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Assessing attitude error of FORMOSAT-3/COSMIC satellites and its impact on orbit determination

Tzu-Pang Tseng [a,b], Cheinway Hwang [a,*], Shan Kuo Yang [c]

[a] Department of Civil Engineering, National Chiao Tung University, 1001 University Road, Hsinchu 300, Taiwan
[b] SPACE Research Centre, Royal Melbourne Institute of Technology (RMIT) University, 394-412 Swanston Street, Melbourne 3001, Australia
[c] Satellite Operation Control Division, National Space Organization 8F, 9 Prosperity 1st Rd, Hsinchu 30078, Taiwan

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Abstract

An attitude determination and control system (ADCS) is critical to satellite attitude maneuvers and to the coordinate transformation from the inertial frame to the spacecraft frame. This paper shows specific sensors in the ADCS of the satellite mission FORMOSAT-3/COSMIC (F3/C) and the impact of the ADCS quality on orbit accuracy. The selection of main POD antenna depends on the beta angles of the different F3/C satellites (for FM2 and FM4) during the inflight phase. In particular, under the eclipse, alternative attitude sensors are activated to replace the Sun sensors, and such a sensor change leads to anomalous GPS phase residuals and a degraded orbit accuracy. Since the nominal attitude serves as a reference for ADCS, the 3-dimensional attitude-induced errors in reduced dynamic orbits over selected days in 2010 show 9.35, 10.78, 4.97, 5.48, 7.18, and 6.89 cm for FM1–FM6. Besides, the 3-dimensional velocity errors induced by the attitude effect are 0.10, 0.10, 0.07, 0.08, 0.09, and 0.10 for FM1–FM6. We analyze the quality of the observed attitude transformation matrix of F3/C and its impact on kinematic orbit determination. With 249 days of GPS in 2008, the analysis leads to the following averaged 3-dimensional attitude-induced orbit errors: 2.72, 2.62, 2.37, 1.90, 1.70, and 1.99 cm for satellites FM1–FM6. Critical suggestions of geodetic payloads for the follow-on mission of F3/C are presented based on the current result.

Keywords: Attitude; Beta angle; FORMOSAT-3/COSMIC; GPS; Kinematic orbit

1. Introduction

The F3/C satellite mission (Fong et al., 2008) is the first constellation satellite mission for global atmospheric research. There are six microsatellites in the mission (named FM1–FM6 in this paper) and each is equipped with two patch GPS antennas. One of the two patch antennas is the default antenna for precise orbit determination (POD) (Hwang et al., 2010). Using Global Positioning System (GPS) radio occultation (GPS-RO), F3/C mission collects global atmosphere and ionosphere soundings to estimate global vertical profiles of temperature, pressure, water vapor and electron density (Wickert et al., 2001; Fong et al., 2008). For the atmospheric applications, a near real-time (NRT) orbit of F3/C satellite within a latency of 2 h is routinely determined by the University Corporation for Atmospheric Research (UCAR), and the orbit accuracy is about 8 cm (Hwang et al., 2009). For the geodetic applications, a post-processing orbit accuracy of 3 cm was achieved (Hwang et al., 2009, 2010) and the kinematic orbits of F3/C satellites have been used to recover the time-varying gravity field (Hwang et al., 2008; Lin et al., 2011).

Earlier studies from Kang et al. (2006), Fong et al. (2008) and Hwang et al. (2009) show that the orbit accuracy of low-Earth orbiter (LEO) could be affected to a great extent by the accuracy of the LEO attitude. In the case of F3/C mission, its orbit accuracy is very sensitive

* Corresponding author. Fax: +886 3 5716257.
E-mail addresses: cheinway@gmail.com, cheinway@mail.nctu.edu.tw (C. Hwang).

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to the attitude data quality. Nearly 30% of the F3/C kinematic orbits were not used in gravity recovery because of suspicion of poor orbit quality caused by poor attitude data (Hwang et al., 2008). Kang et al. (2006) experimented with observed and nominal attitudes for GRACE. Because of the high quality of GRACE attitude data from the gyro and star tracker sensors, Kang et al. (2006) found little difference between the cases of observed and nominal attitudes. This is not the case for F3/C mission: Hwang et al. (2009) found one-cm root-mean-square (RMS) difference in F3/C orbits between the cases of using observed and nominal attitudes.

In this paper, we will review the performance of ADCS of F3/C mission, and present an analysis of attitude control problems, and assess GPS phase residuals in the reduced dynamic orbit determination (Švehla and Rothacher, 2003). The difference between reduced dynamic orbits using observed and nominal attitudes will be used to assess the attitude-induced orbit error. For kinematic orbit determination, a method to verify F3/C satellite orbit error induced by attitude error will be demonstrated. The length of the 3-dimensional baseline vector from the GPS antenna phase center to the spacecraft center of mass (COM), obtained with the use of the observation-based attitude transformation matrix (ATM), will be compared with the length of the nominal offset vector. The nominal baseline is determined in a laboratory to 1 mm accuracy before the satellite launch. This concept originates from the fact that (1) the baseline length is invariant with respect to coordinate frame rotation, and (2) the observation-based ATM is used in the kinematic orbit determination of F3/C satellites, and orbit error due to attitude transformation can be quantified in such a comparison. Important suggestions for POD GPS payloads for the follow-on mission of F3/C satellite (scheduled launch year 2015) will be made.

Here, we stress that the focus of this paper is significantly different from those in earlier papers such as Hwang et al. (2009, 2010). For example, Hwang et al. (2009) presented only an overview of POD in terms of COM, phase center variation, attitude effect, and internal validation of orbit. This paper will focus on the attitude performance of all F3/C satellites, the default antennas with respect to the beta angle, the effect of phase windup on phase residuals, and assessment of the ATM. Additionally, we also account for the attitude effect on the kinematic orbit determination in more detail than Hwang et al. (2009). The result from this paper will be very informative to scientists who use F3/C data in GPS-RO and geodetic applications.

2. Attitude determination and control system for FORMOSAT-3/COSMIC

As shown in Fig. 1, X, Y, and Z form a spacecraft frame. By the definition of the nominal attitude in F3/C mission, the $+Z$ axis points to the nadir direction, the $+X$ axis points to the anti-velocity direction and the $+Y$ axis is given by the right-hand rule. In the F3/C mission, the ADCS refers to a local-vertical local-horizontal (LVLH) coordinate frame, and the frame is defined by a spacecraft position and velocity vectors determined by the onboard GPS navigation system. The LVLH reference frame serves as a nominal spacecraft attitude model. The Euler angles, roll (ϕ), pitch (θ) and yaw (ψ), are defined by the rotation around X, Y, and Z axes of a spacecraft (Wertz, 1991).

