Assessment About Parameters Selection Strategy of ECOMC Solar Radiation Pressure Model for BDS-3 Satellites During the Earth Eclipsing Period

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Abstract. Solar radiation pressure perturbation is the dominant error of POD of navigation satellites, which is directly bound up with the attitude control strategy of satellites and the properties of surface materials. Because of the difference of satellite characteristics, the 5-parameter ECOM model is not completely suitable for BDS-3 satellites during the earth eclipsing period. The higher-order periodic terms of ECOMC model can effectively absorb errors such as thermal radiation that are not modeled during the earth shadow period. This paper studies the variation of D_0, Y_0 and B_0 of ECOMC model with the sun elevation angle, proves that compared with the 5-parameter ECOM model, the ECOMC model is more accurate for navigation satellites POD. In order to solve the problem of excessive parameterization of ECOMC model, this paper analyzes the correlation between 13 solar radiation pressure parameters of ECOMC model. Based on the strong correlations, the 11-parameter ECOMC model for CAST satellites without estimating B_c and D_{4c} parameters and the 12-parameter ECOMC model for SECM satellites without estimating Bc12 parameters are proposed respectively. The experimental results show that compared with the 5-parameter ECOM model, the 11-parameter ECOMC model of CAST satellites can improve the radial, along-track and cross-track accuracy by 74.0%, 65.5% and 61.3%, respectively, and the 1DRMS by 66.7% during the Earth Eclipsing period. The 12-parameter ECOMC model for SECM satellites can prove the radial, along-track and cross-track accuracy by 58.5%, 56.2% and 70.7%, respectively, and the 1DRMS accuracy by 60.0% during the Earth Eclipsing period.

Keywords: Solar radiation pressure · BDS-3 · POD · ECOMC

1 Introduction

As the orbit reference of the Global Navigation Satellite System (GNSS) [1, 3], the satellite precision orbit is generated by the satellite precision orbit determination (POD) technology. The uncertainty of satellite dynamics model of POD mainly comes from the perturbation of non-conservative forces such as solar radiation pressure and earth

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radiation pressure. The solar radiation pressure is the most difficult force to model precisely, because it is directly bound up with the attitude control strategy of satellites and the properties of the surface materials, and is affected by the solar activity, the attitude control error of satellites and the aging of the surface materials of satellites.

In order to improve the accuracy of POD, the specific processing strategy is divided into two aspects. On the one hand, the prior empirical force parameters are added based on the ECOM solar radiation pressure model which is developed by the Center for Orbit Determination in Europe [4]. Two prior compensation models based on the Box-wing (BW) model with estimable parameters and spectrum analysis method were proposed to enhance the 5-parameter ECOM solar radiation pressure model in view of the cuboid nature of the BDS-3 satellite platform [5]. Based on the adjustable BW model [6], A prior solar radiation pressure model for the BDS-3 satellites was established which developed by China Academy of Space Technology (CAST) and Shanghai Engineering Center for Microsatelites (SECM). On the basis of considering the yaw attitude of the satellite, a prior light pressure model applicable to the BDS-3 satellite was constructed through Fourier analysis [7, 8].

On the other hand, the parameter selection strategy and applicability of the solar radiation pressure model are analyzed [9]. By analyzing the parameter selection strategy of the BDS satellite ECOM model [10], it is proved that the solar radiation pressure perturbation force has components related to the orbital period, and it is necessary to add a period term in the D direction to the 5-parameter ECOM model to absorb this component. The 8-parameter ECOM2 and 7-parameter ECOM2 solar radiation pressure models were proposed [11] by analyzing and refining the 5-parameter ECOM model and ECOM2 model, which solved the problem of increasing orbital discontinuity of BDS-3 satellite during the shadow period. The empirical ECOMC solar radiation pressure model proposed by MIT has the most optical pressure parameters, which is a combination of ECOM and ECOM2. Tseng has analyzed the adaptability of the ECOMC model for POD [7], proving that its high-order period term can effectively absorb the unmodeled thermal radiation and other errors during the shadow period and improve orbit accuracy of satellites.

