Quantitative analysis of the errors associated with orbit uncertainty for FORMOSAT-3

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ABSTRACT:

The FORMOSAT-3/COSMIC mission is a micro satellite mission to deploy a constellation of six micro satellites at low Earth orbits. The final mission orbit is of an altitude of 750–800 km. It is a collaborative Taiwan-USA science experiment. Each satellite consists of three science payloads in which the GPS occultation experiment (GOX) payload will collect the GPS signals for the studies of meteorology, climate, space weather, and geodesy. The GOX onboard FORMOSAT-3 is designed as a GPS receiver with 4 antennas. The fore and aft limb antennas are installed on the front and back sides, respectively, and as well as the two precise orbit determination (POD) antennas. The precise orbit information is needed for both the occultation inversion and geodetic research. However, the instrument associated errors, such as the antenna phase center offset and even the different cable delay due to the geometric configuration of fore- and aft-positions of the POD antennas produce error on the orbit. Thus, the focus of this study is to investigate the impact of POD antenna parameter on the determination of precise satellite orbit. Furthermore, the effect of the accuracy of the determined satellite orbit on the retrieved atmospheric and ionospheric parameters is also examined. The CHAMP data, the FORMOSAT-3 satellite and orbit parameters, the Bernese 5.0 software, and the occultation data processing system are used in this work. The results show that 8 cm error on the POD antenna phase center can result in ~8 cm bias on the determined orbit and subsequently cause 0.2 K deviation on the retrieved atmospheric temperature at altitudes above 10 km.

KEY WORDS: FORMOSAT-3, POD, GOX, antenna, phase center offset

1. INTRODUCTION

The FORMOSAT-3 Program is an international collaboration project between Taiwan and US with joint efforts of National Space Organization (NSPO) of Taiwan and University Corporation for Atmospheric Research (UCAR) of US. Its goal is to deploy a constellation of six low Earth orbit (LEO) microsatellites for weather and space weather forecast, climate monitoring, and atmospheric, ionospheric and geodesy research. This project is targeted to place six spacecraft into six different orbits at 700 – 800 km above the Earth ground. It is also known as COSMIC, the Constellation Observing Systems for Meteorology, Ionosphere, and Climate (Rocken et al., 2000).

There are three payloads on each satellite built to pursue the scientific objectives. The GPS occultation experiment (GOX) payload will collect the GPS signals for the study on atmosphere, ionosphere, and geodesy. Each satellite carries four GPS antennas to receive the L1 and L2 signals for the applications of occultation inversion and precise orbit determination (POD). The tiny ionospheric photometer (TIP) payload measures the night sky photon emission. The light wavelength is 135.6 nm and the instrument is used to calculate the total electric density of the area where the satellite faces the earth. The tri-band beacon (TBB) payload transmits three-frequency phase coherent signals. Utilize the coherent radio transmitters to transmit signals at three different frequencies 150, 400, 1067 MHz. When the ground receivers at different locations receive the signals, the electrical density and total electron content (TEC) can be deduced in high resolution. Details for mission, payload, and the associated scientific work are referred to the report of Wu et al. (2005).

The GOX in each microsatellite consists of one GPS receiver (and built-in redundancy) and four patch antennas (two occultation antennas and two POD antennas). In contrast to CHAMP, SAC-C and GRACE satellites having one POD antenna, the fore and aft POD antennas of GOX are installed on the spacecraft's front and back sides, respectively. In specification, the angle between the line linking antenna and spacecraft physical centers and +/- X-axis is 30°, while the angle between the normal to antenna and +/- X-axis is 15°. Here the satellite orbiting direction is basically defined as X-axis of the spacecraft (SC) coordinate system, and the satellite nadir direction is defined as Z-axis. The nearly horizontal orientation of POD antenna is used to support the measurements of ionospheric occultation sounding. However the occasionally awkward situation that the unilateral antenna cannot capture enough fine GPS signals needs to be considered.

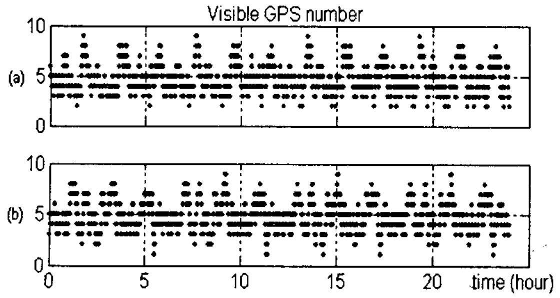

Figure 1. Number of GPS satellite instantaneously received by (a) POD -X antenna and (b) POD +X antenna, respectively.

