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ORIGINAL ARTICLE

Quality assessment of FORMOSAT-3/COSMIC and GRACE GPS observables: analysis of multipath, ionospheric delay and phase residual in orbit determination

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Abstract The precise orbit determination antennas of F3/C and GRACE-A satellites are from the same manufacturer, but are installed in different configurations. The current orbit accuracy of F3/C is 3 cm at arcs with good GPS data, compared to 1 cm of GRACE, which has a larger ratio of usable GPS data. This paper compares the qualities of GPS observables from F3/C and GRACE. Using selected satellites and time spans, the following average values for the satellite F3/C and satellite A of GRACE are obtained: multipath effect on the pseudorange P1, 0.78 and 0.38 m; multipath effect on the pseudorange P2, 1.03 and 0.69 m; occurrence frequency of cycle slip, 1/29 and 1/84; standard error of unit weight, 4 and 1 cm; dynamic–kinematic orbit difference, 10 and 2 cm. For gravity determination using F3/C GPS data, a careful selection of GPS data is critical. With six satellites in orbit, F3/C's large amount of GPS data will make up the deficiency in data quality.

Keywords Cycle slip · FORMOSAT-3/COSMIC · GPS · GRACE · Multipath

Introduction

The FORMOSAT-3/COSMIC (F3/C for short) mission (Fong et al. 2008), launched on April 17, 2006, is a joint Taiwan–US mission for atmospheric, ionospheric and geodetic studies. F3/C consists of a constellation of six satellites, each equipped with two GPS antennas for precise orbit determination (POD). The two patch POD antennas of the F3/C receiver can receive up to 12 channels of GPS signals, of which nine channels are allocated to the default antenna and three channels to another (Hwang et al. 2009). In this paper, only the GPS signals from the default antenna will be used in POD and quality assessment. The payloads of the six F3/C satellites, including GPS, can be found at the web page of National Space Organization (NSPO) of Taiwan (http://www.nspo.org.tw/). Compared to the POD antennas of two GRACE satellites, whose antenna surface normal point to the zenith direction (Fig. 1a), the antenna surface normal of a F3/C antenna form an angle of 15° with the $+X$ or $-X$ direction (Fig. 1b; Hwang et al. 2009). As such, the patch antennas of F3/C are potentially prone to large noises and systematic errors in GPS data because (1) the two solar panels may deflect the GPS signals and (2) the antennas are mounted on the two upper parts of the ring-shaped satellite body that might block some of the GPS signals. Additionally, GRACE satellites are equipped with an ultra-stable oscillator serving as a frequency reference. A comparison of the antenna configurations of the F3/C and GRACE satellites can be made using the data from the web pages http://www.nspo.org.tw/2008e/projects/project3/component.htm (for F3/C) and http://www.csr.utexas.edu/grace/ (for GRACE).

The dynamic method and the kinematic method (Švehla and Rothacher 2003; Jäggi et al. 2006, 2007; Hwang et al. 2009) are two popular methods for POD of a low-earth

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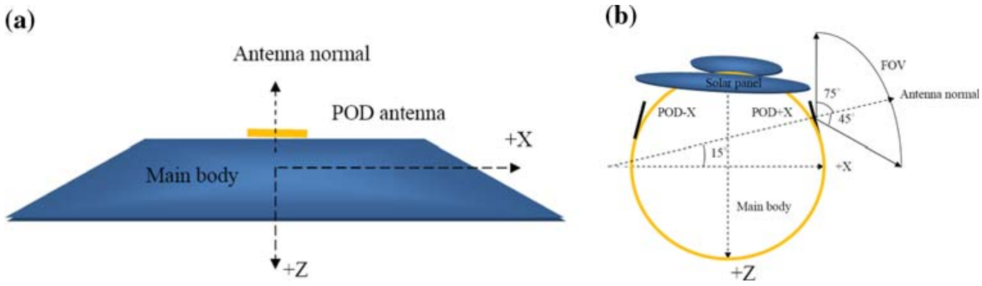

Fig. 1 Side view of satellites **a** GRACE-A and **b** F3/C, showing the normal (central axis of boresight) of the GPS antenna and the field of view (*FOV*)

orbiter (LEO) using GPS data. These two methods are implemented in the Bernese GPS software version 5.0 (Dach et al. 2007). Hwang et al. (2009) demonstrated that, with a proper data selection and processing, the mean accuracy of GPS-determined orbits of the six F3/C satellites reaches 2–3 cm based on overlap analyses. Precise orbits of F3/C satellites can support a number of studies. For example, the kinematic orbits of F3/C have been treated as three-dimensional ranging data to determine the long wavelength temporal variation of the earth's gravity field (Hwang et al. 2008). The gravity signatures from a combined F3/C-GRACE gravity solution were enhanced over those from the GRACE-only solution. However, the percentage of usable kinematic orbits of F3/C for gravity determination can be as low as 30% (Hwang et al. 2008). This suggests that a relatively large portion of F3/C GPS data (both code and phase) are degraded by such factors as multipath effects, cycle slips, excessive ionospheric delays (IOD) and low number of visible GPS satellites that typically contribute to a poor positioning accuracy (Leick 2004).

In general, the quality of F3/C GPS data is inversely proportional to the magnitudes of multipath effects, IODs and the residuals of GPS observables associated with the least-squares parameter estimation. Also, a large multipath effect and fast-varying IOD can result in a cycle slip, and the occurring frequency of cycle slips is an indicator of GPS data quality. Furthermore, phase residuals are part of the outcome in satellite orbit determination using GPS. Phase residuals can be used to detect outliers in GPS data and to compute the a posteriori variance of unit weight that serves as a descriptor of the GPS data quality and the overall fitness of the stochastic and mathematical model in orbit determination.

With the background information about the F3/C GPS data from Hwang et al. (2008, 2009) and the papers from the special issue of IEEE Transactions on Geoscience and Remote Sensing (Volume 46, 2008), the objective of this paper is to assess the overall quality of F3/C GPS data based on multipath effects, IODs, cycle slips, phase residuals and dynamic–kinematic orbit differences (for the last two items, see "Analysis of phase residual" and "Quality assessment based on difference between dynamic and kinematic orbits"). The quality assessment is based on data and outputs in connection to satellite orbit determination. For comparison, the same assessment will be carried out for GPS data from the GRACE mission. For convenience, the six F3/C satellites will be named FM1, …, FM6 in this paper.