Based on the ECOMC solar radiation pressure model, this paper analyzed the variation rule of solar radiation pressure parameters of the traditional 5-parameter ECOM model and 13-parameter ECOMC models of BDS-3 CAST and SECM satellites by using observation data, studied the correlation of solar radiation pressure parameters during the shadow period, and analyzed the applicability of different solar radiation pressure models in POD of BDS-3 satellites. Finally, the influence of different models in POD of BDS-3 satellites during the earth eclipsing period was comprehensively analyzed, and the way to improve the orbit accuracy during the shadow period was explored, which has important reference value for the construction of the solar radiation pressure model of BDS satellite.

2 Applicability Analysis of Solar Radiation Pressure Model

2.1 ECOM/ECOMC Solar Radiation Pressure Model

At present, the commonly used solar radiation pressure model for POD of BDS satellites is the classical 5-parameter ECOM model, whose expression as follow:

$$\begin{cases} a_D = D_0 \\ a_Y = Y_0 \\ a_B = B_0 + B_c \cos u + B_s \sin u \end{cases} \tag{1}$$

Based on the traditional ECOM model, the ECOMC model proposed by MIT is extended to 13 parameters, and its expression as follow:

$$\begin{cases} a_D = D_0 + D_c \cos(\Delta u) + D_s \sin(\Delta u) \\ \quad +D_{2c} \cos(\Delta 2u) + D_{2s} \sin(\Delta 2u) \\ \quad +D_{4c} \cos(\Delta 4u) + D_{4s} \sin(\Delta 4u) \\ a_Y = Y_0 + Y_c \cos(\Delta u) + Y_s \sin(\Delta u) \\ a_B = B_0 + B_c \cos(\Delta u) + B_s \sin(\Delta u) \end{cases} \tag{2}$$

where D_c, D_s, D_{2c}, D_{2s}, Y_c and Y_s are periodic terms, Δu is the orbital Angle of the satellite with respect to the sun. At present, there are few researches on ECOMC solar pressure model for BDS-3 satellite POD during the earth eclipsing period. Moreover, ECOMC model has many parameters and strong correlation between parameters, so it needs to be further analyzed.

2.2 Strategy of Precision Orbit Determination

In this paper, based on the 5-parameter ECOM and ECOMC solar radiation pressure models, the precision orbit determination of BDS-3 satellites is carried out by using 100 observation stations uniformly distributed around the world. The double difference ionosphere-free combined observation data of B1I/B3I frequency band with annual accumulation days from 001–365 days in 2021 were selected, and the coordinate of the station was fixed value plus the constraint of 0.05 m. Except for the solar radiation pressure model, the other models and strategies were consistent. The specific strategy and error processing model are shown in Table 1.

2.3 Analysis of Variation Law of Solar Radiation Pressure Parameters

Figures 1 and 2 respectively show the variation of the solar radiation pressure parameters of BDS-3 satellite 5-parameter ECOM model and ECOMC model with the β Angle. Considering that BDS-3 satellite was independently developed by CAST and SECM manufacturers, the satellite quality information of CAST and SECM is provided in Table 2.

Since BDS-3 MEO satellite is launched into orbit in the “one-arrow binary” mode, the “binary” satellite has similar structure and mass, and the difference of solar radiation

Table 1. Orbit determination strategy and error processing model.