Figure 1 shows an example of the visible GPS satellite by unilateral POD antenna. We use the 24-hour simulated FORMOSAT-3 orbit and the GPS constellation orbits to count the number of GPS satellites entering the field of view (FOV) of the POD antenna. By using the Bernese 5.0 software (Hugentobler, 2004), the visible number at each 30 seconds is symbolized as a dot. Fig.1 (a) and 1(b) show the result associated with POD -X and +X antennas. The situation that the number of visible GPS is less than 4 occupies ~15% of the total events. At least four GPS-transmitted signals are needed to determine LEO orbit so that signals received by two POD antennas must be combined when the number of GPS satellites is less than 4. Even the time delay between POD antennas and GOX receiver may need to be corrected.

On the other hand, the geodetic mission requires the orbit be precisely determined to achieve the order of mm to cm. Therefore the information of physical and phase centers for POD antenna is very important. In this work, the geometric alignment of GOX antennas and cable propagation delays are measured at NSPO. A preliminary analysis for the phase center information in chamber test is done by UCAR group. Furthermore we analyze the impact of antenna phase center offset on the orbit calculation and impact on the occultation inversion to atmospheric parameter profile.

2. GOX ANTENNA CHARACTERISTIC MEASUREMENT

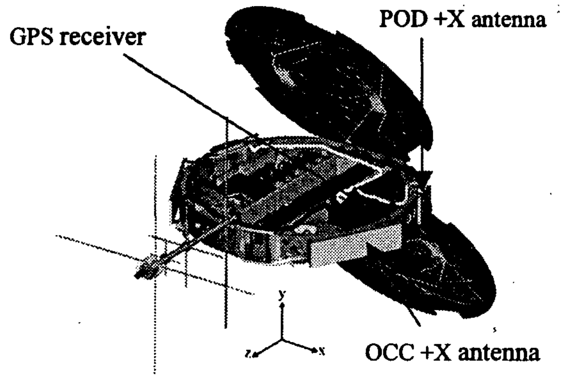

Figure 2. A sketch of FORMOSAT-3 spacecraft showing the configuration of GPS receiver, POD antennas, occultation (OCC) antennas and their associated cables.

In this section we present result of measured antenna parameters, such as antenna physical and phase centers, and cable time delay. It can be seen from Figure 2 that the POD antennas are not tangent to the ring. The bold-white (black) lines that indicate the path of the cables between GPS receiver and POD (occultation) antennas have different lengths.

2.1 Antenna Alignment

During alignment test, the shapes of six FORMOSAT-3 flight models (FMs) are measured by theodolites. Table 1 shows an example of the locations of GOX antenna physical center and the normal angles that between antenna normal and X-axis. The locations of antenna center are aligned in SC coordinate. The occultation antenna is aligned to the depression angle of 27.3° in specification.

Table 1. FM3 GOX antenna alignment result.

GOX antenna	Center locations (cm)			Normal angles
	X	Y	Z	
POD +X	47.211	-0.065	-26.979	14.81°
POD -X	-47.021	-0.083	-27.458	15.34°
Occultation +X	47.138	-0.191	24.181	27.38°
Occultation -X	-46.996	-0.228	24.369	27.16°

2.2 Cable Time Delay

Table 2 shows the cable lengths and the resulted signal time delays. The delay is measured by using the "Network Analyzer 8510" whose accuracy is 0.01 ns. It is found that length difference between POD +/- X cables is ~47 cm and causes ~2 ns delay in data transmissions. In general, the time error of 1 ns may makes the ~30 cm deviation in ground GPS positioning processing. The 2 ns bias must be considered in the combination of POD data collected from +/- X sides.

Table 2. FM3 GOX antenna cable lengths and signal propagation delay.

Antenna cable	Length (cm)	Signal time delay (ns)	
		1227 MHz	1575 MHz
POD +X	51.56	2.21	2.32
POD -X	98.30	4.06	4.15
Occultation +X	67.31	2.80	2.94
Occultation -X	95.50	3.98	4.01

2.3 Antenna Radiation Pattern

Table 3 shows POD antenna phase center measured by UCAR/Ball Aerospace. The measurements were provided by UCAR (Schreiner, 2005). In this anechoic chamber test, the POD antenna (engineering model) is installed on the mockup spacecraft. Therefore the analyzed L1 and L2 phase centers are represented in SC coordinate system. The computed phase center offset with respect to antenna physical center (see Table 1) is also listed. Due to the POD -X antenna is mainly located at -X axis, the 7–8 cm offset exhibits an obvious phase deviation in the zenith of POD antenna.

Table 3. POD -X antenna phase center positions in SC coordinate and the phase center offsets with respect to antenna physical center.

