How GNSS spacecraft orientation errors affect solar radiation pressure modelling

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Outline

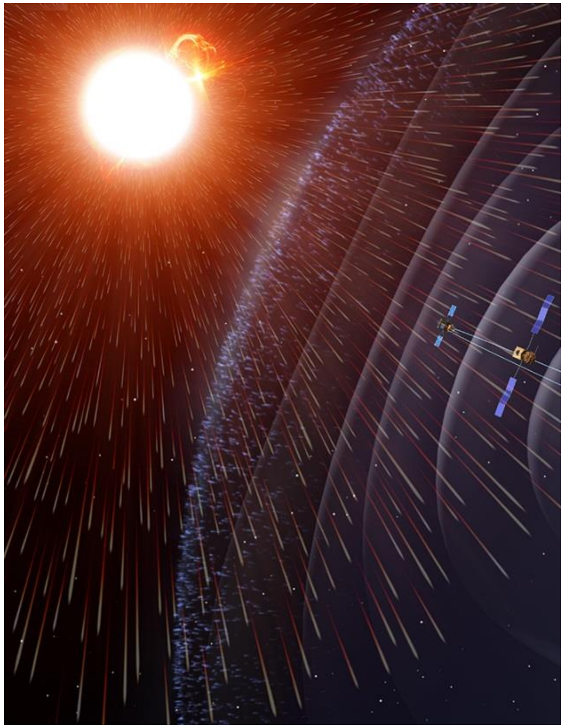
- Solar Radiation Pressure (SRP)
- Simple analytical expressions for SRP model errors arising from small spacecraft attitude-biases
- Experimental results
  - GPS Block II/IIA yaw-bias and its contribution to the Y-bias
  - GPS Block IIF heat-shielding protection tests
  - QZSS/BDS SRP modeling at low β-angles
- Summary and conclusions

Solar radiation pressure (SRP)

- Largest non-gravitational acceleration acting on GNSS satellites (~100 nm/s^2)
- Depends on optical properties, geometry, and orientation of satellite surfaces wrt the Sun:

$$\vec{p} = -\frac{PA}{m} \cdot \cos\Theta \cdot \left[(1-\rho) \cdot \vec{e}_D + 2 \cdot \left(\frac{\delta}{3} + \rho \cdot \cos\Theta \right) \cdot \vec{e}_N \right]$$

P	momentum flux due to Sun
A	surface area
m	satellite mass
$\vec{e}_D$	satellite-Sun unit vector
$\vec{e}_N$	surface normal unit vector
Θ	angle between $\vec{e}_D$ and $\vec{e}_N$
δ	specular reflectivity
ρ	diffuse reflectivity



Courtesy: ESA

Milani et al. (1987)

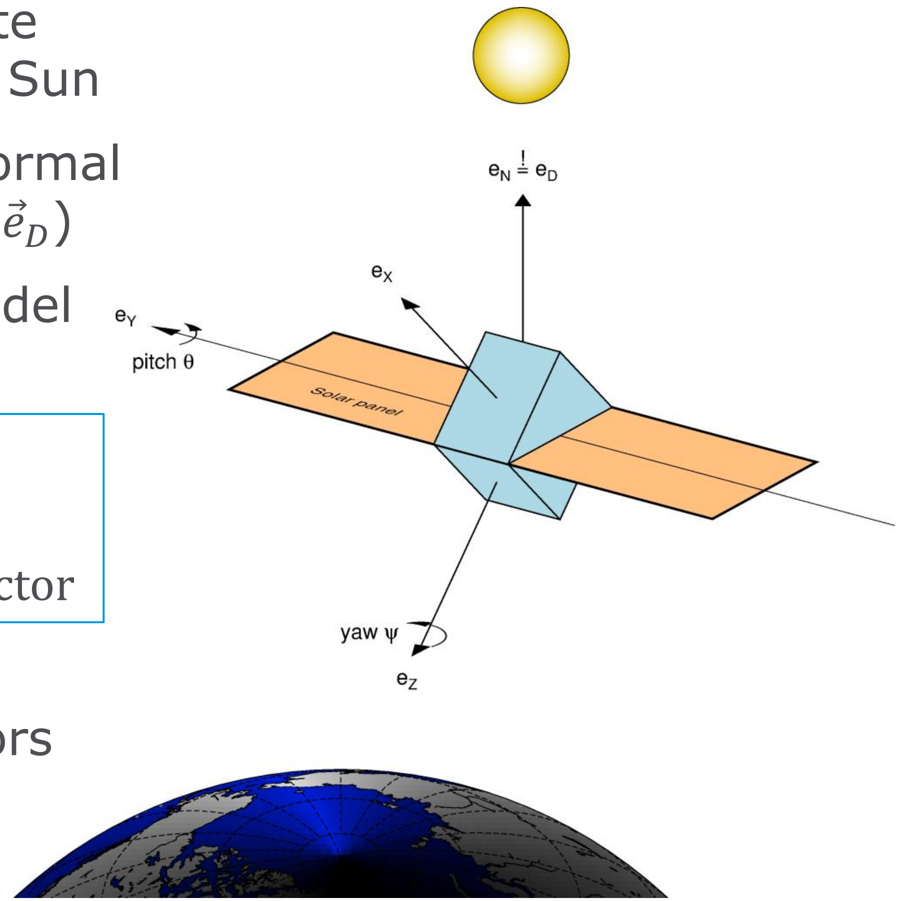
Effect of solar panel pointing error

- Yaw and pitch control such that satellite solar panel (SP) continuously face the Sun
- SRP deviates from SRP model, if SP normal vector deviates from Sun vector ($\vec{e}_N \neq \vec{e}_D$)
- 1st order approximation yields SRP model error $\Delta\vec{p}$ for SP surface:

$$\Delta\vec{p} \approx -\frac{2PA}{m} \cdot \left(\frac{\delta}{3} + \rho\right) \cdot \Delta\vec{e}_N$$

$\Delta\vec{e}_N$ misalignment of solar panel normal vector

- SP pointing error may be attributed to commanded or unwanted attitude errors



SP pointing error due to small attitude-biases

– Rotation of nominal normal vector $\vec{e}_N$ about body-fixed X-, Y- or Z-axis

$$\Delta\vec{e}_N \approx (\vec{e}_X \times \vec{e}_N)\cdot\Delta\phi = -\begin{pmatrix}0\\ \cos\epsilon\\ 0\end{pmatrix}\cdot\Delta\phi$$

