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ORIGINAL ARTICLE

Precise orbit determination for the FORMOSAT-3/COSMIC satellite mission using GPS

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Abstract The joint Taiwan–US mission FORMOSAT-3/COSMIC (COSMIC) was launched on April 17, 2006. Each of the six satellites is equipped with two POD antennas. The orbits of the six satellites are determined from GPS data using zero-difference carrier-phase measurements by the reduced dynamic and kinematic methods. The effects of satellite center of mass (COM) variation, satellite attitude, GPS antenna phase center variation (PCV), and cable delay difference on the COSMIC orbit determination are studied. Nominal attitudes estimated from satellite state vectors deliver a better orbit accuracy when compared to observed attitude. Numerical tests show that the COSMIC COM must be precisely calibrated in order not to corrupt orbit determination. Based on the analyses of the 5 and 6-h orbit overlaps of two 30-h arcs, orbit accuracies from the reduced dynamic and kinematic solutions are nearly identical and are at the 2–3 cm level. The mean RMS difference between the orbits from this paper and those from UCAR (near real-time) and WHU (post-processed) is about 10 cm, which is largely due to different uses of GPS ephemerides, high-rate GPS clocks and force models. The kinematic orbits of COSMIC are expected to be used for recovery of temporal variations in the gravity field.

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1 Introduction

The joint Taiwan–US mission FORMOSAT-3/COSMIC (FM/COSMIC) was launched on April 17, 2006, deploying six micro-satellites at altitudes ranging from 750 to 800 km and at an inclination of 72° in the final mission phase. The expected lifetime is 5 years. The acronym COSMIC stands for constellation observing system for meteorology, ionosphere and climate and will be used hereafter to represent FORMOSAT-3/COSMIC. Each of the satellites is equipped with a global positioning system (GPS) receiver, a tiny ionospheric photometer (TIP) and a tri-band beacon (TBB). For each satellite, the BlackJack (IGOR) GPS receiver (Wu et al. 2005; Schreiner 2005; Montenbruck et al. 2006) was installed with four antennas on the front and back faces of the satellite main frame, which is a ring (Fig. 1).

Two single-patch antennas, mounted on the upper part of the main body, are for precise orbit determination (POD). The other two antennas, dedicated to atmospheric occultation research, are mounted on the lower part; see also Wu et al. (2005) for a detailed description and problem investigation of the GPS payloads. A COSMIC special issue of Terrestrial, Atmospheric and Oceanic Sciences (Lee et al. 2000) documents the scientific objectives and anticipated results of COSMIC. Useful information about the status and data acquisition is available on the web site of Taiwan's National Space Organization (NSPO): http://www.nspo.org.tw/2005e/projects/project3/research.htm. A recent research paper on the geodetic applications of COSMIC GPS data is given by Švehla and Rothacher (2006).

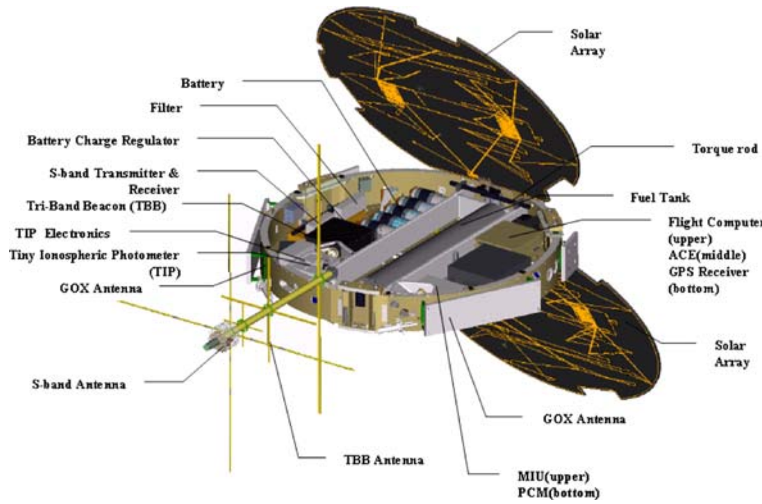


Fig. 1 A COSMIC spacecraft and its payloads

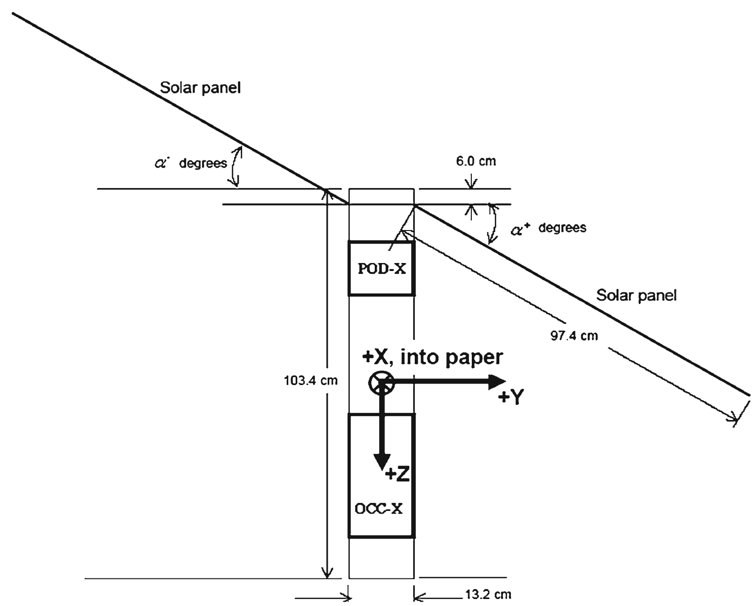


Fig. 2 Spacecraft coordinate frame of a COSMIC satellite, $+X$ is to the direction of flight

Simulation studies of Chao et al. (2000) and Hwang (2001) showed that COSMIC GPS data can be used to determine the Earth's static and temporal gravity fields. Combinations of GPS data from low Earth orbiters (LEO) such as COSMIC, CHAMP and GRACE of different orbit inclinations can produce improved gravity solutions over CHAMP-only or GRACE-only solution. The use of kinematic orbits of a LEO satellite for gravity field determination was demonstrated for the first time by Gerlach et al. (2003). Parallel to this, several alternative methods were developed, e.g.: Reubelt et al. (2004), Mayer-Gürr et al. (2005), and Ditmar et al. (2006). The objective of this paper is to use COSMIC GPS data to assess the achievable accuracy in GPS orbit determination of COSMIC satellites. Due to a large amount of orbital data from the six COSMIC satellites, problems and solutions in the POD will be demonstrated using selected epochs and selected COSMIC satellites. For convenience, the six COSMIC satellites will be named FM1–FM6, following the convention of NSPO.

