2023/2/28 - 3/1
第13回 光・赤外線天文学大学間連携ワークショップ

OISTER連携観測による Visorsatの庇の効果の検証

東京大学 天文学教育研究センター

特任研究員

堀内 貴史 / Takashi Horiuchi

Co-authors

Hidekazu Hanayama, Masatoshi OHISHI, Tatsuya NAKAOKA, Ryo IMAZAWA, Koji S. KAWABATA,
Jun TAKAHASHI, Hiroki ONOZATO, Tomoki SAITO, Masayuki YAMANAKA, Daisaku NOGAMI,
Yusuke TAMPO, Naoto KOJIGUCHI, Jumpei ITO, Masaaki SHIBATA, Malte SCHRAMM, Yumiko OASA,
Takahiro KANAI, Kohei OIDE, Katsuhiro L. MURATA, Ryohei HOSOKAWA, Yutaka TAKAMATSU,
Yuri IMAI, Naohiro ITO, Masafumi NIWANO, Seiko TAKAGI, Tatsuharu ONO, and Vladimir V. KOUPRIANOV

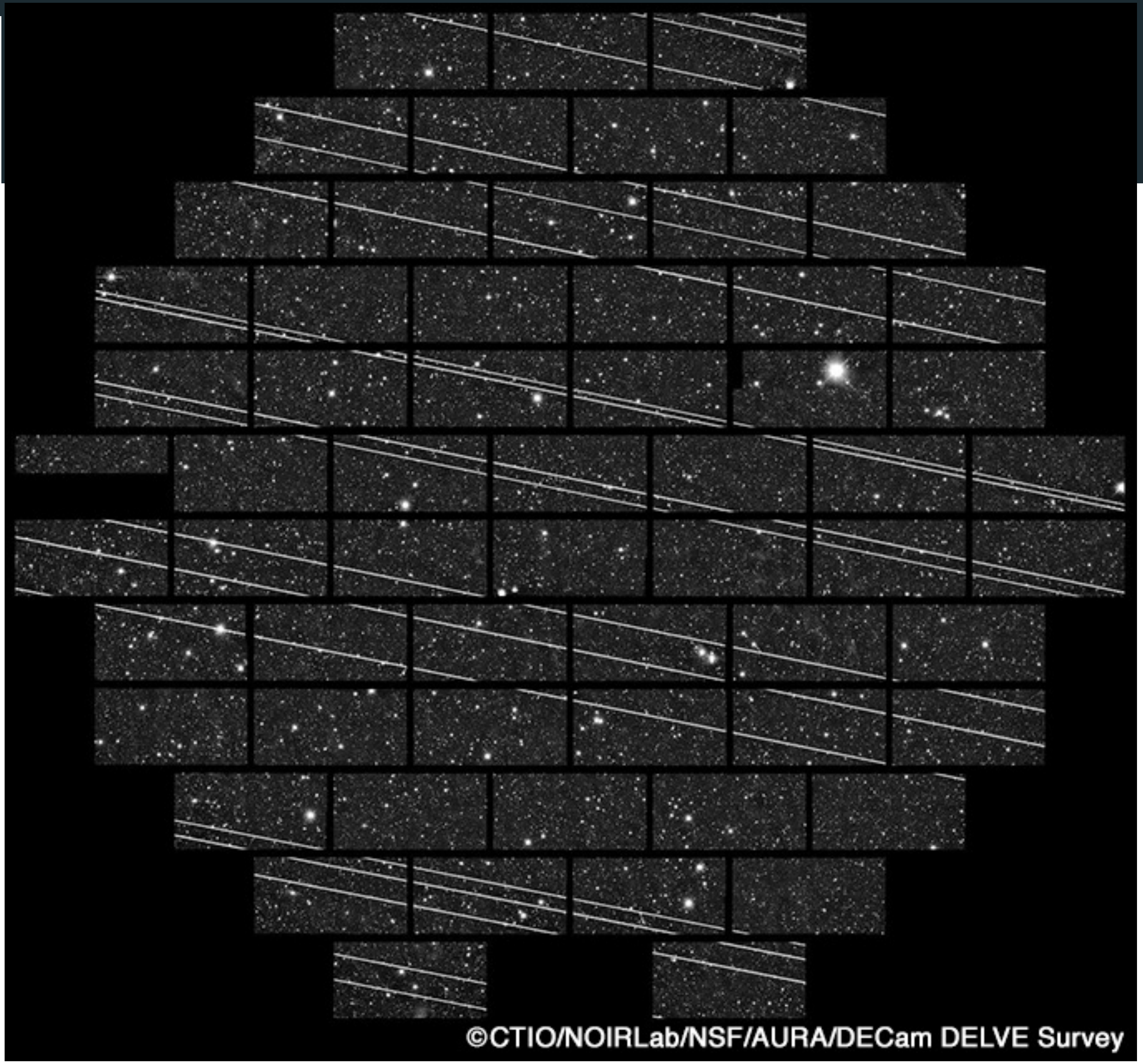
Light pollution from the Starlink satellites

☐ SpaceX launched the first 60 Starlink satellites on May 24, 2019 for high-speed internet communications.

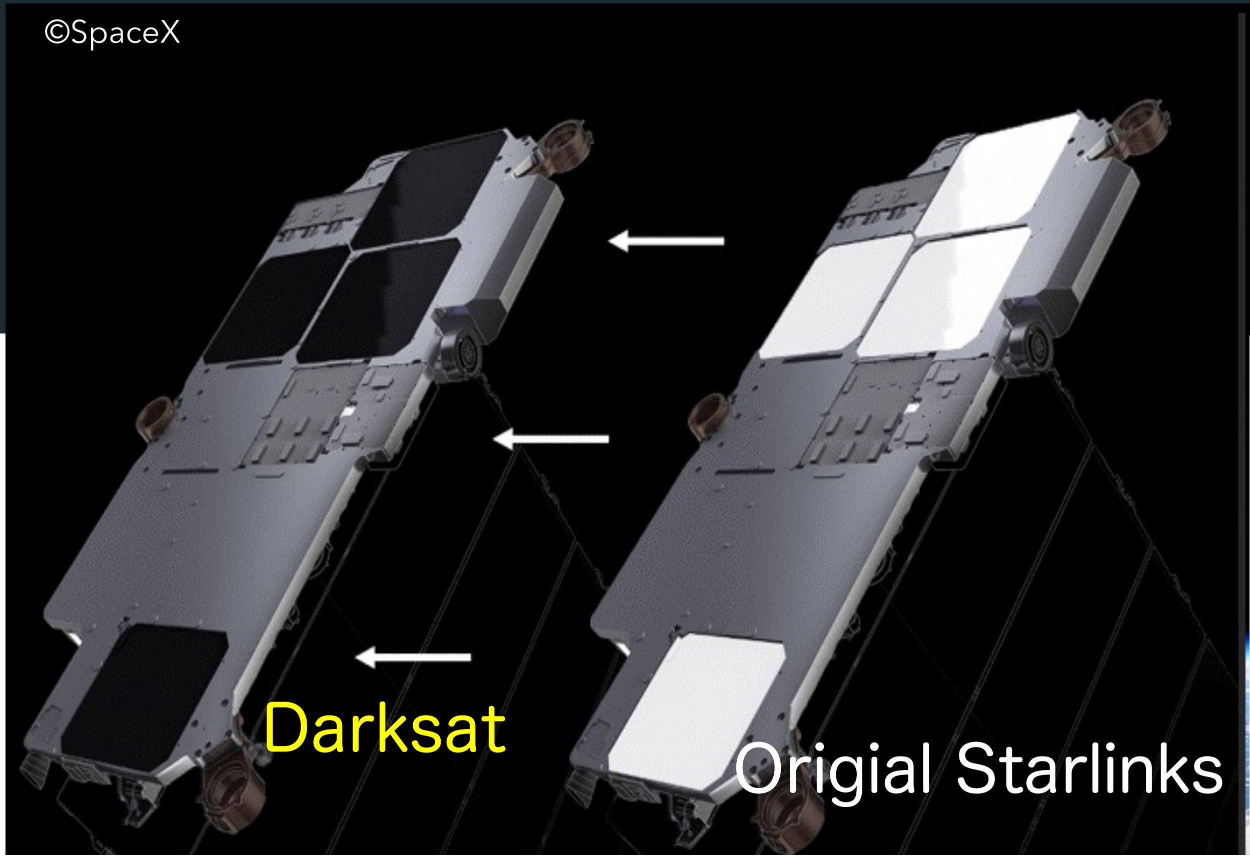
☐ However, the mega-constellation including the Starlink satellites pollutes the environment of astronomical observations (orbital height: 550 km).

