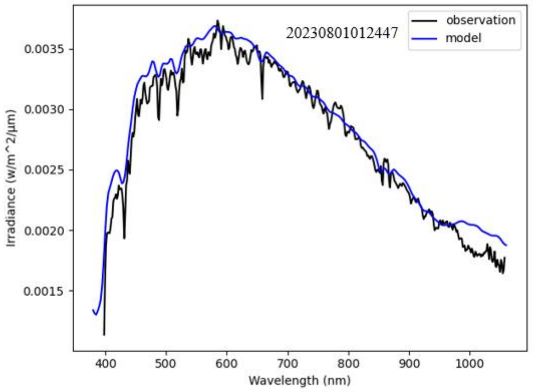
HAOC lunar observations

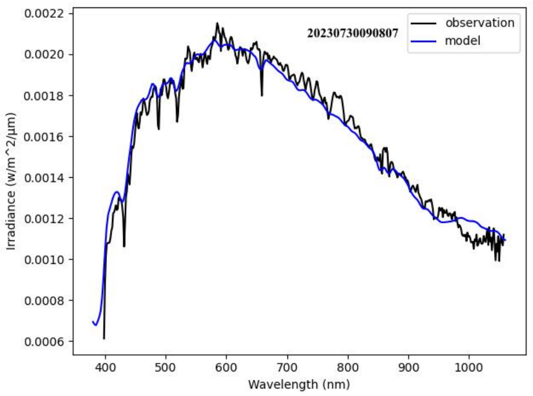
Time	Satellite-Moon distance	Phase angle
2023-08-01T01:24:47	355869.57 km	-12.32°
2023-07-30T09:08:07	370240.43 km	-33.84°



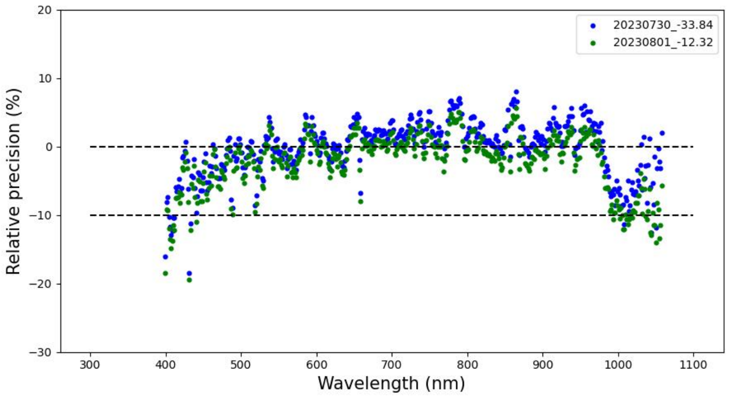
Origional Image | Dark current removal | Moon disk Extracting | Resample Image

Irradiance (measurements vs GIRO)

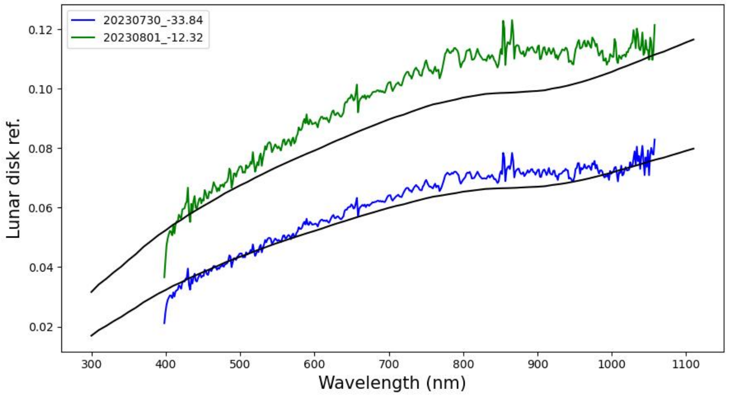




Irradiance relative accuracy (obs_irr-model_irr)/model_irr (%)



Lunar disk reflectance (measurements vs GIRO-black line)