Category	Influencing factors	Strategy or model
Model of observation	Arc length	1 day
	Observations	Double difference B1I/B3I IF observations
	Sampling	30 s
	Elevation angle cut-off	10°
	Satellite and receiver clock	Elimination by double difference
	PCO	igs14.atx
	Initial orbit	Broadcast ephemeris
	Station coordinates	Fixed value of 0.05 m constraint
	Troposphere delay	Saastamoinen model for wet and dry hydrostatic delay with the GMF without the gradient model
	Ionosphere delay	Elimination by the dual-frequency combinations
Model of dynamics	Geopotential	EGM2008 (12 × 12)
	Third-body	JPL DE405
	Solid earth tides, Solid earth pole tides, Ocean tide	FES2004/IERS2010
	Relativistic effect	IERS2010
	Solar radiation pressure model	5-parameter ECOM/ ECOMC model

Table 2. Mass of BDS-3 satellites

Satellite	PRN	Nominal mass [kg]
CAST	C19, C20, C21, C22, C23, C24	941–946
	C32, C33	1007
	C36, C37,C41, C42, C45, C46	1058–1061
SECM	C25, C26	1041–1044
	C27, C28	1014–1018
	C29, C30	1008–1011
	C34, C35	1045–1046
	C43, C44	1075–1078

pressure parameters is less than 1 nm/s^2. Therefore, the variation of solar radiation pressure parameters of one of the "binary" satellites is plotted. Three main parameters

D_0, Y_0 and B_0 are analyzed in this paper. D_0 reflects the acceleration of solar radiation pressure acting on the satellite. Y_0 is the deviation Angle of the solar panel with respect to the nominal position and the constant acceleration along the Y-axis. B_0 is constant acceleration about the Y-axis.

The solar radiation pressure parameters of CAST and SECM satellites are significantly different in magnitude. The parameters of CAST satellites are concentrated in the range of -120–-150 nm/s^2, while those of SECM satellites are concentrated in the range of -65–-80 nm/s^2. Because the solar panel area of SECM satellite is much smaller than that of CAST satellite. The solar radiation pressure parameters of both CAST and SECM satellites are closely related to the satellite mass. The larger the satellite mass is, the smaller it will be.

Because the 5-parameter ECOM model cannot compensate the unmodeled forces during the earth eclipsing period, such as thermal radiation, the Y_0 parameter of the ECOMC model is more stable than that of the 5-parameter ECOM model (The shaded part in the figure is the earth eclipsing period). When the ECOMC model is used for POD, the fluctuation of solar radiation pressure parameters becomes significantly smaller, because the higher-order periodic term in the D direction of the ECOMC model can absorb the unmodeled errors. The Y_0 parameter of the ECOMC model is more discrete than that of the 5-parameter ECOM model, which may be due to the over-parameterization of the ECOMC model in the Y direction. Therefore, it is necessary to conduct correlation analysis on 13 solar radiation pressure parameters of ECOMC model, eliminate strong correlation parameters, reduce excessive parameterization, and improve the orbit accuracy and calculation efficiency of POD.

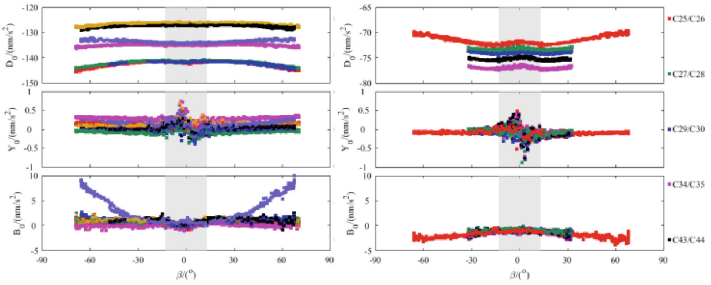

Fig. 1. Variation of SRP of ECOM model for CAST (left) and SECM satellites (right) (the shaded areas are the eclipse periods).

This paper analyzes the orbit accuracy of POD of 2021 BDS C19 satellite using 13-parameter ECOMC model and 5-parameter ECOM model, and the results of other CAST satellites are similar to those of C19 (see Fig. 3).