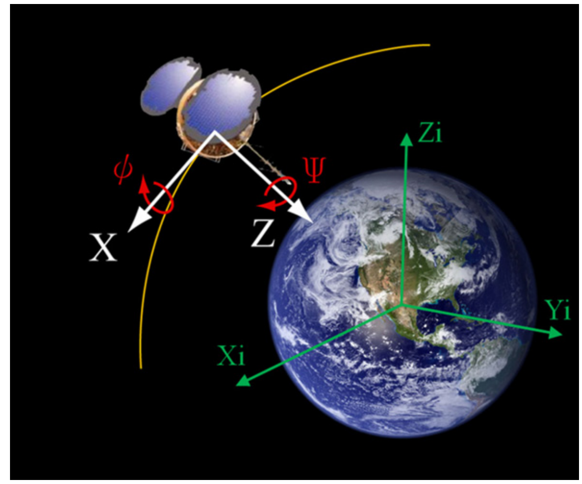

Fig. 1. Spacecraft coordinate frame of F3/C satellite, $+X$ points to the direction of flight and $+Z$ points to the nadir direction. X_i, Y_i and Z_i are based on the inertial frame.

Fig. 2 shows the functions of the ADCS of F3/C, which consists of two Earth horizon sensors, a magnetometer, eight coarse Sun sensors and navigation GPS system. The ADCS also assembles three torque rods, a reaction wheel, and four thrusters for the active attitude control. There are four thrusters on each F3/C satellite. The four thrusters are mounted symmetrically in the X–Z plane (thrust in Y or $-Y$ direction) to achieve the 3-axis attitude control. The F3/C satellites do not have attitude sensors such as gyros and star trackers, which will provide more accurate attitude data. The function of each sensor and each actuator is as follows. The Earth horizon sensor is to determine directly the orientation of a spacecraft with respect to the Earth; the 3-axial magnetometer sensor is to measure the strength and the direction of the geomagnetic field; the coarse Sun sensor is to measure the Sun vector in the spacecraft frame and to provide a reference for onboard attitude control; the navigation GPS system is to provide the position and velocity in the inertial frame; the torque rod is to generate 3-axis torques to resist perturbations in space; the reaction wheel is to provide a precise maneuver about the yaw-axis; the thruster is to produce a thrust for the orbit transfer and attitude maneuver.

In terms of the pointing performance of these attitude sensors of F3/C satellite, the Earth horizon sensors provide more accurate roll and pitch angles within an accuracy of (0.84°, 0.84°) than the magnetometer and coarse Sun sensors. In order to satisfy the inflight pointing requirement, the yaw angle within an accuracy of 0.779° is mainly determined by the magnetometer. The coarse Sun sensors serve

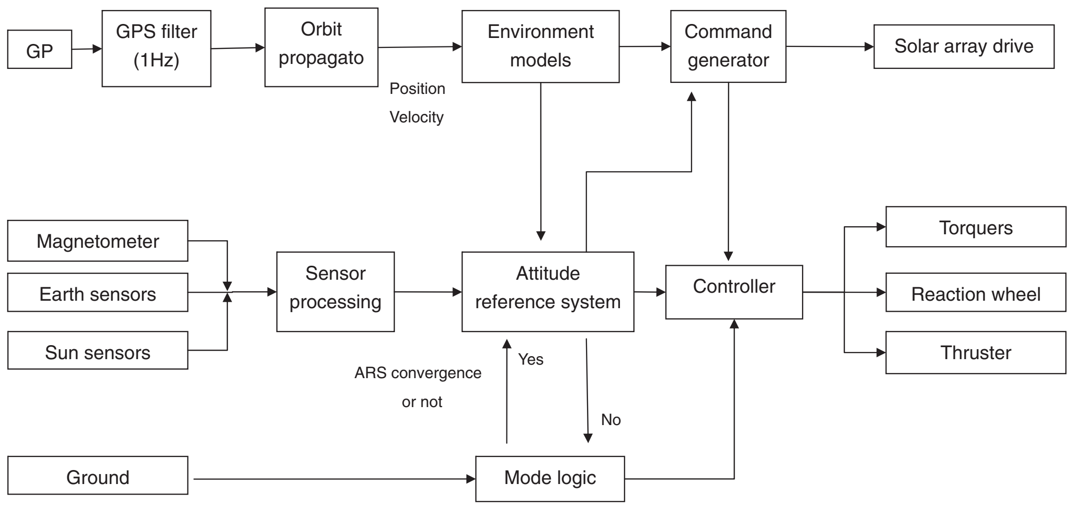

Fig. 2. ADCS functional block diagram (courtesy of NSPO).

as an auxiliary for the yaw determination around the polar areas due to 10 % error of its measurement and the non-activation of the magnetometer (private communication, National Space Organization (NSPO), Taiwan). However, once an attitude determination error occurs, the yaw angle will exceed the allowable angle, and results in anomalous GPS phase residuals ("phase wind-up", see Section 4) and a poor orbit solution (Fong et al., 2008; Hwang et al., 2009).

The nominal attitude serves as a reference for the attitude determination and control. Table 1 shows the pointing knowledge (the accuracy of attitude determination) and pointing accuracy (the accuracy of attitude control) of F3/C mission during the inflight phase. A laboratory test of NSPO shows that, the RMS of the angles (ϕ, θ, ψ) can be determined to $\pm 2°$, $\pm 1°$, and $\pm 2°$, respectively. In Fig. 2, the major estimator, the Attitude Reference System (ARS), is mainly for collecting data from the attitude sensors and the environment models. Different weights are given to these sensors to obtain the optimal attitude of a F3/C satellite by a Kalman filter estimator based on the least-squares principle. For the attitude control, the angle between the actual pointing direction and the ARS-determined direction can be aligned to $\pm 5°$, $\pm 2°$, and $\pm$ 5° in (ϕ, θ, ψ) by the controller in the ADCS.

3. Analysis of attitude determination and control

3.1. Analysis of attitude excursion

An attitude excursion is the standard error of observed attitudes in ϕ, θ, or ψ and is a product in the least-squares estimation of attitudes. Fig. 3(a) shows the daily total attitude excursions (total means the squared root of the sum of the squared excursions in (ϕ, θ, ψ)) and the Sun beta (β) angles of FM6 in 2008. The β angle is the angle between the Earth to Sun vector and the orbit plane. The spikes in Fig. 3(b) mostly occur at $\beta \sim \pm 42°$, and are caused by the mode transitions in the mode logic block of Fig. 2. Compared to other days, the attitude excursions of FM6 (see Fig. 3(a)) during the first 100 days are due to some unexpected errors resulting from the inflight software design (private communication, NSPO). Table 2 shows the total daily mean attitude excursions for FM1–FM6 in 2008. For FM6, if we remove the excursions of the first 100 days, the excursion will be reduced to 4.42, which roughly agrees with those given in other FMs, except for FM1. However, there is no clear reason for the large excursion (8.49) of FM1, but it might be caused by sensor biases and poor attitude controls (private communication, NSPO). Furthermore, such excursions at $\beta \sim \pm 42$ will affect the orbit accuracy of F3/C satellites.

Table 1
The pointing knowledge (the accuracy of attitude determination) and pointing accuracy (the accuracy of attitude control) of F3/C mission during the inflight phase.