2 The COSMIC spacecrafts and GPS payloads

2.1 Spacecraft geometry

Figure 2 shows the geometry and dimension of a COSMIC satellite. The geometry is simple compared to that of a typical Earth-observing satellite such as JASON-1 and ENVISAT. The mass, including propellant, is 62 kg. The origin of the spacecraft coordinate frame is at the geometric center of the ring. The $+X$ and $+Z$ axes point to the direction of flight and nadir, respectively. The BlackJack GPS receiver is designed by the Jet Propulsion Laboratory (JPL) and manufactured by Broad Reach Engineering. It can simultaneously

Table 1 Coordinates of the two POD antennas (in m) in the spacecraft coordinate frame for CSOMIC FM1

Coordinates	POD+X	POD−X
x	0.472	−0.472
y	0.000	0.000
z	−0.269	−0.279

process GPS signals from the two POD antennas and the two occultation antennas. Table 1 shows the coordinates of the two POD antenna centers of FM1 in the spacecraft coordinate frame. The coordinates for the other five satellites differ from those of FM1 by a few millimeter. The angle between the line of coordinate origin—physical center of POD antenna and the $+X$ or $-X$ axis is 30°. The angle between the normal to the antenna patch and the $+X$ or $-X$ axis is 15°. This design also enables ionospheric occultation sounding using the two POD antennas. For comparison, the GPS antenna of GRACE (http://www.csr.utexas.edu/grace/) is mounted 0.45 m above the COM along the radial direction, and it will view more GPS satellites than any one of the two antennas of a COSMIC satellite and is less affected by the multi-path effect.

2.2 Satellite center of mass and variation

The equations of motion of a satellite must refer to the satellite center of mass (COM). Prior to the launch, the COMs of the six satellites have been determined in a NSPO laboratory, with and without propellant fuels with stowed solar panels. However, these pre-launch COM values lead to difficulty in maneuvering the spacecraft. This difficulty comes partly from the inaccurate COMs that cause incorrect exertion of thruster forces to the satellites. It was then decided that the COMs and moments of inertia of all satellites be re-computed using refined measurements of masses of all satellite parts. Also, the new determination is based on the case that the solar panels are deployed. Table 2 shows the coordinates of the COMs for different propellant masses from the post-launch determination. The standard errors of estimated COMs are at sub-mm level. The COMs vary with masses of propellant from a few mm to 1 cm.

For any given propellant mass, the COM coordinates are linearly interpolated from the values given in Table 2. The propellant will be partly consumed before the satellite reaches the final, operational orbit at about 800 km. Because the attitude control does not consume propellants, the COM at the operational orbit will remain the same throughout the remaining mission lifetime, provided that the geometry of the spacecraft does not change and no orbit maneuver is made. Since the rotation of the solar panels affects COM at a sub-mm level, it is neglected.

2.3 Attitude control

In this section, we assess formal errors due to attitude errors using a priori knowledge of the attitude accuracy of COSMIC given by the COSMIC mission center. The attitude control of a COMIC satellite enables the $+X$ and $+Z$ axes to point to the desired directions (Fig. 2) and the attitude data are necessary for transforming satellite coordinates from the spacecraft frame to the inertial frame and vice versa. Unlike the gravity-dedicated mission GRACE, the attitude determination of a COSMIC satellite is based on a combination of outputs from a magnetometer, an earth sensor and a Sun sensor. The attitude controller is a reaction wheel which does not consume propellant fuel. Different weights are given to these sensors to obtain the optimal attitude of a COSMIC satellite. In general, the earth sensor has the largest weight, but it is less accurate at higher latitudes where the ice-covered surface may lead to an erroneous determination of attitude.

The attitude of a satellite is expressed in three Euler angles, i.e., roll, pitch and yaw angles around the X, Y, and Z axes defined in Fig. 2. The Euler angles, the position and velocity determined by an onboard GPS navigational receiver, combine to form the quaternion needed for transformation from the spacecraft frame to the inertial frame. That is (Wertz 1978),

$$\mathbf{r}_I = \mathbf{q}\mathbf{r}_V\mathbf{q}^* \quad (1)$$

Table 2 Coordinates of center of mass (in mm) in the spacecraft coordinate frame at different masses of propellant

	Mass of propellant (kg)			
	6.65	3	2	0
FM1	4/ − 4/ − 33[a]	−3/ − 4/ − 34	−4/ − 4/ − 35	−8/ − 4/ − 36
FM2	4/ − 4/ − 34	−2/ − 4/ − 35	−4/ − 4/ − 35	−8/ − 4/ − 36
FM3	4/ − 7/ − 35	−2/ − 7/ − 36	−4/ − 7/ − 36	−8/ − 7/ − 37
FM4	4/ − 8/ − 34	−2/ − 7/ − 36	−4/ − 7/ − 36	−8/ − 7/ − 37
FM5	4/ − 4/ − 34	−2/ − 4/ − 36	−4/ − 4/ − 36	−8/ − 4/ − 37
FM6	4/ − 4/ − 33	−2/ − 4/ − 35	−4/ − 4/ − 35	−8/ − 4/ − 36

[a] x, y and z components in the spacecraft coordinate frame

Table 3 Attitude errors and attitude-induced coordinate errors (in x, y, z) in the inertial frame

Altitude (km)	Attitude error in roll, pitch, yaw (°)	Coordinate error	
		POD+X (mm)	POD−X (mm)
550	0.6/0.9/1.3	6.8/9.9/0.762	6.4/9.8/7.2
800	2.0/1.0/2.0	10.7/16.6/8.5	9.9/16.5/8.0

where $\mathbf{q}$ is a vector containing the four elements of the quaternion, and $\mathbf{r}_I$, $\mathbf{r}_V$ are coordinate vectors expressed in the spacecraft and inertial frames, respectively. Table 3 shows the estimated errors of Euler angles at the altitudes of 550 and 800 km based on ground tests. Such attitude errors will introduce errors in the coordinate transformation. To estimate such errors, it is convenient to express transformation in Euler angles:

$$\mathbf{r}_I = \mathbf{Q}^{\mathrm{T}}\mathbf{r}_V \tag{2}$$

where $\mathbf{Q}$ is the rotation matrix using Euler angles (Long et al. 1989, pp. 3–72). Matrix $\mathbf{Q}$ can be expressed as

$$\mathbf{Q} = \mathbf{R}_1(\phi)\mathbf{R}_2(-\delta)\mathbf{R}_3(\alpha) \tag{3}$$

where $\mathbf{R}_i$, $i = 1, 2, 3$, are rotation matrices about X, Y and Z (Seeber 2003, p. 11), and ϕ, δ, and α are the roll, pitch and yaw angles, respectively. Let vector $\mathbf{P} = (\phi, \alpha, \delta)^T = (\mathbf{p}_i)^{\mathrm{T}}$ contain the Euler angels. The following differential relationship holds:

$$\mathrm{d}\mathbf{r}_I = \frac{\partial \mathbf{r}_I}{\partial \mathbf{p}^{\mathrm{T}}}\mathrm{d}\mathbf{p} = \mathbf{A}\mathrm{d}\mathbf{p} \tag{4}$$

and

$$\mathbf{A} = \frac{\partial(\mathbf{Q}^{\mathrm{T}}(\mathbf{p})\mathbf{r}_V)}{\partial \mathbf{p}^{\mathrm{T}}} = \sum_{i=1}^{3} \mathbf{e}_i^{\mathrm{T}} \otimes \left(\frac{\partial \mathbf{Q}^{\mathrm{T}}}{\partial \mathbf{p}_i}\mathbf{r}_V\right) \tag{5}$$

where $\mathbf{e}_i$ is a 3×1 vector of all zeros, except for the ith element, and $\otimes$ is the Kronecker product. Given the nominal standard errors of ϕ, δ, α (Table 3) and the coordinates of the two POD antennas (Table 1), the error covariance matrix of the inertial coordinates are derived as

$$\Sigma_{\mathbf{r}_I} = \mathbf{A}\Sigma_{\mathbf{r}_V}\mathbf{A}^{\mathrm{T}} \tag{6}$$