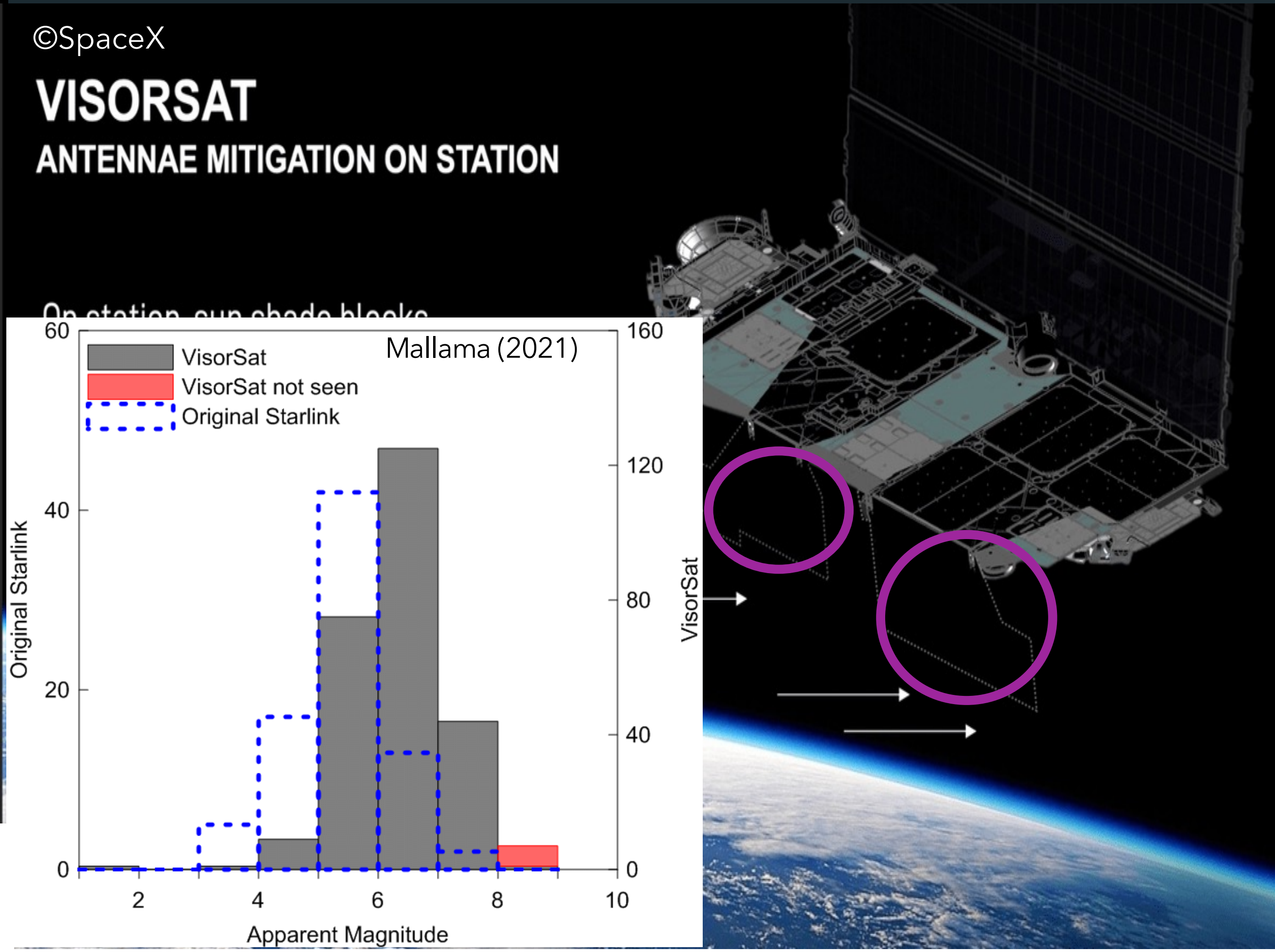
・IAU expressed the concern on that incident.

☐ SpaceX plans to launch 12,000 satellites until mid 2020s.



Light pollution countermeasures by SpaceX - Darksat and Visorsat -



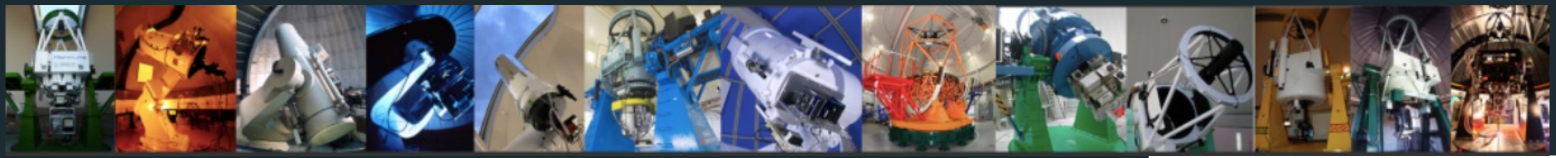


Magnitude at the orbital height of 550 km
(e.g., Horiuchi+2020; Tregloan-Reed+2020)

- Origial Starlink (STARLINK-1113)
  5.33 (g'), 5.60 (Rc), 4.25 (Ic)
- Darksat
  6.10 (g'), 6.00 (Rc), 5.65 (Ic)

Multicolor magnitudes of Visorsat are not well known. ➔➔ Our motivation !

Observation with the OISTER collaboration



© OISTER

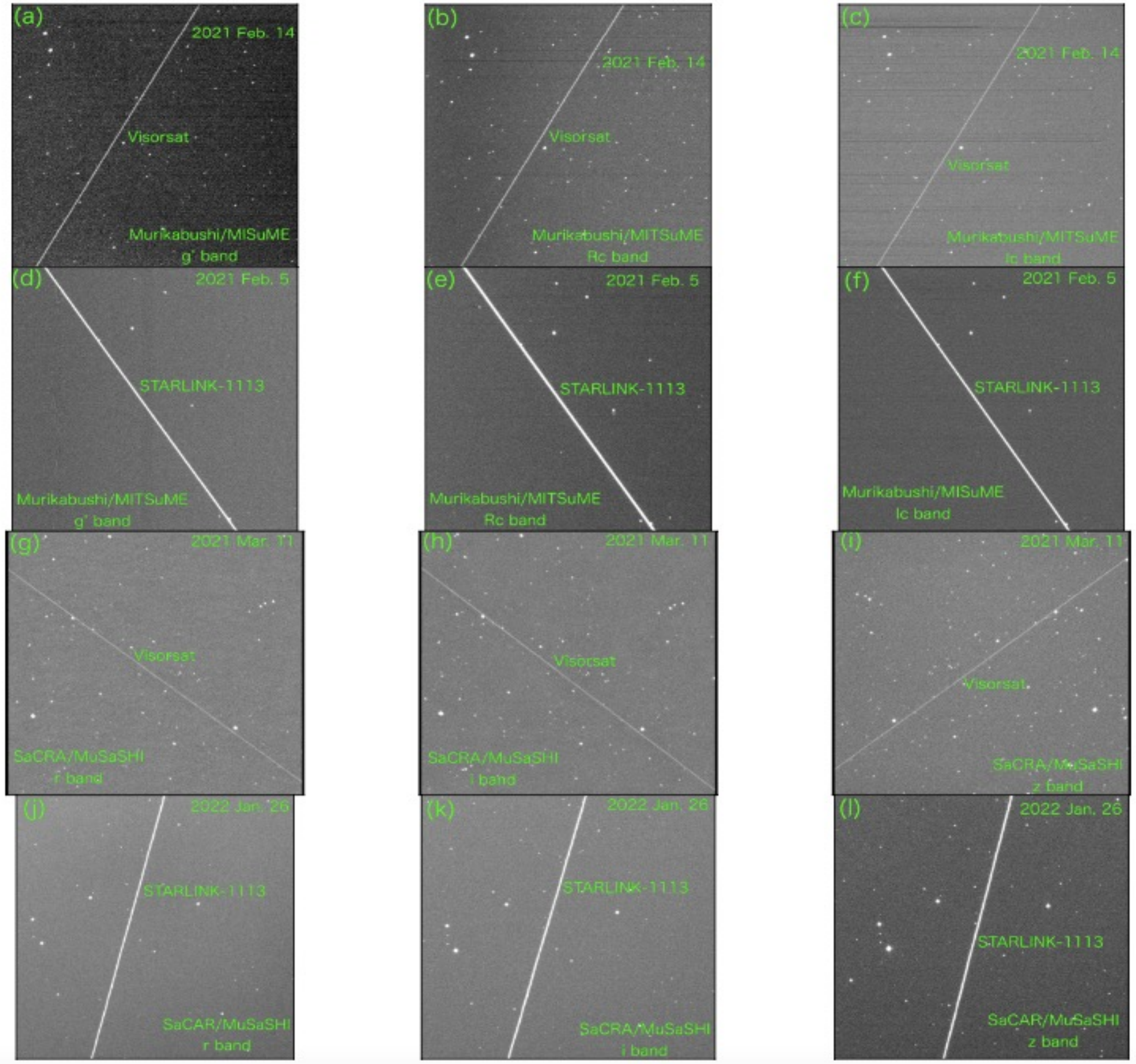
□ Simultaneous multicolor observations with the Japanese OISTER collaboration

→ capture the trail of Visorsat and STARLINK-1113 (original satellite)