Code multipath

In this paper, the code measurements were used to compute a priori orbits, and detect outliers in data preprocessing prior to POD (Bock 2004; Hwang et al. 2009). In this section, the multipath effect of code is assessed. Multipath effect is caused by non-line-of-sight (between the GPS satellite and the LEO receiver) GPS signal propagation (Hofmann-Wellenhof et al. 2001; Leick 2004). Multipath effect may be severe for F3/C due to the way the solar panels are deployed and the use of patch antennas. We determined the multipath effects of code on F3/C and GRACE using the computer program TEQC (Estey and Meertens 1999; Ogaja and Hedfors 2007). TEQC is designed for quality analysis of GPS/GLONASS data and has the following functions http://facility.unavco.org/software/teqc/teqc.html: (1) translation of GPS data from a binary format to a RINEX (The Receiver Independent Exchange Format) format (Gurtner 1994), (2) editing GPS observations, including data selection, metadata extraction and the title revision and (3) quality check (QC) of observation. We used mainly the QC function of TEQC. For purposes of QC the linear combinations of pseudorange and carrier phase observations were used to compute (1) the multipath effects for pseudoranges P1 (MP1) and P2 (MP2) and (2) ionospheric delay (IODs) of carrier phases. A typical output report of QC from TEQC includes cycle slips of GPS carrier phases, MP1 and MP2, and other statistics. MP1 and MP2 can be expressed as (Estey and Meertens 1999)

$$\begin{aligned}\mathrm{MP1} = \varepsilon_{1,P} &- \left(1 + \frac{2}{\alpha - 1}\right)\lambda_1 N_1 + \left(\frac{2}{\alpha - 1}\right)\lambda_2 N_2 \\ &- \left(1 + \frac{2}{\alpha - 1}\right)m_1 + \left(\frac{2}{\alpha - 1}\right)m_2 \qquad (1)\end{aligned}$$

$$\mathrm{MP2} = \varepsilon_{2,P} - \left(\frac{2\alpha}{\alpha-1}\right)\lambda_1 N_1 + \left(\frac{2\alpha}{\alpha-1} - 1\right)\lambda_2 N_2 - \left(\frac{2\alpha}{\alpha-1}\right)m_1 + \left(\frac{2\alpha}{\alpha-1} - 1\right)m_2 \qquad (2)$$

where α is ratio between the squared frequencies of $L1$ and $L2$, i.e., f_1^2/f_2^2; m_i includes the multipath and noise of Li; λ_i is wavelength of Li; N_i is integer ambiguity of Li; $\varepsilon_{i,P}$ contains the multipath and noise of Pi ($i = 1, 2$). The maximum multipath effect on phase is about 1/4 of the wavelength and the noise level of phase is about 0.2–5 mm (Hofmann-Wellenhof et al. 2001, p. 92), so these values are relatively small when compared to code multipath and noise (this will be demonstrated in "Ionospheric delay and cycle slip"). As such, in this paper the phase multipath and noise are ignored when estimating MP1 and MP2 using Eqs. 1 and 2. If the P1 cannot be available the C/A code will be used instead (Estey and Meertens 1999).

As a case study, the MP1 of FM3 and GRACE-A on DOY 201, 2008 were investigated using TEQC. The F3/C GPS data were from the Taiwan Analysis Center for F3/C (TACC, http://tacc.cwb.gov.tw/cdaac/index.html) and GRACE data from ftp://podaac.jpl.nasa.gov/pub/grace/data (LEVEL 1B product). Figure 2a, b shows the patterns of MP1 for FM3 (sampling rate: 1 Hz) and GRACE-A (sampling rate: 0.1 Hz) for each GPS satellite. In Fig. 2a, b, the interval between two consecutive satellites along the vertical axis is 1 m and the symbol 'S' stands for the GPS satellite number and one color is associated with one GPS satellite. In general, the MP1 of FM3 is larger than that of GRACE-A, and this is most likely caused by FM3's solar panels and antenna location. In some cases, the multipath

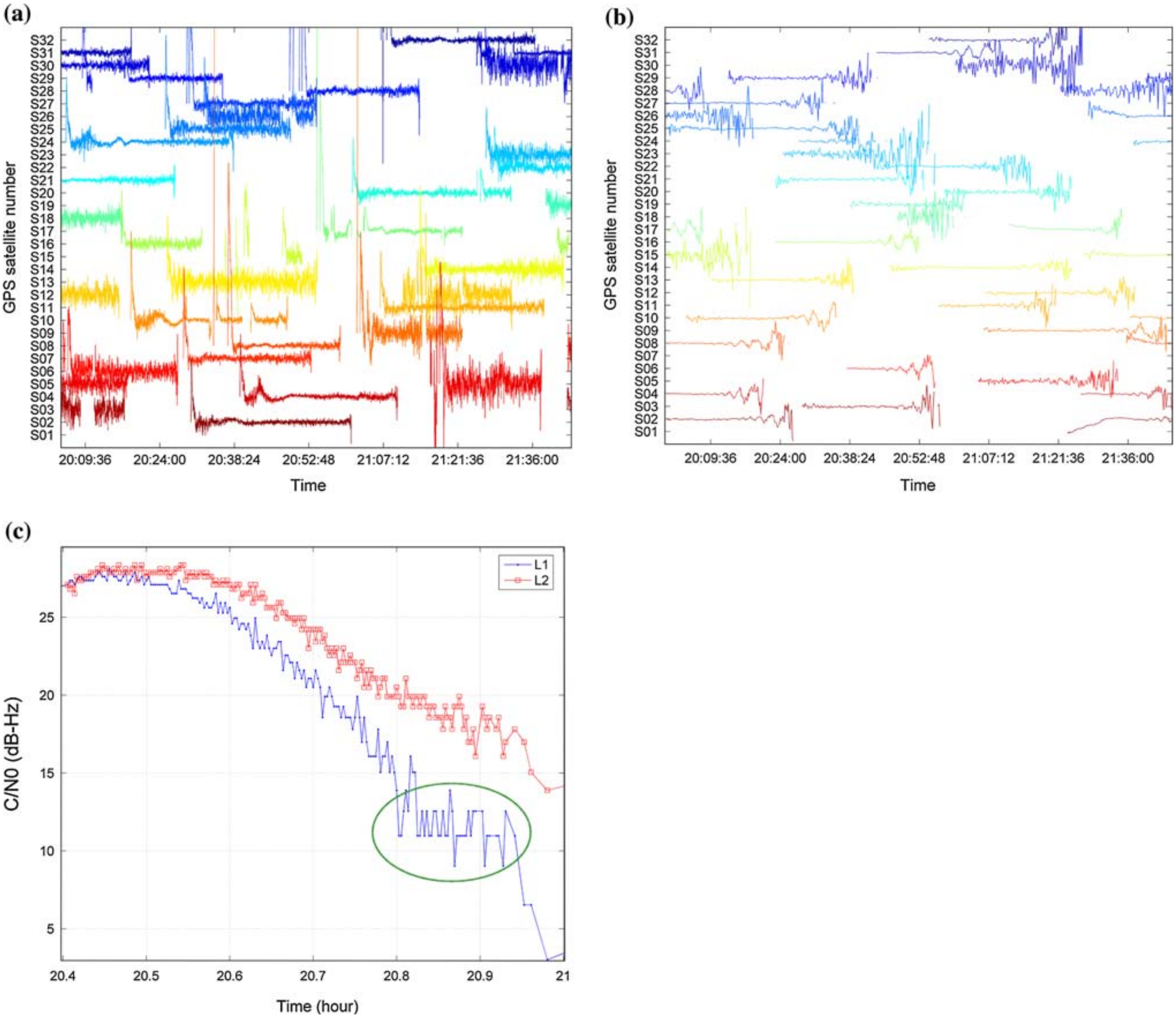

Fig. 2 Multipath effect of P1 (MP1, in m) for **a** FM3 and **b** GRACE-A and **c** C/N_0 values for S23 associated with Fig. 2b on DOY 201, 2008