	Roll	Pitch	Yaw
Pointing knowledge	±2°	±1°	±2°
Pointing accuracy	±5°	±2°	±5°

3.2. The default POD antenna and data volume

In connection to the attitude control of F3/C mission and beta angle in the previous sections, here we show a special situation for the GPS data volume of F3/C satellite from the so-called default antenna, which receives a larger data volume than the other (non-default) antenna. During the inflight operation, the yaw axis of F3/C satellite varies constantly with the β angle in order to maximize the Sun exposure because of the structure of the solar panel. For the transition of the default antenna at $\beta = 0°$, the forward antenna is rotated to the backward direction with a period of about 60 days via a yaw-flip maneuver. In the case of $\beta > 0°$, the POD+X antenna will be the default POD

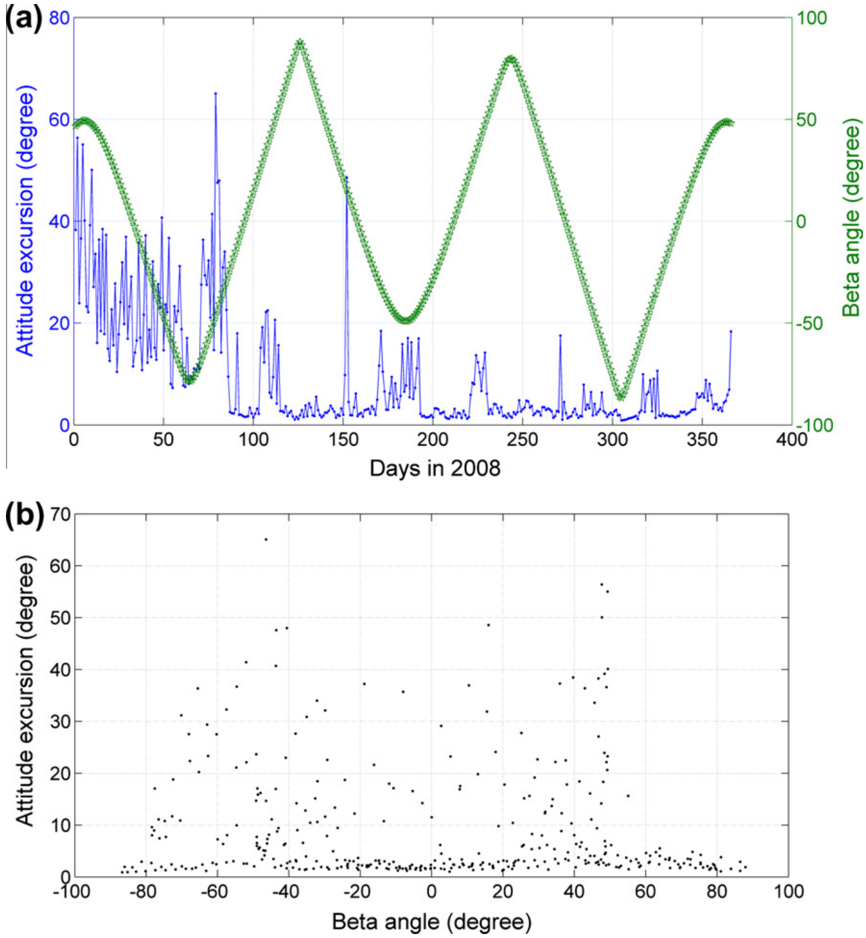

Fig. 3. (a) Daily attitude excursions (blue) and β angles (green) of FM6 in 2008; (b) the attitude excursion as a function of β angles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
The mean daily attitude excursions for F3/C satellites in 2008.

FM1	FM2	FM3	FM4	FM5	FM6
8.49°	3.24°	3.56°	3.60°	4.09°	9.10°

antenna; for $\beta < 0°$, the POD $-X$ antenna will be the default POD antenna. Fig. 4 shows data volume of both POD antennas as a function of β angle for FM4. Currently, only the default antennas of both FM2 and FM4 vary with β angles, and the other F3/C satellites always use the POD$+X$ antenna as the default POD, regardless of $\beta > 0°$ or $\beta < 0°$ due to the low SNR problems in the POD − X antennas (Fong et al., 2008 and private communication, NSPO).

4. Analysis of phase residual resulting from yaw variation

4.1. Phase residual as a function of yaw variation and/or beta angle

During the eclipse period of about 30 min, the attitude of F3/C satellite is mainly measured by the magnetometer and the Earth horizon sensors. The Sun sensors dominate the attitude determination system when the F3/C satellite is out of the eclipse (private communication, NSPO). Fig. 5 shows the yaw variation in eclipse for FM4 DOY 178, 2008. The shift from one sensor to another before and after the eclipse will result in anomalous attitude (spikes). The spikes also result in large perturbations in the estimated orbits. Fig. 6 compares phase residuals, yaw and β angles. In general, small phase residual indicates good GPS data quality and good satellite orbit and vice versa.

Fig. 6(a) suggests that large phase residuals, occurring between two thick vertical lines in the figure, are associated with the variation of the yaw angle. The outliers in Fig. 6(a) are identified using the 2.5-sigma criterion and are not used in the final orbit solution. If the outliers were not removed, they would have degraded the overall accuracy of the final orbit of F3/C satellite. Fig. 6(b) shows the phase residual as a function of the yaw angle. In general, if parameters such as clock error and integer ambiguity in the equation of GPS observation are properly modeled, a phase residual will contain only the random noise and the multipath effect of the phase. However, this

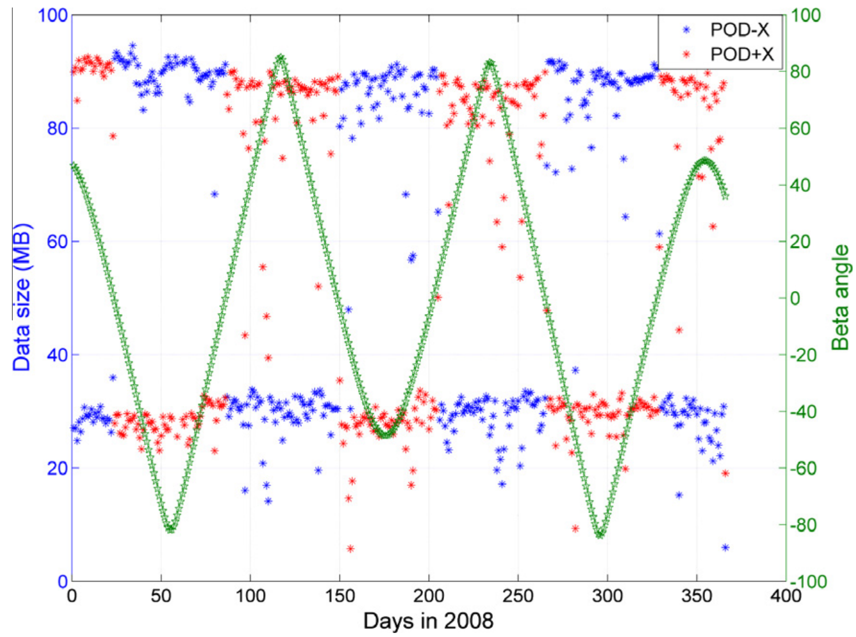

Fig. 4. Data volume of both POD antennas as a function of β angle for FM4.

