
# GOSAT-2 Lunar Calibration for FTS-2 and CAI-2

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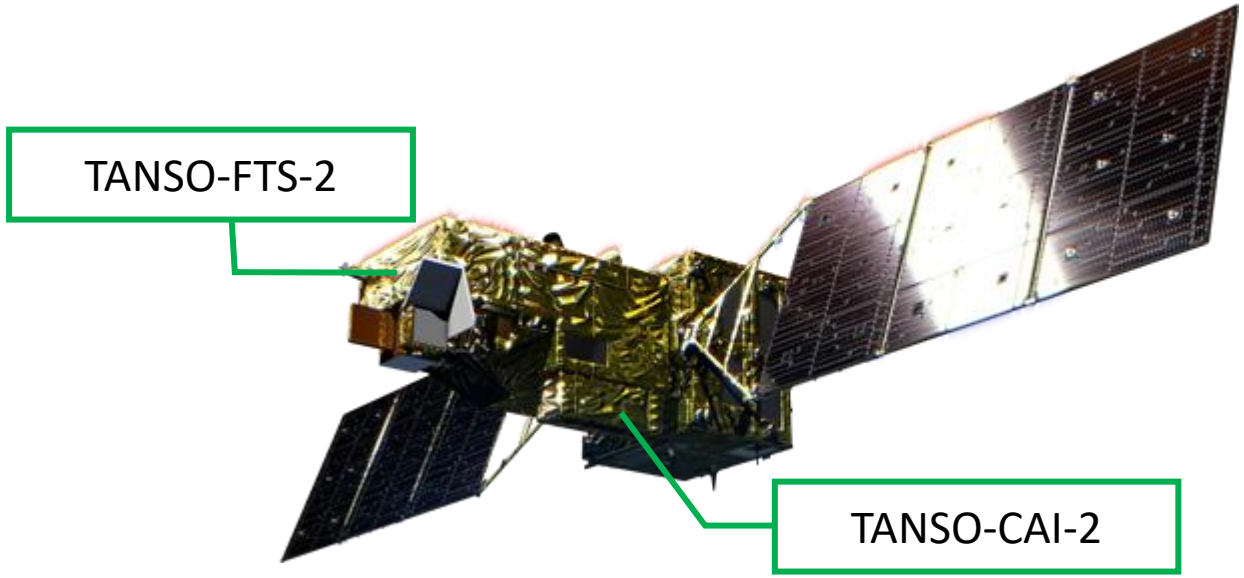
# Contents

# 1.Introduction

# GOSAT-2 Overview

## Greenhouse gases Observing SATellite-2 (GOSAT-2)

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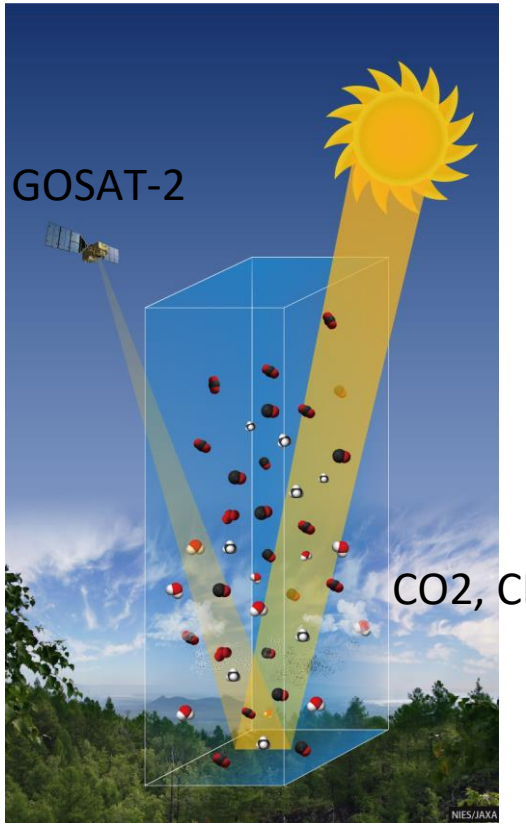


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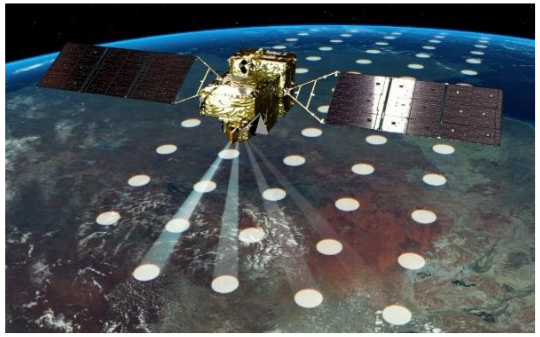
https://www.gosat-2.nies.go.jp/jp/about/observation/

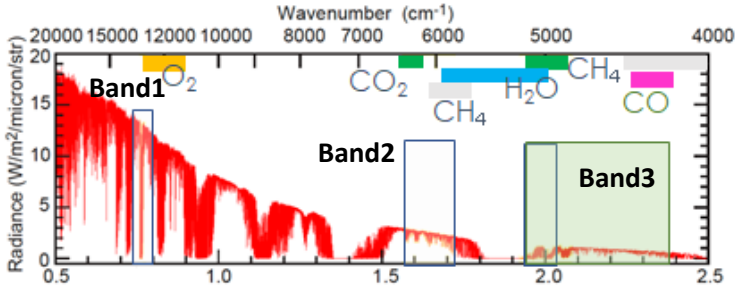
- The GOSAT-2 was launched on October 29, 2018, operating over 5 years.
- The GOSAT is also operating since 2009 over 14 years.
- The GOSAT-2 carries Thermal and Near Infrared Sensor for Carbon Observation-2 (TANSO-2) sensors :
  - FTS-2 (Fourier Transform Spectrometer-2)
  - CAI-2 (Cloud Aerosol Imager-2)

# FTS-2 Overview

## ■ TANSO-FTS-2 (Fourier Transform Spectrometer)

| | Band1 | Band2 | Band3 | Band4 | Band5 |
|---|---|---|---|---|---|
| | SWIR | | | TIR | |
| Target Gases | $O_2$ | $CO_2$, $CH_4$, $H_2O$ | $CO_2$, CO, $H_2O$ | $CH_4$, $H_2O$ | $CO_2$, $O_3$ |
| Spectral Coverage (μm) | 0.75 - 0.77 | 1.56 - 1.69 | 1.92 - 2.38 | 5.5 - 8.4 | 8.4 - 14.3 |
| Spectral Coverage ($cm^{-1}$) | 12,950 - 13,250 | 5,900 - 6,400 | 4,200 - 5,200 | 1,188 - 1,800 | 700 - 1,188 |
| **Spectral Resolution (nm)** | **~0.01 @0.76μm** | **~0.05 @1.6μm** | **~0.1 @2.0μm** | **~1 @7μm** | **~2.5 @11μm** |
| Detector | Si | MCT | | | |
| Exposure | 4 sec | | | | |
| Footprint size (nadir) | 15.8 mrad | | | | |
| Polarimetry | Yes (P and S channels) | | | No | |



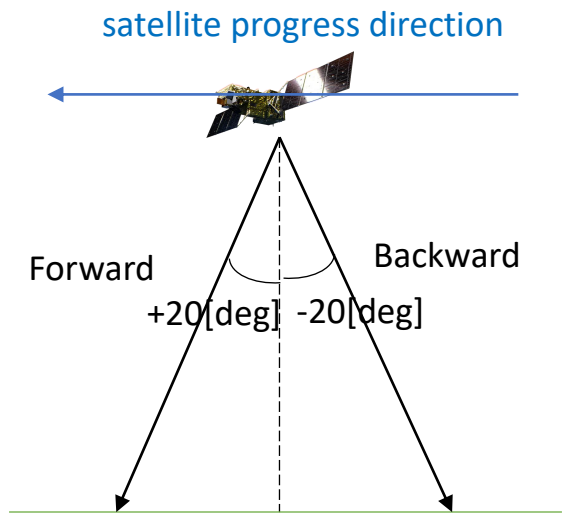



- FTS-2 is the Fourie Transform Spectrometer that has **high spectral resolution about 0.01[nm] at 0.76 [μm].**
- FTS-2 performs discrete observations that integrate each sounding for 4[sec], shown as upper right figure.
- **FTS-2 has a multiplex advantage that enables observing all wavelength(0.75~14.3μm) and two linear orthogonal polarization (P and S) channels at the same time.**
- Although FTS-2 has TIR bands, lunar calibration only observes SWIR band1~3.

