

Lunar model validation using ground-based Hyper-spectral measurement

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Overview

- **Introduction**
- **Instrumentation and Observation**
- **Data Processing and Result**
- **Comparison and Analysis**
- **Summary and Future**

Introduction

The Moon as an On-orbit Calibration Target, “solar diffuser”, extremely photometrical stable($<10^{-8}/\text{year}$) (Kieffer, H. H. 1997, Icarus)

- Advantages:
 - +Appropriate radiance range for the most Earth-viewing instruments
 - +normal Earth-observing optical path without restriction
 - +Spectrally bland (from returned Apollo samples)
 - +Accessible to spacecraft regardless of orbit
 - +Useful as a common transfer source between spacecraft
- Disadvantages
 - Spacecraft attitude maneuver
 - Non-uniform reflectance and complex photometric behavior

Lunar model

Introduction

* **ROLO model** (Kieffer, H. H. & T. C. Stone 2005)

- A、 -VNIR 23 bands, 350-950 nm - SWIR 9 bands, 950-2500 nm
- B、 8+ years in operation, phase angle coverage from eclipse to 90°
- C、 ~1200 observations fitted for each band, mean absolute residual ~1%
- D、 Absolute uncertainty: 5-10%, Relative uncertainty 1% (on orbit)

Application

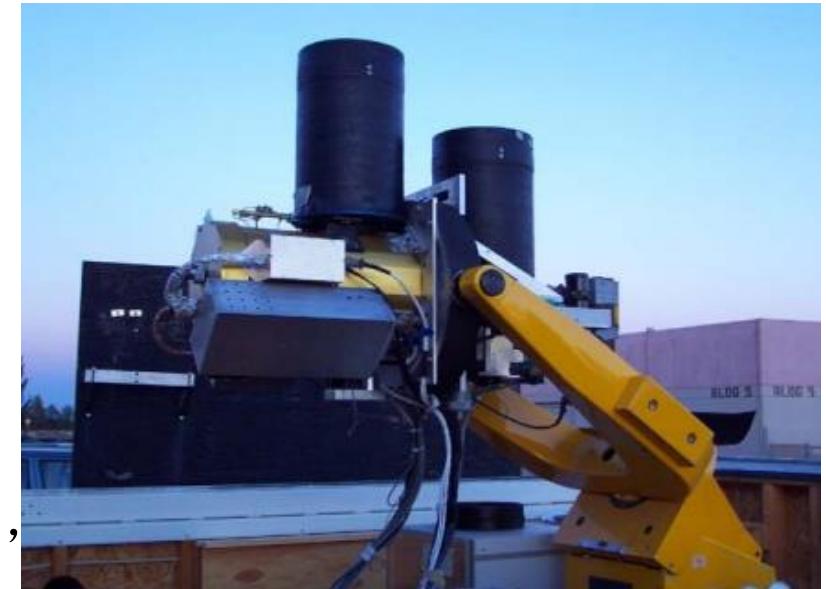
- A、 On-orbit calibration: radiometric stability monitor, cross calibration ,
- B、 Nocturnal aerosol measurements

* **MT2009 model** (Miller & Turner 2009).

- A、 hyper-spectral irradiance, 300 to 2800 nm
- B、 solar source observation, lunar spectral albedo data, phase functions derived from Lane and Irvine

Application

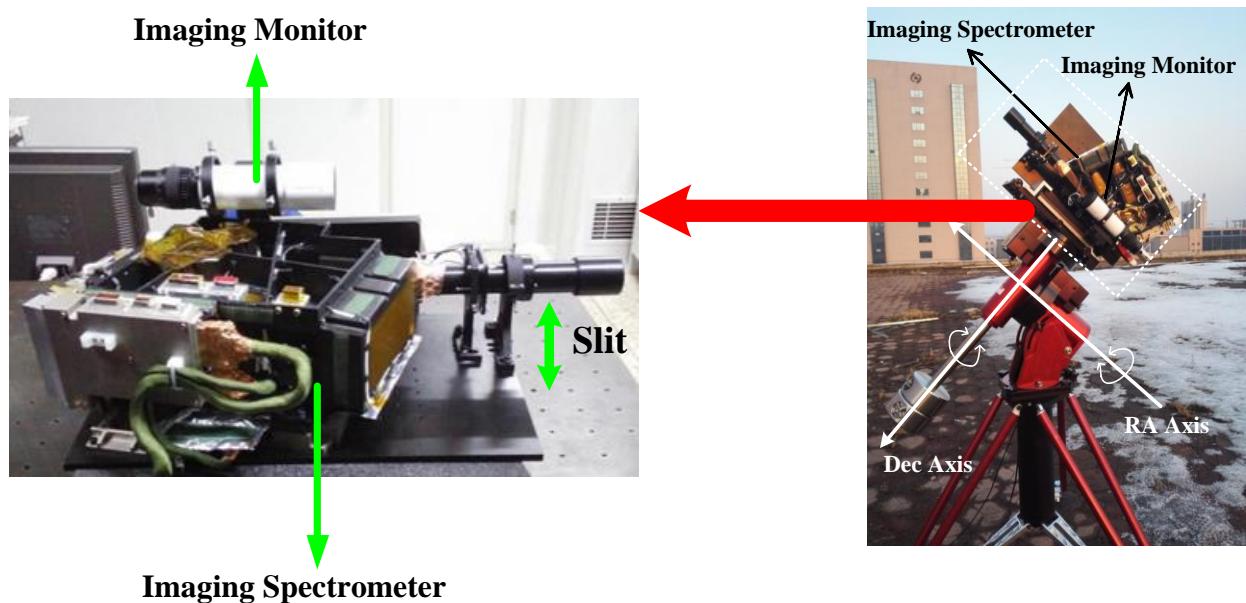
- A、 Night Band Nighttime Environmental Applications



**Ground-based observations:
Calibration accuracy and consistency**

Instrumentation and Observation

1. Ground-based observation system : imaging spectrometer, equatorial mount and imaging monitor



2. Automated scanning observation: park the spectrometer as the Moon moves across the field of view
orbit prediction of the moving Moon and time bias

Instrumentation and Observation

Lunar observations in Lijiang city (3.175 km altitude)

