Attitude estimation of GLONASS-M+ and -K2 satellites

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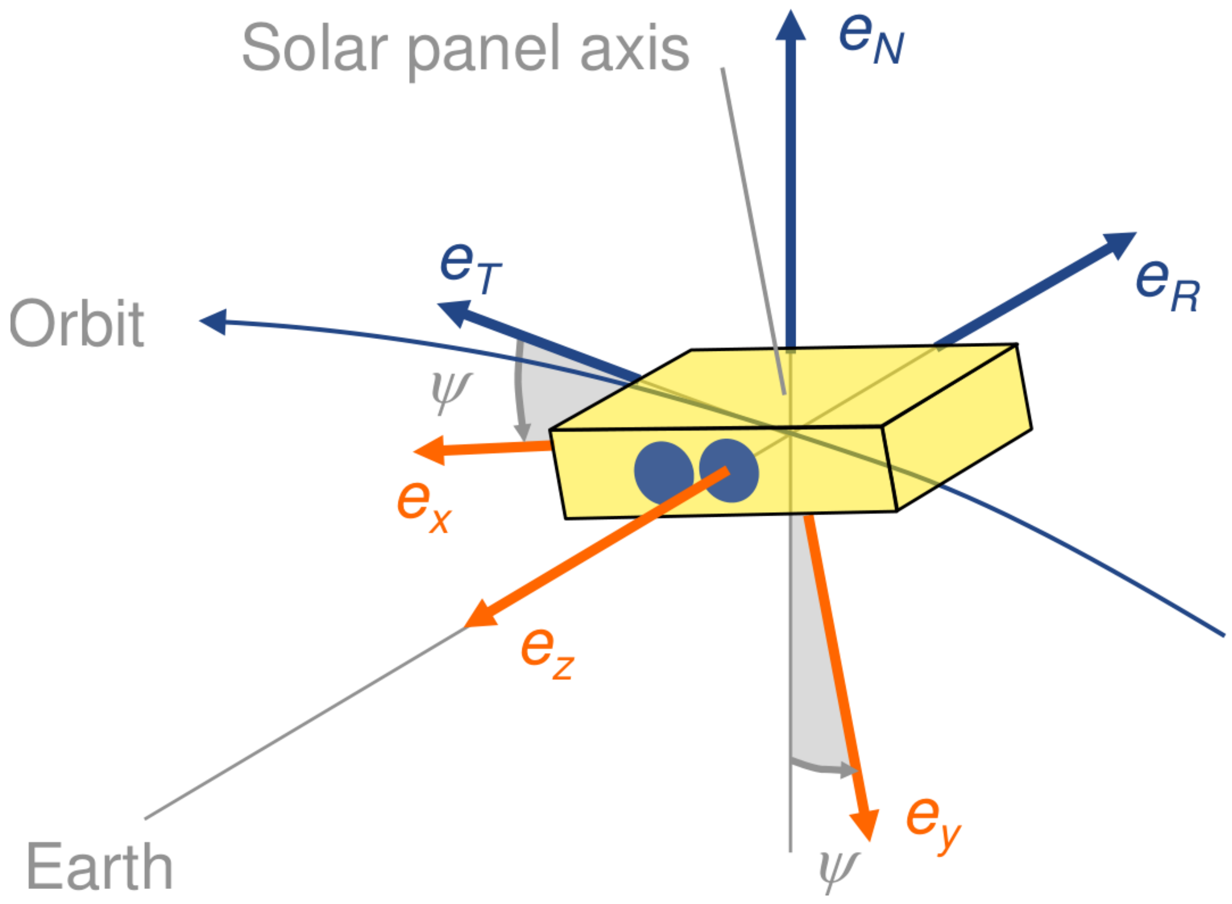
DLR