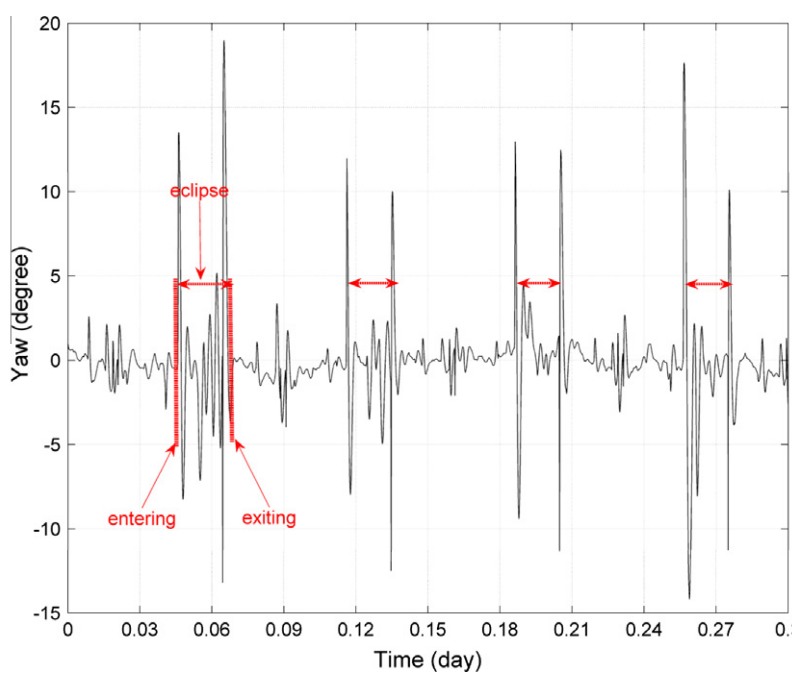

Fig. 5. The yaw variation in eclipse for FM4 DOY 178, 2008.

is not the case of F3/C mission due to the additional effect introduced by the yaw variation. According to Hofmann-Wellenhof et al. (2008, p. 157), the maximum effect of multipath on L1 phase measurement is about 5 cm (1/4 cycle of L1 wavelength). The residuals in Fig. 6 are given by the ionosphere-free linear combination with a wavelength of 10.7 cm. Therefore, the maximum effect of multipath should not exceed 3 cm. In Fig. 6(b), most residuals are acceptable when the yaw angles are between $-2°$ and $2°$, which is the range of the pointing knowledge of yaw (Table 1). Large phase residuals of >3 cm occur at yaw angles outside of the $-2°$ to $2°$ range, with some occurring at 0° yaw angle. Fig. 6(c) shows the daily posteriori standard deviations (STDs) of L1 phase residuals as a function of β angle for FM5 (DOY 118-366, 2008). Large STDs occur at β angle around $\pm 42°$, and even around some high β angles (more than 45°). This is because the mode transition in the mode logic block of Fig. 2 is usually activated around β angle of $\sim\pm 42°$. The analysis in this section suggests that satellite attitude (especially

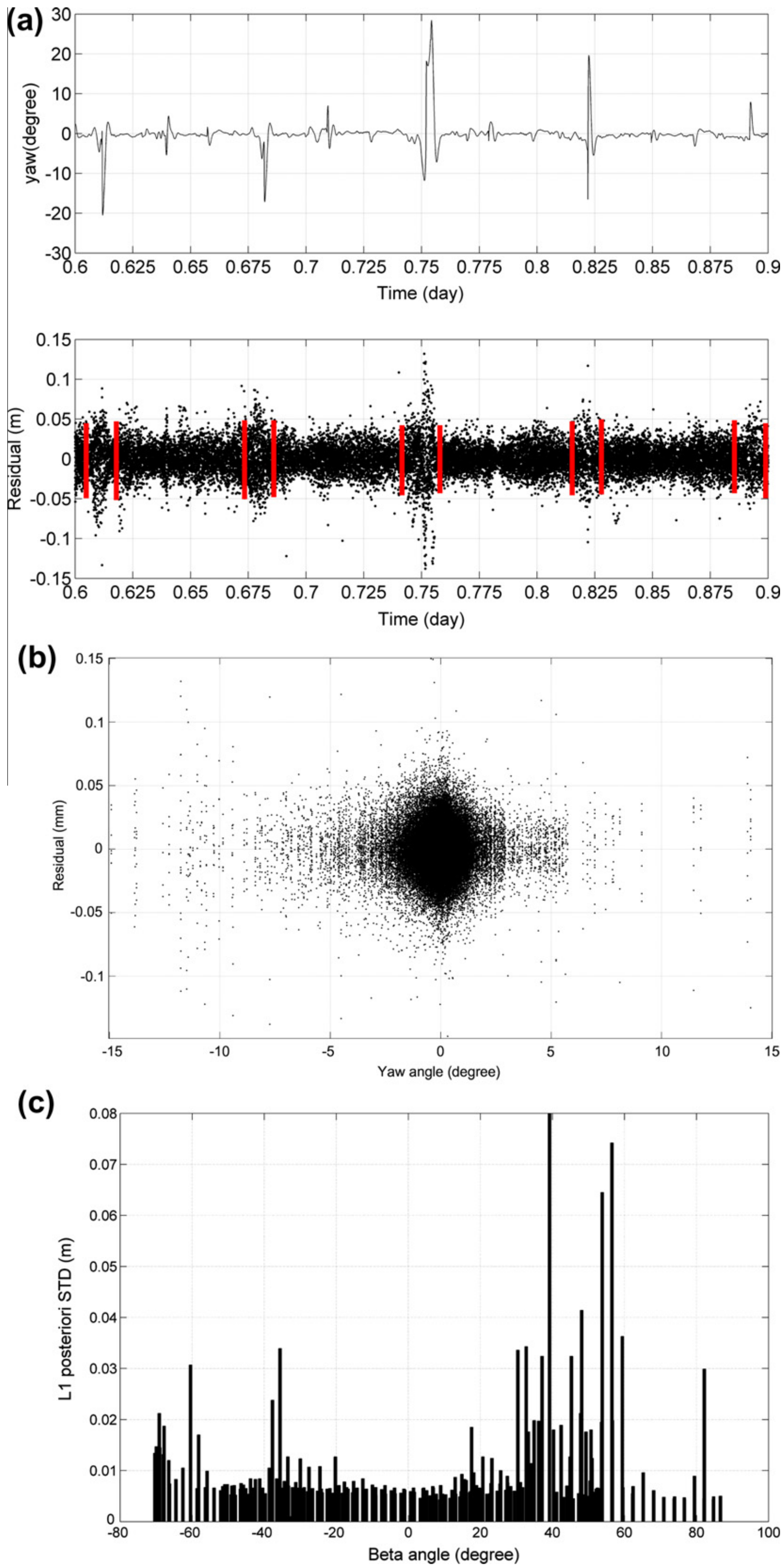

Fig. 6. (a) Phase residuals associated with yaw variation for FM4 DOY 148, 2008. A time window between two thick vertical lines contains phase outliers; (b) phase residuals as a function of the yaw angle for FM4 DOY 148, 2008; (c) the daily posteriori STDs of L1 phase residuals as a function of β angle for FM5 (DOY, 118-366, 2008).