(1) 2015.12~2016.2 (2) 2017.11~ now

Slew rate: $(6.6\text{--}7.2)\times 10^{-5}$ rad/s

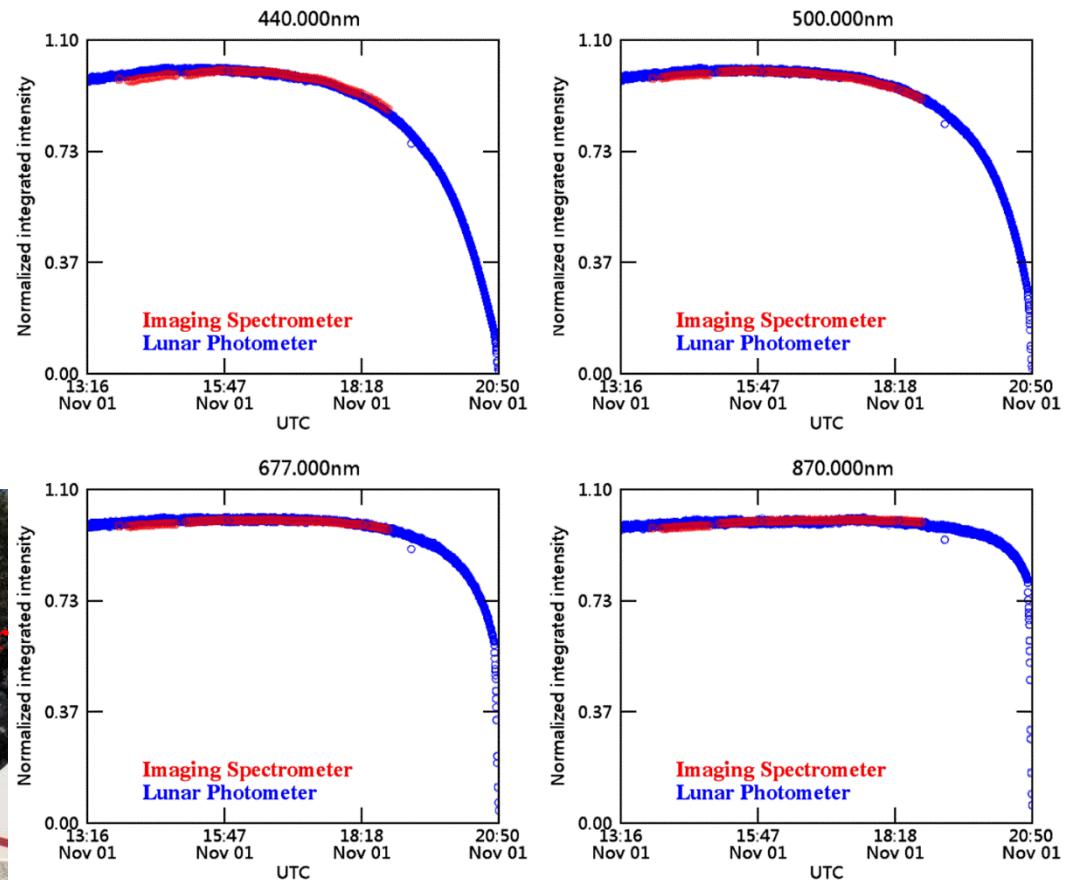
Scanning time(limb to limb): 0.9~1.7 s,

Exposure time: 0.4~1.7 s

Phase angle: $-83^\circ \sim 87^\circ$



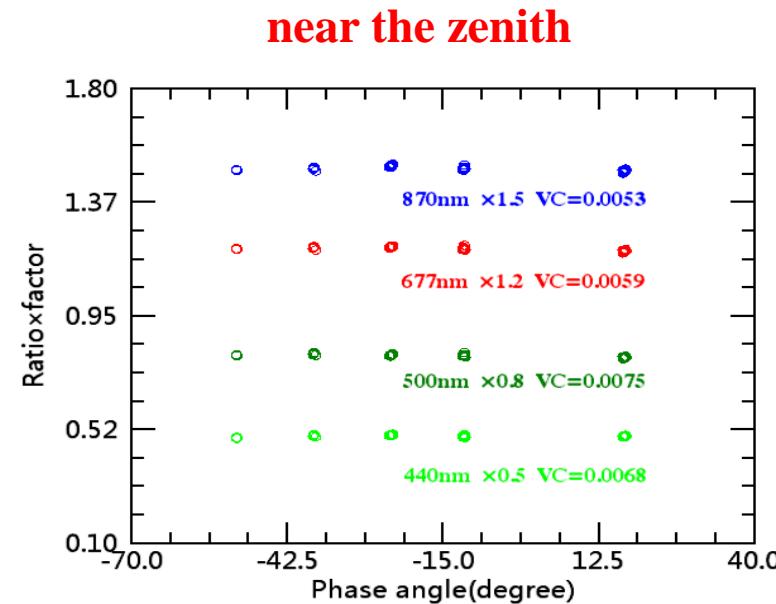
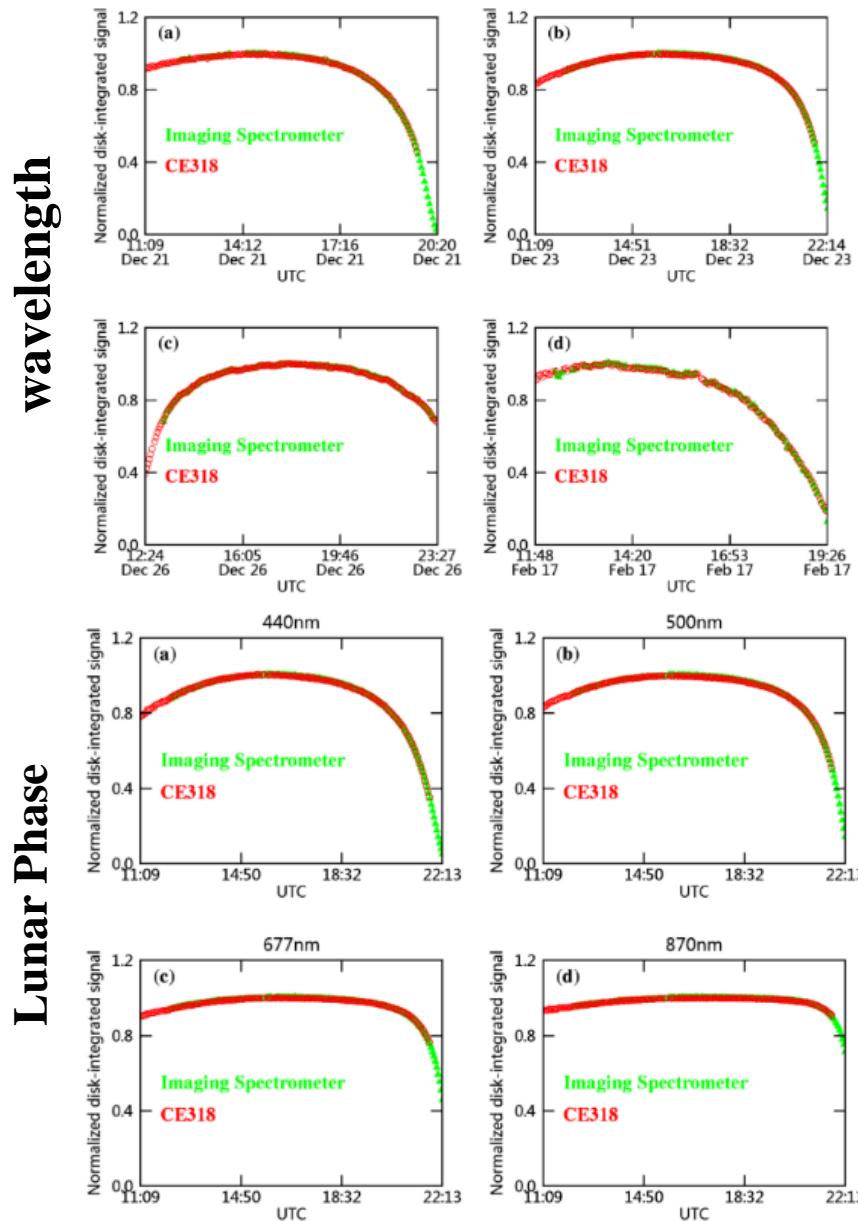
Instrument Performance : Cross-Comparison



a. Lunar Photometer: 280-1040 nm , 2nm

b. Imaging spectrometer: 400-1000 nm, 2-10nm⁶

Imaging Spectrometer and lunar CE318 Cross-Comparison :

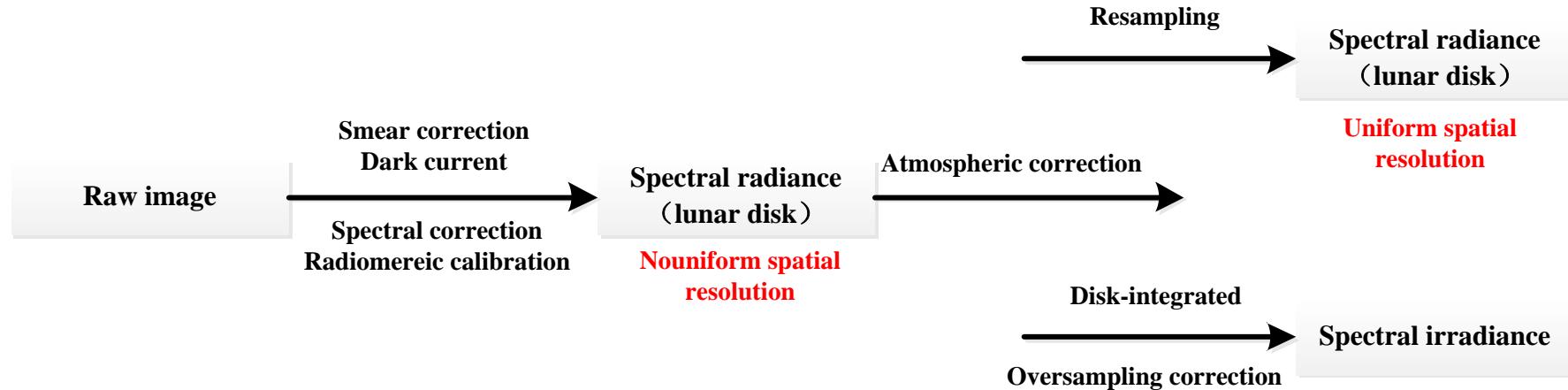


VC= variable coefficient or relative standard deviations

- (1) 2015.12.23 : 440, 500, 677, 870nm
- (2) 500nm: 2015.12.21, 2015.12.23, 2015.12.26, 2016.2.17
- (3) spectrometer/CE318U ratio: **normalization values*factor**

consistent tendency: instrument stability

Data Processing and Result



The TOA irradiance summation equation:

$$I^{TOA}(\lambda_k) = \frac{\Omega_p}{T_{atm}(\lambda_k) T_{integral} f_{oversample}} \sum_{i=1}^{N_{track}} \sum_{j=1}^{N_{cross}} \frac{DN_{i,j}(\lambda_k)}{R_{i,j}(\lambda_k)}$$

