In-orbit experiment of satellite-induced code pseudorange deviations of BeiDou system

Shaojun Bi, *Beijing Institute of Spacecraft System Engineering, china*
Changgang Zheng, *University of Electronic Science and Technology of China*
Congwei Yang, *Beijing Institute of Spacecraft System Engineering, china*
Jinjun Zheng, *Beijing Institute of Spacecraft System Engineering, china*
Chengyan He, *National Time Service Center, china*
Jiaxing Liu, *Beijing Institute of Spacecraft System Engineering, china*

BIOGRAPHY (IES)

Shaojun Bi, senior engineer, graduated from Beijing University of technology with a master's degree, engaged in the system design of navigation satellites.
Changgang Zheng, born in 1998, the student of University of Electronic Science and Technology of China, engaged in the navigation signal processing and data analysis.
Congwei Yang, senior engineer, graduated from China academy of space technology with a master's degree, engaged in the system design of navigation satellites.
Jinjun Zheng, doctor, researcher, had been engaged in post-doctoral research in electronic information field in Tsinghua university, currently working on the system design of navigation satellites.
Chengyan He, doctor, engineer, graduated from National Time Service Center with a doctor's degree, engaged in the navigation signal processing and data analysis.
Jiaxing Liu, doctor, senior engineer, graduated from Tsinghua university, engaged in the system design of navigation satellites.

ABSTRACT

In allusion to the phenomenon that the multipath value of BeiDou MEO satellite of its regional system varies with the elevation angle of observation station, we designed an in orbit experiment using test satellite of BeiDou global system on the basis of theoretical analysis and ground test. During the in orbit test, we adjusted the attitude of the satellite repeatedly to simulate the different elevation angles of ground station, used narrow beam of large aperture receiving antenna on the ground to suppressed the multipath effect of ground environment, and reduced influence of ionospheric and other space environment by fast attitude adjustment. We implemented in orbit test according to the design and the result is that the influence of the multipath of the new generation test satellite of BeiDou global system on received data of users is less than 0.1 m, which is equivalent to the GPS satellites, and has a great improvement over the MEO satellite of BeiDou regional system.

INTRODUCTION

Lambert Wanninger and Susanne Beer carried out a long time measurement of MEO satellite in BeiDou regional system using small aperture antennas of different observation stations of IGS, and found a phenomenon of variation of multipath (MP) with the angle of elevation [1][2] .The influence of common errors such as ionosphere, satellite orbit and clock error was deducted in the calculation of MP value. Therefore, the MP value could reflect the effect of noise and the multipath characteristic of signal transmission.With no multipath effect caused by the satellite body , the MP value is just random noise , and its variance value would increase with the elevation angle , and generally fluctuates within ± 1m .In orbit test of MP value with Beidou Global system Test Satellite also showed the similar phenomenon, and the variation of MP value with elevation angle was different with different receiver.The fluctuation of MP value is an important factor that causes the false range deviation of the satellite navigation signal received by the ground receiver, which will lead to the difference of the satellite and ground pseudorange observed by the receiver at different time and different locations. It is difficult to eliminate the pseudorange deviation by filtering and modifying parameters, which will eventually worsen the navigation accuracy of BeiDou satellite navigation system.

The most possible reason of MP value fluctuating with the elevation of the satellite is the multipath effect of the satellite signal, that is, the signal reflects on the outer surface of the satellite or in the interior of the satellite[3][4], resulting in the diverse MP values of transmitting signal to different directions, as shown in figure1.

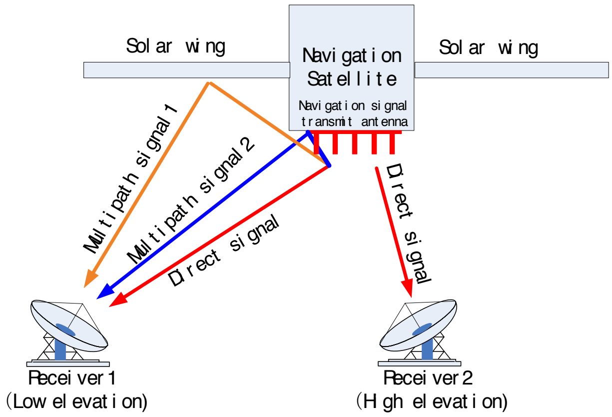


Figure 1. schematic diagram of generation of satellite multipath

In reaction to the phenomenon, we analyzed the surface layout and material characteristics, and mainly simulated the microwave reflection characteristics of the antenna and the solar wing of the new generation BeiDou satellite launched in 2015. The result shows that the design of the satellite could not result in meter-scale pseudorange variation.

In order to verify the result, we developed a Radio Model satellite, and carried out wireless multipath test in a compact range environment. The result of the test is consistent with that of the earlier computer simulation[5]. The problem is that this result is limited because of the size of the test field cannot fully represent the actual working state of the satellite in orbit.

Therefore, we carried out a further 1km distant-field ground test to strengthen this result. The satellite unfolded all the large components according to the actural on-track working state during the test. And the result shows that the solar wings installed on both sides (±X,±Y), of the satellite and the reflector antenna have no significant influence on the fluctuation of the MP value[6]. However, the diatant-field ground test did not totally reappear the pseudorange variation phenomenon for the big measurement noise caused by the multipath effect of ground surface.