Attitude of GNSS Satellites

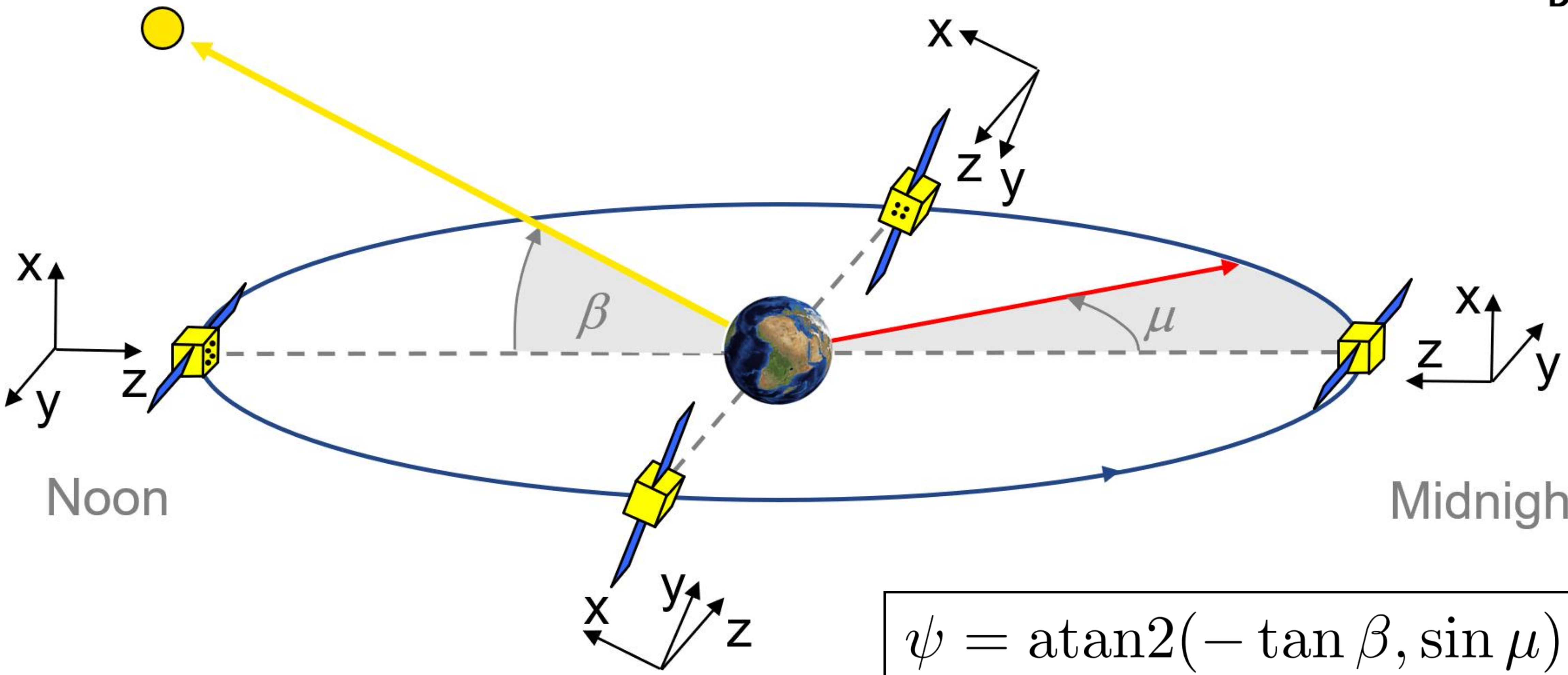


Orbit frame: e_R, e_T, e_N

Body-frame: e_X, e_Y, e_Z

Yaw angle: ψ

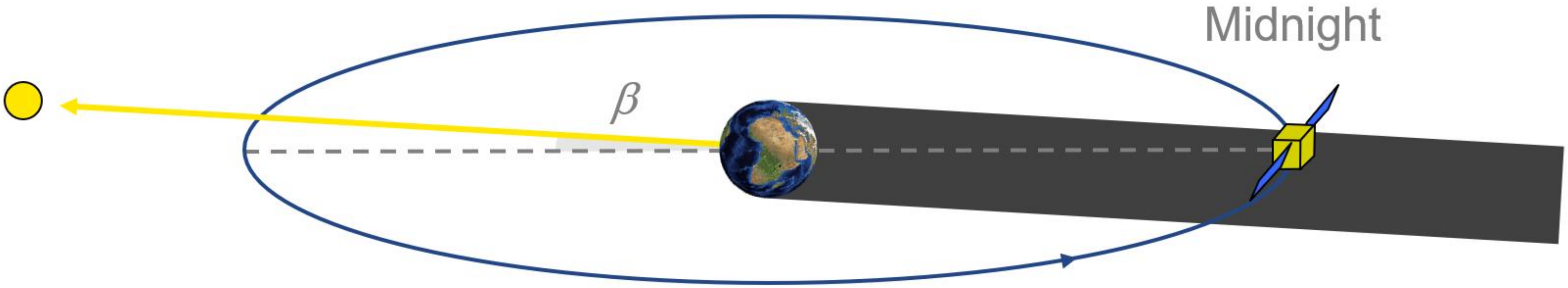
Nominal Yaw-Steering



$$\psi = \operatorname{atan2}(-\tan\beta, \sin\mu)$$

β elevation of Sun above orbital plane μ orbit angle w.r.t. midnight

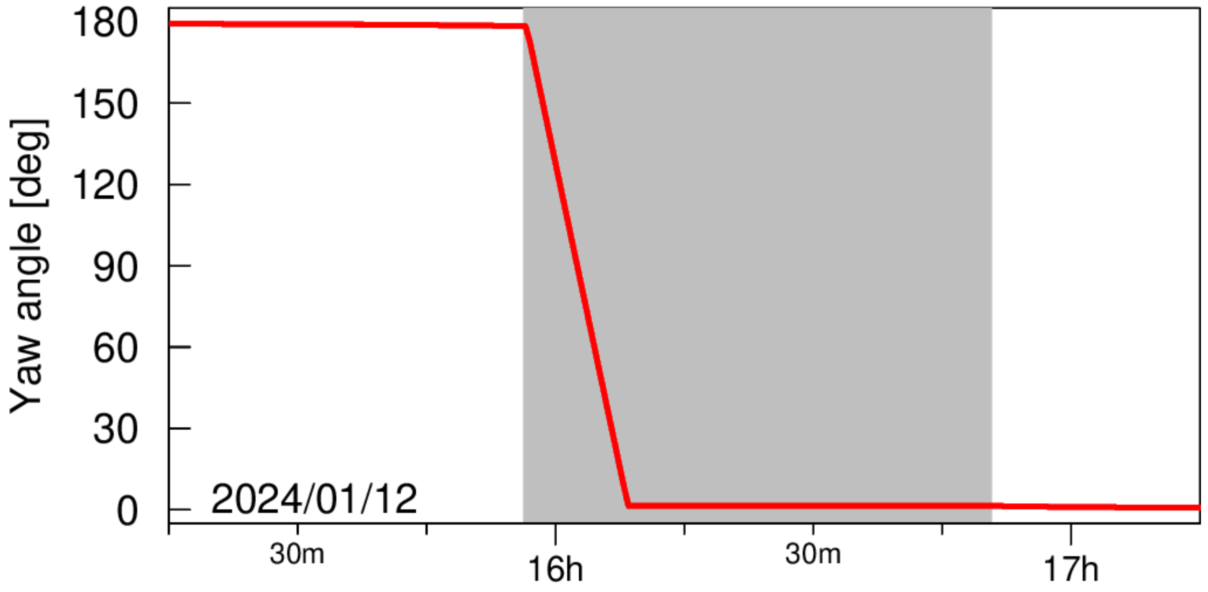
Rate-limited Yaw Steering



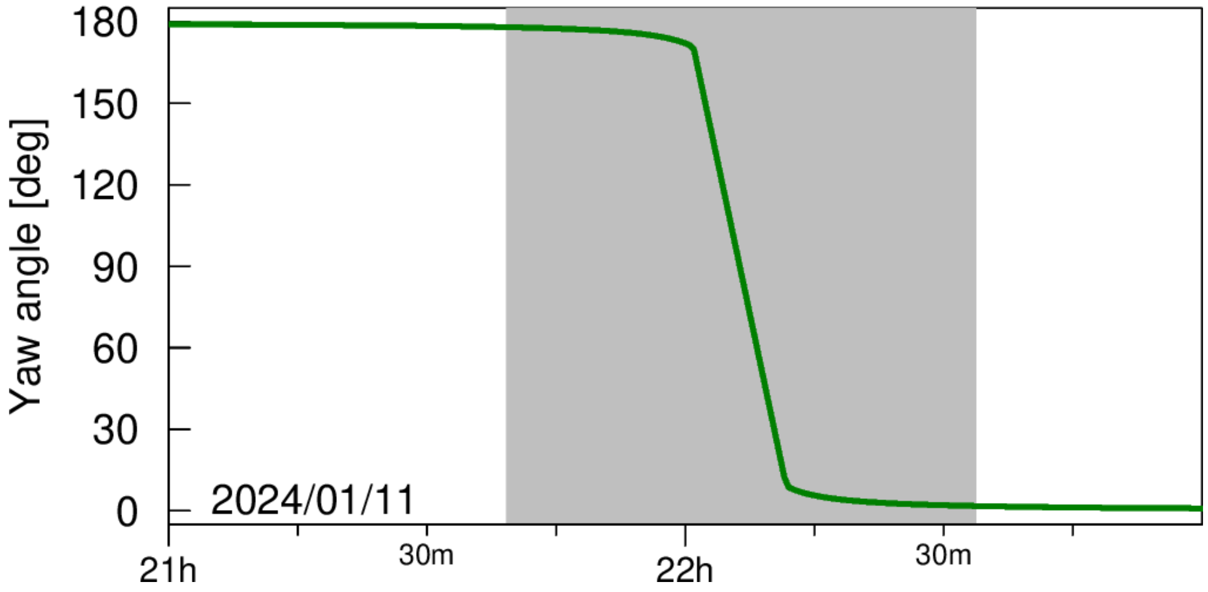
- Maximum yaw rate $\dot{\psi}_{\text{max}} \lesssim 0.25\,^\circ/\text{s}$
- Nominal yaw rates exceed hardware limits for small elevations of the Sun above the orbital plane $|\beta_{\text{GLO}}| \approx 2.0^\circ$
