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ScienceDirect

Advances in Space Research 57 (2016) 234–244

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

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A new empirical solar radiation pressure model for BeiDou GEO satellites

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Received 10 June 2015; received in revised form 29 October 2015; accepted 30 October 2015
Available online 9 November 2015

Abstract

Two classic empirical solar radiation pressure (SRP) models, the Extended Center for Orbit Determination in Europe (CODE) Orbit Model ECOM 5 and ECOM 9 have been widely used for Global Positioning System (GPS) Medium Earth Orbit (MEO) satellites precise orbit determination (POD). However, these two models are not suitable for BeiDou Geostationary Earth Orbit (GEO) satellites due to their special attitude control mode. With the experimental design method this paper proposes a new empirical SRP model for BeiDou GEO satellites, which is featured by three constant terms in DYX directions, two sine terms in DX directions and one cosine term in the Y direction. It is the first time to reveal that the periodic terms in the D direction are more important than those in YX directions for BeiDou GEO satellites. Compared with ECOM 5 and ECOM 9, the BeiDou GEO satellite orbits are significantly stabilized with the new SRP force model. The average orbit overlapping root mean square (RMS) achieved by the proposed model is 7.5 cm in the radial component, which is evidently improved over those of 37.4 and 13.2 cm for ECOM 5 and ECOM 9, respectively. In addition, the correlation coefficients between GEO orbit overlaps precision and the elevation angle of the Sun have been decreased to −0.12, 0.21, and −0.03 in radial, along-track and cross-track components by using the proposed model, while they are −0.94, −0.79 and −0.29 for ECOM 5 and −0.70, 0.21 and 0.10 for ECOM 9. Moreover, the standard deviation (STD) of Satellite Laser Ranging (SLR) data residuals for the GEO satellite C01 is reduced by 37.4% and 16.1% compared with those of ECOM 5 and ECOM 9 SRP models.

Keywords: BeiDou; Geostationary Earth Orbit (GEO); Solar radiation pressure (SRP); Precise orbit determination (POD)

1. Introduction

The Chinese BeiDou navigation satellite system (BDS) is one of three operational navigation systems in the world. It is characterized by three types of satellite constellations including the Geostationary Earth Orbit (GEO), Inclined Geosynchronous Orbit (IGSO) and Medium Earth Orbit (MEO) (Sun et al., 2012; Gao et al., 2009). The signal multiplexing mode of BDS is Code Division Multiple Access (CDMA) which is similar to that of the Global Positioning System (GPS) (China Satellite Navigation Office, 2013). The first BDS satellite known as M1 was launched in 2007 (Sun et al., 2012; Hauschild et al., 2012). A regional navigation constellation including 5 GEO, 5 IGSO and 4 MEO satellites was completed at the end of 2012 (Yang et al., 2014). The eventual BDS constellation will consist of 5 GEO, 3 IGSO and 27 MEO satellites in 2020 (China Satellite Navigation Office, 2012; Jin, 2013).

At present, the performance of BeiDou satellites precise orbit determination (POD) has not reached the comparable level with GPS. This may be explained by several factors including the inaccurate solar radiation pressure (SRP) model (Steigenberger et al., 2013), frequent GEO maneuvers

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http://dx.doi.org/10.1016/j.asr.2015.10.043
0273-1177/

(Xie et al., 2012), IGSO/MEO attitude control mode switches (Guo et al., 2013), the unknown antenna phase center offset (PCO) and variation (PCV) of BeiDou satellites (Dilssner et al., 2014), and the difficulty of integer ambiguity resolution (He et al., 2013; Liu et al., 2014b). To improve the orbit quality of BeiDou satellites, this paper is focused on the enhancement of the empirical SRP model for GEO satellites.

Several empirical SRP models have been developed to improve the quality of GPS satellite orbits. Rodriguez-Solana et al. (2012) summarized the empirical SRP models utilized on GPS satellites. Among the empirical SRP models, the Extended Center for Orbit Determination in Europe (CODE) Orbit Model (ECOM) is a classic model accepted by some of the International GNSS Service (IGS) analysis centers and it is implemented in the Bernese software (Beutler et al., 1995; Dach et al., 2007). At most 9 parameters can be estimated in the ECOM SRP model (Beutler et al., 1994). Later, Springer et al. (1999a) showed that only 5 from the 9 possible parameters are the most important ones for GPS satellites POD, this model is called ECOM 5.

