B10

静止衛星の測光・分光（同時）観測

Simultaneous Photometry and Spectroscopy of GEO Satellites

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未知のスペースデブリの特性を知る手法を確立するためには、まず運用中の静止衛星を対象とした光学観測を行い、ライトカーブやスペクトルについての基礎的データを収集することが有効である。ライトカーブから衛星の形状や運動状態が推測でき、スペクトルは衛星の材質を反映している。 我々は静止衛星を対象に、美星スペースガードセンターの 1.0m 望遠鏡と 0.5m 望遠鏡で測光観測を、隣接する美星天文台の 101cm 望遠鏡で低分散分光観測を同時に行った。観測対象としたのは静止軌道上の東経 140° 付近にある、気象衛星ひまわり 8 号 (国際標識番号: 2014-060A)、ひまわり 9 号 (同 2016-064A)、オーストラリアの通信衛星 SKY MUSTER(同 2015-054A)の 3 機である。 本講演では、各衛星のライトカーブやスペクトルの特徴とその時間変化について報告する。また 9 月末にみちびき 3 号(QZS-3, 2017-048A) の観測も予定しており、良質なデータが取得できれば併せて報告する予定である。

The basic study of optical light curves and spectra of active satellites in geostationary Earth orbit (GEO) is quite useful to construct some methods to understand characteristics of unresolved space debris. Analysis of the light curves helps to estimate the shape and motion of each object and spectral measurements enable to discuss surface materials. We have made simultaneous observations at adjacent observatories. Bisei Spaceguard Center (BSGC) has 1.0-m/0.5-m telescopes to acquire light curves and the 101cm telescope with a low-resolution spectrograph has been used at Bisei Astronomical Observatory (BAO) located 100m from BSGC. The target objects are three GEO satellites located at around 140o E.: Japanese meteorological satellites HIMAWARI-8/9 (International Designator 2014-060A/2016-064A) and an Australian communication satellite SKY MUSTER (2015-054A). In this paper, we discuss photometric and spectroscopic characteristics and their temporal changes. Additionally, observations of another satellite QZS-3 (2017-048A) are scheduled in late September and it is possible to present supplemental data.

Contents

1.Introduction

Aims:

basic study of optical light curves and spectra of active satellites in geostationary Earth orbit (GEO) in order to construct some methods to understand characteristics of unresolved space debris

Methods:

- Photometry
  light curves→ information of the shape and the motion
- Spectroscopy
  spectra → information of surface materials

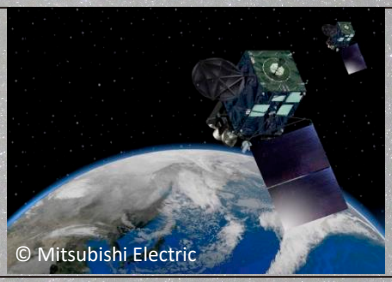
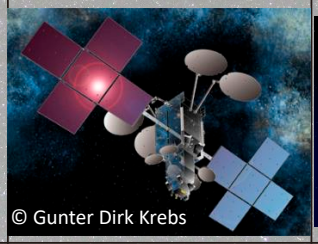
Target Objects

Quasi-Zenith Satellite

SAT NAME	HIMAWARI-8	HIMAWARI-9	SKY MUSTER	QZS-3 (MICHIBIKI-3)
Int'l Designator (COSPAR ID)	**2014-060A**	**2016-064A**	**2015-054A**	**2017-048A**
NORAD ID	40267	41836	40940	42917
Launch	2014-10-07	2016-11-02	2015-09-30	2017-08-19
Orbit	GEO (140.65° E)	GEO (140.75° E)	GEO (140° E)	GEO (127° E)
Operator	Japan Meteorological Agency (JPN)		NBN Co Limited (AUS)	Cabinet Office (JPN)
Mission Type	Weather		Communication	Navigation
Manufacturer	Mitsubishi Electric		Space Systems/Loral	Mitsubishi Electric
Bus	DS2000		SSL 1300	DS2000

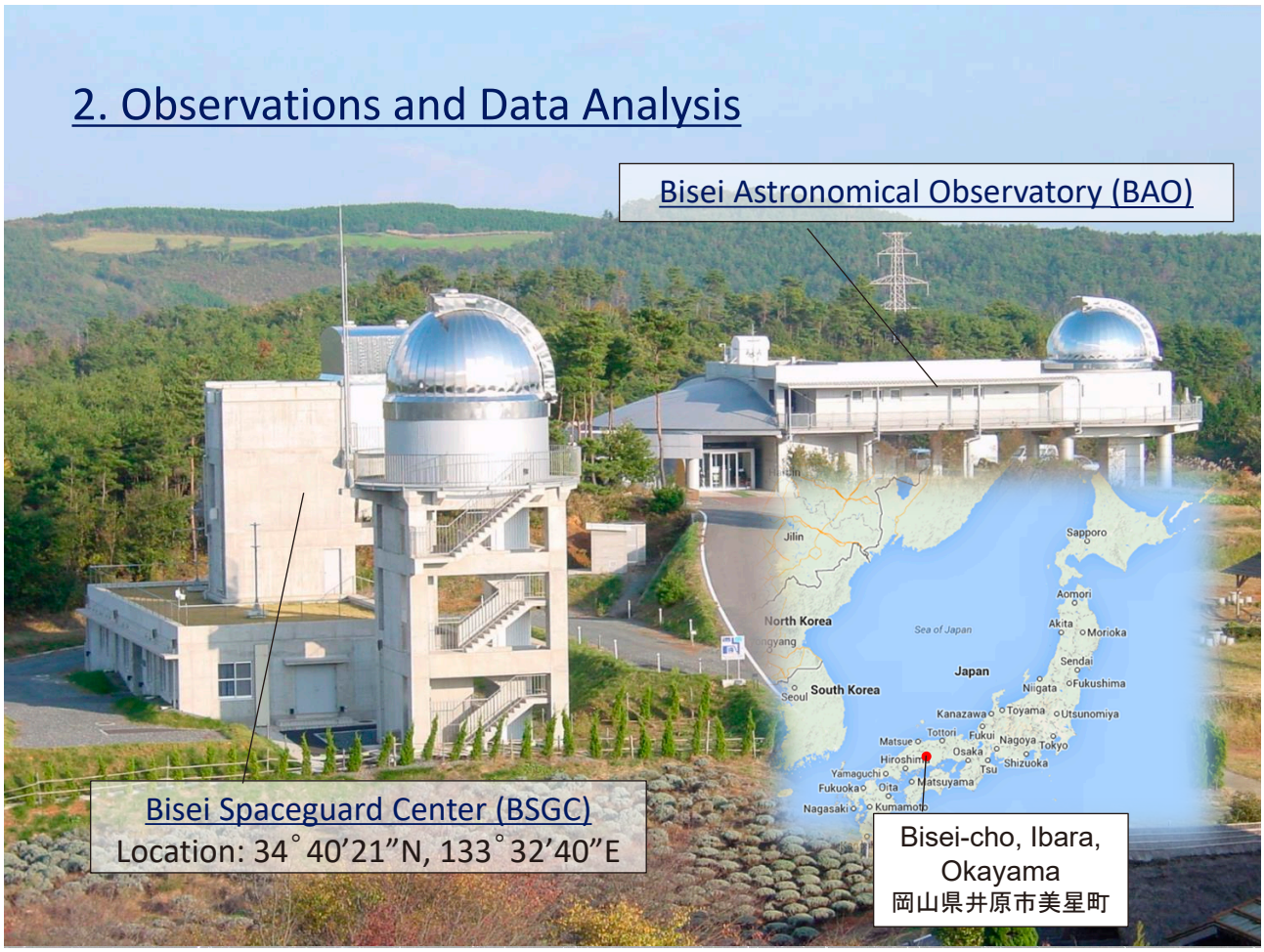
Target Objects

Quasi-Zenith Satellite

SAT NAME	HIMAWARI-8	HIMAWARI-9	SKY MUSTER	QZS-3 (MICHIBIKI-3)
Int'l Designator (COSPAR ID)	2014-060A	2016-064A	2015-054A	2017-048A
Dimensions (in-orbit) (stowed)	5.1m×8.0m×5.3m 2.2m×2.1m×2.9m		12m × 26m × 9m 3m × 3.5m × 8.5m	7.1m×19.0m×5.4m ?
Launch mass Dry mass	3,450kg 1,300kg		6,440 kg ?	4.3 t 1.7 t
Power generation (End-of-Life)	2.2kW		16.4kW	6kW
				

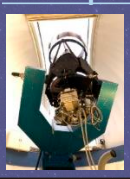
ref: Meteorological Satellite Center (2018), Takahara, T. et al (2014) & Cabinet Office (2019)
https://spaceflight101.com/ariane-5-va231/sky-muster-ii/

2. Observations and Data Analysis



Instrument Specifications

ref: https://www.bao.city.ibara.okayama.jp/

Site	Bisei Spaceguard Center (BSGC)  		Bisei Astronomical Observatory (BAO) 
Observation Type	**Photometry**		**Spectroscopy**
Telescope	**1.0-m Reflector**	**0.5-m Reflector**	**101-cm Reflector**
Focal Ratio Optical Configuration Mounting	F/3.0 Cassegrain Equatorial, Open fork	F/2.0 Cassegrain Equatorial, Open fork	F/2.8 (composite F/12) Folded Cassegrain South Equatorial, Open fork
CCD Camera	Special order	Apogee Alta U42 (partly SBIG ST-10)	ANDOR DU-440BV
Chip Array Size (pixels) Pixel Size (μm) Pixel Scale	*2k-4k* back-illuminated, fully-depleted CCDs x 4 2048 x 1104 /CCD --- 2.1”/pixel with binning	EV2 CCD42-40 2048 x 2048 13.5 x 13.5 2.93”/pix	 2048 x 512 13.5 x 13.5 ---
Others	• Filter: W(4900-9100 Å) • Field of View(R.A.x decl): 72’ x 148’ • Limiting magnitude: 18.7 (2 min exposure)	• Filter: W(4900-9100 Å) • Field of View(R.A.x decl): 100’ x 100’ • Limiting magnitude: 17 (2 min exposure)	• Spectrograph (Low-dispersion) - Gratings: 300 lines/mm (R~1500@6500 Å) - Dispersion: 162 Å /mm - Wavelength: 3600-8000 Å - Slit Length: 25mm (7’) - Slit Width: 120μm (2”)

Observation Schedule (Photometry & Spectroscopy)

Date	Weather	BSGC (Photometry)		BAO (Spectroscopy)	
		Time (UTC)	Number of shots	Time (UTC) including exposures for Flat, Comp & standard stars	Target
2018 19 May	☀	15:47～16:22	159	14:55～16:34	HIMAWARI 8 HIMAWARI 9 Sky Muster
13 Oct	☀💧	N/A		14:51～19:14	HIMAWARI 8 HIMAWARI 9 Sky Muster
2019 16 Feb	☀/☁	17:46～19:10 (intermittently)	98	14:38～18:50	HIMAWARI 8
04 May	☀	11:44～11:56 15:39～18:07	573	15:03～18:42	HIMAWARI 8
2020 18 Jan	☀	N/A		14:17～18:40	Sky Muster
17-18 Apr	☂ ☁	N/A		N/A	QZS-3
27 Sep	☀💧	10:07～14:50	334	14:36～19:34	QZS-3 +α
25 Dec	☀→☁	9:38～19:33	1071	13:25～18:50	QZS-3 +α

characteristics of spectra by satellite

temporal changes of spectra

Observation Schedule (Photometry & Spectroscopy)

Date	Weather	BSGC (Photometry)		BAO (Spectroscopy)	
		Time (UTC)	Number of shots	Time (UTC) including exposures for Flat, Comp & standard stars	Target
2018 19 May	☀	15:47～16:22	159	14:55～16:34	HIMAWARI 8 HIMAWARI 9 Sky Muster
		Simultaneous Observations (by a miracle)			
13 Oct	☀💧	N/A		14:51～19:14	HIMAWARI 8 HIMAWARI 9 Sky Muster
2019 16 Feb	☀/☁	17:46～19:10 (from mid-night)	98	14:38～18:50	HIMAWARI 8
		bad data (for unknown reasons)			
04 May	☀|☁	11:44～11:56 15:39～18:07	573	15:03～18:42	HIMAWARI 8
				bad data (due to clouds)	
2020 18 Jan	☀	N/A		14:17～18:40	Sky Muster
17-18 Apr	☂☁	N/A		N/A	QZS-3
27 Sep	☀💧	10:07～14:50	334	14:36～device failure	QZS-3 +α
25 Dec	☀→☁	9:38～19:33	1071	13:25～18:50	QZS-3 +α
				missing standard star spectrum (due to bad weather)	

Image of the BSGC 1.0m Telescope

designed for survey and tracking of:

- **Space Debris** in orbit
- Minor Planets especially **Near Earth Objects (NEOs)**

