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Ray-tracing solar radiation pressure modeling for QZS-1

Francesco Darugna [a,b], Peter Steigenberger [c,*], Oliver Montenbruck [c], Stefano Casotto [d]

[a] *Università degli Studi di Padova, Department of Industrial Engineering, Via Gradenigo 6/a, 35131 Padova, Italy*
[b] *Geo++ GmbH, Steinriede 8, 30827 Garbsen, Germany*
[c] *Deutsches Zentrum für Luft- und Raumfahrt (DLR), German Space Operations Center (GSOC), Münchener Straße 20, 82234 Weßling, Germany*
[d] *Università degli Studi di Padova, Department of Physics and Astronomy, Vicolo dell'Osservatorio 3, 35122 Padova, Italy*

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Abstract

Precise orbit determination requires accurate models for the orbital perturbations. Next to the well-known gravitational forces, the solar radiation pressure (SRP) is the main perturbation for navigation satellites. SRP results from the interaction between the photons of the Sun and the surfaces of the satellite. Hence, its modeling depends on proper knowledge of the geometry and optical properties of the satellite. Previous work showed that the use of an a priori box-wing model for the SRP significantly improves the estimated orbit products as well as orbit predictions compared to purely empirical models. However, the presently available box-wing models for the first satellite of the Japanese Quasi-Zenith Satellite System, QZS-1, do not consider an accurate geometry. Based on a computer-aided design model of the QZS-1 satellite, a ray-tracing simulation is performed to compute SRP accelerations in a more realistic manner. The resulting SRP model is validated through QZS-1 precise orbit determination over a two year data arc covering yaw-steering and orbit-normal attitude regimes. In yaw-steering mode, the ray-tracing model shows a better overall performance than a box-wing model and improves the standard deviation of QZS-1 satellite laser ranging residuals by a factor of three compared to orbits without a priori model. On the other hand, the ray-tracing SRP model does not account for thermal accelerations and thus performs worse than an adjusted box-wing model in orbit-normal mode.

Keywords: Solar radiation pressure; Ray-tracing model; QZSS; SLR

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1. Introduction

Solar radiation pressure (SRP) is the dominant non-gravitational perturbation for global (and regional) navigation satellite systems (GNSSs) that require cm-level orbit knowledge for high-precision geodetic applications (Bock and Melgar, 2016). Therefore, precise orbit determination (POD) of GNSS satellites requires an accurate SRP model. Since Earth gravity field and luni-solar gravitational perturbations are well described nowadays, the SRP represents the key objective for precise orbit determination and prediction of the satellites mentioned above. So far, different kinds of SRP models have been developed: models based on ray-tracing and thermal analysis (Ziebart, 2004; Gini, 2014), analytical and semi-analytical models based on generic box-wing models (Rodriguez-Solano et al., 2012) and purely empirical models such as the empirical CODE orbit model (ECOM; Beutler et al., 1994; Springer et al., 1999) and its successor ECOM-2 (Arnold et al., 2015), developed at the Center for Orbit Determination in Europe (CODE).

Models based on ray-tracing techniques require an accurate description of the geometrical and optical properties of the satellite, while box-wing models only consider a simplified spacecraft geometry. ECOM and ECOM-2 do not

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* Corresponding author.

E-mail addresses: francesco.darugna@geopp.de (F. Darugna), peter.steigenberger@dlr.de (P. Steigenberger), oliver.montenbruck@dlr.de (O. Montenbruck), stefano.casotto@unipd.it (S. Casotto).

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require a priori information, but their performance depends on the selection of the estimated parameters. These parameters are given in a Sun-oriented DYB-frame with D pointing towards the Sun, Y along the solar panels axis, and B completing a right-handed system. For ECOM, usually five parameters are estimated: three constant terms in D-, Y-, B-direction and sine/cosine terms in B-direction. ECOM-2 adds higher harmonic terms but usually only the 2nd and 4th order terms in D-direction are considered resulting in a total number of nine parameters. It is important to select an appropriate set of ECOM parameters in order to take into account the properties of the spacecraft and to ensure that all parameters are observable. As an example, the 5-parameter ECOM resulted in large systematic errors for the Galileo satellites (Steigenberger et al., 2015a) that could be overcome by estimating the additional parameters of ECOM-2 (Prange et al., 2017).