Ω_p = solid angle, $T_{atm}(\lambda_k)$ =spectral transmission, $T_{integral}$ =integration time, $f_{oversample}$ =oversampling factor, $R_{i,j}(\lambda_k)$ =spectral responsivity, N_{cross} = number of pixels in spatial dimension, N_{track} =number of pixels along the track direction, $DN_{i,j}$ = pixel value of the raw image

DN Signal preprocessing

(1) Dark current

$$DN_{dark} = (\text{green line 1} + \text{green line 2}) / 2$$

$$DN_0(\lambda_k) = DN_{raw}(\lambda_k) - DN_{dark}(\lambda_k)$$

(2) Smear correction

$$DN_{smear} = \text{blue line 3}$$

$$DN(i) = DN_0(i) - DN_{smear}(i)$$

(3) Area selection

1、 spatial dimension \times scanning dimension

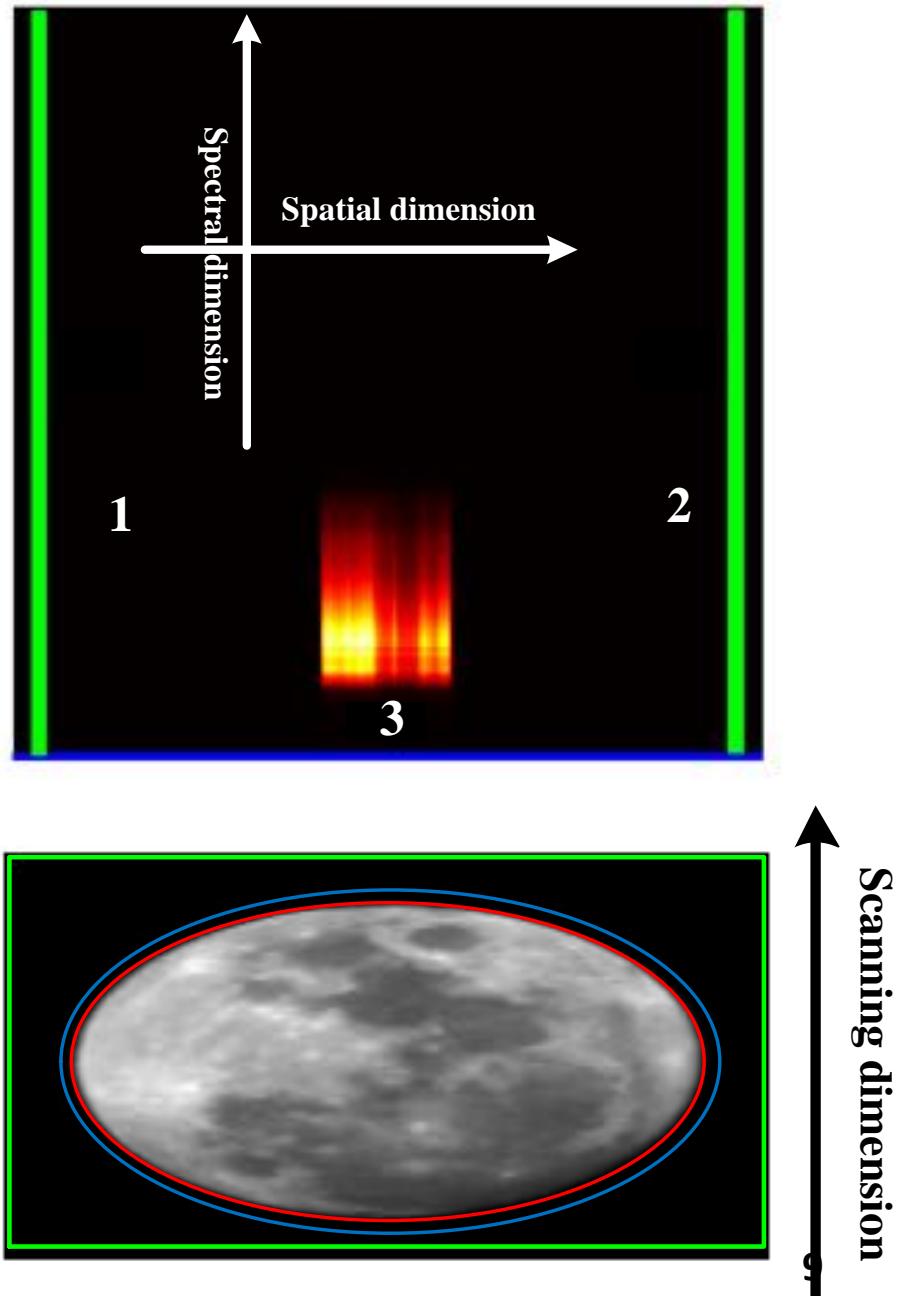
Green line: disk-integrated signal

Blue line — Green line: $\sim 0.04\% \times$ disk-integrated signal

Red line: threshold value

2、 spectral dimension

>273 channels, 400-1000nm



(4) Oversampling factor

The oversampling factor is defined as

$$T_{moon} = \frac{\psi_{track}}{\omega_{track}}$$

$$f_{oversampling} = \frac{T_{moon}}{T_{scan}}$$

ψ_{track} =IFOV along the track direction,

T_{moon} =time of one IFOV for the moon,

T_{scan} =scanning time for one frame,

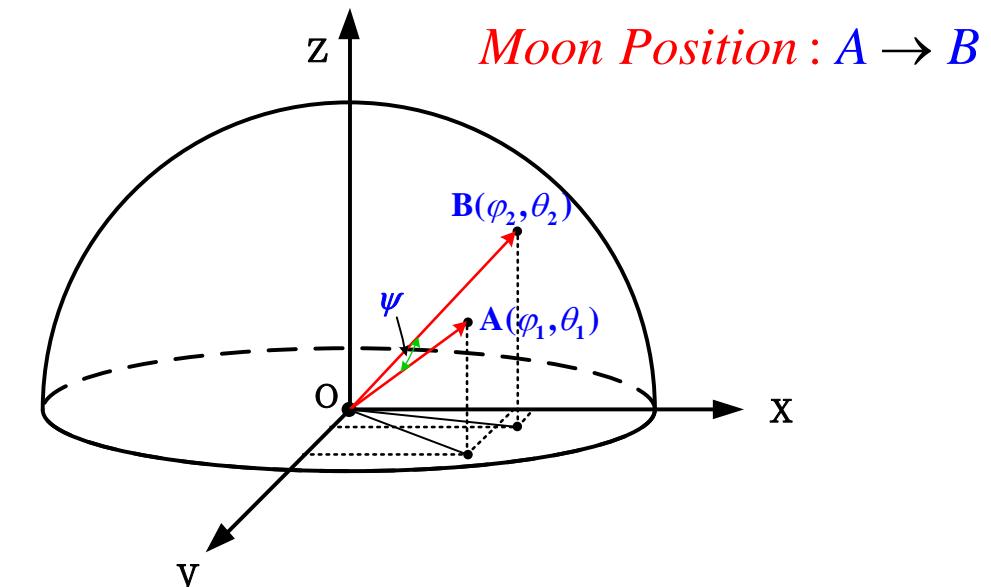
θ = lunar zenith angle,

φ = lunar azimuth angle,

R = distance between the Moon and the observation site,

ΔT_0 = time interval

SAMPA



$$OA = [\sin(\theta_1)\sin(\varphi_1), \sin(\theta_1)\cos(\varphi_1), \cos(\theta_1)] R_A$$

$$OB = [\sin(\theta_2)\sin(\varphi_2), \sin(\theta_2)\cos(\varphi_2), \cos(\theta_2)] R_B$$

$$\cos(\psi) = \frac{OA \cdot OB}{|OA| \times |OB|}.$$

$$\psi = \Delta T_0 \times \omega_{track}$$

$$\begin{aligned} \omega_{track} = & \frac{1}{\Delta T_0} \cos^{-1} [\sin(\theta_1)\cos(\varphi_1)\sin(\theta_2)\cos(\varphi_2) \\ & + \sin(\theta_1)\sin(\theta_2)\sin(\varphi_1)\sin(\varphi_2) + \cos(\theta_1)\cos(\theta_2)] \end{aligned}$$

(5) Spectral correction

prism imaging spectrometer——spectrum shift
bandwidth: 2-10 nm

- A: Characteristic spectrum lines: mercury lamp
- B: Molecular absorption lines: water vapor, oxygen
relative drift-magnitude: <1 pixel in one night

correction: minimum integer pixels
lunar spectrum——spectral calibration,
residual error: <0.5 pixel