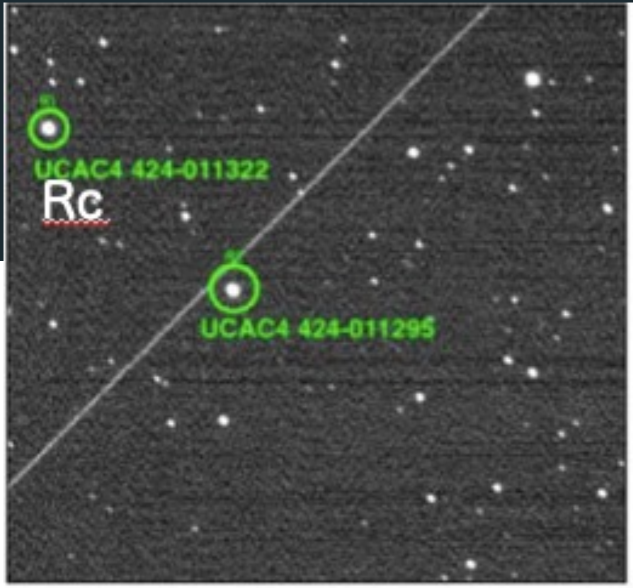
□ Telescopes/instruments:

- Murikabushi and Akeno 50 cm/MITSuME (g, R, I)
- SaCRA/MuSaSHI (r, i, z)
- Kanata/HONIR (B, V, H)
- Nayuta/NIC (J, H, K)
- Kyoto 40cm (B)
- Prika/MSI (U)
- PROMPT6@CTIO (V; other than OISTER)

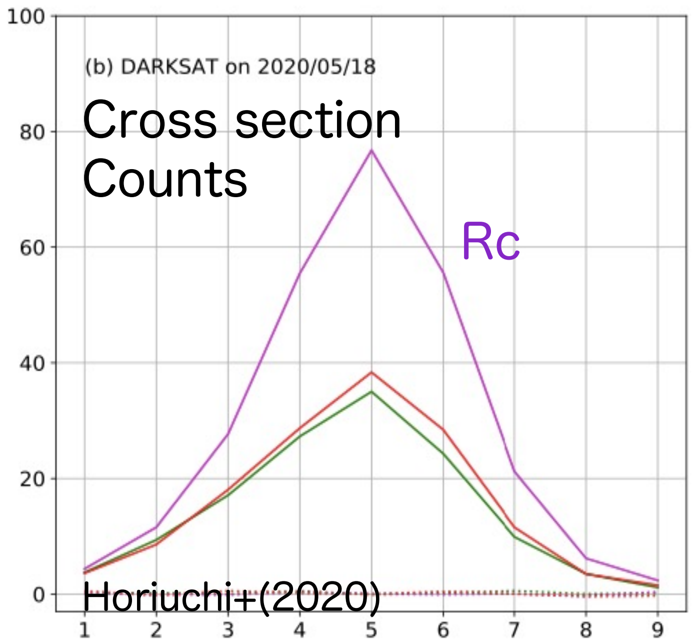
12 bands



Magnitude estimation 1



Using "Projection" in DS9, we estimated average cross section counts of satellite trails (f_{sat})



The observed flux is inversely proportional to the satellite velocity, V_{sat}.

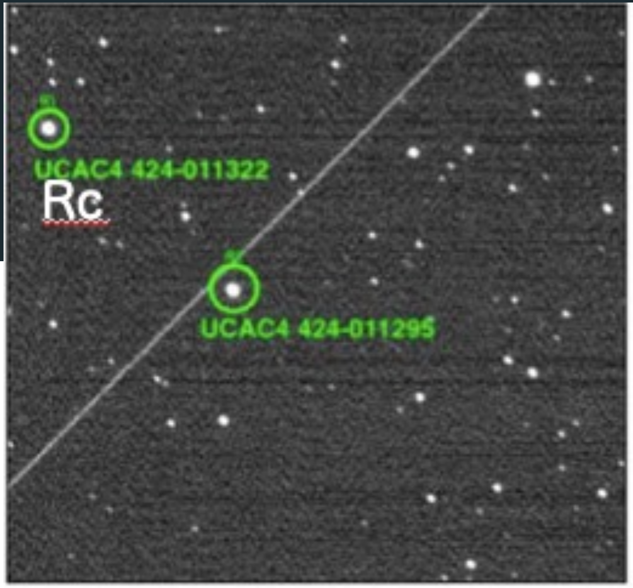
Elongated reference stars (f_{star}) by tracking off

V_{star} = 15 cos δ arcsec s^{-1}

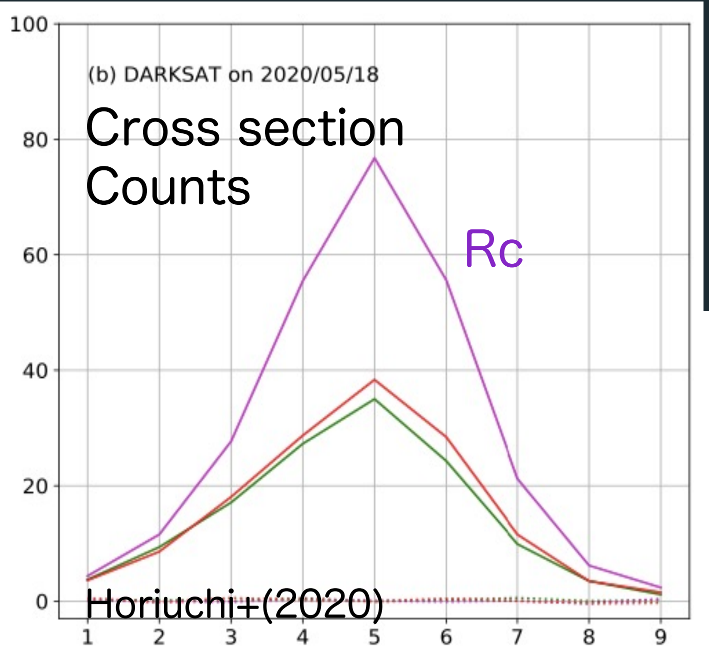
Apparent magnitudes of the satellites, m_{sat}

$$m_{sat} = m_{star} - 2.5 \log \left(\frac{V_{sat}}{V_{star}} \frac{f_{sat}}{f_{star}} \right)$$

Magnitude estimation 2



Using "Projection" in DS9, we estimated average cross section counts of satellite trails ($f_{\rm sat}$)



The observed flux is inversely proportional to the satellite velocity, $V_{\rm sat}$.

Satellite trail (streak)
vs.
Point source

Apparent magnitudes of the satellites, $m_{\rm sat}$

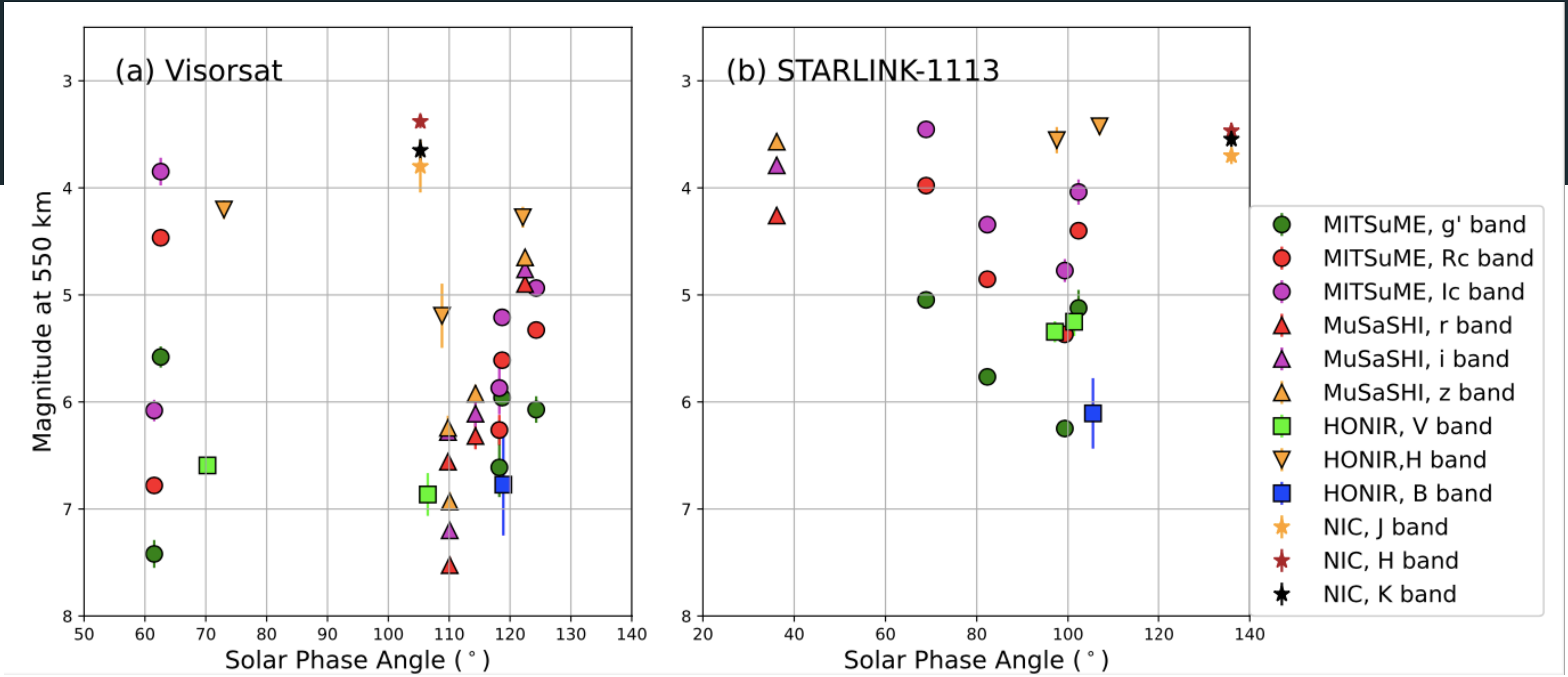
$$m_{\rm sat} = m_{\rm star} - 2.5\log\left(\frac{f_{\rm sat}V_{\rm sat}t_{\rm exp}}{f_{\rm exp}}\right)$$