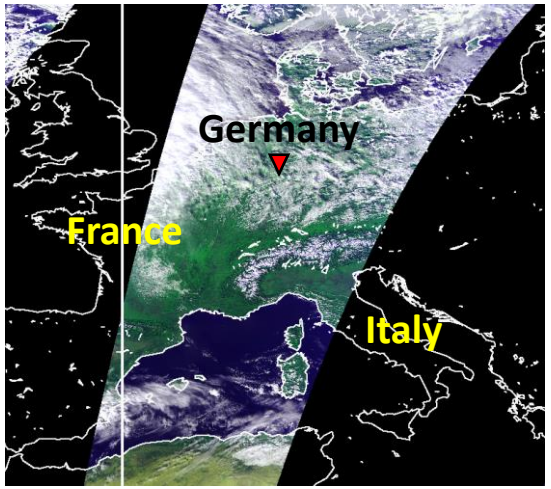
# CAI-2 Overview

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

| | Band1 | Band2 | Band3 | Band4 | Band5 | Band6 | Band7 | Band8 | Band9 | Band10 |
|---|---|---|---|---|---|---|---|---|---|---|
| | AT+20[deg](Forward) | | | | | AT-20[deg](Backward) | | | | |
| | UV | VIS | | | SWIR | UV | VIS | | | SWIR |
| Central Wavelength (μm) | **0.339** | 0.441 | 0.672 | 0.865 | 1.63 | **0.377** | 0.546 | 0.672 | 0.865 | 1.63 |
| Bandwidth(μm) | 0.013 | 0.012 | 0.013 | 0.011 | 0.073 | 0.012 | 0.013 | 0.013 | 0.011 | 0.073 |
| Spatial Resolution(m) | 0.46 | | | | 0.92 | 0.46 | | | | 0.92 |
| Swath | 920(km) / 1.29(rad) / 74(deg) | | | | | | | | | |

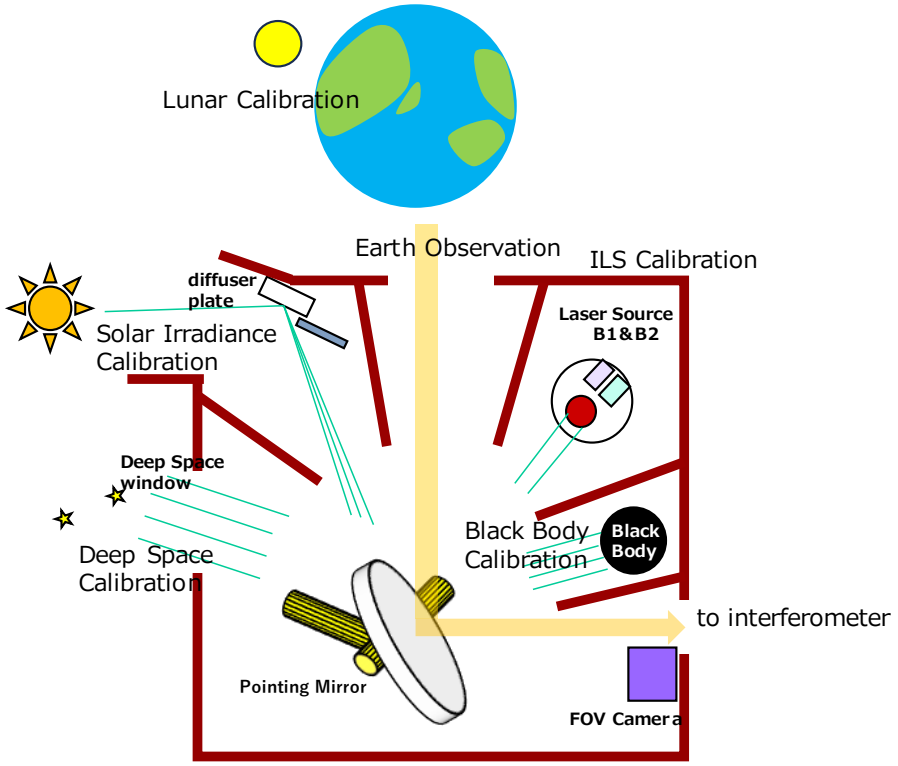



- CAI-2 is the Imager, has 10 bands(UV~SWIR) shown as upper table.
- **It has an advantage of UV bands (340 and 380 nm) for aerosol retrieval.**
- CAI-2 observes both Forward and Backward (5 bands each) at the same time shown as upper right figure.
- The spatial resolution of Band05 and Band10 are twice that of the other bands.
- CAI-2 has about 2000 pixels linear Si-CCD array (※Band5/10 are 1000 pixels linear InGaAs array).




CAI-2 image around Darmstadt (Nov. 08, 2023)

# FTS-2/CAI-2 Calibration System Overview




**FTS-2 Calibration System**

## ■ FTS-2

- FTS-2 has calibration system shown as left figure.
- Radiometric calibration strategy :

| | Calibration | Frequency |
|---|---|---|
| Relative | Lunar calibration | every month |
| | Solar Irradiance Calibration | every path (※suspended since Jan.2021 due to shutter trouble) |
| Absolute | Vicarious Calibration evaluated at the Railroad Valley, USA | every year |

## ■ CAI-2

- CAI-2 doesn't have on-board calibration instruments.
- Radiometric calibration strategy :

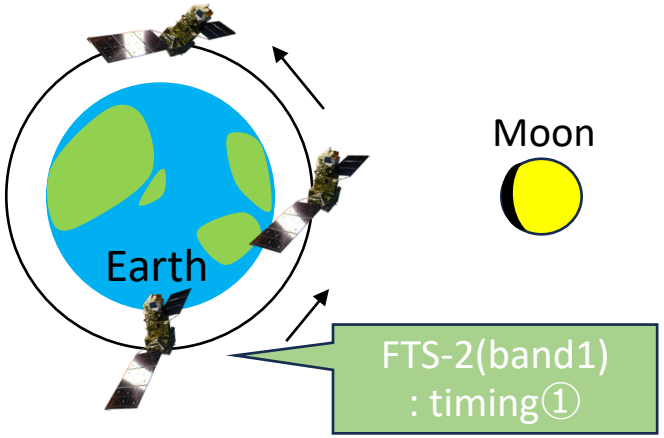
| | Calibration | Frequency |
|---|---|---|
| Relative | Lunar calibration | every month |
| Absolute | Vicarious Calibration evaluated at the Railroad Valley, USA | every year |
| | Vicarious Calibration using other satellite data(ex. VIIRS) | every month |