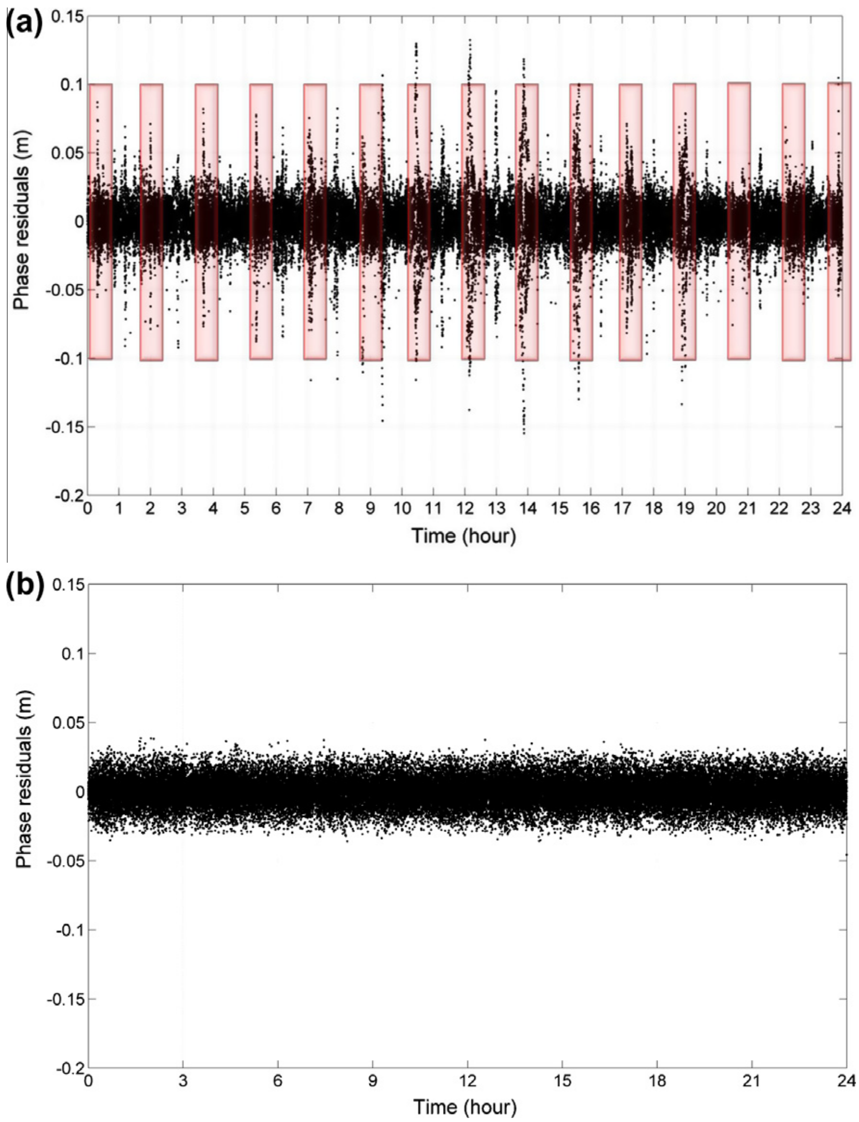

Fig. 7. Phase residuals of (a) FM2 (DOY 209, 2008) and (b) GRACE-A (DOY 263, 2007).

yaw angle) and β angle have major impacts on GPS phase residuals and satellite orbit quality.

4.2. Phase wind-up effect on phase residuals

Based on the discussion of Section 4.1, the GPS phase residuals in the eclipse and in the Sun acquisition exhibit different patterns of spikes. The GPS signal is transmitted to the receiver antenna via a right-hand circular polarization (RHCP) system, which is different from a linear polarization system. Thus, an effect called "phase wind-up" (PWU) (Wu et al., 1993) on the carrier phase measurement will appear if the orientation between the receiver antenna and the GPS antenna is changed (the yaw effect). Fig. 7(a) shows the phase residuals of FM2 and the shaded periods in red show the time of entering and exiting the eclipse. At the instants of entering and exiting the eclipse, FM2 suffers a dramatic vibration, resulting in large phase residuals. For comparison, Fig. 7(b) shows the phase residuals of GRACE-[1]A, which are uniformly smaller and are not affected by PWU. Fig. 7(b) shows the phase residuals of GRACE-A, which are uniformly smaller and are not affected by PWU. This is due to the fact that the GRACE POD antenna (both A and B satellites) is located just above the satellite's COM (Kang et al., 2006). The location of the GRACE POD antenna will minimize the PWU effect.

As an experiment, we compare the phase residuals of F3/C and GRACE-A satellites with and without GPS data affected by PWU. A 2.5-sigma criterion was used to exclude the PWU-affected GPS signals of F3/C. Table 3 shows the phase residuals of F3/C and GRACE-A satellites with and without PWU effects. There is no outlier in the GRACE-A phases under the 2.5-sigma criterion, so

[1] For interpretation of color in Fig. 7, the reader is referred to the web version of this article.

Table 3
Standard deviations of phase residuals (in cm) associated with reduced dynamic orbits based on 1-day orbit solution with and without yaw effect (PWU).

	With yaw effect	Without yaw effect
FM1 (DOY 306, 2008)	1.62	1.33
FM2 (DOY 209, 2008)	1.68	1.26
FM3 (DOY 161, 2008)	1.68	1.29
FM4 (DOY 182, 2008)	2.02	1.39
FM5 (DOY 181, 2008)	1.63	1.31
FM6 (DOY 215, 2008)	1.35	1.17
GRACE- A (DOY 263, 2007)	–	0.98

no STD is given in the case of GRACE-A with yaw effect (Table 3). In general, the STDs of phase residuals for F3/C satellites are about 1.6 cm with PWU effect. FM6 gives a relatively small STD of 1.35 cm as compared to the other F3/C satellites. However, FM4 showed a larger STD of 2.02 cm than other F3/C satellites and it is caused by the relatively poor attitude control as compared with other F3/C satellites. Without PWU, on average the STDs of residual were reduced to 1.3 cm, except for FM6 (1.1 cm). In particular, the STD of FM4 was significantly reduced when PWU was removed. However, even if the PWU effect was removed, the overall STDs of F3/C were still larger than that of GRACE-A (0.98 cm). On average, PWU effect results in a 4 mm measurement error in F3/C GPS phase observations. With this experiment, it is suggested that the location of POD antenna for COSMIC-2 be mounted on the zenith face of the satellite above the COM in order to eliminate the PWU effect.

For orbit solutions using undifferenced phases, estimating receiver clock error can also largely reduce the PWU effect (Kouba, 2009). The clock absorption of PWU errors (caused by yaw-attitude errors) is valid only when yaw angles are around antenna boresight axis. However, this is not the case for the F3/C satellite mission and will hence result in F3/C orbital errors. Furthermore, the x-offset of about 0.5 m as the F3/C satellite will cause even larger orbit errors when the attitude angle is wrong. More detailed studies about PWU effect on GPS data processing can be found in Bar-Server (1996), Hugentobler et al. (2003) and Kouba (2009).