Typical magnitudes of Visorsat

- Magnitudes at a 550 km height.
- U band magnitude was not able to obtain because of the sensitivity of Pirka/MSI (Hokkaido Univ.).
- Visorsat is dimmer than STARLINK-1113 as a trend.
- The longer the observed wavelength, the brighter the satellite magnitudes become.

Band	Visorsat (mag)	STARLINK-1113 (mag)
B	6.77 ± 0.48	6.11 ± 0.33
V	6.61 ± 0.12	5.25 ± 0.13
g‘	6.07 ± 0.12	5.12 ± 0.17
Rc	5.32 ± 0.04	4.40 ± 0.08
Ic	4.94 ± 0.07	4.04 ± 0.12
r	4.90 ± 0.02	4.26 ± 0.03
i	4.76 ± 0.02	3.79 ± 0.03
z	4.65 ± 0.02	3.57 ± 0.02
J	3.80 ± 0.24	3.70 ± 0.08
H	3.38 ± 0.06	3.47 ± 0.05
K	3.65 ± 0.11	3.55 ± 0.07

Phase angle dependence on magnitudes



- ☐ The satellite magnitudes are minimized around solar phase angle (Sun-Sat-Observer) of 90°.
- ☐ The magnitudes of Visorsat are ~ 1 mag dimmer than those of STARLINK-1113.

Blackbody model of the satellite flux

- ☐ In order to estimate the albedo, a_{mod}, of the starlink satellites, we construct the blackbody model of the satellite (AB) flux.

- ☐ Assuming a_{mod}(STARLINK-1113) ~ a_{mod}(Visorsat), we estimated covering foctor, C_{f}, of the sun visor on Visorsat (where U_{f} = 1 - C_{f}).

$$F_{\mathrm{RS}} = \pi \left(\frac{R_{\odot}}{1\ \mathrm{au}} \right)^2 B(\lambda,\ T_{\odot})\, a_{\mathrm{mod}}\, p(\theta)\, U_{\mathrm{f}} \left(\frac{r_{\mathrm{sat}}}{h_{\mathrm{T}}} \right)^2 \frac{\lambda^2}{c}$$

$$F_{\mathrm{REs}} = a_{\mathrm{E}} \left(\frac{R_{\oplus}}{R_{\oplus} + h_{\mathrm{T}}} \right)^2 \left\{ 1 - \left(\frac{R_{\oplus}}{R_{\oplus} + h_{\mathrm{T}}} \right)^2 \right\} \frac{p(\phi)}{p(\theta) U_{\mathrm{f}}} F_{\mathrm{RS}}$$

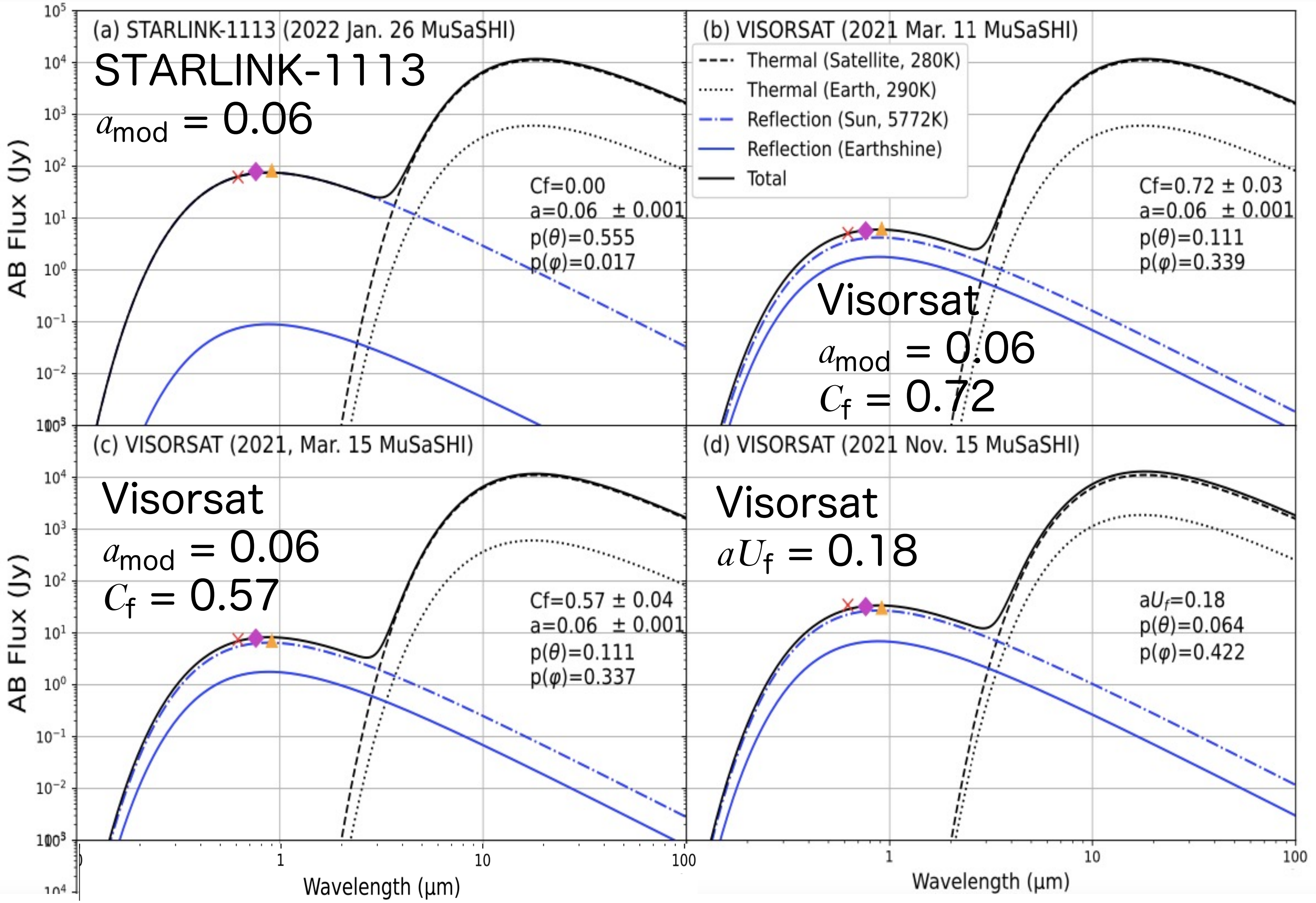
$$F_{\mathrm{TS}} = \pi \epsilon \left(\frac{r_{\mathrm{sat}}}{h_{\mathrm{T}}} \right)^2 B(\lambda,\ T_{\mathrm{sat}}) \frac{\lambda^2}{c}$$

$$F_{\mathrm{TE}} = \pi \epsilon \left(\frac{R_{\oplus}}{R_{\oplus} + h_{\mathrm{T}}} \right)^2 B(\lambda,\ T_{\mathrm{E}})\, a_{\mathrm{mod}} \left(\frac{r_{\mathrm{sat}}}{h_{\mathrm{T}}} \right)^2 \frac{\lambda^2}{c},$$

F_{RS} : sunlight reflection
F_{REs} : earthshine reflection
F_{TS}: thermal radiation of the satellite
F_{TE}: reflection of Earth’s thermal radiation

Blackbody fitting to the satellite flux (ex1)

