Precise estimation of PCV and its influence on POD for COSMIC-2

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ABSTRACT

To ensure that ensure the normal operation of the Constellation Observing System for Meteorology, Ionosphere and Climate-2 (COSMIC-2) satellite mission, it is crucial to perform precise orbit determination (POD) using the onboard GPS data. This study aims to enhance the accuracy of POD by performing an in-flight correction of the phase center variation (PCV) for the GPS receiver antenna on the COSMIC-2 satellite. Using the simplified dynamics method to perform orbit determination for COSMIC-2 satellites, we estimate the PCV model using both the direct approach and residual approach, and evaluate the orbit determination results through internal and external consistency assessments. The results show that the root mean square (RMS) value of overlapping orbit comparisons accuracy without considering PCV correction is at the centimeter level, while the RMS value of the reference orbit comparison accuracy is at the decimeter level. With the PCV model corrections approximated by the direct approach and residual approach, 3D RMS values experience a reduction of 2.5mm and 1.3mm, respectively, based on 4-hour overlap orbit comparison.

Keywords: COSMIC-2 satellites, phase center variation, precise orbit determination

1. INTRODUCTION

COSMIC-2 is a remote sensing satellite developed in collaboration between the National Space Organization (NSPO) of Taiwan and the National Oceanic and Atmospheric Administration (NOAA) of the United States. Its main purpose is to supply meteorological data for forecasting, ionospheric studies, and climate research [2] . COSMIC-2 is designed to operate for a period of five years, a 525 km ultimate altitude, an orbital period of approximately 97 minutes around the Earth [1] .

Errors like tropospheric and ionospheric delays can be removed for low-Earth orbit (LEO) satellite orbit determination accuracy by using the right models or observation combinations. Nevertheless, it is challenging to reduce antenna phase center variation (PCV) using models and combinations[3]. Studies conducted by Montenbruck et al. [4] and Jäggi et al. [5] have demonstrated the significant impact of PCV on the precision of orbit determination. Despite ground calibration of the receiver antenna phase center before to launch, the high velocity of LEO satellites in orbit makes them susceptible to multipath effects and other factors, causing the actual antenna data received by the satellite receivers to differ from the initial calibration values. Hence, it is critical to accurately determine the in-flight PCV model to determine COSMIC-2's orbit with precision.

There has already been relevant research on the precise orbit determination of COSMIC-2 satellites [6] . Weiss et al. [7] successfully achieved orbiting for COSMIC-2 utilizing simplifying dynamic methods, attaining a 3D orbital precision within 10 cm for validation overlap. Similarly, Jäggi et al. [6] conducted a comprehensive assessment of the orbit accuracy for COSMIC-2 by employing the diminished dynamic and kinematic orbit determination methods. Kong et al. [8] POD for COSMIC-2 was carried out utilizing the reduced dynamic approach and reported a mean RMS of less than 2 cm for the 3D orbits of six COSMIC-2 satellites during a four-hour overlapping period. These studies collectively demonstrate the importance of precise orbit determination for both the COSMIC-1 and COSMIC-2 satellites and highlight the effectiveness of the reduced dynamic and kinematic methods in achieving high orbiting accuracy, and due to the high demand for data quality in kinematics, we use reduced dynamic methods to achieve POD in this study [9,10] . However, there is a lack of investigation into PCV's effects on the POD of this constellation.

The effect of PCV on other LEO satellites' POD has a certain basis, which can provide a reference for COSMIC-2. Hwang et al. [11] used simplified dynamic methods for the POD of COSMIC-1 satellites and found that incorporating PCV

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corrections could improve the internal consistency accuracy of the orbits. Yuan et al. [12] considered PCV's effects on the orbit determination accuracy of the ZY3-01 satellite, and the results showed an enhancement at the millimeter level.

The reduced dynamic orbit determination approach is then employed in this study to achieve POD for COSMIC-2. Two methods, namely the residual approach and the direct method, are utilized to calculate the PCV model for the GPS antenna on COSMIC-2 during its in-flight operation, and conduct internal and external accuracy assessment. Finally, analyze the PCV models' effects from both methods on precise orbit determination.

2. DATA AND ORBIT DETERMINATION STRATEGY

This study uses the COSMIC-2 satellite GPS observation data supplied by Taiwan's Central Weather Bureau. The observation data time is DOY124-130. Table 1 displays the specific orbit determination approach.

Table 1. Satellite orbit determination strategy.