5. Quantifying attitude effect and assessing attitude transformation matrix

5.1. Quantifying attitude effect using reduced dynamic orbit determination

As stated in Section 2, the nominal attitude serves as a reference for ADCS. Here we quantify the attitude effect on orbit by comparing orbits based on observed attitudes and nominal attitude in the reduced dynamic orbit determination. Fig. 8 shows the differences in orbit and velocity of FM6 between the cases of observed attitudes and nominal attitudes in a one-day orbit solution. In Fig. 8(b), the pattern of velocity differences is due to the estimated stochastic pulses at a 6-min resolution in the orbit determination in Bernese (Beutler et al., 1994). Based on the result of Fig. 8, the attitude effect on FM6 is 3.61, 3.89 and 3.51 cm in radial (R), along-track (T) and cross-track (N) directions, respectively; see Seeber (2003) for the definitions of directions). Such attitude effects on the velocity of FM6 are 0.06, 0.05 and 0.06 mm/s in these three directions, respectively. For the GPS-RO application, the relative velocity of LEO satellite with respect to GPS satellites has to be about 0.1 mm/s and the accuracy requirement of LEO POD is about 30 cm (Melbourne, 2004). The investigation here suggests that attitude error will cause an orbit error up to few cm and a velocity error approaching 0.1 mm/s. As a result, the science products of F3/C, particularly radio occultation profiles and Earth gravity fields, will be degraded (Schreiner et al., 2010). Table 4 shows the attitude effect of F3/C satellites on the reduced dynamic orbit over selected days in 2010. On average, the attitude effect on F3/C satellites is about 3 cm in position and 0.05 mm/s in velocity. As stated in Section 3, FM1 suffers a poor attitude control, which causes relatively large orbit errors compared to other F3/C satellites. Furthermore, FM2 has the largest attitude-induced orbit error in the along-track direction, which is attributed to the low numbers of visible GPS satellites in the orbit solution.

5.2. Quality assessment of attitude transformation matrix

The analyses so far indicate that there might be problems and errors in F3/C attitude determination and control. For each of the six F3/C satellites, NSPO has determined the baseline between the antenna and COM vectors in the spacecraft frame to mm accuracy, and such baselines are shown in Table 5. An idea to assess the quality of ATM is to create the new components (called the converted baseline) after applying the ATM on the components of Table 5, and the converted 3-dimensional baseline will then be compared with the given baseline of Table 5. The idea is implemented by the following equation

$$D(t) = |(\mathbf{A}(t) + \boldsymbol{\delta}_1(t)) \cdot \tilde{\mathbf{r}}_V| - |\tilde{\mathbf{r}}_V| \quad (1)$$

where $\mathbf{A}(t)$ denotes the attitude transformation matrix. $D(t)$ denotes the baseline difference between the converted and the given baselines, $\tilde{\mathbf{r}}_V$ is the antenna-COM vector obtained from Table 5, and $\boldsymbol{\delta}_1(t)$ is the epoch-wise error matrix of $\mathbf{A}(t)$ and caused by the uncertainty in attitude control. Here we quantify such an attitude error by comparing the converted baseline with the given one determined by NSPO. In theory, the magnitude of the difference is governed by the accuracy of ATM since the 3-dimensional baseline cannot be changed in any given coordinate frame. If $\boldsymbol{\delta}_1(t)$ is sufficiently small, $D(t)$ should be at level of the numerical error, which is about few mm. As an example, Fig. 9 shows $D(t)$ for FM3 on DOY 209, 2008. Based on the ADCS output (Fig. 2), two different types of data quality of the attitude control on this day were found: (1) bad quality over 0.2–

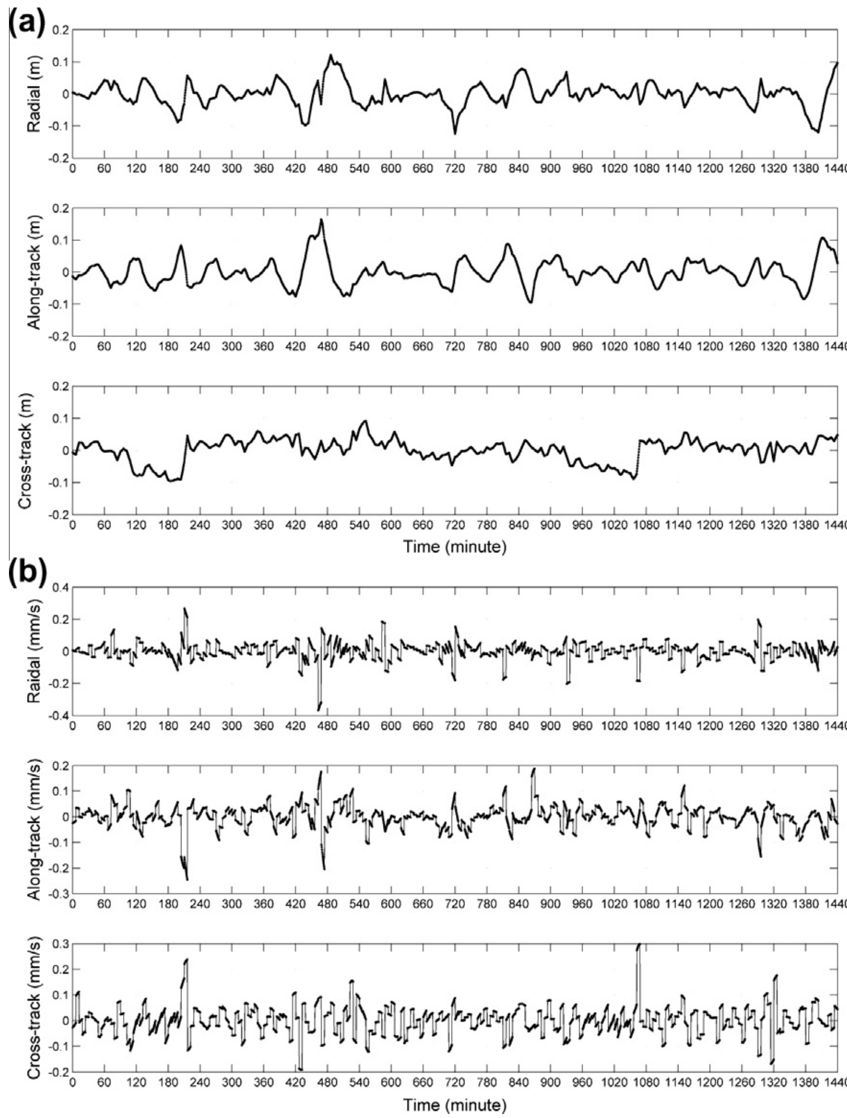

Fig. 8. Differences in (a) orbit and (b) velocity of FM6 (DOY 127, 2010) between the cases of using observed and nominal attitudes based on the reduced dynamic orbit determination.

Table 4
The orbit and velocity RMS differences between using the observed and nominal attitudes: FM1 (DOY 168-231, 2010), FM2 (DOY 208-271, 2010), FM3 (DOY 44-88, 2010), FM4 (DOY 188-250, 2010), FM5 (DOY 102-162, 2010) and FM6 (DOY 80-140, 2010).