- Different concepts for rate-limited yaw steering

GLONASS Attitude

GLONASS-M and -M+



GLONASS-K1 and -K2



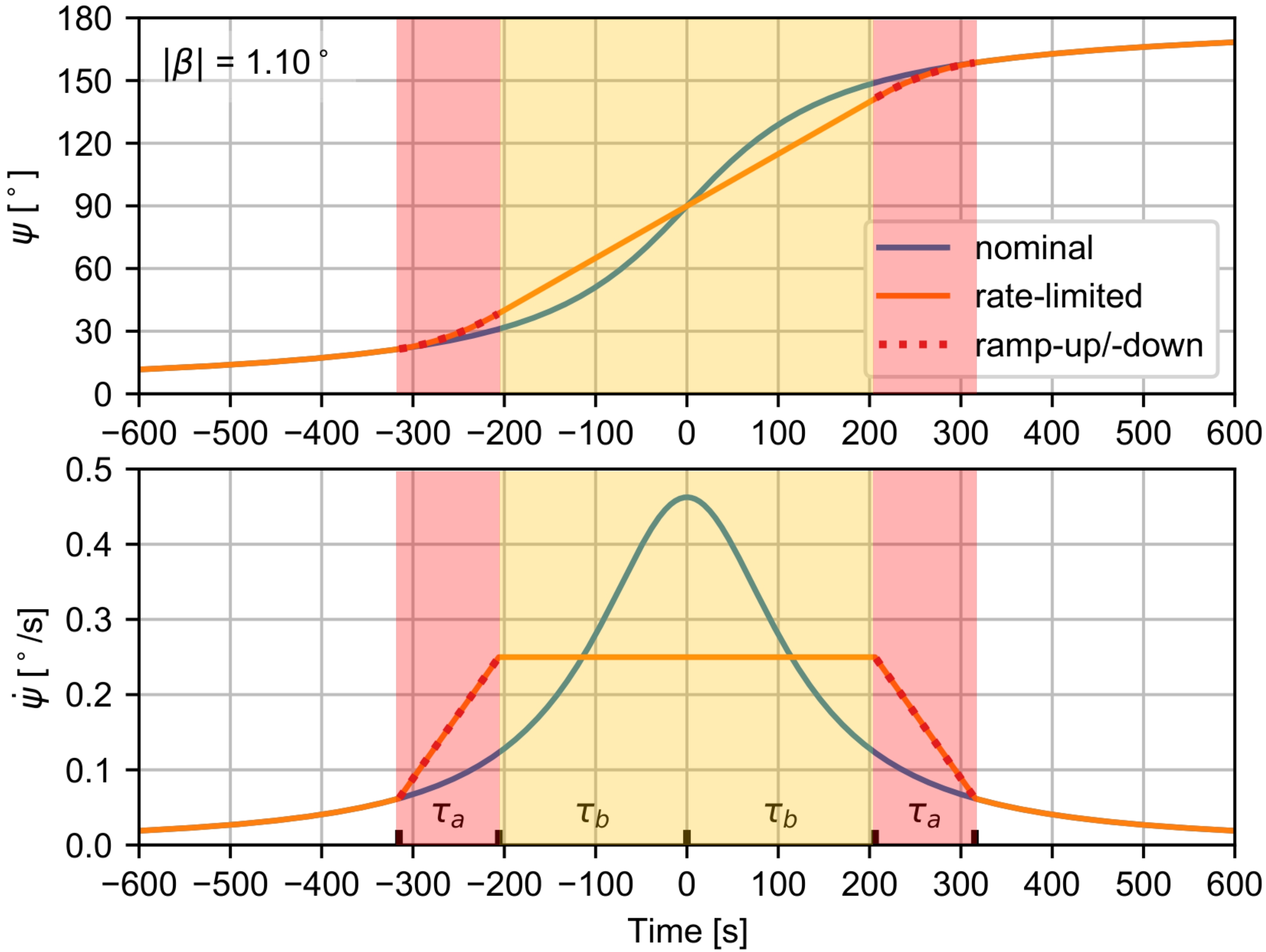
Reverse kinematic precise point positioning

Dilsner, F., Springer, T., Gienger, G., & Dow, J. (2011). The GLONASS-M satellite yaw-attitude model. *Advances in Space Research*, *47*(1), 160–171. https://doi.org/10.1016/j.asr.2010.09.007

GLONASS CDMA Interface Control Document

Russian Space Systems (2016). GLONASS Interface Control Document: General Description of Code Division Multiple Access Signal System, Edition 1.0