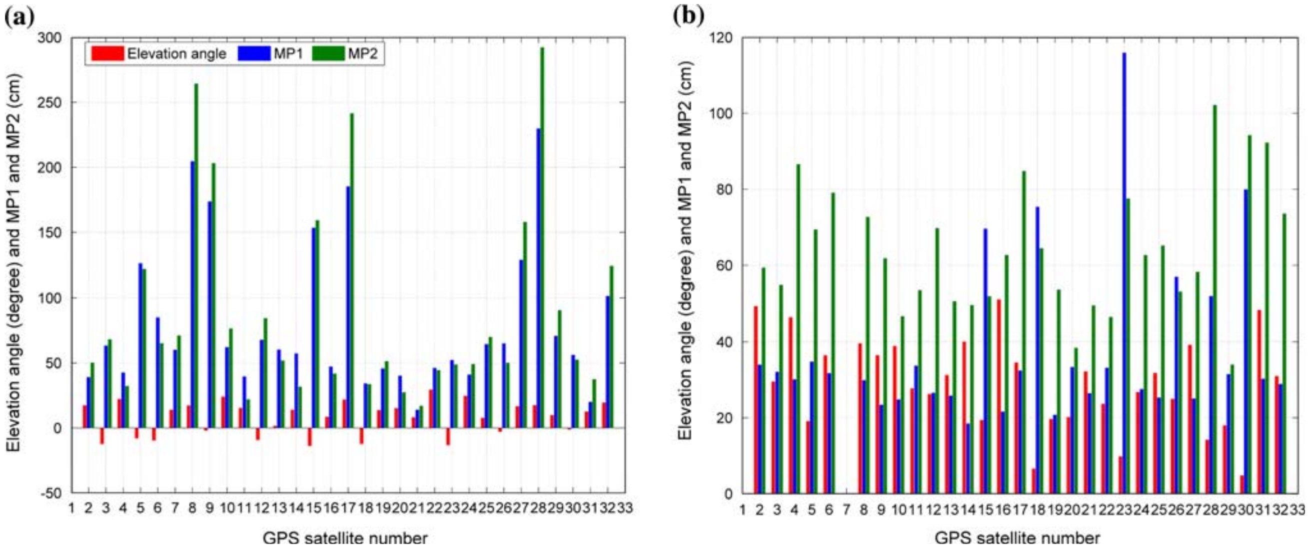

Fig. 3 Mean elevation angle and RMS values of MP1 and MP2 for **a** FM3 and **b** GRACE-A on DOY 201, 2008

effect can be very large—up to 23 m for S09 on FM3. Compared to the FM3 satellite the GRACE-A experiences smaller multipath effects, but there are still relatively large multipath effects for some of the GPS satellites, e.g., S15, S23 and S30. In one extreme case, the multipath effect of GRACE-A reaches 4 m for S23 associated with the unstable carrier-to-noise ratio (C/N_0) in the last part of the arc, as shown in Fig. 2c. Here, C/N_0 is defined as

$$C/N_0 = 20 \cdot \log_{10}\left(\frac{\mathrm{SNR}}{\sqrt{2}}\right) \tag{3}$$

where SNR is GPS signal-to-noise ratio. In Fig. 2c, the C/N_0 of $L1$ and $L2$ is given for S23, and the unstable C/N_0 values of $L2$ appear in the last part of the arc. This shows a large multipath and will lead to an unstable C/N_0 value. For most GPS signals transmitted to FM3, the MP1 effects oscillate rapidly, while for GRACE-A the oscillations are smaller. Figure 3 shows the relationship between mean elevation angle and the RMS values of MP1 and MP2 for FM3 and GRACE-A in a period of 1.5 h on DOY 201, 2008. The elevation angle in Fig. 3 (and in TEQC) is counted from the plane perpendicular to the normal of the WGS84 (GRS80) ellipsoid. For GRACE-A, the elevation angles are always larger than zero, while for FM3 the elevation angles range from negative values to values <25°(except S22). Since the multipath effect of GRACE-A is smaller than that of FM3, it is expected that the a priori orbit of GRACE-A will outperform F3/C satellite orbits. In fact, examinations of multipath effects over some selected arcs of F3/C satellites and GRACE-A resulted in more or less the same conclusions as here on the pattern and magnitude of multipath effects. Therefore, the examples given in Figs. 2 and 3 are representative of the features of multipath effects on the GPS observations of F3/C and GRACE-A satellite.

Table 1 summarizes the report of TEQC on the GPS data used on DOY 336, 2008. The acceptance ratio in Table 1 is defined as the ratio between the total number of visible GPS satellites and the expected ones in 24 h. On average, the acceptance ratio of F3/C is about 37% less than that of GRACE-A, and the multipath effect of F3/C is 40 cm larger. The low acceptance ratio of FM3 suggests that many GPS signals are simply too weak to reach the antennas of FM3. For F3/C, MP2 is 30 cm larger than MP1. For GRACE-A, MP2 is 31 cm larger than MP1. A large difference between the mean elevation angles of F3/C and GRACE-A (14.3 vs. 33.0; Table 1) will naturally lead to different qualities of GPS data from these two missions: a low or even negative elevation angle will experience a larger ionospheric effect in the space.