POD -X antenna		X_{SC} (cm)	Y_{SC} (cm)	Z_{SC} (cm)
Phase center position	L1	-53.73	0.14	-25.65
	L2	-54.98	-0.44	-25.45
Phase center offset	L1	-6.71	0.22	1.81
	L2	-7.96	-0.36	2.01

3. IMPACT ANALYSIS

The measurements addressed in the previous section are required for the purpose of geodetic research, and subsequently for atmospheric studies. In this section, the impact of POD antenna phase center on the determination of satellite orbit and atmospheric parameter profile is discussed.

3.1 Orbit impact due to antenna phase bias

The Bernese 5.0 software is utilized to study impact of antenna phase center bias on the orbit positioning. The challenge of combining two sideways-pointing POD antennas is not discussed, but instead we concentrate on the errors resulting from phase center offset. We also assume that cable time delays through different wires are the same. Bernese 5.0 supplies the antenna phase center position onboard LEO satellite and is used to process unilateral antenna-received data for POD. For simplification, we choose the L3 channel at -X side to examine the degree of the impact.

Initially Bernese software is used to simulate the received GPS data based on the orbits of FORMOSAT-3 and GPS constellation. Then, we input the FM3 POD -X antenna physical center position (in Table 1) as the phase center position. That is, no phase offset is given. The obtained orbit is taken as the based orbit. Subsequently, 1 cm offset is added to the zenith (or horizon) of POD -X antenna to estimate its deviation from the based orbit.

Figure 3 shows an example of the 24-hour orbit deviation resulted by 1 cm offset to the antenna zenith. It is presented in (a) SC frame and (b) Earth centered coordinate, respectively. In this section we add the subscript such as X_{SC} to distinguish with that X in Earth coordinate. It can be seen that the antenna phase bias will directly affect the computed orbit. There is nearly same order deviation in the X_{SC} direction, i.e., $\Delta X_{SC} \sim 1$cm. Note that POD antenna is mainly aligned in X_{SC} direction. Fig. 3(b) also presents the result in Earth coordinate. The oscillatory variation is due to the Z_{SC} pointing to Earth in the circular orbiting whose period is 90-100 minutes.

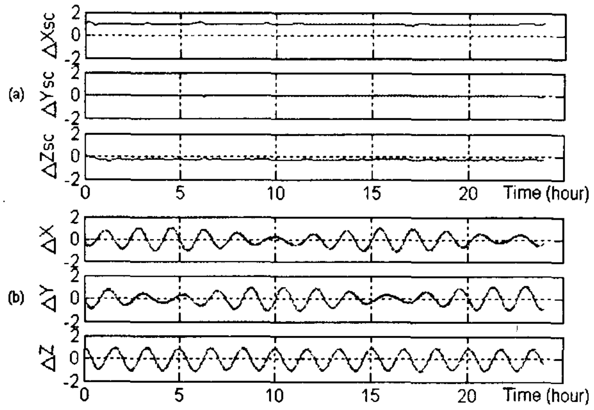

Figure 3. 24-hour orbit deviation (cm) due to antenna phase center offset of 1 cm in the zenith of POD -X antenna. The deviation is shown in (a) spacecraft coordinate and (b) Earth centered coordinate.

We determine the orbit deviation from orbital RMS difference. It is found that the 1cm phase bias leads to 0.6 cm RMS difference. The orbit impact from phase bias at various directions is studied. Table 4 shows result of six cases with phase center offset in the Up (zenith), East and North (horizon) directions, with respect to POD -X antenna. Both of the orbit RMS differences for FORMOSAT-3 and CHAMP are shown. The North of antenna is identical to Y_{SC}. In 24-hour orbiting the orientations for the Up (zenith) and East of antenna continuously vary, but Y_{SC} maintains nearly same direction. Therefore here is no difference between the orbital RMS differences resulted by North +/- 1 cm offsets, respectively.

Table 4. Orbital RMS differences caused by various phase center offsets.

Phase center offset	FORMOSAT-3	CHAMP
	RMS (cm)	RMS (cm)
Up +1cm	0.61	0.62
Up −1cm	0.61	0.56
North +1cm	0.44	0.48
North −1cm	0.44	0.48
East +1cm	0.58	0.58
East −1cm	0.57	0.59

3.2 Atmospheric impact due to orbital error

Will the antenna phase bias affect the primary mission of FORMOSAT-3, the weather forecast or the atmospheric occultation sounding? We study how the orbital accuracy influences the retrieved profiles of atmospheric parameters, such as bending angle, refractivity, and temperature. Although there is also phase center offset in the occultation antenna, it can be neglected. The occultation antenna is of high-gain radiation pattern with a narrow FOV in theta-cut or the spacecraft X-Z plane. During an occultation event with a period of several minutes, the factor of a nearly unchanged antenna phase offset can be completely eliminated in excess phase and the followed Doppler phase shift processing. Therefore only the orbit error coming from POD antenna bias is considered here.