GLONASS-K Rate-Limited Attitude



1. Ramp-up phase

   Up to ~ 140 s

2. Constant yaw rate

   Up to ~ 550 s

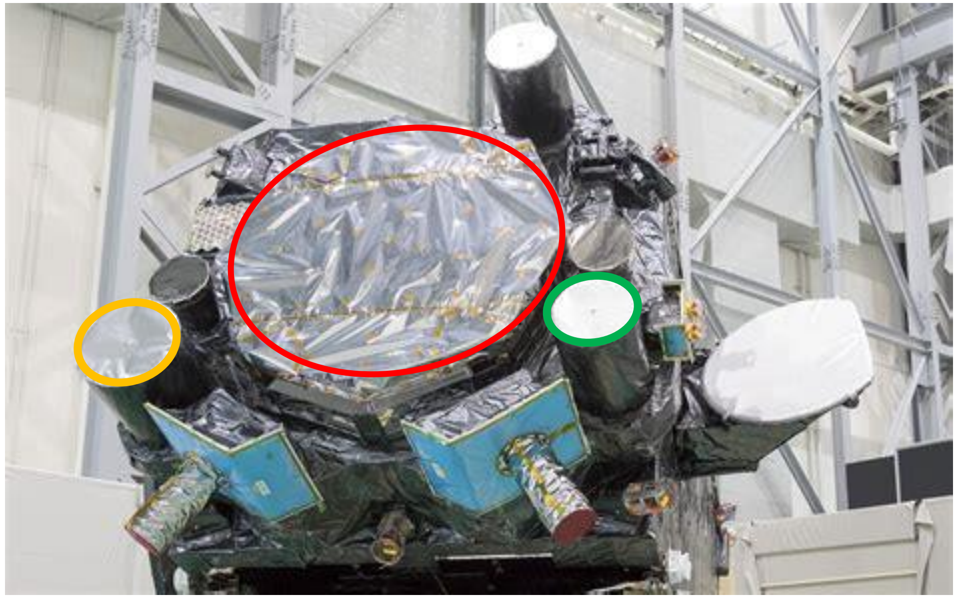
3. Ramp-down phase

   Up to ~ 140 s

GNSS Satellites with Multiple L-Band Antennas

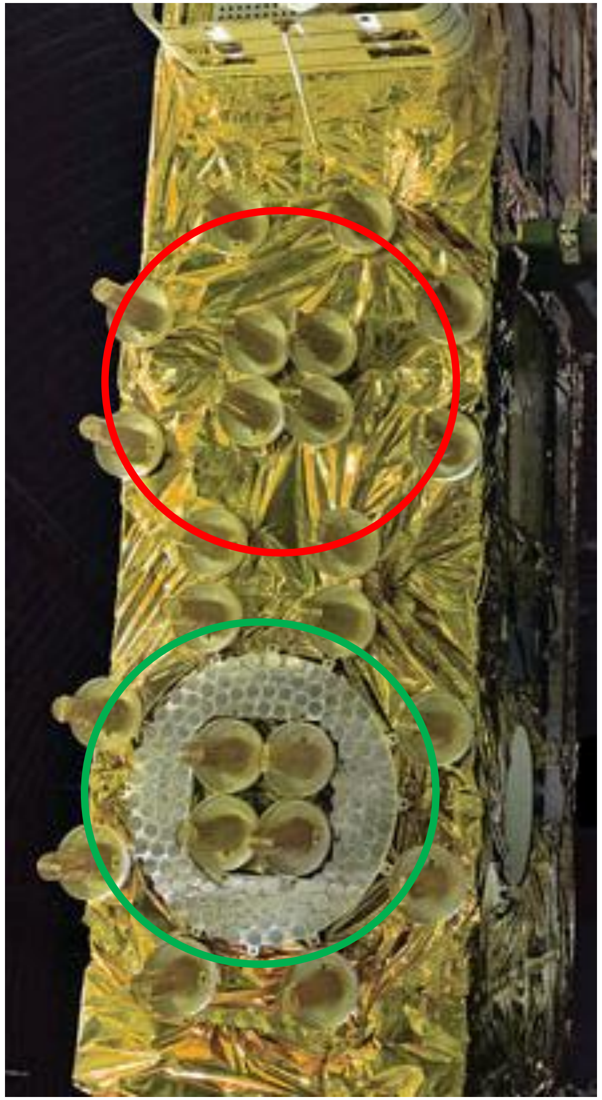
GNSS satellites with two or three antennas:

- QZSS
  - L-Ant: L1/L2/L5
  - L1S-ANT
  - L5S-ANT
- GLONASS-M+
  - L1/L2 FDMA
  - L3 CDMA
- GLONASS-K2
  - – L1/L2 FDMA
  - – L1/L2/L3 CDMA



QZS-3; Image: Mitsubishi

Hauschild, A. (2019). GNSS yaw attitude estimation: Results for the Japanese Quasi-Zenith Satellite System Block-II satellites using single- or triple-frequency signals from two antennas. *Navigation*, *66*(4), 719–728. https://doi.org/10.1002/navi.333



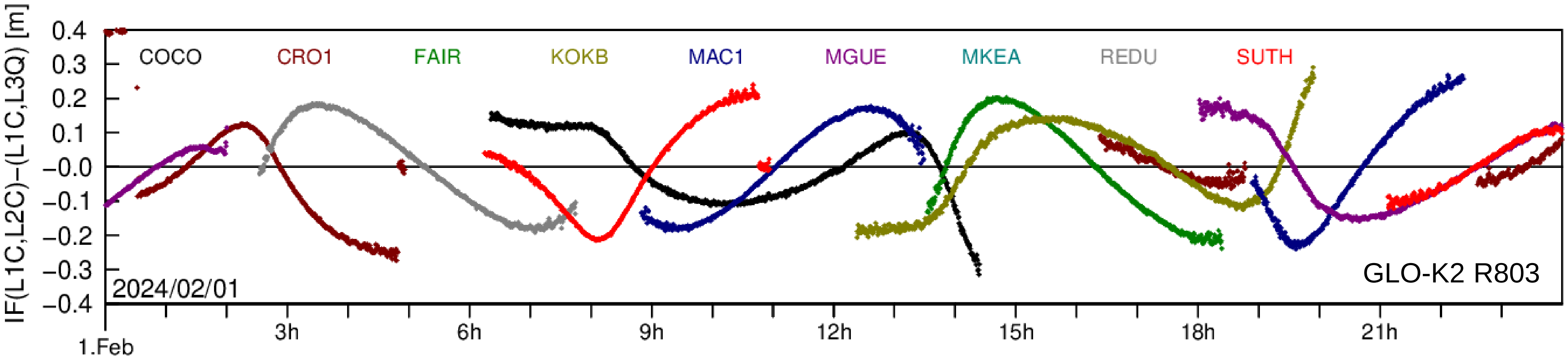
GLONASS-K2; Image: ISS Reshetnev

Triple Carrier Combination

Difference between two ionosphere-free linear combination (geometry-free)

$$\mathrm{IF}(\varphi_a, \varphi_b) - \mathrm{IF}(\varphi_a, \varphi_c) = (\gamma_{ab} - \gamma_{ac})\varphi_a - \gamma_{ab}\varphi_b + \gamma_{ac}\varphi_c$$

$$\gamma_{ab} = \frac{f_b^2}{f_a^2 - f_b^2}, \qquad \gamma_{ac} = \frac{f_c^2}{f_a^2 - f_c^2}$$