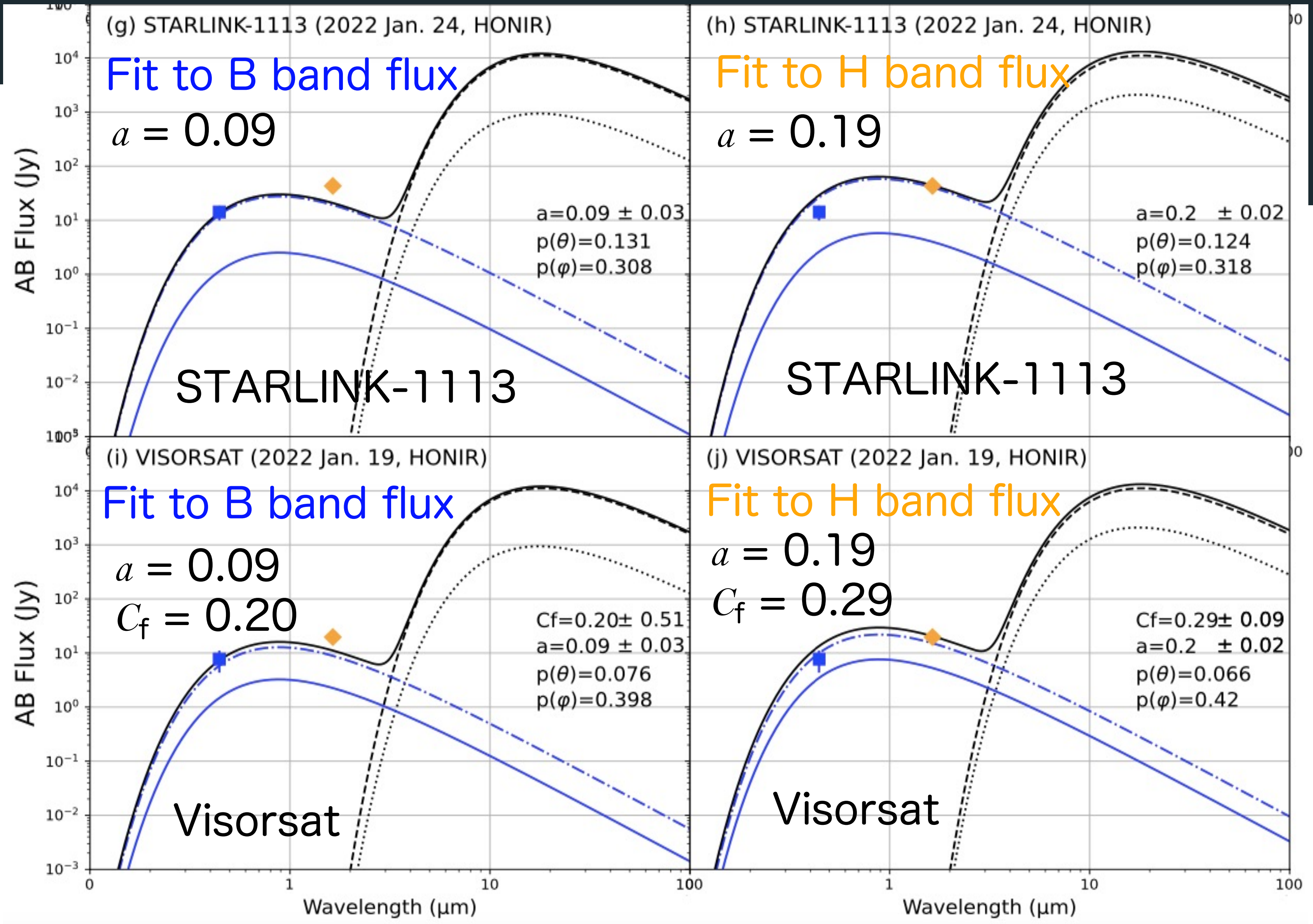
- ☐ Model fitting to r, i, and z band flux obtained with SaCRA/MuSaSHI (Saitama Univ.).
- ☐ Together with the results with other telescopes, the range of the covering factor is $0.18 < C_f < 0.92$.



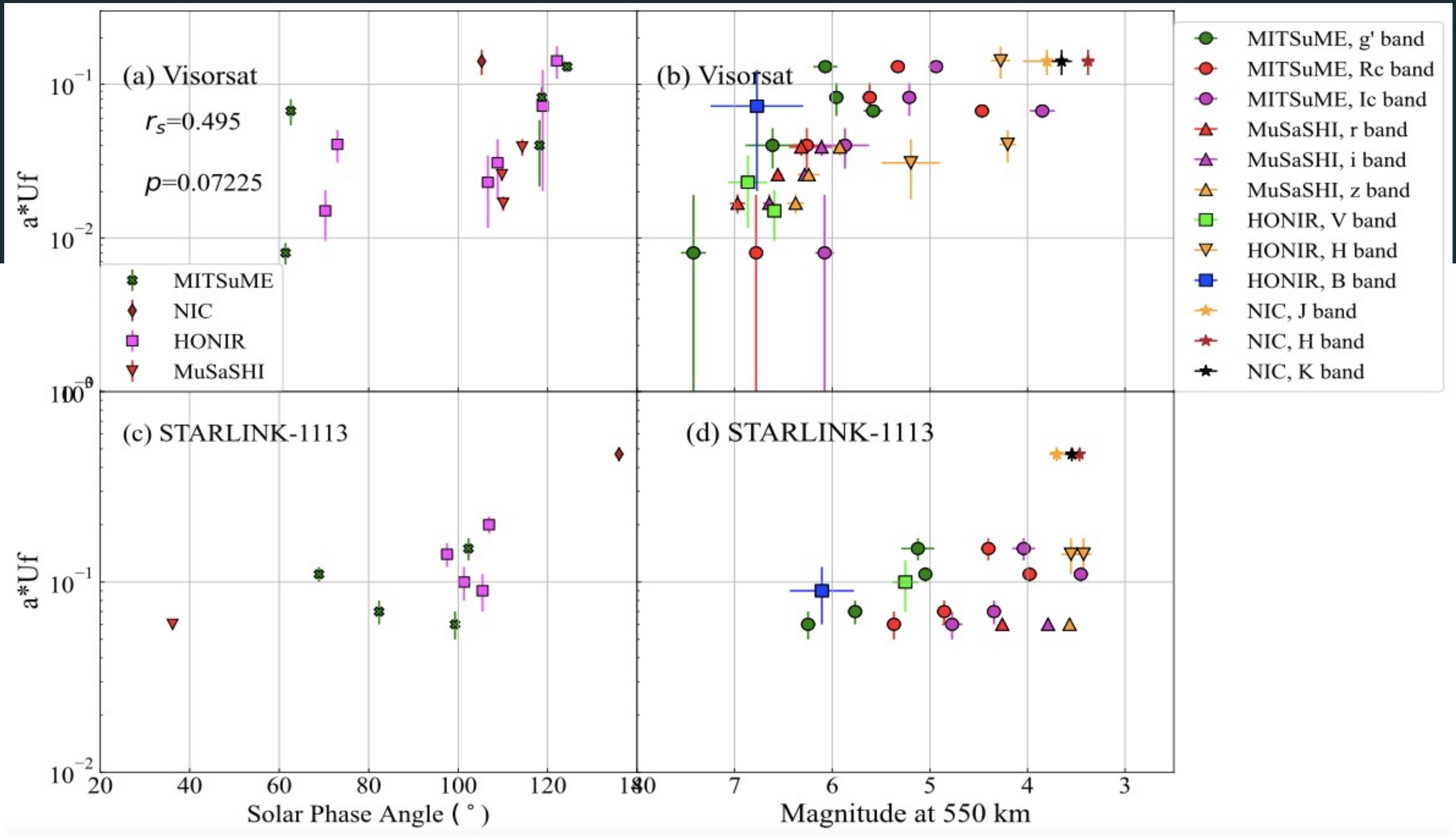
Flux model for B and H bands (ex2)

- ☐ B and H bans flux obtained with Kanata/HONIR (Hiroshima Univ.)

- ・The albedo of H band is about twice larger than that of B band.
- ・・The reflectivity of satellite surface materials likely become higher at the longer wavelength.



The relation between covering factor, brightness, and phase angle



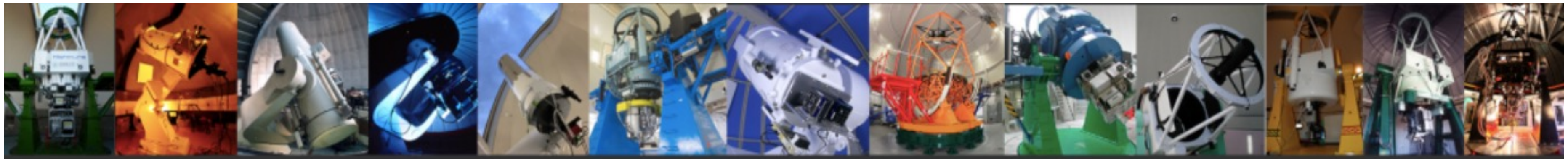
The smaller the covering factor is, the brighter the magnitudes of Visorsat tend to become.

Summary

☐ We observed Visorsat and STARLINK-1113 with the OISTER collaboration.