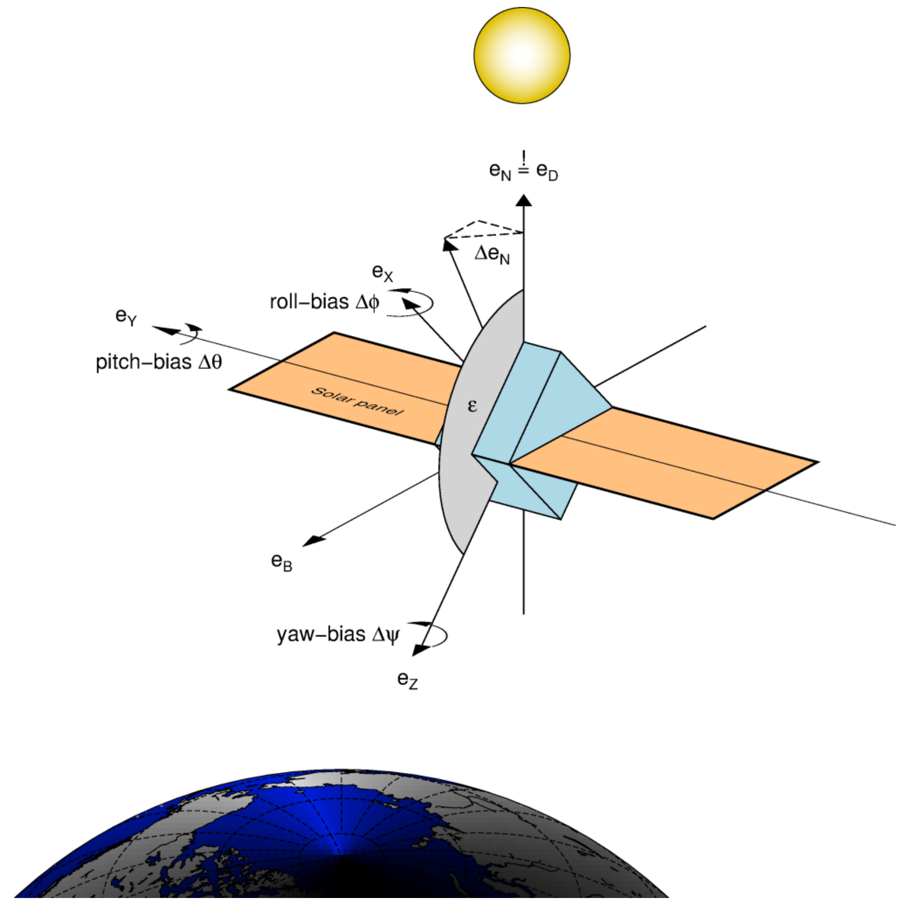
$\Delta\phi$: twist around X-axis ("roll-bias")

$$\Delta\vec{e}_N \approx (\vec{e}_Y \times \vec{e}_N)\cdot\Delta\theta = -\begin{pmatrix}0\\ 0\\ 1\end{pmatrix}\cdot\Delta\theta$$

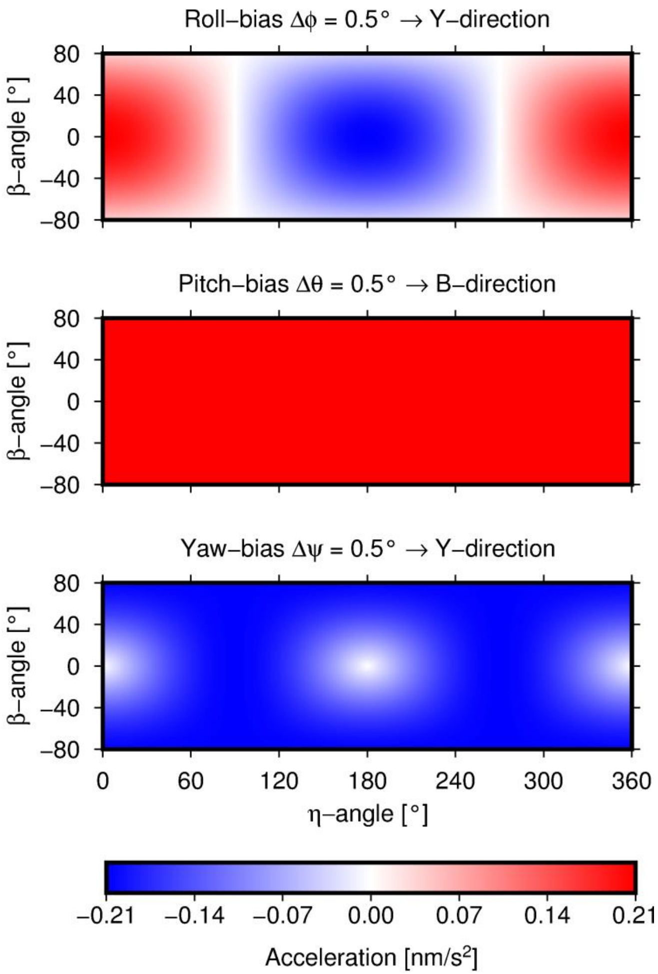
$\Delta\theta$: twist around Y-axis ("pitch-bias")

$$\Delta\vec{e}_N \approx (\vec{e}_Z \times \vec{e}_N)\cdot\Delta\psi = \begin{pmatrix}0\\ \sin\epsilon\\ 0\end{pmatrix}\cdot\Delta\psi$$

$\Delta\psi$: twist around Z-axis ("yaw-bias")



SRP model error due to 0.5° attitude-biases



$$\Delta\vec{p}(\varepsilon) = \frac{2PA}{m} \cdot \left(\frac{\delta}{3} + \rho\right) \cdot \begin{pmatrix} 0 \\ \cos\varepsilon \\ 0 \end{pmatrix} \cdot \Delta\phi$$