Attitude Estimation

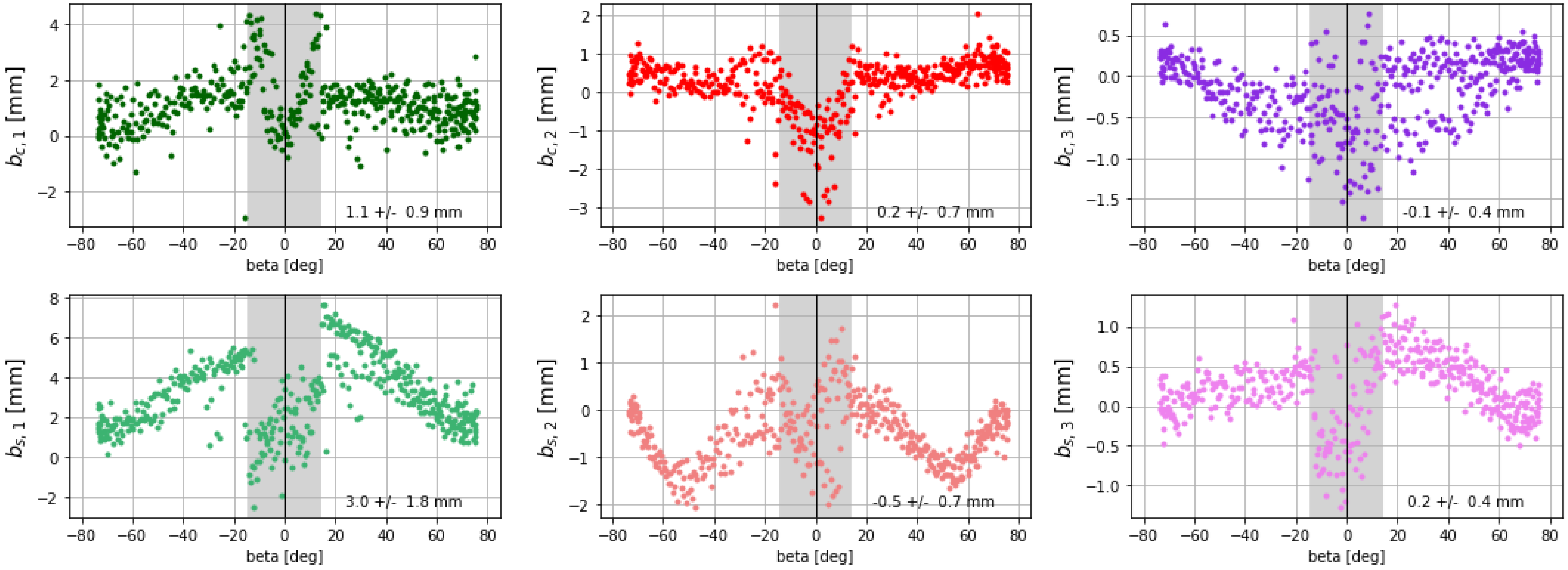
$$\varphi_{\text{tri}} = \mathbf{e}^T \mathbf{R}_z(\psi)^T \mathbf{d}_{\text{tri}} + A_{\text{tri}} + \frac{\lambda_{\text{tri}}}{2\pi}\Psi + b_{\text{tri}} + \varepsilon_{\text{tri}}$$

$\mathbf{e}$	receiver-to-satellite line-of-sight unit vector
$\mathbf{R}_z$	rotation around the spacecraft z-axis
ψ	yaw angle
$\mathbf{d}_{\text{tri}}$	baseline
A_{tri}	carrier phase ambiguities
Ψ	relative antenna rotation angle
b_{tri}	satellite bias
ε_{tri}	noise and unmodeled errors

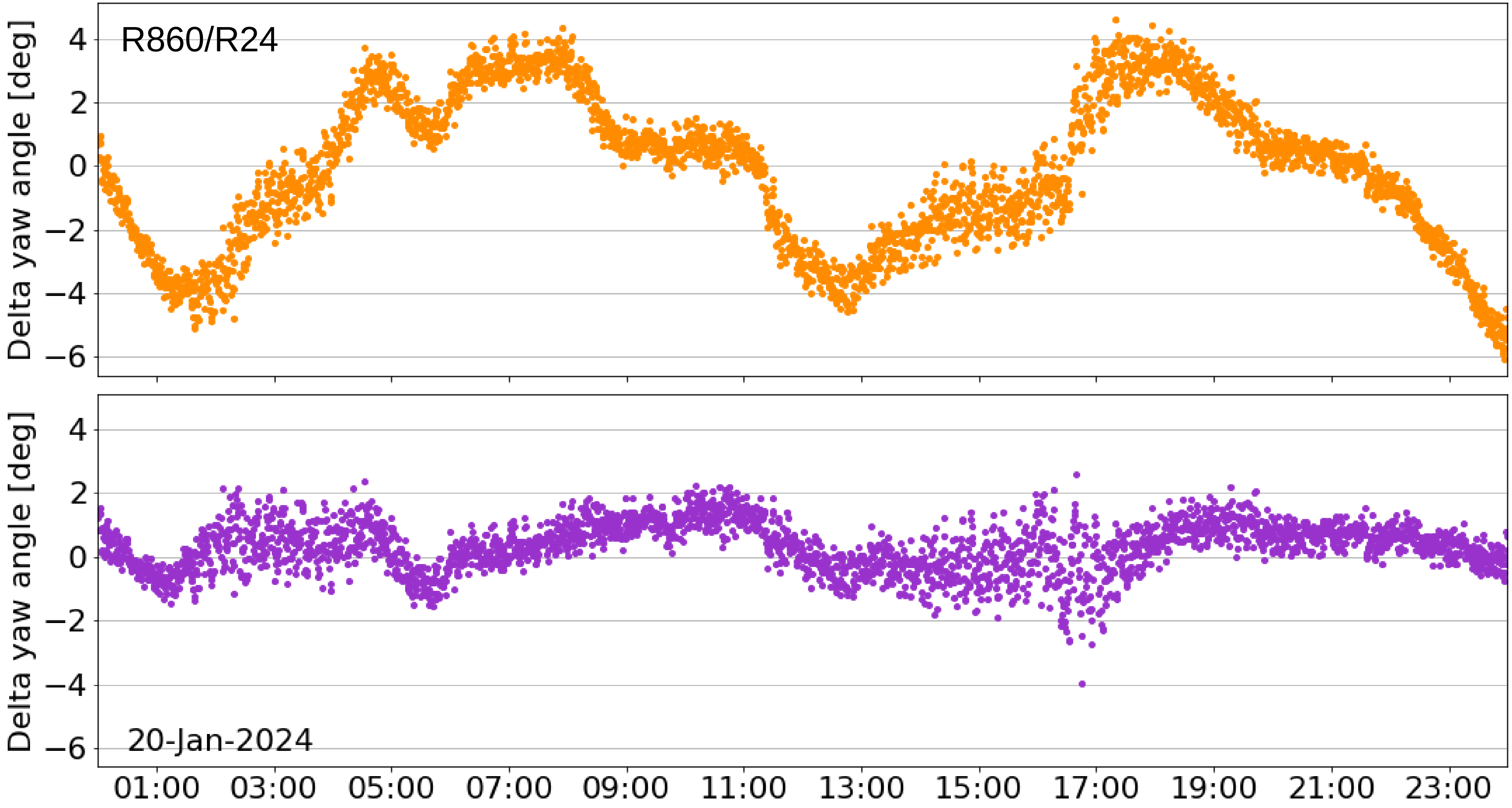
$$\mathbf{d}_{\text{tri}} = (\gamma_{ab} - \gamma_{ac}) \cdot \text{PCO}_a - \gamma_{ab} \cdot \text{PCO}_b + \gamma_{ac} \cdot \text{PCO}_c$$