Generally, three classes of SRP models based on ECOM have been applied to the POD of BeiDou satellites. The first class of SRP models, in which no a priori value and no additional parameters are used, has been documented in many publications. Montenbruck et al. (2013) employed the modified Bernese software to solve for the BeiDou satellite orbits. Daily orbit products with the three dimensional (3D) root mean square (RMS) accuracy in the range of 1–10 m are obtained. With the same software, Steigenberger et al. (2013) tested several subsets of the ECOM SRP parameters for BeiDou non-GEO satellites while only one SRP parameter was estimated for GEO satellites. An orbit consistency at the decimeter level was achieved for GEO satellites. However, it showed a clear correlation between the RMS values of the 2-day orbit fits of GEO satellites and the elevation of the Sun above the orbital plane. Cui et al. (2014) and Zeng et al. (2014) modeled the SRP acceleration for all BeiDou satellites with only ECOM 5. Liu et al. (2014a) solved the BeiDou satellite orbits only using ECOM 9 as the SRP model. The above three articles published in 2014 demonstrated that the RMS of the orbit overlapping reached 1–2 decimeters in the radial component. In the second class of SRP models, physical models were introduced to determine the BeiDou satellite orbits. Zhu et al. (2013) used the ECOM 9 SRP model with the box-wing model as an a priori model. Guo et al. (2013) studied the POD of IGSO satellites during the yaw maneuvers with the ECOM and adjustable box-wing model. The Satellite Laser Ranging (SLR) validation indicated that the orbit accuracy is better than 30 cm during the yaw maneuvers. For the third class, empirical SRP models without a priori models, but with additional parameters were utilized to estimate the BeiDou satellite orbits. He et al. (2013) investigated the performance of BeiDou satellite orbits using the ECOM 5 together with velocity breaks every 12 h. The results showed that the radial component RMS of overlapping orbits is better than 10 cm. Zhao et al. (2013) determined BeiDou satellite orbits with ECOM 5 SRP model. To compensate for the force modeling deficiencies, an empirical acceleration was added in the along-track for GEO satellites. The RMS of SLR residuals reaches 68.5 cm for the GEO satellite. Lou et al. (2014) presented the ECOM 5 is better than ECOM 9 SRP model for non-GEO satellites, and he also compared three SRP models for GEO satellites.

There are two obvious differences between BDS and GPS satellites. One is the altitude of the satellites, which is about 35786 km and 21528 km for BeiDou non-MEO and MEO satellites. But all of the GPS satellites fly in MEO at an altitude of about 20200 km. The other is the attitude control mode. The GEO satellites always adopt the yaw-fixed attitude mode (Zhao et al., 2013), but the non-GEO satellites of BDS switch the attitude mode from yaw-steering mode to yaw-fixed mode when the elevation angle of the Sun above the orbital plane is smaller than 5° and when the yaw angle is smaller than 4° (Guo et al., 2013; Wang et al., 2013; Zhu et al., 2014). In contrast to BeiDou satellites, all of the GPS satellites adopt the nominal yaw attitude mode when no attitude maneuver occurs (Bar-Sever, 1996; Kouba, 2009). Literature to date demonstrates that the ECOM 5 SRP model is valid for BeiDou non-GEO satellites during the yaw-steering attitude mode (Steigenberger et al., 2013; Zhao et al., 2013; Lou et al., 2014). However, the SRP model for BeiDou GEO satellites is controversial. On the one hand, only using one parameter cannot accurately describe the SRP for GEO satellites (Steigenberger et al., 2013). On the other hand, the ECOM 5 is also not suitable though additional parameters e.g. empirical acceleration (Zhao et al., 2013) and velocity breaks (He et al., 2013) are taken into consideration. Therefore, it is of great value to develop a specific SRP model for BDS GEO satellites.

In this study a new empirical SRP model exclusively for BDS GEO satellites is developed. Based on the general POD strategy of BeiDou satellites in Section 2, we test different subsets of periodic parameters in three axes of a Sun-oriented coordinate system to obtain an optimized SRP model for GEO satellites in Section 3. More specifically, we adopt the experimental design method to improve the optimization efficiency and investigate in which direction the periodic terms of ECOM SRP model is the most important. Performance assessment of the new SRP force model in terms of orbit overlaps, predicted orbit comparisons, SLR residuals and post-fit residuals analysis is conducted in Section 4. Some concluding remarks are provided in Section 5.

2. POD strategy

2.1. Basic SRP model

As shown on Fig. 1, the **R**, **T** and **N** are three axes of the orbit frame, also known as radial, along-track and cross-track components, respectively; the unit vector of orbit