	Position (cm)				Velocity (mm/s)			
	R	T	N	3D	R	T	N	3D
FM1	4.54	5.38	6.15	9.35	0.06	0.05	0.07	0.10
FM2	3.70	9.47	3.57	10.78	0.08	0.05	0.04	0.10
FM3	2.32	3.33	2.86	4.97	0.04	0.03	0.05	0.07
FM4	3.02	3.04	3.42	5.48	0.04	0.04	0.05	0.08
FM5	3.51	5.19	3.50	7.18	0.06	0.05	0.05	0.09
FM6	3.67	4.33	3.91	6.89	0.06	0.05	0.06	0.10

0.4 days, and (2) good quality during 0–0.2 and 0.4–1 days. These qualities correspond well to $D(t)$ in Fig. 9. The RMS of $D(t)$ at different time periods are summarized in Table 6. Over the period of good quality (0–0.2 and 0.4–1 days), the RMS of $D(t)$ are at a few mm level. Over this period (0–0.2 and 0.4–1 days), the baselines differences are largely due to the numerical error and the accuracy limitation of those attitude sensors. However, over the period of bad quality (0.2–0.4 days), the RMS are few cm. Such attitude-induced errors to F3/C orbits are hardly observed by differencing overlapping orbit arcs (Hwang et al., 2009, 2010), because such errors will be the same for the two overlapping orbits based on the same orbit determination approach and therefore will be canceled when differencing. Over one day (on DOY 209, 2008), the averaged attitude-induced errors are about 2 cm in the 3-dimensional baseline. Fig. 10 shows the RMS values of daily baseline differences for FM5 over 249 days, starting from DOY 118, 2008. Table 7 shows the daily averaged RMS values of $D(t)$ over the 249 days for all F3/C satellites. From Table 7, the averaged 3-dimensional baseline differences are 2.72, 2.62, 2.37, 1.90, 1.70, and 1.99 cm for FM1–FM6, respectively. These numbers suggest that the overall quality of FM4-6 ADCS is better than that of FM1-3.

Table 5
Coordinates of the two POD antennas (in m) in the spacecraft coordinate frame for F3/C determined by NSPO.

Satellite	POD+X ($x/y/z$)	Total (3D)	POD − X ($x/y/z$)	Total (3D)
FM1	0.468/0.005/−0.257	0.5339	−0.474/0.005/−0.261	0.5441
FM2	0.469/0.005/−0.256	0.5343	−0.474/0.005/−0.260	0.5406
FM3	0.468/0.005/−0.255	0.5330	−0.474/0.004/−0.260	0.5406
FM4	0.468/0.005/−0.255	0.5330	−0.475/0.005/−0.260	0.5415
FM5	0.468/0.005/−0.256	0.5335	−0.475/0.005/−0.260	0.5415
FM6	0.468/0.004/−0.256	0.5335	−0.474/0.005/−0.261	0.5441

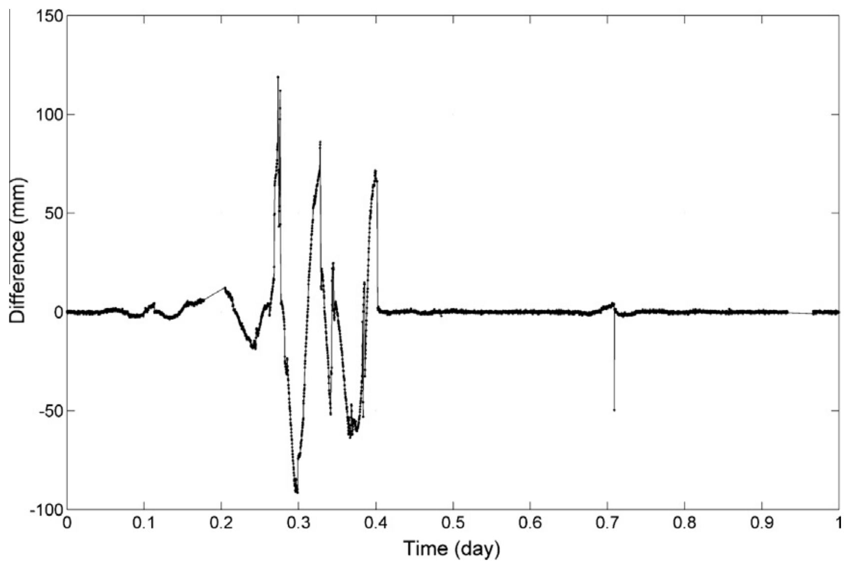

Fig. 9. Differences between the converted and the given baselines for FM3 DOY 209, 2008.

Table 6
RMS of the differences between the converted and the given baselines (see Fig. 8).

	Day 0–0.2 and 0.4–1	Day 0.2–0.4	Day 0–1
Difference (mm)	1.24	40.34	18.57

Table 7
Averaged RMS differences over 249 days, starting from DOY 118, 2008 between the converted and the given baselines.

	FM1	FM2	FM3	FM4	FM5	FM6
Total (cm)	2.72	2.62	2.37	1.90	1.70	1.99

5.3. Attitude effect on kinematic orbit determination

Based on the previous discussion, we now demonstrate the attitude effect on the kinematic orbit determination in this section. In the kinematic orbit determination, the antenna position was first determined in the Earth-fixed frame and then transformed to the inertial frame considering the Earth rotation, polar motion, nutation and precession (Seeber, 2003). Here, the epoch-wise antenna position in the inertial frame is represented as $\mathbf{r}_\mathbf{I}^\mathbf{ANT}(t)$. The inertial position of COM, denoted as $\mathbf{r}_\mathbf{I}^\mathbf{COM}(t)$, cannot directly be determined using GPS measurements. Therefore, $\mathbf{r}_\mathbf{I}^\mathbf{COM}(t)$ was determined by the position transformation of $\mathbf{r}_\mathbf{I}^\mathbf{ANT}(t)$ and the inverse transformation of $\mathbf{A}(t)$ on the coordinates of two POD antennas (Table 5) as follows

$$\mathbf{r}_\mathbf{I}^\mathbf{COM}(t) = (\mathbf{r}_\mathbf{I}^\mathbf{ANT}(t) + \delta_2(t)) - (\mathbf{A}(t) + \delta_1(t))^{-1}\tilde{\mathbf{r}}_\mathbf{V} \quad (2)$$

where $\boldsymbol{\delta}_2(t)$ denotes the epoch-wise error vector of $\mathbf{r}_\mathbf{I}^\mathbf{ANT}(t)$ and is mainly caused by the effect of phase center variation (PCV) and GPS-related errors, such as GPS orbits and GPS clocks (Griffiths and Ray, 2009). Eq. (2) is mainly used to estimate LEO kinematic orbits in Bernese GPS software (Dach et al., 2007, 2009). If the error vector $\delta_\mathbf{1}(t)$ is large, the term $(\mathbf{A}(t) + \delta_\mathbf{1}(t))^{-1}\tilde{\mathbf{r}}_\mathbf{V}$ of Eq. (2) will significantly affect the estimation of $\mathbf{r}_\mathbf{I}^\mathbf{COM}(t)$. Thus, the large baseline differences (i.e. 0.2–0.4 days in Fig. 9) will result in the attitude-induced orbit error to F3/C kinematic orbits.