Table 1 A summary report of TEQC for FMs and GRACE-A based on GPS data on DOY 336, 2008

Satellite	Sampling rate (Hz)	Acceptance ratio (%)	Mean		Mean elevation angle (°)
			MP1 (m)	MP2 (m)	
FM1	1	30	0.77	1.01	11.99
FM2	1	40	0.61	0.74	11.77
FM3	1	35	0.74	0.89	11.58
FM4	1	40	0.79	1.00	12.38
FM5	1	33	1.02	1.50	16.28
FM6	1	43	0.75	1.03	22.20
GRACE-A	0.1	50	0.38	0.69	32.99

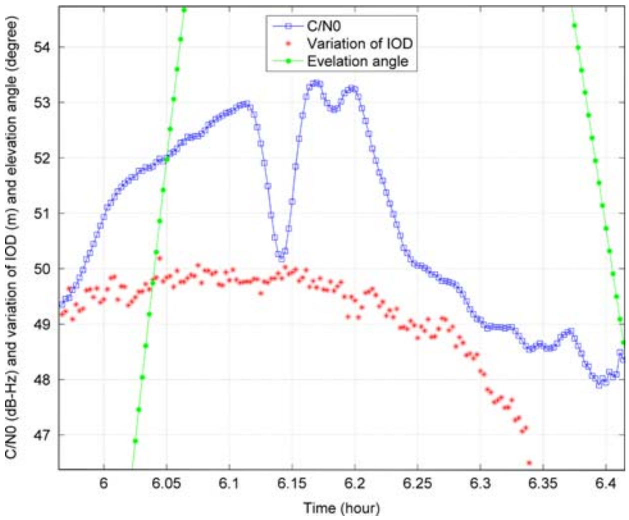

Fig. 4 Variations of IOD (shifted by 50 m) and *C*/*N*$_0$ and elevation angle in the antenna frame for S20 on DOY 27, 2008

Ionospheric delay and cycle slip

The IOD and cycle slip on carrier phase were investigated using the geometry-free linear combination of *L*1 and *L*2, abbreviated with *L*4. Use of *L*4 will also eliminate the receiver clock error and GPS satellite clock error. Including multipath effect, *L*4 can be expressed as

$$L4 = \frac{1-\alpha}{\alpha} I_1 + \lambda_1 N_1 - \lambda_2 N_2 + m_1 - m_2 \tag{4}$$

where I_1 is ionospheric delay (IOD) of *L*1. The difference between two consecutive *L*4 values is

$$D_k = L4_{k+1} - L4_k = \frac{1-\alpha}{\alpha}\left[I_1^{k+1} - I_1^k\right] + \left(\Delta m_{12}^{k+1} - \Delta m_{12}^k\right) \tag{5}$$

where *k* is epoch number and $\Delta m_{12} = m_1 - m_2$. If no multipath and cycle slip occurs, the variation of D_k in Eq. (5) will be just due to the variation of IOD (I_1), and such a variation is expected to be smooth over time. Figure 4 shows the time variations of D_k and *C*/*N*$_0$ for FM4 on DOY 27, 2008. Both variations are larger than normal at the later part of the arc where the elevation angle approaches zero. Thus, the common cause of the fast variations of D_k and *C*/*N*$_0$ is the low elevation angle (Montenbruck and Kroes 2003).

Any high-frequency oscillations in D_k with amplitudes exceeding few millimeters are likely caused by multipath effects, and a sudden, large jump in D_k is caused by cycle slip. The time derivative of D_k can be approximated by

$$\dot{D}_k = \frac{D_k}{\Delta t} \tag{6}$$

where $\Delta t = t_{k+1} - t_k$. Figure 5 shows $\dot{D}_k$ of FM3 and GRACE-A at selected satellite arcs. In Fig. 5a and b, a

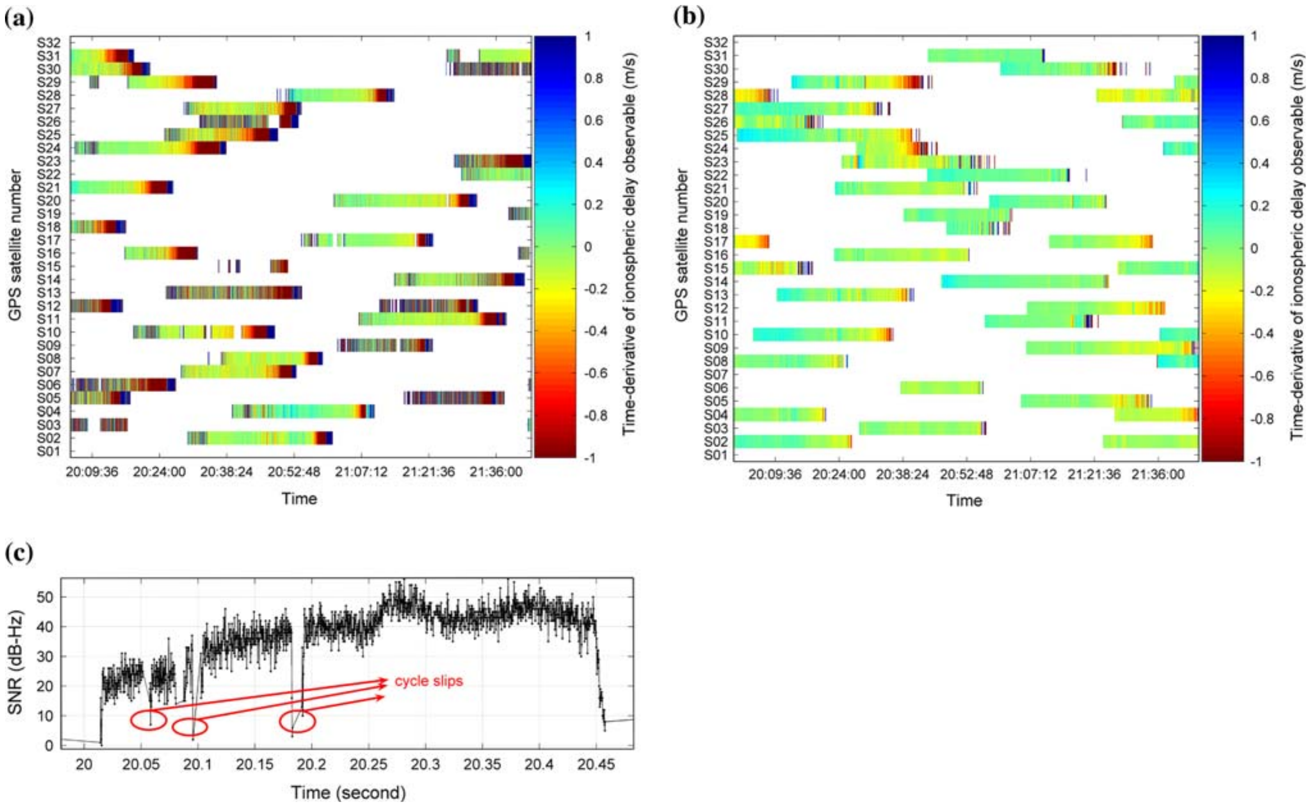

Fig. 5 Time derivative of ionospheric delay (IOD) for **a** FM3, **b** GRACE-A and **c** SNR of S06 for FM3 associated with Fig. 5a on DOY 201, 2008

