
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) subtracting empirical corrections from the GNSS tracking data, and 2) computing 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 be easily adjusted to the real 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 the satellite consisting of a box (hot spots) 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 solar surfaces.

2. Yaw attitude during eclipse seasons

Modeling the solar radiation pressure requires precise knowledge of the Sun-Earth-satellite configuration, i.e., the attitude of the satellite. The nominal attitude of a GNSS satellite is given by 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 maneuver: - GPS IIA (Bar-Sever, 1996)
- GPS IIR (Kouba, 2009)
- GLONASS-M (Diltsner et al., 2010)

These models (with a print hardware rate) have been implemented in a development version of the Bernese GPS Software.

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 angle of the solar panel 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:

\[ \frac{\partial a}{\partial \beta} = \frac{a_{\beta}}{\beta} \]

until it basically depends on:

- the Euler angles (\( \phi, \theta, \psi \))
- the attitude of the satellite
- the area and optical properties of the solar panels and satellite mass.

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

4. Yaw attitude and solar radiation pressure

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

The shadow-turn only occurs if the solar panels are not 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

The adjustment 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 Diltsner et al. (2010), respectively.

Fig. 5 shows the parameters of the box-wing model estimated for 2008. Some improvement (smaller variation during eclipse seasons) can be observed for GPS IIA satellites, while for the newer satellites (including GLONASS-M and GPS IIR) the yaw attitude model for GLONASS-M is used.

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 angles.

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 newest 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, matching the data of specific satellites, SVN 701 and SVN 713, that behave differently than other GLONASS-M satellites.

6. Impact on GNSS orbits

7. Outlook

Derivations from nominal attitude have a clear impact on the computed solar radiation pressure acting on the satellites, which in turn affects the orbit. Therefore further investigations are required on how to deal with the post-shadow-turn for precise orbit determination.

REFERENCES
Bar-Sever YE (1996) Yaw maneuvers - solution with nominal attitude. For all data with |\( \beta \)| < 13.5° of 2008 and for the satellites PN-2 (2009) and Diltsner et al. (2011). The orbit prediction error (after u = 0° and u = 180°+13.5°) is in sunlight. In Fig. 4 the impact on the solar radiation pressure impacting GPS satellites.

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