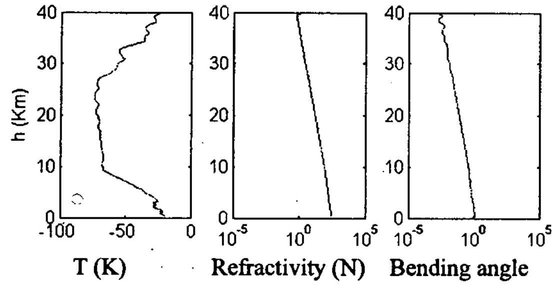

Figure 4. An example of profiles of dry temperature, refractivity, and bending angle inversed from Champ data on 10 August 2002.

By using the occultation data processing system installed at Taiwan Analysis Center for COSMIC (TACC), we take the CHAMP data to retrieve the atmospheric profiles as base profiles. Figure 4 shows an example of the retrieved profiles for dry temperature, refractivity, and bending angle. We then add artificial noise on CHAMP orbit to get new set of profiles, which are compared with the atmospheric profiles of reference. Six case studies are shown in Figure 5. In case (a), we add 10 cm orbit shift in X_{SC} direction of the LEO orbit, i.e., leoOrb and leoPod files, and then re-process the full TACC procedures. The discrepancies on refractivity and bending angle from corresponding reference are very small so we show temperature discrepancy only.

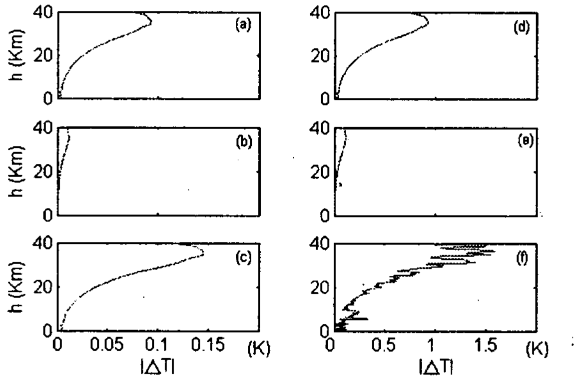

Figure 5. Profiles of temperature discrepancy, ΔT, due to LEO orbit shift with (a) X_{SC} shift +10 cm, (b)Y_{SC} shift +10 cm, (c)Z_{SC} shift +10 cm, (d)Xv shift +100 cm, (e)Y_{SC} shift +100 cm, and (f)Z_{SC} shift +100 cm.

It can be seen from Fig. 5(a) that magnitude of temperature discrepancy, |ΔT|, due to orbit shift of X_{SC} +10cm is less than 0.2 K. Fig. 5(b) and 5(c) show the results of Y_{SC} +10cm and Z_{SC} +10cm. We enlarge the orbit shift in next three cases as (d)X_{SC} +100cm, (e)Y_{SC} +100cm, and (f)Z_{SC} +100cm. The 10-times rising results seem show that the total effect in altitude profile is linearly correlative to orbit shift.

The weak effect from Y_{SC} is because the occultation plane in this base event is nearly orthogonal to Y_{SC}. The presence of a maximum temperature discrepancy at ~35 km altitude is still under investigation by the scientific community. However it is found in every case that the discrepancy quickly decreases as an exponential decay. We think the very weak discrepancy in lower atmosphere with $h \leq 20$ km might be originated from the strong constraint of optimization process by a background ECMWF ancillary model.

4. CONCLUSIONS

In this paper we present the instrumental measurements for GOX onboard FORMOSAT-3. The antenna positions in alignment test are necessary to the instrumental calibration in each GOX data set. The measured cable time delay for signal transmission needs to be corrected for combining the GPS data collected from POD +/- X antennas to determine satellite orbit.

In the orbit impact study, it is shown that the POD antenna phase bias directly affects the computed orbit with a magnitude of 1:1 ratio in SC coordinate, equivalent to an orbit determination deviaiton of 0.6 cm in Earth centered coordinate system. The subsequently inversed atmospheric temperature appears to have 0.2 K difference for the case of 10 cm orbit error.

The other factor of antenna phase parameters is also important to provide the basic L1/L2 calibration values. Up to now, the unique GOX antenna phase information is based on the UCAR/Ball test report. The complete chamber test for six GOX assemblies may not be done at NSPO due to the pressure of launch schedule. However we are conceiving the needs to conduct additional GOX outdoor function and performance test. Both the phase center offset and variation will then be defined.

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