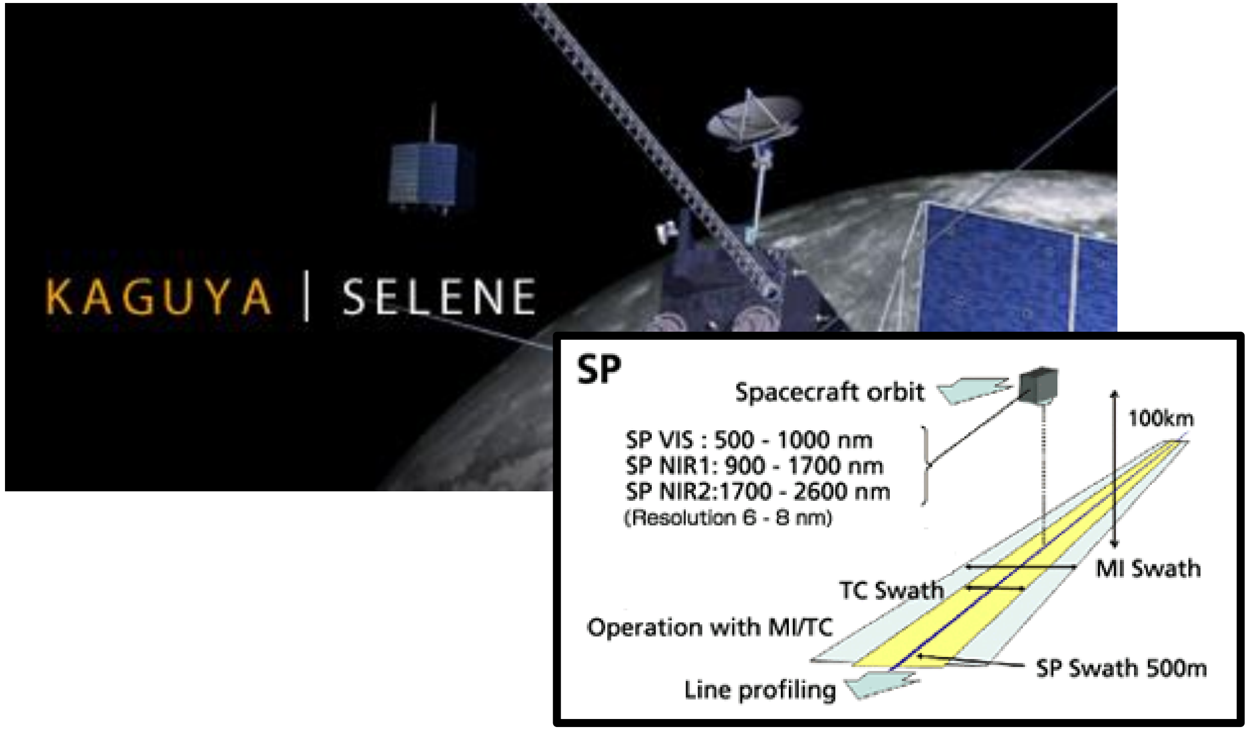
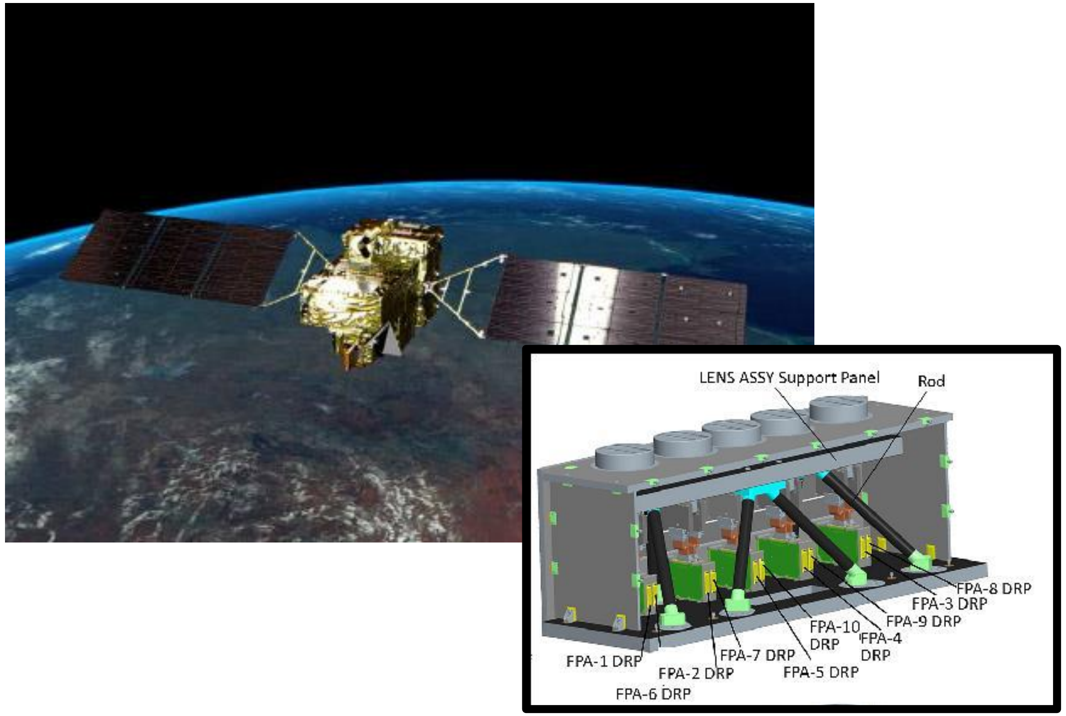
# Application of a disk-resolved lunar brightness model (SP model):

## Flat-field calibration for a pushbroom sensor with cross-track scan

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4th Joint GSICS/IVOS Lunar Calibration Workshop, 4-8 December 2023

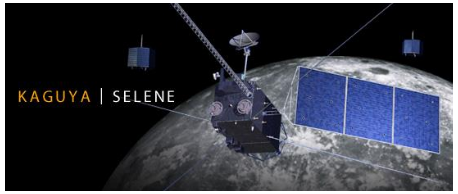
# Topics

- **Introducing "SP model" and its performance**
  - model and code release

- **Flat-field calibration with SP model**
  - example with GOSAT-2/CAI-2's Moon observations

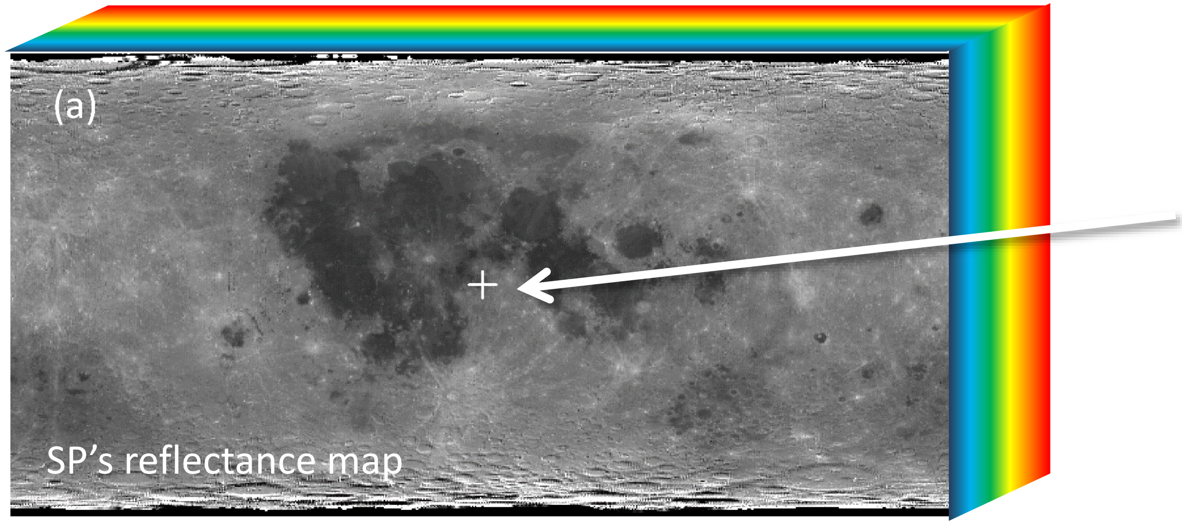
# SP model

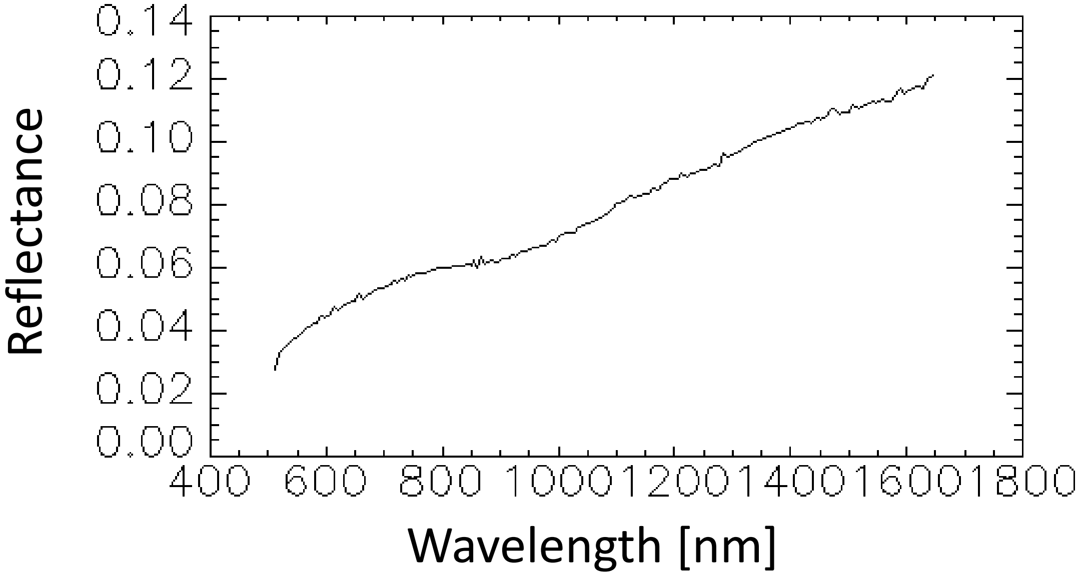
A "Disk-resolved" hyperspectral lunar brightness model based on SELENE/Spectral Profiler (SP) reflectance map




2007 - 2009

Hyperspectral reflectance map + parameters




**Data source:**

Spectral Profiler (SP), point sensor

- integrating 70 M observations

**Spectral range:**

512 – 1650 nm (160 channels)

Δλ = 6 nm (VNIR) & 8 nm (SWIR)

**Spatial resolution of the map:**

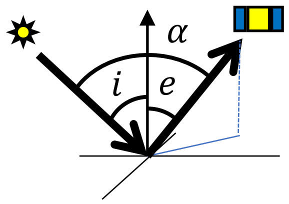
Published: 1˚ x 1˚ and **0.5˚ x 0.5˚**

**BRDF effect of the lunar surface** :

Approximated with a practical function of incident, emission and phase angles [Yokota et al., 2011]

0.5x0.5: Corresponding to ~40 μrad resolution from the Earth (or ~30 m/pix resolution of LEO, e.g. Landsat series)

# SP model




## Model Formulation

Converting reflectance to radiance

**Eq.1** $$R_{SP}(\lambda, lon, lat) = r_{SP}(\lambda, lon, lat, 30°, 0°, 30°)A(\lambda, i, e, \alpha)\frac{I_{Sun}(\lambda)}{\pi}\left(\frac{1AU}{D_{Sun-Moon}}\right)^2$$

- $r_{SP}(\lambda, lon, lat, 30°, 0°, 30°)$: SP's lunar reflectance at a reference geometric condition
- $A(\lambda, i, e, \alpha)$: Approximation of BRDF effect
- $\left(\frac{1AU}{D_{Sun-Moon}}\right)^2$: Distance correction

[Yokota et al., 2011 & Kouyama et al., 2016]

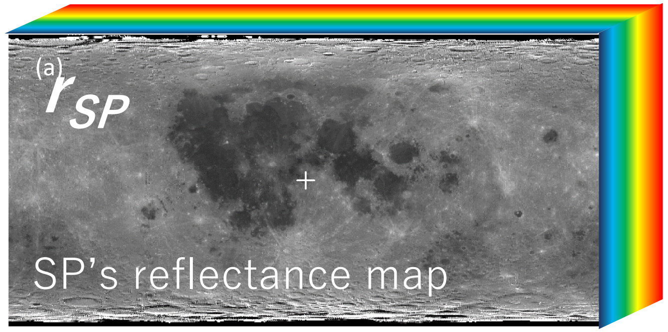
## Model Operation

**Inputs**

1. **SP's reflectance map**
2. **Observation geometry: Positions of Sun, Moon, and Satellite**
3. **Camera specification: Resolution, SRF**

**Outputs**

SP's reflectance map (hyperspectral cube)