The results show that the orbit accuracy of POD of the 5-parameter ECOM model is poor, which is caused by the cuboid configuration of BDS-3 satellites. When the β Angle is large, the satellite $+$X direction is subject to solar illumination, and the solar radiation pressure perturbation force changes little with the movement of the satellite. When the β Angle is small, during the earth eclipsing period, the $+$X, $+$Z and $-$Z directions of the satellite are subject to solar illumination in turn. Due to the different areas of the X and Z

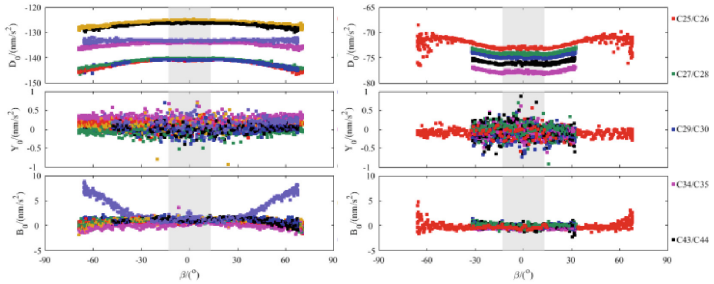

Fig. 2. Variation of SRP of ECOMC model for CAST (left) and SECM satellites (right) (the shaded areas are the eclipse periods).

planes of the satellite, the solar radiation pressure perturbation changes periodically and obviously with the movement of the satellite. The accuracy of the satellite orbit becomes worse, Because the D_0 constant term of the 5-parameter ECOM model cannot absorb the periodic error.

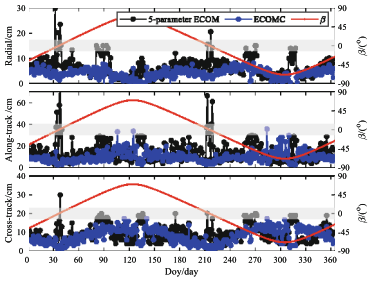

Fig. 3. Orbit accuracy of C19 for ECOM and ECOMC.

Compared with the 5-parameter ECOM model, the 13-parameter ECOMC model added higher-order periodic term parameters in the D and Y directions. BDS-3 CAST satellite can improve the satellite orbit accuracy during the earth eclipsing period, in which the along-track accuracy is improved the most, the radial accuracy improves the second, and the cross-track accuracy improves the least.

The variation trend of orbit accuracy of SECM satellite is consistent with that of CAST satellite, but the orbit accuracy of SECM satellite is higher than that of CAST satellite. It is proved that adding the high-order period term of the solar radiation pressure model can effectively improve the orbit accuracy of POD of BDS-3 satellite during the earth eclipsing period.

3 ECOMC Model Improvement Method

3.1 Correlation Analysis of Solar Radiation Pressure Parameters of ECOMC Model during the Earth Eclipsing Period

Although the 13-parameter ECOMC model can improve the orbit accuracy of BDS-3 satellites during the earth eclipsing period, which has the problem of over-parameterization. By using the correlation analysis of the optical pressure parameters, the number of solar radiation pressure parameters can be reduced on the basis of ensuring the orbit accuracy of the satellite, and the solution efficiency can be improved to solve the problem of over-parameterization of the model.

In order to analyze the correlation of solar radiation pressure parameters of ECOMC model during the earth eclipsing period, CAST C19 and SECM C25 satellites were selected as representatives for analysis, and the other satellites showed similar performance (see Fig. 4).

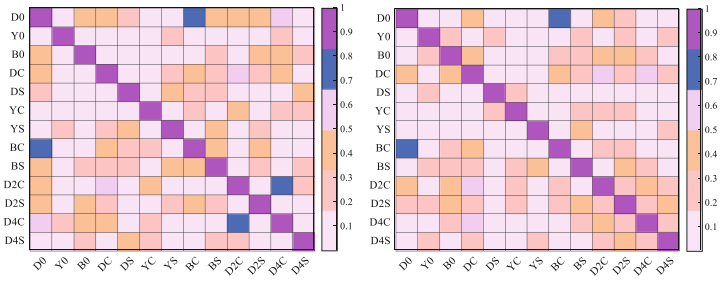

Fig. 4. Orbit accuracy of C19 (left) and C25 (right)for ECOM and ECOMC.