Table 3 also shows the standard errors of the inertial coordinates caused by errors in Euler angles at the altitudes of 550 and 800 km. The coordinate errors in Table 3 are based on typical Euler angles from COSMIC. These attitude-induced errors are at the centimeter level and will propagate into errors in orbit determination. For comparison, the two GRACE satellites are equipped with a star-camera for attitude control and the attitude accuracy of GRACE satellites are less than 0.4°. For POD, it is possible to replace observed attitudes by "nominal" attitudes, the latter being determined by the satellite's position and velocity vectors (Neumayer et al. 2005). As demonstrated by Kang et al. (2006) for the GRACE mission, the mean orbit difference between the cases of using nominal and measured attitudes data is 0.1 mm, which is significantly less than those given in Table 3 (for COSMIC satellites). Later in this paper (Sect. 5.2), we will show that use of nominal attitudes of COMIC results in a better orbit accuracy.

Table 4 Antenna phase center offsets (in mm) from the anechoic chamber test

Frequency	North	East	Up
L1	−34.5/ − 29.9[a]	−1.6/1.9	59.8/59.8
L2	−39.7/ − 35.1	4.2/ − 3.9	71.3/71.4

[a] POD+X/POD−X

2.4 Phase center offset and variation of antenna

The phase center offset and phase center variation (PCV) of the two POD antennas were determined in an anechoic chamber using a mockup satellite of COSMIC, built by University Corporation for Atmospheric Research (UCAR). The L1 and L2 phase centers were estimated for L1 and L2 frequencies and for eight different solar array drive (SAD) angles. Table 4 shows the average absolute phase center offsets of L1 and L2. As expected, the largest offset lies in the component perpendicular to the antenna (the vertical component, zenith angle = 0°). Figure 3 shows the PCV of L3 as a function of azimuth angle and zenith angle for an SAD angle of 0° (i.e., edge on to velocity vector). Table 5 shows the maximum PCVs of L3 for different SAD angles. On average, the PCVs are small at small zenith angles. The largest PCV (absolute values) occur at azimuths of 140°–165° and 290°–350° and at large zenith angles (>80°). Figure 4 shows the PCV as a function of zenith angle for L1 and L2 frequencies (averaged over azimuths and SAD angle = zero). The PCV varies smoothly with zenith angle, and ranges from few mm (high zenith angle) to <2 cm (low zenith angle). In general, the PCV of L1 is larger than that of L2 at higher zenith angles (>60°). The PCV of L3 is also important for the occultation research because ionosphere-free excess phase is required when processing occultation data. More analysis of the impact of PCV on POD is given in Sect. 5.3.

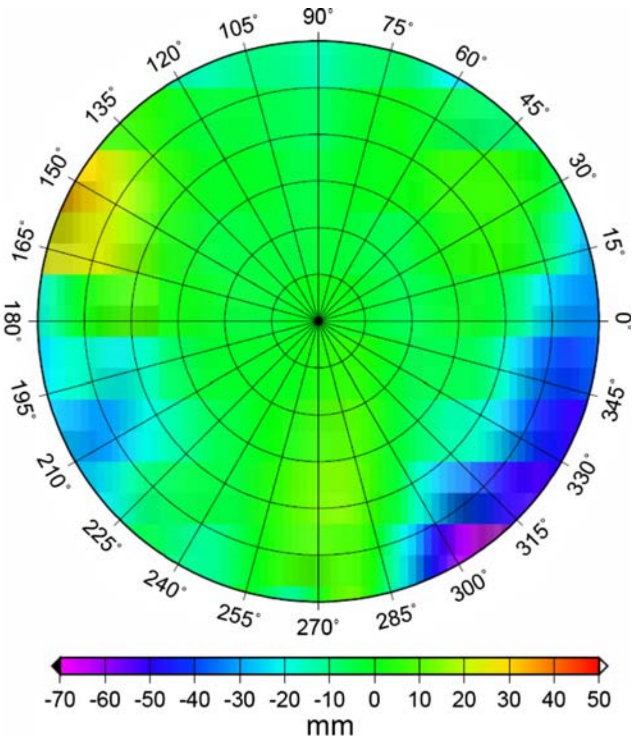


Fig. 3 Phase center variations of L3 as a function of azimuth (0°–360°) and zenith angle (0°–90°). The zenith angle is 0° at the center and 90° at the edge

Table 5 Maximum PCV of L3 for different solar array drive (SAD) angles

SAD angle (°)	Maximum PCV (cm)
0	6.37
45	6.24
90	4.91
135	6.90
180	5.29
225	12.06
270	5.70
315	6.93

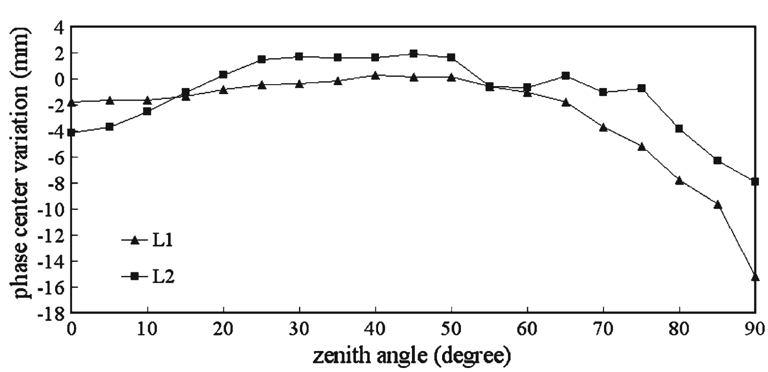
2.5 Cable delay difference between two GPS antennas

According to Wu et al. (2005), the difference in the lengths of the two cables connecting the POD+X and POD−X antennas to the GPS receiver is about 47 cm, which will cause a 2-ns signal delay. If the GPS data from POD+X and POD−X are to be used simultaneously for the orbit determination, i.e., two-antenna solution, such a cable delay difference must be removed. One method to remove this delay is to solve for two receiver clock corrections, instead of just one, in the COSMIC orbit determination. As an example, Fig. 5 shows the differences between the two clock corrections estimated for the two antennas for FM5, day 216, 2006 (based on the reduced dynamic method, see Sect. 4.1). The differences in Fig. 5 have a RMS value of 2.89 ns, which agrees with the value (2 ns) given by Wu et al. (2005) based on a laboratory test. Some of the large differences in Fig. 5 are due to estimation errors and low numbers of visible GPS satellites in one of the two POD antennas. At any epoch, the receiver clock corrections estimated separately for two antennas also absorb the cable delay. Since data from the single GPS-antenna were used for POD in this paper, the cable delay difference can be ignored. However, if data from the two POD antennas are combined and the cable delay is handled properly, the number of GPS satellites used in the POD will increase considerably. In particular, such a two-antenna solution will improve kinematic POD.