Observation geometry → **Eq.1** ← Camera projection

Disk-resolved radiance cube

SRF (band) integration

1. **Disk-resolved radiance image**

Disk integration for irradiance

2. **Simulated Moon irradiance**

Sample codes are available: https://github.com/TKouyama/SP_LunarCal_example

# Simulating Moon observations

Observed
ASTER/Band 2 (660 nm)
April 14, 2003

Simulated

# Simulating Moon observations

April 13, 2003

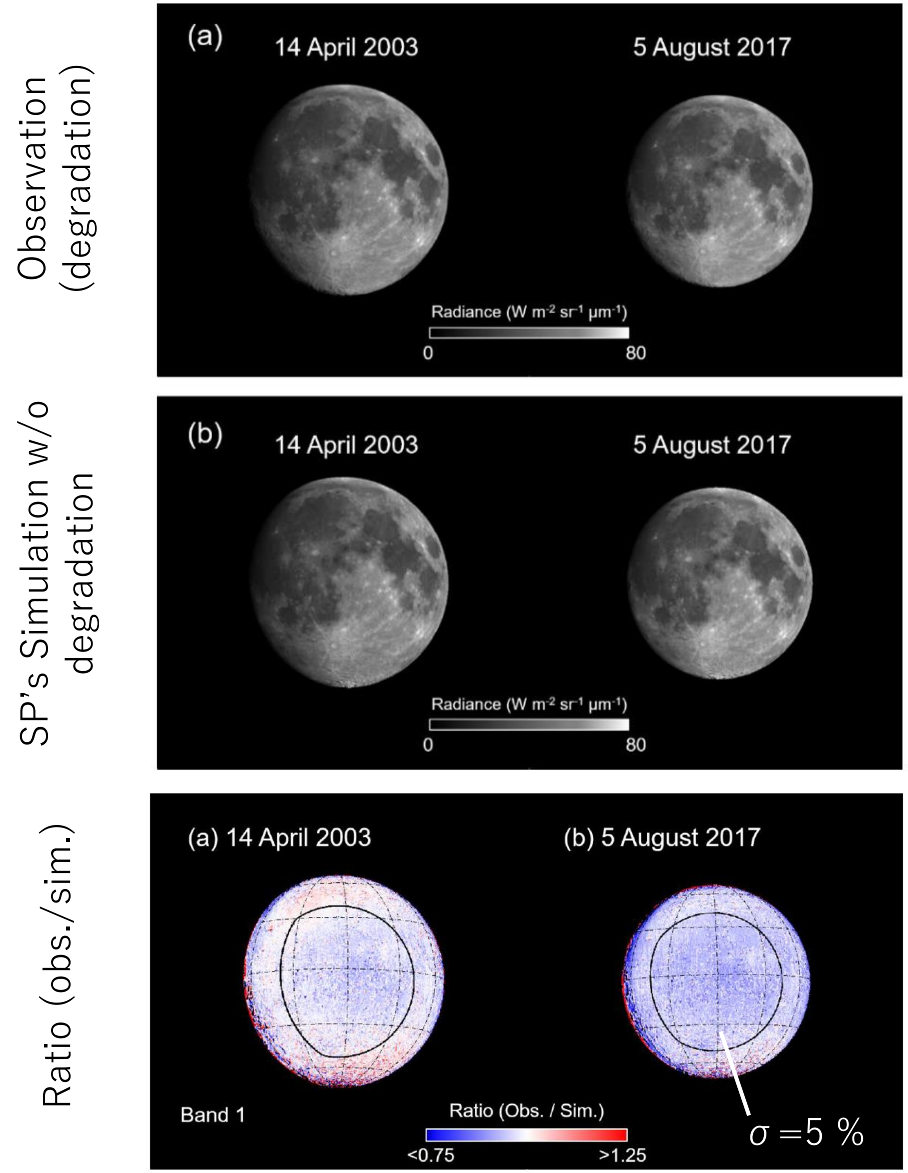
April 15

April 18

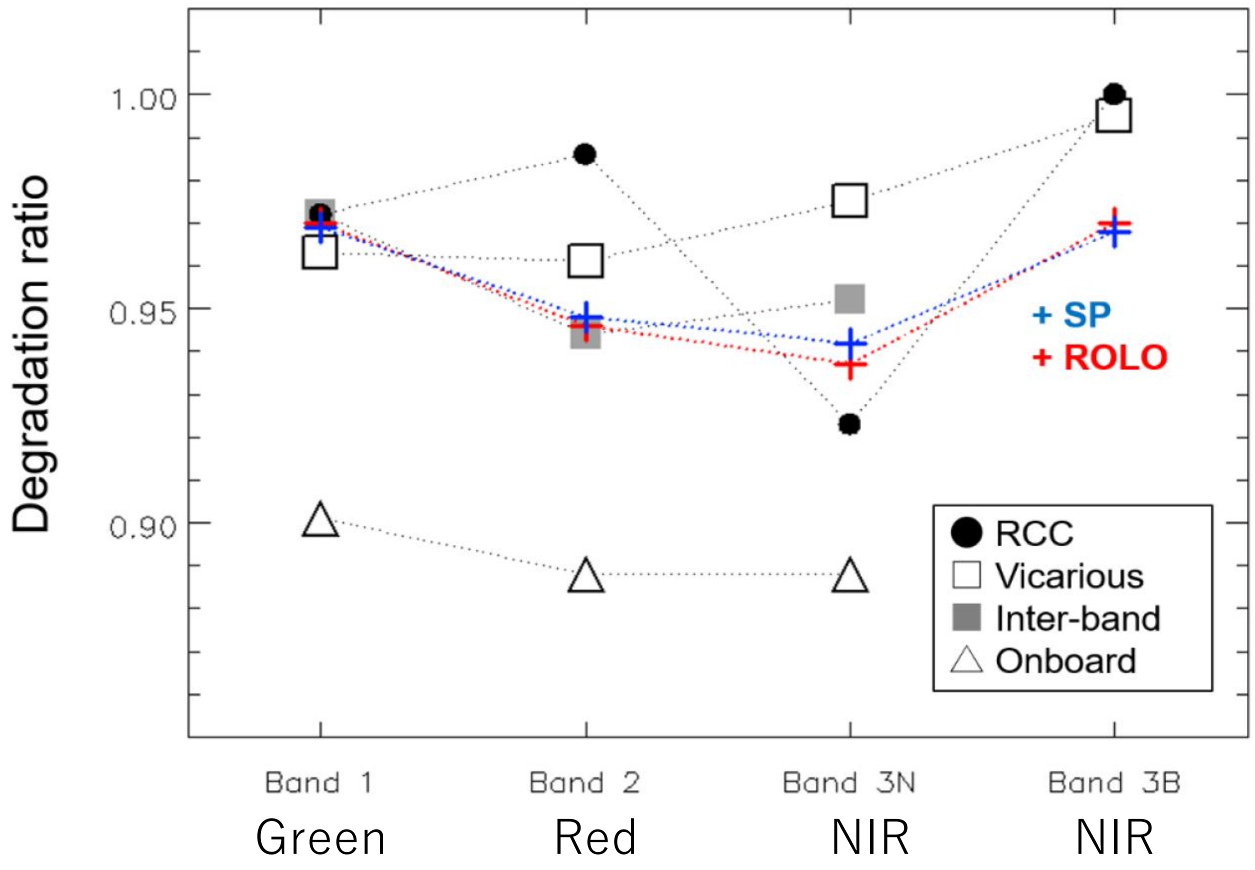
Note: MTF assessment might be possible with SP model + simulation

# SP model performance for assessing sensitivity degradation

## Example 1: ASTER




Sensitivity degradation of ASTER from 2003 to 2017

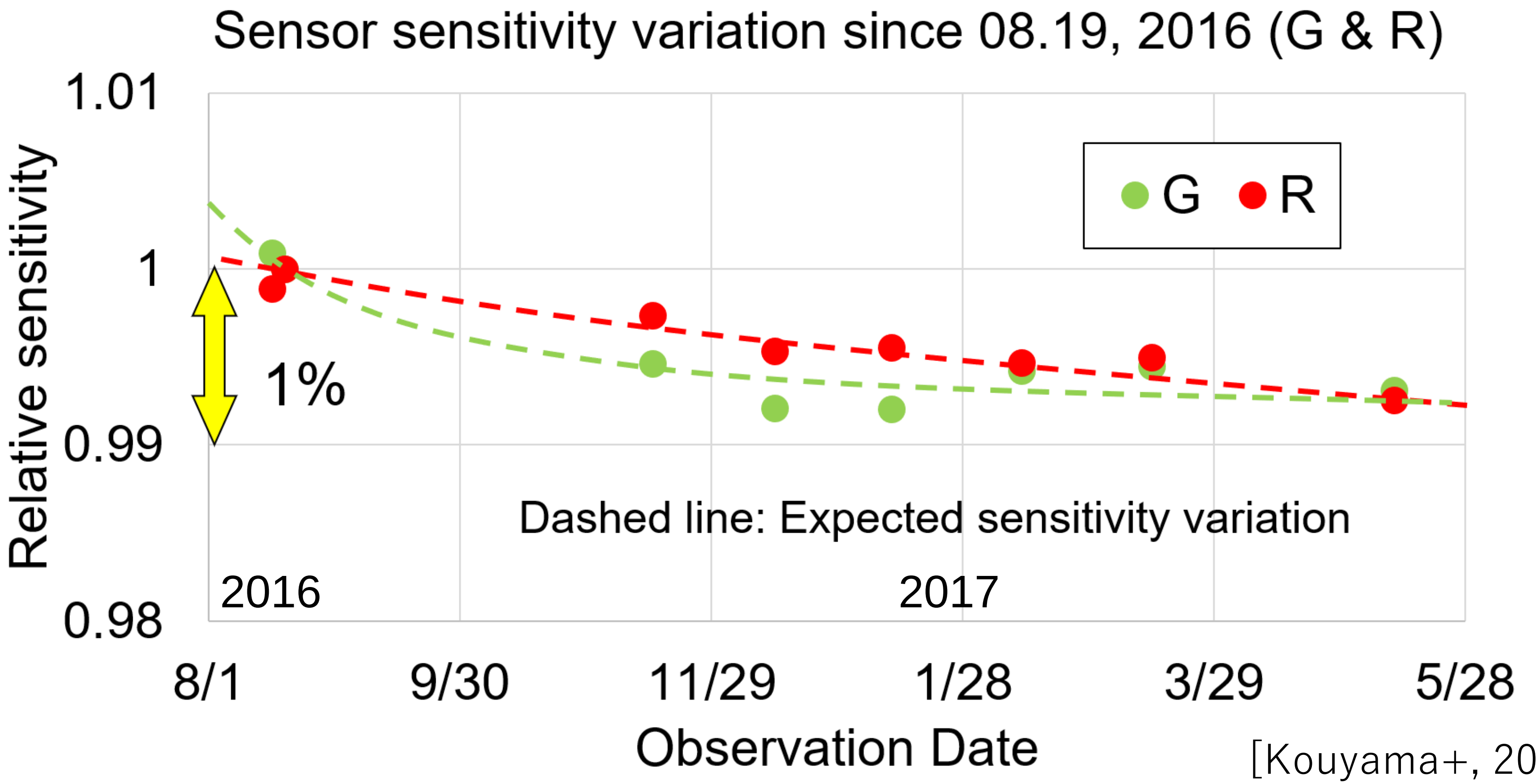



Well consistent with ROLO model (within 1 % difference) in terms of evaluating relative degradation

# SP model performance for assessing sensitivity degradation

## Example 2: Small satellite

**Hodoyoshi-1**

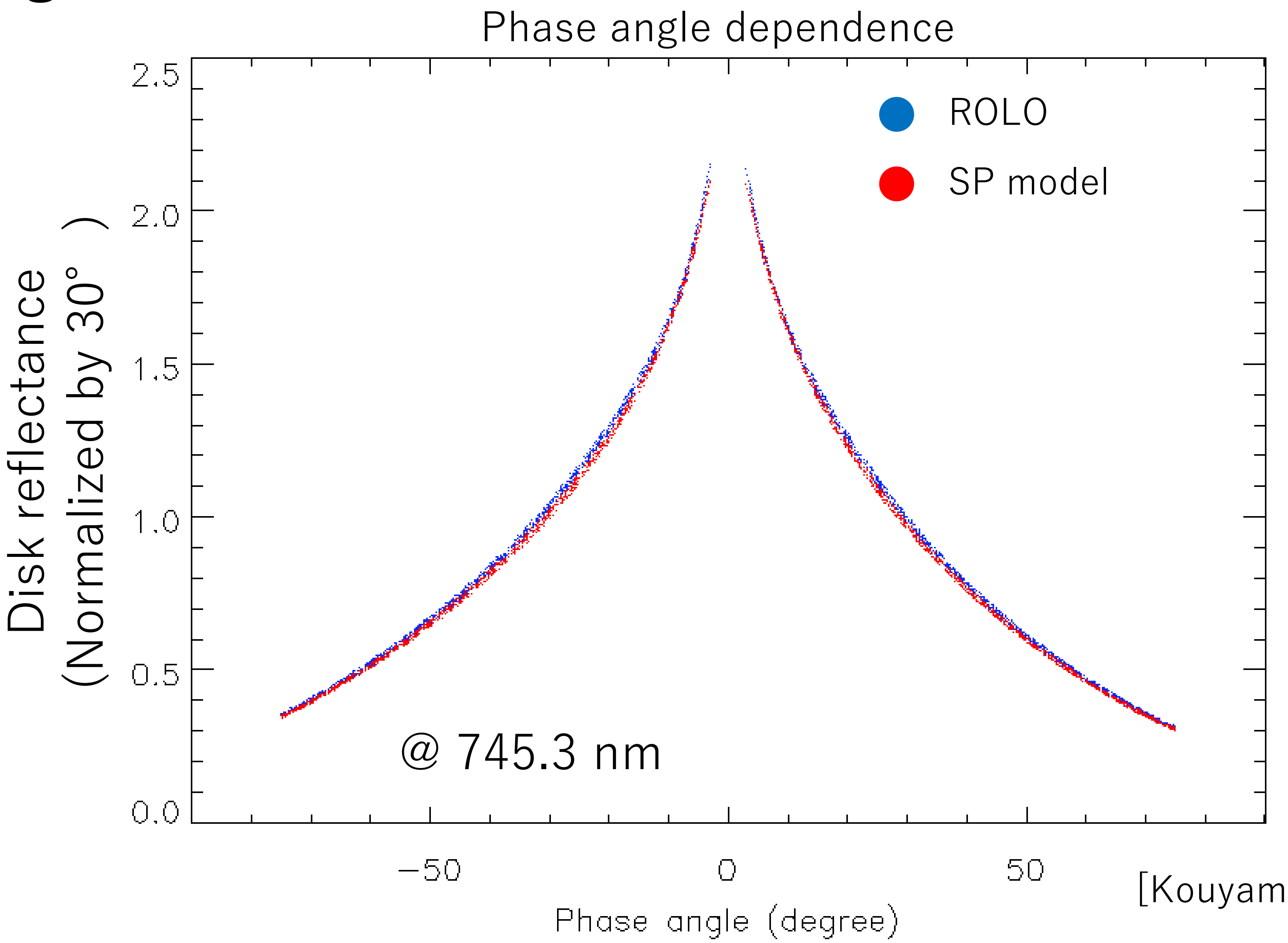



[Kouyama+, 2018]