# 2. FTS-2 evaluation of radiometric degradation

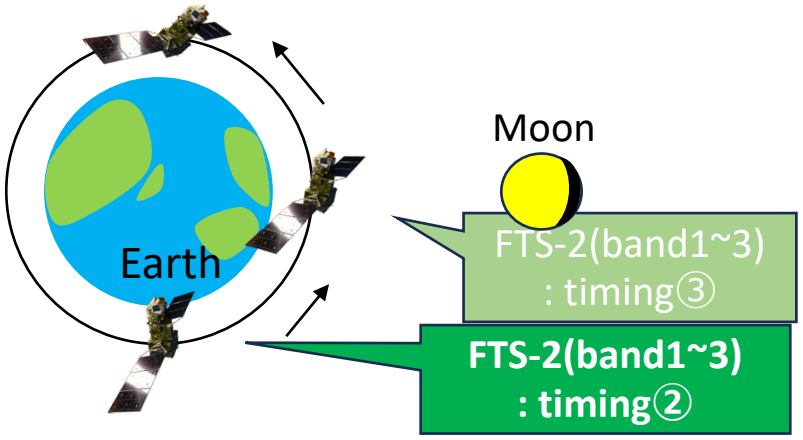
# FTS-2 Lunar Calibration Operation

GOSAT-2 Lunar Calibrations are operated in two days around full moon(**phase angle around ±7-8 [deg]).**

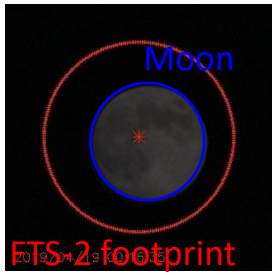
## ■ day1 : Waxing gibbous moon



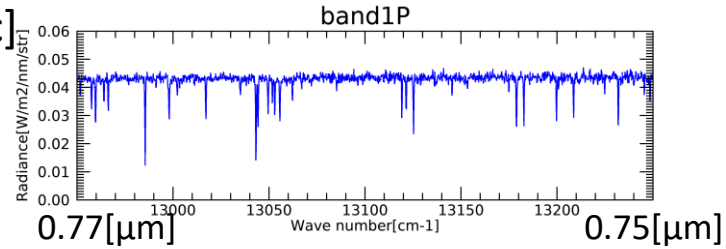

## ■ day2 : Waning gibbous moon




- Keep looking at the moon, integrate for 4 [sec] per sounding and observes 10-30 soundings.
- Used for the evaluation of radiometric degradation.
- FTS-2 modulation efficiency depends on orbital ambient temperature, so, we only used the timing② data.




integrate 4 [sec] each sounding




**The advantage of FTS-2 lunar calibration data**

- High-frequency observation (almost every month)
- Long-term dataset (over 5 years)
- phase angle around ±7-8[deg], less lunar polarization (Coyne and Pellicori, 1969, Toledano et al., 2023(preprint))

# Flowchart of FTS-2 Lunar Calibration Evaluation

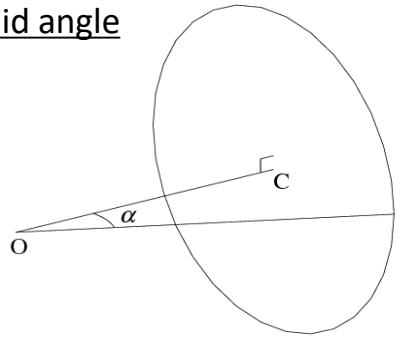
■ **Beam dilution IFOV correction**

・Moon size is smaller than FTS-2 footprint, so observed radiance are diluted and underestimated.

・We corrected this effect using correction coefficient that ratio of solid angle.

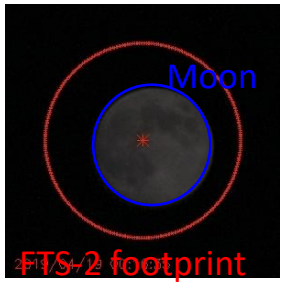
$$Coef. = \omega_{moon} / \omega_{FTS2-IFOV}$$

・Solid angle




$$\omega = 2\pi(1 - cos\alpha)$$

$\omega: Solid\ angle \quad \alpha: Half\ IFOV$




・Lunar Radius =1738[km]

・FTS-2 IFOV [mrad]

| b1P | b1S | b2P | b2S | b3P | b3S |
|---|---|---|---|---|---|
| 15.89 | 15.89 | 15.84 | 15.85 | 15.83 | 15.83 |

FTS-2 L1B Lunar calibration data

Radiance conversion for V220

Beam dilution correction

**GIRO part**

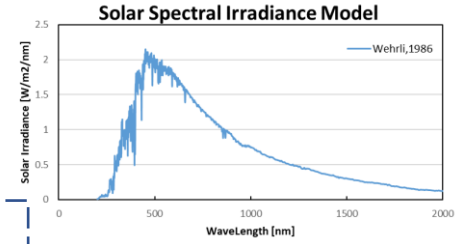
・Observation time
・Satellite position (ECI@J2000)

GIRO

**GIRO Reflectance Spectrum※**

※We only used GIRO Reflectance Spectrum because we want to compare spectral radiance.

Spectral Radiance
・Solar model Wehrli(1986) x Reflectance




Spectral Radiance ∗ FTS-2 Spectral Response Function

※Omitted due to relative evaluation

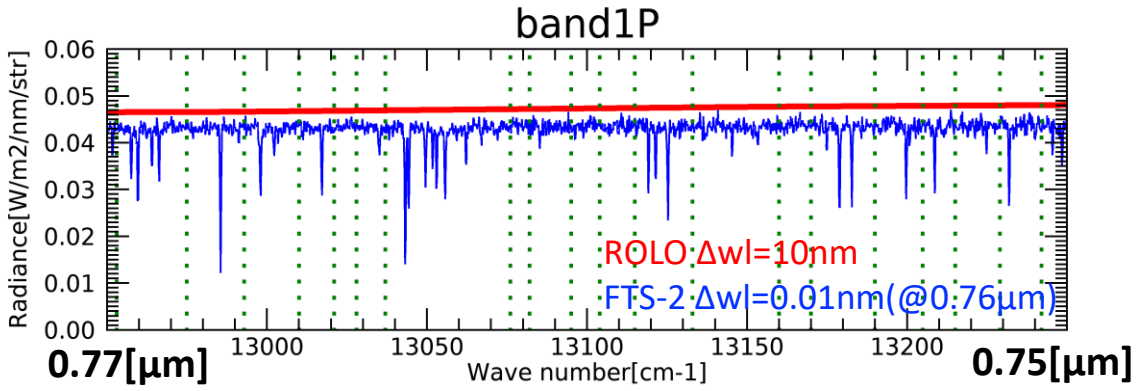
Distance Correction (Sun-Moon)