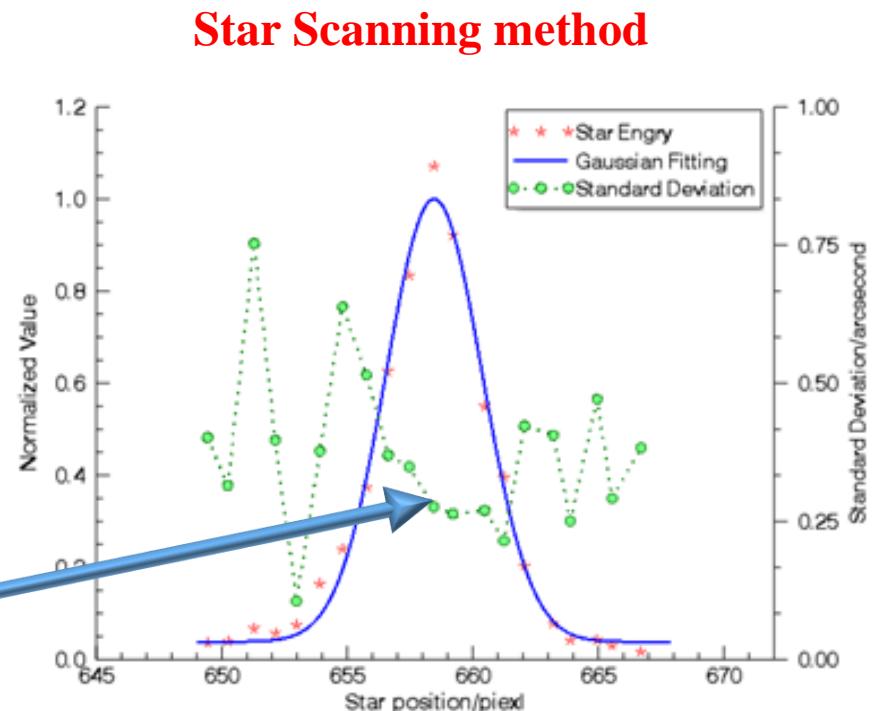
(6) Solid angle

$$\Omega_p = IFOV_{cross-track} IFOV_{track}$$

$$\text{Angular velocity: } f_{oversample} = \frac{IFOV_{track}}{T_{scan} \omega_{track}}$$

$$I_{irradiance} = A \bullet \frac{\Omega_p}{f_{oversample}} = A \bullet IFOV_{cross-track} T_{scan} \omega_{track}$$

$$= B \bullet \underline{\underline{IFOV_{cross-track}}}$$



$$\text{Ellipse fitting: } f_{oversample} = \frac{piexl_{track} \times IFOV_{track}}{piexl_{cross-track} \times IFOV_{cross-track}}$$

$$I_{irradiance} = A \bullet \frac{\Omega_p}{f_{oversample}} = A \bullet (IFOV_{cross-track})^2 \frac{piexl_{cross-track}}{piexl_{track}}$$

$$= C \bullet \underline{\underline{(IFOV_{cross-track})^2}}$$

(7) Radiometric calibration

Lamp + Reference plate

To ensure low stray light level (~lunar observation)

System: Lamp + Reference plate + Aperture slot

A. Small field of view

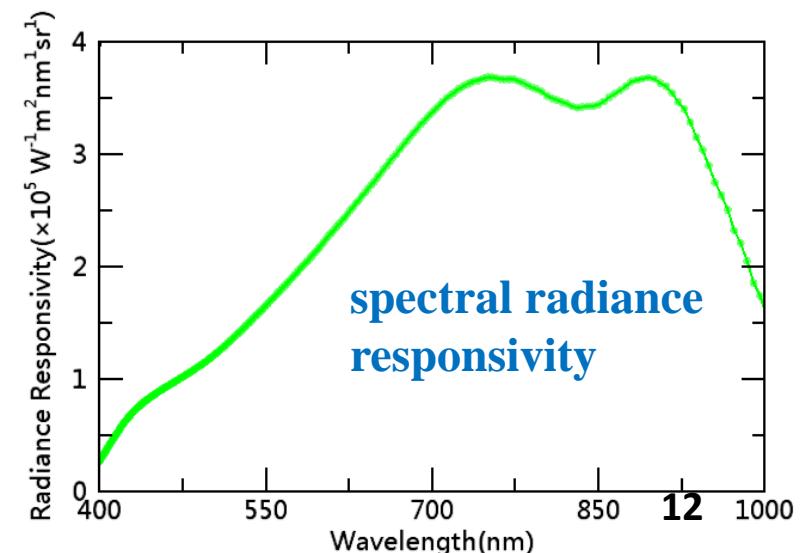
Field angle Ψ_{aperture} of the Aperture slot with respect to the instrument

B. Fill the field of view

approximately above 0.5°

Lunar observation ~ Linearity of CDD detector $<0.5\%$

total uncertainty 1.5% (1 sigma)



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National Institute of Metrology, China (NIM)

(8) Atmospheric Correction

A. Aerosol Optical Depth:

sun-photometer CE318, lunar-photometer CE318U, LIDAR
rural aerosol model

B. Water vapor :

radiosonde balloons and

C. Ozone, Rayleigh scattering, etc. :

mid-latitude winter conditions
1976 US standard atmosphere

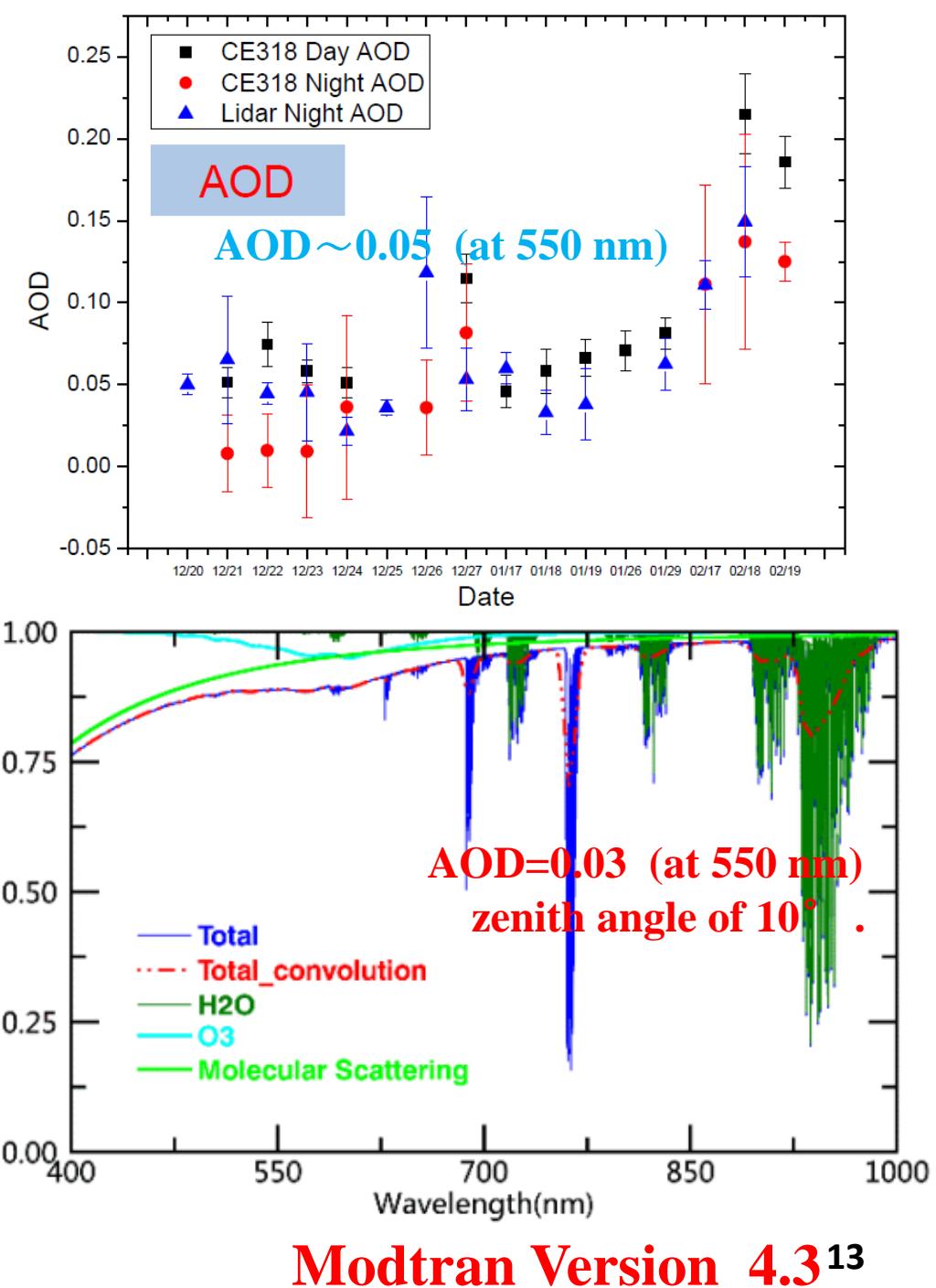
D. Zenith angle:

ephemeris DE421 SPICE toolkit

E. Transmission spectra:

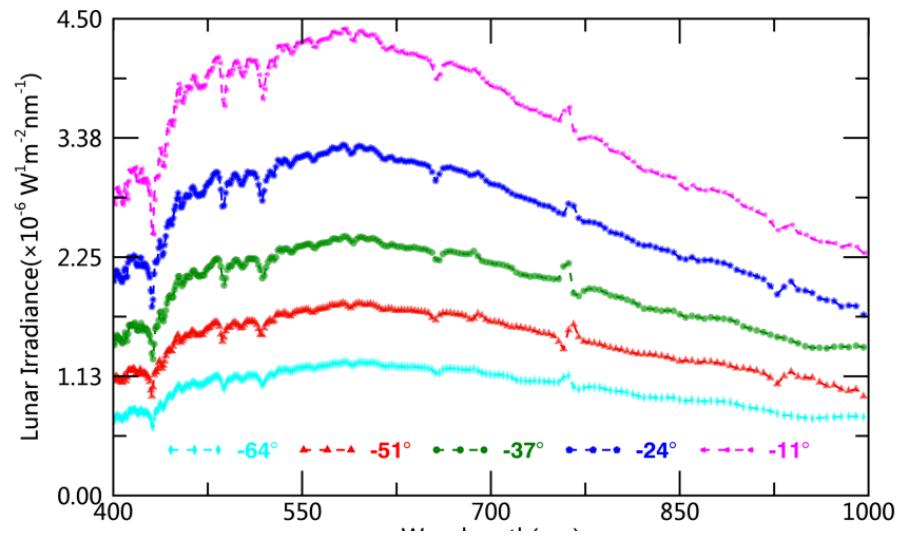
$$T_k^{atm} = \frac{\int_{\lambda_1}^{\lambda_2} T_m^{atm}(\lambda) SRF_k(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} SRF_k(\lambda) d\lambda}$$

Excellent seeing (< 1'')

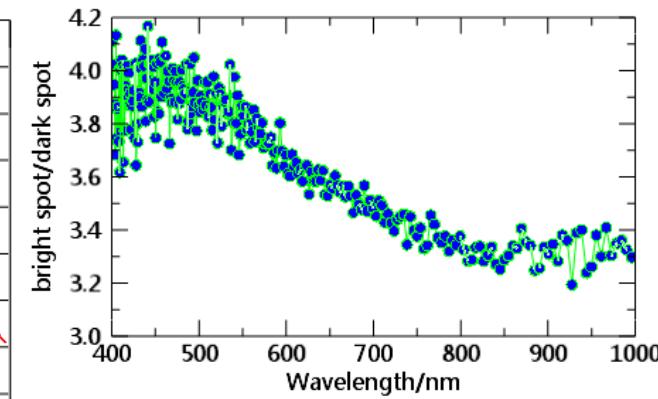
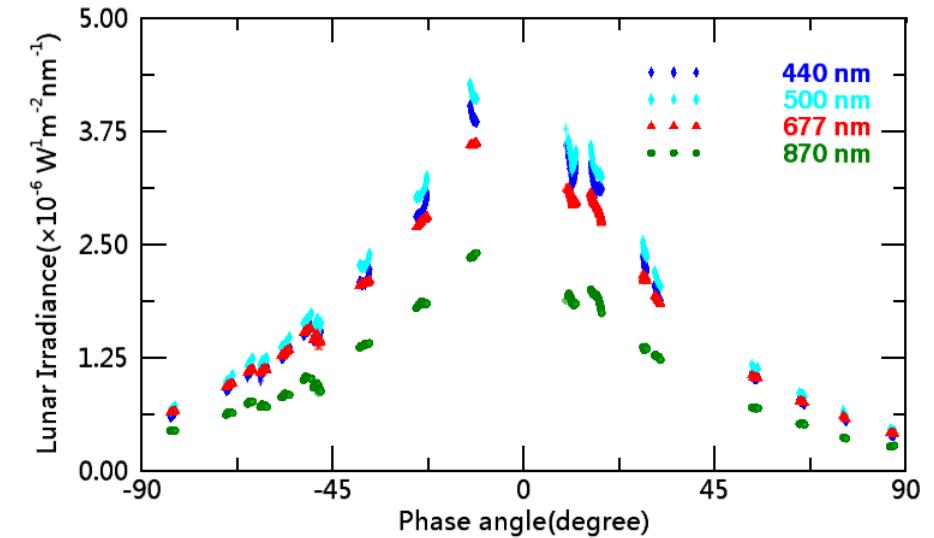
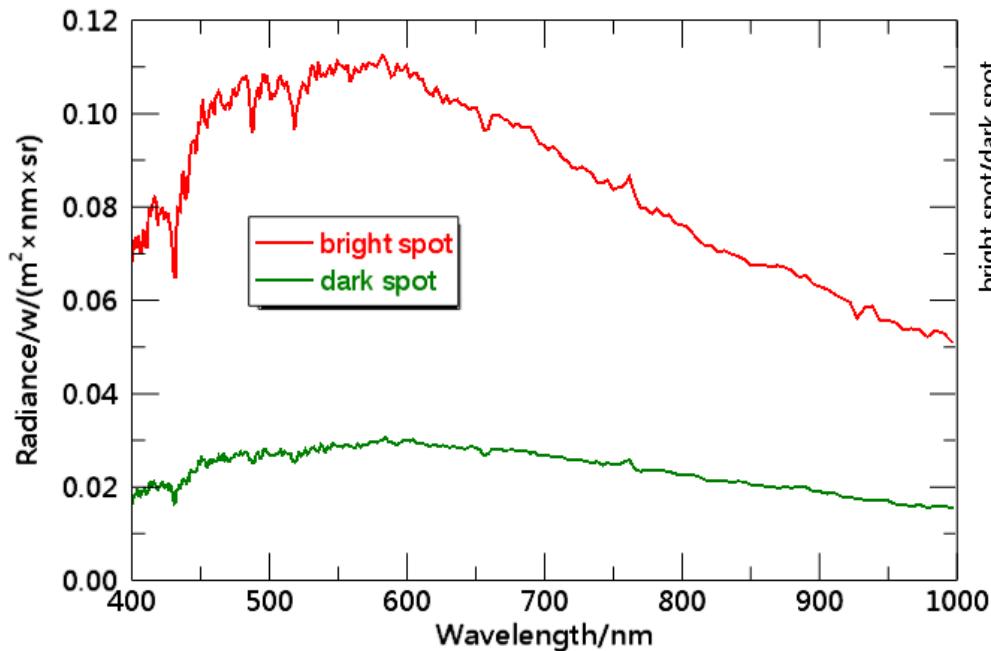