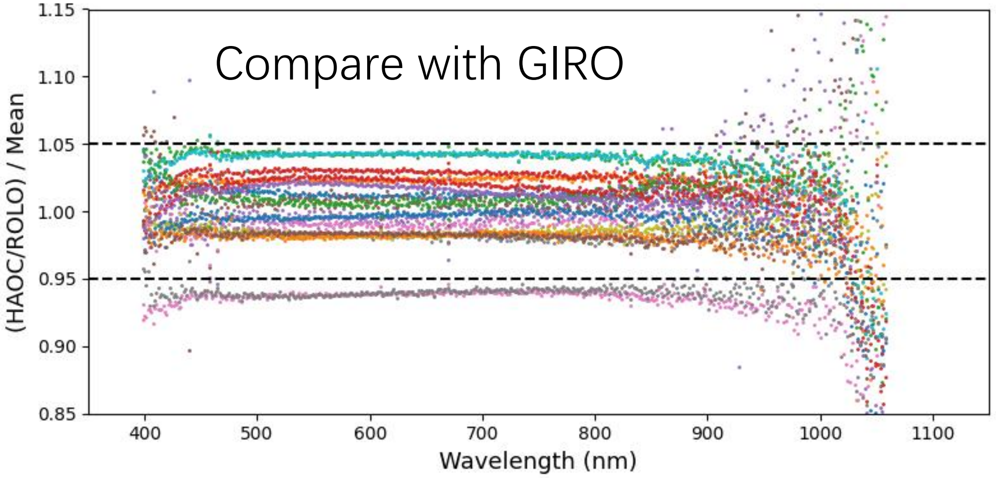


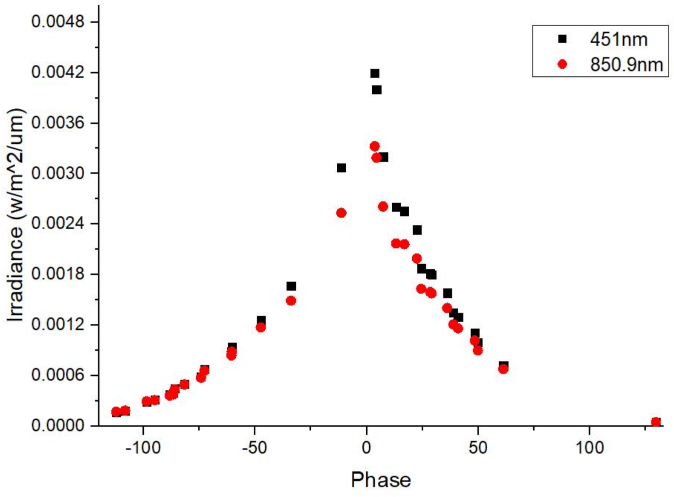
- Improving calibration accuracy based on the solar cross calibration technology;
- Provide high-precision on-orbit observation data