- Same as other models, small sensitivity degradation (< 1 %) can be tracked

FYI

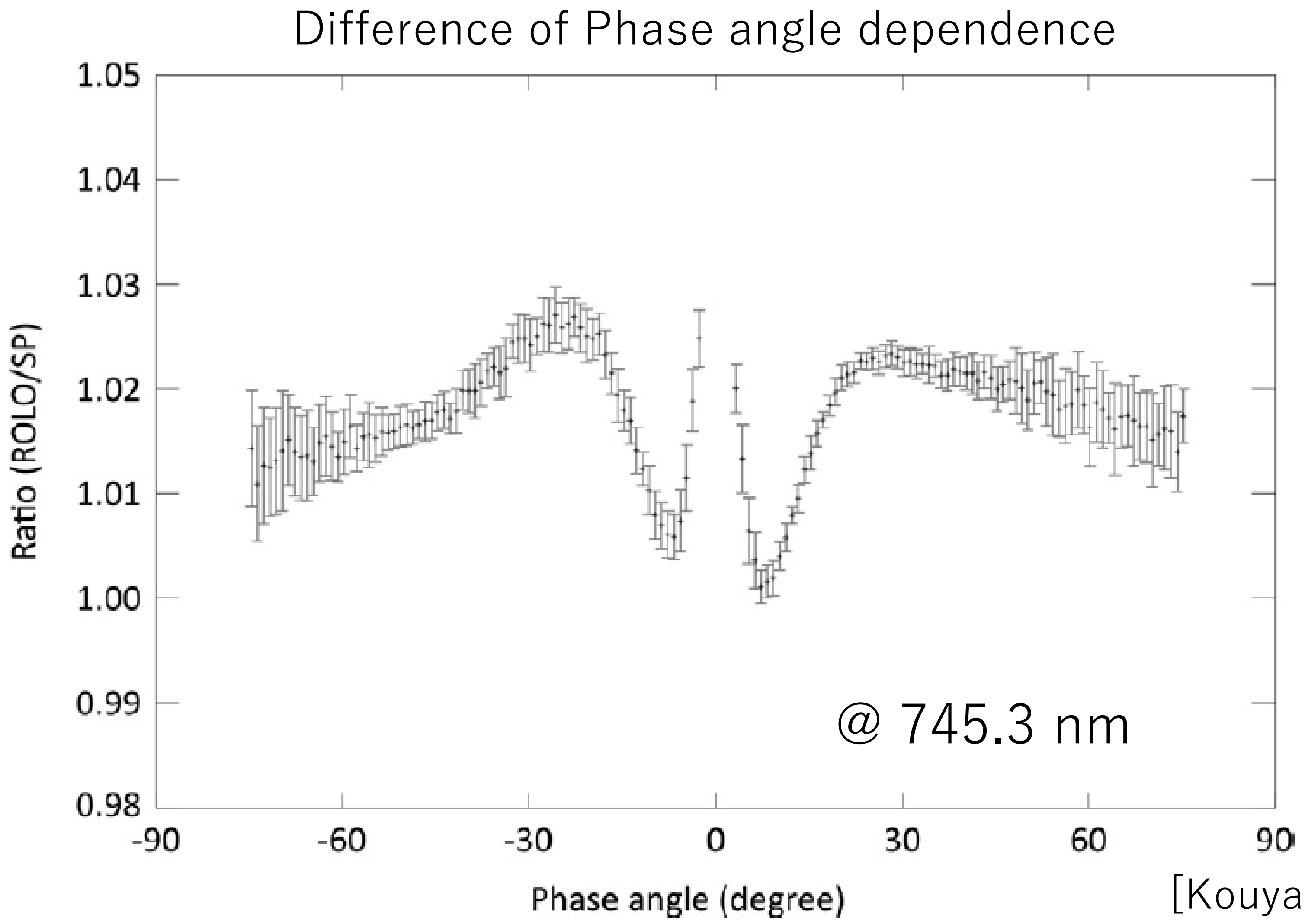
# Comparing with ROLO model




[Kouyama+, 2016]

FYI

# Comparing with ROLO model

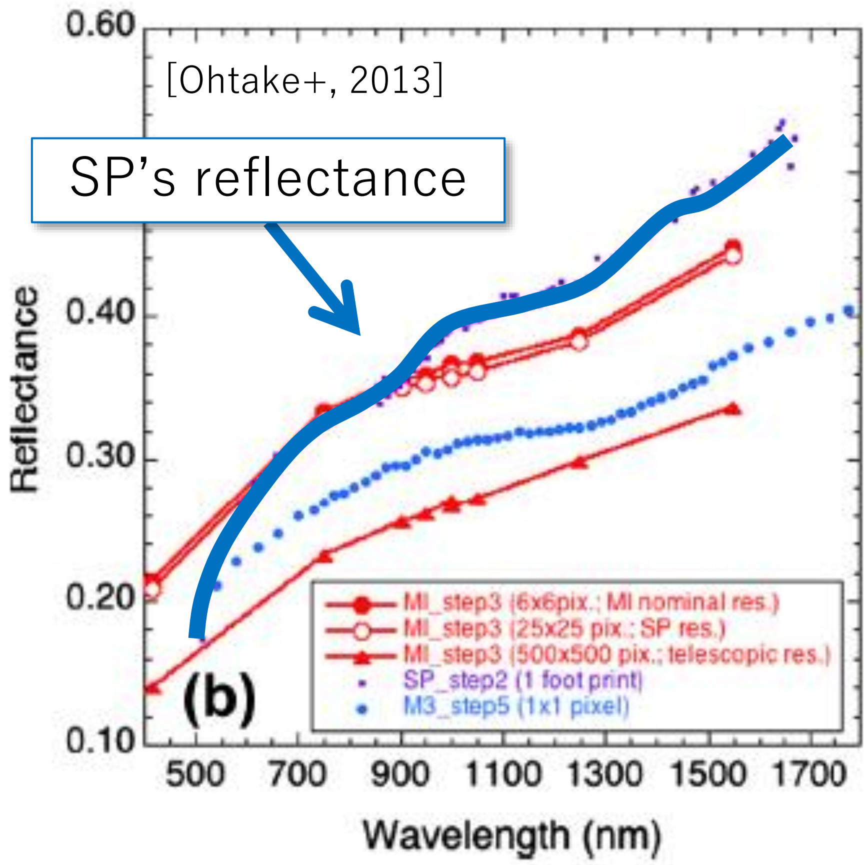



[Kouyama+, 2016]

*This shape is different in different wavelengths

FYI

# SP model accuracy and correction

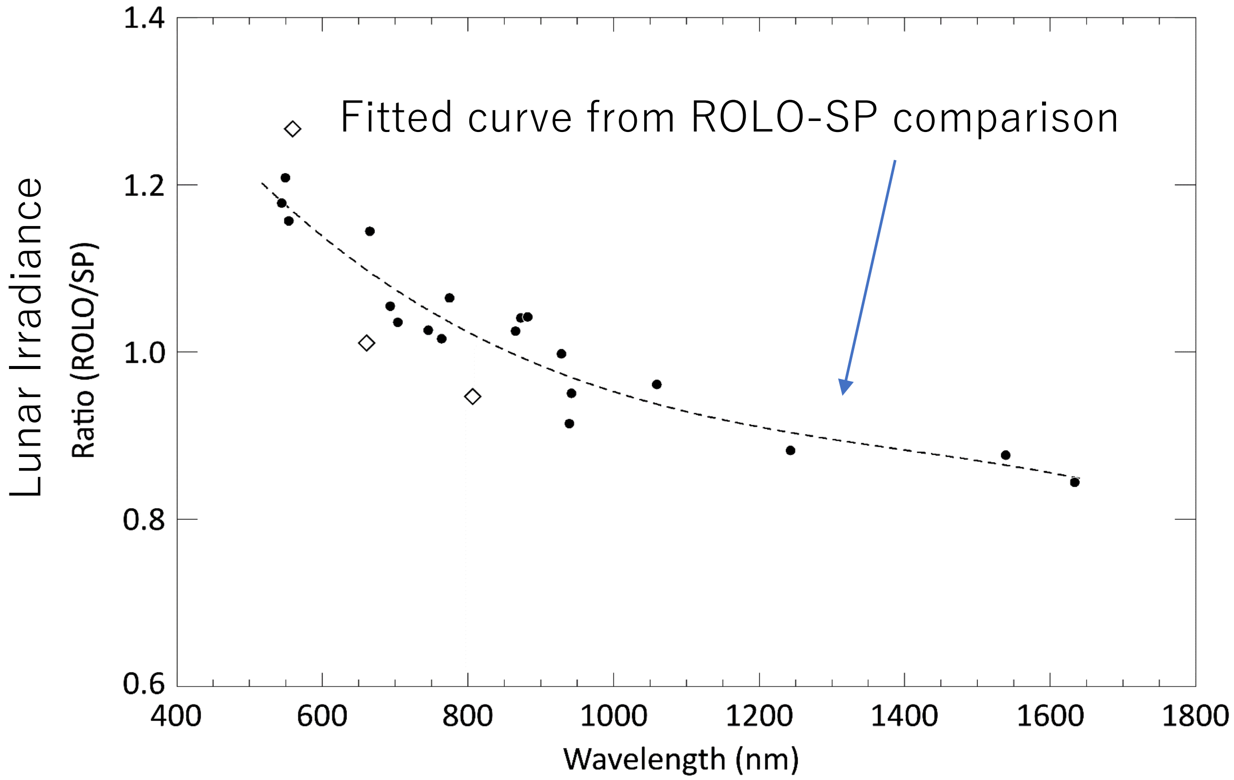



SP reflectance shows a "reddening" trend

- darker in shorter wavelength
- brighter in longer wavelength.

(cf. Ohtake+, 2010 & 2013)

**Correction coefficient based on ROLO**

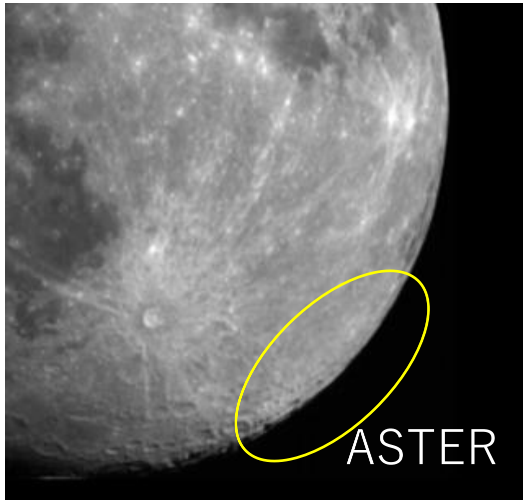


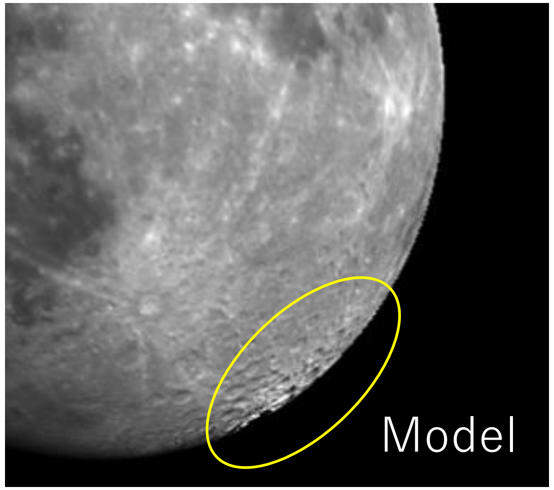
# Some technical and operational issues in SP model

- Due to SP's characteristics (reddening trend),"absolute value" in SP model has large error.
  - SP model requires a reliable model for correction.
  e.g., correction with ROLO has been proposed.

Communication with community is essential!

- In high emission angle and high latitude regions, model accuracy seems not to be high that may cause some uncertainty in irradiance measurements.

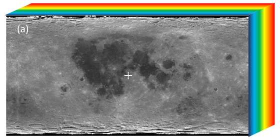





Yokota's recommendation: emission angle < 45 degrees.