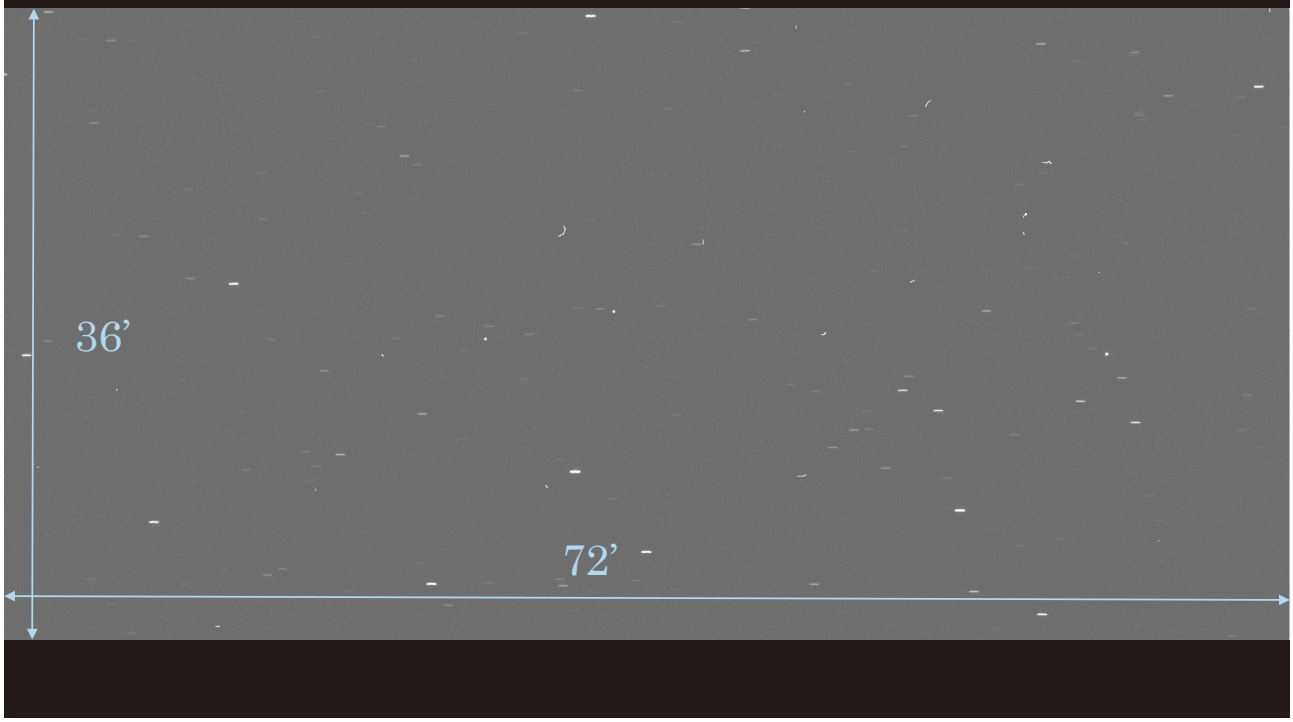


Image of the BSGC 1.0m Telescope

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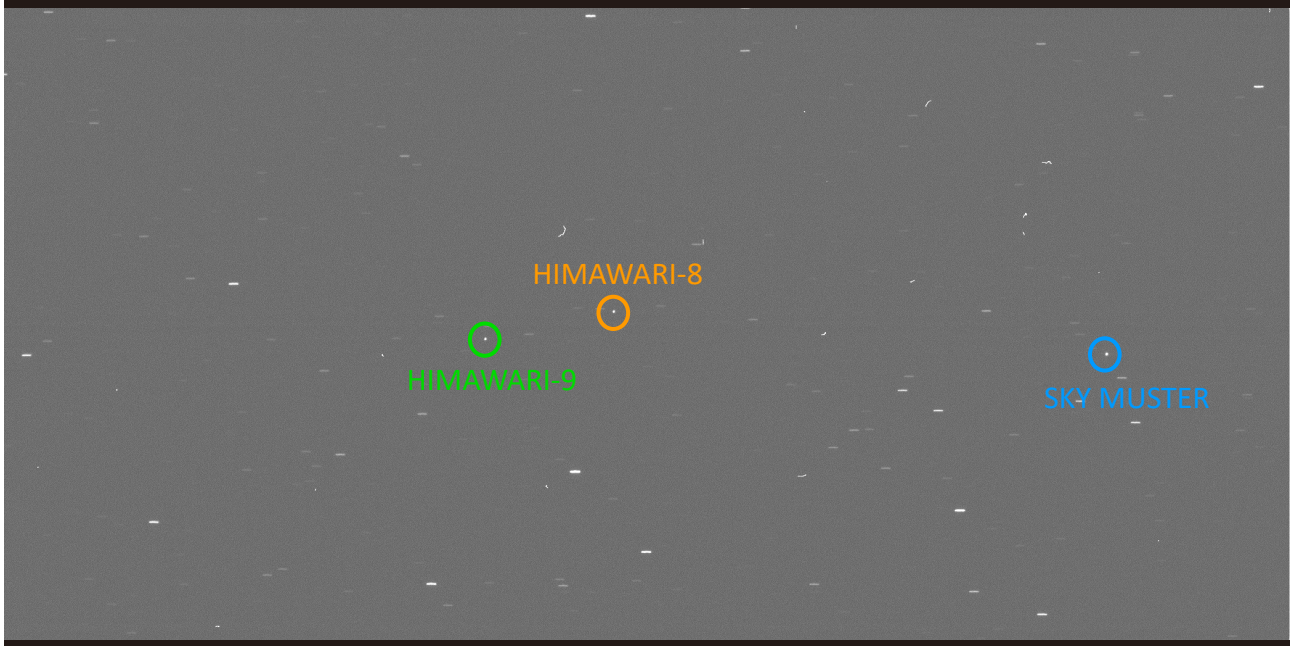
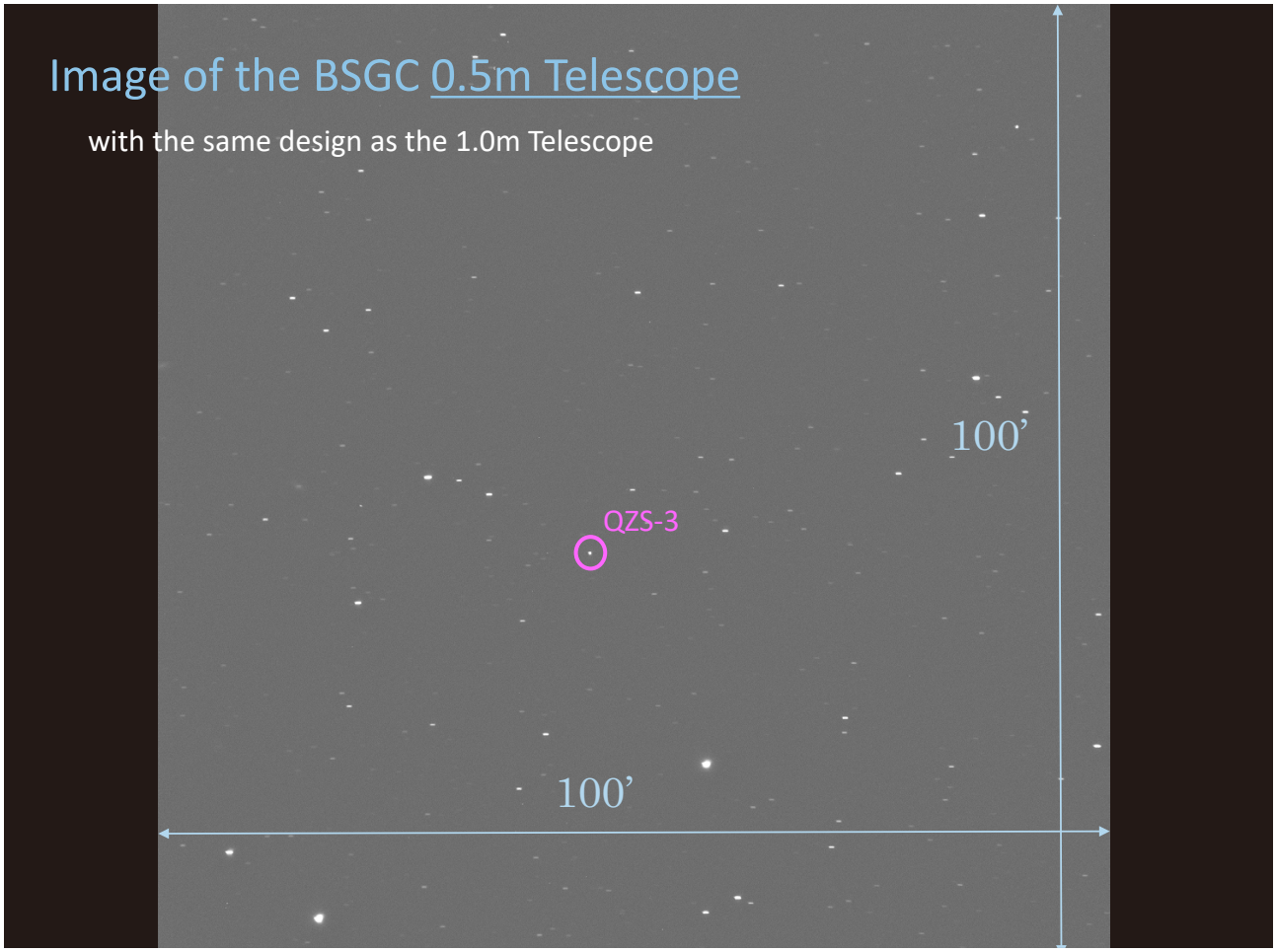
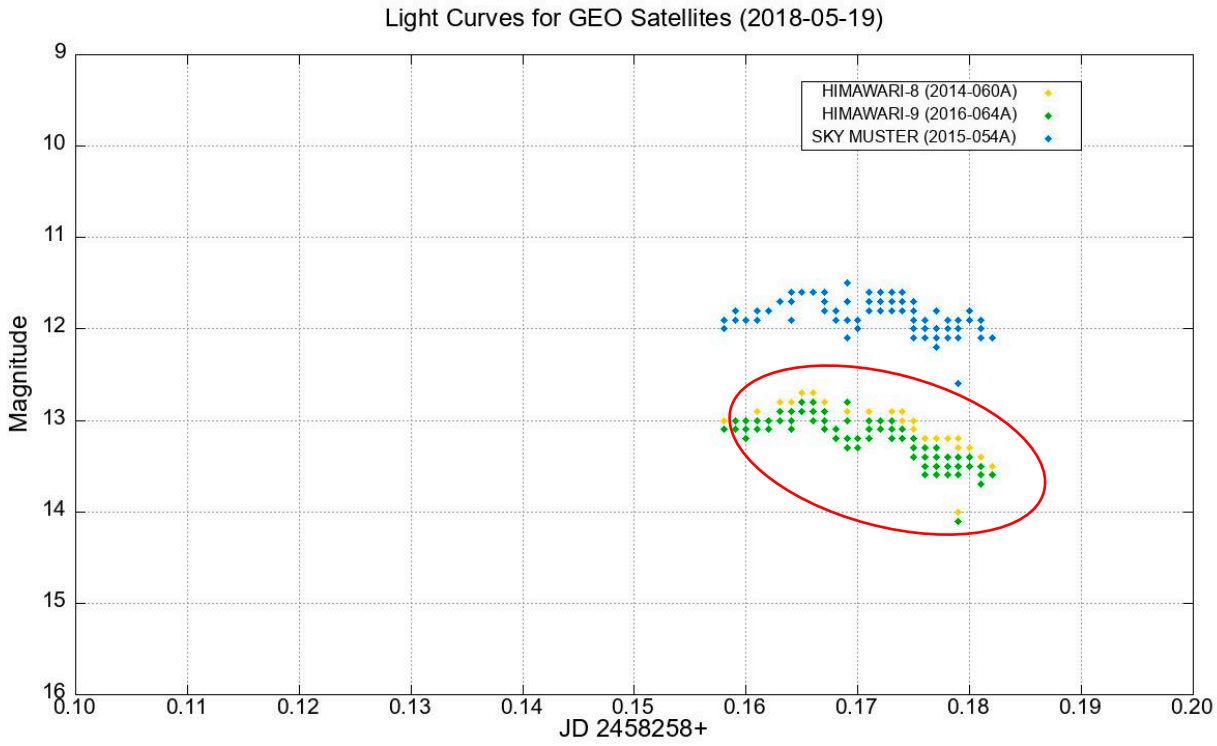


Image of the BSGC 0.5m Telescope

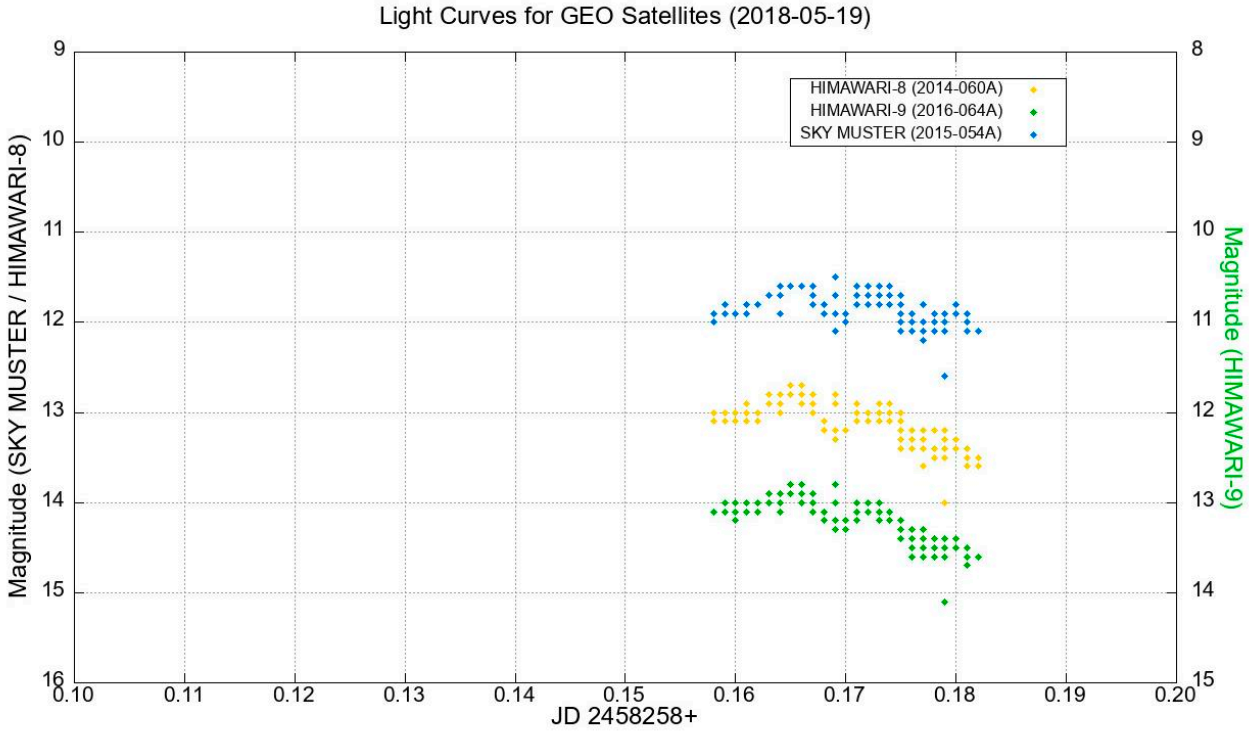
with the same design as the 1.0m Telescope



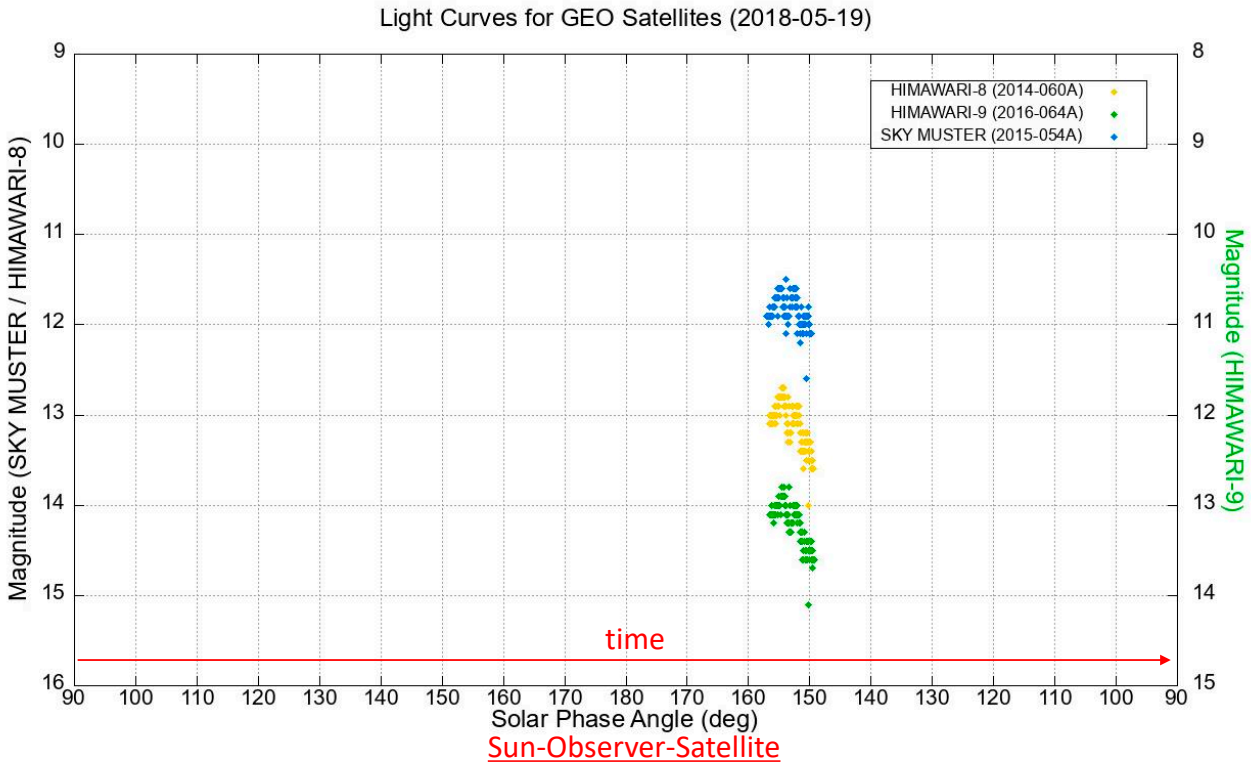
3. Results and Discussion
Light Curves (Time-Magnitude) for HIMAWARI-8/9 & SKY MUSTER



