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Solar Radiation Pressure and Attitude Modeling of GNSS Satellites

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1. Solar radiation pressure ➞ box-wing model

The main non-gravitational orbit perturbation acting on GNSS satellites is the solar radiation pressure. There are two main approaches to model this force:

1) adjusting empirical parameters that fit best the GNSS tracking data, and
2) computing the a priori force from analytical models based on the detailed satellite structure and information available on ground.

The first one is not based on the physical interaction between solar radiation and the satellite, while the second one can not be easily adjusted to the real on-orbit behaviour of the satellites, e.g., changes due to aging of optical properties or deviations from nominal attitude.

In this study an intermediate approach is used, an analytical box-wing model based on the physical interaction between the solar radiation and a satellite consisting of a bus (box shape) and solar panels (Rodriguez-Solano et al., 2011). Furthermore, some of the parameters of the box-wing model can be adjusted to fit the GNSS tracking data, namely the optical properties of the satellite surfaces.

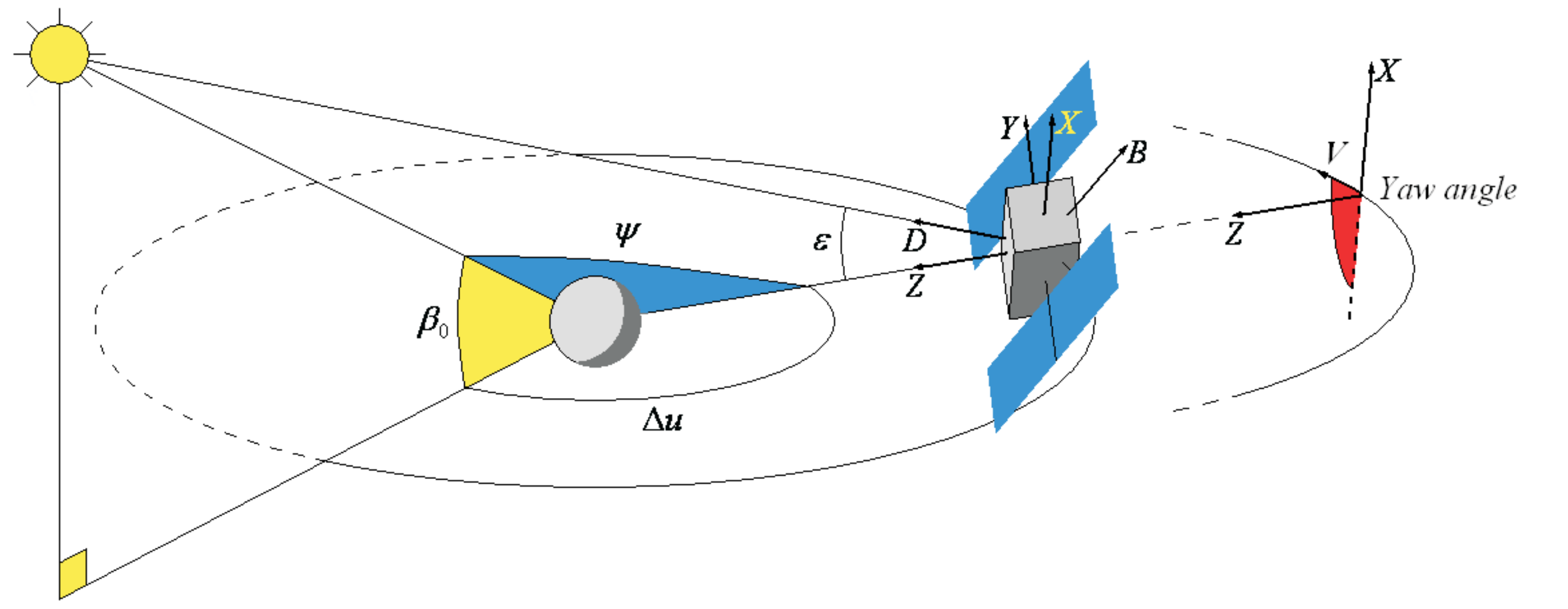


Fig. 1: Nominal yaw attitude of GNSS satellites. Relative geometry of Sun, Earth and satellite. Illustration of DYB (Sun-fixed) and XYZ (body-fixed) frames.

2. Yaw attitude during eclipse seasons

Modeling the solar radiation pressure requires precise knowledge of the orientation of the satellites in space, i.e., their attitude. The nominal attitude of the GNSS satellites is given by acomplishing two conditions at the same time:

1) Navigation antennas pointing to the center of the Earth, and
2) Solar panels pointing to the Sun.

However, during eclipse seasons GNSS satellites perform yaw maneuvers, because the Sun sensors cannot follow the Sun or because the maximum hardware yaw rates of the satellites cannot be exceeded.