- Accurate image registration is required for image x image comparison

# SP model: Release status



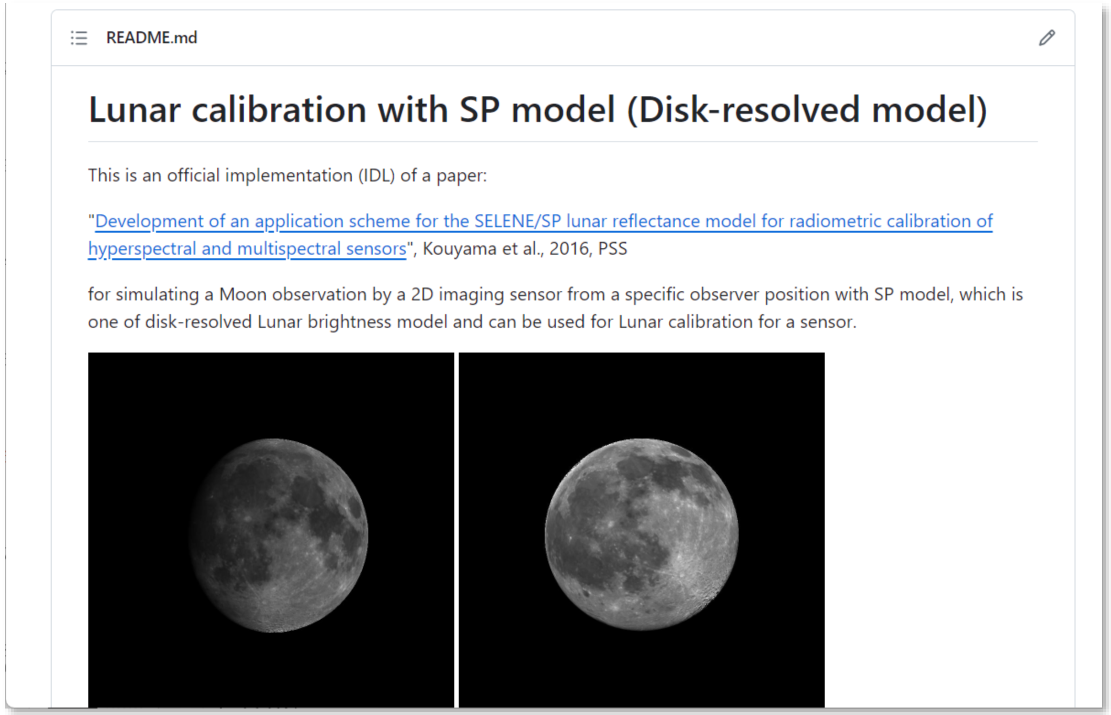

1. **2011 version (Validated)**
   515 nm – 1615 nm
2. **2012 version (Not yet)**
   515 nm – 2053 nm

## Model

- Hyperspectral reflectance map:
  https://archive.jlpeda.isas.jaxa.jp/pub/product/moon-selene-sp/
- Parameters:
  https://www.sciencedirect.com/science/article/pii/S0019103511003009

## Sample code for simulating a Moon observation

https://github.com/TKouyama/SP_LunarCal_example


README.md

Lunar calibration with SP model (Disk-resolved model)

This is an official implementation (IDL) of a paper:

"Development of an application scheme for the SELENE/SP lunar reflectance model for radiometric calibration of hyperspectral and multispectral sensors", Kouyama et al., 2016, PSS

for simulating a Moon observation by a 2D imaging sensor from a specific observer position with SP model, which is one of disk-resolved Lunar brightness model and can be used for Lunar calibration for a sensor.

**Language:**
- IDL
- Confirmed with GDL environment

**Simple testing:**
- In IDL/GDL CUI, just type

```
IDL> .compile main_sp_model.pro
IDL> main_sp_model
```

## Lots of to do…

- Improving input / output format
- Image registration part has been under preparation

Any feedback is welcomed!

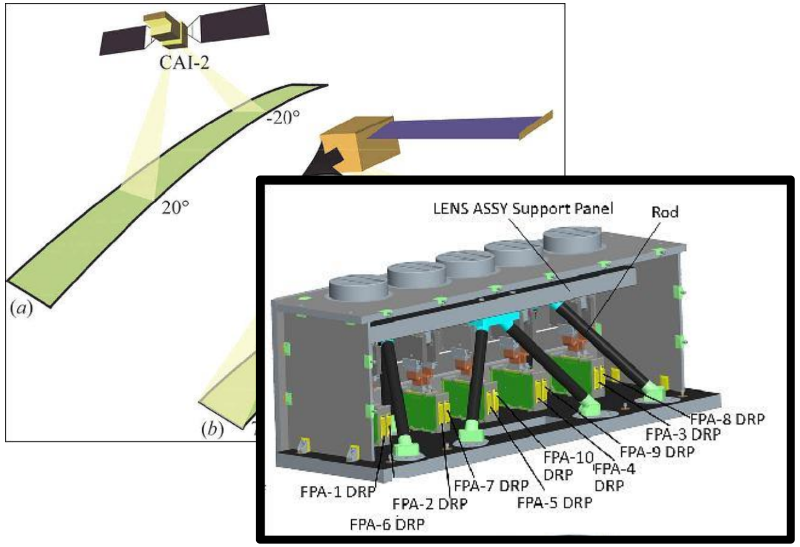
The implementing issue is also true with SP model

# Topics

- **Introducing “SP model” and its performance**
  - model and code release

- **Flat-field calibration with SP model**
  - example with GOSAT-2/CAI-2’s Moon observation

# GOSAT-2/CAI-2




Pushbroom-type sensor

## CAI-2 (Cloud and Aerosol Imager-2)

- **Bands:** 10 bands [UV - Near Infrared]
  5 optics, and each has forward and backward FOVs

| Forward | Band1 | Band2 | Band3 | Band4 | Band5 |
|---|---|---|---|---|---|
| | 333 - 353 | 433 - 453 | 664 - 684 | 859 - 879 | 1585 - 1675 |
| **Backward** | **Band6** | **Band7** | **Band8** | **Band9** | **Band10** |
| | 370 - 390 | 540 - 560 | 664 - 684 | 859 - 879 | 1585 - 1675 |

- **Spatial resolution**: 500 m/pix from 613 km altitude
  → Moon = 20 pixel
- **Swath:** 1000 km (more than 2000 pixels)
  → Hard to find a uniform target on the Earth

If we focus on flat-field calibration…:

- Statistical approach may work to assess the calibration, e.g. averaging many lines and many observations.
  ⇔ We need to care about any possible bias in data

**Dome-C**

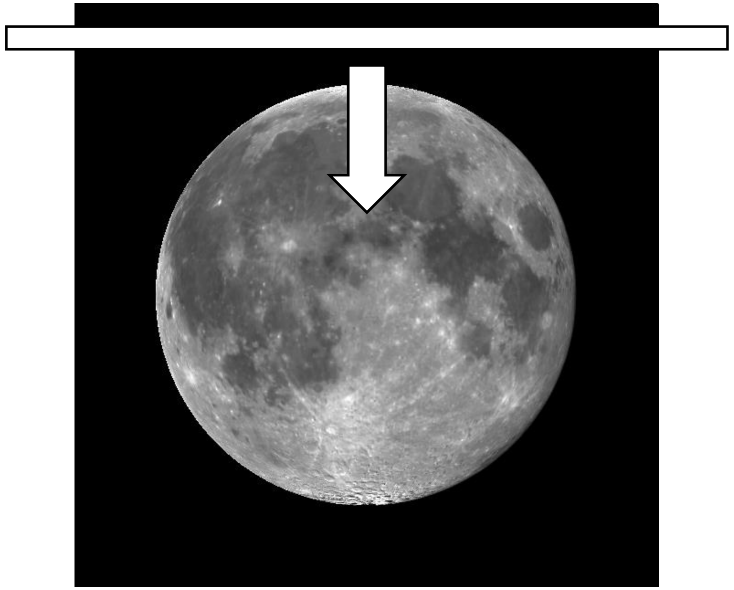

**Can lunar calibration contribute?**

Sensor and observation detail: Aki Sato's presentation (3k) "GOSAT-2 Lunar Calibration for FTS-2 and CAI-2"

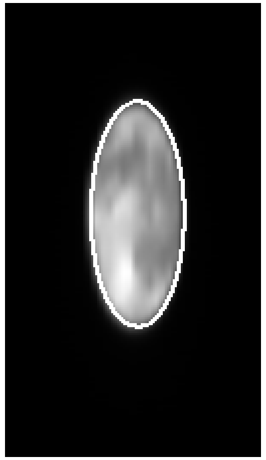
# GOSAT-2/CAI-2's Moon observation

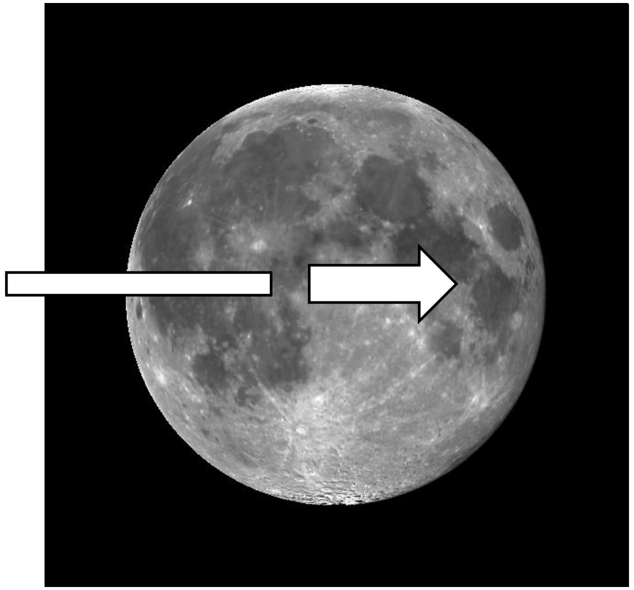
**Along track scan**
only a part of a sensor observes the Moon
→ Typical sensitivity degradation in a sensor