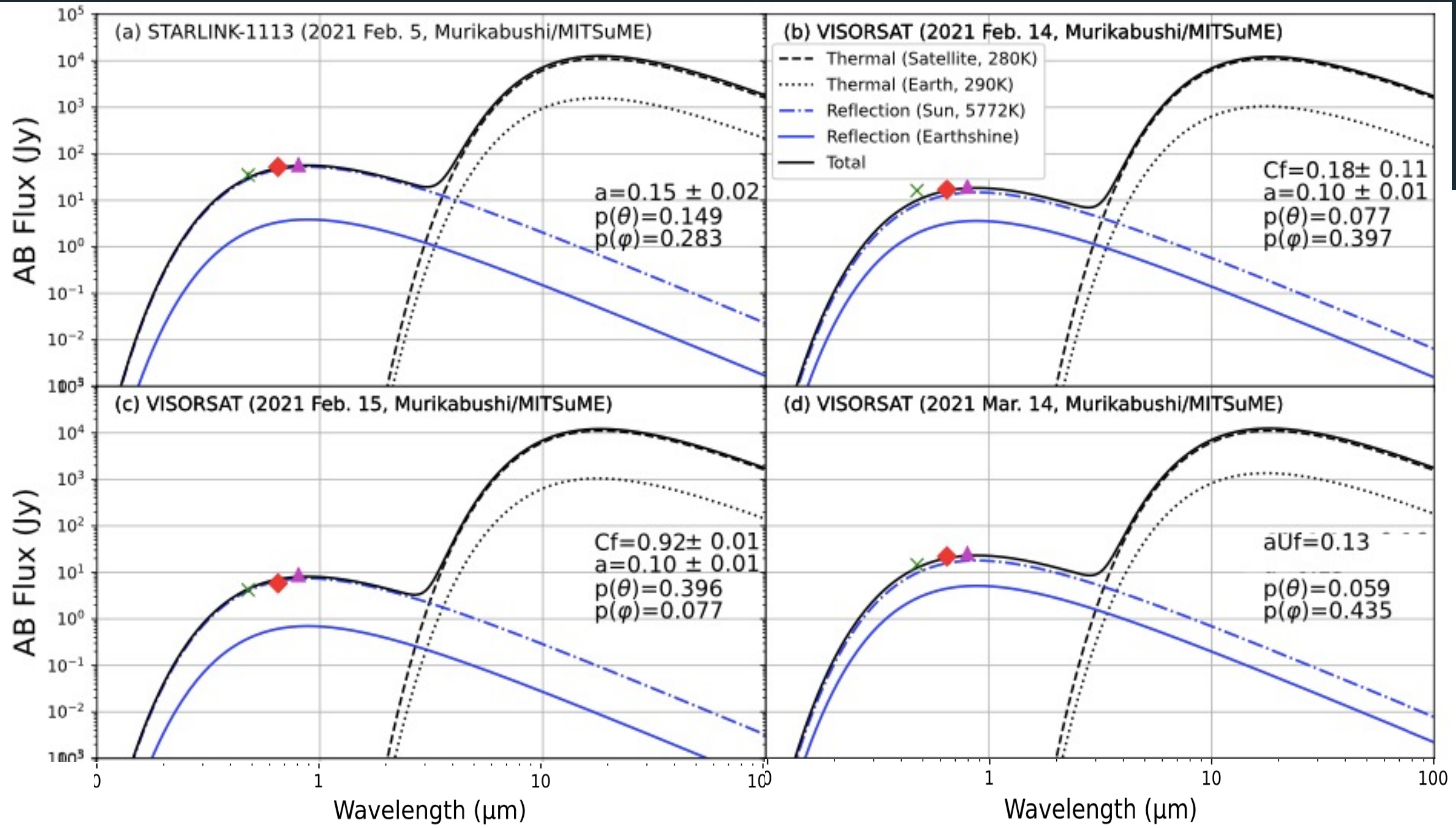
- In most cases, Visorsat (~ 6 – 7 mag) is dimmer than STARLINK-1113 (~ 5 – 6 mag) as a trend.
- By assuming the blackbody radiation, we estimated a covering factor, Cf, and its range of 0.18 $< C_{\mathrm{f}} <$ 0.92.
- The reflectivity of satellite surface materials likely become higher at the longer wavelength.

☆ While we showed the shading effect of the sun visor of Visorsat, the observational impact from Visorsat is still profound (Horiuchi+ submitted).

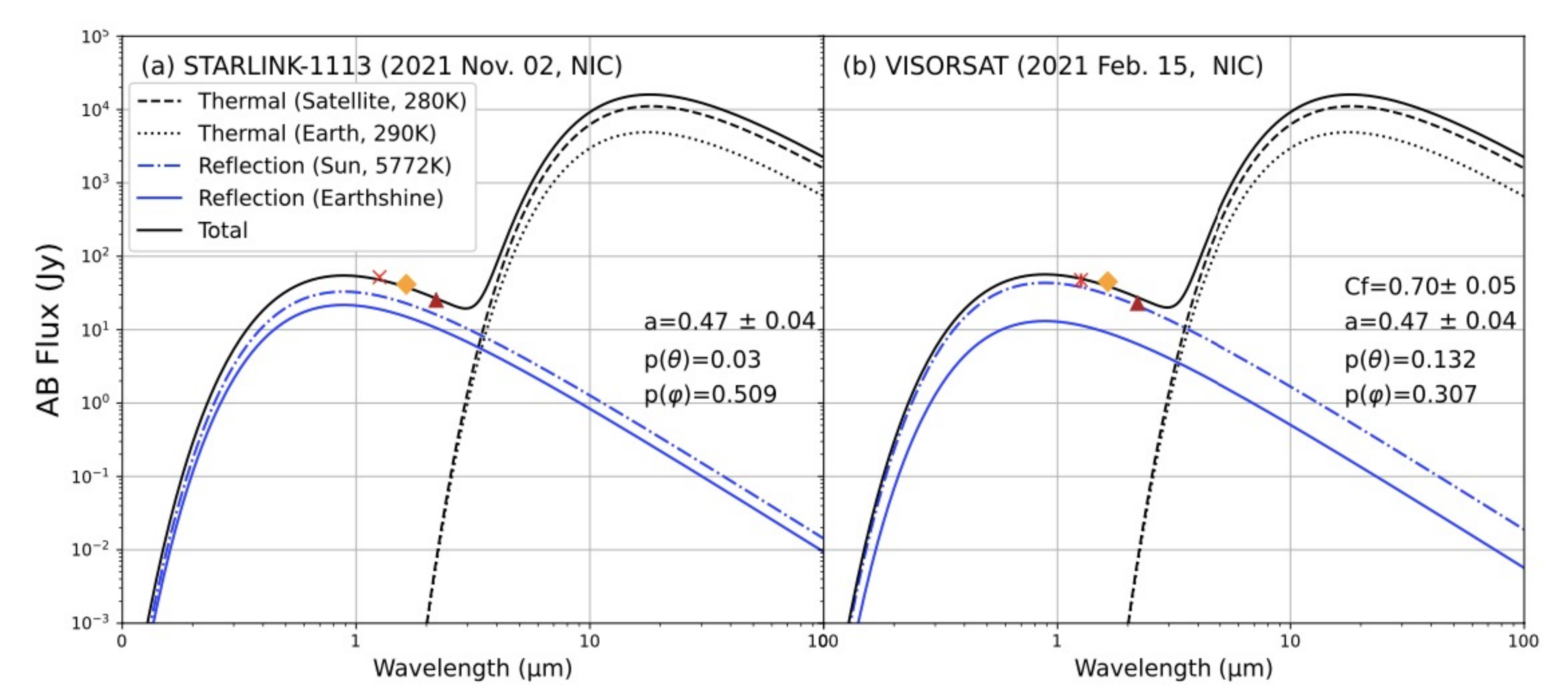


© OISTER

Blackbody fitting to the satellite flux (ex3)

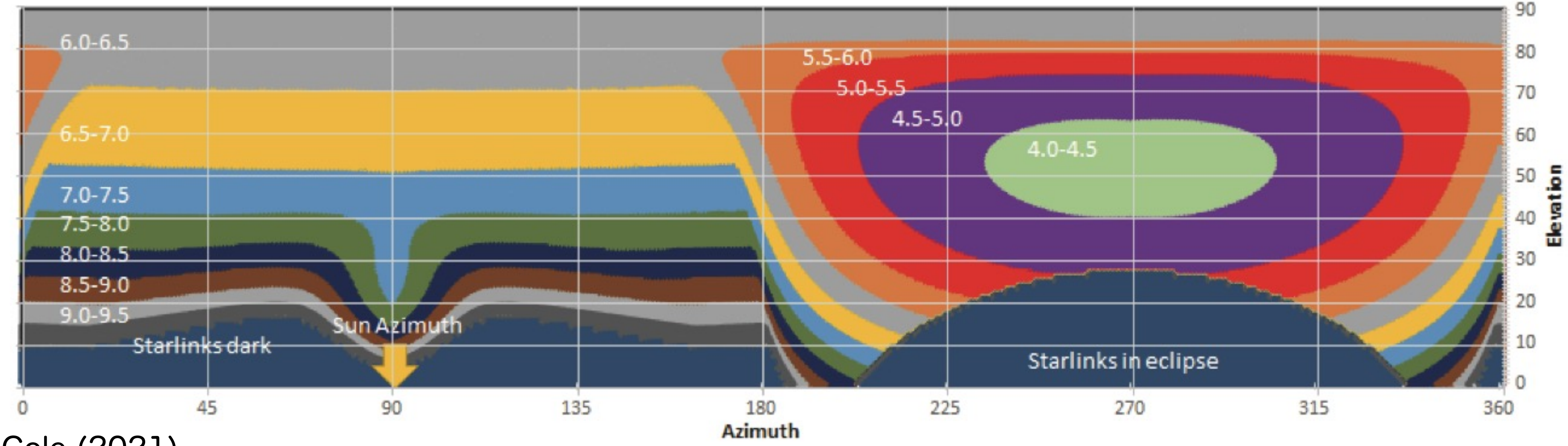


Blackbody fitting to the satellite flux (ex4)



☐ The albedo of near infrared bands (J, H, and K) is somewhat higher than that of optical region.