Zero mean, once-per-rev

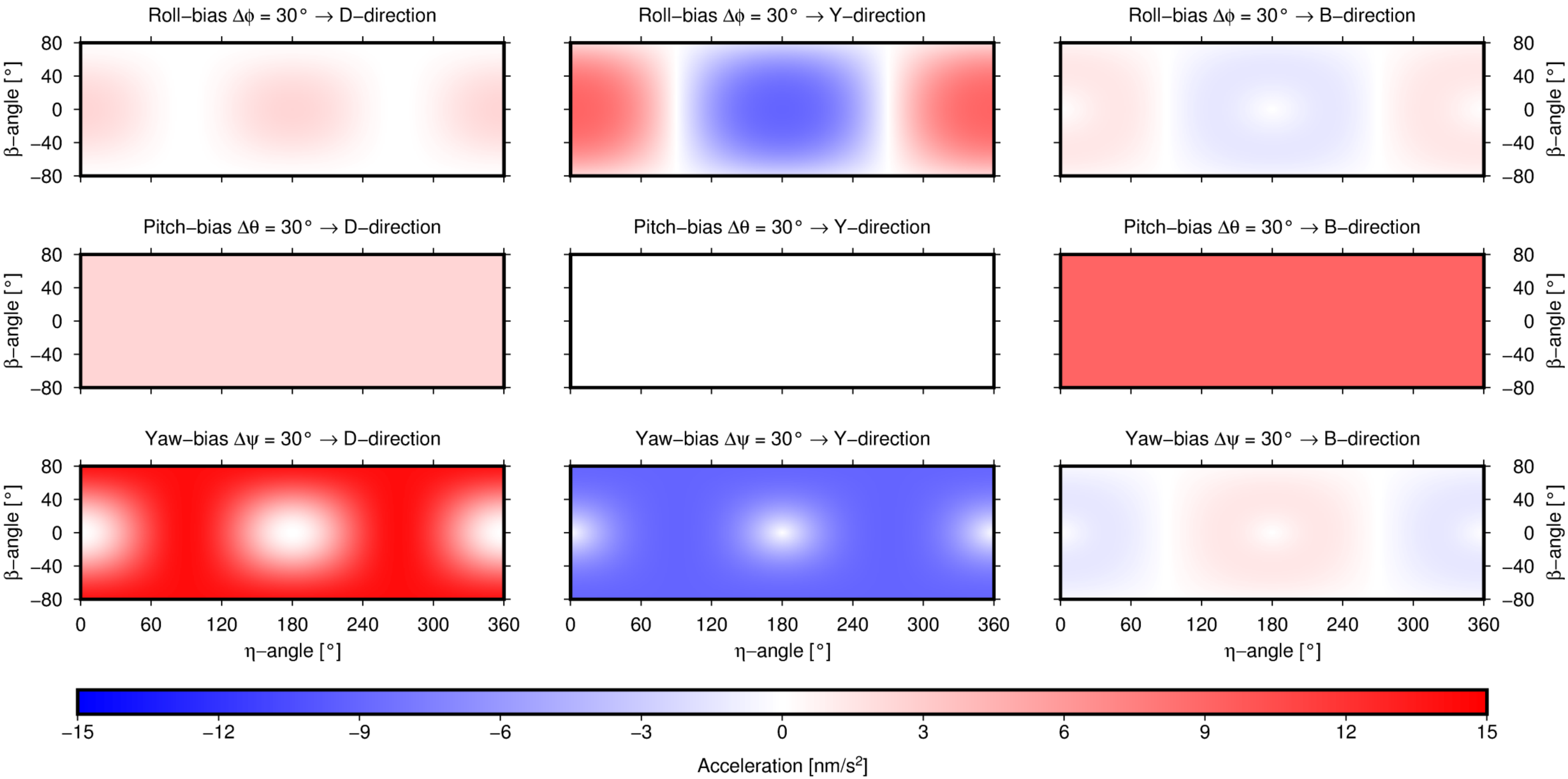
$$\Delta\vec{p}(\varepsilon) = \frac{2PA}{m} \cdot \left(\frac{\delta}{3} + \rho\right) \cdot \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \cdot \Delta\theta$$

Non-zero mean, but compensable if known

$$\Delta\vec{p}(\varepsilon) = -\frac{2PA}{m} \cdot \left(\frac{\delta}{3} + \rho\right) \cdot \begin{pmatrix} 0 \\ \sin\varepsilon \\ 0 \end{pmatrix} \cdot \Delta\psi$$