Models	
N-body	JPL DE405
Mean earth gravity	EGM2008_SMALL
Relativity	IERS2010XY
Solid-earth tides	TIDE2000
Ocean Tides	FES2004
precise ephemeris	sample interval of 15 minute
clock offset	sample interval of 30 seconds
Antenna PCO and PCV	Igs14.atx
Elevation threshold	5°
Interval of sampling	20 s
Pseudostochastic pulses	12 min
Arc length of orbit calculation	24 h

3. RECEIVER ANTENNA PHASE CENTER CORRECTION

Generally speaking, antenna phase center correction refers to the difference between the position of the antenna phase center and the antenna reference point (ARP), which is composed of antenna PCO and PCV. In this study, the 7-day PCO mean parameter is adopted as a fixed value, and the modeling of PCV is mainly for the onboard GPS receivers of the COSMIC-2 mission.

In this paper, both the residual approach and the direct method will be employed to compute the PCV. The direct approach entails incorporating the PCV directly and finding a solution for it in the observation equations, while in the residual method [4] , the residuals of observations are utilized to modeling PCVs. In this study, when the residual method is being carried out, divide the sky into a grid of 10° by 10° blocks based on azimuth and elevation angles. For each grid node, average all phase residual values from the surrounding ±5° blocks to determine the PCV value. Use linear interpolation to calculate the corresponding phase center variation values at specific azimuth and elevation angles [3] . The computation process is realized by three times of iteration, and the results gained after the last time iteration are taken as the final PCVs. In Figure 1, the 10° by 10° PCV models for six satellites that were acquired using the direct approach are shown in 1a through 6a, while the 10° by 10° PCV models that were generated using the residual method are shown in 1b through 6b.