3 Status and acquisition of COSMIC GPS POD data

Figure 6 shows the orbit maneuver schedule for the COSMIC mission. Some of the COSMIC satellites stayed at a lower altitude of 525 km for as long as 520 days before being raised to the final altitude of 711 km (FM3) and 800 km (others). At present, six COSMIC LEOs are at the final altitude of 800 km, except FM3 (at 711 km). A combination of low (525 km) and high (711–800 km) orbits can be used for gravity recovery. The lower orbits will be more sensitive to the higher

Fig. 4 Average phase center variations of a POD antenna for L1 and L2 from the anechoic chamber test



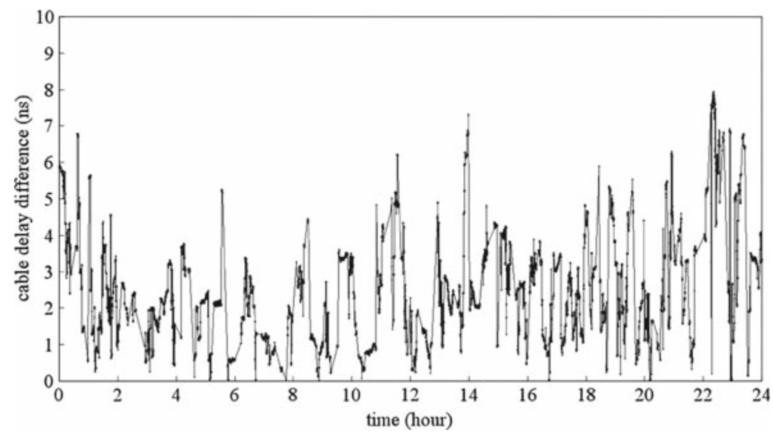


Fig. 5 Differences between clock corrections for the POD+X and POD−X antennas of FM5, day 216, 2006

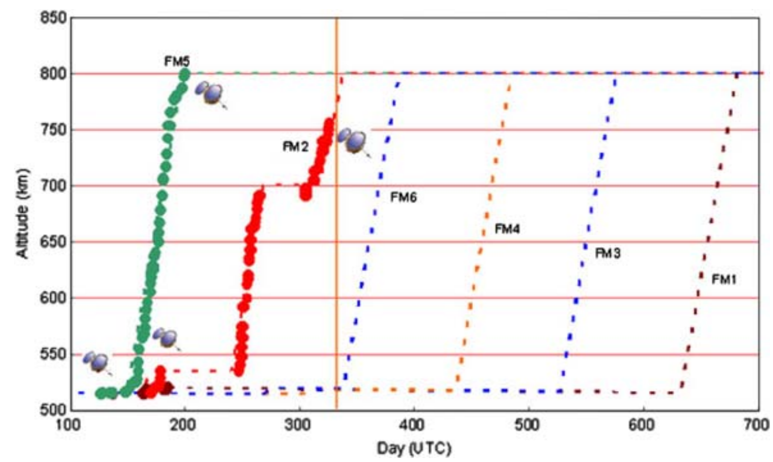


Fig. 6 Orbit maneuver schedule of COSMIC. The day is counted since January 1, 2006 (courtesy: NSPO of Taiwan)

frequency gravity components than the higher orbits, but the former will experience a relatively large air drag that might degrade gravity solutions if air drag is not properly modeled. Also, in the first 13 months, FM3 and FM 4 form a tandem flight separated by about 80 km at an altitude 525 km, making it possible to produce GRACE-like range observables (but the accuracy far less than that of GRACE) using kinematic GPS baseline solutions.

Because of the onboard GPS receiver software design, the numbers of visible GPS satellites at POD+X and POD−X are not equal. For example, Fig. 7 shows the numbers of tracked GPS satellites at the two POD antennas for satellite FM1 on day 189, 2006. Due to the GPS receiver software, the POD antenna in the aft direction (can be POD+X or POD−X) will always track more GPS satellites. In Fig. 7, POD+X is the antenna with more tracked GPS satellites. POD−X has less than three GPS satellites most of the time, so GPS data from the POD−X alone cannot be used for sufficient kinematic orbit determination and to form double-differenced observables between PODE−X and POD+X. The GPS POD and attitude data are available on the TAAC web site of Central Weather Bureau of Taiwan (http://tacc.cwb.gov.tw/cdaac/index.html). The sampling interval of GPS POD carrier-phase and code observables is 5 s. Real-time data are usually available within a few hours. Request of COSMIC GPS data should be sent to NSPO using the contact information at the NSP web site.

4 Methods of orbit determination for COSMIC

4.1 Reduced dynamic orbit determination

The software used for POD in this paper is Bernese Version 5.0 (Hugentobler et al. 2005). Two approaches are available in Bernese 5.0 for POD with GPS: the reduced dynamic and kinematic approaches; see Švehla and Rothacher (2003, 2005a). Hereafter reduced dynamic is named dynamic for short. In the dynamic orbit determination with Bernese 5.0, the code GPS measurements are used to obtain a priori kinematic orbit, which is then used to compute a priori dynamic orbit. The a priori dynamic orbit is used for the GPS clock synchronisation and then for pre-processing of phase measurements. The orbit parameters are estimated in the last step. Pre-processing of phase measurements is based on the estimation of the position differences between epochs along the priori orbit. Cycle slips in the phase observables,