Dedicated models for different satellite types provide the yaw angle during the maneuvers for:

- **GPS IIA** (Bar-Sever, 1996)
- **GPS IIR** (Kouba, 2009)
- **GLONASS-M** (Dilssner et al., 2010)

These previous models (with a priori hardware rates) have been implemented in a development version of the Bernese GPS Software.

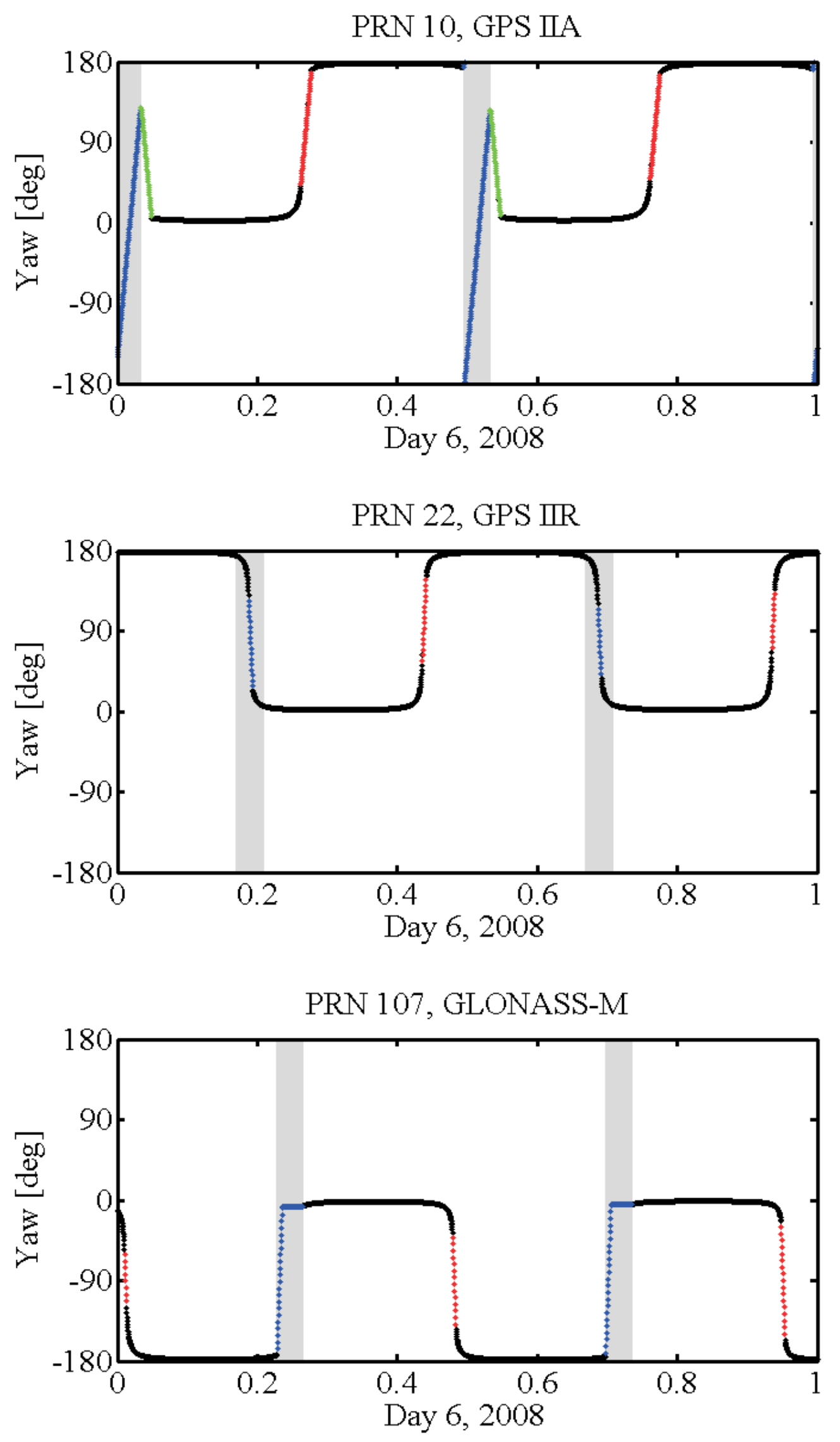
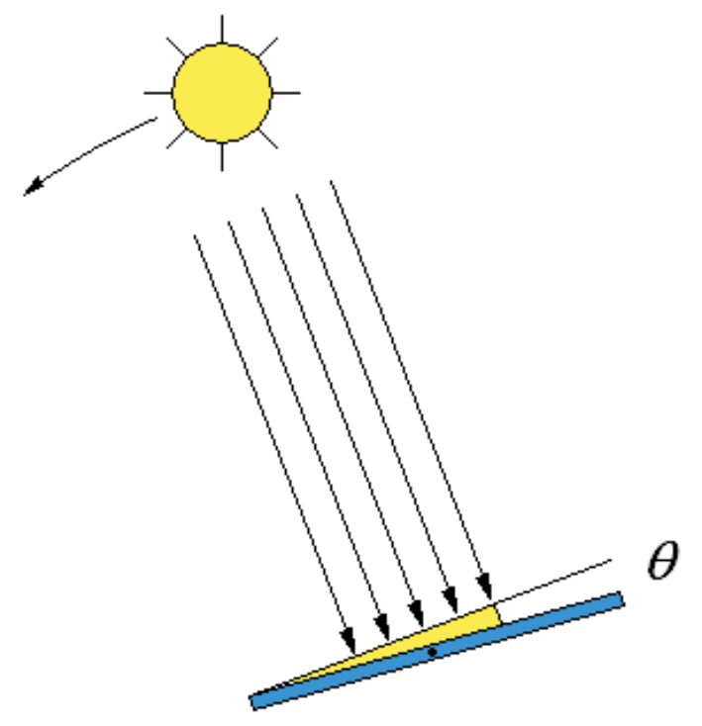