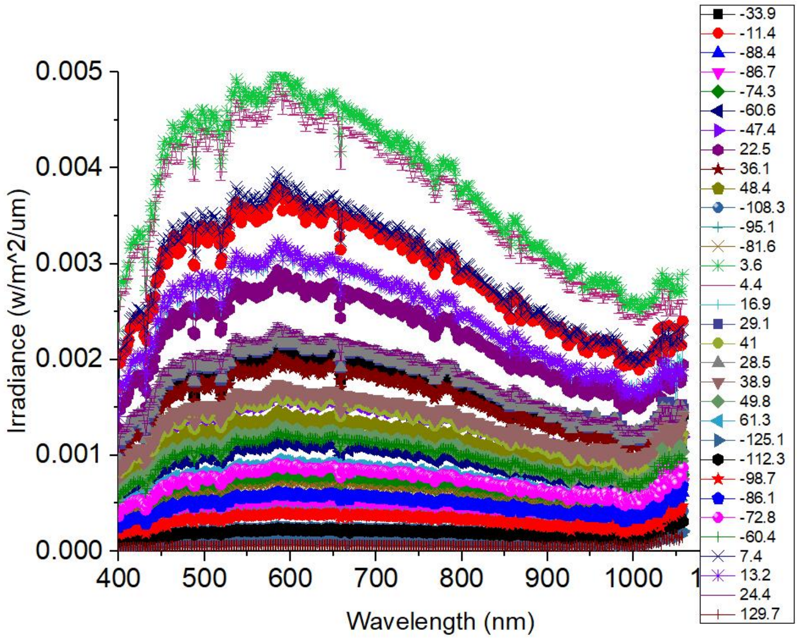
3.2 HAOC lunar Dataset Accumulation

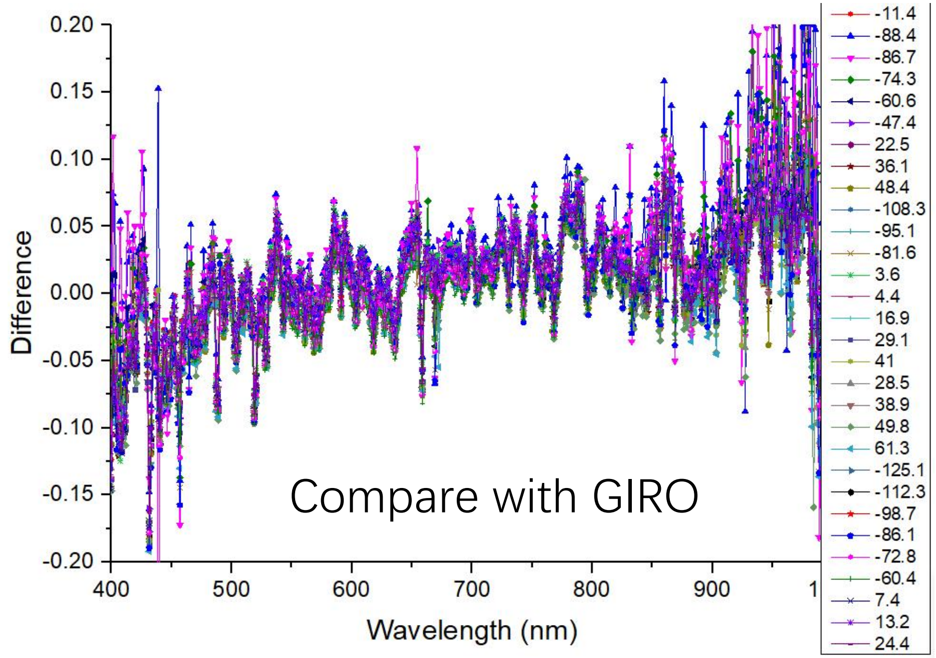
- **More and More Lunar Measurement**
  - Lunar observation 8~10 times per month
  - Total 50+ dataset accumulated by now
  - Phase angle dependence is reasonable
  - Most of Ob/GIRO difference within 5%
  - Larger difference at the spectral region >900nm with large SNR

Phase angle range: **-90° to 12.3°, 4.1° to 47.5°**









4. AI black-box Model development: Informed machine learning application

- **Pure data-driven deep learning model**
  - Conventional machine learning starts with a specific problem with training data and can be expressed as a regression problem
  - Lack of understanding of the patterns presented by the data, as well as knowledge
  - Predictions may not be consistent with the above properties
- **Status:**
  - Not enough new measurements with high-accuracy
  - A lot of observations have been accumulated
  - Smoothness properties of the lunar reflectance spectrum are known
- **Two types of a priori knowledge**
  - GIRO simulation results
  - Monotonicity of the lunar reflectance spectrum