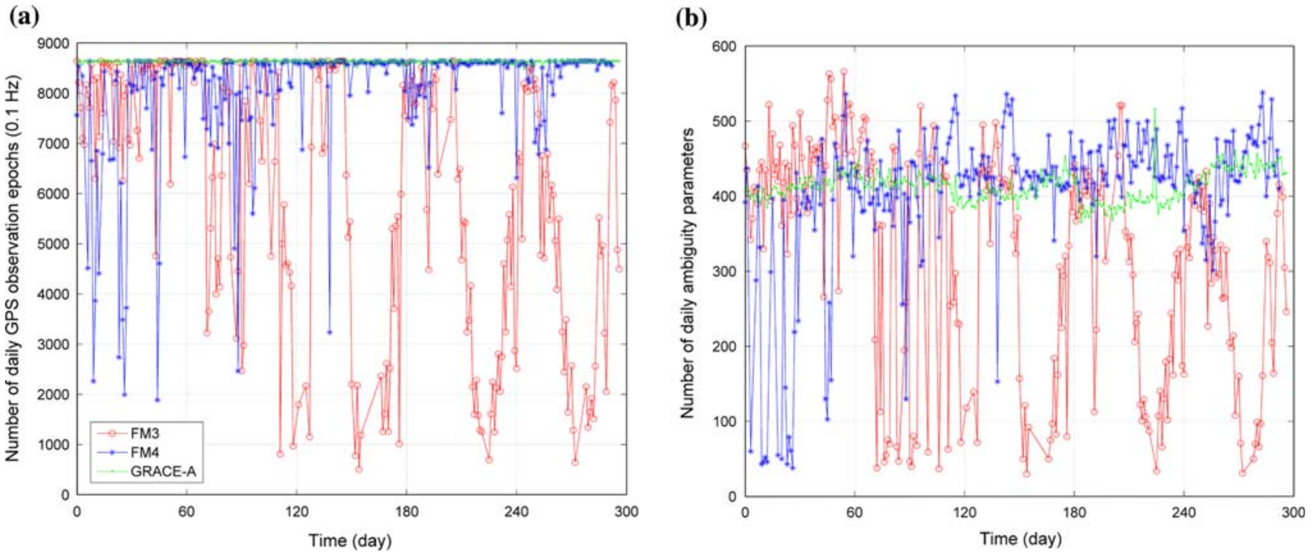

Fig. 6 **a** Number of daily GPS observation epochs and **b** number of daily ambiguity parameters for satellites FM3, FM4 and GRACE-A, since DOY 100, 2007

cycle slip is associated with a discontinuity in $\dot{D}_k$. A gap in $\dot{D}_k$ is most likely caused by bad attitude control or low SNR. A sudden change in $\dot{D}_k$ might be caused by a cycle slip or an outlier (Bock 2004), so Bernese uses a criterion based on differences between two successive observables of $L1$, $L2$ or $L3$ (see "Analysis of phase residual" for $L3$) to distinguish cycle slips from outliers in the data preprocessing (Dach et al. 2007). The $\dot{D}_k$ values (shown in brown to blue colors in Fig. 5) in the later part of each arc were caused by discontinuities in phase data. For FM3, the occurrence frequency of cycle slip is relatively large in the GPS signals from S03, S05, S06, S09, S12, S18, S23 and S26. In the case of S06 for FM3, the cycle slip was associated with the low SNR of $L2$ (no SNR of $L1$ in the RINEX file), see Fig. 5c. For GRACE-A, a relatively large number of cycle slips occur in the GPS signals from S23, S28 and S29. No IOD effect was occurred to GRACE-A. In Fig. 5, 147 cycle slips in FM3 are detected, compared to 67 cycle slips in GRACE-A. On average, the occurrence percentages of cycle slip for FM3 and GRACE-A are 1/29 and 1/84, respectively. Also, at the ending section of a FM3 arc, the variation of $\dot{D}_k$ is relatively large due to the negative elevation angles that give rise to a large IOD variation. For GRACE-A, such a fast variation of $\dot{D}_k$ did not occur because the elevation angles are always larger than zero. Again, large IOD and low C/N_0 are mostly associated with low elevation angle.

A large number of cycle slips will result in a substantial reduction of degree of freedom and degrade orbit accuracy. Figure 6 shows the daily numbers of GPS observation epochs and daily numbers of ambiguity parameters for satellites FM3, FM4 and GRACE-A over 300 days starting from DOY 100, 2007. To reduce the computing time, we used a sampling interval of 10 s for both F3/C and GRACE-A (0.1 Hz). Over the time span in Fig. 6, the average daily number of effective observation epochs for FM3 and FM4 is under 8,640 (an effective observation epoch means an epoch with at least one GPS signal). This suggests that tracking of GPS signals by FM3 and FM4 are not stable. The number of daily ambiguity parameters for FM3 or FM4 varies rapidly, but is a uniform for GRACE-A (about 400 daily). FM3 is the worst in terms of stability of GPS signal. The low number of ambiguity parameters of FM3 is simply due to the low number of effective observation epochs. Table 2 shows the average daily ambiguity parameters for F3/C and GRACE-A over 300 days. Because the number of ambiguity parameters of FM4 is close to that of GRACE-A, the GPS signal of FM4 is less interrupted, when compared to other satellites of F3/C.

Table 2 Number of average daily GPS ambiguity parameters

	FM1	FM2	FM3	FM4	FM5	FM6	GRACE-A
Daily ambiguity	198	253	286	406	212	158	413

Analysis of phase residual

As an alternative way of GPS data quality analysis, the phase residuals associated with dynamic orbit determination were assessed using the ionosphere-free linear combination $L3$. The orbits of both F3/C and GRACE-A satellites in this paper were determined by the Bernese GPS software version 5.0 (Dach et al. 2007). GPS-determined orbits of CHAMP, GRACE and F3/C satellites using both the dynamic and the kinematic approaches have been