Az, El dependence of magnitudes



Cole (2021)

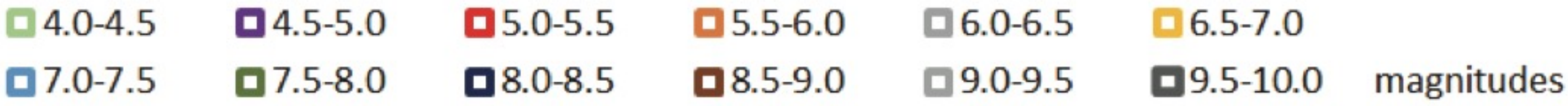


Figure 21: The modelled apparent magnitude of the visorsat across the sky using updated best-fit parameters for the June 2021 dataset. This plot is for the pointing mode with the solar-panel at a fixed angle with respect to the local vertical at the spacecraft, in this case 5° towards the Sun-azimuth. The modelled solar azimuth is 90° and depression angle 15°.

Simulation of the impact on astronomical observations with a large telescope

Tyson et al. (2020) simulated the impact from the Starlink satellites on LSST observations

- Using artificial satellite trails at the level corresponding to v0.9 Starlink satellites, they showed the negative impact on CCDs

-- the main trail is ~1000 times brighter than important astronomical signals.

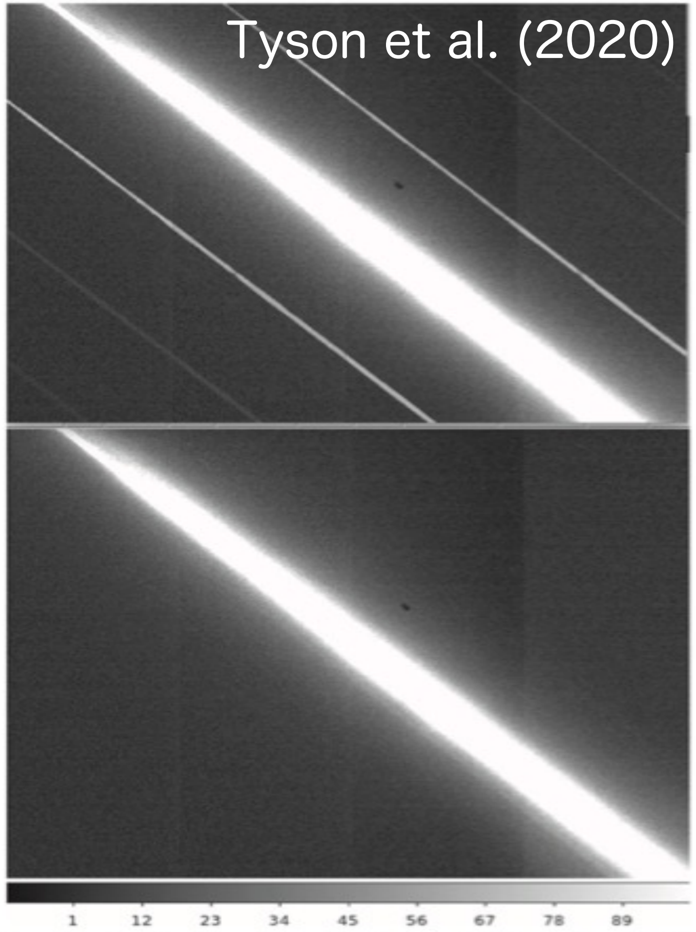


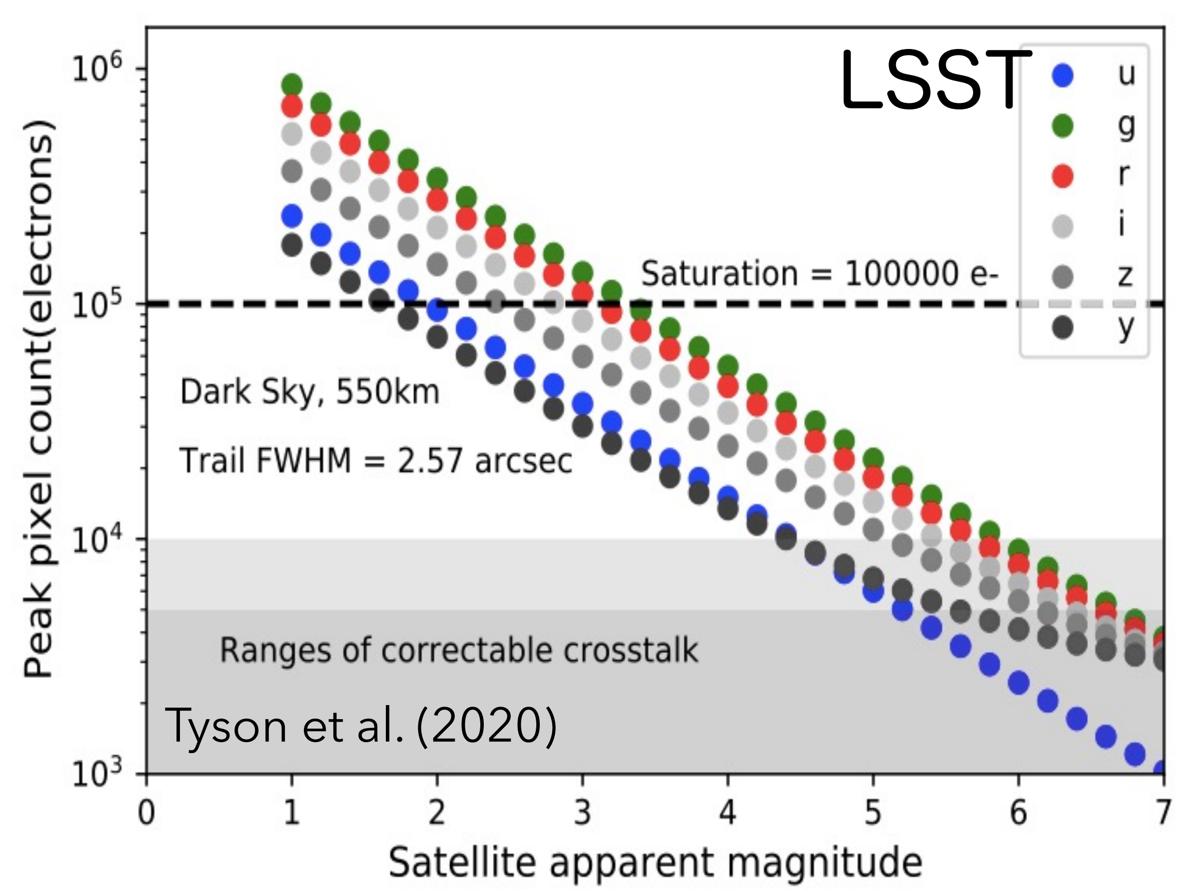
Figure 11. Top: the image that results when an artificial satellite trail at the level corresponding to v0.9 Starlink satellites (bright, but below pixel saturation) is projected onto a e2v CCD in the laboratory. Four of 16 channels of a single raw CCD image are shown, and six crosstalk stripes induced by the main trail are visible. Below: the same image after a preliminary nonlinear crosstalk correction algorithm has been applied (see Section 7.1). While the crosstalk trails are nearly removed, the remaining trail itself is several hundred pixels wide and has a surface brightness ~1000 times that of important astrophysical signals.