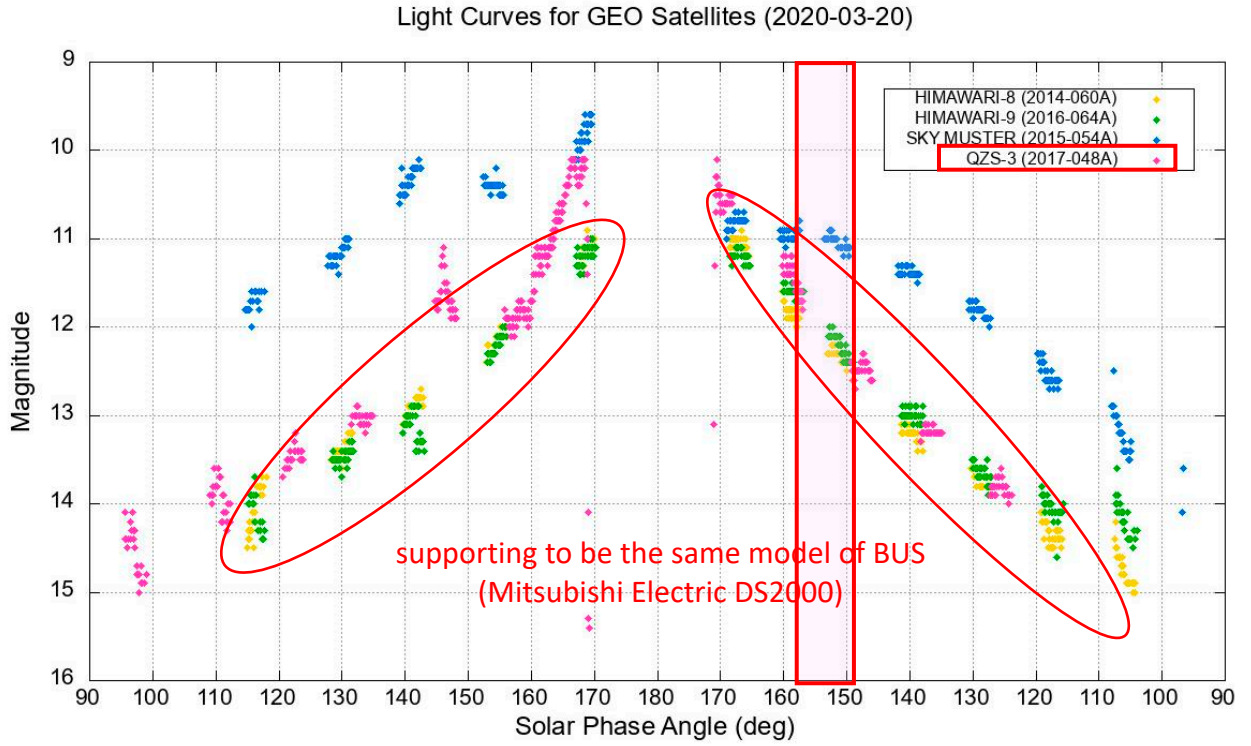
Light Curves (Time-Magnitude) for HIMAWARI-8/9 & SKY MUSTER



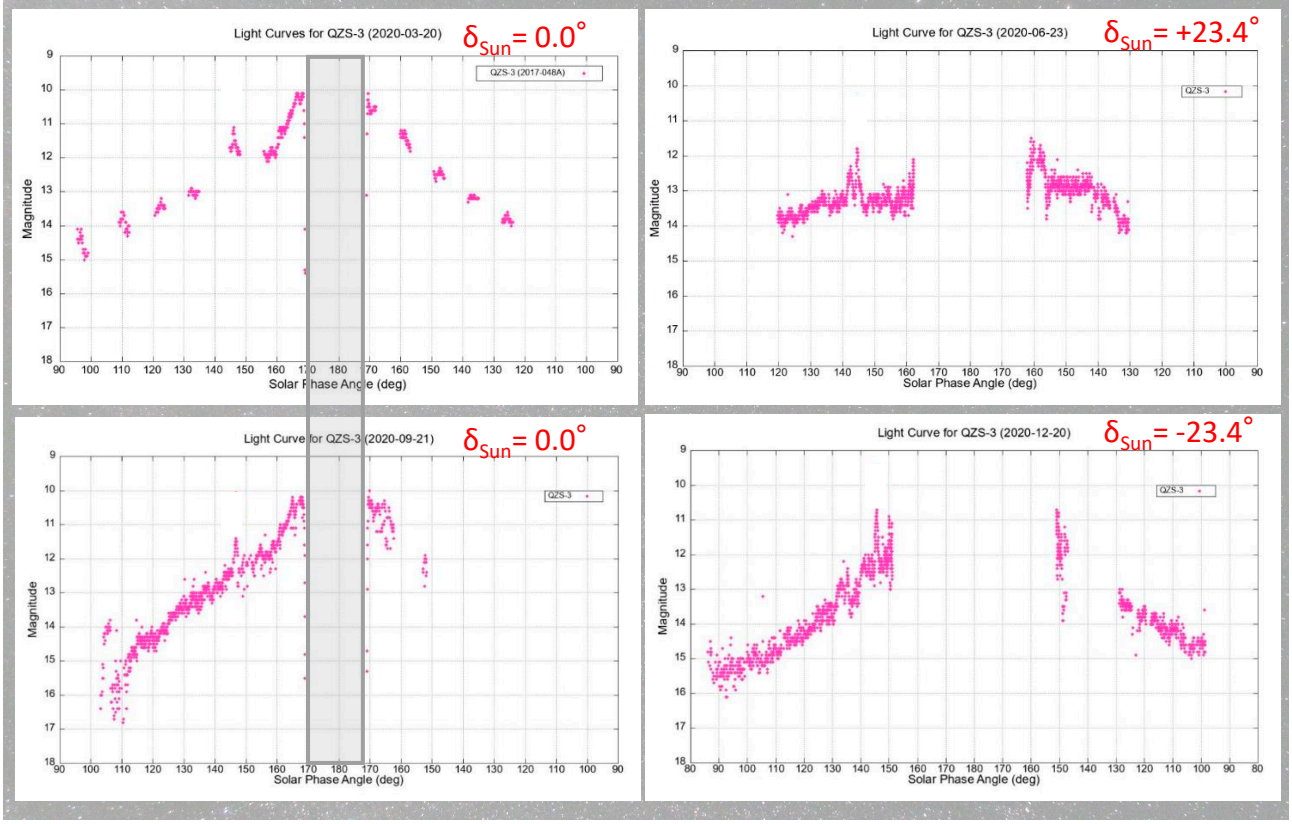
Light Curves (Solar Phase Angle-Magnitude) for HIMAWARI-8/9 & SKY MUSTER



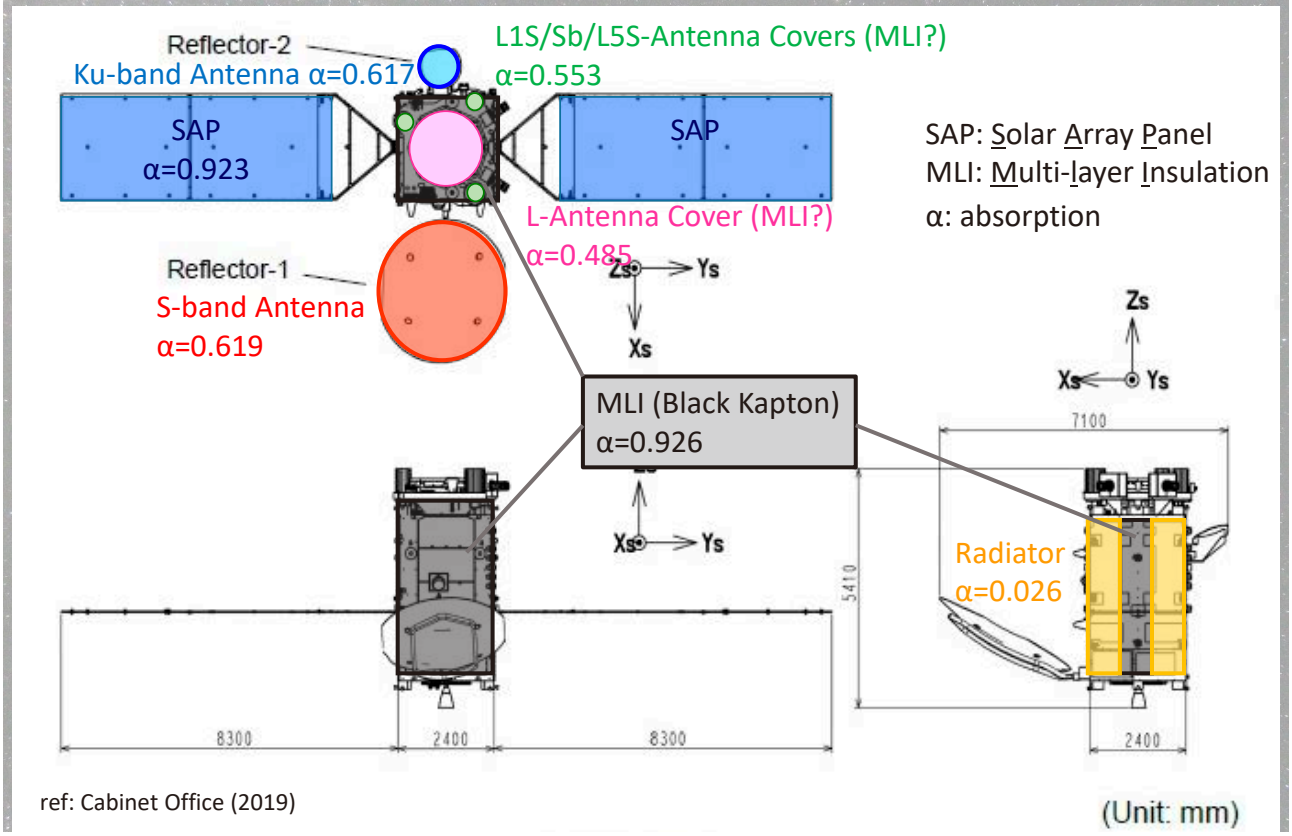
Light Curves for GEO Satellites with the 0.5m Telescope during the Vernal Equinox (2020-03-20)



Light Curves for QZS-3 (in each season)

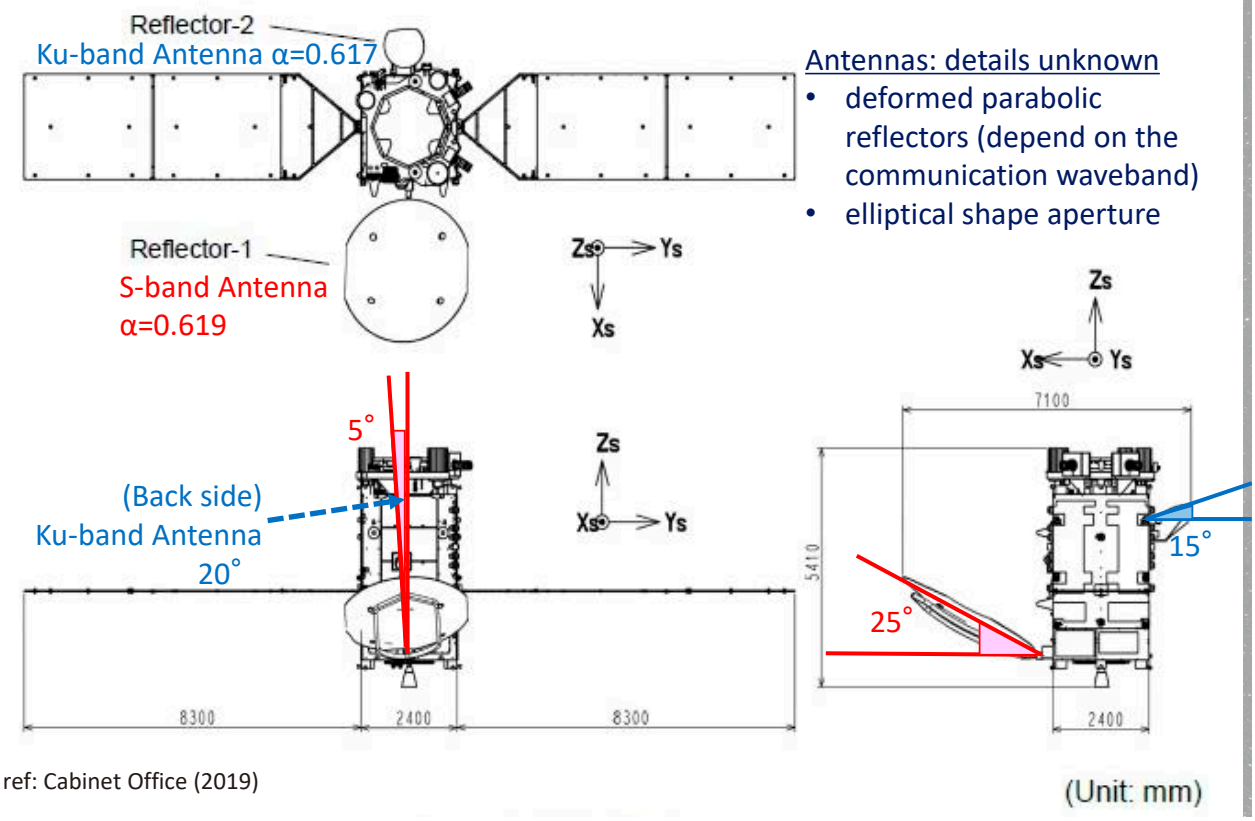


Geometry and Materials of QZS-3



ref: Cabinet Office (2019)

Geometry and Materials of QZS-3



Antennas: details unknown

- deformed parabolic reflectors (depend on the communication waveband)
- elliptical shape aperture

ref: Cabinet Office (2019)

Conditions for a Light Curve Simulation

- The shape of antennas

  →assumed planar antennas

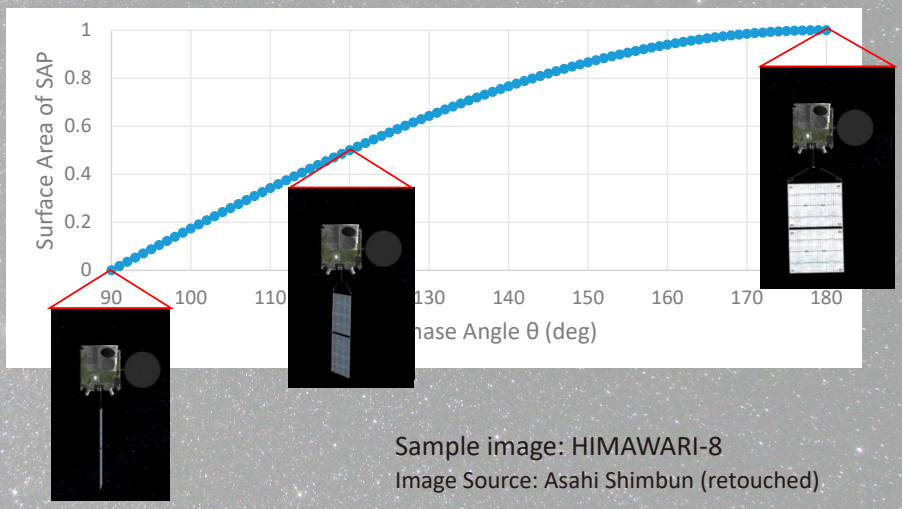
- Variations in absorption rates due to long-term deterioration

  →ignored

- Surface areas of each material

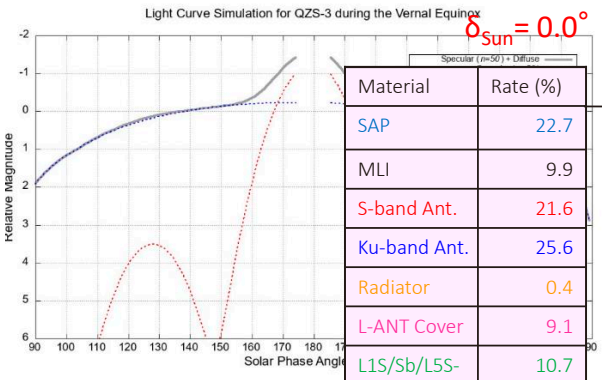
  SAP ∝ cos (180° – θ) (θ: Solar Phase Angle)

  The others = const.