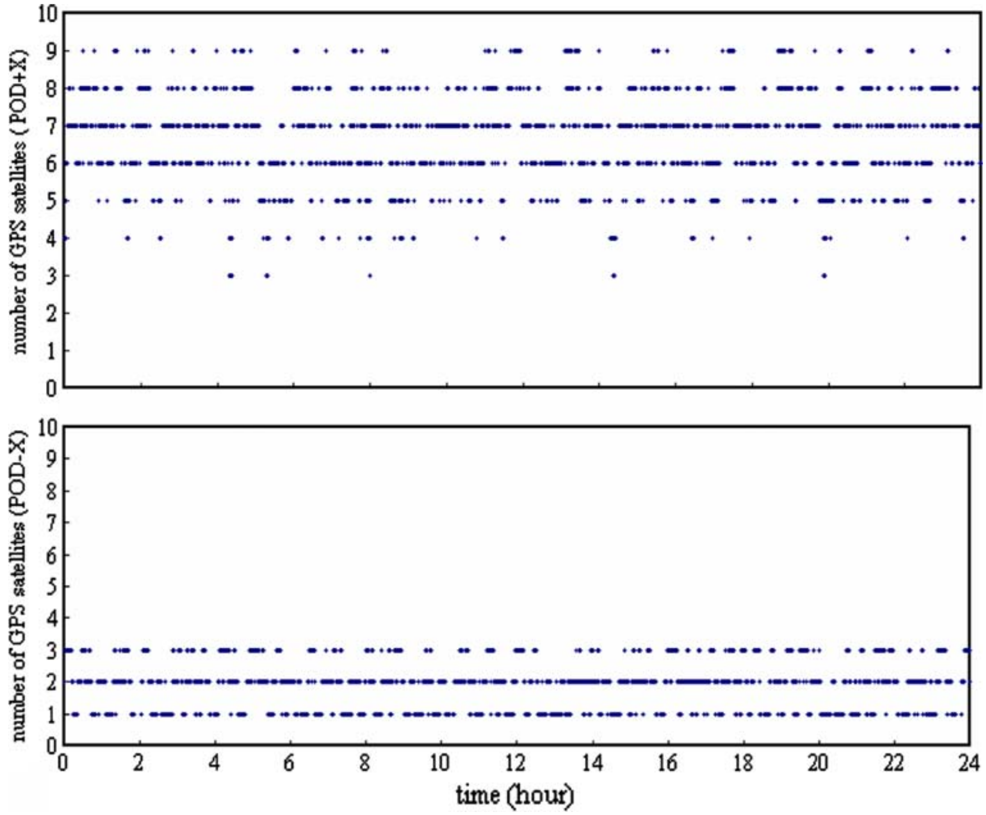


Fig. 7 Numbers of visible GPS satellites at the POD+X (*top*) and $-X$ antennas of FM1, day 189, 2006

if existent, are then marked and for every cycle-slip a new ambiguity parameter is set up in the POD. Such "cleaned" phase observables are used in the module "GPSEST" to determine the parameters that model the dynamics of the satellite. These parameters include the initial state vector (six Keplerian elements), nine solar radiation coefficients and three pseudo-stochastic pulses every 6 min in the radial, along-track and cross-track directions. Usually, pulses can be estimated in six directions (radial, along-track, and cross-track, or alternatively, direction sun-satellite, y direction, and x direction in a satellite-fixed system). However, use of three alternative directions for the estimation of stochastic pulses would produce the same result if the quality of the GPS data is comparable to those of CHAMP and GRACE missions. The pseudo-stochastic pulses were originally developed for orbit determination of GPS satellites by Beutler et al. (1994). Furthermore, Jäggi (2006) and Beutler et al. (2006) estimate pseudo-stochastic accelerations for dynamic orbit determination, but this option is not implemented in the Bernese GPS software version 5.0 used in the paper. In this paper, for the reduced-dynamic POD we followed the approach developed by Švehla and Rothacher (2003), who demonstrated for the first time that frequent estimation of pseudo-stochastic pulses absorb efficiently mis-modeled LEO perturbing forces, including air drag and solar radiation, allowing for 1–3 cm POD. Standard force model, such as solid, pole and ocean tides (IERS Conventions 2003), JPL planetary ephemeris DE200 and the Earth gravity model GGM02S (Tapley et al. 2005), were used to integrate satellite equations of motion. Numerical integration and data pre-processing are repeated several times until no further improvement is achieved.

We use zero-differenced phases of GPS for both the dynamic and kinematic orbit determinations, which require high precision GPS satellite orbits and clocks. The use of consistent sets of GPS satellite orbits and high-rate GPS satellite clock information is essential, and in this paper they are provided by the Center for Orbit Determination in Europe (CODE, http://www.aiub.unibe.ch/igs.html); see also Bock et al. (2004). Use of zero-difference carrier-phase measurements for POD is a very efficient approach compared to that based on double-differences, since there is no need to form baselines between the LEO and GPS ground stations, and the GPS satellite orbits and clocks can be used throughout the whole estimation process. When using double-differenced carrier-phase measurements, a large number of double-difference measurements and ambiguities will be created due to short satellite arcs and multiple ground stations, subsequently weakening the ambiguity resolution (Švehla and Rothacher 2003).

4.2 Kinematic orbit determination

In the kinematic POD based on zero-differences GPS measurements, satellite coordinates are estimated together with one GPS receiver clock parameter every epoch. Since the GPS phase measurements are used, phase ambiguities are common parameters in the least-square adjustment and estimated as common parameters. The epoch-wise parameters are pre-eliminated from the normal equation system. The GPS precise coordinates and high-rate clocks are kept fixed in the solution. Because the satellite coordinates in the kinematic solution are determined epoch-wise, rather than using numerical integration of equations of motion as in the dynamic solution, the satellite trajectory from the kinematic solution depends on the number of visible GPS satellites and therefore is less smooth than that from the dynamic solution. Kinematic POD with an accuracy of 1–3 cm was demonstrated for the first time for the CHAMP satellite (Švehla and Rothacher 2005a) and later a 1–3 cm accuracy was obtained for the GRACE mission (Švehla and Rothacher 2004). However, kinematic POD is extremely sensitive to the GPS receiver performance. In the case of missing phase data or insufficient number of GPS measurements, the kinematic orbit may have missing epochs, gaps or spikes when tracking geometry is poor. This is the main problem with the kinematic POD of the COSMIC mission where GPS antenna field of view is considerably reduced. The COSMIC POD antenna boresight vector is not zenith pointing as in the case of CHAMP and GRACE missions, but it is tilted by 75° towards the flight direction (Figs. 1, 2). In addition, the multipath effect, caused by the rotating solar panels, should have a significant effect on the performance of the kinematic POD of COSMIC. More about the kinematic POD for the gravity field determination can be found in Švehla and Rothacher (2005a). As a final note, in our regular kinematic orbit determination for the COSMIC mission, we first produce a 30-h orbit arc (from −3 h of a GPS day to +3 h), which is then truncated to a 24-h arc (0–24 h of a GPS day) for further applications, especially for gravity recovery.

5 Effects of satellite attitude, PCV and COM on COSMIC orbits

In Sect. 2, the information about COM, attitude and PCV has been given. In this section, these issues will be further addressed using COSMIC GPS measurements and numerical examples.