Fig. 2: Yaw maneuvers performed by GNSS satellites: noon-turn, shadow-turn and post-shadow-turn. Nominal yaw attitude in black.

3. Solar panel rotation lag angle



It was found that a pure box-wing model interacting with solar radiation is not sufficient for precise orbit determination. In particular a rotation lag angle of the solar panels was identified by Rodriguez-Solano et al. (2011). This deviation of the solar panels from nominal attitude is a key factor to obtain precise GNSS orbits.

The partial derivative of the solar panel rotation lag angle is shown in Fig. 3. It can be written as:

$$\frac{\partial \vec{f}}{\partial \theta_{SB}} = -\frac{A_{SP}}{M}\frac{S_0}{c}2\left(\frac{\delta_{SP}}{3}+\rho_{SP}\right)\operatorname{sign}(\dot{\epsilon})\vec{e}_B$$

and it basically depends on:

- the sign of the rate of the angle (ε) formed by Earth, satellite and Sun shown in Fig. 1.
- the area and optical properties of the solar panels and satellite mass.

Daily solar panel rotation lag angles have been estimated together with the parameters of the box-wing model using tracking data for 2008 and are shown in Figs. 5 and 6.

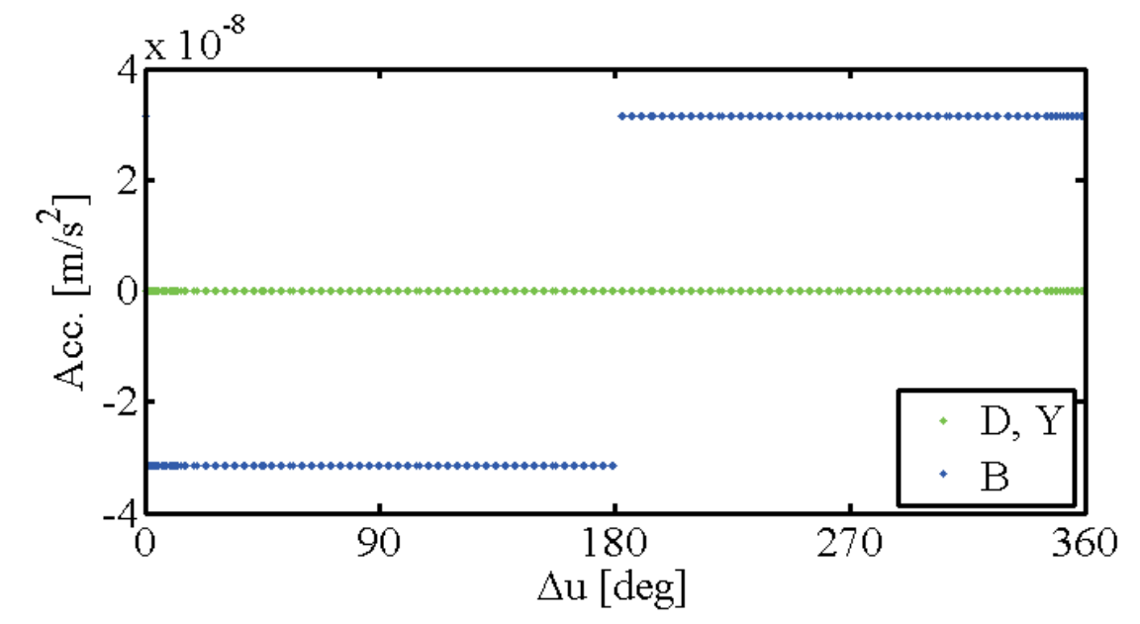
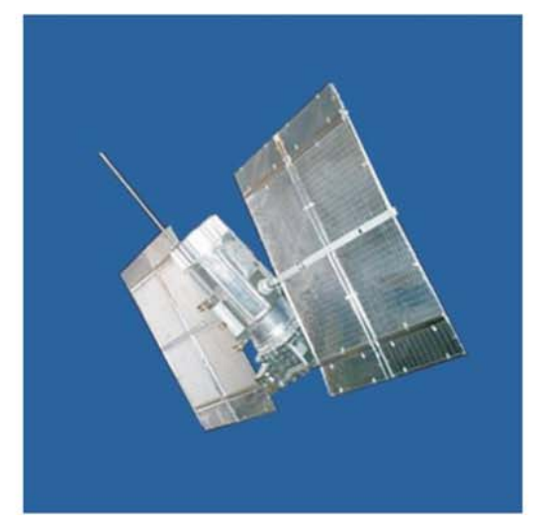