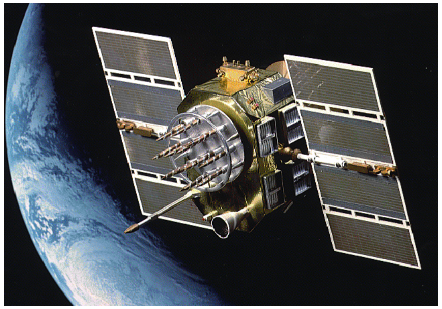
Non-zero mean, twice-per-rev

SRP model error due to large attitude-biases



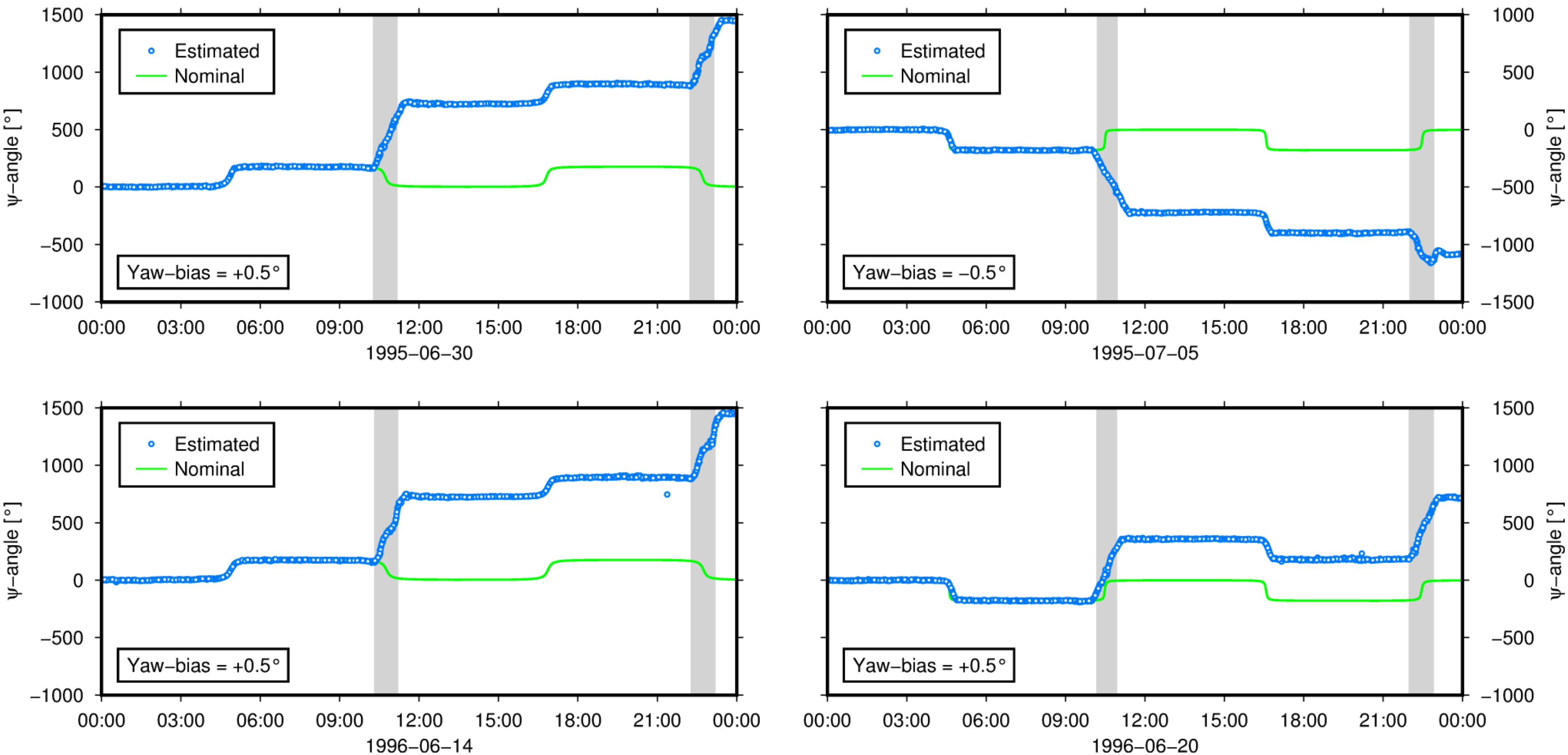
GPS II/IIA yaw-bias scheme

- GPS II/IIA yaw-bias (Bar-Sever 1996):
  - Since Nov 1995, yaw-bias of +0.5° is generated in ACS of II/IIA spacecraft to control its yaw-motion during Earth eclipse
  - Prior to Nov 1995, yaw-bias sign was kept opposite to that of β
  - Sign of yaw-bias determines turn direction during shadow phase
- Use reverse point positioning (RPP) technique to validate yaw-bias scheme
  - Bias too small to be seen in yaw estimates
  - Turn direction during eclipse reveals its sign



GPS Block II/IIA artist drawing

GPS-13: Yaw-bias monitoring with RPP



GPS II/IIA Y-bias: Estimated vs. Simulated

- Y-bias estimation
  - Five day dynamic fit estimating state plus three constant and two periodic CODE SRP parameters (D0, Y0, B0, BC, BS)
- Y-bias simulation
  - Yaw-bias acceleration in Y-direction as function of μ and β:

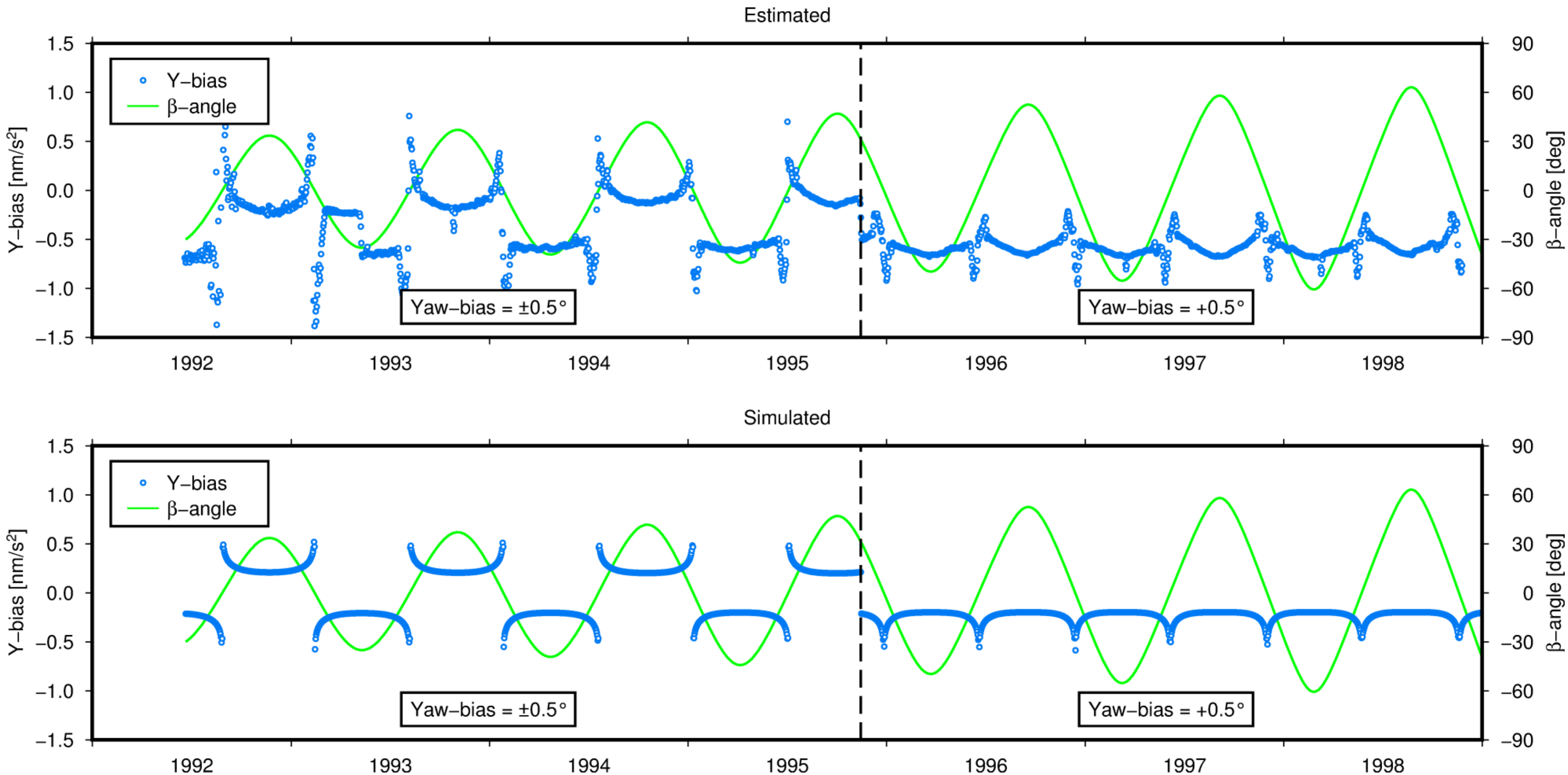
$$p_Y(\mu,\beta) = -\frac{2PA}{m}\cdot\left(\frac{\delta}{3}+\rho\right)\cdot\sqrt{1-\cos\mu\cdot\cos\beta}\cdot\Delta\psi$$

  - Averaging over one orbital revolution yields “net effect”:

$$p_Y(\beta) = \frac{1}{2\pi}\cdot\int_0^{2\pi} p_Y(\mu) = -\frac{4PA}{m\pi}\cdot\left(\frac{\delta}{3}+\rho\right)\cdot E(\cos^2\beta)\cdot\Delta\psi$$