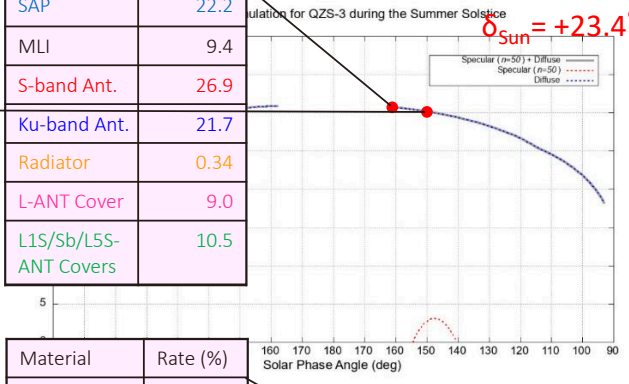
Sample image: HIMAWARI-8
Image Source: Asahi Shimbun (retouched)

Light Curve Simulations for QZS-3 (in each season)



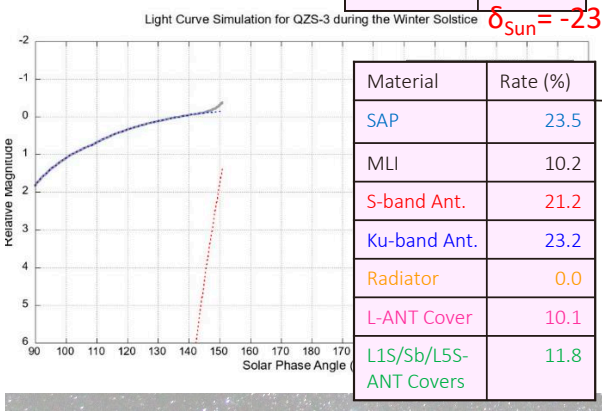
δ_{Sun} = 0.0°

Material	Rate (%)
SAP	22.7
MLI	9.9
S-band Ant.	21.6
Ku-band Ant.	25.6
Radiator	0.4
L-ANT Cover	9.1
L1S/Sb/L5S-ANT Covers	10.7



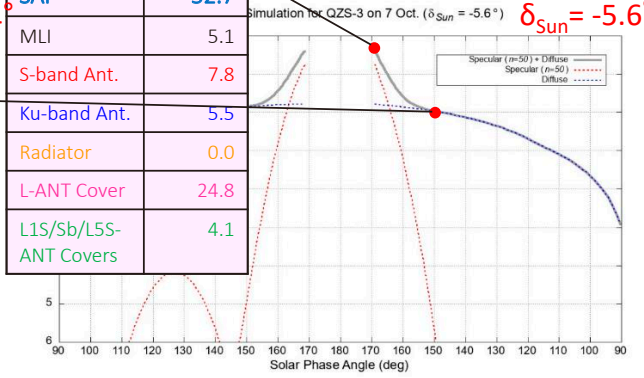
δ_{Sun} = +23.4°

Material	Rate (%)
SAP	52.7
MLI	5.1
S-band Ant.	7.8
Ku-band Ant.	5.5
Radiator	0.0
L-ANT Cover	24.8
L1S/Sb/L5S-ANT Covers	4.1



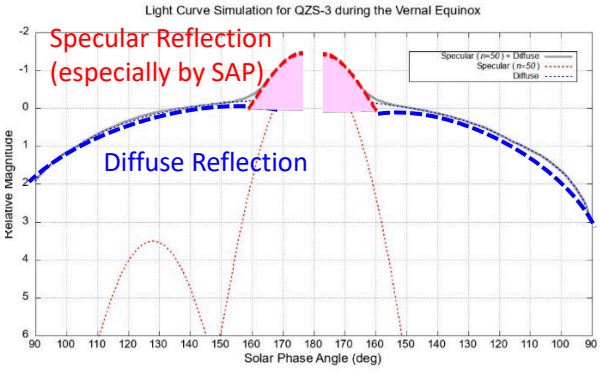
δ_{Sun} = -23.4°

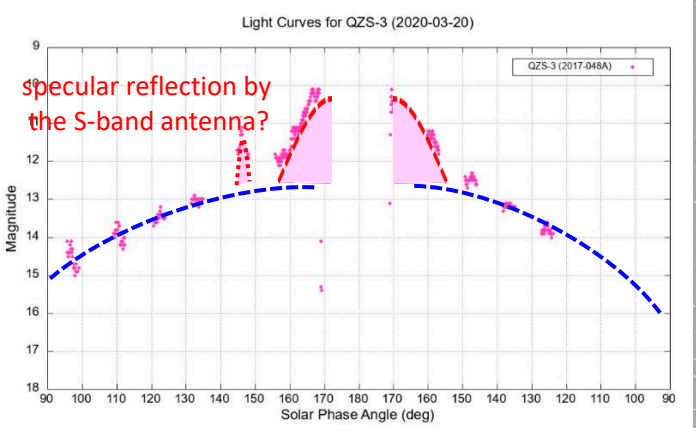
Material	Rate (%)
SAP	23.5
MLI	10.2
S-band Ant.	21.2
Ku-band Ant.	23.2
Radiator	0.0
L-ANT Cover	10.1
L1S/Sb/L5S-ANT Covers	11.8



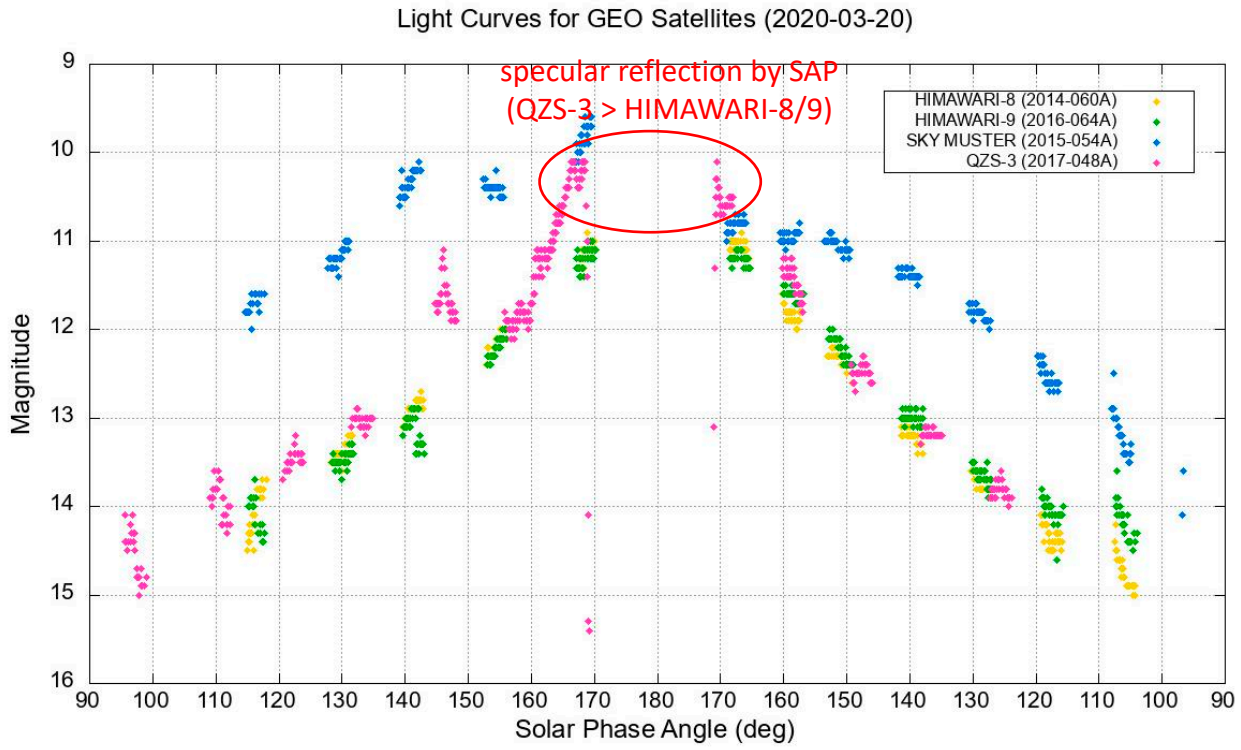
δ_{Sun} = -5.6°

Light Curve Simulations for QZS-3

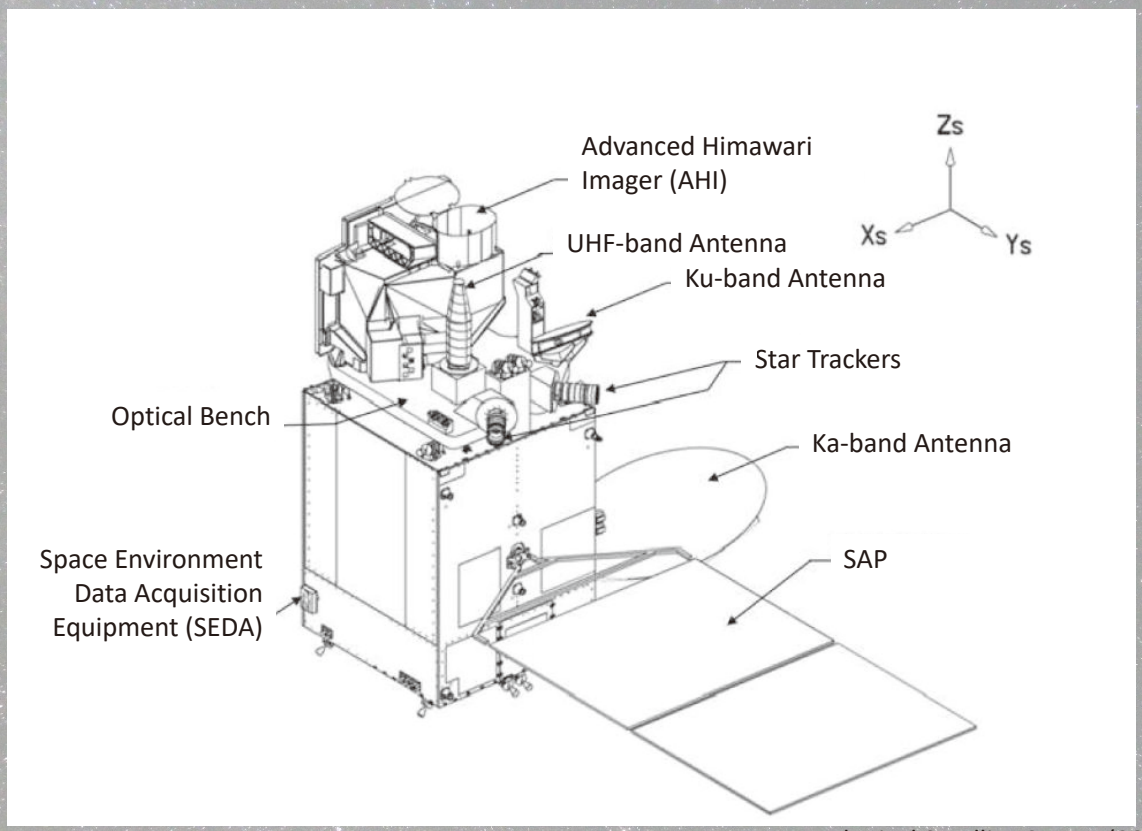




Light Curves for GEO Satellites (2020-03-20)

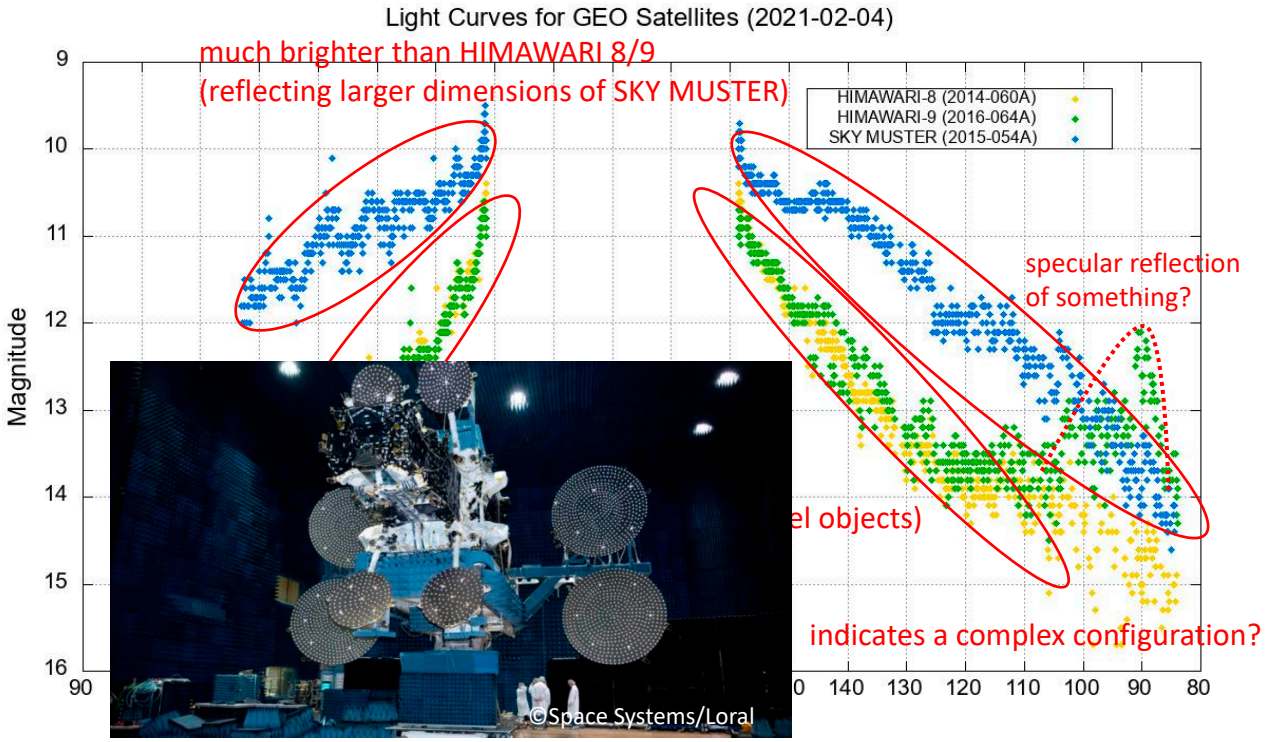


Configuration of HIMAWARI-8/9

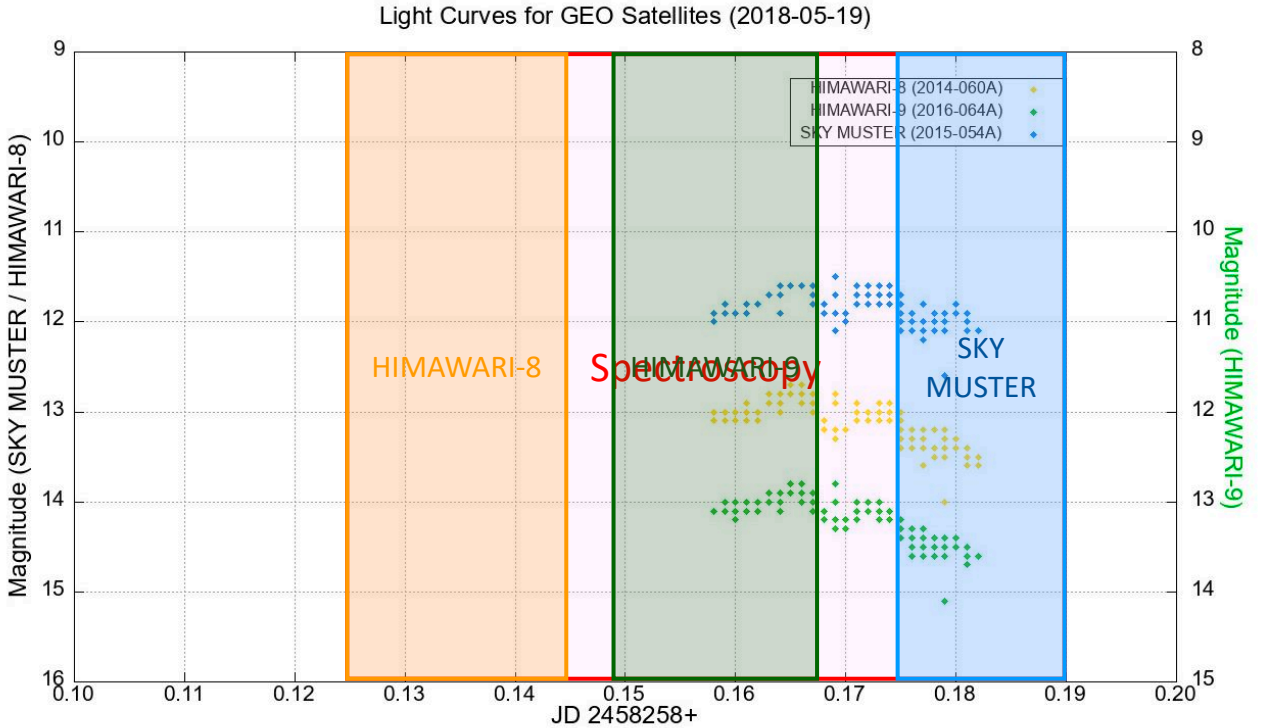


Meteorological Satellite Center (2018)