Data + Prior knowledge

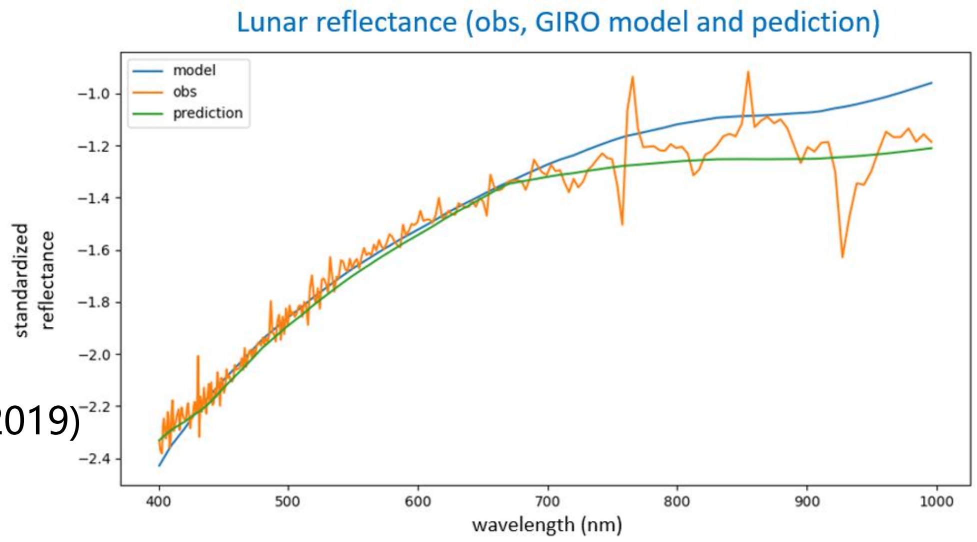
$$f = \arg\min_f \left(\overbrace{\lambda_l \sum_i Loss(\hat{f}(x_i), y_i)}^{\text{label-based empirical error}} + \overbrace{\lambda_r R(f)}^{\text{regularization term}} + \overbrace{\lambda_k Loss(\hat{f}(x_i), x_i)}^{\text{knowledge-based}} \right)$$

NSMC NCSW

Lunar albedo simulation based on the GLIS dataset

Priori-Knowledge guided simulation of Albedo

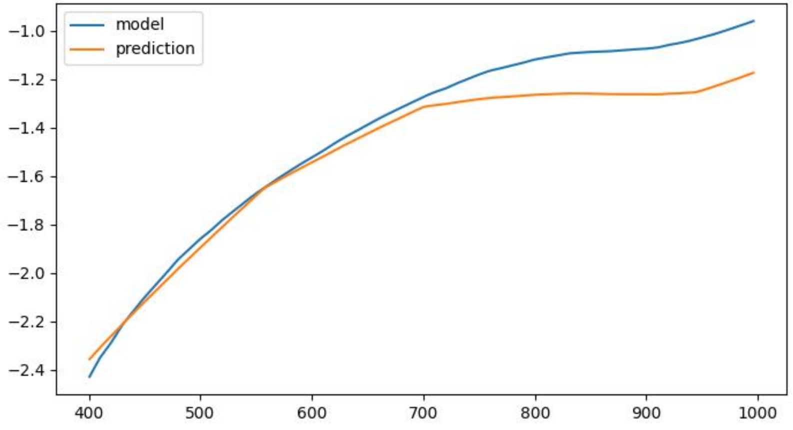
- Lunar albedo measurements
  - A. GLIS: 3265 observations (2017-2018)
  - B. Spectral range: 400-1000 nm (259 channels)
  - C. Features: wavelength, photometric angle, analog value
- Unlabeled datasets
  - A. 400673 unlabeled data, 1813 timestamps (December 2015- April 2019)
  - B. Wavelength grid: 300- 2500nm, 10 nm steps
- Simulation
  - A. Predicted reflectance is close to model-smoothed reflectance
  - B. Absorption band results need to be corrected



Simulations during the observation period (2017-2018)

Next

a) GLIS reflectance correction for atmospheric absorption bands
b) Consider strong constraints (hard coding) to design neural networks
c) Using complete GLIS dataset, HAOC measurements
d) Accuracy of GLIS spectra as actual spectral content? (add reference spectrum)



Simulations outside of coverage

Path Forward

- **Continuous accumulation of data.**
  - Consistency correction of space- and ground-based synergistic observations
  - Continuation of the lunar radiation observation campaign to improve the dataset. A future dataset will contain lunar hyperspectral emission data for the full lunar phase angle.

- **Data- and prior knowledge-driven neural network design**
  - Using multiple calibration results and instrument maintenance activities to obtain consistent GLIS datasets (reprocessing)
  - Training on clean dataset, FY-3G HAOC … data for constraint and validation

Thank you for your attention!