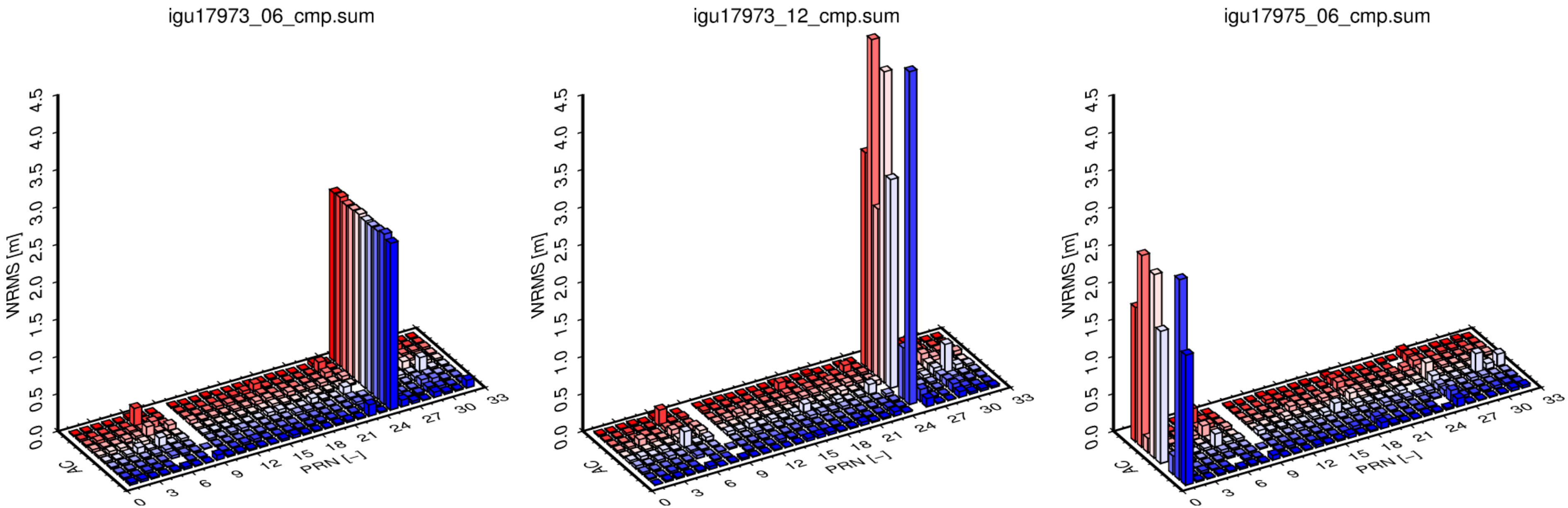
$E(\cos^2\beta)$: Complete elliptic integral of 1^{st} kind

GPS-13 Y-bias: Estimated vs. Simulated



GPS-62/63: Evidence of a problem

- Orbit modeling issues of GPS IIF satellites SVN-62/63 on June 18/19, experienced by all IGS Analysis Centers (ACs)
- Exceptional large WRMS differences between individual AC Ultra-Rapid orbit predictions and IGS Rapids of up to 4.5 m

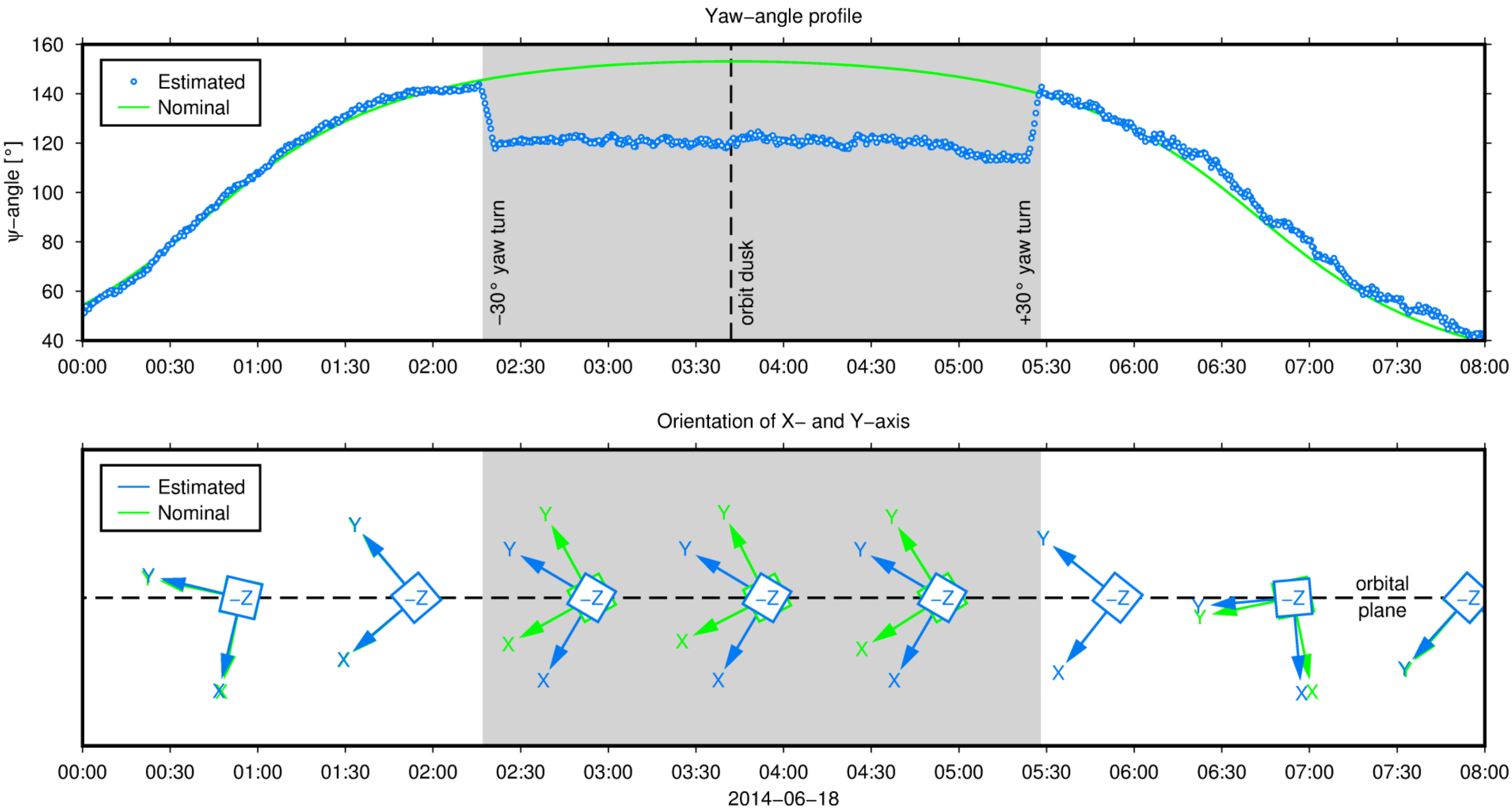


GPS-62/63: Yaw-bias characterization test

- Yaw-bias characterization test performed by USAF
  - Testing of satellites´ heat shielding protection
  - Satellites turned -30º (GPS-62) and -20º (GPS-63) around Z-axis to expose +Y-side to direct sunlight
  - Each test lasted for more than 3 hours, starting 1½ hours before orbit dusk
- Strong impact on orbital dynamics, particular in D- and Y-direction of Sun-fixed coordinate system
  - Effect of non-nominal attitude spreads over entire arc
  - Cannot be accommodated by empirical standard parameter set (5 SRPs + 3 CPRs)