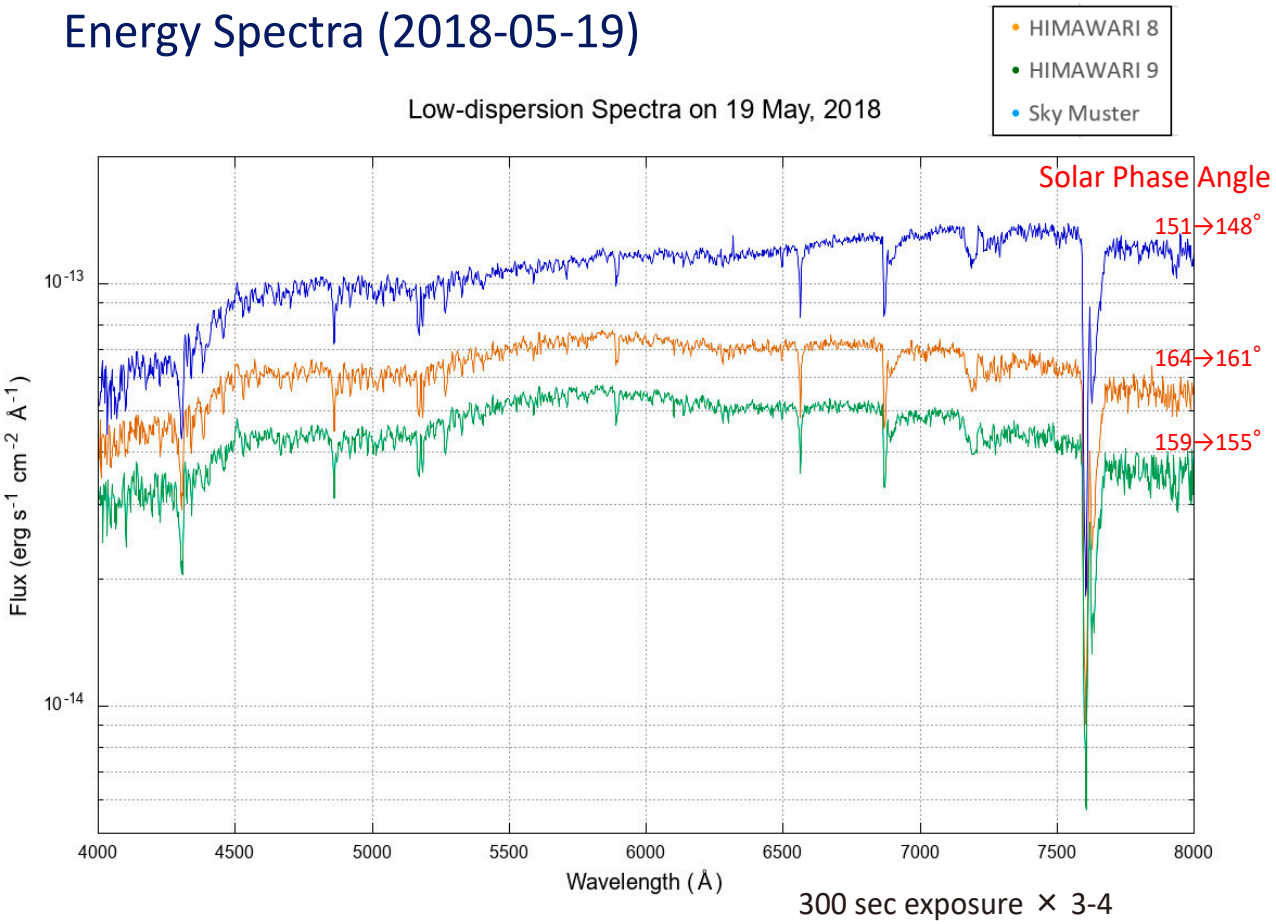
Light Curves for HIMAWARI-8/9 & SKY MUSTER (2021-02-04)



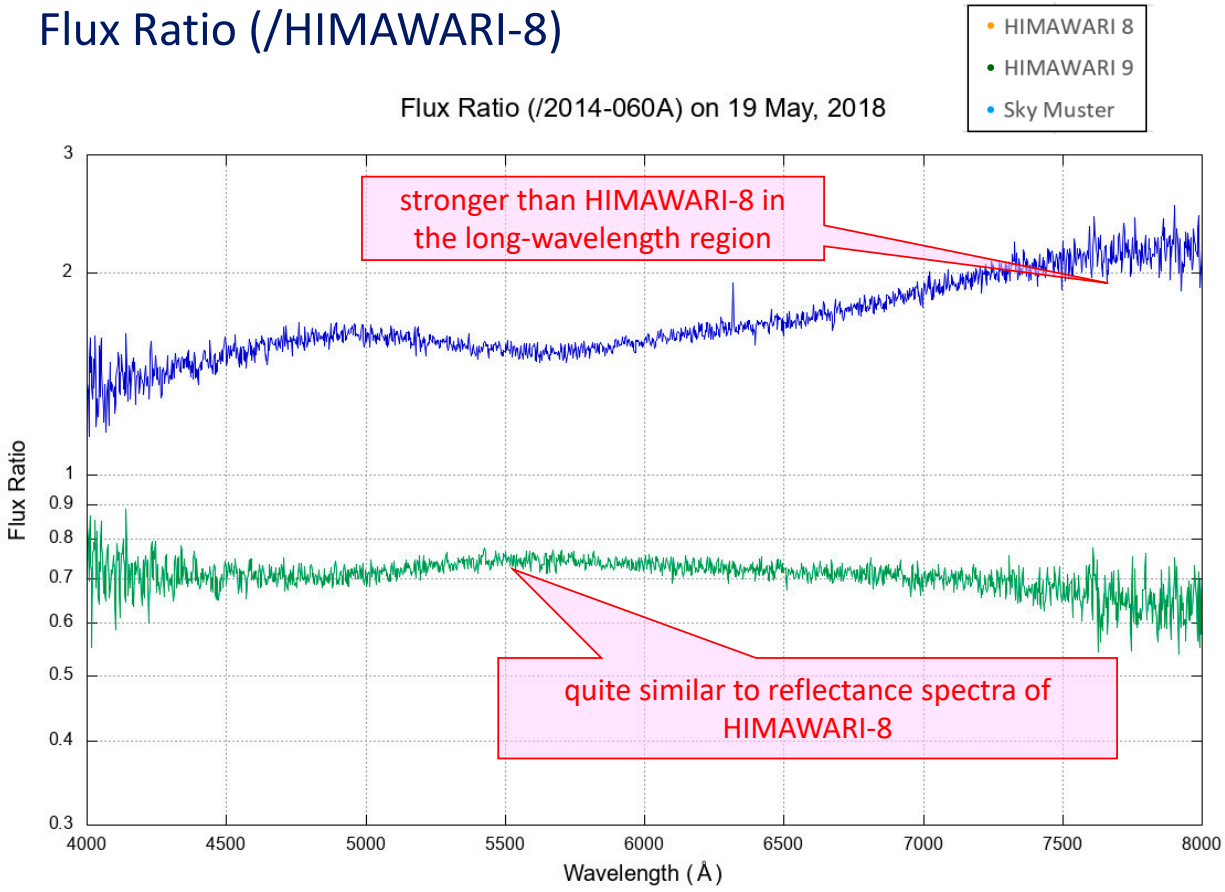
Simultaneous Observation Schedule (2018-05-19)



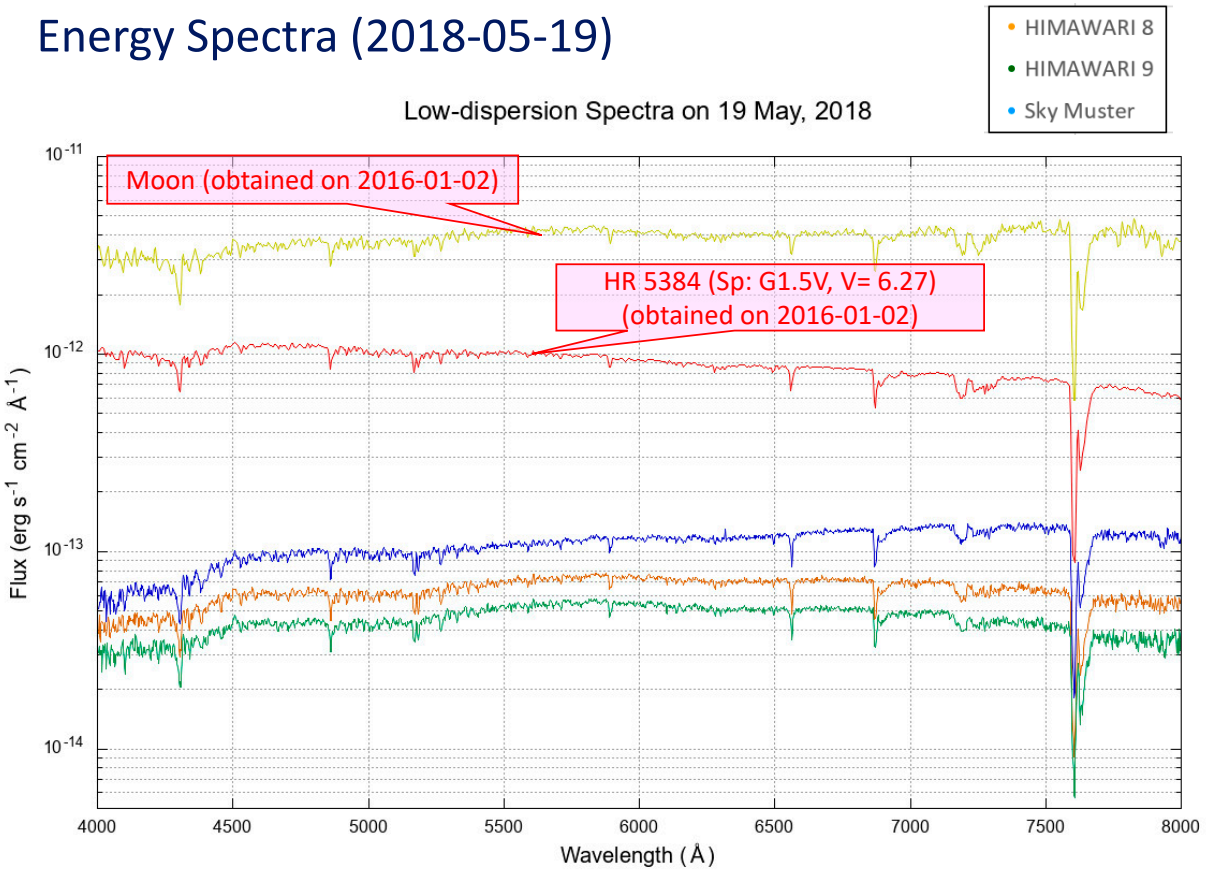
Energy Spectra (2018-05-19)



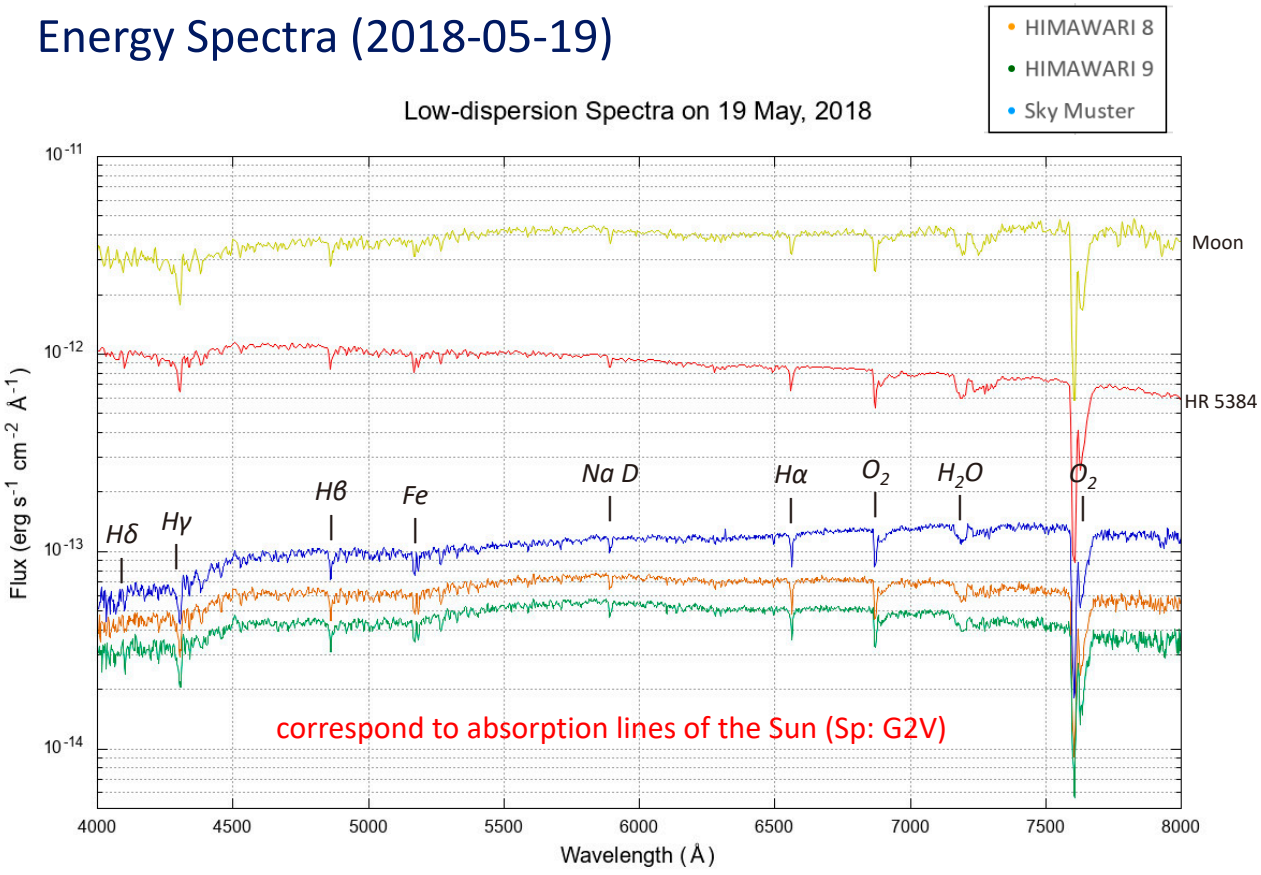
Flux Ratio (/HIMAWARI-8)