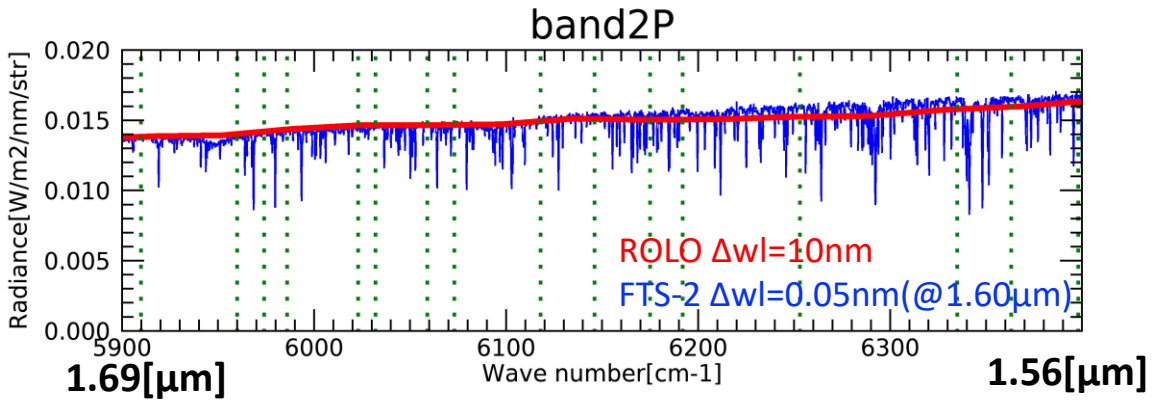
FTS-2/GIRO Radiance Degradation Trend

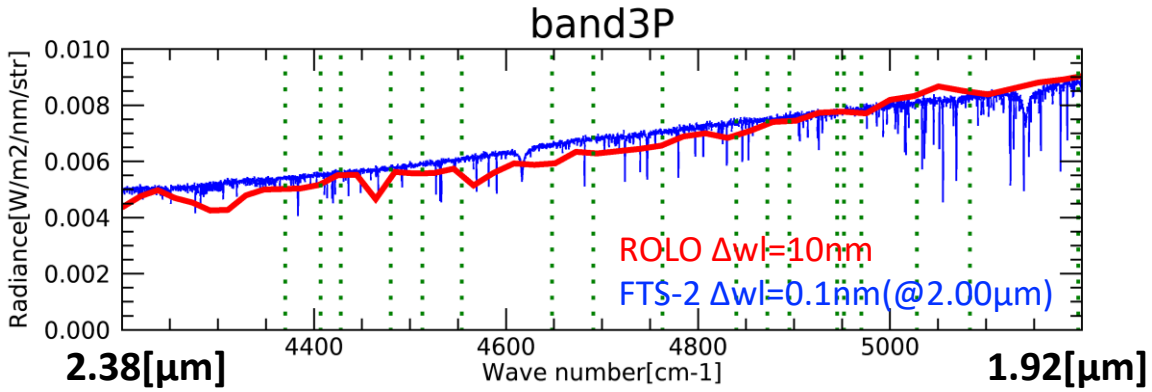
Phase angle correction

I will explain later page.

# Evaluation wave numbers




- Spectral resolution of FTS-2 is quite higher than ROLO Reflectance Spectrum.
- Left images show the difference of spectral resolution.
  - Red line : ROLO Radiance Spectrum
    - converted Reflectance into Radiance
    - spectral resolution remains ROLO spectral reflectance
    - don't convolute FTS-2 SRF
  - Blue line : FTS-2 Radiance Spectrum
- So, we used some wavenumbers (16~20 points) and averaged for evaluation of radiometric degradation.
  - Green dashed line : evaluation wave numbers, avoiding the Fraunhofer lines

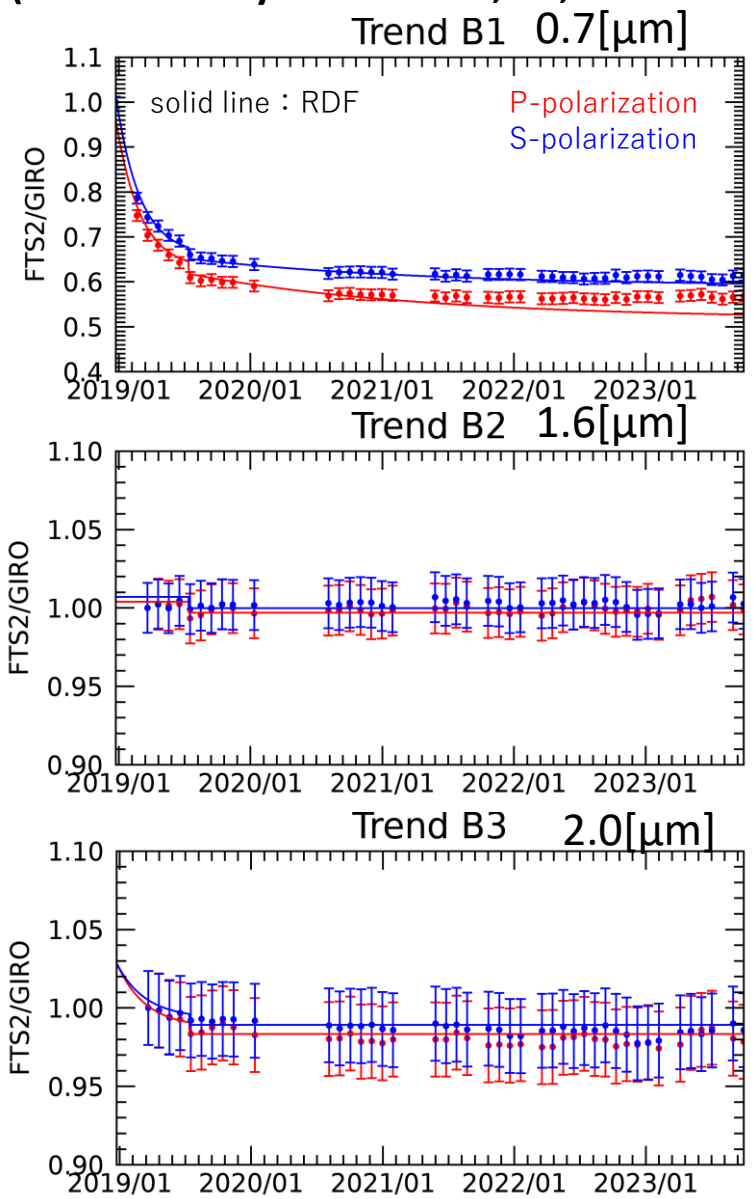
- **We can provide FTS-2 high spectral resolution lunar calibration data.**

# Results of FTS-2 radiometric degradation

- Right images are FTS-2/GIRO ratio time series trend normalized by 1st lunar calibration(B1:Dec2018, B2,3:Mar2019).
- Solid line is Radiometric Degradation Factor(RDF) that currently applied FTS-2 Level 1B.
- **Lunar calibration enables to evaluate relative radiometric trend with high precision. We found that the current RDF especially band1P was overcorrected about 4.2% in Sep2023.**
- We will apply to this result to the next Level 1B version up.

(※around on Jun.2019, FTS-2 instrument temperature changed, so radiance also changed and RDF has step.)

**FTS-2/GIRO ratio time series trend**
**(normalized by B1:Dec2018, B2,3:Mar2019)**




## ■ Degradation of FTS-2 as of Sep. 2023

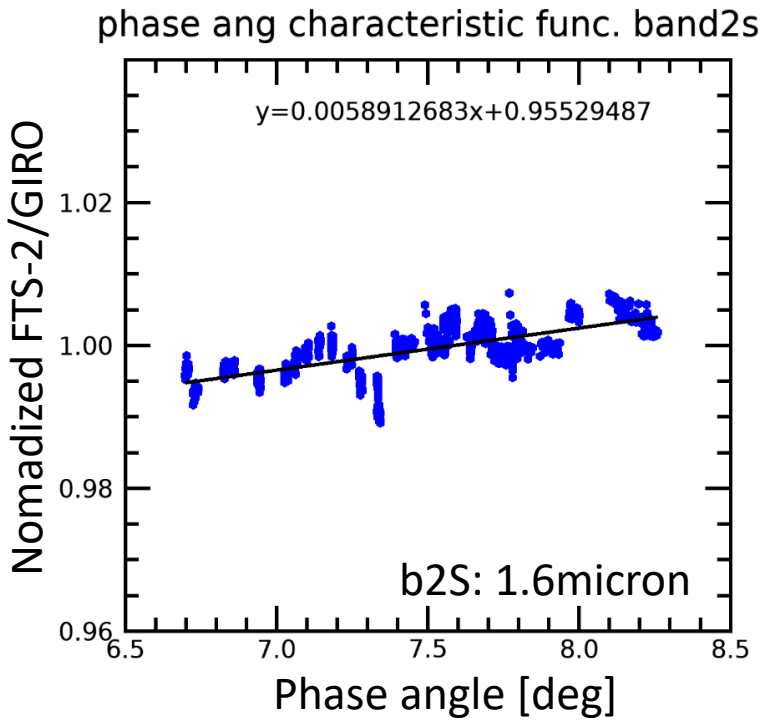
| Band | Band1P | Band1S | Band2P | Band2S | Band3P | Band3S |
|---|---|---|---|---|---|---|
| 1 - FTS2/GIRO [%] | 43.1% | 38.4% | 0.1% | -0.3% | 2.2% | 1.4% |