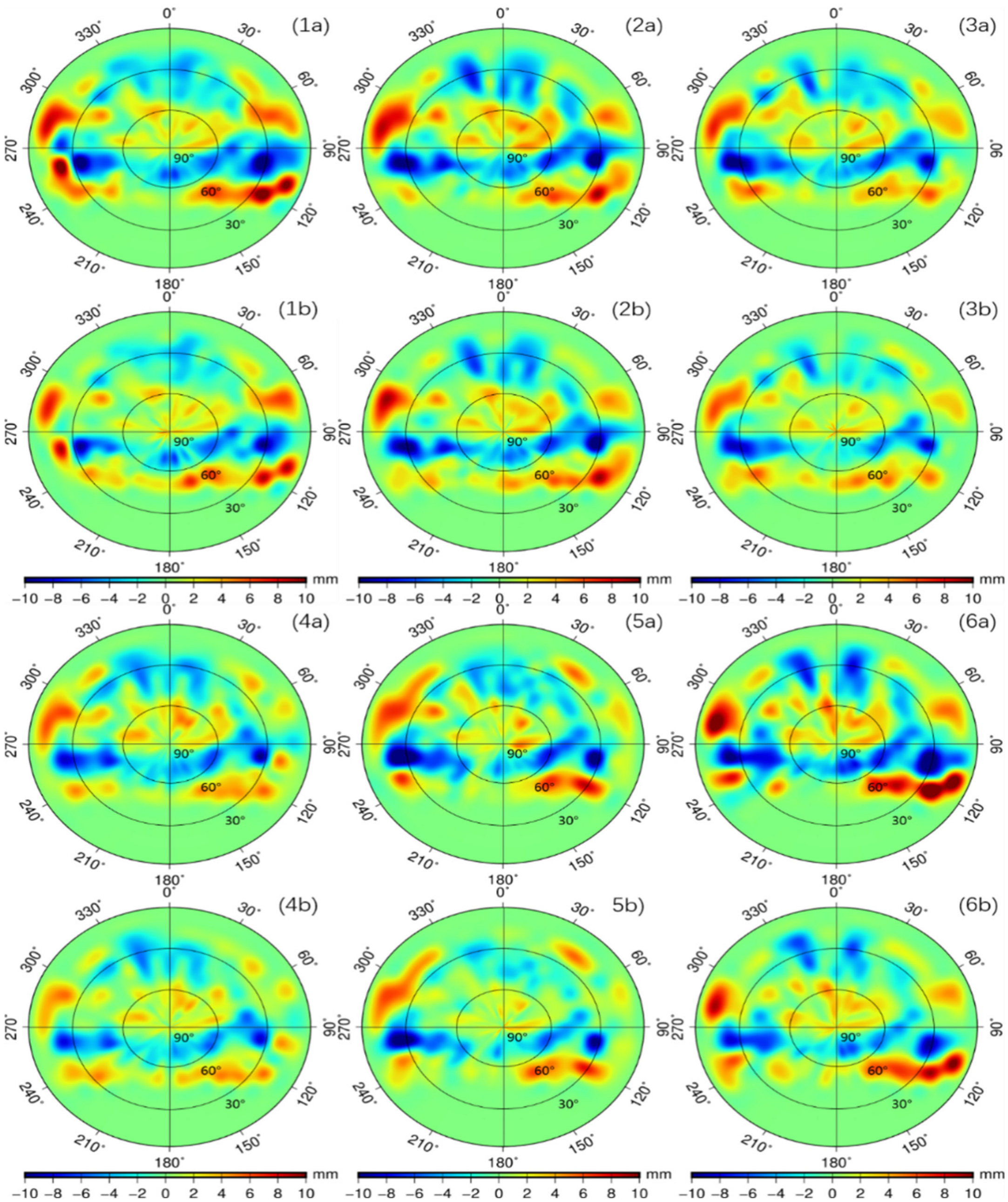

Figure 1. The estimated PCV maps. The altitude angle is 90˚ at the center and 0˚ at the edge.

From Figure 1, it is evident that the models obtained for each satellites are generally resemblance, likely due to the similarity in receiver equipment and satellite construction. In both models calculated using the residual approach and the direct method, larger absolute values are found in regions with lower elevation angles. This is attributed to the lower quantity and quality of observational data at lower elevation angles.

4. EFFECT OF PCV ON THE ACCURACY OF POD FOR COSMIC-2

The main orbit accuracy evaluation method includes internal and external conformity accuracy assessments. This study assesses the internal orbit accuracy by overlap orbit comparison and assesses the external orbit accuracy by orbit comparison between the ones determined by reduced dynamic method and ones released by Taiwan's Central Weather Bureau to assess.

4.1 Internal evaluation of orbit accuracy

There are two separate orbital segments built up: one from 0:00 to 18:00 and another from 12:00 to 24:00 in DOY 125,2022, with an overlap of 6 hours. To avoid boundary effects, select an intermediate 4 hours. Although the data in overlapping segments are the same, the two solutions are obtained independently through separate orbit determinations. Therefore, they can be used to evaluate the internal consistency accuracy of the orbit [8] .

Table 2 shows the RMS value statistics for the overlapping orbit comparison on DOY125, 2022, at 4-hour intervals. Figure 2 displays the 3D directional average RMS values.

Table 2. RMS values statistics of 4-hour overlapping orbit comparison on DOY 125, 2022 (mm).

	Method	Satellite 1	Satellite 2	Satellite 3	Satellite 4	Satellite 5	Satellite 6	Mean
	No-PCV	11.2	7.2	8.2	8.1	8.3	12.7	9.3
R	Direct	9.2	5.7	8.2	8.0	7.9	9.8	8.1
	Residual	10.2	5.9	8.6	7.5	8.2	10.9	8.6
	No-PCV	16.9	11.7	10.0	15.9	10.9	20.7	14.4
T	Direct	14.6	9.8	10.3	14.0	11.3	15.3	12.6
	Residual	15.0	10.0	10.4	14.8	11.4	16.2	12.9
	No-PCV	9.1	10.5	10.4	7.7	6.9	7.8	8.7
N	Direct	7.9	8.8	9.1	8.4	6.5	7.3	8.0
	Residual	8.4	8.7	9.4	7.8	6.3	7.6	8.0
	No-PCV	23.5	18.0	17.4	19.7	15.7	25.7	20.0
3D	Direct	19.6	14.9	16.5	18.5	15.6	19.7	17.5
	Residual	20.8	15.1	16.9	18.7	15.7	21.1	18.1

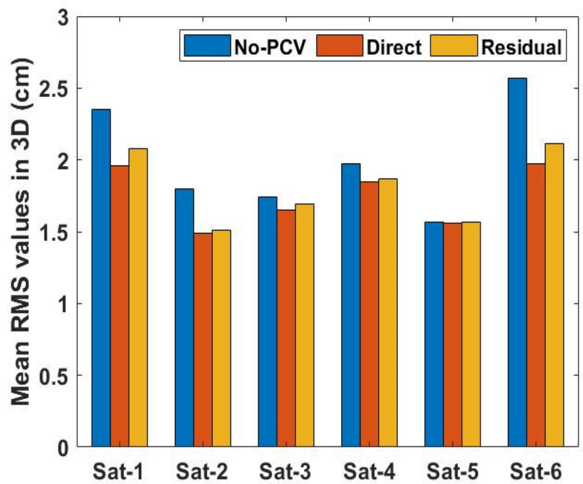

Figure 2. Mean RMS values of orbit differences for three schemes with 4h overlap in 3D on DOY 125, 2022.