Fig. 3: Partial derivative of solar panel rotation lag angle for GPS IIR.

GPS IIA

GPS IIR



GLONASS

GLONASS-M

4. Yaw attitude and solar radiation pressure

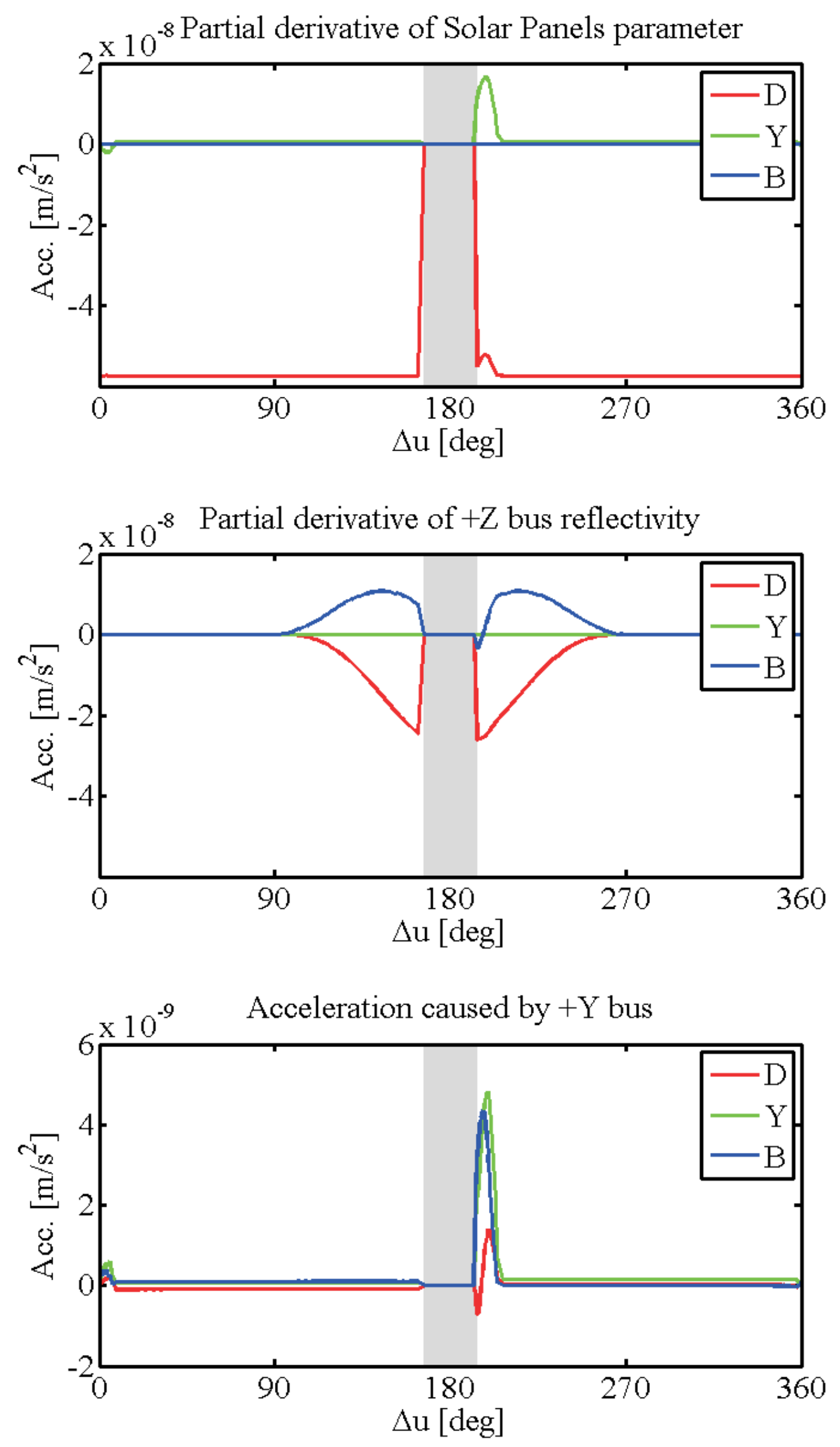


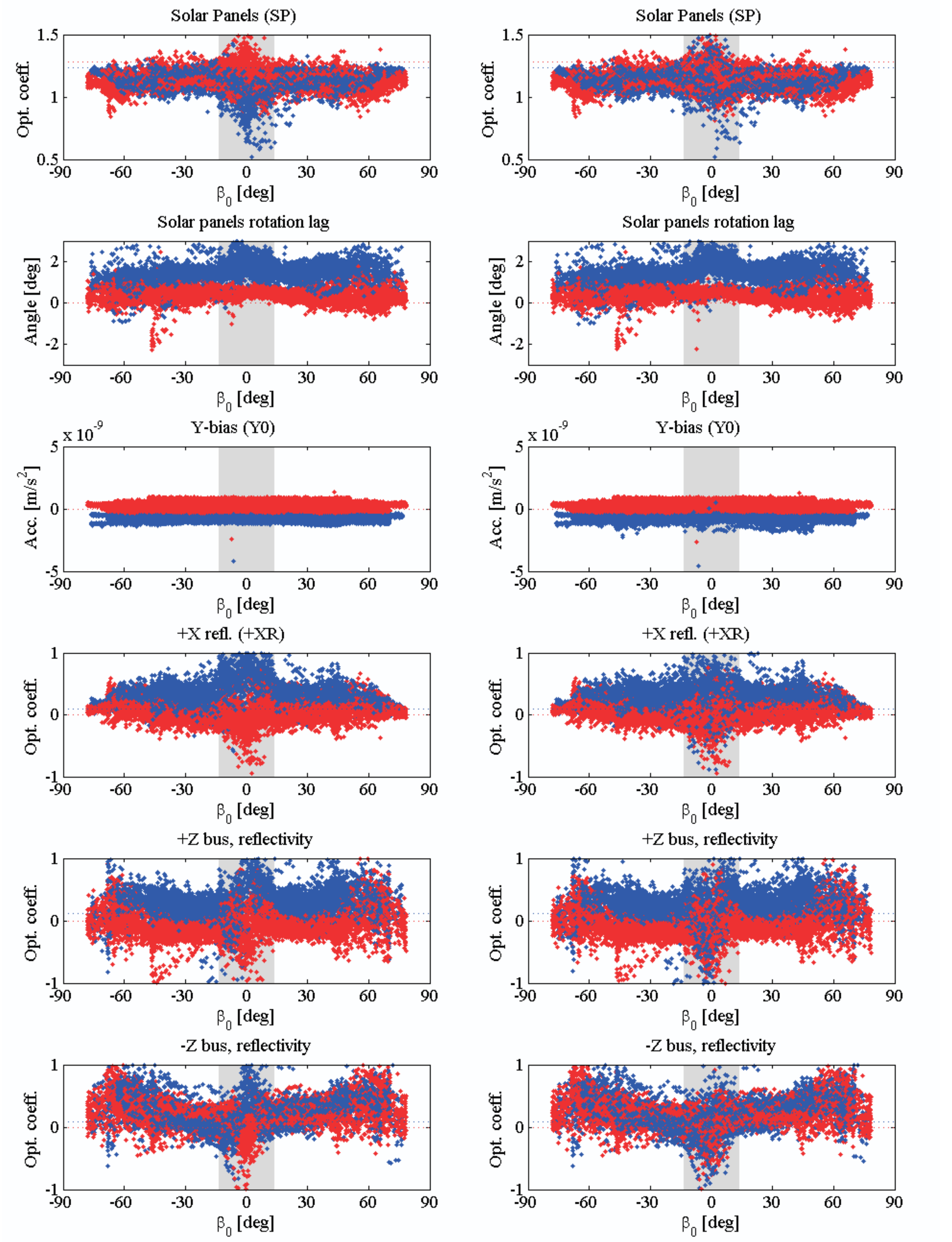
Fig. 4: Impact of yaw maneuvers on the solar radiation pressure for PRN 10 (GPS IIA satellite), for day 6 of 2008 ($\beta_0 = 2°$).

The yaw maneuvers performed by GNSS satellites have an impact on the computed solar radiation pressure acting on the satellites (Fig. 4), compared to models considering only nominal yaw attitude.

The shadow-turn clearly does not have an influence on the solar radiation pressure but the noon-turn does, since the satellite is illuminated by the Sun and not following nominal attitude for β_0 close to zero. In Fig. 4 the noon-turn occurs around Δu close to zero.

More problematic is the post-shadow-turn performed by GPS IIA, since the deviation from nominal attitude is large for $|\beta_0| < 13.5°$ and it is performed when the satellite is in sunlight. In Fig. 4 the impact on the partial derivatives of the box-wing model due to deviations from nominal attitude is shown. Additionally the acceleration caused by the Y surfaces of the satellite is shown. This acceleration was taken into account as a priori information for the box-wing model.