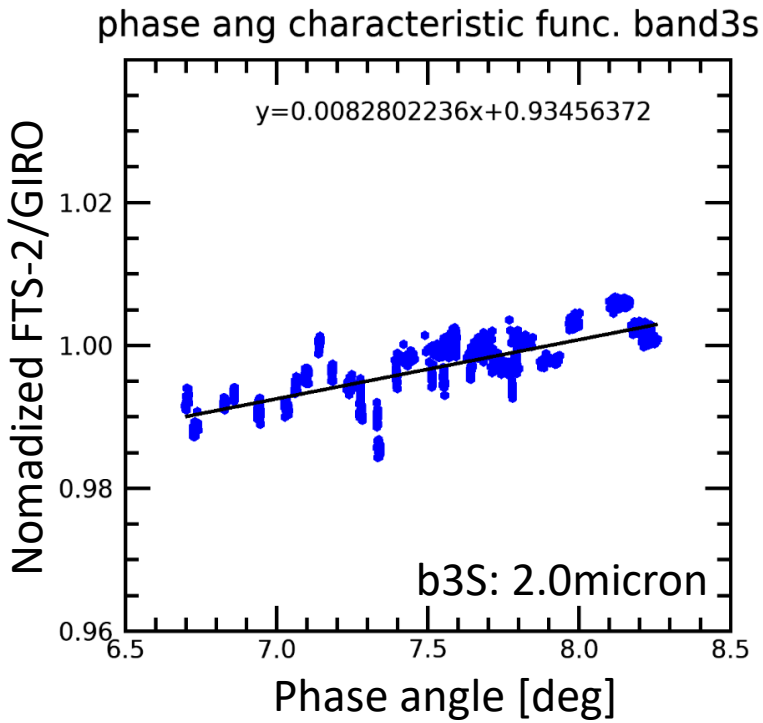
where, Band1P/S compared to Dec2018,
Band2P/S and Band3P/S compared to Mar2019

# FTS-2 phase angle correction

GIRO reflectance around 7-8[deg] phase angle has 1-2 % uncertainty in SWIR region, which is shown by both GOSAT-2 and GCOM-C.

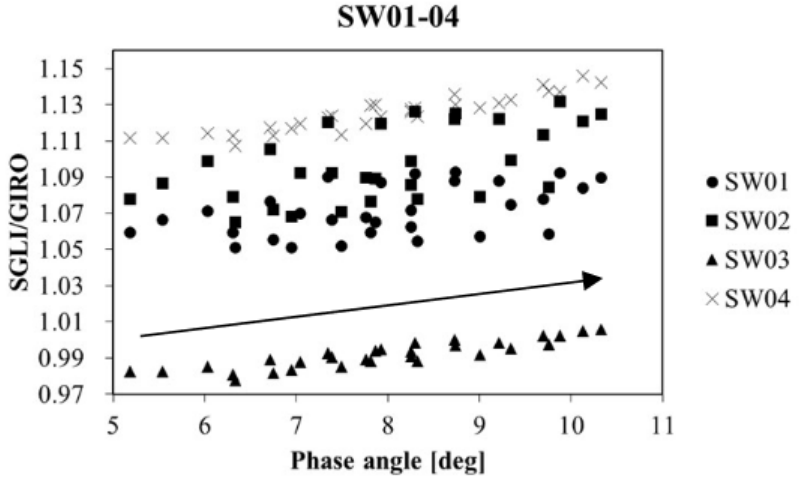
## GOSAT-2/FTS-2




## GCOM-C/SGLI

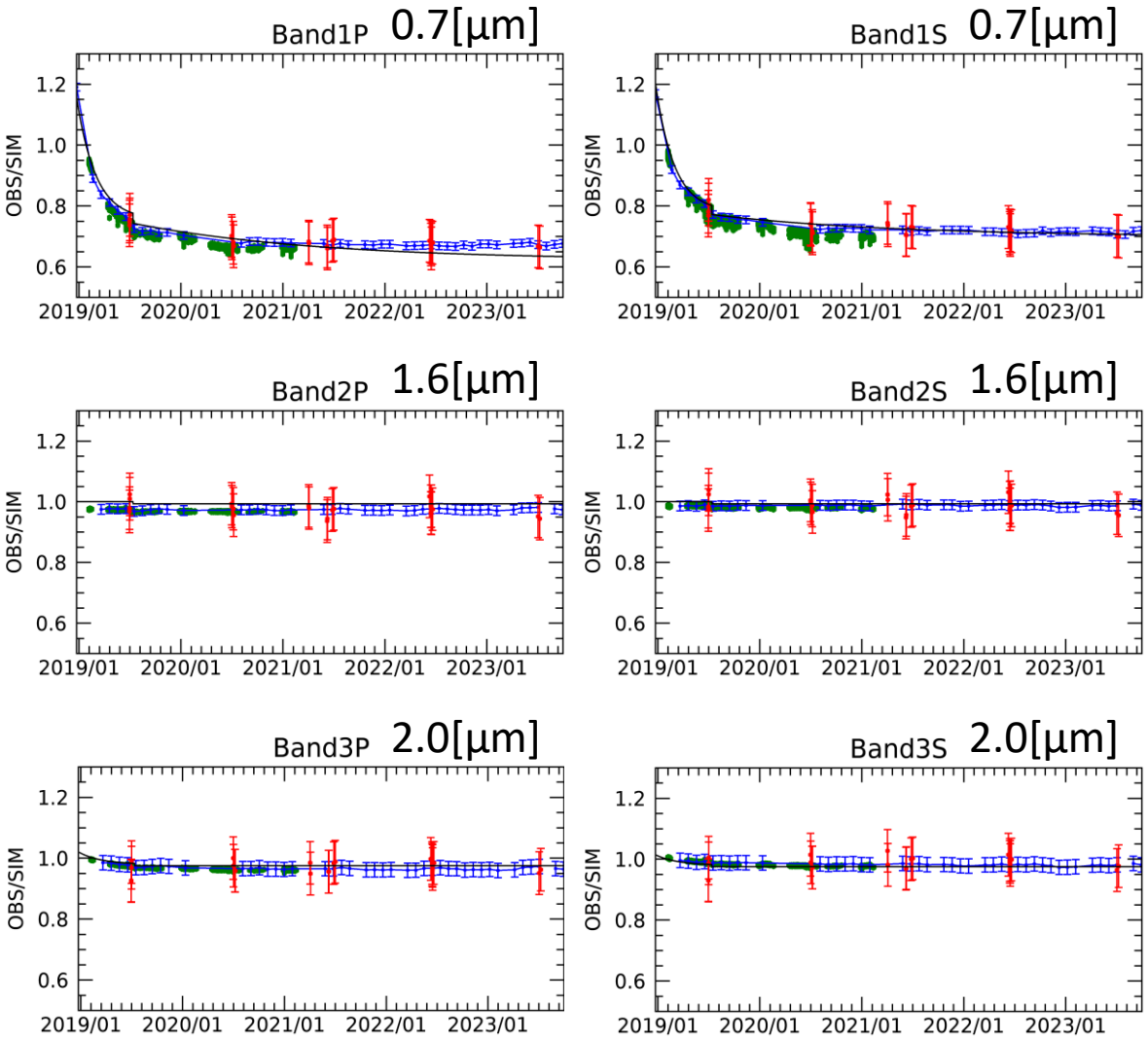
| CH | SW1 | SW2 | SW3 | SW4 |
|---|---|---|---|---|
| WL [nm] | 1050 | 1380 | 1630 | 2210 |




※Reported by Taichiro Hashiguchi at the 3rd Lunar Calibration Workshop(17a)

- The latest years data are plotted during stable response and less degradation.
- It shows no time dependency but phase angle dependency.
- We corrected this effect by estimating phase angle characteristic functions from the GOSAT-2 data.