Simulation of the impact on astronomical observations with a large telescope

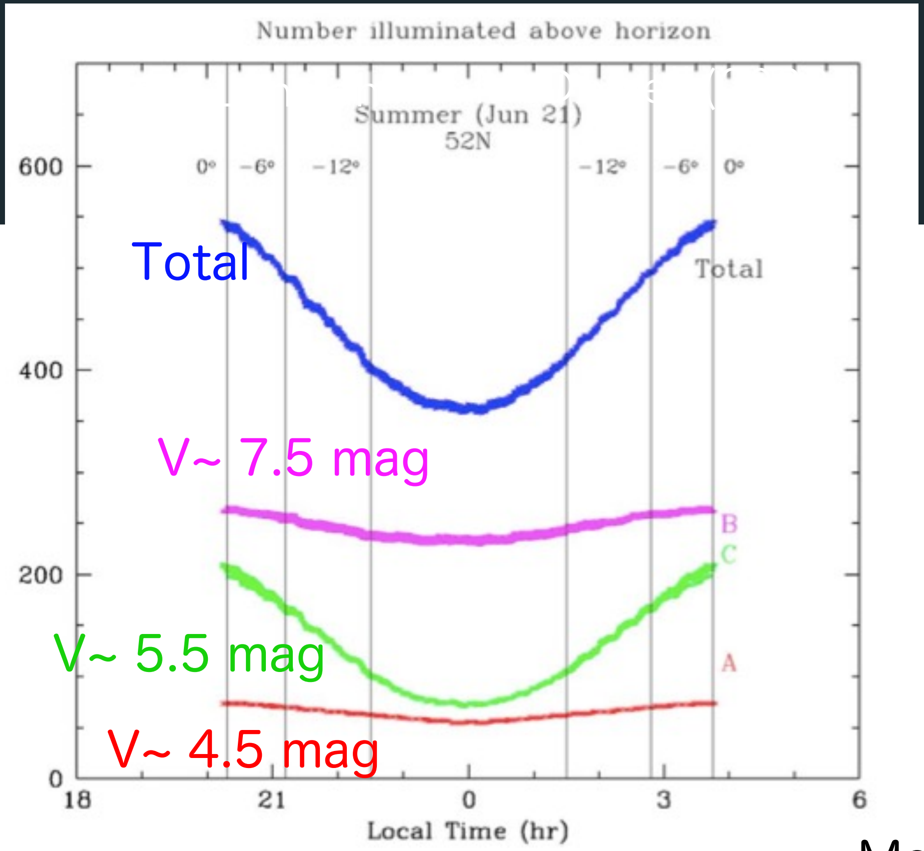
Tyson et al. (2020) simulated the impact from the Starlink satellites on LSST observations

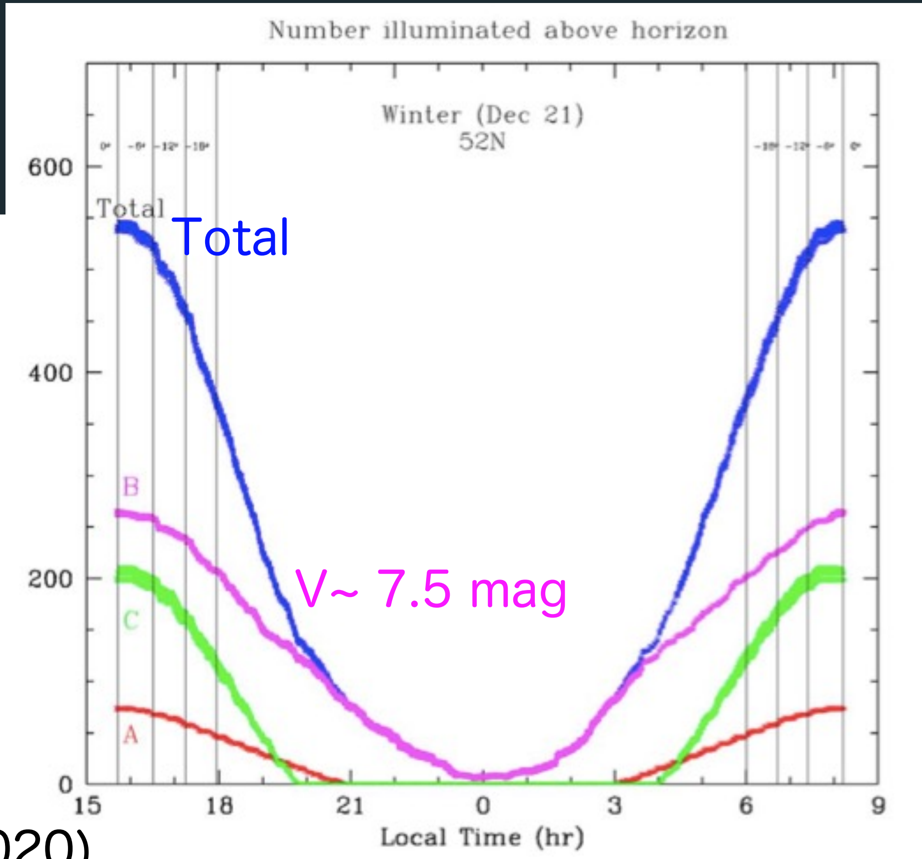
-a satellite magnitude - CCD counts (e-) relation was verified in six passbands: u, g, r, I, z, and y bands

-- the CCD will saturate at ~3.5 and ~1.5 mag in g and y bands, respectively.



Relation between time of day and number of satellites

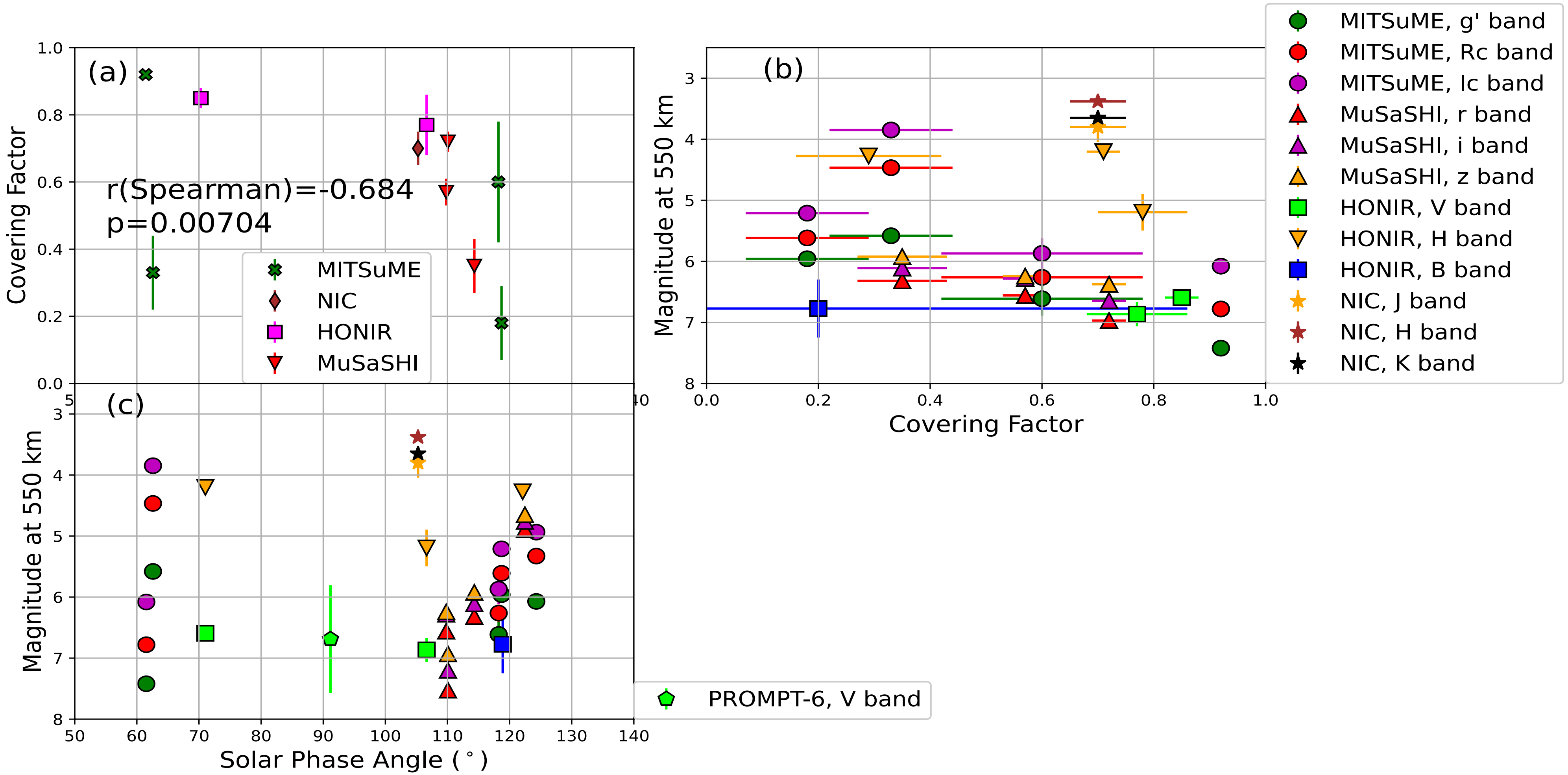




McDowell (2020)

The Starlink satellites can be observed even in the middle of the night.

The relation between covering factor, brightness, and phase angle



The smaller the covering factor is, the brighter the magnitudes of Visorsat tend to become.