**Cross track scan:**
Whole pixels observe the Moon → Good for assessing sensitivity deviation among pixels

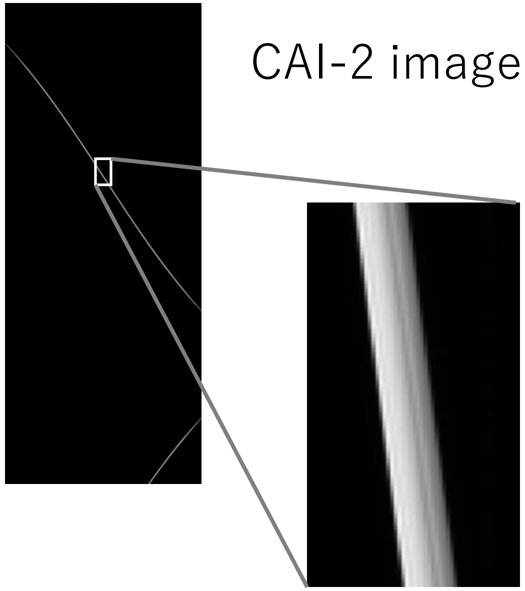


CAI-2 image





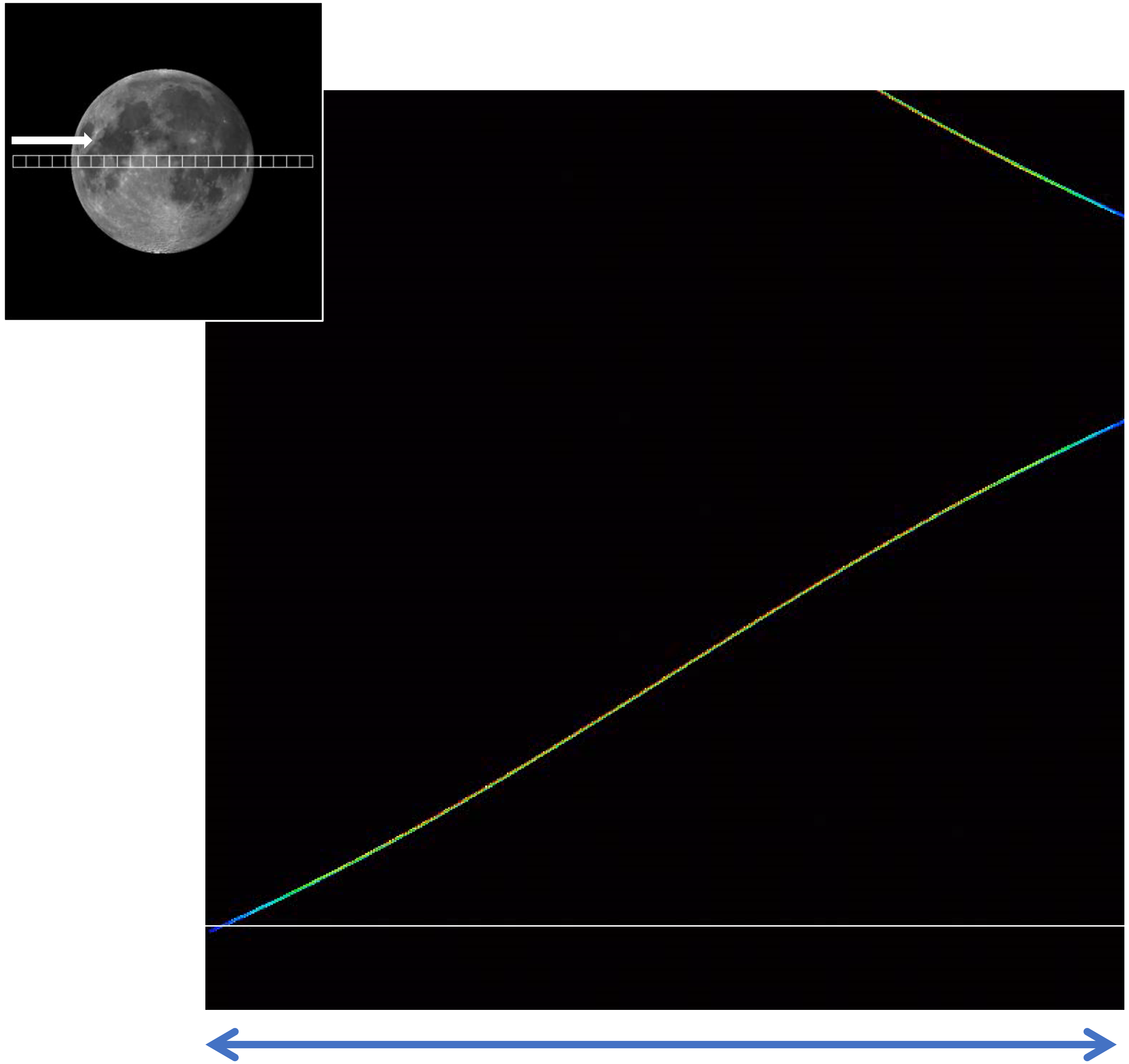
CAI-2 image



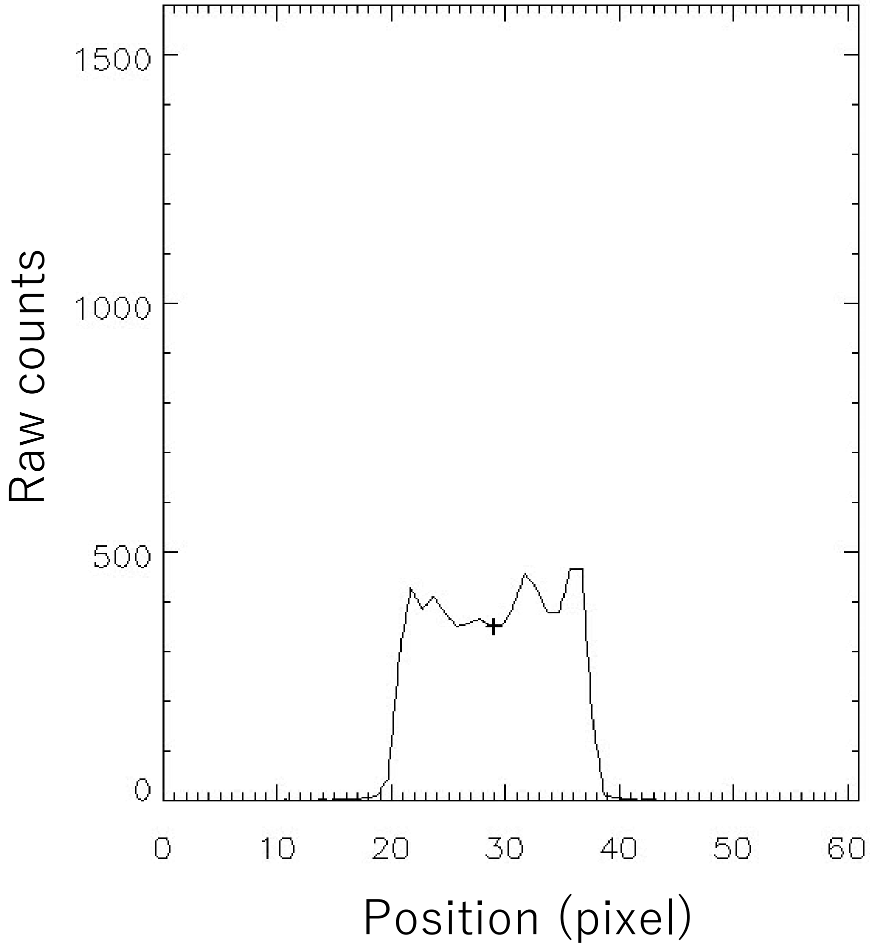
- GOSAT-2 conducts both along-track scan and cross track scan almost every month

Sensor and observation detail: Aki Sato's presentation (3k) "GOSAT-2 Lunar Calibration for FTS-2 and CAI-2"

# Example of CAI-2's Moon observation with Cross track scan

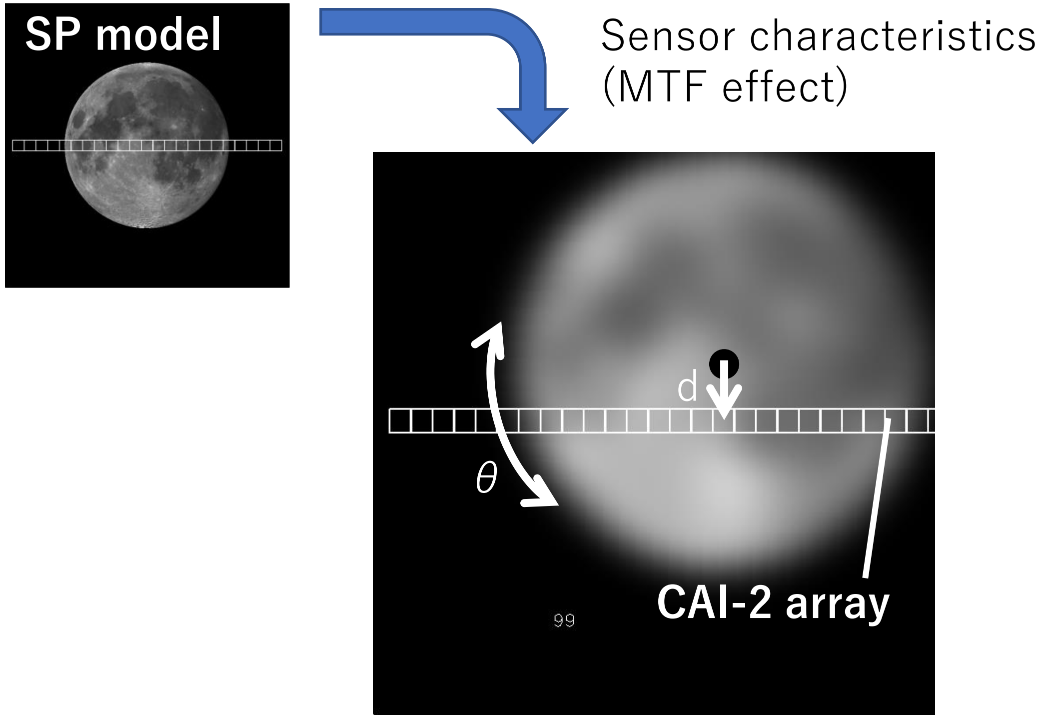



The width of the Moon was just 20 pixels

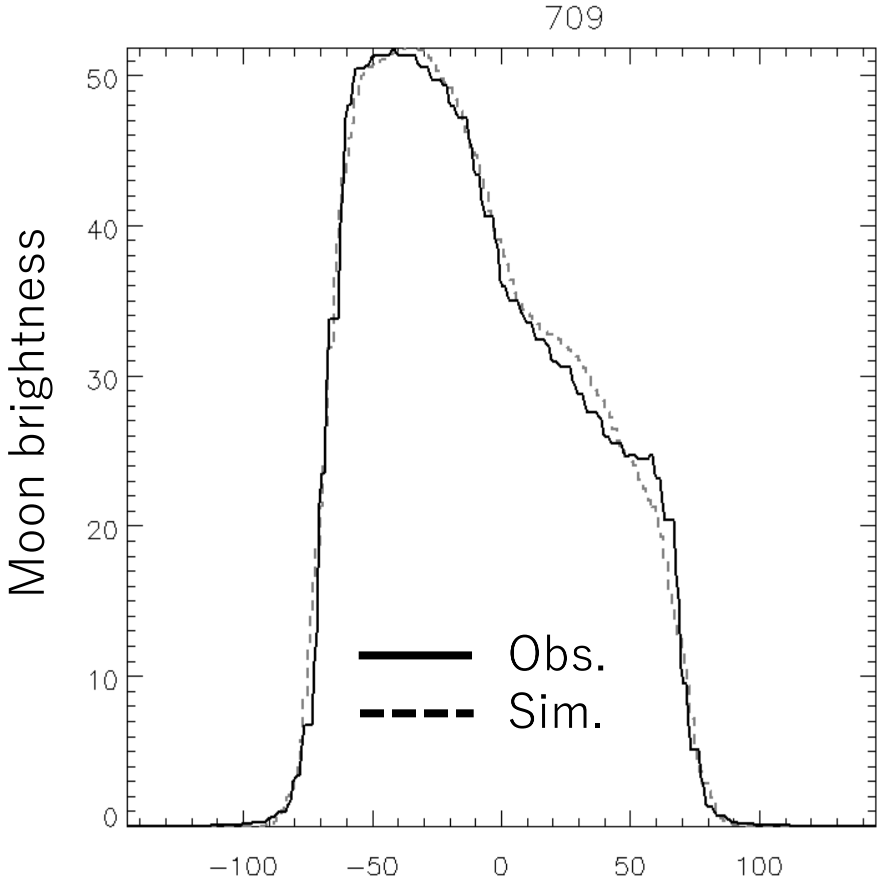


# Finding scan position on the Moon with SP model simulation

The problem is difficulty of determining scan position on the Moon from 1D profile




**Example of matching**




Pixel position (0 = center of the Moon)
*oversampled

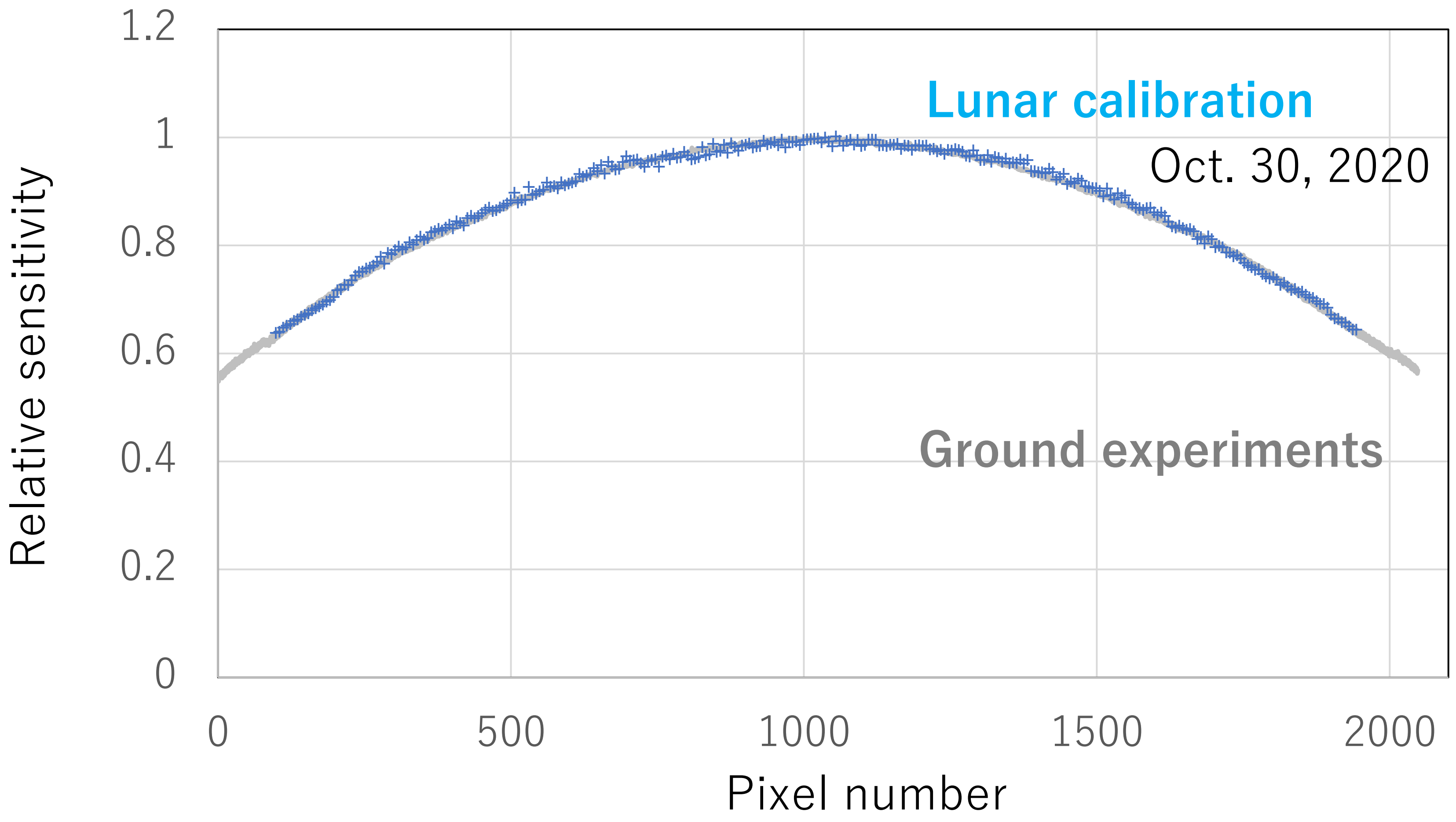
- A scan position can be represented with:
  - *d*: scan distance from the Moon center
  - *θ*: scan angle from a reference (i.e. East-West)

- Brightness profile from SP model can be used for determining the best *d* and *θ* for each scan, for instance, by finding the highest correlation coefficient

Preliminary results

# Sensitivity deviation among pixels

**CAI-2/Band4** (859 – 879 nm), center band for Moon observation sequence



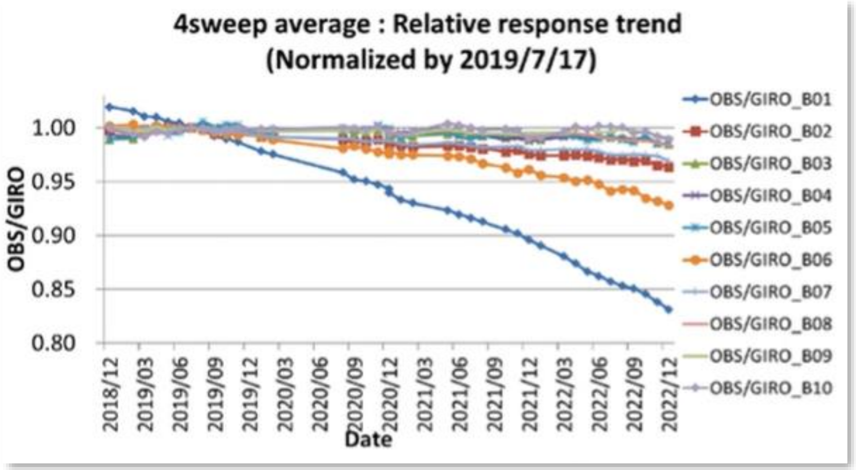

- Lunar calibration provided a consistent sensitivity profile with that from ground experiments (main component = vignetting effect)

Preliminary results

# Assessing temporal variation of sensitivity at various positions in a sensor

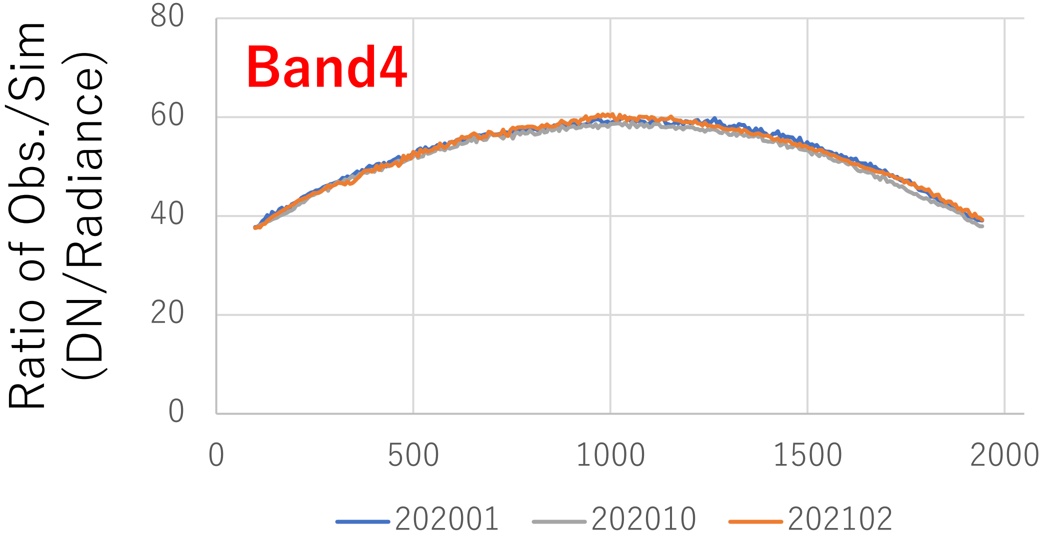
- We tested the flat-field evaluation with three different observations:
  - Jan. 2020
  - Oct. 2020
  - Feb. 2021

- In Band 4, there was no significant sensitivity variation among different pixels, which is consistent with other reports.
- Any abnormal pixel position has not been detected.