GPS Block IIF artist drawing

GPS-62: Yaw-bias detection with RPP



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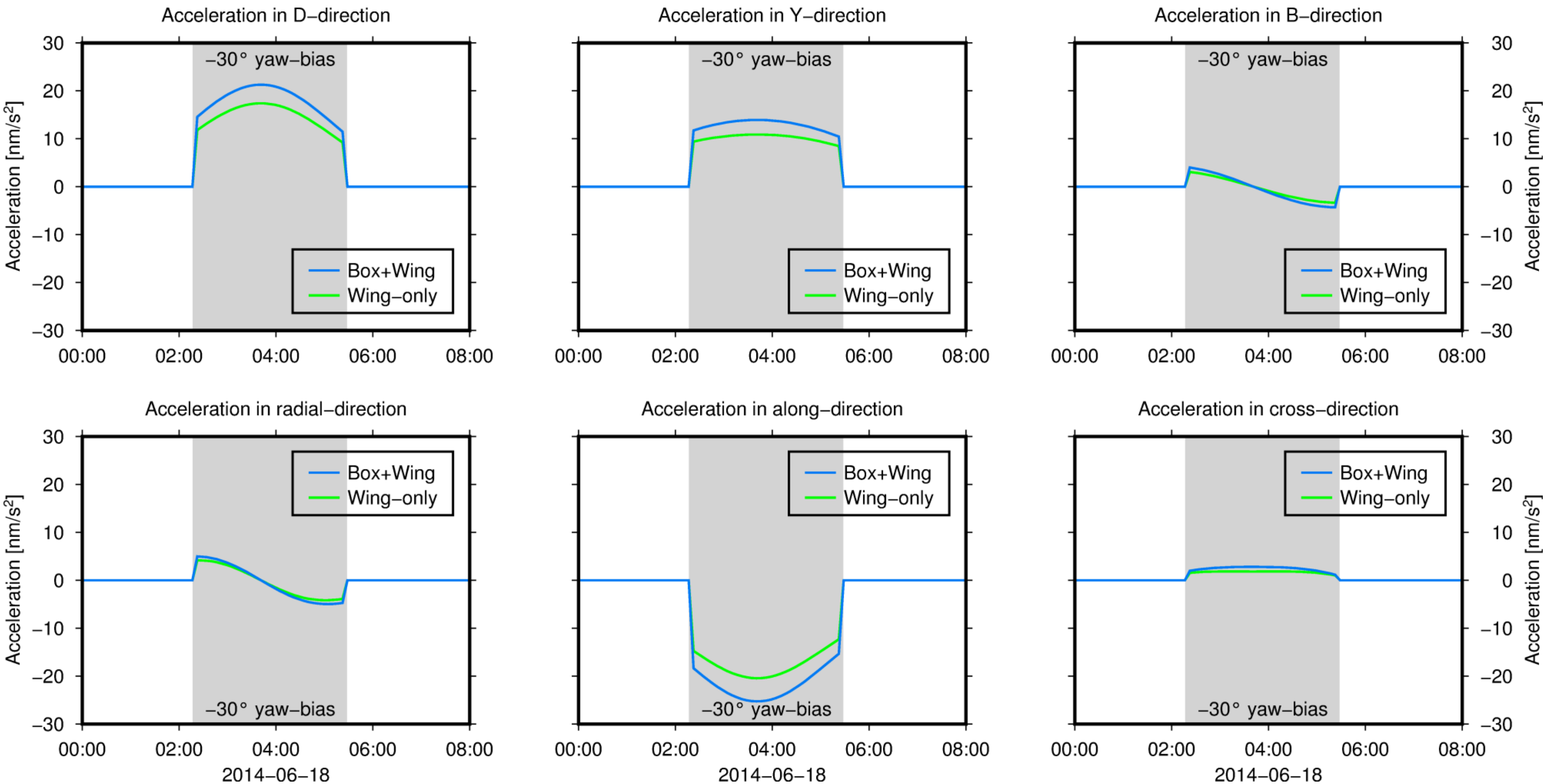
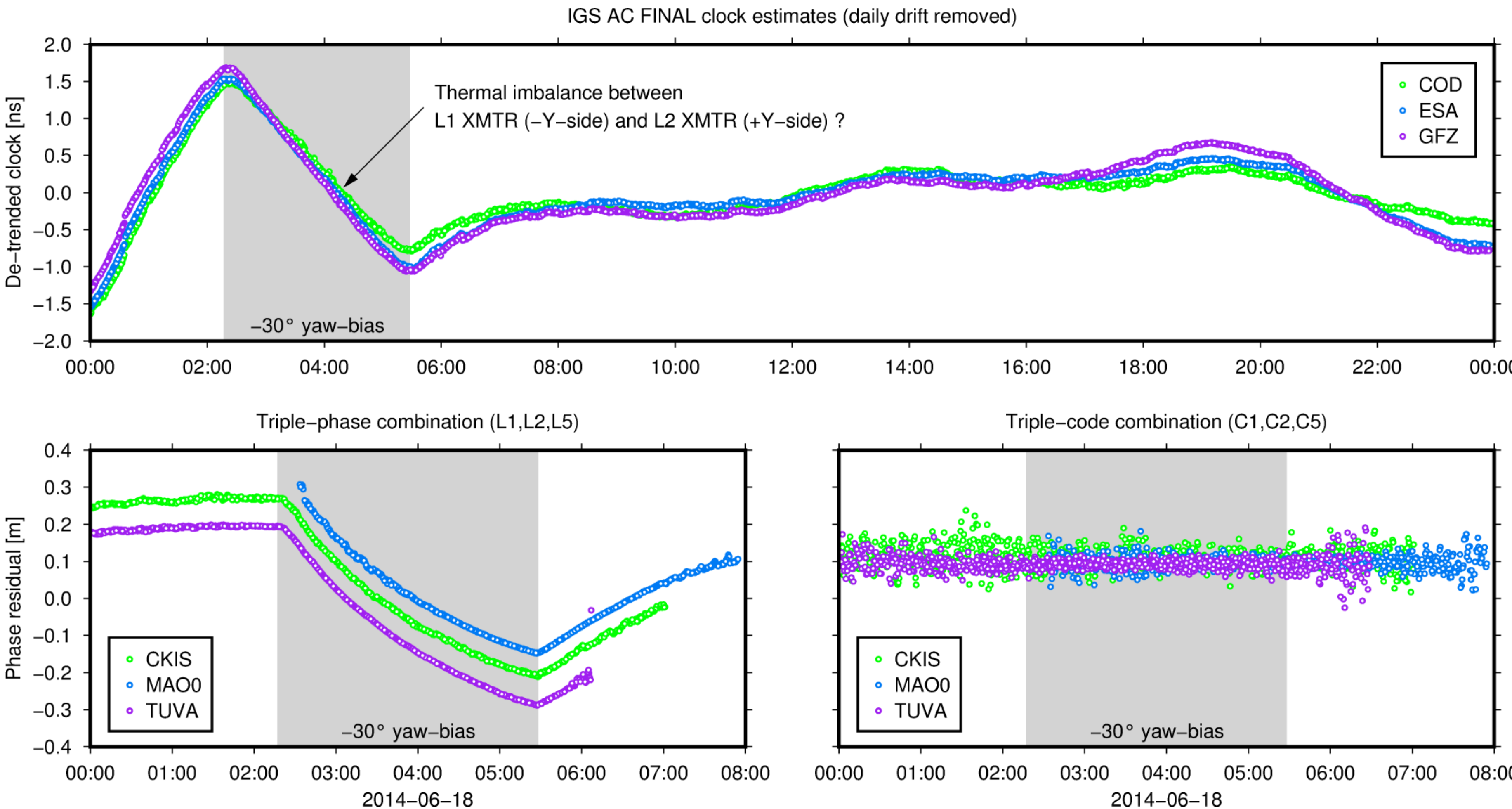
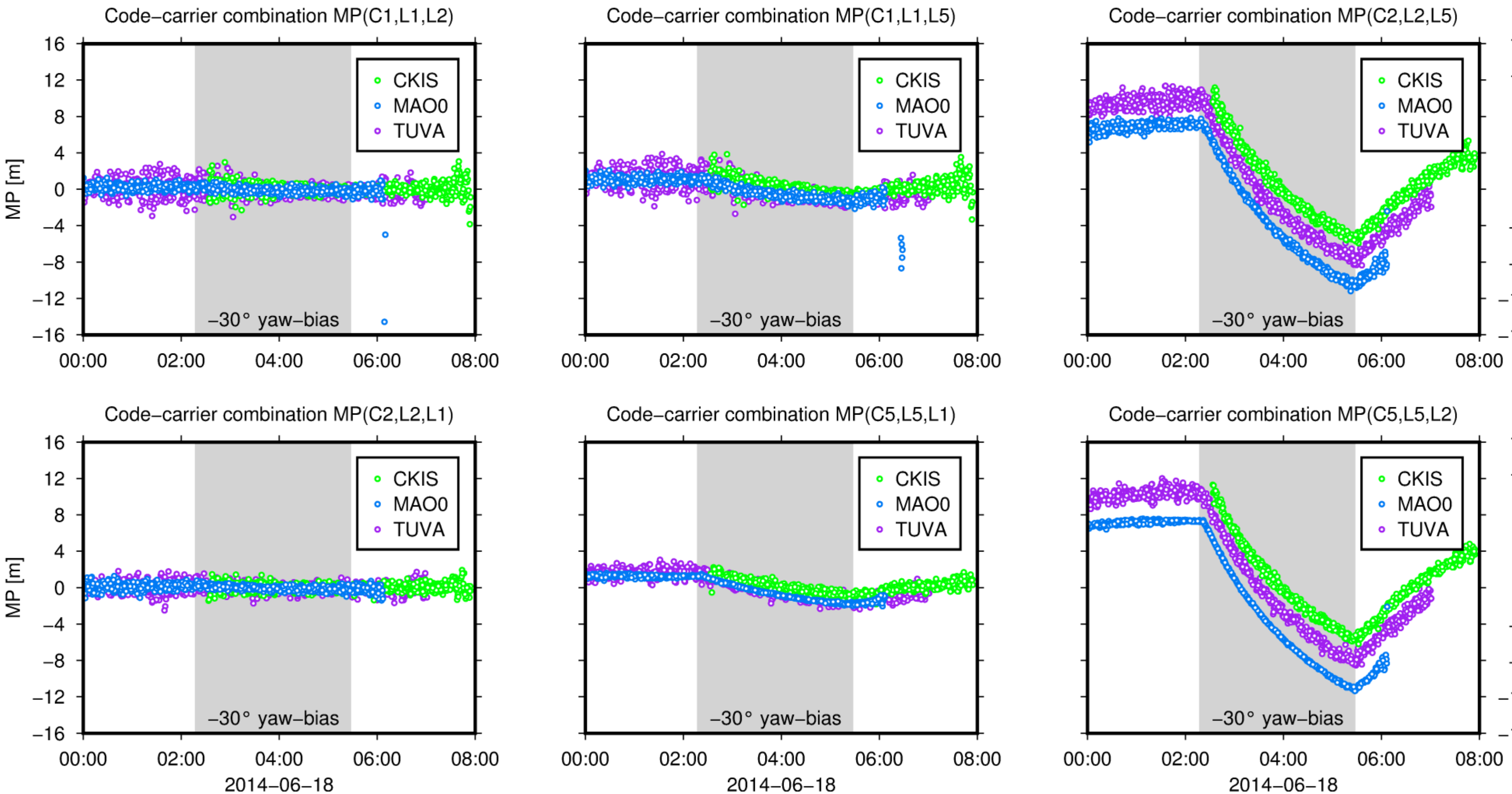
GPS-62: Yaw-bias impact on SRP modelling