# Result comparison between the calibration methods




- Compared with other results of radiometric calibrations.
  - ① Vicarious calibration results evaluated at the Railroad Valley, USA every year
  - ② Solar Irradiance Calibration (on-board) results that evaluated every path. (※ Unfortunately, it had suspended since Jan.2021 due to shutter trouble)
  - ③ Lunar Calibration results that evaluated every month.
- **Degradation trends are all consistent**. (※Absolute values of ②, ③ adjusted to ①.)

## ■ The absolute radiance difference [%]

We use lunar calibration data only for degradation evaluation, but as a reference, estimated the absolute radiance difference between GIRO and FTS-2 data corrected by ①Vical.

(Ex. Band1P: GIRO is 20.7% lower than corrected FTS-2 data)

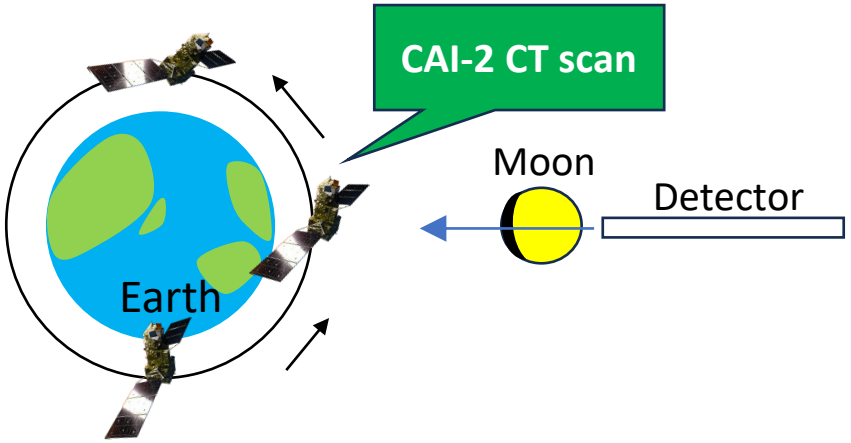
| | P polarization | S polarization |
|---|---|---|
| band01(0.7μm) | -20.7% | -23.0% |
| band02(1.6μm) | -3.7% | -6.2% |
| band03(2.0μm) | -6.2% | -7.5% |

# 3. CAI-2 evaluation of radiometric degradation

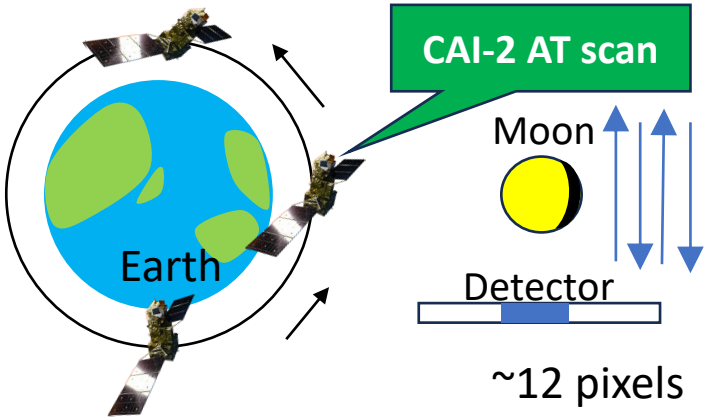
# CAI-2 Lunar Calibration Operation

GOSAT-2 Lunar Calibration are operated in two days around full moon(**phase angle around ±7-8 [deg]**)

## ■ day1 : Waxing gibbous moon

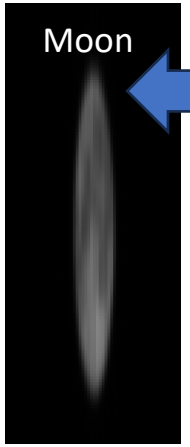



## ■ day2 : Waning gibbous moon



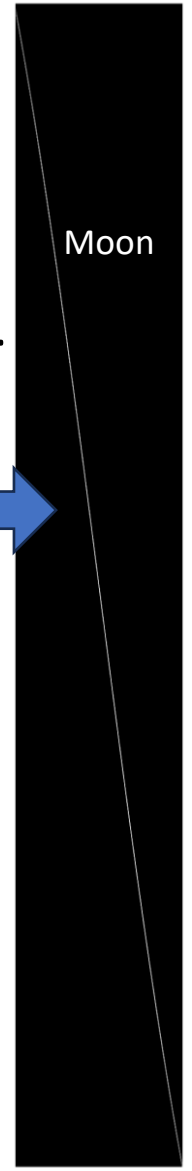

~12 pixels

## ■ CAI-2 Lunar Calibration




● <u>Along Track(AT) Scan in day2 path</u>
- Sweep in the AT direction 4 times
- Used for the evaluation of radiometric degradation.

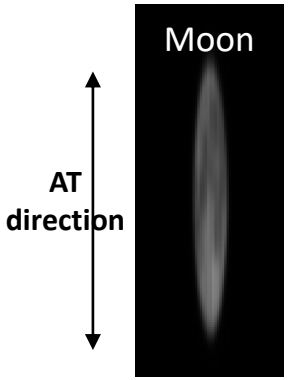
● <u>Cross Track(CT) Scan in day1 path</u>
- Sweep in the CT direction only once.
- Used for the evaluation of pixel-to-pixel sensitivity difference.




**The advantage of CAI-2 lunar calibration data**
- High-frequency observation (almost every month)
- Long-term dataset (over 5 years)

# CAI-2 Radiometric Degradation Evaluation

## ■ Method of radiometric degradation evaluation

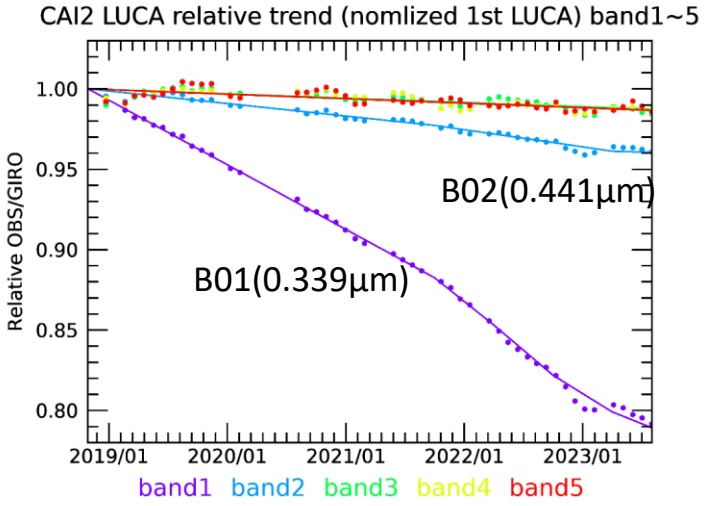



- Compared GIRO integrated irradiance $I_k^{GIRO}$ and CAI-2 integrated irradiance $I_k^{CAI-2}$
- Since the moon is observed with oversampling in the AT direction, we corrected this effect by estimating the oversampling factor $f_{OS}$.
  (ex. 1 sweep : pitch rate ~0.08[deg/sec], pitch rate stdev ~8.01E-5)

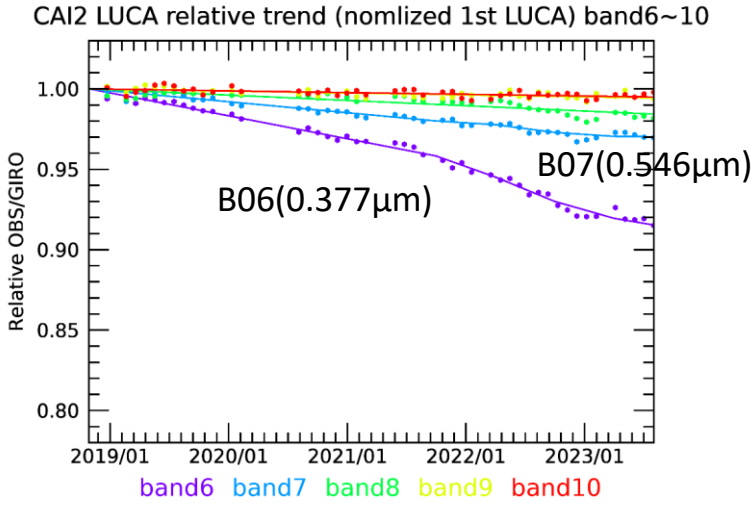
$$\text{Relative OBS/GIRO} = \left(\frac{I_k^{CAI-2}}{f_{os}}\right) / I_k^{GIRO}$$