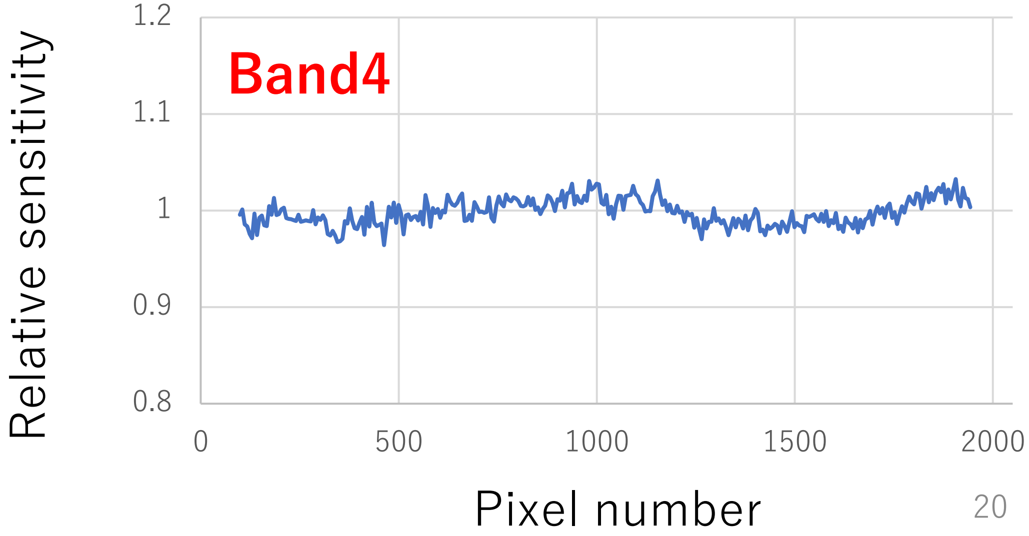



- How about other bands?

**Comparison of three observations**




**2020 Jan. => 2021 Feb.**



# Summary

## SP model

- SP model and sample codes have been published.
  - at this moment, there is no plat to update SP model itself
  - implementation can be improved any time

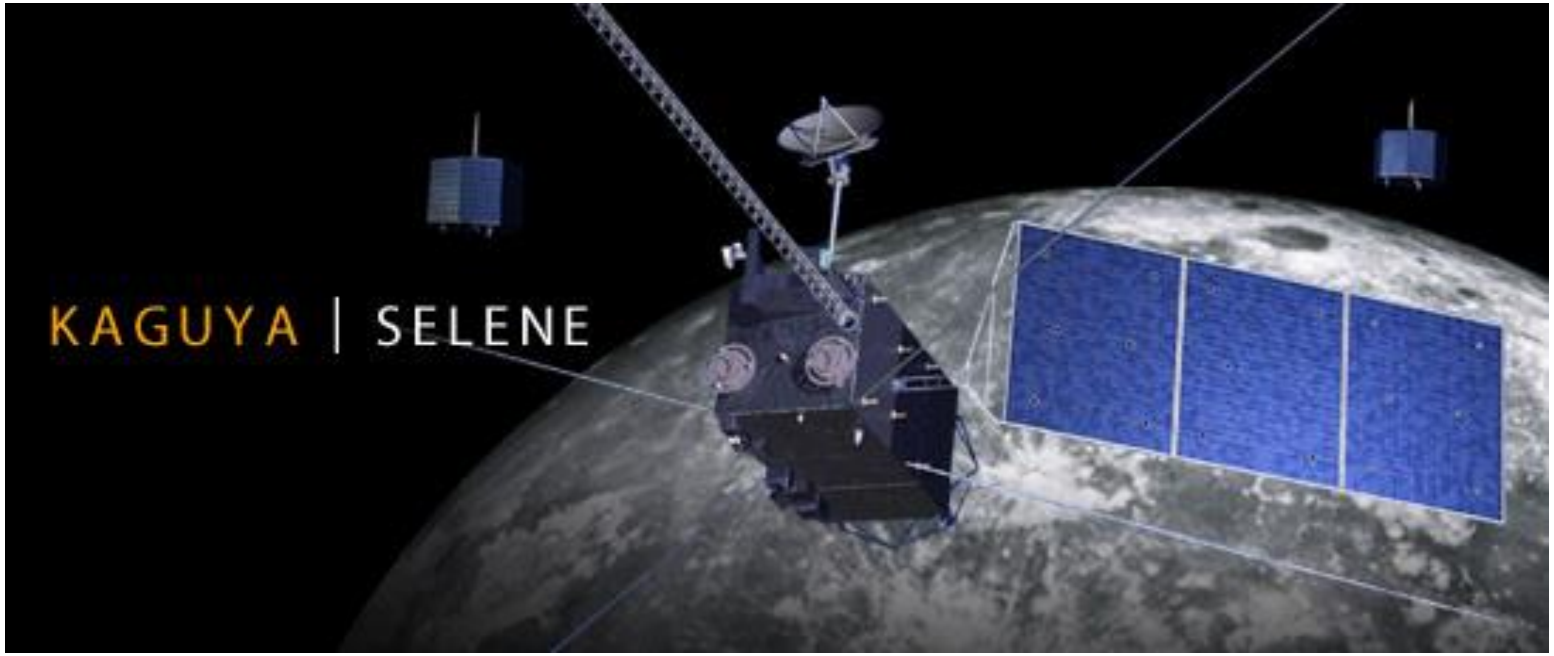
## New application with a radiance (=disk-resolved) model

- It can be used for assessing accuracy of flat field correction, if a special operation (cross-track scan) can be conducted.
  - detail temporal variation in a sensor can be investigated

- MTF check in space?

# Backup slides…

# SELENE(KAGUYA) and SP

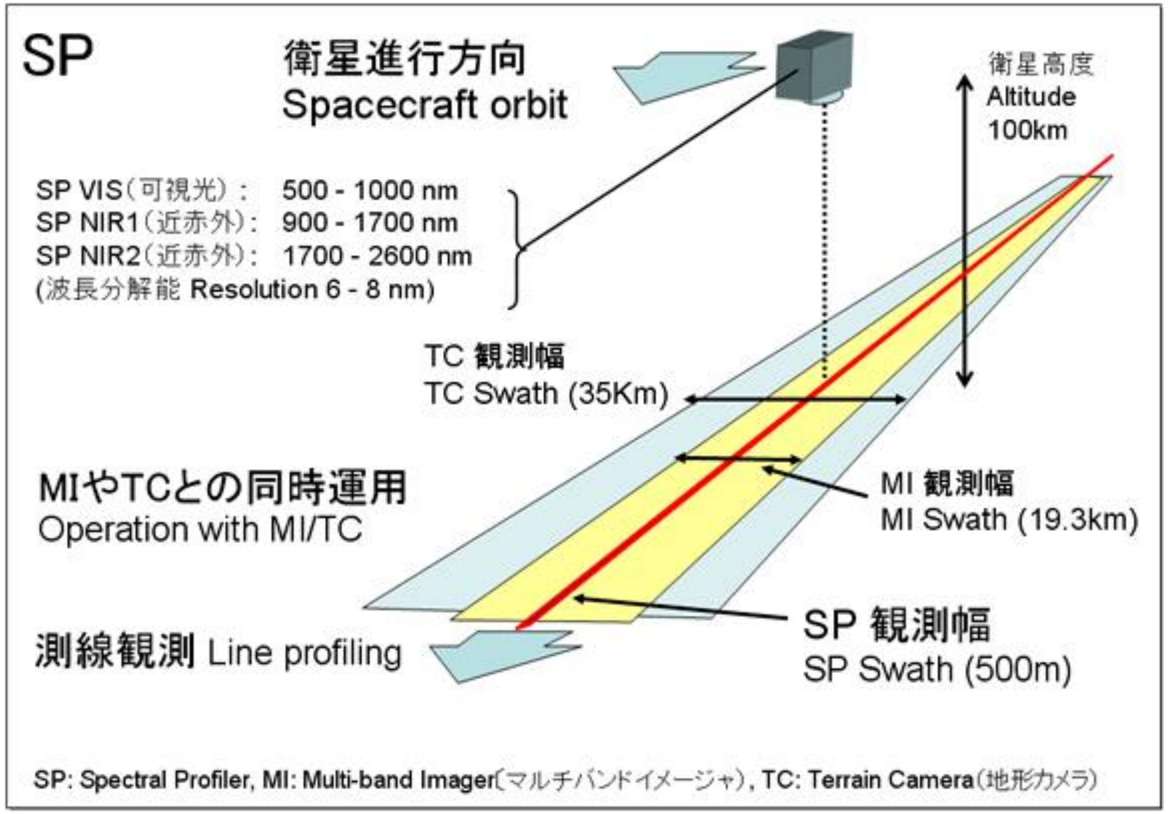



SELENE:
Polar orbit (non sun-synchronous)
Altitude: 100 km
Grand track repeat cycle: ~ 30 days
Mission period: 2007 – 2009 (1.5 years)

Observation with various
solar incident angle condition.

# SELENE(KAGUYA) and SP

## SP: Spectral Profiler




Sensor type:
Spectrometer

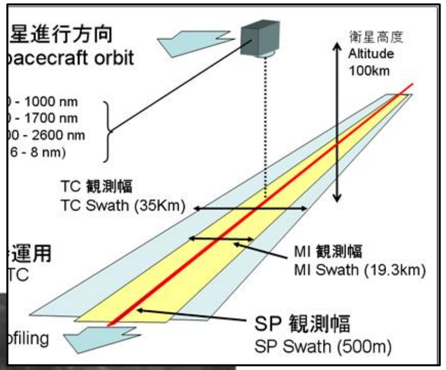
Spectral range:
500-2600 nm

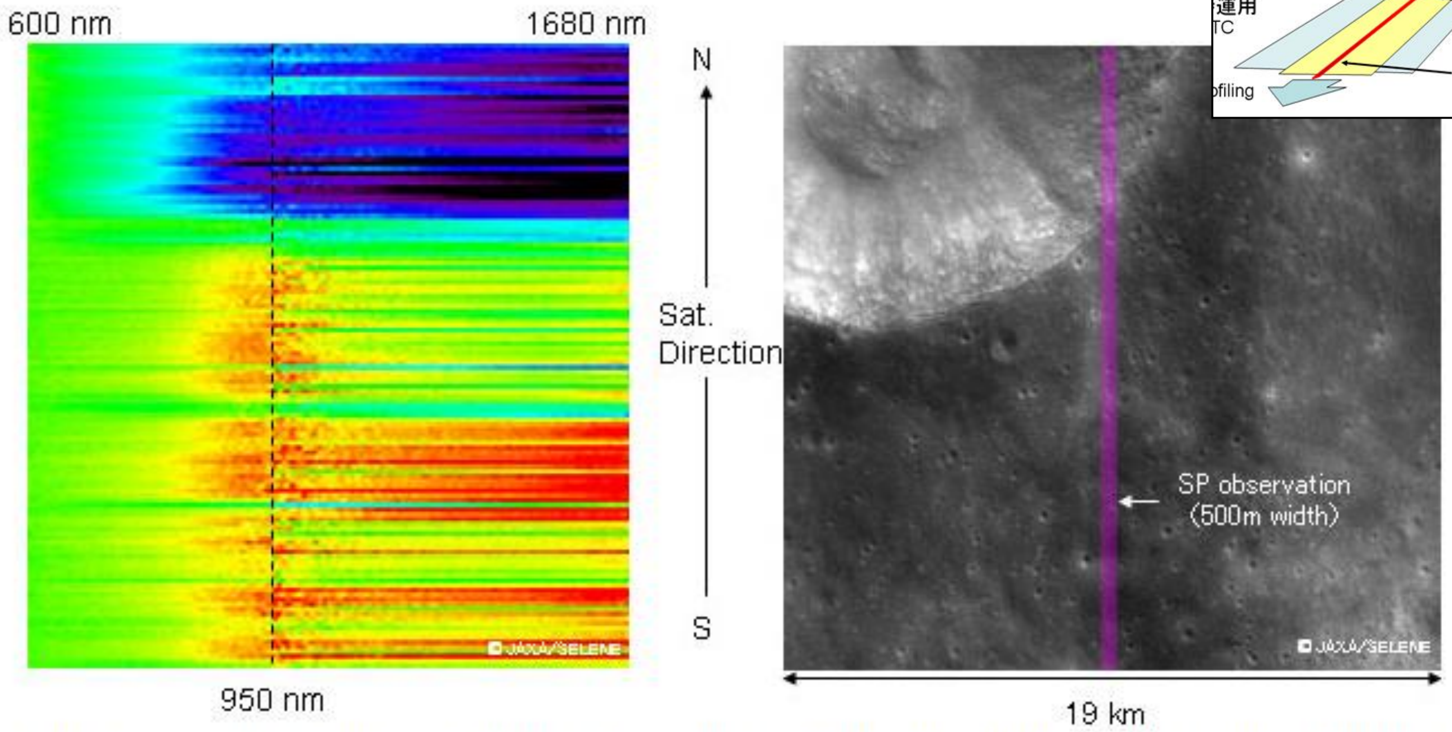
Spectral resolution:
6 nm (VNIR 520-960 nm)
8 nm (NIR-SWIR > 900 nm)