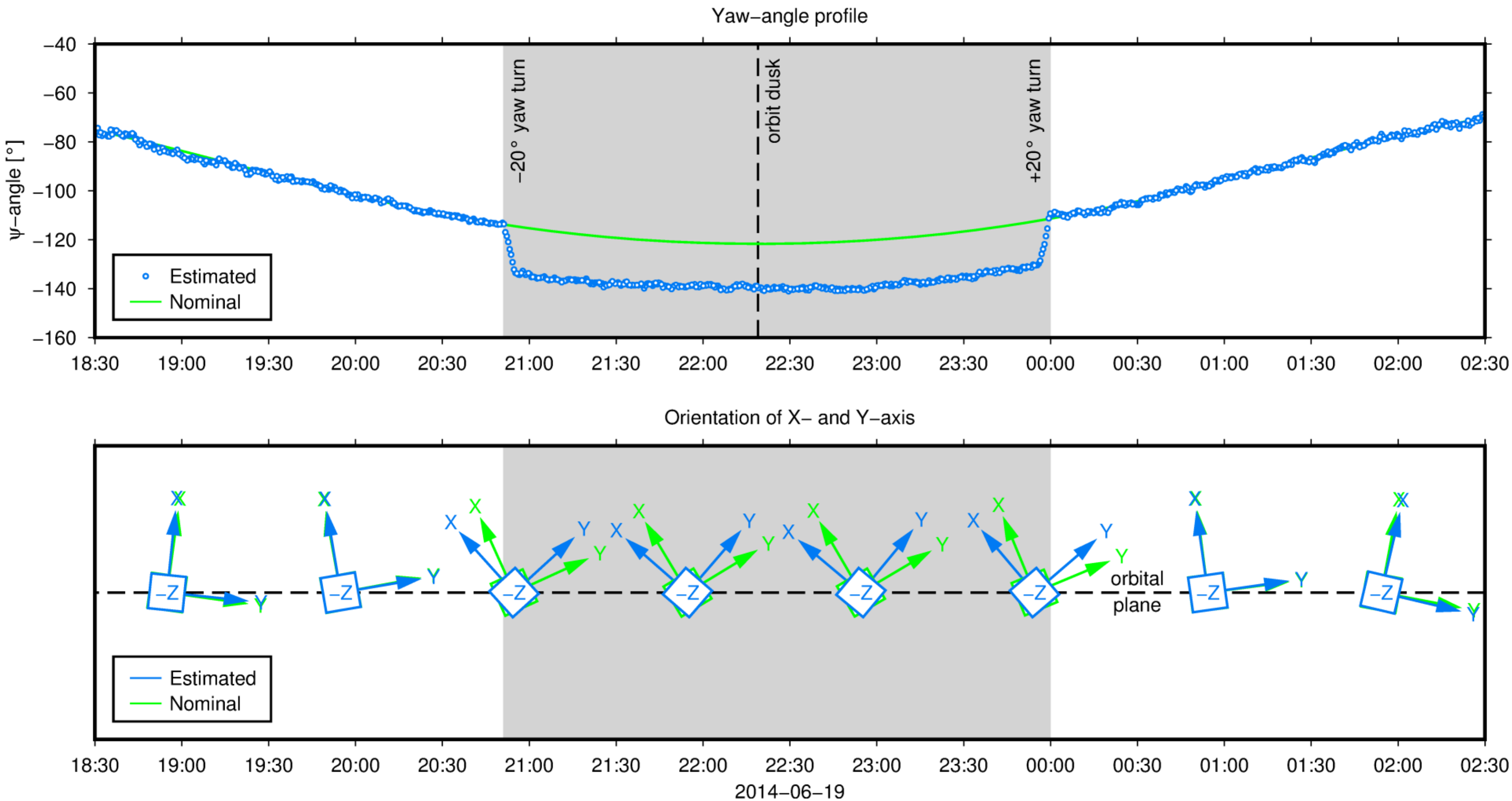
GPS-62: Yaw-bias impact on range data (1/2)