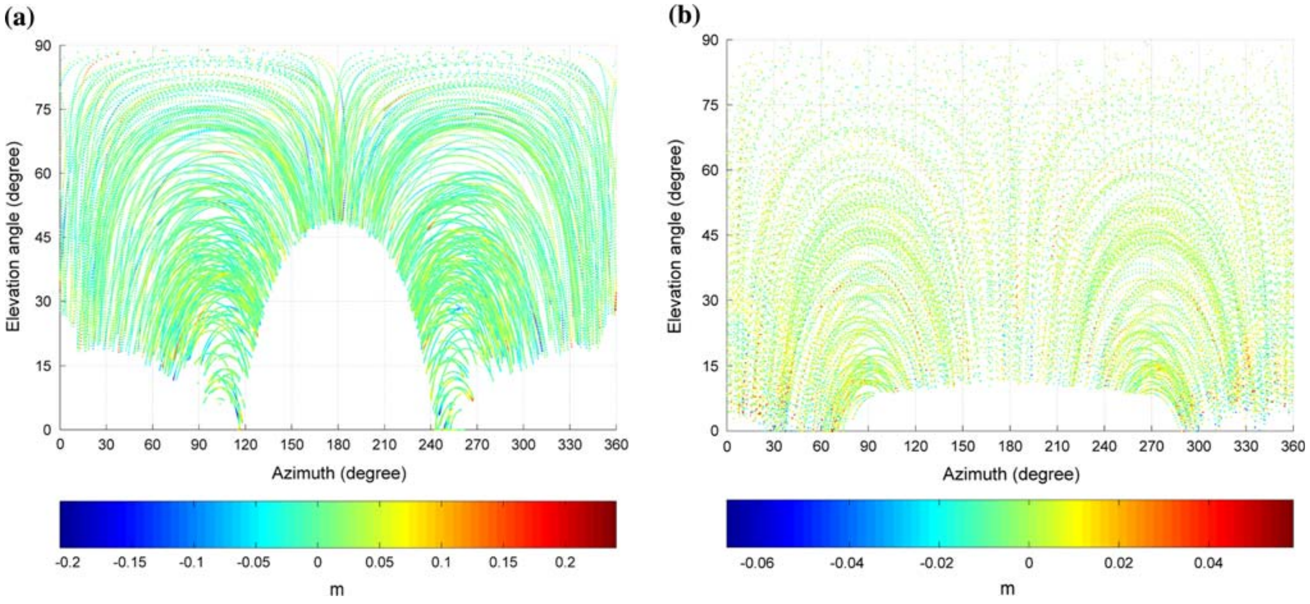

Fig. 7 Phase residuals (for 1 day) from the dynamic orbit determination for **a** FM3 and **b** GRACE-A, shown in different *color scales*

documented by Švehla and Rothacher (2003), Jäggi et al. (2007) and Hwang et al. (2009). Using an overlapping analysis, the orbit accuracy of F3/C is about 3 cm, compared to 1 cm in the case of the GRACE satellites (Hwang et al. 2009). Figure 7a and b shows the phase residuals of FM3 and GRACE-A with respect to elevation angle and azimuth from the dynamic orbit determination. These residuals were analyzed in the antenna frame. The phase residuals of FM3 range from −0.2 to 0.2 m. In Fig. 7a and b, the different patterns of distributions of phase residuals are due to the different antenna configurations on the F3/C and GRACE-A satellites. Due to the field of view (FOV) of the F3/C GPS antenna (120°, see Fig. 1), there is a void zone of GPS signals from azimuths 120–240° in the antenna frame, as shown in Fig. 7a. For both FM3 and GRACE-A, relatively large phase residuals occur at low or even negative elevation angles. The RMS value of the phase residuals of FM3 is 2.71 cm, compared to 0.8 cm of GRACE-A.

To assess the overall quality phase observables for the six F3/C satellites, we computed the standard error of unit weight for each satellite over 300 days, starting from DOY 100, 2007. In this paper, a standard error of unit weight is defined as

$$\hat{\sigma}_0 = \sqrt{\frac{V^T P V}{\beta}} \tag{7}$$

where $\boldsymbol{V}$ is a vector containing all phase residuals and $\boldsymbol{P}$ is weight matrix for the phase observables, β is the degree of freedom in the least-squares parameter estimation associated with the orbit determination. Here, we used a uniform weight (unitless) for all phase observables. Figure 8 shows the distribution of the standard errors for FM1 to FM6, and Table 3 shows the average standard errors over 300 days. There are two possible reasons for the long data gaps in Fig. 8: (a) few and/or poor GPS observations exist in these gaps and (b) poor attitude control disables POD (Hwang et al. 2009). The variations of the standard errors of FM5 and FM6 are small, in comparison with those for other satellites of F3/C. The F3/C satellites contain less observations than GRACE-A; on average, FM2 and FM4 contain about 30,000 observations daily, compared to 60,000 of GRACE-A. The standard error of FM3 is the largest (4.37 cm), followed by FM4 (3.70 cm). FM6 has the lowest standard error of 1.80 cm. It is not clear why the

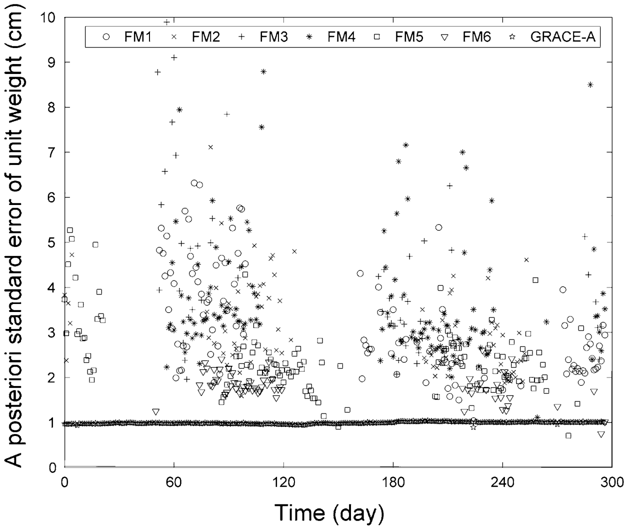

Fig. 8 The a posteriori standard error of unit weight for COSMIC satellites, since DOY 100, 2007

Table 3 Average daily number of GPS observations (0.1 Hz) and a posteriori standard error of unit weight (cm) for six COSMIC satellites over 300 days since DOY 100, 2007

	FM1	FM2	FM3	FM4	FM5	FM6	GRACE-A
Daily number	14,860	30,450	27,480	32,020	14,260	25,110	57,640
Standard error	3.22	3.11	4.37	3.70	2.41	1.80	0.99

variations for FM5 and FM6 are smaller. Perhaps the GPS signal strengths and attitude controls of FM5 and FM6 were good during this period of time. The average standard error of FM1, FM2 and FM4 is about 3.00 cm. GRACE-A has the lowest standard error of 0.99 cm. According to Comp and Axelrad (1998), multipath effects of phases may range from few millimeters to few centimeters. If systematic errors such as clock error, ionospheric delay, and ambiguity parameter are properly modeled in the least-squares estimation of orbit parameters, the phase residuals in Eq. (7) will largely come from the multipath effect of phase. Under this condition, the RMS value of multipath effect is roughly of the order of the standard error defined in Eq. (7). As such, F3/C's multipath effect of phase is of the order of few centimeters.