Several sources can contribute to the error of GPS-determined orbit, e.g., GPS orbit, GPS clock, PCV, attitude and phase multipath. An internal orbit accuracy of 3 cm for F3/C satellites was reported by Hwang et al. (2009) using the orbit-overlap approach. Based on an analysis of phase residuals and orbit overlaps, (Hwang et al., 2010) show that the quality of F3/C GPS observations is inferior to GRACE mainly due to the degraded qualities in GPS tracking and attitude data of F3/C satellites. As stated before, the RMS differences in Table 4 and 7 are

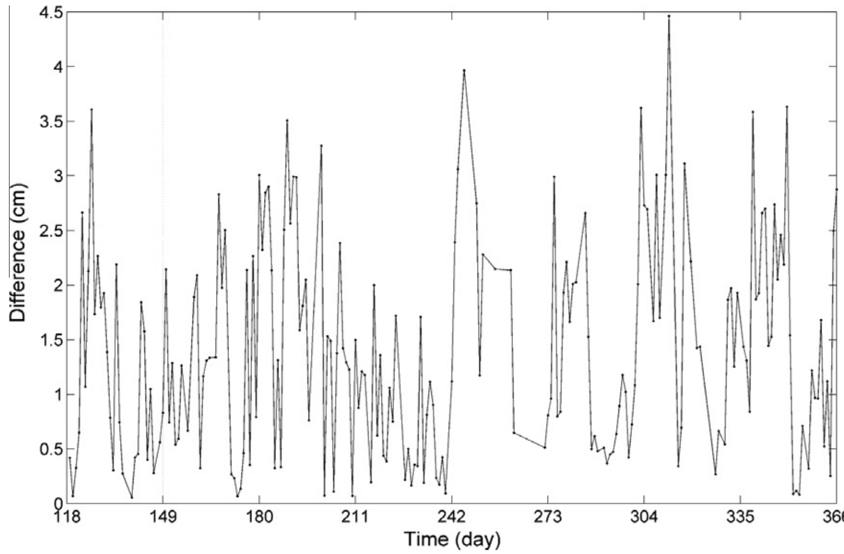

Fig. 10. Daily RMS difference between the converted and the given baselines for FM5 over 249 days, starting from DOY 118, 2008.

mainly caused by attitude errors and are on the order of few cm (RMS). This suggests that attitude errors with the order of few cm will be propagated into the external orbit accuracy for F3/C satellites if satellite laser ranging (SLR) data is used for the orbit validation, but this is not the case in F3/C mission. This leads to the conclusion that, because of the accuracy limitation of the ADCS of F3/C satellite, it is not likely to obtain an orbit accuracy of better than 2 cm for the six F3/C satellites. For comparison, Švehla and Rothacher (2003) reported a 1-cm orbit accuracy for the CHAMP and GRACE satellites.

A final remark is given to a consequence of attitude quality here. Hwang et al. (2009) show that a simulated 1-cm bias to the COM of GRACE-B satellite in the spacecraft *Z* direction can be recovered to one mm accuracy in the kinematic orbit, but such a COM bias for F3/C can only be recovered to one cm accuracy. The difference in the capability of recovering the COM bias can be explained by the fact that the overall quality of the GRACE satellite attitude system, which includes attitude sensors and controls, is better than that of the F3/C attitude system.

6. Conclusions and recommendations for the COSMIC follow-on mission

This paper presents a detailed analysis of the ADCS of F3/C satellite and its consequence on orbit accuracy. The result shows that frequent and relatively large attitude maneuvers have degraded the GPS signal quality of F3/C satellite. We conclude that the attitude error dominates the orbit error of F3/C satellite. Such an assessment method is important for a mission like F3/C mission, which has a less sophisticated attitude control system than the ones used in gravity missions such as GRACE or GOCE (Bock et al., 2011).

The PWU effect mainly depends on the control of satellite orientation. For the ionosphere-free L1/L2 combination, approximately a 10.7-cm error due to the PWU will be induced when a 360°-rotation of the satellite is made. In another word, a 6°-error in attitude will result in a 2-mm error in the phase measurement. For a 50-cm lever arm (like F3/C satellites), the same error will result in a 5-mm error in the modeled phase center location. Therefore, the attitude knowledge for POD should be determined to better than 5° at all time.

The example given in Section 5 suggests that the percentage of the high-error period over the entire period is about 20%. The example is mainly to show the attitude problem of F3/C. Due to the amount of F3/C orbit data, it is difficult to present all the percentages of high-error period for all F3/C satellites. Also, only about 70% of daily F3/C orbits can be used for gravity recovery (Hwang et al., 2008; Lin et al., 2011) because of the attitude-induced error. Based on the attitude transformation method in Section , for future work we will develop an algorithm to flag the periods of bad attitude and poor orbit solution. We will recommend that GPS data in such periods cannot be used for gravity recovery and radio occultation.

Based on the result from this paper, a discussion of the geodetic payload of COSMIC-2 is given below. COSMIC-2 is the follow-on mission of F3/C satellite, and is currently approved by NSPO and NSF of USA (private communications, NSPO, 2011). This mission is scheduled to launch in 2015 to continue the science of F3/C. This mission will consist of 13 satellites. Six of the 13 satellites will be deployed at a low-inclination orbit and the others deployed at a high-inclination orbit. Each COSMIC-2 satellite will be equipped with the new generation GPS-RO receiver of BlackJack (called TriG), in order to collect DORIS, GPS, Galileo and GLONASS navigational signals (Esterhuizen et al., 2009). The TriG receiver is being developed for a variety of NASA missions, such as GRACE-2, Jason-3 and ICESAT-2.

Depending on the mission budget, a SLR retro-reflector will be installed on some of the COSMIC-2 satellites to validate the GPS-determined orbit and for gravity recovery. The TriG receiver is developed by JPL and supports 29 channels for GPS satellites, 30 channels for Galileo satellites and 18 channels for GLONASS satellites. The TriG receiver will provide more precise RO profiles than the current F3/C RO receivers. The weight of each COSMIC-2 satellite will be about 100 kg to improve the stability of the satellite platform and accommodate more payload than F3/C.

As shown in this paper and Hwang et al. (2009, 2010), the attitude control system is critical to the orbit accuracy of a F3/C satellite, and this will be also true for COSMIC-2. Since some of the COSMIC-2 satellites will be equipped with a laser retro-reflector and possibly an accelerometer, it is expected that a better geodetic result than F3/C will be obtained from this mission. As such, we suggest that:

(1) Better attitude sensors and controls than F3/C, such as three-axis gyro and star tracker, should be installed on the COSMIC-2 satellites.
(2) If two antennas are to be deployed on the COSMIC-2 satellite as in F3/C, the default antenna should be placed on the zenith direction of the satellite body.
(3) The solar panel should be so installed that it can avoid blocking GPS signals and minimize the multipath effect.

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