5.1 Effect of satellite COM on orbit

To inspect the impact of the satellite COM variation on the COSMIC orbit determination, we applied a 2 cm bias to the satellite COM (Table 2) in the spacecraft Z direction (Fig. 2). Table 6 shows the RMS differences between the orbit components with and without the 2 cm bias for the cases of kinematic and dynamic orbits and satellite FM5 on day 216, 2006. The spacecraft Z direction is almost parallel to the radial direction, so a 2-cm bias will introduce a 2-cm difference in the radial direction. However, this is not the case for the result given in Table 6. In addition to the ∼2-cm difference in the radial direction, there is a ∼2-cm difference in along-track direction. The cross-track difference is zero as expected. The 3D RMS differences exceed 3 cm. Apparently, the given bias (2 cm) has been amplified during the orbit determination. Possible reasons of the amplification are: (1) the antenna of COSMIC is not in the zenith direction, producing multi-path effects and other noises that are aliased into the given bias in Z, (2) GPS satellite geometry is weak, and (3) the attitude control (in this example) is not proper and subsequently affects the transformation of the given bias to the correct directions. For comparison, we applied a 1-cm bias to the COM of GRACE B satellite (day 233, 2003) in the spacecraft Z direction and Table 6 shows the RMS differences between the GRACE orbits with and without such a bias. As seen in Table 6, there is a dominant 1-cm difference in the radial direction and sub-cm (but non-zero) differences in other two directions. The 3D RMS difference is about 1 cm, which is close to the given bias. This example highlights that in order not to degrade the orbit accuracy of COSMIC, it is important to determine precisely the COMs for all COSMIC satellites, as carried out in Sect. 2.2.

Table 6 RMS differences (in cm) between orbits with and without COM bias

	Radial	Along-track	Cross-track	Total
FM5 (2 cm bias in spacecraft Z)				
Dynamic orbit	2.90	1.80	0.00	3.41
Kinematic orbit	2.12	2.12	0.00	3.00
GRACE B (1 cm bias in spacecraft Z)				
Dynamic orbit	1.02	0.29	0.17	1.07
Kinematic orbit	1.00	0.30	0.57	1.12

5.2 Effect of attitude error and choice of attitude data

To demonstrate the effect of attitude error on orbit and to choose the proper attitude data for POD, we experimented with orbit determination using observed and nominal attitude. As previously stated, nominal attitudes are determined by satellite position and velocity vectors, and this capability is implemented in Bernese 5.0. As an example, Fig. 8 shows observed attitudes of FM5 from day 214 to 220, 2006 and Table 7 shows the statistics. The yaw angles oscillate more rapidly than other two angles, ranging from −54.5°

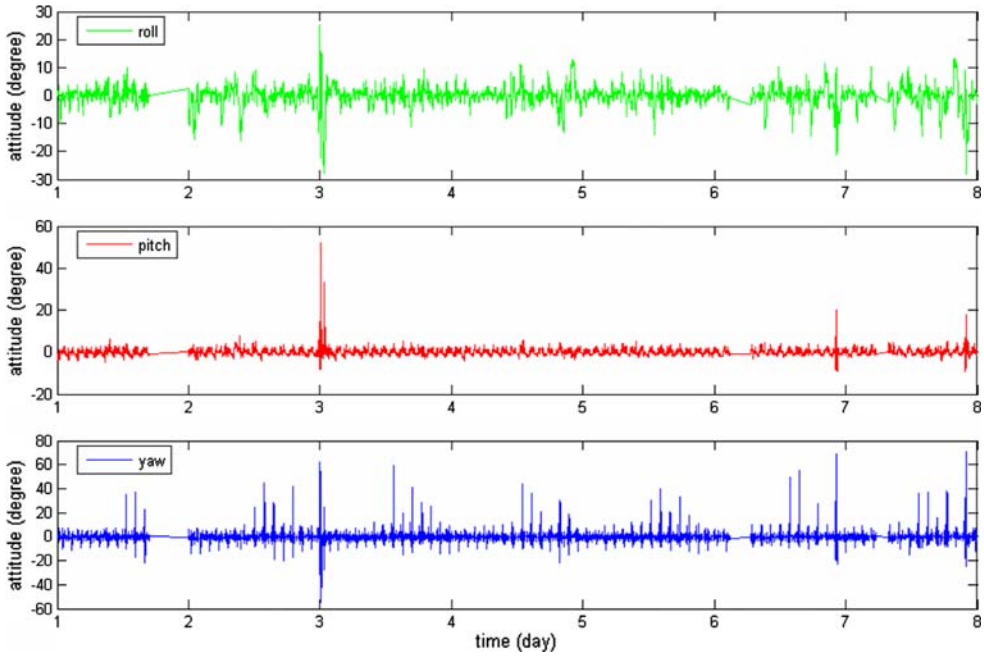


Fig. 8 Observed attitudes of FM5 from day 214 to 220, 2006

Table 7 Statistics of observed attitudes (in degree), FM5, day 214–220, 2006

	Roll	Pitch	Yaw
Min	−284	−9.3	−54.5
Max	25	51.7	71.3
RMS	3.7	1.7	4.5

to 71.3°. There are several places where abrupt changes of attitudes occur, which should be due to attitude adjustment. A large variation in the yaw angles suggests that the satellite undergo a rapid rotation around the spacecraft Z axis (Fig. 2) and the attitude control module attempts to maintain the spacecraft X axis in parallel to the flight direction based on observed attitudes. Because the mass of COSMIC satellite is small (62 kg) compared to that of a GRACE satellite (480 kg), exertion of attitude control will produce large dynamics of the spacecraft, leading to degraded GPS observations and poor transformation between the spacecraft coordinate system and the inertial coordinate system.

Figure 9 shows the differences in orbits using observed and nominal attitudes. The RMS orbit differences are 11 and 3 cm in the dynamic and kinematic orbit cases, respectively, with biases being nearly zero. The orbit differences are highly correlated with the observed attitudes (Fig. 8). Large differences occur when there are no observed attitudes and when the observed attitudes are anomalous. This example suggests that attitude has a great impact on the orbit accuracy.

Table 8 shows RMS overlap differences (5 h, see Sect. 6.1) using observed and nominal attitudes for FM5 orbits from day 214 to 220, 2006. For the dynamic orbit, use of nominal attitudes leads to smaller overlap differences. For the kinematic orbit, the observed and nominal attitudes produce virtually the same overlap differences. This result is consistent with that given by Neumayer et al. (2005), who argue that nominal attitudes are mostly free from anomalous values and can fill the gaps due to missing attitude observations. Because of this result and the analysis presented in Sect. 2.3, for later experiments and future orbit determinations of COSMIC satellites, we decided to use nominal attitudes instead of observed attitudes.