## ■ Time Series Trend of Lunar Calibration

*B01-B05(Forward)*



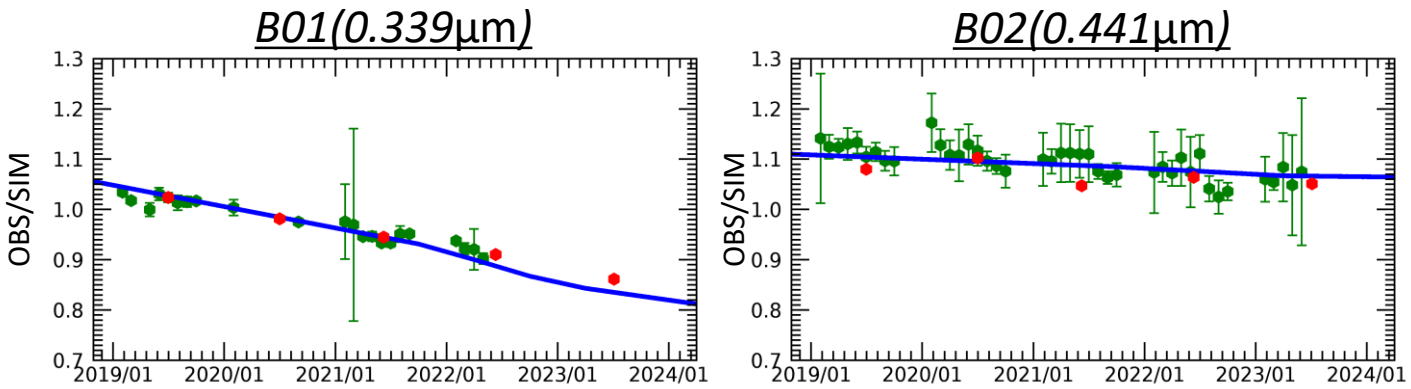

*B06-B10(Backward)*




- Lower left images show the results of evaluation of radiometric degradation.
- It is relatively radiometric degradation from 1st lunar calibration(Dec.2018).
- Wavelength are the shorter, the degradation are the larger, both Forward and Backward.

# Result comparison between the calibration methods

## ■ Comparison with other results (two examples)




- Compared between other radiometric calibration results.
  - ① Vicarious calibration results that evaluated at the Railroad Valley, USA
  - ② Vicarious calibration results using other satellite data(ex. VIIRS)
  - ③ Degradation curve estimated from Lunar Calibration results
- As the left images show, all of degradation trends are consistent. (※absolute value of ③ adjusted to ①,②.)

## ■ The absolute value difference[%]

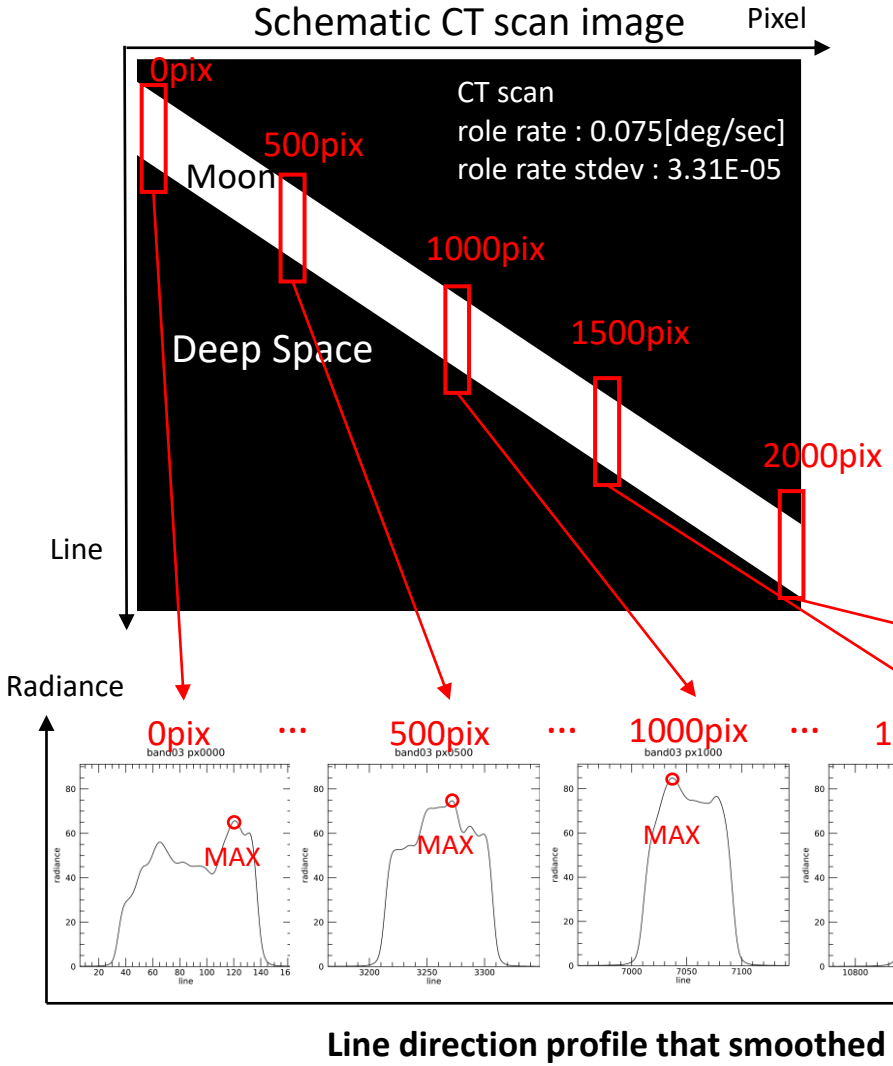
We use lunar calibration data only for degradation evaluation, but as a reference, estimated the absolute radiance difference between GIRO and corrected CAI-2 data by ① and ②.
(Ex. Band1: GIRO is 13.1% lower than CAI-2 data corrected by ① and ②)

| B01 0.339μm | B02 0.441μm | B03 0.672μm | B04 0.865μm | B05 1.63μm | B06 0.377μm | B07 0.546μm | B08 0.672μm | B09 0.865μm | B10 1.63μm |
|---|---|---|---|---|---|---|---|---|---|
| -13.1% | -5.2% | -9.3% | -9.7% | +6.3% | -8.6% | -5.2% | -14.0% | -10.1% | +6.2% |

# 4. CAI-2 evaluation of pixel-to-pixel sensitivity difference

# Method of evaluation

CAI-2 some bands have sensitivity difference between even and odd pixels, so we evaluated that pixel-to-pixel sensitivity difference using the Lunar Calibration CT Scan data.