Satellite Bias Estimates

$$b_{\text{tri}} = \sum_{i=1}^{n} \left(b_{c,i}\cos(i\mu) + b_{s,i}\sin(i\mu)\right)$$



Impact of Satellite Bias Estimation (1)



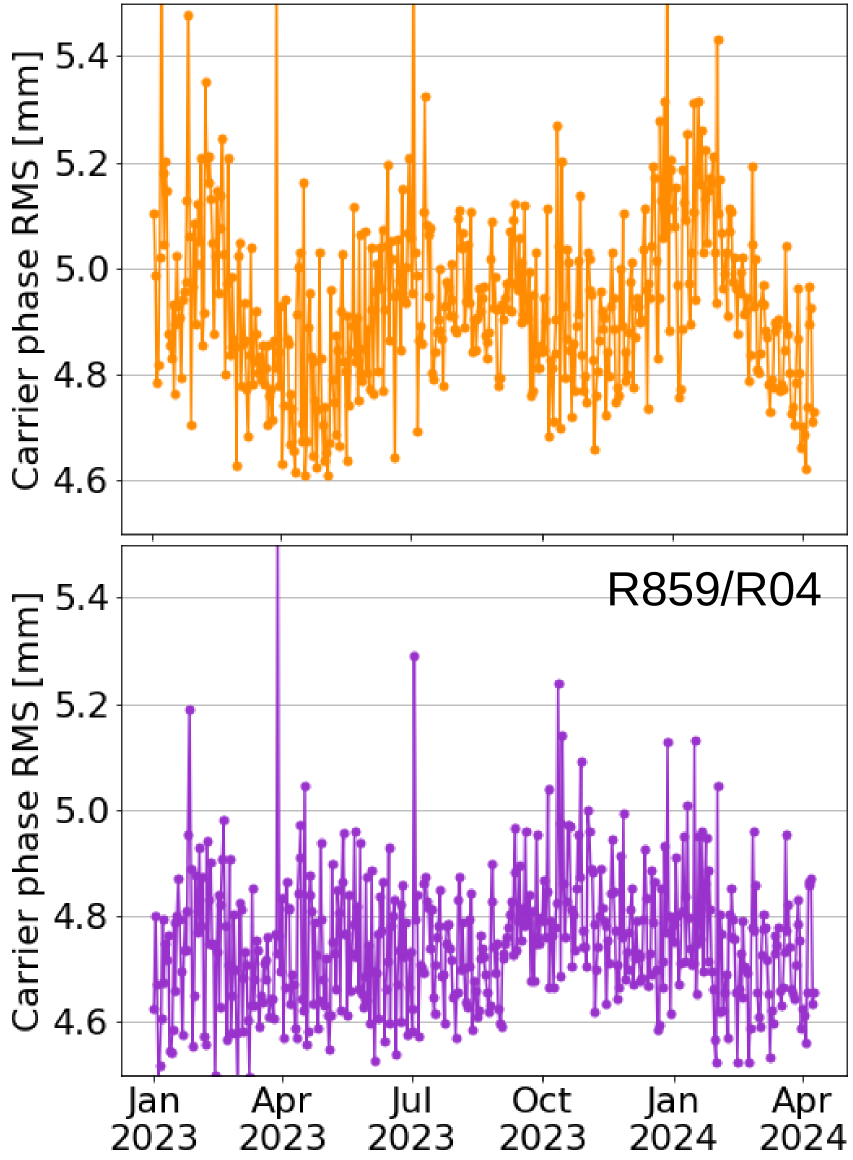
Without IFB estimation

RMS: 2.3°

With IFB estimation

RMS: 0.8°

Impact of Satellite Bias Estimation (2)