5. Box-wing parameter estimation



NOMINAL ATTITUDE **+ YAW MANEUVERS**

Fig. 5: Daily box-wing parameters estimated for 2008 as a function of the Sun elevation above the orbital plane (β_0), with nominal attitude (left) and with yaw maneuvers (right). All satellites **GPS IIA** and **GPS IIR** in 2008 are shown in the plots.

The adjustable box-wing model has been used for computing GPS and GLONASS orbits for the year 2008, using the strategy of the Center for Orbit Determination in Europe (CODE). Two solutions were computed, one using the nominal yaw attitude and one including the yaw attitude models during eclipse seasons from Bar-Sever (1996), Kouba (2009) and Dilssner (2010).

Fig. 5 shows the parameters of the box-wing model estimated for 2008. Some improvent (smaller variation during eclipse seasons) can be observed for GPS IIA satellites for the optical properties of the satellite and for the solar panels parameter. However, there are still variations of the parameters during eclipse seasons, which could not be eliminated by using the yaw attitude models (with a priori hardware rates). The reason for the lower improvement can be the incorrect modeling of the post-shadow-turn, since the rotation direction for this maneuver can be ambigous.

The variation of the parameters for GPS IIR during eclipse seasons was almost unchanged by including the noon-turn yaw maneuvers. This indicates that the remaining variation is mainly due to modeling issues of the parameters of the box-wing model for small β_0 angles.

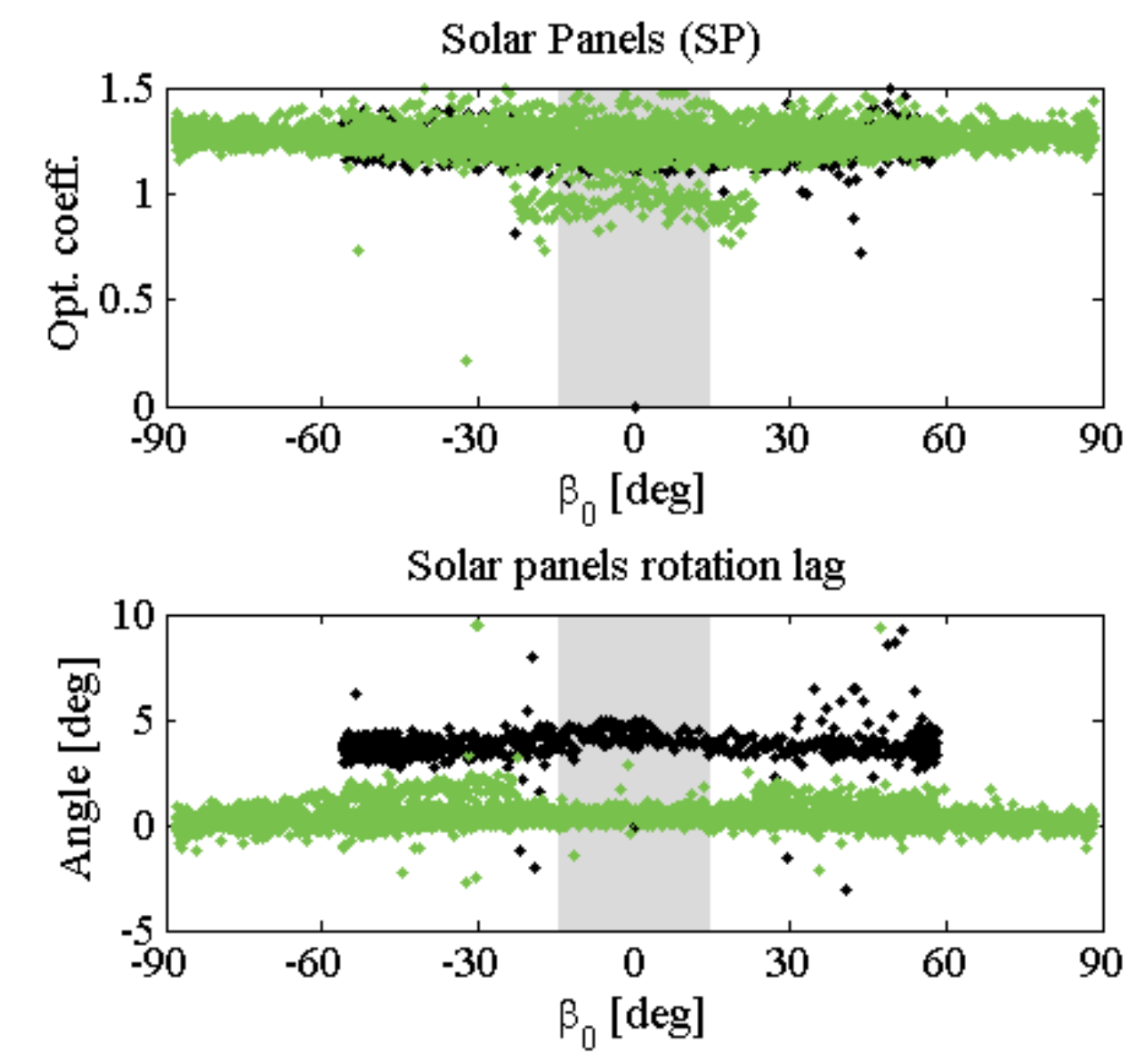


Fig. 6: Solar panels parameter and rotation lag angle estimated for **GLONASS** and **GLONASS-M** satellites during 2008, using the yaw attitude model for GLONASS-M.