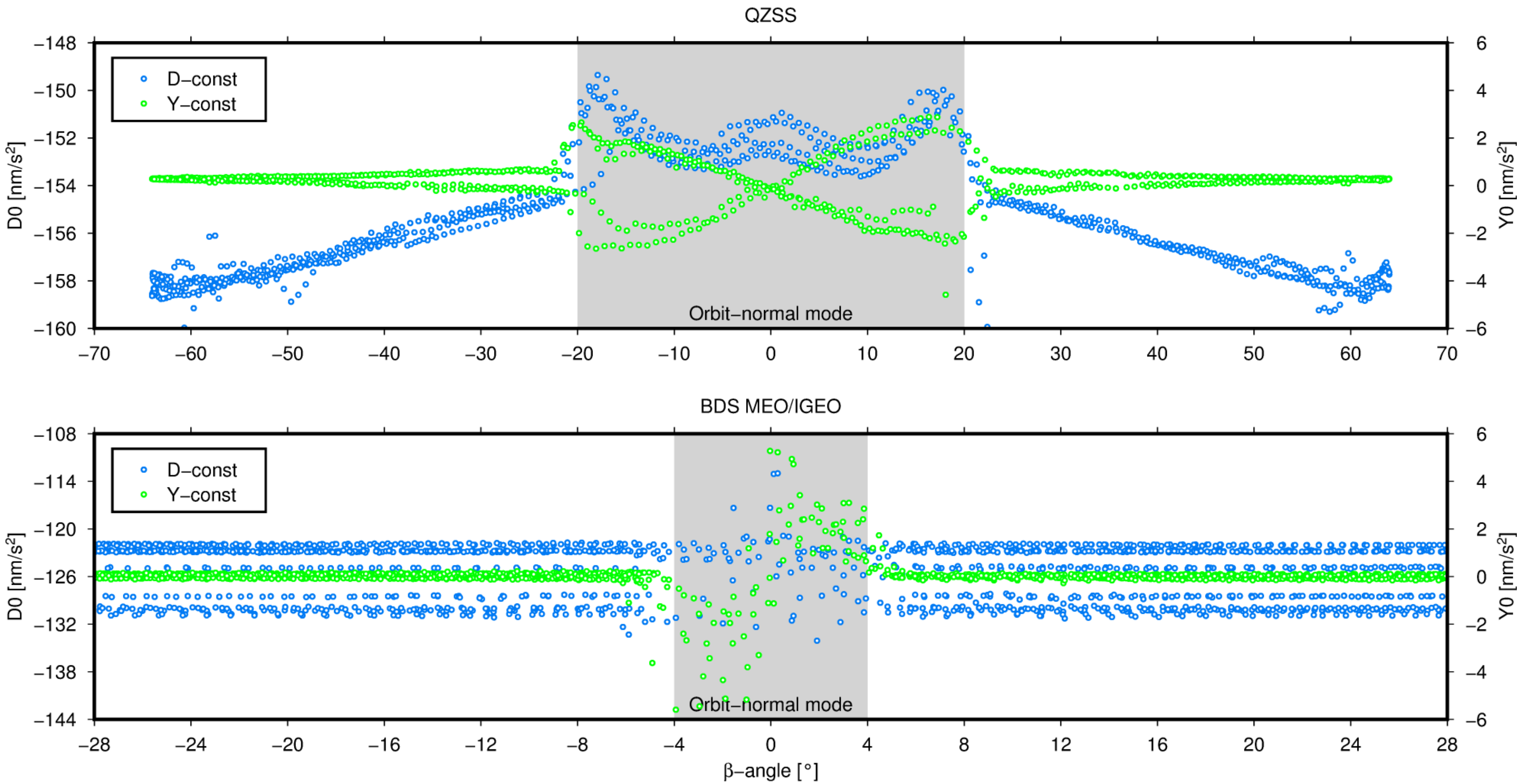
GPS-62: Yaw-bias impact on range data (2/2)



GPS-63: Yaw-bias detection with RPP



QZSS/BDS SRP modeling at low β-angles



Summary and conclusions

- Yaw-bias dynamically most relevant attitude-bias
  - Causes twice-per-rev perturbations with non-zero mean in D- and Y-direction
  - Empirical orbit parameters “soak up” most of the effect
  - RPP is a powerful tool for identifying such biases
- GPS Block II/IIA/IIF experiments
  - Confirm high sensitivity of Y-bias against variations in yaw
  - 0.5° yaw-bias produces 0.25 nm/s^2 Y-bias
  - Temporary deviation (of 3 h) from nominal yaw-attitude (of 30°) is devastating for precise orbit determination and prediction
- Yaw-attitude modeling is a key element for QZSS/BDS