Without bias Estimation

Median: **4.9 mm**

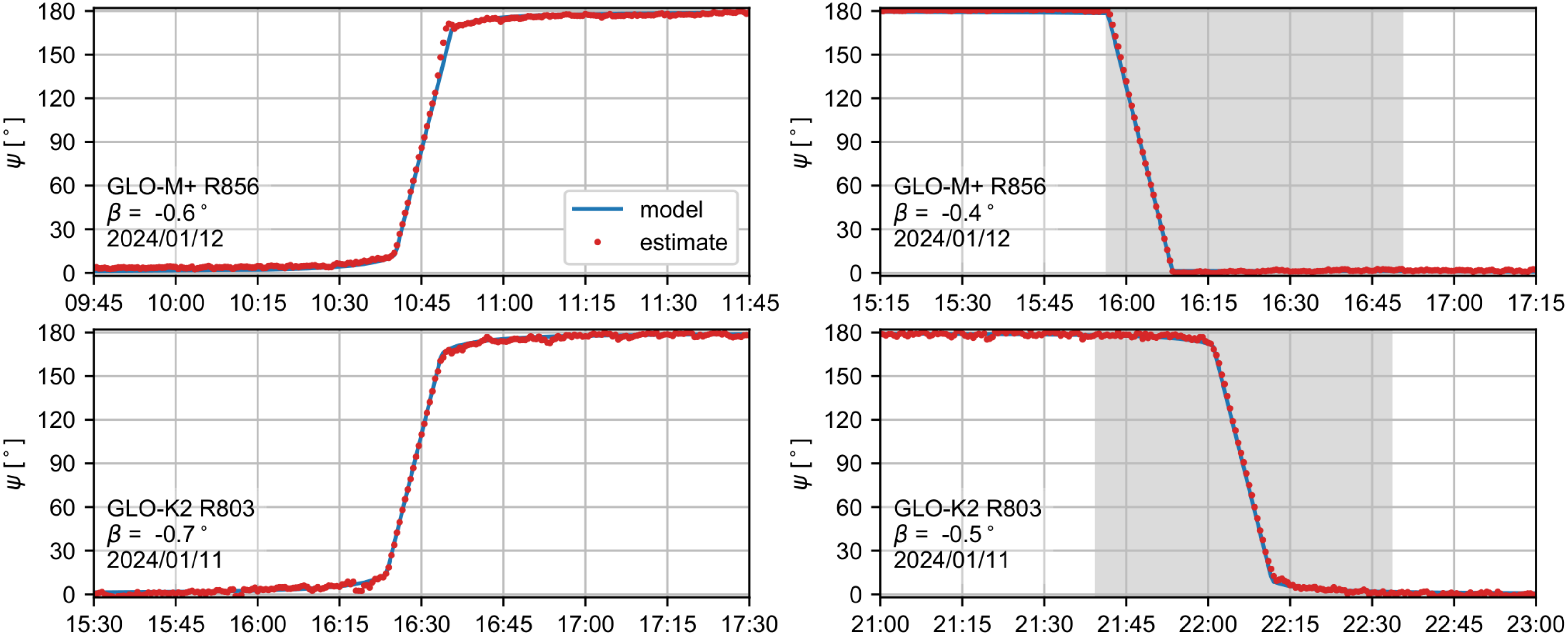
With bias Estimation

Median: **4.7 mm**

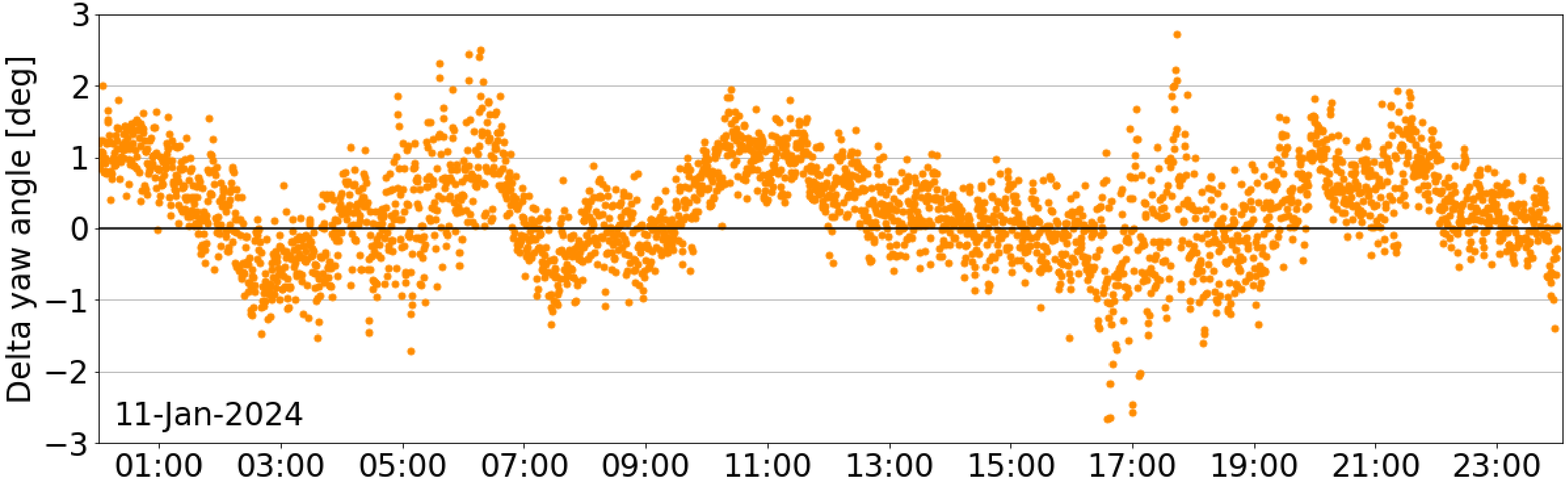
RMS of estimated attitude w.r.t. nominal attitude

Type	PRN	SVN	With Bias	Without Bias
M+	R04	R859	0.7°	1.3°
M+	R05	R856	0.7°	1.2°
M+	R12	R858	0.9°	1.0°
M+	R16	R861	0.6°	0.9°
M+	R21	R855	0.7°	1.9°
M+	R24	R860	0.8°	1.9°
K2	R26	R803	0.6°	1.8°