Quality assessment based on difference between dynamic and kinematic orbits

It is also possible to evaluate the quality of GPS data using the difference between the reduced dynamic orbit and kinematic orbit (called dynamic–kinematic difference) over the same arc. The degree of consistency between dynamic and kinematic orbits is an indirect way of checking the quality of F3/C GPS data. In the case of Bernese GPS software version 5.0, the reduced dynamic orbit is determined using the so-called pseudo-stochastic pulse parameters every 6 min and simplified orbit dynamical parameters to model the perturbing forces of the satellite (Jäggi et al. 2006), while the kinematic orbit is obtained without knowing the orbit dynamics much in the same way as determining the trajectory of an aircraft carrying a GPS receiver. Hence, the dynamic orbits will be smoother than kinematic orbits. However, kinematic orbits mainly depend on the quality of GPS observations and the number of GPS observations (Bock 2004). This means that a bad kinematic orbit solution leads to a large dynamic–kinematic orbit difference. Therefore, it is possible to use the dynamic–kinematic orbit difference as an indirect indicator of GPS data quality. The kinematic orbits of F3/C and GRACE-A satellites in this paper were determined using undifferenced GPS phase observables, with high-rate GPS clock errors and GPS precise orbits from Center for Orbit Determination in Europe (CODE; Dach et al. 2009).

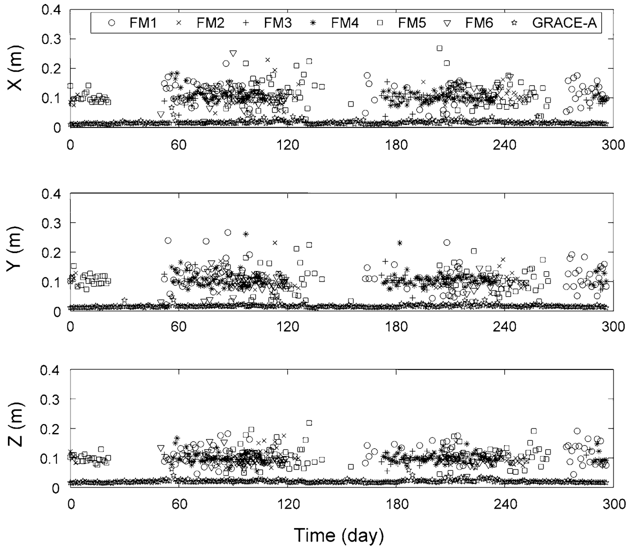

Fig. 9 RMS differences in the earth-fixed system *XYZ* between kinematic and dynamic orbits, since DOY 100, 2007

Figure 9 shows the daily RMS values of the dynamic–kinematic orbit differences in the earth-fixed system over 300 days, and Table 4 summarizes the statistics of the differences. The RMS dynamic–kinematic differences for F3/C and GRACE-A are about 10 and 2 cm, respectively. If the quality of GPS data is sufficiently good, one would expect an RMS dynamic–kinematic difference of 3 cm for F3/C, which is based on the overlapping analysis (Hwang et al. 2009). The 10 cm dynamic–kinematic difference for F3/C is significantly larger than the 3-cm overlapping difference, and this discrepancy is mainly caused by bad

Table 4 Statistics of daily RMS values (in cm) of the dynamic–kinematic orbit differences in the earth-fixed system over 300 days since DOY 100, 2007

Satellite	*X*	*Y*	*Z*
FM1	11.60	11.72	11.17
FM2	10.59	10.34	9.89
FM3	9.63	10.34	9.78
FM4	10.83	10.86	10.11
FM5	10.94	10.31	10.46
FM6	10.66	9.55	9.04
GRACE-A	1.76	1.70	2.09

kinematic orbits, which are in turn due to frequent cycle slips, large multipath effects, small number of tracked GPS satellites, plus poor attitude control, antenna phase center variation and the poor geometry of tracked GPS satellites (Hwang et al. 2009). The 2 cm dynamic–kinematic difference for GRACE-A is close to the 1-cm overlapping difference. In addition, for F3/C satellites the differences in the *xyz* components are quite consistent, while for GRACE-A the *z*-component is slightly larger than the other two components.

Conclusions

With selected satellites and time spans, this paper analyzes the quality of GPS data from F3/C and GRACE in terms of multipath effect, the time derivative of IOD, cycle slip, phase residual and dynamic–kinematic orbit difference. For all analyses, it is concluded that F3/C contains larger multipath effect, the time derivative of IOD and phase residual than GRACE, resulting in a smaller ratio of usable GPS data for POD. Large multipath effect introduces cycle slips that increase the number of estimated parameters in the orbit determination, eventually degrading the orbit accuracy. In this study, we compared the orbit difference (dynamic–kinematic) of F3/C with GRACE in order to see what happened to F3/C GPS data. However, the kinematic orbit depends on the quality of GPS observations and the geometry of tracked GPS satellites. A good kinematic orbit may be obtained even if only 4 GPS satellites are collected by GRACE satellite, but a bad kinematic orbit may be obtained even if 5 or 6 GPS satellites are collected by F3/C. For gravity determination using F3/C data, either in the one-step approach (Chao et al. 2000) or in two steps (Hwang et al. 2008), it is critical to perform a detailed quality check and to select usable GPS data. F3/C will contribute to gravity information associated with an inclination angle of around 72°. With six satellites, the quantity of GPS data in the F3/C mission will make up for the deficiency in the GPS data quality. As demonstrated by Hwang et al. (2008), F3/C's kinematic orbits can be used to enhance the GRACE-only gravity solution, especially in the low-degree gravity harmonic coefficients. With fine, selected GPS data, the potential of F3/C GPS data for gravity research is to be explored.

The result from this analysis will help to guide GPS data selection and processing for precise orbit and gravity determination research. In addition, the experience learnt from this analysis will help to improve the design of POD antenna in the future COSMIC-2 mission, which is under planning. For example, for COSMIC-2, it is suggested that the POD antenna should point to the zenith direction, and the solar panels, the POD antenna and the GPS reception should be so designed that multipath effects and cycle slips are minimized.

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References

Bock H (2004) Efficient methods for determining precise orbits of low earth orbiters using the global positioning system. Geodätisch-geophysikalische Arbeiten in der Schweiz, Band 65, Schweizerische Geodätische Kommission, Institut für Geodäsie und Photogrammetrie, Eidg. Technische Hochschule Zürich, Zürich

Chao BF, Pavlis EC, Hwang C, Liu CC, Shum CK, Tseng CL, Yang M (2000) COSMIC: geodetic applications in improving earth's gravity model. Terrestrial Atmospheric Ocean Sci 11:365–378

Comp CJ, Axelrad P (1998) Adaptive SNR-based carrier phase multipath mitigation technique. IEEE Trans Aerosp Electron Syst 34:264–276

Dach R, Hugentobler U, Fridez P, Meindl M (2007) Bernese GPS software-version 5.0. Astronomical Institute, University of Bern, Switzerland

Dach R, Brockmann E, Schaer S, Beutler G, Meindl M, Prange L, Bock H, Jäggi A, Ostini L (2009) GNSS processing at CODE: status report. J Geod 83(3–4):353–365. doi:10.1007/s00190-008-0281-2

Estey LH, Meerten CM (1999) TEQC: the multi-purpose toolkit for GPS/GLONASS data. GPS Solutions 3(1):42–49