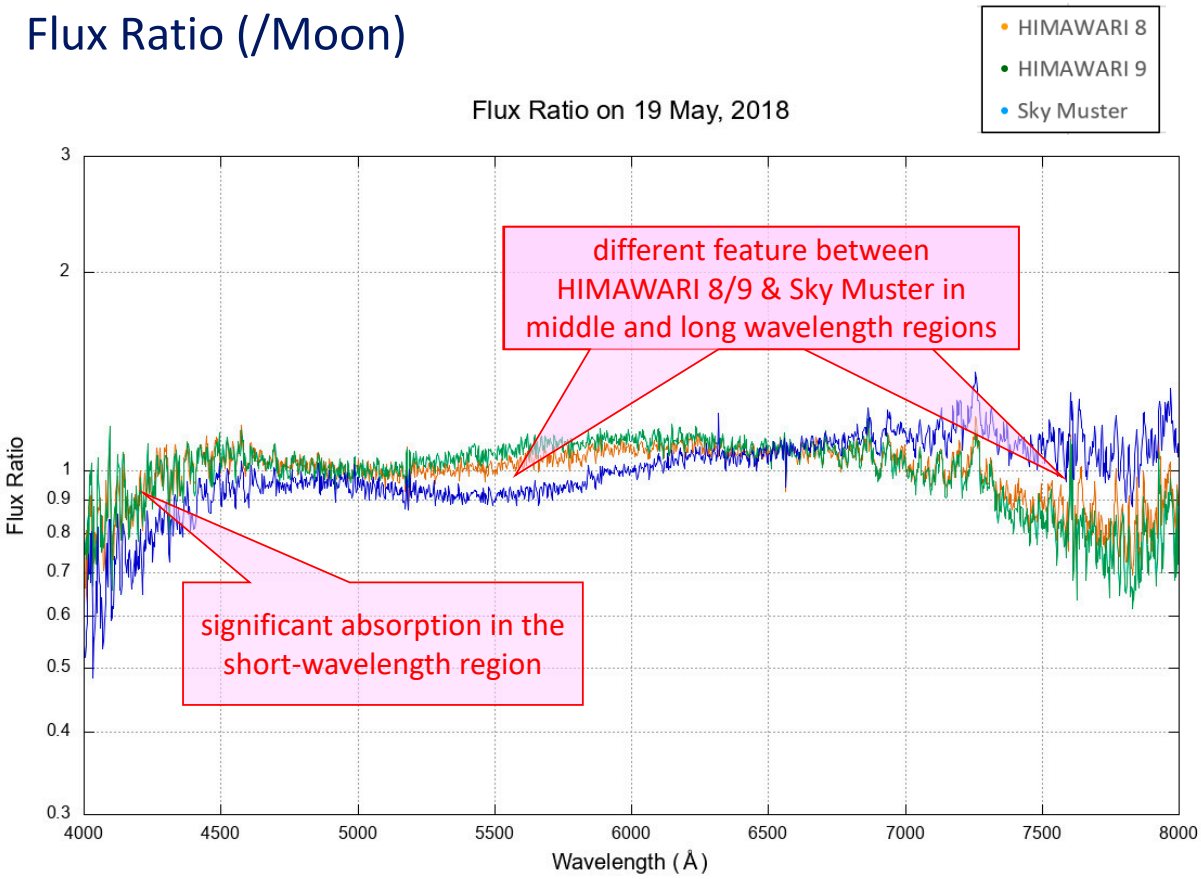
Energy Spectra (2018-05-19)



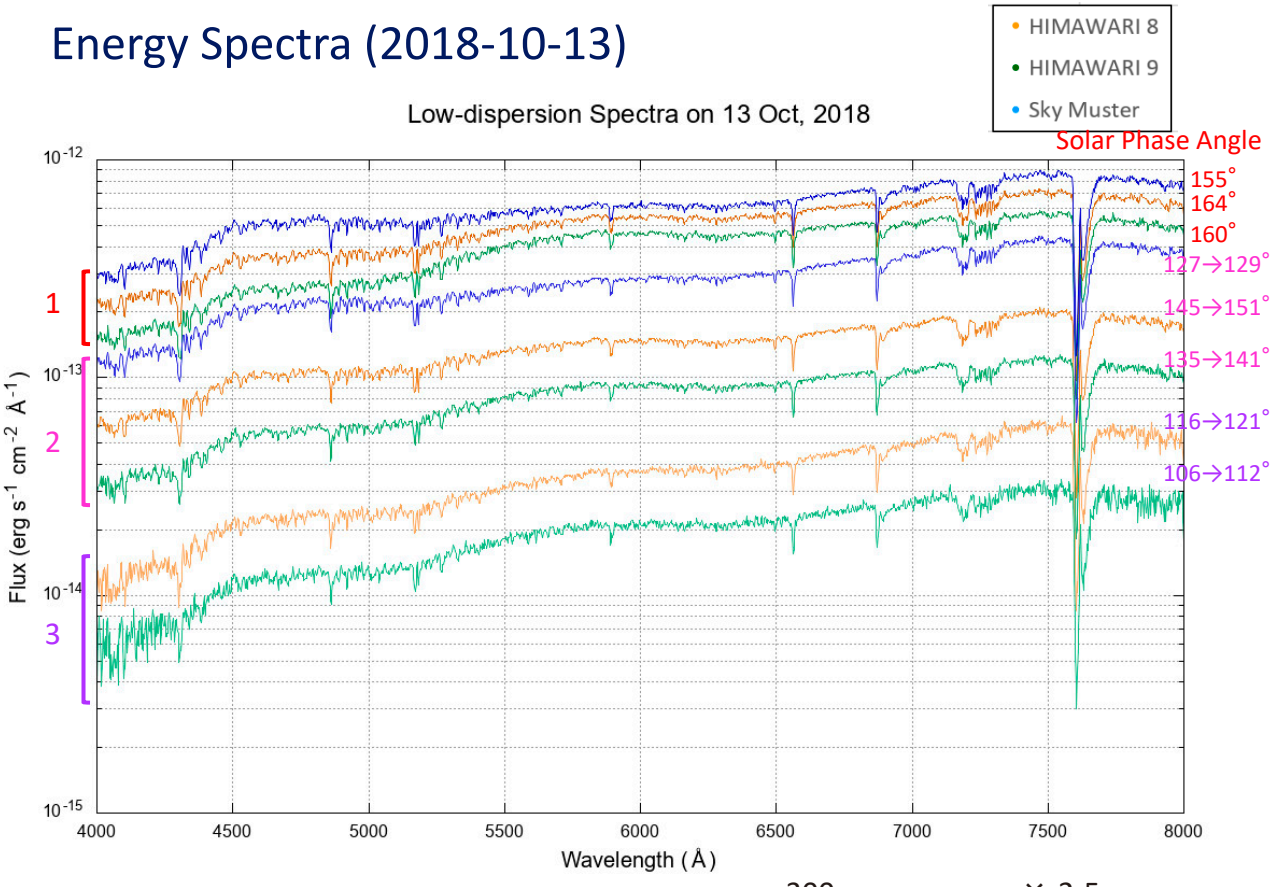
Energy Spectra (2018-05-19)



Flux Ratio (/Moon)

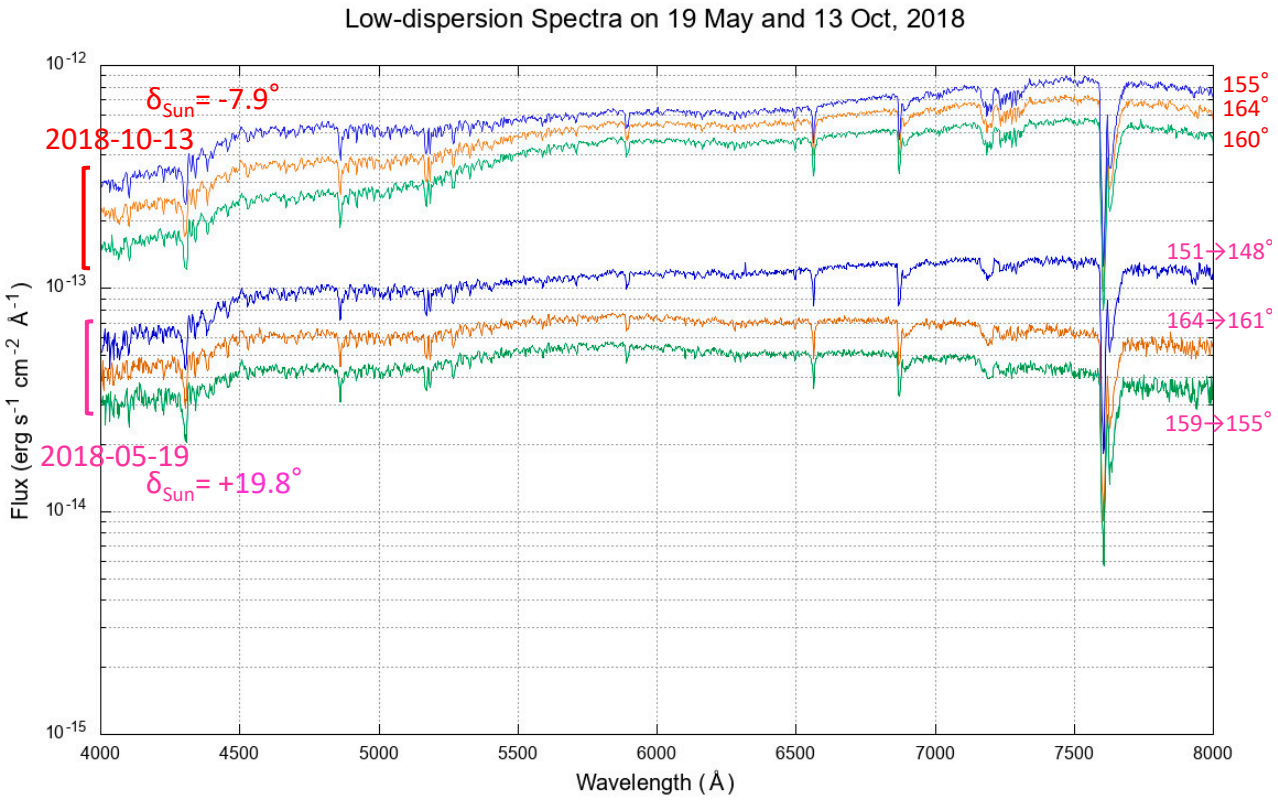


Energy Spectra (2018-10-13)

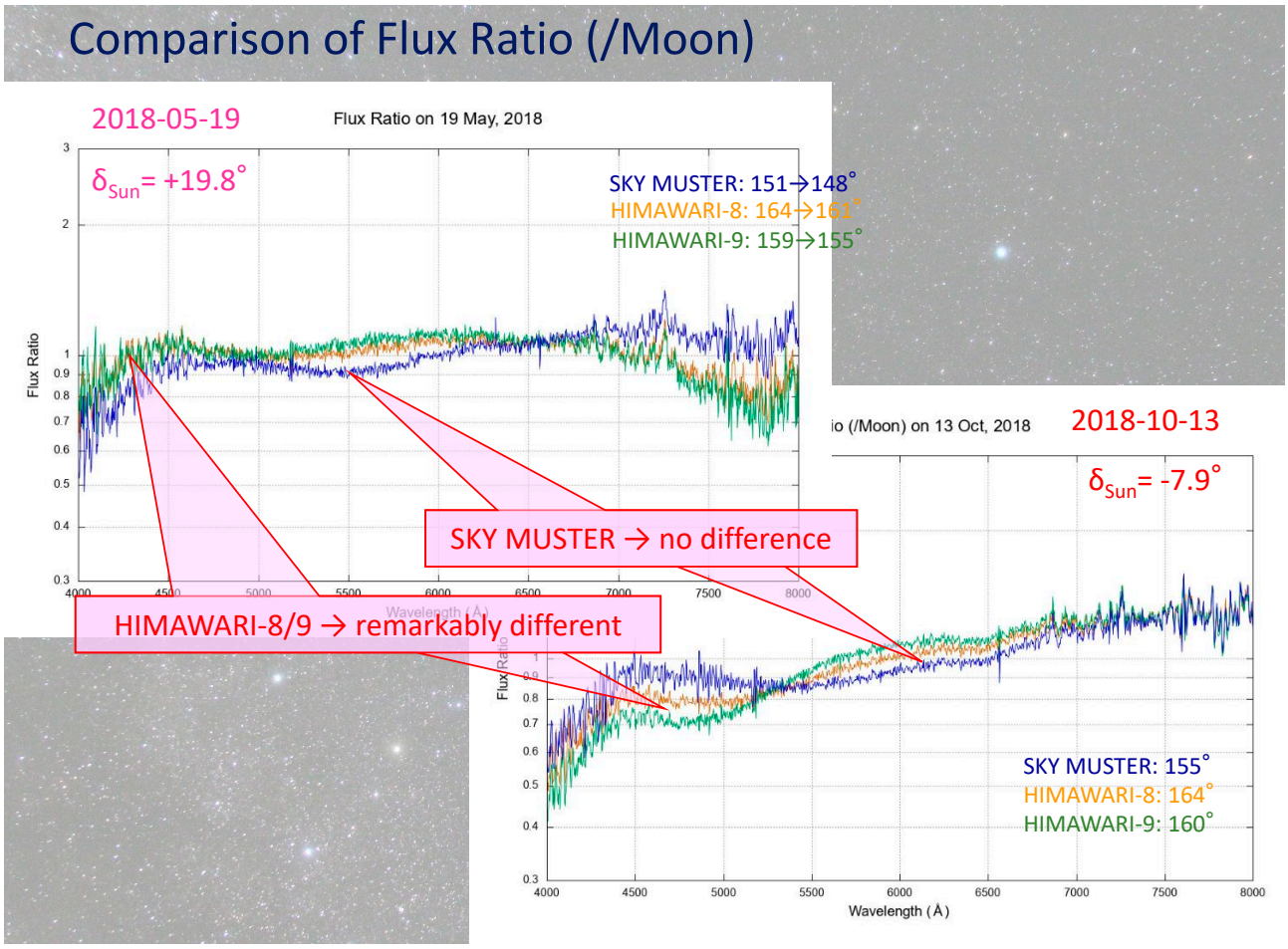


300 sec exposure × 2-5

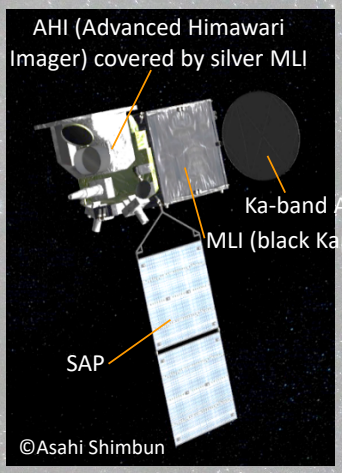
Comparison of Spectra (2018-05-19 vs 2018-10-13)



Comparison of Flux Ratio (/Moon)



Reflectance Spectra of each Material



MLI: gold (left) and silver (right)

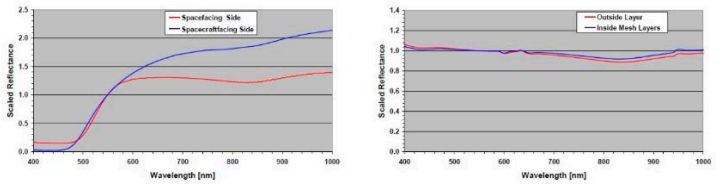


Figure 7: Reflectance spectra of 'gold' Kapton (left) and 'silver' (right) multi-layer insulation material (data provided by K. Abercromby).