Observation swath
500 m

# SELENE(KAGUYA) and SP

SP: Spectral Profiler

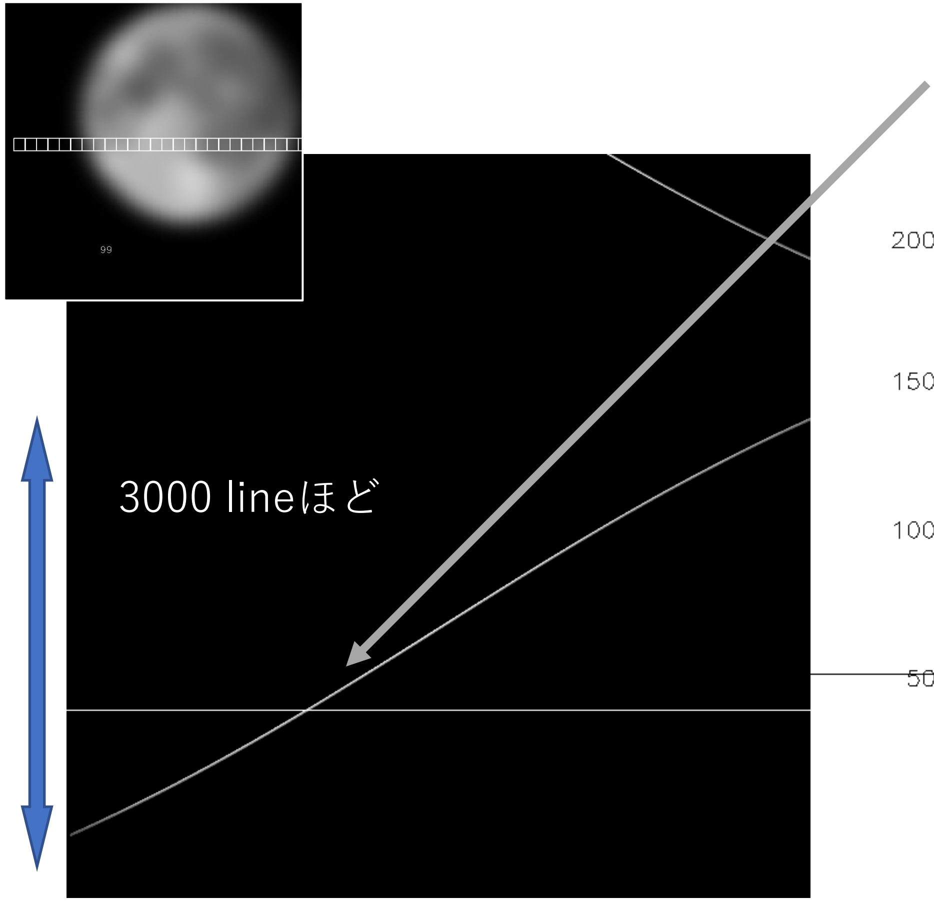


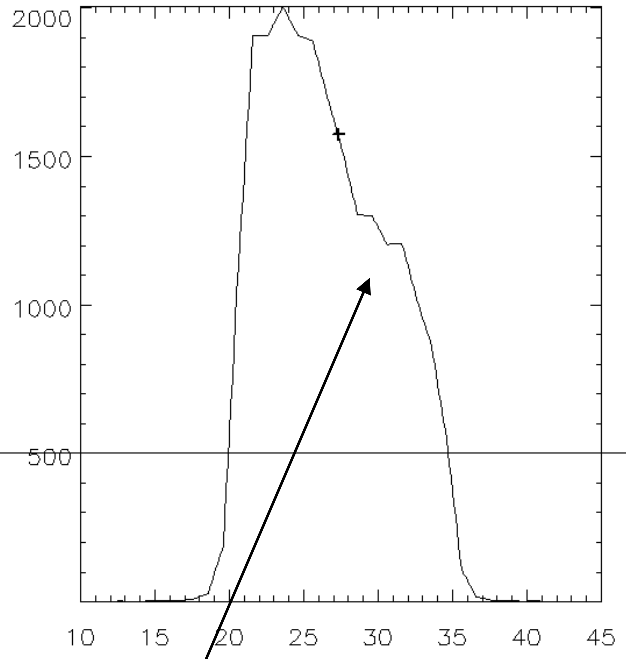

SP data near the crater shown in Fig. 2　　Same crater image simultaneously observed by MI

http://global.jaxa.jp/press/2007/12/20071214_kaguya_e.html

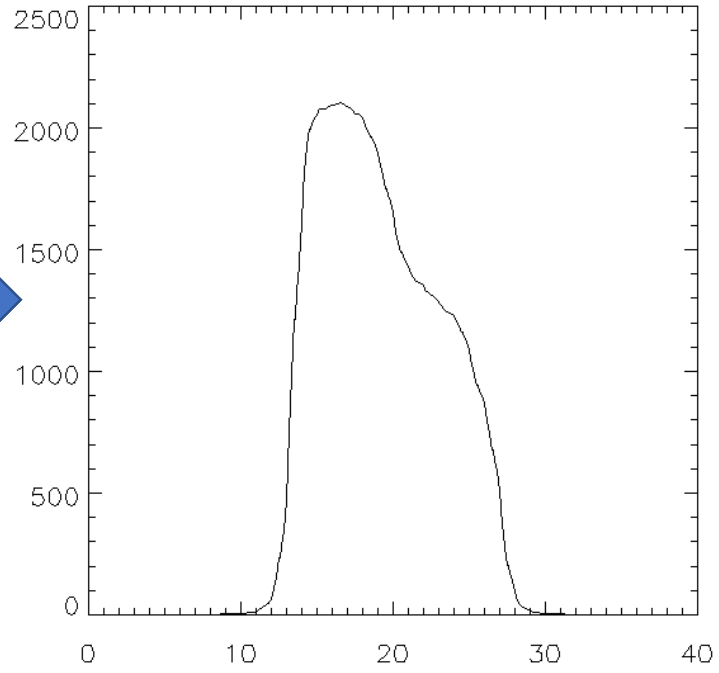
# ① 観測された輝度プロファイルを扱いやすい形に処理




あるLineでの
輝度プロファイル

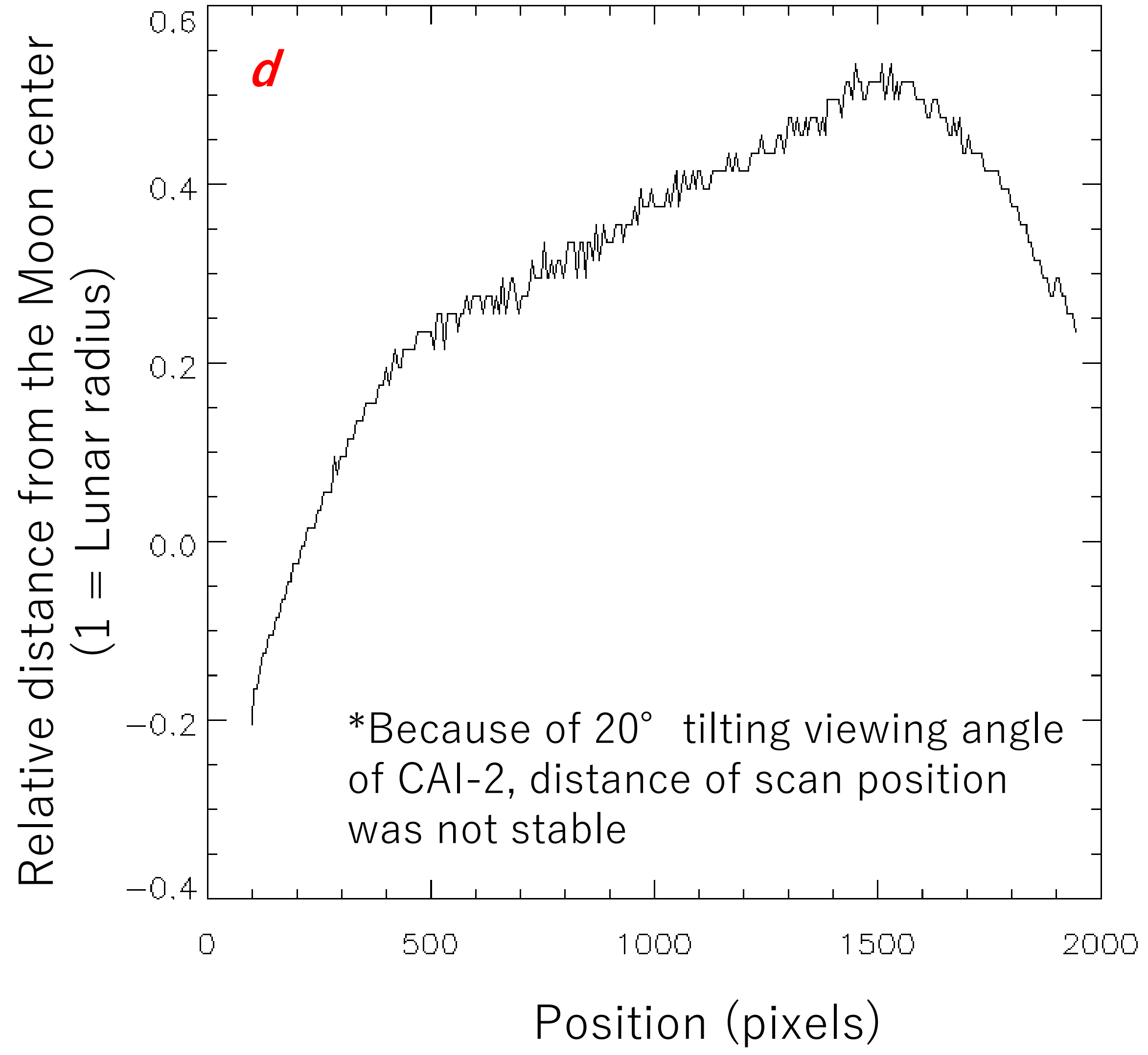


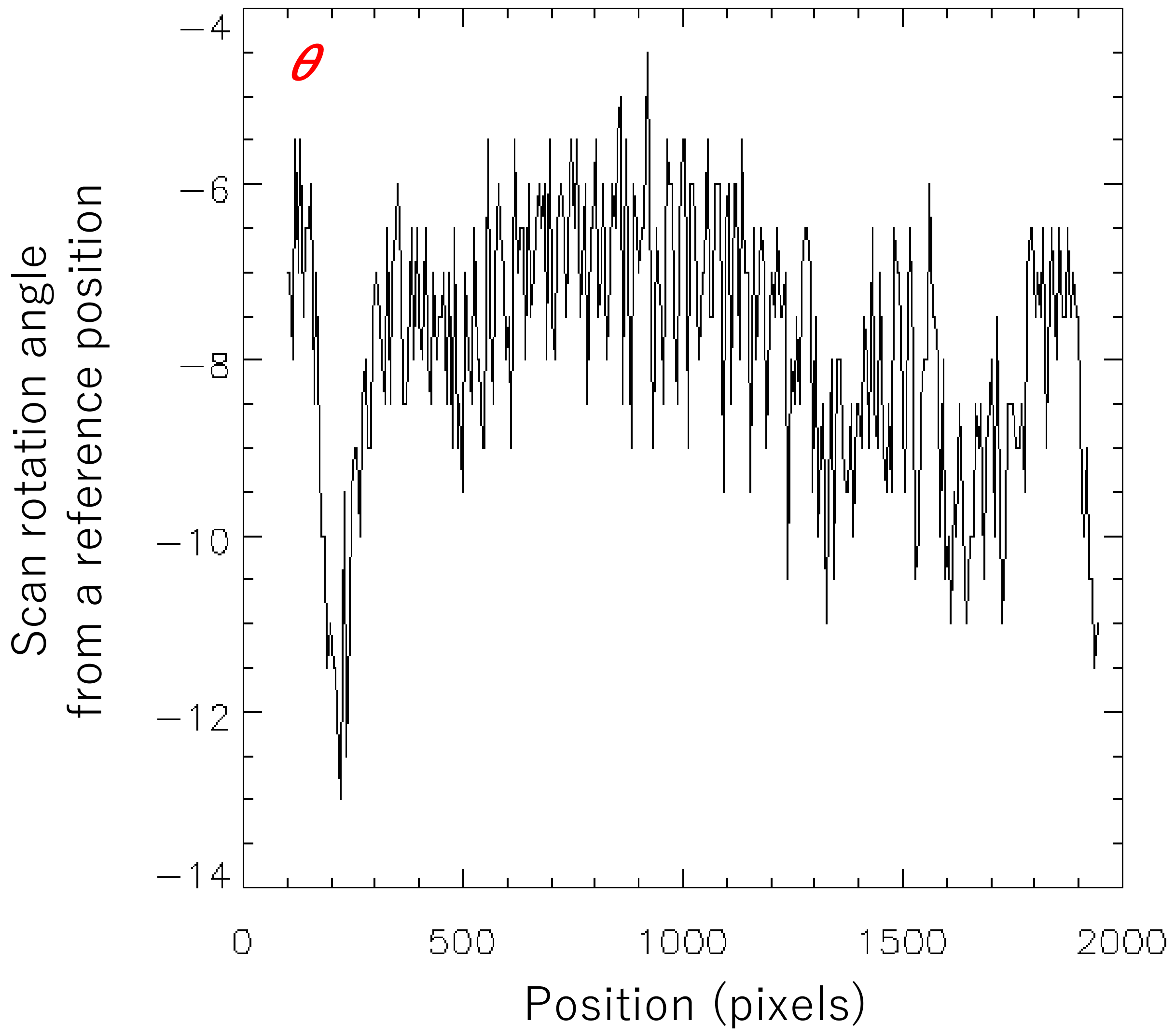

近傍50 ~ 60 line分を重ね合わせて
滑らかなプロファイルに
(超解像的効果を活用
 Taguchi et al., 2011)