Fong CJ, Yang SK, Chu CH, Huang CY, Yeh JJ, Lin CT, Kuo TC, Liu TY, Yen NL, Chen SS, Kuo YH, Liou YA, Chi S (2008) FORMOSAT-3/COSMIC constellation spacecraft system performance: after 1 year in orbit. IEEE Trans Geosci Remote Sens 46:3380–3394

Gurtner W (1994) RINEX: the receiver-independent exchange format. GPS World 4:48–52

Hofmann-Wellenhof B, Lichtenegger H, Collins J (2001) Global positioning system: theory and practice. Springer Wien New York, ISBN 3-211-83472-9

Hwang C, Lin TJ, Tseng TP, Chao BF (2008) Modeling orbit dynamics of FORMOSAT-3/COSMIC satellites for recovery of temporal gravity variations. IEEE Trans Geosci Remote Sens 46:3412–3423

Hwang C, Tseng TP, Lin T, Švehla D, Schreiner B (2009) Precise orbit determination for the FORMOSAT-3/COSMIC satellite mission GPS. J Geodesy 83(5):477–489. doi:10.1007/s00190-008-0256-3

Jäggi A, Hugentobler U, Beutler G (2006) Pseudo-stochastic orbit modeling techniques for low Earth orbiters. J Geodesy 80(1):47–60. doi:10.1007/s00190-006-0029-9

Jäggi A, Hugentobler U, Bock H, Beutler G (2007) Precise orbit determination for GRACE using undifferenced or doubly differenced GPS data. Adv Space Res 39(10):1612–1619

Leick A (2004) GPS satellite surveying, 3rd edn. Wiley, Hoboken

Montenbruck O, Kroes R (2003) In-flight performance analysis of the CHAMP BlackJack GPS Receiver. GPS Solutions 7:74–86. doi:10.1007/s10291-003-0055-5

Ogaja C, Hedfors J (2007) TEQC multipath metrics in MATLAB. GPS Solutions 11:215–222. doi:10.1007/s10291-006-0052-6

Švehla D, Rothacher M (2003) Kinematic and reduced–dynamic precise orbit determination of low Earth orbiters. Adv Geosci 1:47–56

Author Biographies

Cheinway Hwang received a BS in surveying engineering from National Cheng Kung University in 1984, a MS and a PhD in geodetic science in 1989 and 1991 from the Ohio State University. He was a postdoctoral research associate in Department of Earth Sciences, Oxford University, 1991–1993. He is now professor of geodesy, Department of Civil Engineering, National Chiao Tung University, Taiwan. He received the NASA/JPL/CNES Certificate of Appreciation for contribution the TOPEX/POSEIDON 3-year prime mission in 1996, Distinguished Research Awards of National Science Council of Taiwan in 1998, 2000, and 2002. He is a fellow of IAG, and was the chairs of IAG special study groups 3.186 (1999–2003) and 2.3 (2003–2007) and president of IAG commission 2.5 (2007–2011). He is now a member of the Editorial Boards of Journal of Geodesy and Journal of Applied Geodesy. His major research area is in satellite geodesy.

Tzu-Pang Tseng was born in 1980 in Taiwan. He received the BS and MS degrees from National Cheng-Kung University (NCKU) and National Chiao-Tung University (NCTU), Taiwan, in 2004 and 2006, respectively, and now he is working toward his PhD degree in NCTU, Hsinchu, Taiwan. He is a member of American Geophysical Union (AGU) and his research focuses on precise orbit determination (POD) of FORMOSAT-3/COSMIC satellites and GPS data processing. He did his research work at Technische Universität München (TUM), Germany, on satellite data analysis in 2005 and 2008. The FORMOSAT-3/COSMIC satellite mission is first constellation mission in the world, so he is currently developing the application of FORMOSAT-3/COSMIC POD.

Ting-Jung Lin was born in 1977. He received the BS and MSE degrees from the National Chiao-Tung University, Tainan, Taiwan, ROC, in 1988 and 1991, respectively, where he is currently working toward the PhD degree. His current research activities include time-varying gravity recovery using GPS data and precise orbit determination.

Dražen Švehla recently moved from TU München to European Space Agency where he works in the field of precise orbit determination of LEO and GNSS satellites. The last 9 years at TU München, he worked as research assistant (research group leader), and in parallel, was chairman of the ESA Topical Team on Geodesy (ACES). He has been a pioneer in the field of precise GPS applications in the LEO orbit, starting with the precise orbit determination of the CHAMP satellite, first formation of LEO satellites (GRACE A&B) and first constellation of six satellites in the LEO orbit (COSMIC mission). Dražen introduced the geometrical method in the orbit determination of LEO satellites based on GPS (independent of the force field) and for the first time demonstrated relative GPS-based orbit determination of LEO satellites in the formation flying with the mm-accuracy (GRACE mission). Dražen is a member of several WG of IAG, IVS and GGOS.

Urs Hugentobler received his PhD in astronomy in 1998 from University of Bern, Switzerland. He was head of the GPS research group at the Astronomical Institute of the University of Bern from 1999 to 2006 and responsible for the development of the Bernese GPS Software. He is now professor of geodesy at the Institute for Astronomical and Physical Geodesy in the Faculty of Civil Engineering at Technische Universität München, responsible for the research field satellite geodesy, and head of the Research Institution Satellite Geodesy that operates, together with the German Federal Agency for Cartography and Geodesy, the geodetic observatory in Wettzell, Germany. He is member of the International GNSS Service (IGS) Governing Board and director of the GGOS Bureau for Standards and Conventions.

Benjamin Fong Chao received the BS degree in Physics from National Taiwan University in 1973, the PhD degrees in Earth Sciences, Scripps Institution of Oceanography, in 1981 from the University of California. He was a NRC Research Associate and Geophysicist in NASA/GSFC, 1981–1996 and a head and chief, 1997–2006. He is now professor and Dean of geodesy, College of Earth Sciences, National Central University, Taiwan. He received GSFC Outstanding Performance Awards, 1991, 1992, 1994, 1995, 1996, 1998, 2000, 2003, 2004, Excellence in Refereeing of Journal Geophysical Research, American Geophysics Union, 1990, Honorary Professorship from Graduate University of the Chinese Academy of Sciences, Beijing, 2005 and TSMC Outstanding Chair Professorship, 2006, 2007, 2008. He is fellow, IAG, and was the chairs of IUGG/IAG Special Study Group “Global Geodynamic Variations” (1991–1994) and IERS/GGFC Special Bureau for Mantle (1998–2006). He was a president in Geodesy Section of American Geophysical Union, 2002–2006. He serves as a member of Editorial Board, *Journal Geodynamics*, 1996–present, a member of Editorial Board, *Earth, Planets and Space*, 1997–present. His major research area is in Earth/Planetary rotation dynamics, gravitational variations, global changes in geophysical fluid, global geodynamics and seismology and digital data analysis and inverse theory.