Schildknecht, T. et al. (2009)

Materials with wavelength dependence

~~MLI (gold)~~

SAP

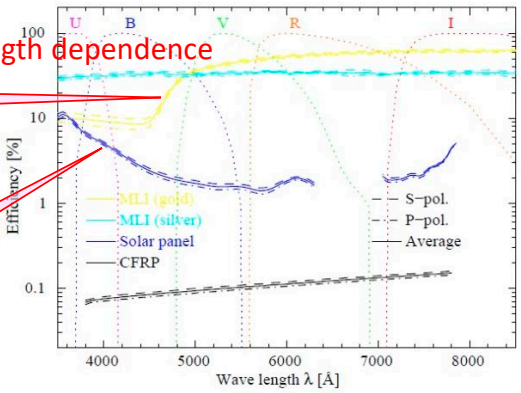
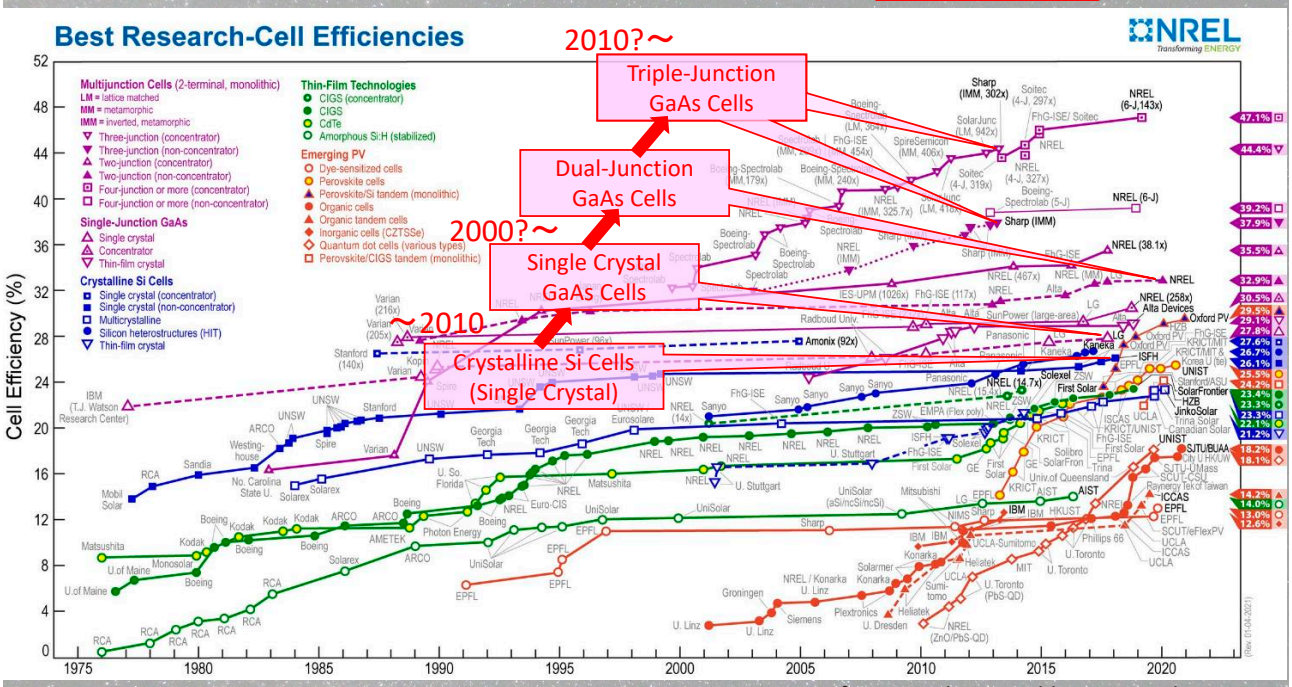


Fig. 3. Spectral reflectance of typical materials.

Endo, T. et al. (2017)

Best Research-Cell Efficiency Chart

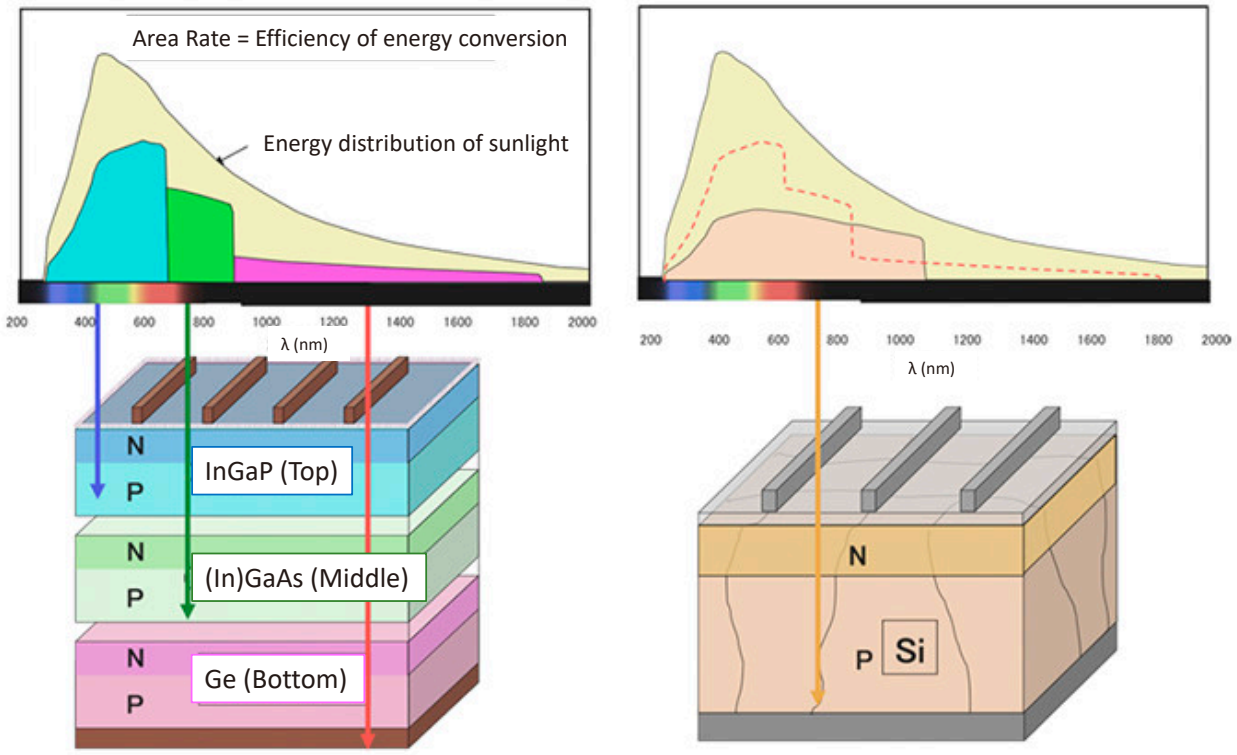
for Spacecrafts



ref: National Renewable Energy Laboratory

Some information on SAP enables us to estimate the rough age of a satellite!

Structure and Efficiency for Solar Energy Utilization of Triple-Junction InGaP/GaAs/Ge and Crystalline Si Cells



ref: https://www.nedo.go.jp/hyoukabu/articles/201111sharp/index.html

Reflectance Spectra of Crystalline Si and Triple-Junction Cells

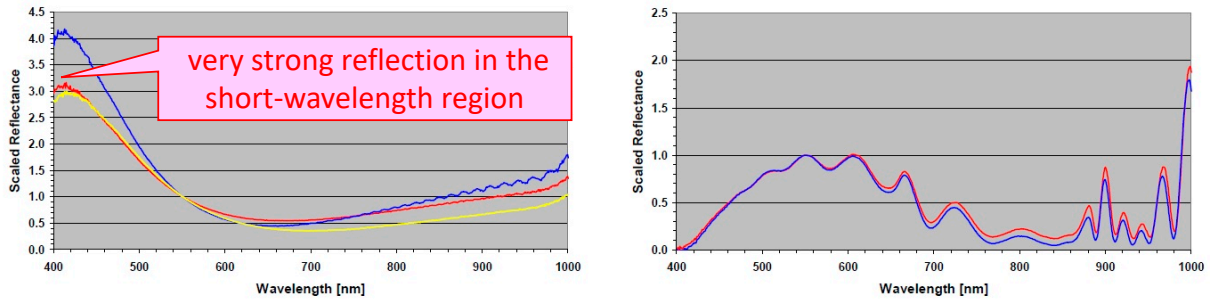
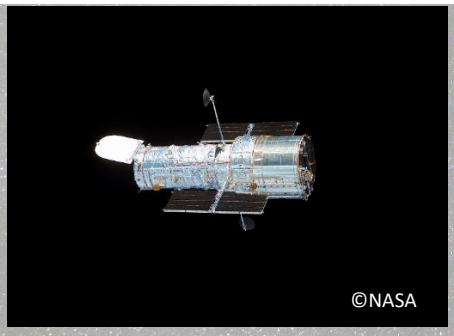


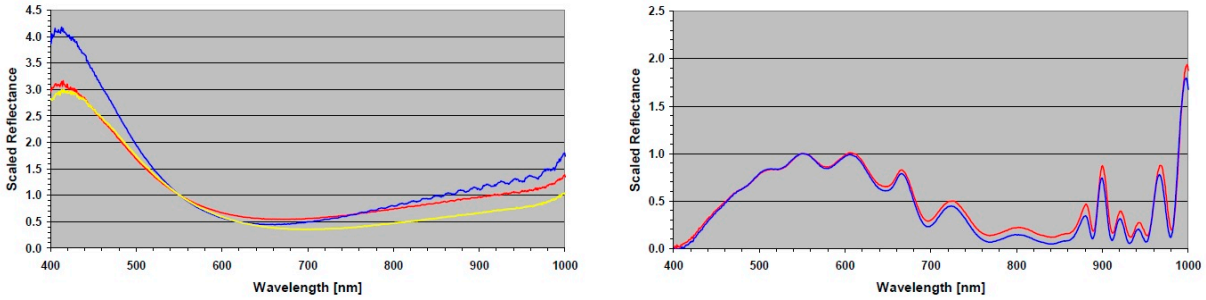
Figure 6: Reflectance spectra of two laboratory samples of solar cells. Left: solar cell sample from the Hubble space telescope solar array retrieved in March 2009 (~8.25 years in space); right: triple junction solar cell sample.

Schildknecht, T. et al. (2009)



Replacement of SAP from Si to GaAs cells in Service Mission 3B (March 2002)

Reflectance Spectra of Crystalline Si and Triple-Junction Cells



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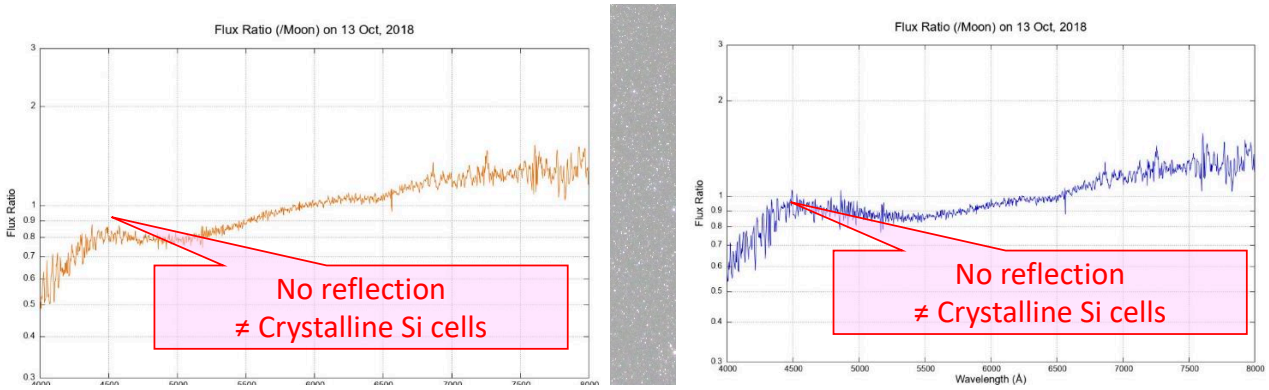
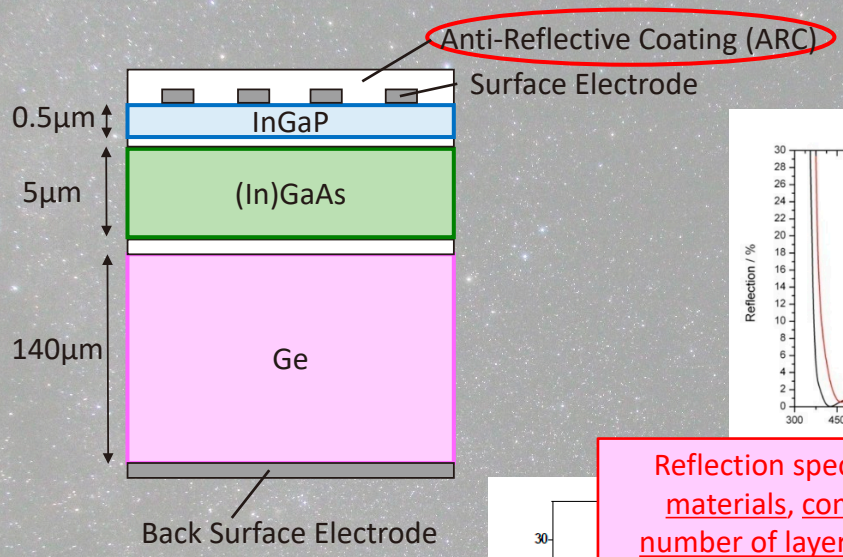
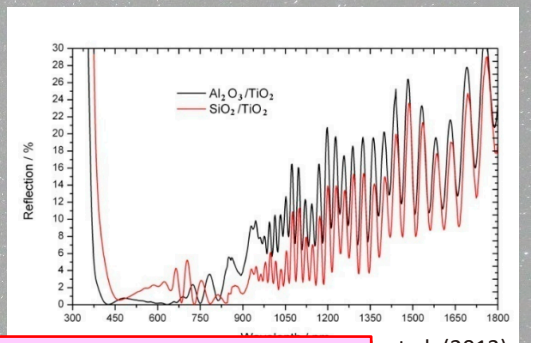
Schildknecht, T. et al. (2009)



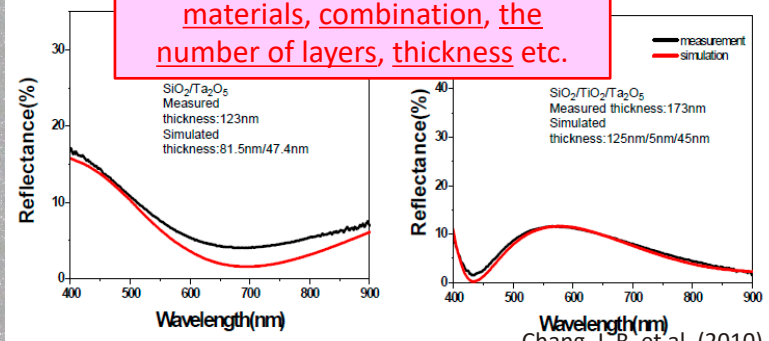
Cross Sectional View of InGaP/GaAs/Ge Cells





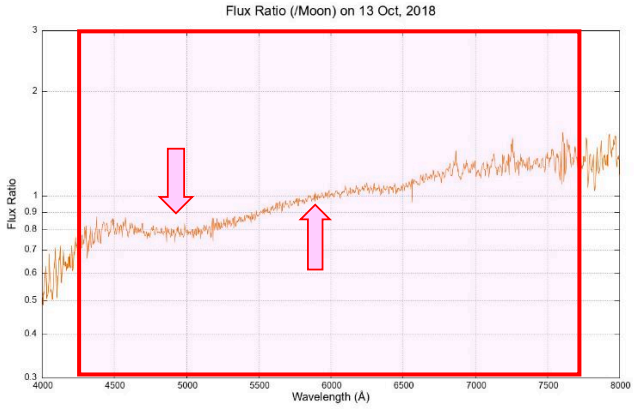
. et al. (2013)

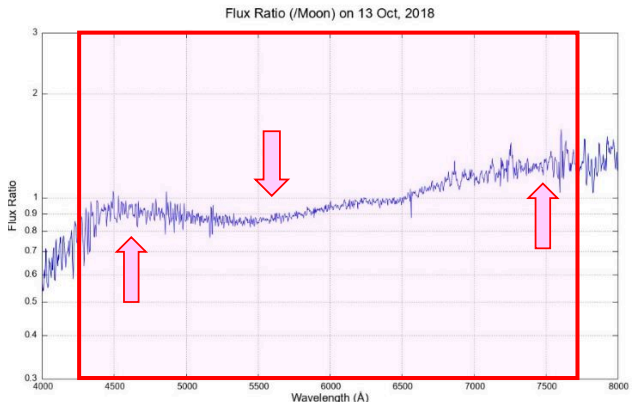
Reflection spectra depend on materials, combination, the number of layers, thickness etc.