According to Table 2, following the PCV model's adoption into consideration, the precision of the orbit determination five satellites gained relatively significant improvement, except for Sat-5. Sat-6 got the most significant orbit accuracy improvement, after incorporating the models computed using the residual approach and the direct method, the 3D direction's orbit determination accuracy increased by 6.0 mm and 4.6 mm, respectively. From Figure 2, It is clear that the direct approach model estimation contributes more to the increase in the precision of orbit determination in contrast to the model estimated using the residual method. Besides, it should be noted that no matter which scheme is applied, the RMS values of orbit differences of the 4h overlap arc in this study are smaller than those (about 15cm) published by Taiwan's Central Weather Bureau.

4.2 External orbit accuracy assessment

Using the Central Weather Bureau of Taiwan's satellite reference orbits for scientific orbit comparison with the simplified dynamic orbit solutions, external consistency assessments were conducted based on RMS values. Table 3 presents the statistical results of scientific orbit comparisons for seven days from DOY 124 to DOY 130.

Table 3. Statistics results of RMS value comparison of scientific orbits of various schemes (mm).

	Method	Satellite 1	Satellite 2	Satellite 3	Satellite 4	Satellite 5	Satellite 6	Mean
	No-PCV	75.0	84.2	68.8	71.7	99.7	65.8	77.5
R	Direct	73.2	83.5	69.2	70.4	100.7	66.8	77.3
	Residual	73.3	84.0	68.8	71.2	100.1	66.9	77.2
	No-PCV	109.2	111.5	94.3	108.3	133.4	83.6	106.7
T	Direct	105.2	109.3	94.0	106.2	134.2	87.3	106.0
	Residual	105.9	109.9	93.7	105.6	133.1	85.1	104.5
	No-PCV	28.5	27.6	39.3	32.8	47.7	28.2	34.0
N	Direct	28.5	23.9	36.5	34.4	45.4	23.8	32.1
	Residual	27.5	25.4	37.6	31.2	46.0	26.3	32.3
	No-PCV	136.2	142.6	123.7	134.1	175.1	110.3	137.0
3D	Direct	132.0	139.7	122.8	132.2	176.0	112.7	135.9
	Residual	132.5	140.8	122.7	131.3	174.8	110.7	134.5

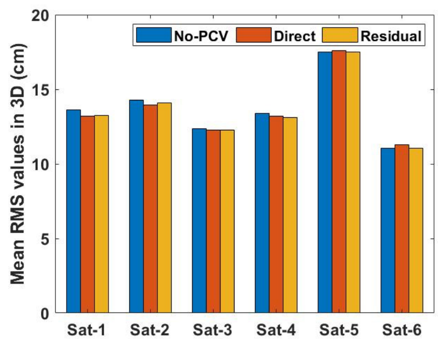

Figure 3. Comparison of 3D RMS values of scientific orbits of various schemes.

From Table 3 and Figure 3, for the residual approach and the direct approach, the increase in precision of orbit computation for Sat-1 is the most significant. After incorporating the models estimated using the residual approach and the direct approach, the orbit determination accuracy for this satellite in the 3D direction improved by 4.2 mm and 3.7 mm, respectively.

5. CONCLUSIONS

For reliable data for ionosphere research and weather forecasting, the COSMIC-2 mission is essential. To ensure the success of this mission, POD plays a vital role. Receiver antenna phase center error, being one of the important variables influencing the accuracy of orbit determination, has to be considered.

In this research, the reduced dynamic approach was utilized for the POD of COSMIC-2, and estimate the PCV using both the residual approach and the direct method. Evaluate the orbit determination accuracy through comparing overlapping orbits and scientific orbits. Due to the zenith tilt angle of 75°, the GPS signal is blocked, so holes will appear in the estimated model.

The PCVs estimated by the residual approach showed relatively similar features to those estimated by the direct method. By considering the PCV model calculated using the direct approach, Sat-6 demonstrated a significant improvement in overlap orbit accuracy, with a 6mm improvement in 3D direction. Similarly, by taking into account the PCV model that the residual approach computed, Sat-1 showed the most significant improvement in external orbit accuracy, with a 4.2mm improvement in the 3D direction. Overall, the estimation of PCVs in this study significantly enhanced the accuracy of POD for COSMIC-2, surpassing the accuracy published by Taiwan's Central Weather Bureau.s.

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DATA AVAILABILITY STATEMENT

Our sincere thanks go to the Central Weather Bureau for providing space-borne GPS data for COSMIC-2; CODE Analysis Center at AIUB for providing GPS satellite orbits, clocks and Earth rotation parameters.

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