5.3 Effect of PCV on orbit

PCV is a function of GPS satellite zenith angle and azimuth (Leick 2004, p. 234). Here we show the impact of PCV on the satellite orbit. Table 9 lists the RMS overlap orbit differences (5 h) with and without PCV and the difference between kinematic orbits (with and without PCVs) and reduced-dynamic orbits (with and without PCVs), respectively, using GPS data of FM5 from day 214 to 220, 2006. In the case of kinematic orbit, the improvement due to PCV is at the sub-cm level; in the case of dynamic orbit, the improvement is smaller and at the sub-mm level. Thus, the improvements for dynamic and kinematic orbits due to PCV are different. In fact, the estimation of pseudo-stochastic pulses makes the orbit less dynamic. The smaller sensitivity of the dynamic orbit on the

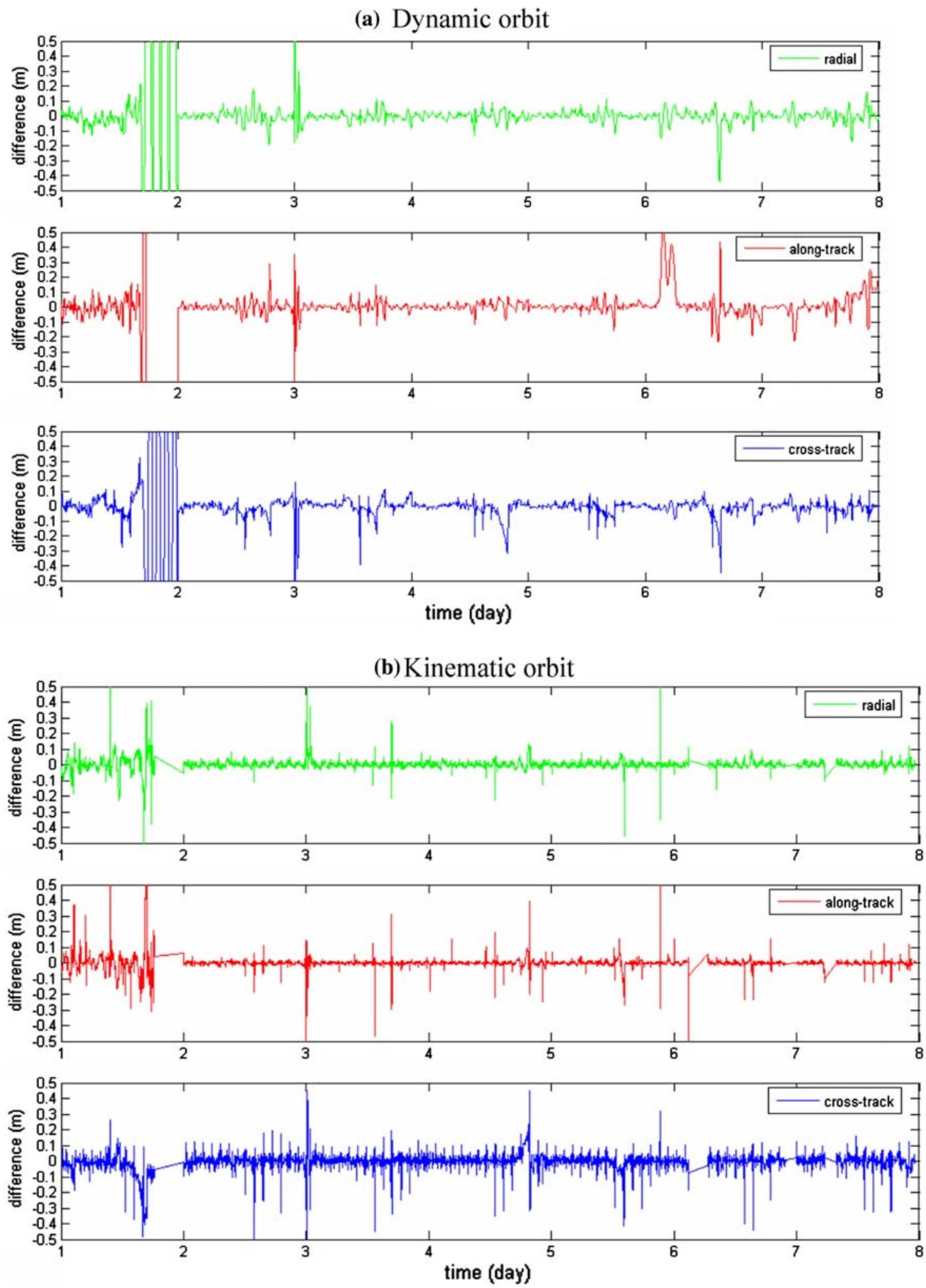


Fig. 9 Differences between orbits using nominal and observed attitudes, FM5, day 214–220, 2006

PCV is due to a small number of pulses (<15) in the dynamic solution (see Sect. 4.1). This example also shows that the PCV data from the anechoic chamber tests (Sect. 2.4) are indeed useful in improving orbit accuracy for both dynamic and kinematic cases, and will be used for all COSMIC orbit determinations.

Table 8 RMS overlap differences of orbits (in cm) computed with observed and nominal attitudes, FM5, day 214 to 220, 2006

	Kinematic orbit	Dynamic orbit
Nominal attitude	2.37/3.00/2.17[a]	2.39/1.96/1.05
Observed attitude	2.35/3.00/2.17	3.17/2.62/1.51

[a]Radial/along-track/cross-track

Table 9 RMS overlap differences of orbits (in cm) with and without PCV (FM5, day 214 to 220, 2006)

PCV	Kinematic orbit	Dynamic orbit
With	2.37/3.00/2.17[a]	2.39/1.96/1.05
Without	2.80/3.23/2.40	2.43/2.02/1.12
With–Without	1.05/1.11/1.05	0.494/0.626/2.06

[a]Radial/along-track/cross-track

6 Assessment of orbit accuracy

6.1 Assessment based on orbit overlaps

Because COSMIC satellites do not have laser retro-reflector arrays or DORIS antennae for an independent orbit determination other than GPS, an external assessment of orbit accuracy from GPS is not possible. Therefore, our assessment of orbit accuracy is based on orbit overlaps. One option would be to use the overlap epoch at the beginning and end of the 24-h arc, implying that different GPS measurements have been used for different arcs. Alternatively, a 6-h overlap of two 30-h arcs (3 h at the start and the end of an orbit arc) can be used to assess internal orbit accuracy because the same GPS measurements are used for both arcs (Kang et al. 2006). However, the overlap epoch at the end point of a 24-h arc will yield an imperfect estimation for the internal accuracy because of the edge effect (Kang et al. 2006). A 6-h overlap arc can be truncated to a 5-h arc (removing 30 min at the beginning and the end of the 6-h arc) to reduce the edge effect.

Tables 10 and 11 show the RMS overlap differences based on the full 6 (with edge effect) and 5-h (without edge effect) orbit overlaps for all six COSMIC satellites from the kinematic and dynamic orbits, based on data from day 214–239, 2006. The original sampling interval of GPS data is 5 s. The 5-s GPS data can be decimated and filtered to a coarser sampling interval to improve GPS data quality. Normally, a coarser sampling interval than 5 s is needed in gravity recovery using orbital perturbations; e.g., CHAMP, at an altitude of 454 km, uses a 30-s sampling interval. As an example, Table 10 shows the RMS overlap differences using a 30-s sampling interval (5-h overlaps), which are a few mm smaller than the 5-s overlap differences.