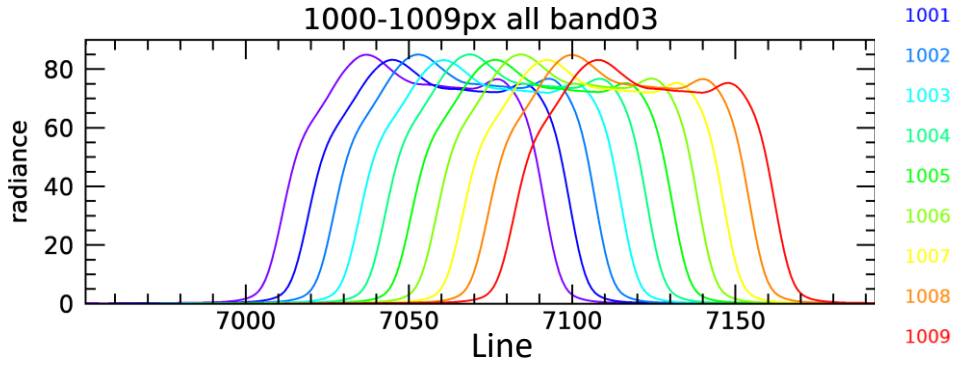



**Line direction profile that smoothed 5[lines]**

- CAI-2 Lunar Calibration CT scan sweeps all over the pixels.
- **We evaluated the difference using the fact that CT scan data are oversampled in the pixel direction, shown as lower right figure.**
- We got the Maximum values of line direction profile for each pixel, shown as lower left figure.
- The pixel-to-pixel sensitivity difference can be estimated from the ratio of...

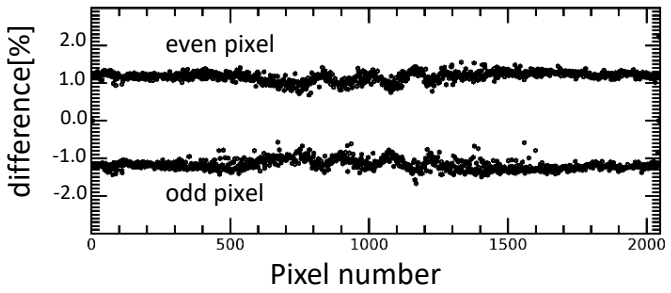
$$\frac{\textit{the maximum value for each pixel}}{\textit{the average of the maximum values of surrounding some pixels}}$$

☐ Line direction profile around 1000[pix]

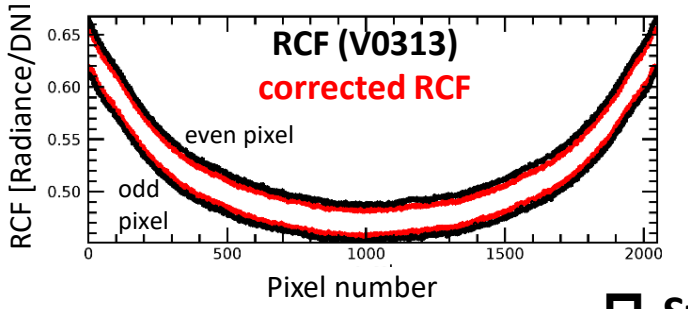


# Corrected CAI-2 Level 1B image

☐ Estimated pixel-to-pixel sensitivity difference(Band3)

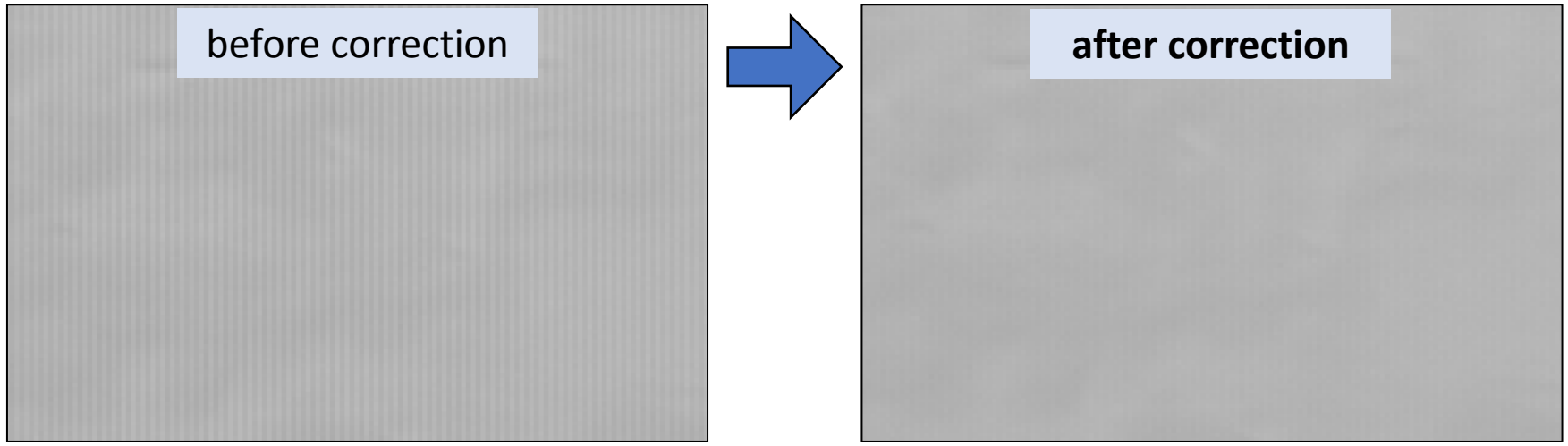



☐ corrected RCF (Band3)




- We confirmed the reproducibility of this sensitivity difference using three times lunar calibrations all over the pixels.
- The Radiance Conversion Factor(RCF) was corrected by using the estimated difference.
- We applied corrected RCF to make CAI-2 Level 1B, **the stripe image between even and odd pixels could be decreased shown as the lower figure.**
- **We were able to evaluate the pixel-to-pixel sensitivity difference using only lunar calibration CT scan data in orbit.**

☐ **Stripe on the antarctica ice of CAI-2 Level1B image(Band3)**



# Summary & Future plan

## Summary

### FTS-2 evaluation of radiometric degradation

- FTS-2 has high spectral resolution and two linear orthogonal polarization P and S.
- We use lunar calibration data for radiometric degradation. The evaluated relative radiometric trend was high precision, and it was consistent with the other method results.
- FTS-2/GIRO ratio has dependency on the phase angle around 7[deg] in SWIR region, and this trend was also shown in the GCOM-C/SGLI result.

### CAI-2 evaluation of radiometric degradation

- We use lunar calibration data for radiometric degradation. The evaluated relative radiometric trend was high precision, and it was consistent with the other method results.

### CAI-2 evaluation of pixel-to-pixel sensitivity difference

- We were able to evaluate the pixel-to-pixel sensitivity difference using only lunar calibration CT scan data in orbit.

## Future plan

- We will update radiometric parameter of FTS-2 and CAI-2 using the result of lunar calibration.
- The 3rd generation of the GOSAT series, GOSAT-GW/TANSO-3 will be launched in JFY2024.

# Discussion point

- **Lunar Model**
  - We hope to SWIR phase angle dependency (around ±7-8deg) will correct more accurately and release more high spectral resolution model data. We look forward to LSICS.
  - We can provide FTS-2 high spectral resolution lunar data.
- **Lunar Model for absolute calculation**
  - As a reference information, we estimated absolute radiance difference between GIRO and corrected FTS-2 and CAI-2 data. ※GOSAT-2 absolute value evaluation result has about 7% uncertainty, so this is just reference information.

**■ FTS-2**

Solar Irradiance model

- GIRO : Wehrli
- corrected FTS-2 : TSIS-HSRS

| | P polarization | S polarization |
|---|---|---|
| band01(0.7μm) | -20.7% | -23.0% |
| band02(1.6μm) | -3.7% | -6.2% |
| band03(2.0μm) | -6.2% | -7.5% |

**■ CAI-2**

Solar Irradiance model

- GIRO : Wehrli
- corrected CAI-2 : 2000 ASTM

| B01 0.339μm | B02 0.441μm | B03 0.672μm | B04 0.865μm | B05 1.63μm | B06 0.377μm | B07 0.546μm | B08 0.672μm | B09 0.865μm | B10 1.63μm |
|---|---|---|---|---|---|---|---|---|---|
| -13.1% | -5.2% | -9.3% | -9.7% | +6.3% | -8.6% | -5.2% | -14.0% | -10.1% | +6.2% |

**We will provide GOSAT-2 Lunar Data**

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