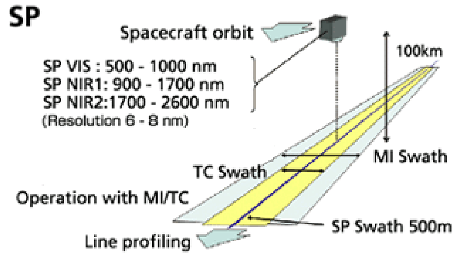

(本当は解像できていないのに)プロファイル上に凸凹
→　サブピクセルレベルでのスキャン位置の違いで大きく変化

# Example of *d* & *θ* for Band 4 for 202010 observation



# SP model: “Disk-resolved” hyperspectral lunar brightness model based on SELENE/Spectral Profiler (SP) reflectance map




**Dataset for the model** — **Spectral Profiler (SP)** onboard SELENE

## Sensor specifications/observations

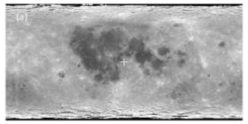
Spectroscopy with a point observation

- **Spectral coverage**
  513 – 2600 nm (3 detectors: VIS, NIR1, NIR2)
- **Swath**
  500 m swath (point observation)
- **Orbit and Observation**
  “Non”-sun synchronous, and Nadir observation
  = Various incident & phase angle conditions
  ⇔ Narrow emission angle range

## SP’s reflectance maps

Integrating 70 M SP observations into a hyperspectral map

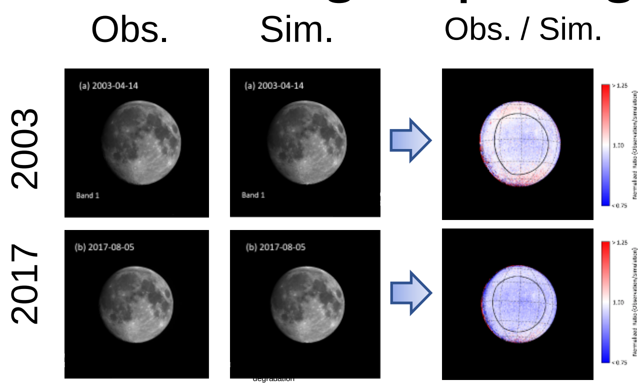
- **Map grid interval** (=spatial resolution of the model)
  0.5° x 0.5° in longitude and latitude
  = Corresponding to resolution of 25 m / pix
- **Map spectral coverage**
  516 – 1600 nm (160 channels) / Δ $\lambda$ = 6 - 8 nm
  (NIR2 region has been under preparation)
- **BRDF effect**
  Simple approximation (will be updated in future)



## Any observation geometry can be simulated by SP model

## Contributing to updating ASTER’s RCC

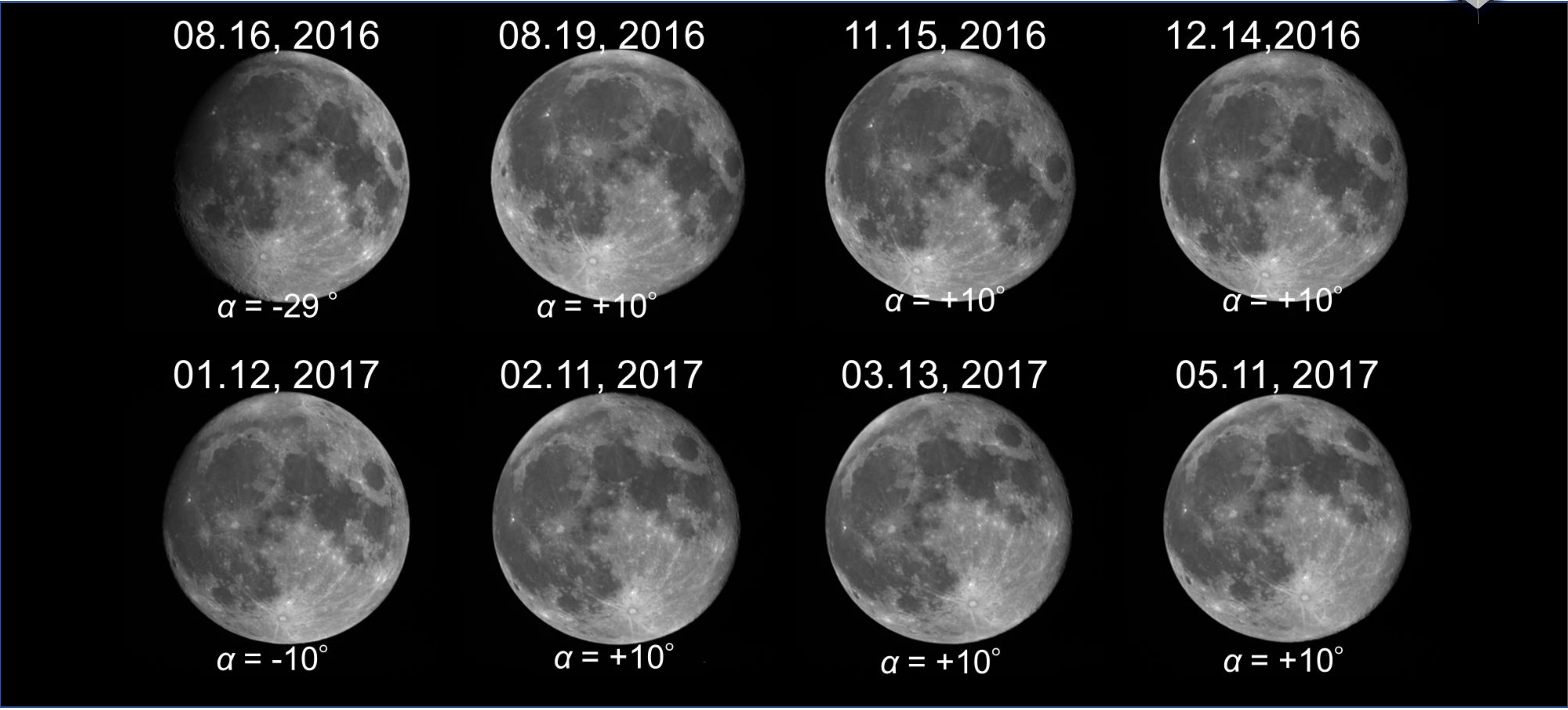
*Radiometric Correction Coefficients




- ASTER’s sensitivity degradation from 2003 to 2017 was successfully determined within 1 % uncertainty.
- New RCC curves were defined with the lunar calibration result as a constraint.

[Kouyama et al., 2019; Tsuchida et al., 2020]

# 小型衛星に対する月校正例(ほどよし1号)

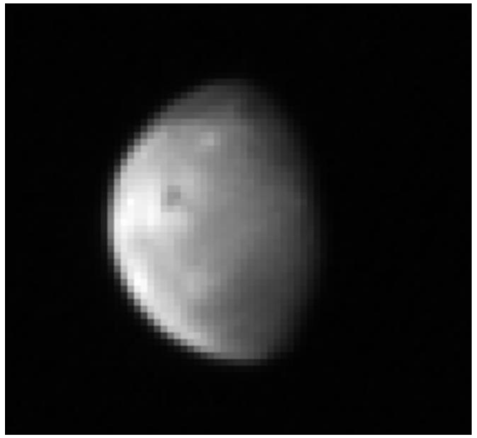



α: Phase angle

Moon appearance was different at every observation

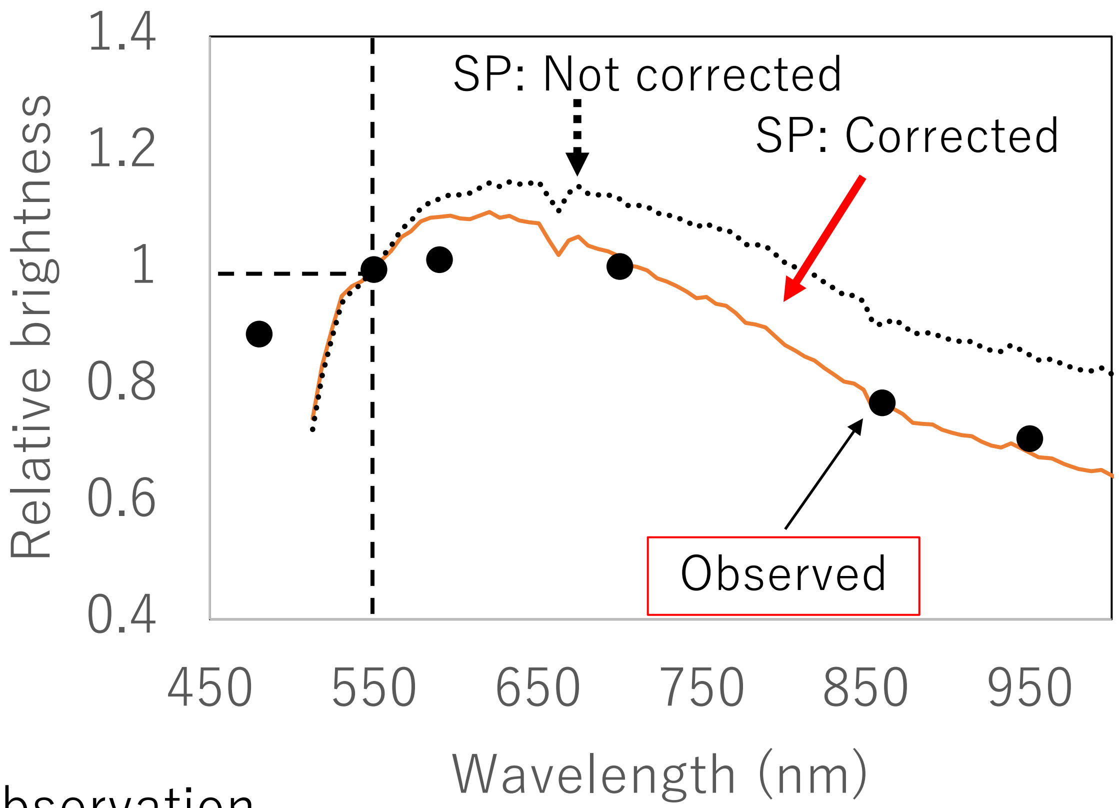
# SP model accuracy and correction

Hayabusa2



Lunar irradiance comparison

(Normalized by 550 nm)




Better spectral consistency with observation

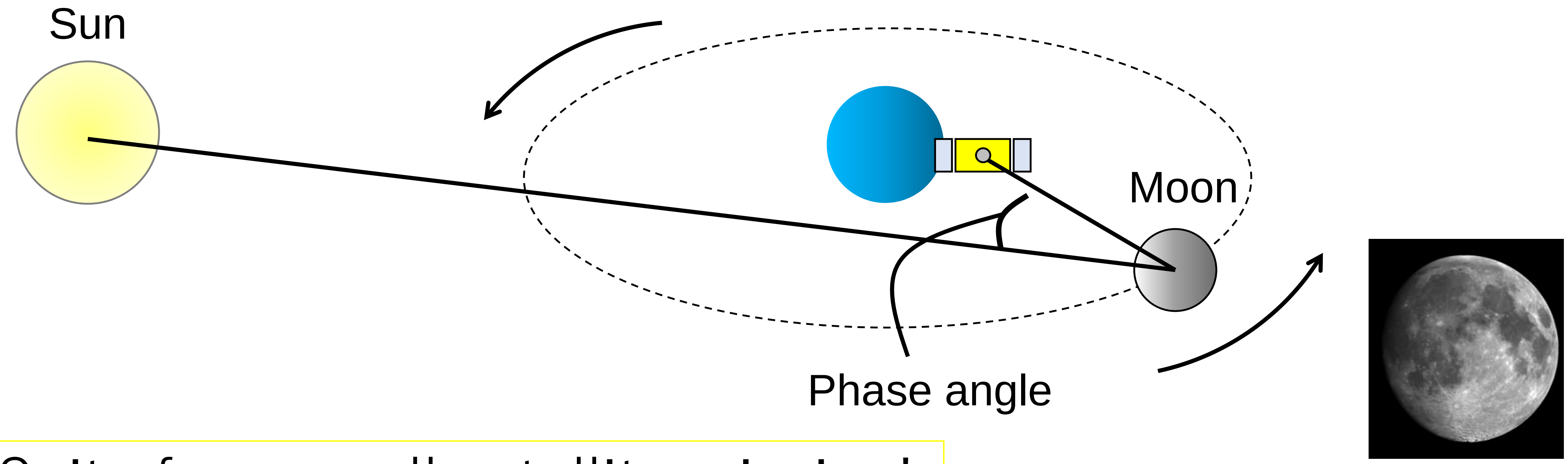
[after Suzuki et al., 2017, Icarus]

# Lunar calibration

Using the Moon as a radiometric calibration target

No special instrument is required → Low cost

Easy to repeat (Every month)




Suite for a small satellite mission!