The correlation of solar radiation pressure parameters of CAST and SECM satellites is not consistent. As can be seen from Fig. 4, there is a strong correlation between the solar radiation pressure parameters D_0 and B_C, between D_{2C} and D_{4C} of CAST satellites, a strong correlation between the solar radiation pressure parameters B_C and D_{4C} of SECM satellites during the earth eclipsing period. Considering the above correlation, the 11-parameter ECOMC model without B_C and D_{4C} parameters was used for POD of CAST satellites. The 12-parameter ECOMC model without B_C parameters was used for POD of SECM satellites. The 5-parameter ECOM model and the 13-parameter ECOMC model are also given for comparison, as shown in Table 3.

3.2 Result Analysis

Based on the POD strategy and error processing model shown in Table 1, the experiment adopts the precision ephemeris of German Research Centre for Geosciences (GFZ) as the reference orbit. Different solar radiation pressure models were selected for POD of CAST and SECM satellites of BDS-3 system, and the applicability of different solar radiation pressure models to BDS-3 satellites was obtained through orbit accuracy analysis. Figure 5 shows the mean precision orbit determination accuracy results of CAST

Table 3. SRP models of BDS-3 POD

Model	Solar radiation pressure parameters
5-ECOM	D_0, Y_0, B_0, B_c, B_s
ECOMC	$D_0, Y_0, B_0, D_c, D_s, D_{2c}, D_{2s}, D_{4c}, D_{4s}, Y_c, Y_s, B_c, B_s$
11-ECOMC	$D_0, Y_0, B_0, D_c, D_s, D_{2c}, D_{2s}, D_{4s}, Y_c, Y_s, B_s$
12-ECOMC	$D_0, Y_0, B_0, D_c, D_s, D_{2c}, D_{2s}, D_{4c}, D_{4s}, Y_c, Y_s, B_s$

(C19/C20, C21/C22, C32/C33) and SECM (C25/C26) satellites entering the ground shadow period.

During the earth eclipsing period, the orbit accuracy of POD of SECM satellites using the same solar radiation pressure model is slightly higher than that of CAST satellites. Compared with the 5-parameter ECOM model, the 13-parameter ECOMC model can effectively improve the orbit accuracy of POD of CAST and SECM satellites. The 11-parameter ECOMC model without solar radiation pressure parameters B_C and D_{4C} for CAST satellites and the 12-parameter ECOMC model without solar radiation pressure B_C for SECM satellites can further improve the orbit accuracy of POD. The adaptability of different satellites to different solar radiation pressure models is not completely consistent. For example, when determining the precision orbit of C32/C33 satellite, the Cross-track accuracy of the 11-parameter ECOMC model is improved compared with that of the 13-parameter ECOMC model, but the radial and Along-track accuracy are slightly worse.

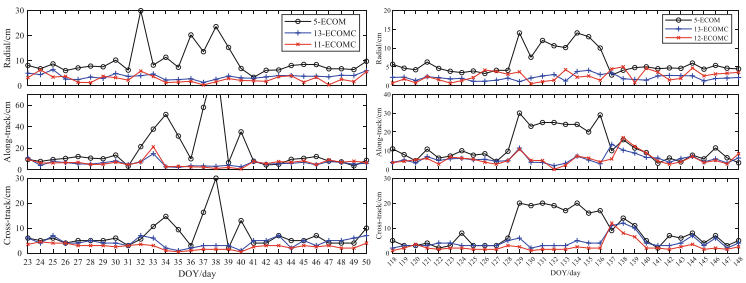

Fig. 5. Accuracy of CAST (left) and SECM (right) satellites

Table 4. The accuracy of different models during the Earth Eclipsing Period.