The solar panel parameter and rotation lag angle for GLONASS and GLONASS-M are shown in Fig. 6. Note that the rotation lag angle is larger for the older satellite blocks, around 4° for GLONASS and 1.5° for GPS IIA, while for the newer satellite blocks (GLONASS-M and GPS IIR) the rotation lag angle is close to zero.

Moreover, in Fig. 6 there are some anomalous estimated parameters for GLONASS-M satellites, more visible for the solar panel parameter and $|\beta_0| < 22.5°$ (clearly outside the eclipse season). These anomalous parameters correspond to two specific satellites, SVN 701 and SVN 713, that behave differently than other GLONASS-M satellites.

6. Impact on GNSS orbits

Fig. 7: Radial orbit differences (solution with yaw maneuvers - solution with nominal attitude) for all days with $|\beta_0| < 13.5°$ of 2008 and for the satellite PRN 10 (**GPS IIA**). Althought the yaw noon-turn and post-shadow-turn occur mainly after Δu = 0° and Δu = 180°+13.5° respectively, they introduce orbit perturbations (up to 10 cm) over the whole orbital revolution.

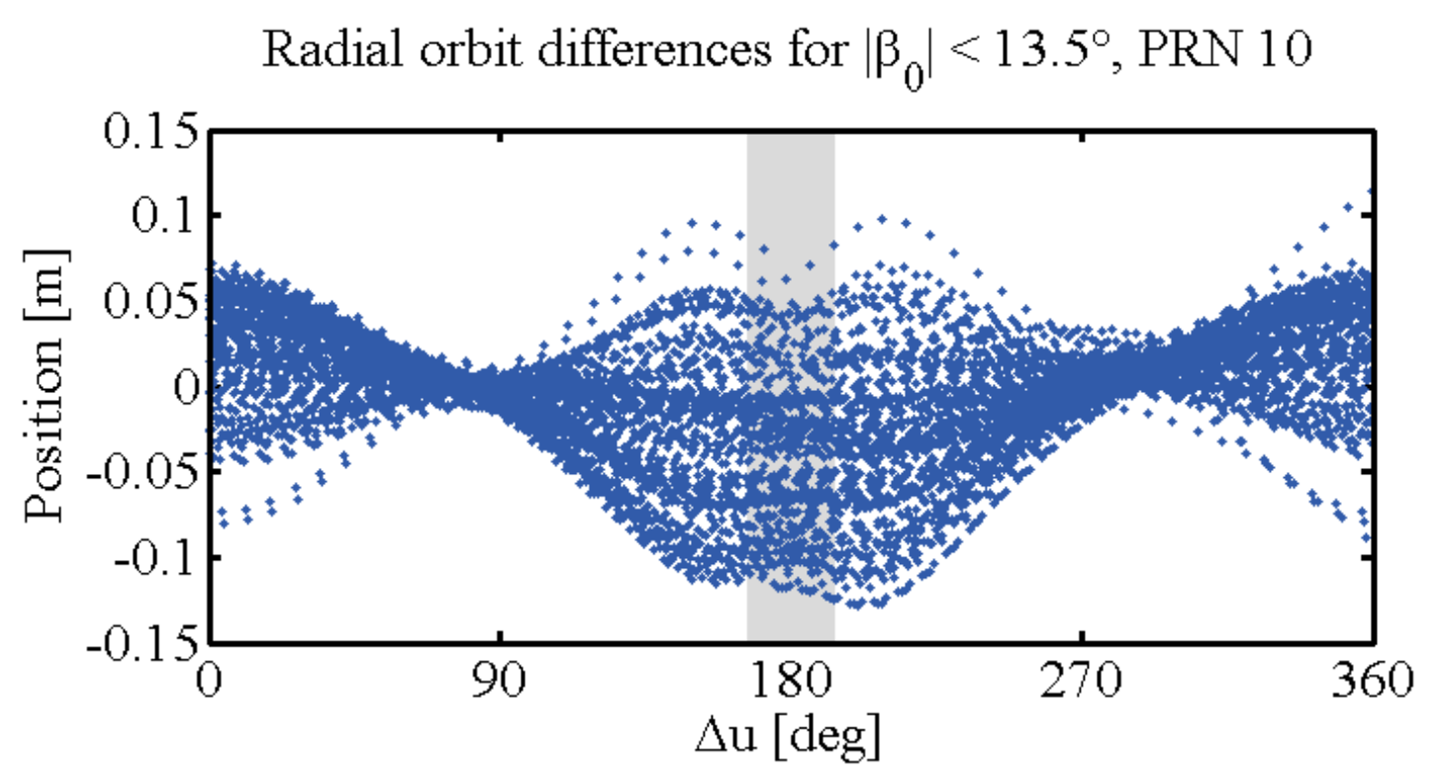
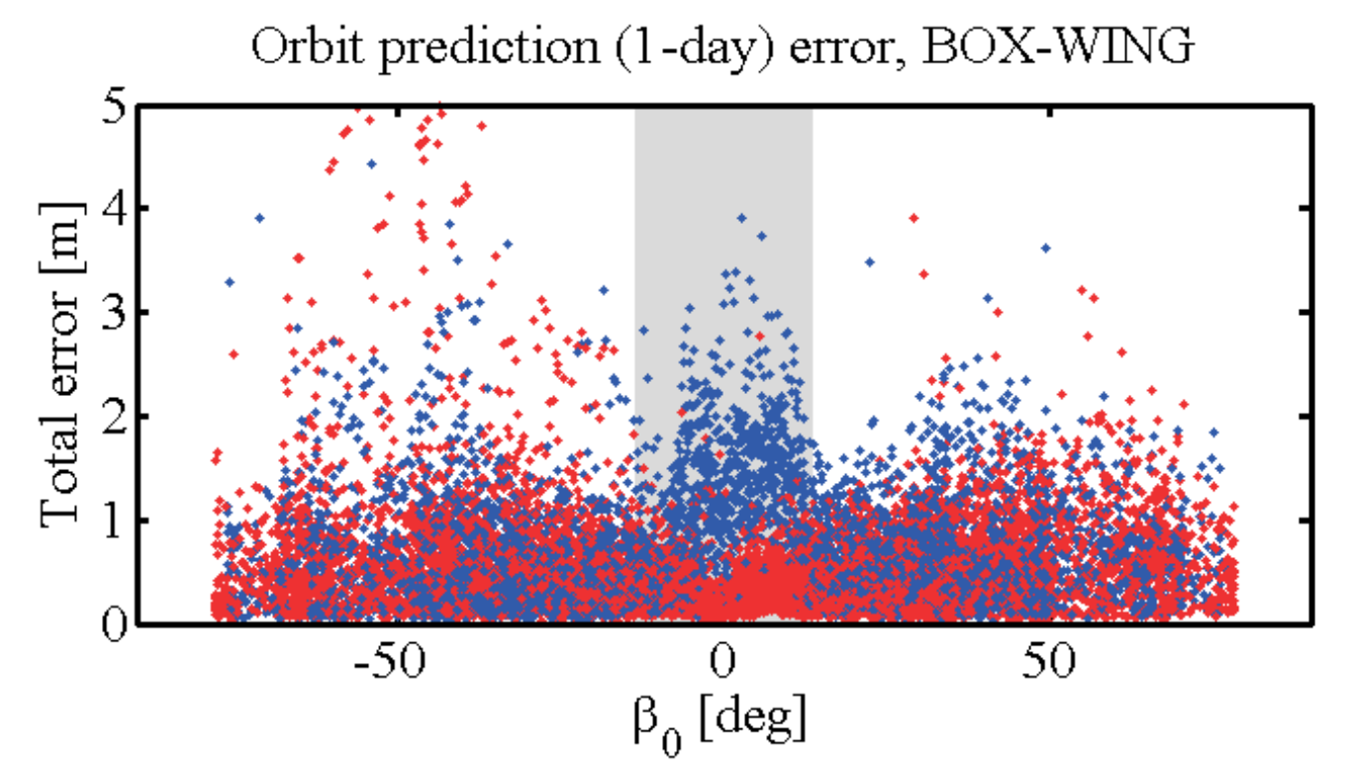


Fig. 8: The orbit prediction error (after one day) is shown for all **GPS IIA** and **GPS IIR** satellites of 2008 (including yaw maneuvers) as a function of the Sun elevation angle above the orbital plane (β_0). The error is computed as the 3D RMS of the difference between predicted and observed orbits over one day. The larger errors during eclipse seasons for GPS IIA are present for the solutions with and without yaw maneuvers.



7. Outlook

Deviations from nominal attitude have a clear impact on the computed solar radiation pressure acting on GNSS satellites and consequently on the orbits. Problems still remain mainly for **GPS IIA** satellites, in particular the modeling of the **post-shadow-turn** is very challenging since the rotation direction can be ambiguous. In fact, previous studies recommend to erase the observation data during the post-shadow-turn. While this approach can lead to lower residuals during the maneuvers, the same procedure cannot be applied for orbit integration where the box-wing model cannot be simply erased. Therefore further investigations are required on how to deal with the post-shadow-turn for precise orbit determination.

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