The deployment of the Quasi-Zenith Satellite System (QZSS; Inaba et al., 2009; Kogure et al., 2017), the Japanese regional navigation satellite system, started in 2010 with its first satellite QZS-1 (“Michibiki”). QZSS broadcasts GPS-compatible signals to serve as an augmentation system for GPS and to provide highly precise and stable positioning services, focusing on the Asian-Pacific region. The orbit of QZS-1 is an elliptical inclined geosynchronous orbit (IGSO) in order to spend a longer time over the Japanese region than over the other regions. Between June and October 2017, two 2nd generation IGSO satellites (QZS-2 and -4) as well as a geostationary satellite (QZS-3) were launched (Cabinet Office, 2017a). The QZSS service will start in 2018 and offer three simultaneously visible satellites at all times from locations in the Asia-Oceania regions (Cabinet Office, 2017a). Expansion into a seven-spacecraft constellation using both IGSO and geostationary orbits is expected by 2023 (Kogure, 2016).

QZS-1 employs two different attitude modes: the yaw-steering (YS) mode and the orbit-normal (ON) mode (Ishijima et al., 2009), depending on the elevation of the Sun above the orbital plane (β-angle). In nominal YS mode, which is employed for $|\beta| > 20°$, the solar panel axis is perpendicular to the Sun and Earth directions and the navigation antenna points towards the Earth (Bar-Sever, 1996). For $|\beta| < 20°$, the spacecraft switches to ON attitude, in which the solar panel axis is maintained perpendicular to the orbital plane (Montenbruck et al., 2015).

Similar to Galileo, QZS-1 has an elongated body shape that has to be taken into account in the SRP modeling. The two different attitude modes have been considered in the development of a semi-analytical box-wing model by Montenbruck et al. (2017a). This model combines an analytic a priori model with a set of five empirical ECOM parameters and achieves a significant improvement w.r.t. the use of purely empirical models. QZS-1 orbits obtained in this way show a better than 10 cm RMS consistency with satellite laser ranging (SLR) measurements, the day boundary discontinuities are reduced by two thirds w.r.t. the orbits obtained without any a priori model and the orbit-clock variations are reduced by up to 85% during ON mode. Nevertheless, the use of a box-wing model cannot completely remove orbit errors and the necessity of estimating empirical SRP parameters. The performance of a box-wing model as a priori model in POD for QZS-1 has been also investigated in Zhao et al. (2018). The results of that work show also that the combination of ECOM with an a priori box-wing model can improve the quality of the estimated orbits by up to a factor of three compared to orbits without a priori model, and achieves RMS SLR residuals of 8 cm in YS mode. However, Montenbruck et al. (2017a) and Zhao et al. (2018) had to make assumptions about geometry and optical properties of QZS-1 as no detailed information about these was available at the time of those studies.

Ray-tracing techniques consider a computer-aided design (CAD) model which allows to take into account the geometric properties of the satellite and its individual components in great detail. For instance, ray-tracing techniques have been used for the precise orbit determination of GLONASS (Ziebart, 2004) and the low Earth orbit gravity field mission GOCE (Gini, 2014), improving the estimated orbits of these spacecraft. In Gini (2014) the ray-tracing model for the SRP reduced the empirical acceleration by about 20%. Within the present study all ray-tracing computations were performed with the commercial Zemax OpticStudio software, which has earlier been suggested for SRP modeling by Gini (2014).

This paper extends the work described in Montenbruck et al. (2017a) and aims to achieve a better SRP description by taking into account the detailed structure of QZS-1. Therefore, a ray-tracing model of solar radiation pressure for the QZS-1 satellite described by a CAD geometry is developed. The reference frames involved in this work, i.e., the YS, the ON, and the body-fixed frame, are introduced in Section 2. The geometrical and optical properties are described in Section 3 taking into account the previous considerations about QZS-1. The ray-tracing approach is described in Section 4 together with the implementation of the model into an optics software. The results of the ray-tracing are then used to compute gridded accelerations, which can be easily introduced into the POD software. The performance of the QZS-1 ray-tracing model in precise orbit determination is evaluated in Section 5 by analyzing estimated ECOM parameters, SLR residuals, day boundary discontinuities, and orbit predictions. We furnish also a critical comparison with the results obtained with the semi-analytical model presented in Montenbruck et al. (2017a) and the empirical ECOM-2 model (Arnold et al., 2015).

2. Reference frames

Unlike the 2nd generation QZSS IGSO satellites, QZS-1 employs two different attitude modes: the YS mode and the ON mode (Cabinet Office, 2017b). Within the YS mode, the x, y, z spacecraft body axis as defined by the manufacturer

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