5-ECOM					13-ECOMC				11/12-ECOMC			
Satellite	R (cm)	A (cm)	C (cm)	1DRMS (cm)	R (cm)	A (cm)	C (cm)	1DRMS (cm)	R (cm)	A (cm)	C (cm)	1DRMS (cm)
CAST	9.08	16.67	6.70	11.67	3.23	5.27	4.06	4.28	2.36	5.75	2.59	3.89
SECM	6.77	12.73	8.87	9.78	2.13	5.32	4.28	4.13	2.81	5.57	2.60	3.91

Detailed statistics of orbit accuracy of POD using different solar radiation pressure models during the earth eclipsing period are shown in Table 4. Compared with the traditional 5-parameter ECOM model, the orbits accuracy of radial, along-track and cross-track of CAST satellites using the 13-parameter ECOMC model is improved by 64.3%, 68.4% and 39.4%, respectively, and the 1DRMS is improved by 63.3%. Compared with the 5-parameter ECOM model, the orbits accuracy of radial, along-track and cross-track of CAST satellites using the 11-parameter ECOMC model is improved by 74.0%, 65.5% and 61.3%, respectively, and the 1DRMS improved by 66.7%. Compared with the 13-parameter ECOMC model, the orbits accuracy of radial and cross-track of CAST satellites using the 11-parameter ECOMC model is improved by 26.9% and 36.2%, respectively, the orbits accuracy of along-track decreased by 9.1%, and the 1DRMS improved by 9.1%.

Compared with the traditional 5-parameter ECOM model, the orbits accuracy of radial, along-track and cross-track of SECM satellites using the 13-parameter ECOMC model is improved by 68.5%, 58.2% and 51.8%, respectively, and the 1DRMS is improved by 57.8%. Compared with the 5-parameter ECOM model, the orbits accuracy of radial, along-track and cross-track of SECM satellites using the 12-parameter ECOMC model is improved by 58.5%, 56.2% and 70.7%, respectively, and the 1DRMS improved by 60.0%. Compared with the 13-parameter ECOMC model, the orbits accuracy of cross-track of SECM satellites using the 12-parameter ECOMC model is improved by 39.2%, the orbits accuracy of radial and along-track decreased by 31.9% and 12.5%, respectively, and the 1DRMS improved by 5.3%.

4 Conclusions

Based on the observation data and precision ephemeris as the reference orbit from GFZ in 2021, this paper analyzes the adaptability of two solar radiation pressure models, ECOM and ECOMC, in CAST and SECM satellites of the BDS-3 system POD. The conclusion is as follows:

The D_0 parameter of the solar radiation pressure model are closely related to the satellite mass. The larger the satellite mass is, the smaller it is. The magnitude of the D_0 parameter of CAST and SECM satellite is significantly different.

Compared with the 5-parameter ECOM model, using the 13-parameter ECOMC model for POD, both CAST and SECM satellites of BDS-3 system can improve the orbit accuracy, but the orbit accuracy of SECM satellites is higher than that of CAST satellites. The addition of higher-order period terms in the D and Y directions of the solar radiation pressure model can effectively improve the orbit accuracy of BDS-3 satellite during the earth eclipsing period.

ECOMC solar radiation pressure model was over-parameterized during the earth eclipsing period. There is a strong correlation between parameters D_0 and B_C, between parameters D_{2C} and D_{4C} for CAST satellites of BDS-3 system. And there is a strong correlation between parameters D_0 and B_C for SECM satellites of BDS-3 system.

Precise orbit determination was carried out for CAST satellites without estimating B_C and D_{4C}, and for SECM satellites without estimating. The experimental results show that compared with the 5-parameter ECOM model, using the 11-parameter ECOMC model

for CAST satellites, the orbit accuracy of radial, along-track and cross-track is improved by 74.0%, 65.5% and 61.3%, respectively, and the 1DRMS orbit accuracy is improved by 66.7%. Using 12-parameter ECOMC model for SECM satellite, the accuracy of radial, along-track and cross-track is improved by 58.5%, 56.2% and 70.7%, respectively, and 1DRMS is improved by 60.0%. The adjusted ECOMC model can greatly improve the orbit accuracy of POD of BDS-3 satellites during the earth eclipsing period.

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