Result

A. Irradiance



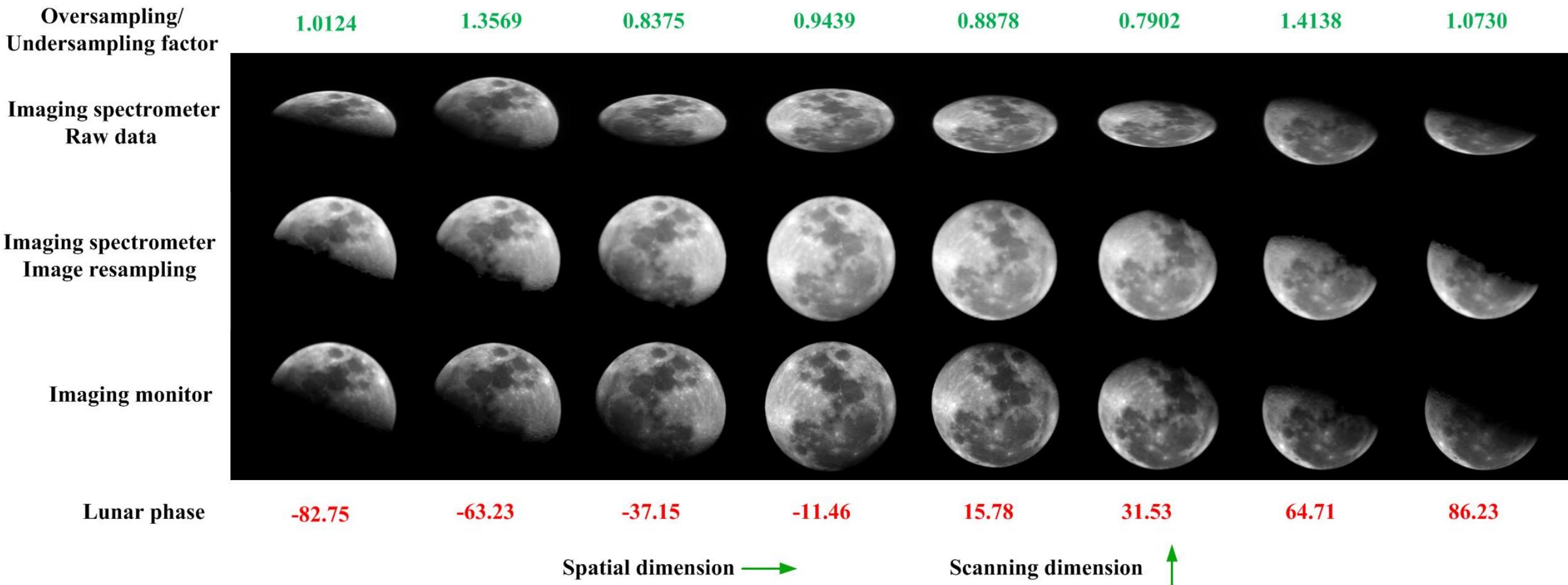
B. Radiance



TOA
Atmospheric
Correction

Phase angle=-11.46

C. Typical lunar images



$$N_{\text{moon}} = \frac{T_{\text{disk}}}{T_{\text{scan}}} = \frac{T_{\text{disk}}}{f_{\text{oversample}} T_{\text{moon}}} = \frac{\Omega_{\text{moon}}}{f_{\text{oversample}} \psi_{\text{instantaneous}}}.$$

T_{disk} = time of one lunar disk ($\Omega_{\text{moon}} \approx 0.5^\circ$) ,

①Oversampling/Undersampling : 0.75-1.45 ② Scanning lines: ~100 (0.5°) ③ Spatial resolution: $20 \text{ km} \times 20 \text{ km}$

Comparison and Analysis

Measured/model irradiance comparisons

Percent disagreement between the imaging s

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

Difference: 5-10% (on orbit) ~7%
13% in 603 nm

(Velikodsky, Y. I., et al. 2011)

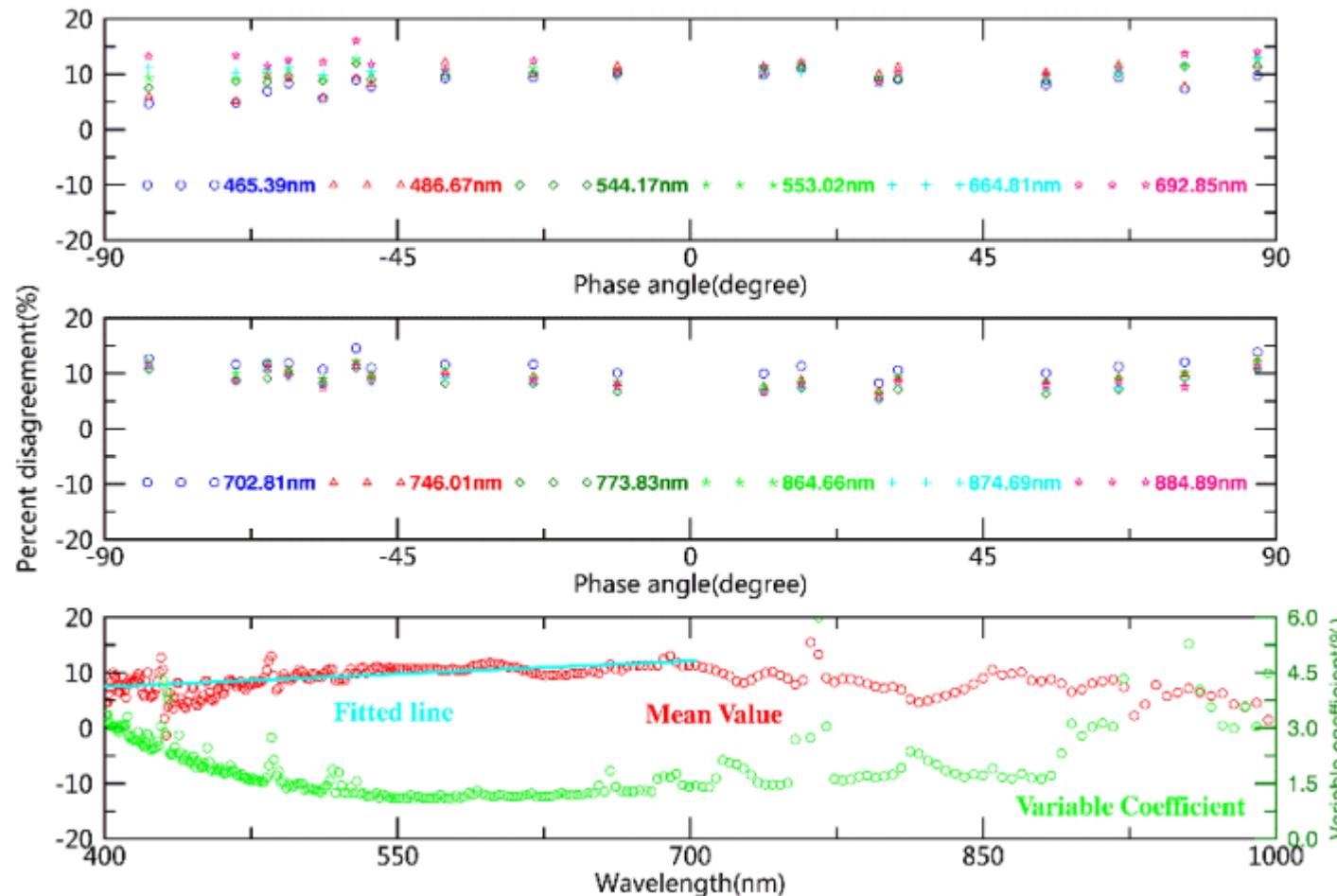
Uncertainty: 1% (on orbit)

Lunar observations in Lijiang:

Difference (Mean value) : 7-12%, shape ~8.6%

Uncertainty (Variable coefficient) : 1-3%

ROLO model



ROLO Over Time

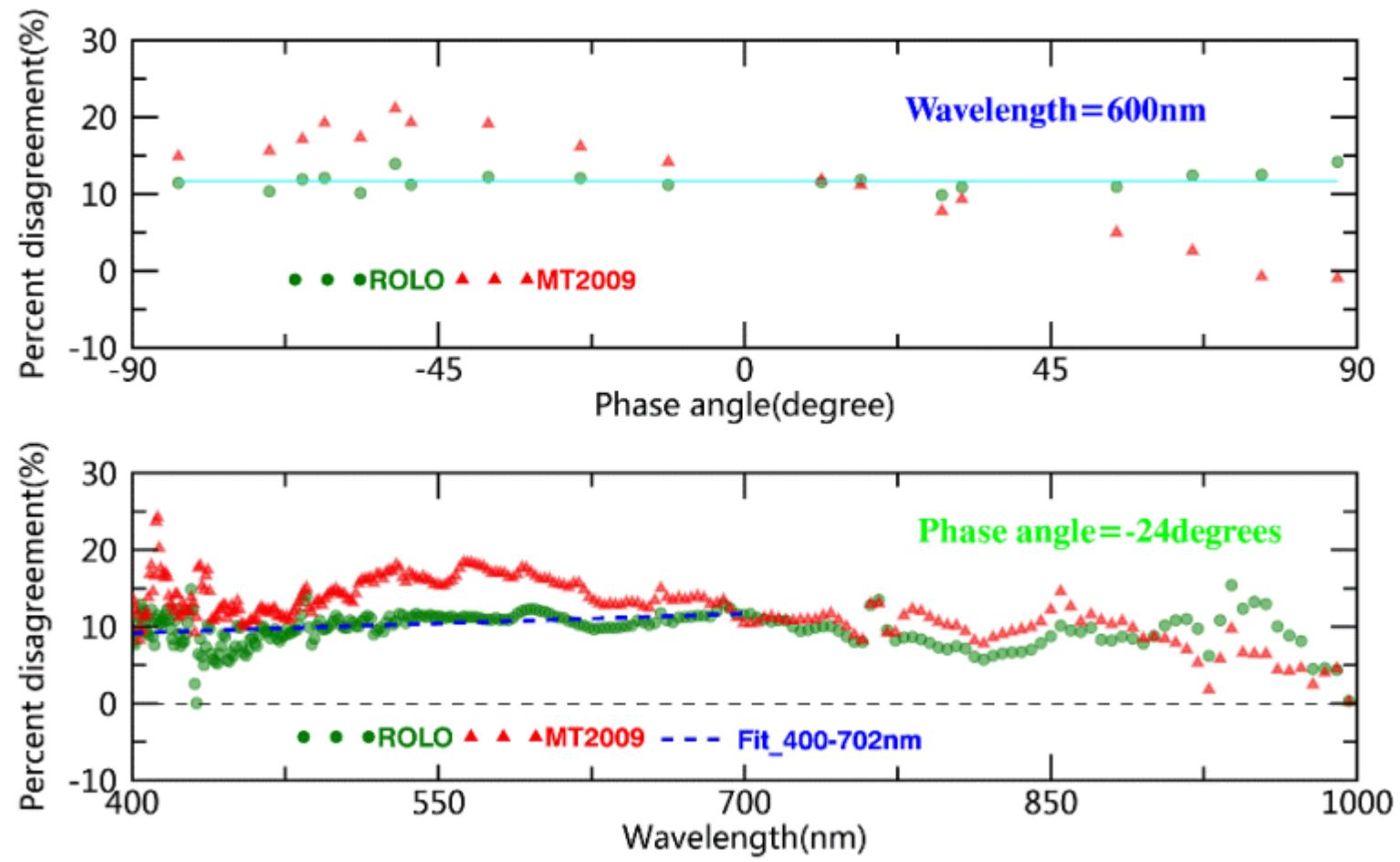
Measured/model irradiance comparisons

ROLO VS MT2009

- (1) Lunar Phase : 600nm
- (2) Spectrum : -24 degree

MT2009 model: 10-17%

Lunar Phase : GIRO model >MT2009 model



Measured/model irradiance comparisons in lunar phase

The slope of fit lines (400-700nm) in different phase angle is

$$P_{fitting}(\lambda, \theta) = a_{slope}(\theta)\lambda + b(\theta) \quad \begin{cases} 400nm < \lambda < 700nm \\ -90^\circ < \theta < 90^\circ \end{cases}$$

Fit lines of the slope with phase angle is

$$a_{slope} = \begin{cases} A_1\theta + B_1 & 0 > \theta > -90^\circ \\ A_2\theta + B_2 & 0 < \theta < 90^\circ \end{cases}$$

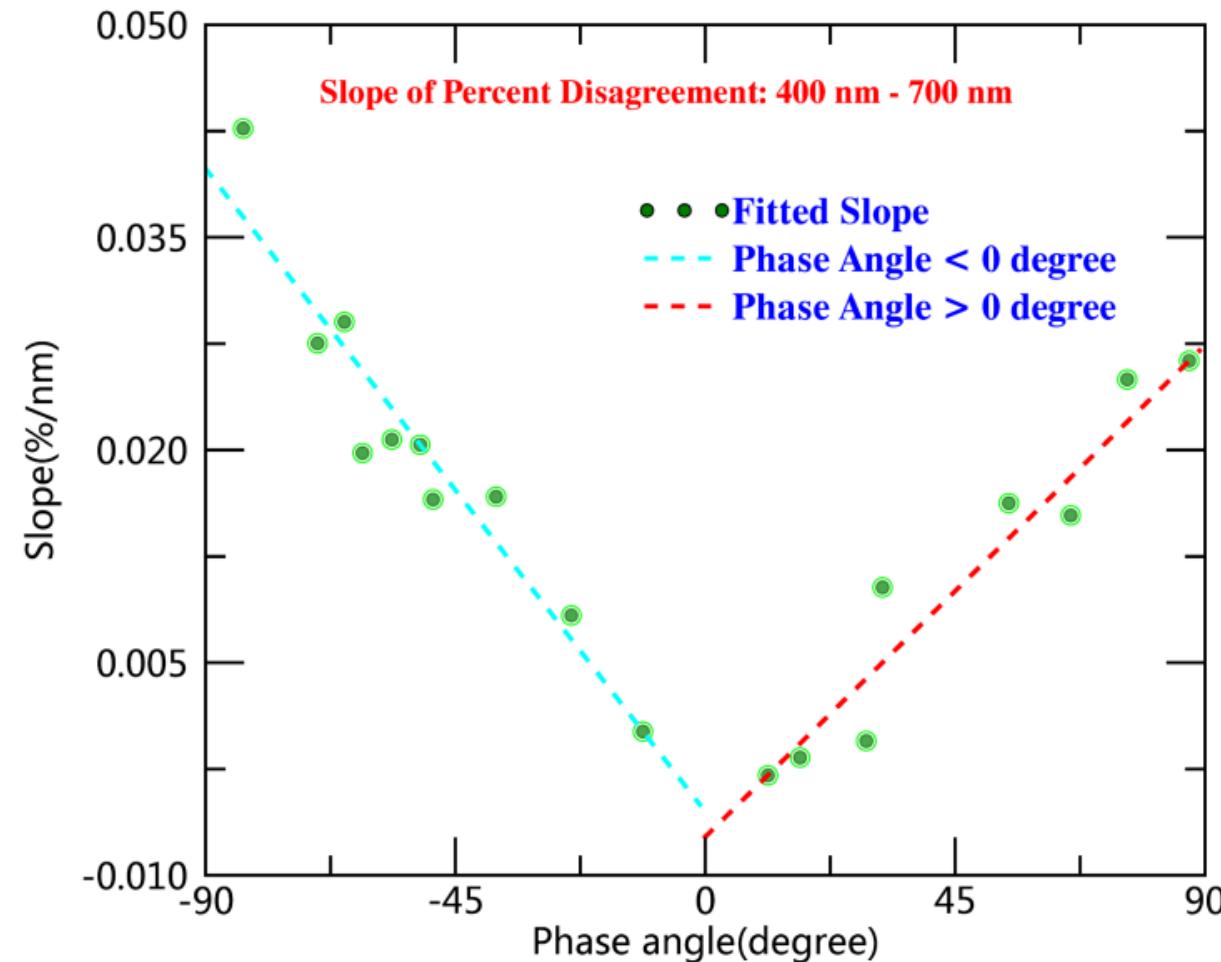
The phase angle is not associated with

- A. transmission spectra ~ AOD
- B. calibration coefficient

there is a significant linear trend in the slope with phase angle (negative and positive)

The tilt of the whole spectral shape of the percent disagreement increases with phase angle (absolute value).

The ratios between measured irradiance and lunar model show a significant reddening as the phase angle increases



Lunar band ratio (LBR) comparison

The ratio between the lunar irradiance for different bands (λ) and the reference band (λ_0) is

$$LBR_{instrument}(\theta, \lambda | \lambda_0) = \frac{I_{instrument}^{TOA}(\theta, \lambda)}{I_{instrument}^{TOA}(\theta, \lambda_0)}$$

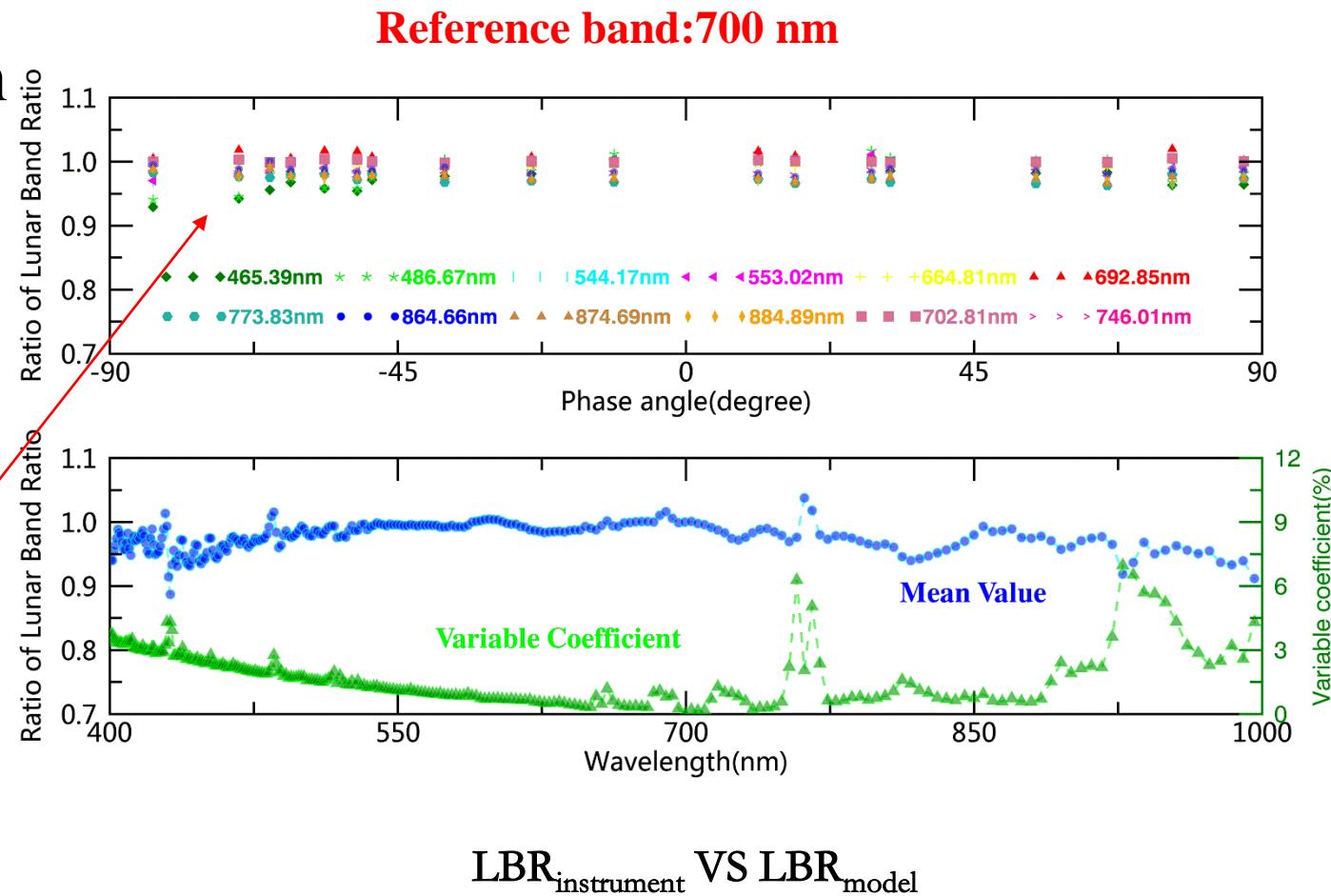
$$LBR_{model}(\theta, \lambda | \lambda_0) = \frac{I_{model}(\theta, \lambda)}{I_{model}(\theta, \lambda_0)}$$