Chang, L-B. et al. (2010)

Identification of Anti-Reflective Coatings





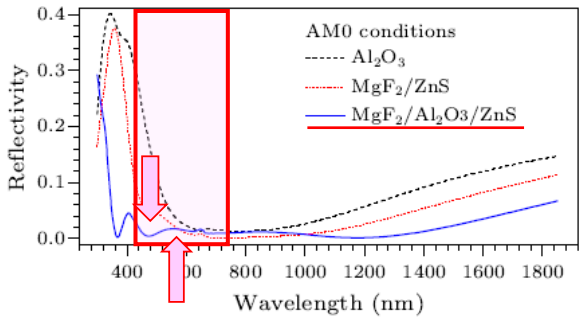
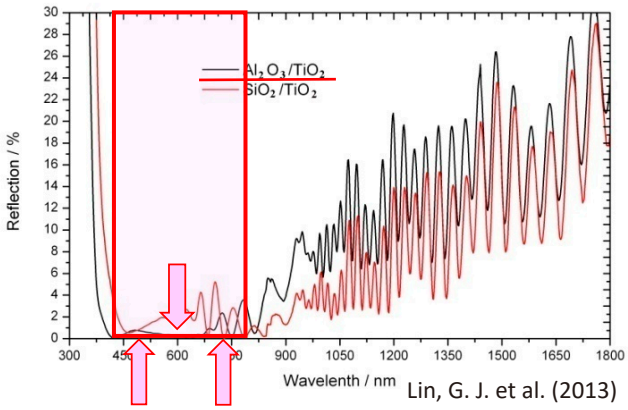


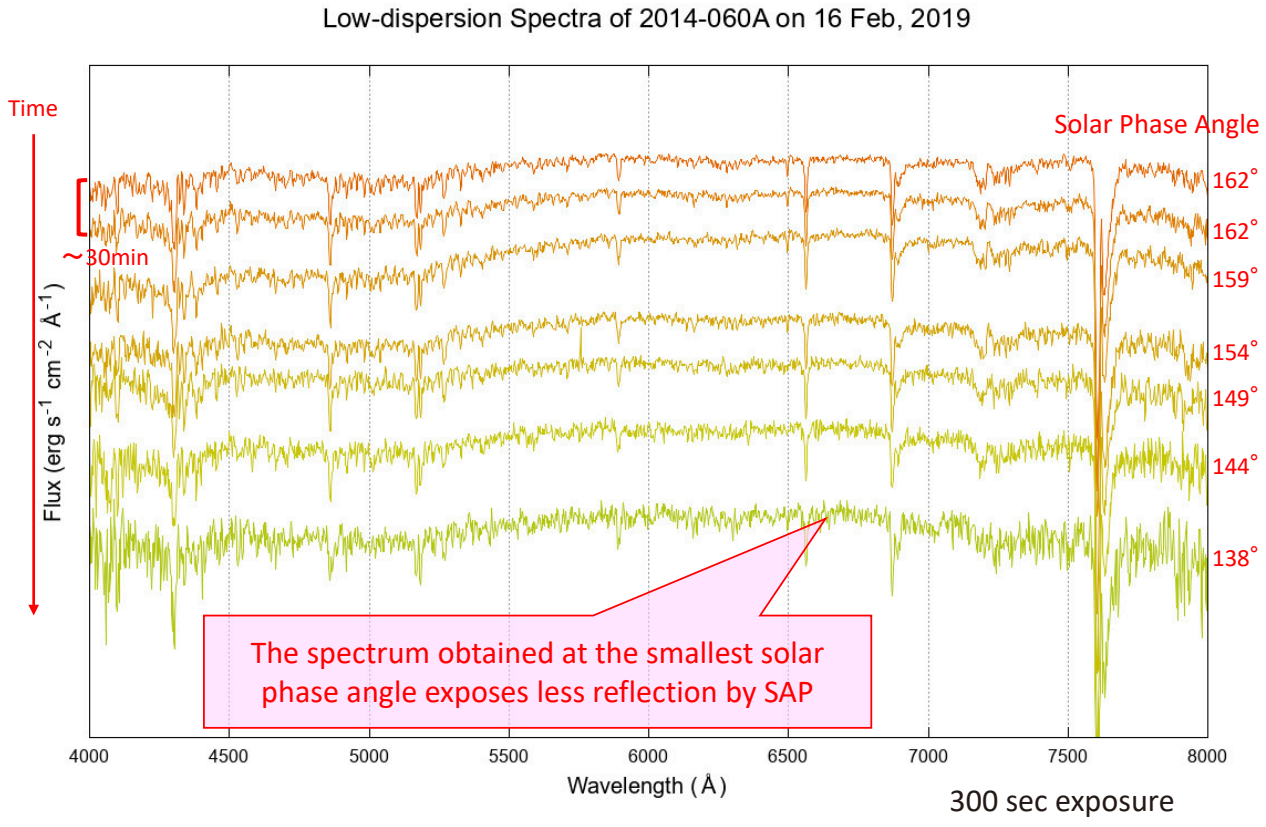
Fig. 9. ARC reflectivity vs wavelength under the AM0 condition.

Zhan, F. et al. (2011)



Lin, G. J. et al. (2013)

Temporal Changes of Spectra for HIMAWARI-8



Normalized Spectra by the Last Data (with the Smallest Solar Phase Angle)

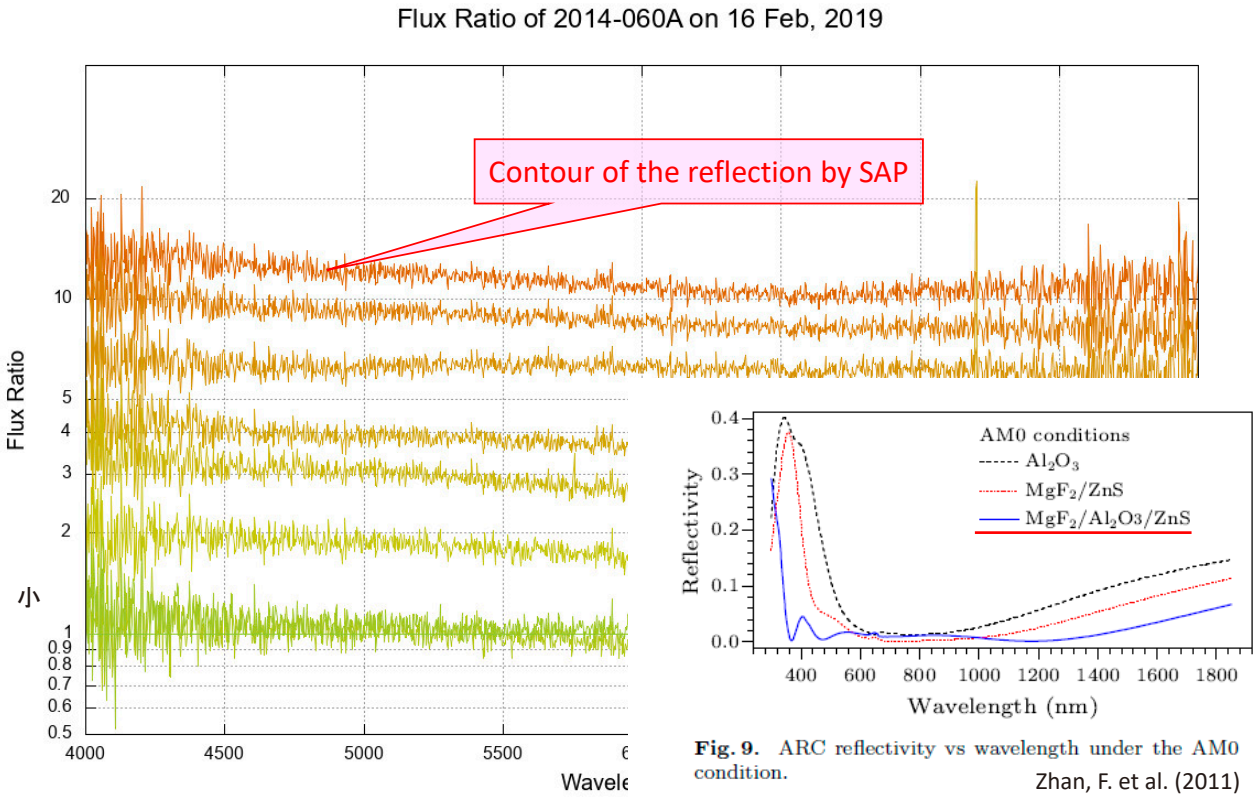
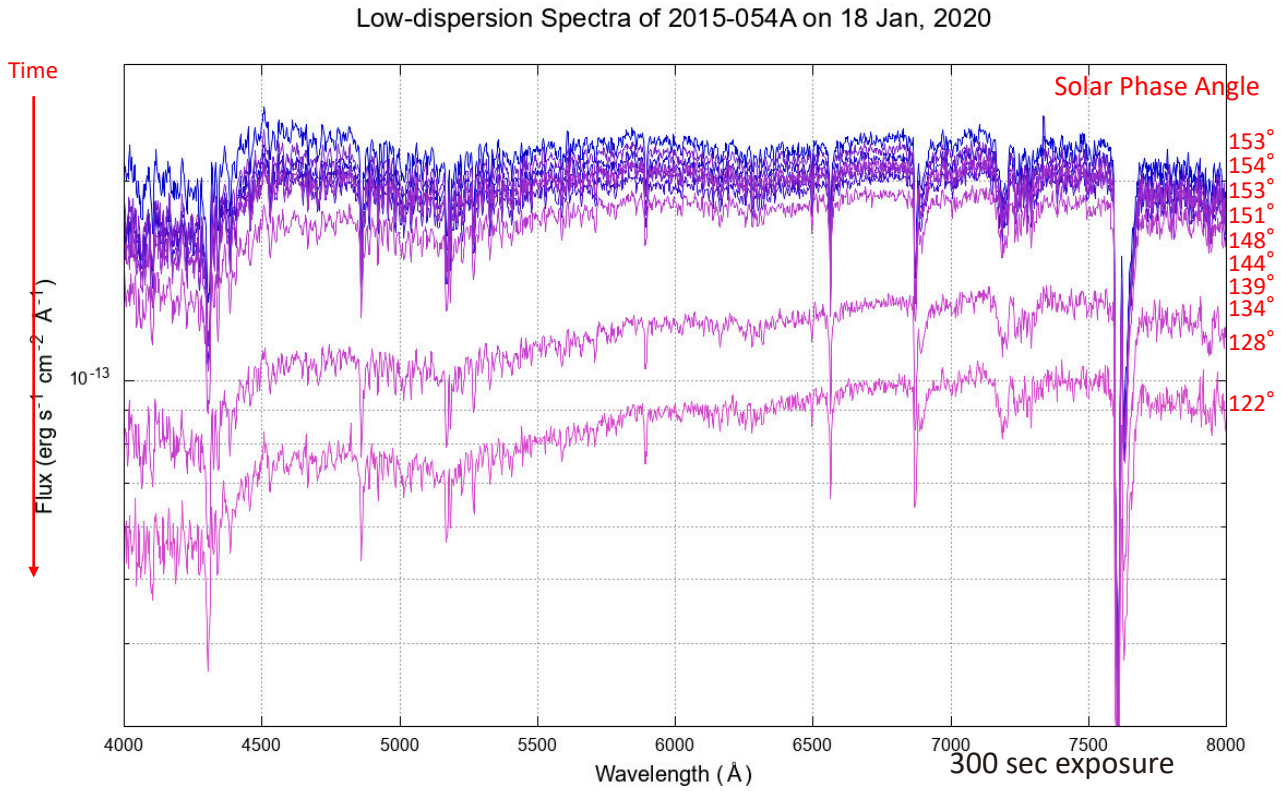


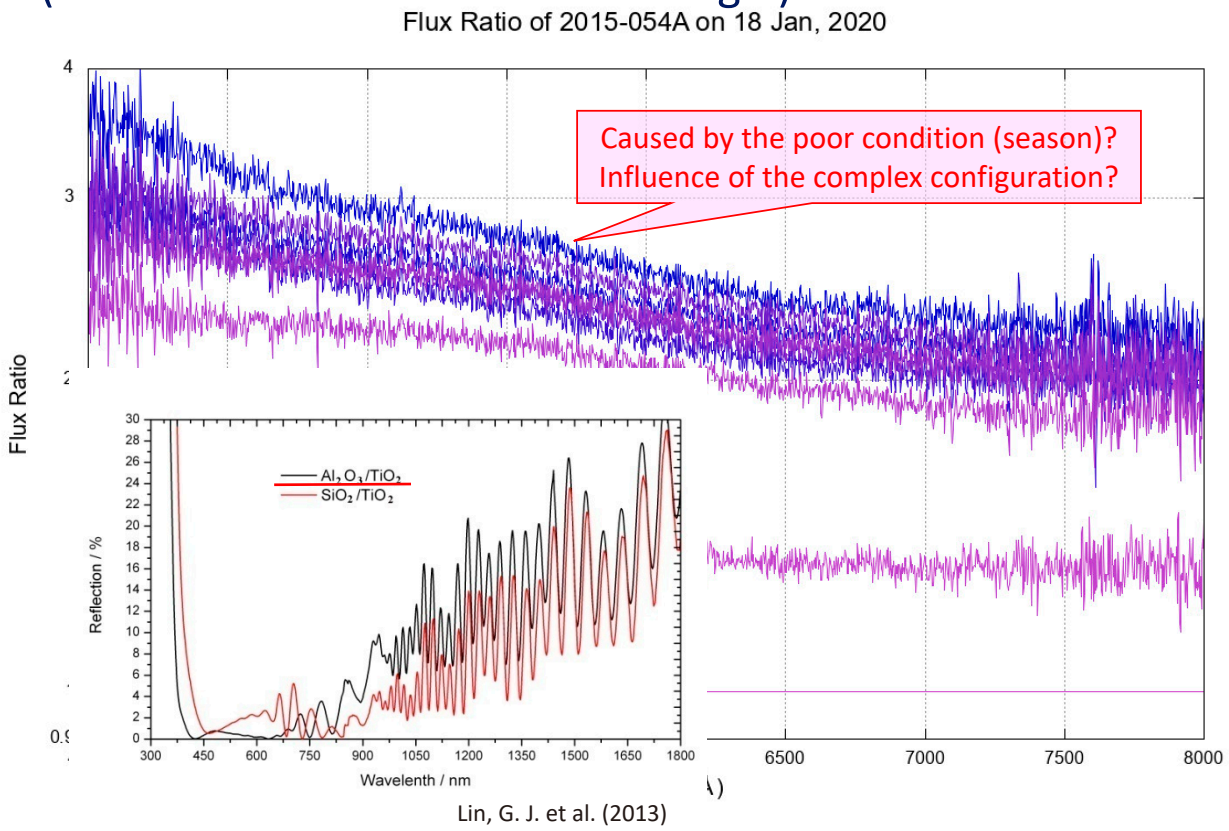
Fig. 9. ARC reflectivity vs wavelength under the AM0 condition.

Zhan, F. et al. (2011)

Temporal Changes of Spectra for SKY MUSTER



Normalized Spectra by the Last Data (with the Smallest Solar Phase Angle)



Lin, G. J. et al. (2013)

4. Conclusions

1. Light curves for GEO satellites yield information about their own dimensions and configurations
   - HIMAWARI-8/9 have very similar light curves
   - SKY MUSTER has a brighter light curve profile than HIMAWARI-8/9
2. The brightness / intensity of spectra of a satellite varies with the solar phase angle and with the season (the declination of the Sun)
   - (brighter) large solar phase angle ⇔ small solar phase angle (dimmer)
   - (brighter) δ_{Sun}=-5.6 ⇔ summer solstice: δ_{Sun}=+23.4 (dimmer)
3. The contour of each spectrum shows characteristics of SAP including ARC and also varies with the solar phase angle and with the season

Future Works

1. Application of the light curve simulation model for QZS-3 to other satellites (HIMAWARI-8/9, SKY MUSTER…)
2. Follow-up photometric / spectroscopic observations to know temporal changes of light curves / spectra
3. Additional spectroscopic observations for satellites (including QZS-3) especially with other types of SAP cells

Thank you for your attention!

★Acknowledgements★

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- Flight Dynamics Team of JAXA and Japan Space Forum for providing opportunities of photometric observations

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Any comments or suggestions are welcome!