Table 10 RMS overlap differences of orbits (in cm) based on 5 and 6-h overlaps using kinematic approach for 25 days

	Radial		Along-track		Cross-track	
	5 h	6 h	5 h	6 h	5 h	6 h
5 s sampling interval						
FM1	2.49	2.70	2.86	2.99	2.69	3.13
FM2	2.62	2.69	2.50	2.56	2.70	3.17
FM3	2.96	3.22	3.73	3.76	4.18	4.33
FM4	3.33	3.35	3.23	3.25	4.20	4.34
FM5	2.49	2.58	2.62	2.77	3.50	3.86
FM6	3.40	3.43	3.19	3.58	4.71	4.79
30 s sampling interval (5 h)						
FM1	2.51		1.85		2.28	
FM2	2.06		1.89		2.04	
FM3	2.38		3.08		3.52	
FM4	2.59		2.65		3.51	
FM5	1.87		2.10		2.87	
FM6	2.64		3.08		4.17	

Table 11 RMS overlap differences of orbits based (in cm) on 5 and 6-h overlaps using dynamic approach for 25 days

	Radial		Along-track		Cross-track (cm)	
	5-h	6-h	5-h	6-h	5-h	6-h
5 s sampling interval						
FM1	2.68	2.86	2.70	3.07	2.81	3.19
FM2	2.37	2.42	2.29	2.40	2.05	2.10
FM3	2.67	2.72	2.85	2.88	3.05	3.17
FM4	2.92	3.00	3.27	3.32	3.23	3.29
FM5	2.35	2.58	2.40	2.43	3.14	3.16
FM6	2.65	2.66	2.51	2.57	3.35	3.44
30 s sampling interval (5 h)						
FM1	2.62		2.23		2.74	
FM2	1.83		1.63		1.50	
FM3	2.45		2.45		2.62	
FM4	2.25		2.77		2.79	
FM5	1.98		2.21		2.99	
FM6	2.10		2.06		2.86	

The internal accuracy assessment (Tables 10 and 11) based on orbit overlaps indicates a 2–3 cm noise level (excluding systematic errors), which is less precise than the 1–2 cm orbit consistency of kinematic and reduced-dynamic orbits for GRACE satellites obtained by Švehla and Rothacher (2005b), who used exactly the same software as in this paper. We believe that the slightly worse COSMIC orbit accuracy is mainly due to the non-ideal antenna orientation on the

Table 12 RMS orbit differences (in cm) between NCTU and UCAR and between NCTU and WHU, FM5, days 216 to 218, dynamic orbit

Satellite	NCTU–UCAR	NCTU–WHU
FM1	13.5/14.3/18.5[a]	8.3/8.2/11.6
FM2	9.7/9.0/6.5	6.6/6.5/5.5
FM3	9.8/10.0/7.2	5.6/5.5/5.7
FM4	10.7/11.7/13.2	14.7/18.2/8.8
FM5	10.8/11.2/10.3	9.3/11.4/9.4
FM6	9.9/11.5/9.7	7.5/7.4/5.8

[a]Radial/along-track/cross-track

satellite body (Figs. 1 and 2) and number of tracked GPS satellites. A noise reduction in the kinematic orbit could be achieved by means of the normal point technique or some other smoothing technique, which is particularly useful for gravity recovery. Internal orbit accuracy obtained in this paper reflects only consistency between orbit overlaps and consistency between dynamic and kinematic orbits. Any remaining systematic errors in the orbits can only be detected by a comparison with external tracking data such as SLR. For gravity field recovery based on COSMIC kinematic orbits, possible systematic errors in the orbit can be reduced by a suitable mathematic model in the estimation of gravity field. For example, most orbit errors contain components at the one- or two-CPR frequency bands, which can be effectively absorbed by some empirical error models, see, e.g., Colombo (1984) and Balmino (1994).

6.2 Comparison with UCAR and WHU orbits

To see if there are systematic errors in our POD, we carried out two "external" comparisons. Table 12 compares our post-processed dynamic orbit with those from UCAR (near real-time) and Wuhan University (WHU, post-processed) for FM5 from day 216 to 218, 2006. UCAR uses Bernese 5.0 for dynamic orbit determination and IGS ultra-rapid predicted GPS orbits and precise 30-s GPS clocks. The IGS ultra-rapid GPS ephemerides have an accuracy of about 10 cm, compared to the 3–4 cm accuracy of the final ephemeris. UCAR's mission is to support real-time atmospheric application of COSMIC and does not have orbit solutions based on the IGS final GPS orbits as used in this paper. The dynamic orbit of WHU in Table 12 was computed by the software "PANDA" (Liu and Ge 2003). PANDA uses zero-differenced GPS phases (as in this paper) and the final IGS GPS ephemeris to compute the dynamic orbit. In the dynamic orbit of WHU (Table 12), the atmospheric drags are based on the DTM 94 model and two empirical parameters along radial, along-track and cross-track directions are estimated every 90 min. No pseudo stochastic parameters are estimated in the WHU orbits. PANDA is becoming increasingly popular for positioning in the Asian-Pacific geodetic community. The NCTU–UCAR and NCTU–WHU orbit differences are both at the 10 cm level per component, with the NCTU–WHU orbit differences being smaller. The larger NCTU–WHU orbit differences for the case of FM4 in Table 12 are due to the fact that PANDA cannot properly remove anomalous observations of FM4 (GPS observables and attitudes). (Note that the NCTU–UCAR orbit differences for FM4 are normal). The fact that the NCTU–UCAR orbit differences are larger than NCTU–NCTU orbit differences (Table 11) highlights the importance of using precise GPS ephemerides and high-rate GPS clock information for orbit determination of LEO to cm accuracy. The reason of the 10-cm difference between the NCTU and WHU orbits is yet to be investigated, but we believe the major cause is the different approaches of modeling satellite perturbing forces (see Sect. 4.1 in the case of Bernese 5.0).

7 Conclusions and suggestion

The focus of this paper has been orbit determination of six COSMIC satellites. The impact of the satellite COM, attitude, and GPS antenna PCV was addressed using numerical examples. Because of the large amount of GPS data (six satellites, more than 2 years), the numerical examples given in this paper are limited, and more will be given as our computing facility improves. In particular, we find that for COSMIC orbit determination, the observed attitude information should be replaced by the nominal in order to improve the orbit accuracy. The orbit overlap analyses suggest that the accuracy of the dynamic and kinematic orbits is at the 2–3 cm level. It is noted that, for atmospheric occultation research using COSMIC, a cm-orbit is over qualified. The potential application of COSMIC kinematic orbits is the determination of temporal variations in the gravity field. Given the dense spatial coverage of the six COSMIC satellites, it will be interesting to see how COSMIC data alone and combined with the GRACE KBR data perform in the gravity field recovery. For the purpose of gravity recovery, the current kinematic orbit accuracy of COSMIC should be improved and this may be achieved by (1) combining GPS data from the two POD antennas, (2) using improved attitude data (collaborating with NSPO), (3) using improved antenna phase center offsets and variations and (4) using ambiguity resolution.

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