Attitude Estimation Results

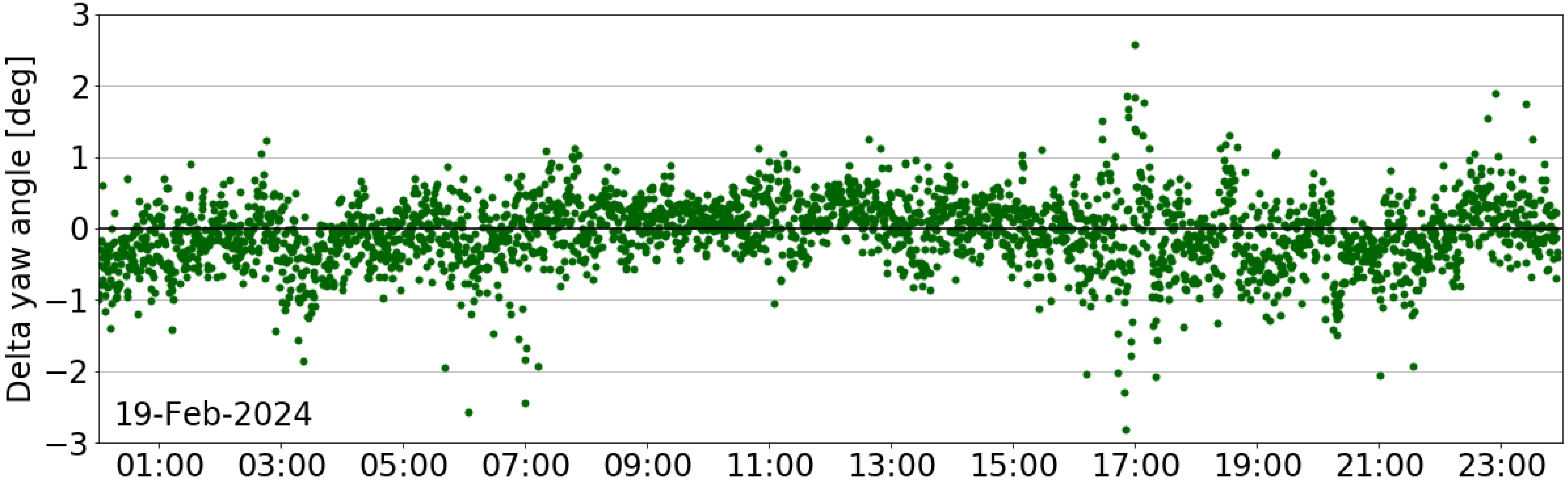


Attitude Precision



GLONASS M+
R860/R24

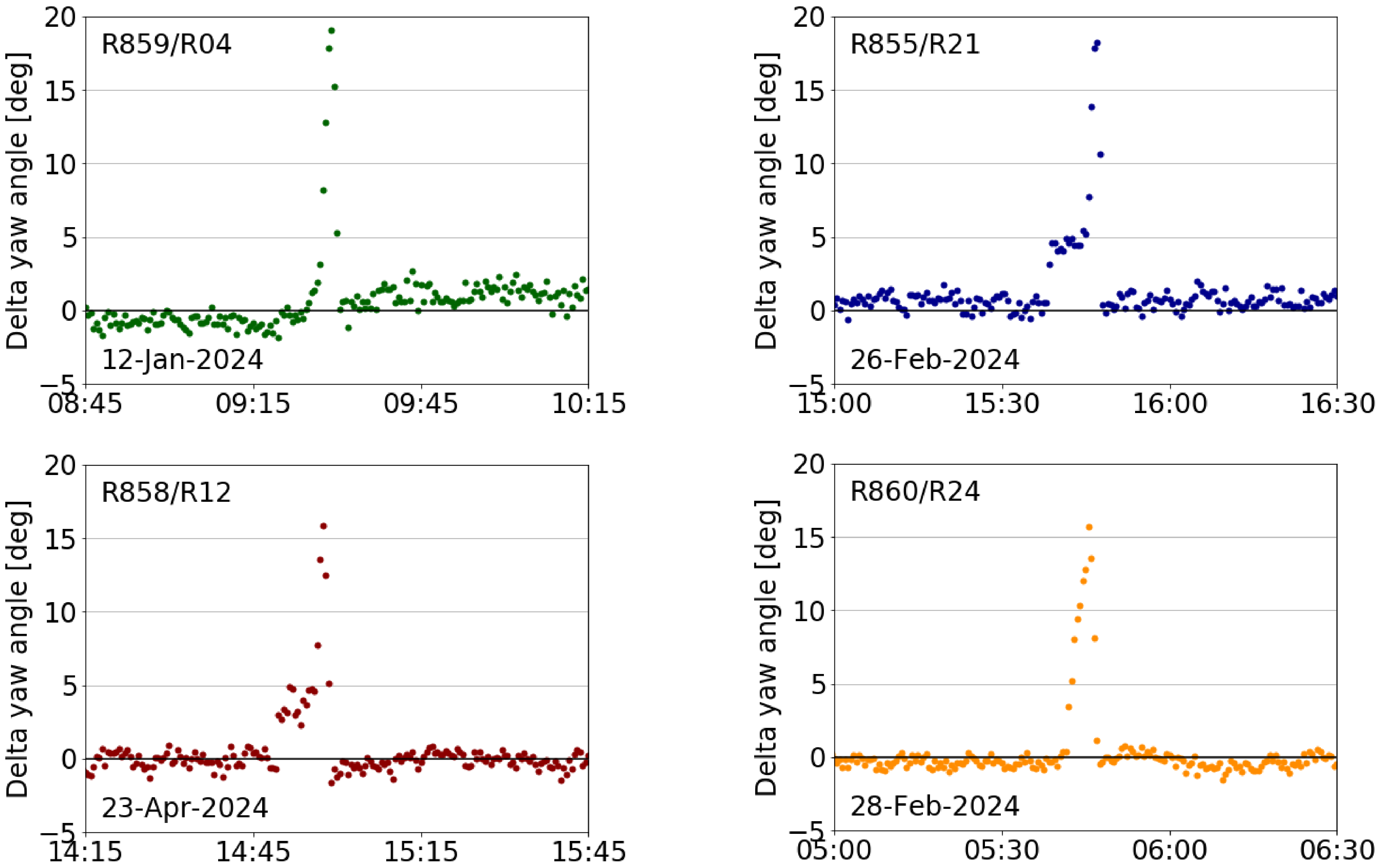
STD: 0.7°



GLONASS K2
R803/R26

STD: 0.5°

GLONASS M+ Attitude Anomalies during Noon Turns



Summary and Conclusions

- Attitude estimation from triple-frequency observations of two antennas
- In general good agreement of estimated attitude with models
- GLONASS-K2: consistency at the 1° level if orbit-periodic biases are considered
- GLONASS-M+: anomalous yaw accelerations during rate-limited noon turns
  - Yaw offsets up to 20°
- Attitude information included in L1 and L3 CDMA navigation message
  - Currently transmitted by K1B and K2 satellites
  - Included in RINEX 4.02

Steigenberger, P., Montenbruck, O., & Hauschild, A. (2024). Antenna and attitude modeling of modernized GLONASS satellites. *Advances in Space Research*, *74*(7), 3045–3059. https://doi.org/10.1016/j.asr.2024.07.001