$$R(\theta, \lambda | \lambda_0) = \frac{LBR_{instrument}}{LBR_{model}}$$

θ = phase angle, λ_0 =reference band, λ =some band,

$LBR_{instrument}$ = spectrometer, LBR_{model} = GIRO model,

R= consistency of the LBRs between the lunar model and measurements



$LBR_{instrument}$ VS LBR_{model}

- (1) Lunar Phase : LBR consistency
- (2) Spectrum : R (λ) (mean value) , variable coefficient

band to band stability /spectral radiometric performance

Phase Reddening

The ratio between the (TOA) irradiance $I(\theta, \lambda)$ and the irradiance $I(\theta_0, \lambda)$ is

$$Ratio_i(\theta | \theta_0, \lambda) = \frac{I_i(\theta, \lambda)}{I_i(\theta_0, \lambda)} = a_i(\theta | \theta_0)\lambda + b_i(\theta | \theta_0)$$

θ =phase angle, λ = 400nm-1000nm

a_i =slope

b_i = intercept

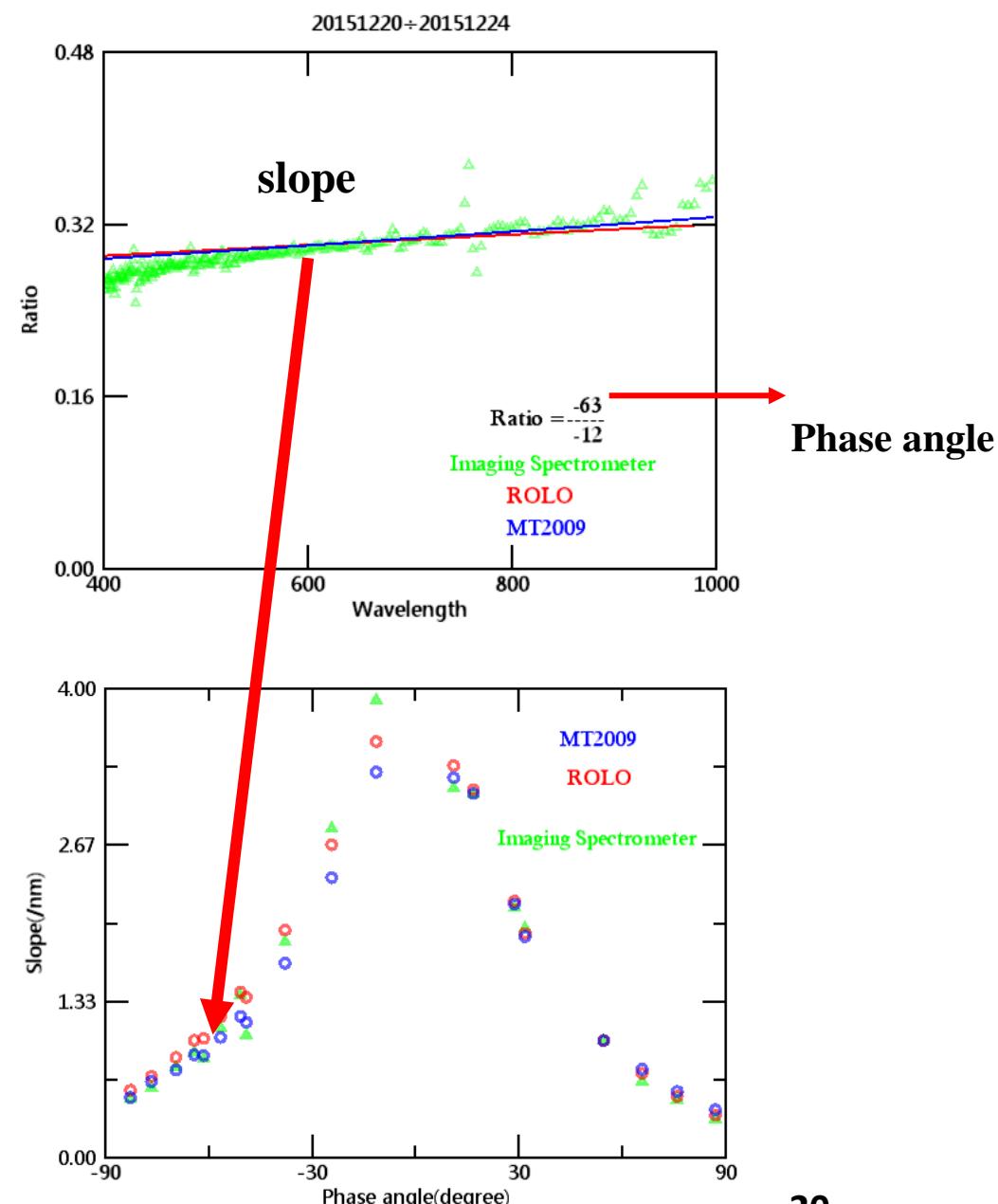
$i=1$ imaging spectrometer

$i=2$ ROLO

$i=3$ MT2009

(1) $Ratio_i \sim \lambda$ (2) Slope(a_i) $\sim \theta$

Slope: **ROLO VS MT2009 VS Spectrometer**
atmospheric correction or lunar model
ROLO > MT2009



Lunar observations

Dominant Sources

(1) Absolute Scale

Lamp-Plate system:

QTH lamp, hemispherical reflectivity and Lambertian characterization

(2) Spatial stray

Instrument calibration: systematic deviation

Lunar observation: $\sim 0.5^\circ$

(2) Atmospheric correction

atmospheric characterization tools:

AOD: ~ 0.05 0.012(550 nm) zenith angle: 10°

Transmission spectra : 0.6~1.7%(400-1000nm)

(3) Spectrum Shift Correction

Spectral dimension: Maximum drift-magnitude of 0.5 pixel

Secondary sources

(1) Pixel IFOV in the cross-track direction

(2) Scanning mode (one lunar disk) : angular

velocity, movement trajectory, orientation of the slit

(3) Instrument: stability, linearity

(4) oversampling factor

Lunar model: ROLO

(1) Instrument calibration: Vega

(2) Atmospheric correction : Standard stars

Comparison and Analysis

(1) phase angle

(2) spectrum

Summary

- Stability of out-field instrument in different observation conditions
 - humid, dry, temperature, attenuation, lunar polarization, etc.
- Standardization of data processing is precondition of comparison
 - different sampling method, area selection, etc.
- Atmospheric corrections, calibration and instrument performance are the key contributing factors

Future

- Enables precise accounting of instrument spectral response functions
 - instrument calibration in the manner of lunar observation (stay light)
 - different approaches to the radiometric response calibrations
- Improves the accuracy of atmospheric corrections
 - evaluation of the AOD data from different instruments
 - different approaches to atmosphere corrections (Lunar-Langley method?)
- Comparison with the other data source from different instruments on orbit or on the ground
 - data quality, reliability data
- Collect more lunar data in Lijiang
 - validate and improve the current lunar models

Thank you