In order to further analyze and determine the mechanism of pseudorange variation accompanying with elevation, we implemented in orbit test with the new generation of BeiDou navigation satellite. This paper introduces the method, implementation and result of the test.

TEST METHOD

Method of equivalent simulation for changing elevation

Adopting the scheme of attitude manuver of satellite to simulate the elevation change of observation station, that is the observation elevation is quickly traversed in a short time by attitude control of the satellite as shown in Figure 2. The position relationship between the satellite and the receiver and other conditions like ground environment and working state of the receiver can be considered unchanged during the test.

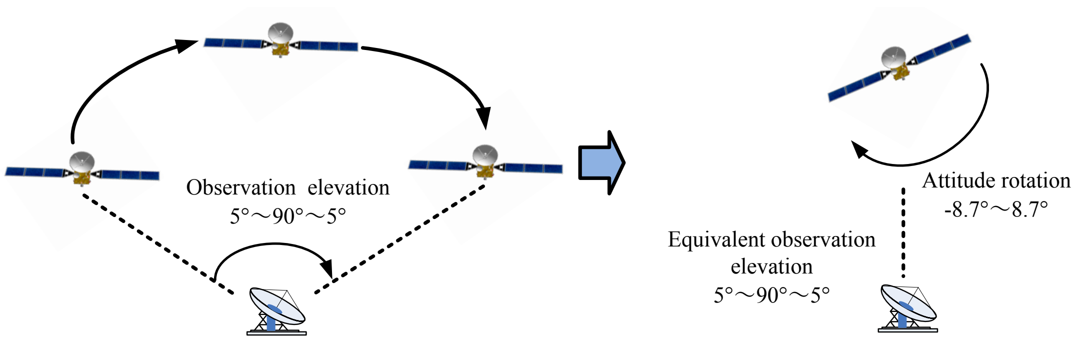


Figure 2. schematic diagram of equivalent method for elevation variation of ground station

Method of multipath evaluation for transmit signal of the satellite

Using the method of measuring the MP value of navigation signal to evaluate the multipath characteristics of the satellite signal, combining with telemetry of satellite attitudes and orbital parameters, we could get the elevation and azimuth angle between the ground station and the satellite in the satellite coordinate system, and finally analyze and determine the corresponding relationship between MP value fluctuation and change of satellite observation elevation angle.

The MP value can be calculated as follows:

$$P_i = \rho_j + RcvClk - SatClk_j + Com_j + rel_j + Ecc_j + Ion_j + Trop_j + Gtide_j + \zeta_j^{Ant}$$

$$\varphi_i = \rho_j + RcvClk - SatClk_j + Com_j + rel_j + Ecc_j - Ion_j + Trop_j + Gtide_j + windup_j + Amb_j$$

Where:

$\rho_j^i \ (i = Rcv \ \ or \ \ Ant)$ is geometric distance between Satellite j and ground antenna or receiver when transmitting the signal.

$RcvClk_j$ is clock error of the receiver clock offset.

$SatClk_j$ is clock error of the satellite.

Com_j is phase center correction navigation antenna of satellite.

rel_j is the relativistic effect.

Ecc_j is the eccentricity correction for receiver of the station.

Ion_j is the ionospheric propagation delay, the effect of which on pseudo-distance observation and phase observation is the same and opposite in sign at the same time.

$Trop_j$ is the tropospheric delay.

$Gtide_j$ is the earth tide effect.

ζ_j^{Ant} is multipath noise of pseudo-interval.

$windup_j$ is the phase wrapping effect.

Amb_j is the ambiguity parameters[7].

Then, MP value can be obtained by subtracting the above two formulas:

$$\zeta_j^{Ant} = P_i - \varphi_i - 2Ion_j + windup_j + Amb_j$$

Among which, Ion_j can be calculated by the measured phase value of dual-frequency carrier, Amb_j is a constant parameter with no contribution to the fluctuation of MP, and $windup_j$ can be calculated as follows:

$$D = x - k(k \cdot x) - k \times y$$

$$D_{Rev} = x_{Rev} - k(k \cdot x_{Rev}) - k \times y_{Rev}$$

$$windup_j = sign(k \cdot (D \times D_{Rev}))cos^{-1}(\frac{D \cdot D_{Rev}}{|D||D_{Rev}|})$$

Where:

k is the unit vector from satellite to receiver antenna.

x, y are the unit vectors for the satellite.

x_{Rev}, y_{Rev} are the unit vectors for the receiver,

$windup_j$ is the correction of the phase wrapping center caused by yaw rotation of the satellite, the unit is period[8].

The relationship between the observation elevation of satellite to ground station and the pitch of ground station to satellite body is shown as below. In order to avoid the case of no solution for elevation which caused by too large pitch during the attitude manouver of the satellite, the pitch of ground station to satellite was used to calculate MP instead of elevation of satellite to the station. The pitch and the elevation are basically linear relationship, and the relationship of the two angles of IGSO satellite is shown in figure 3.

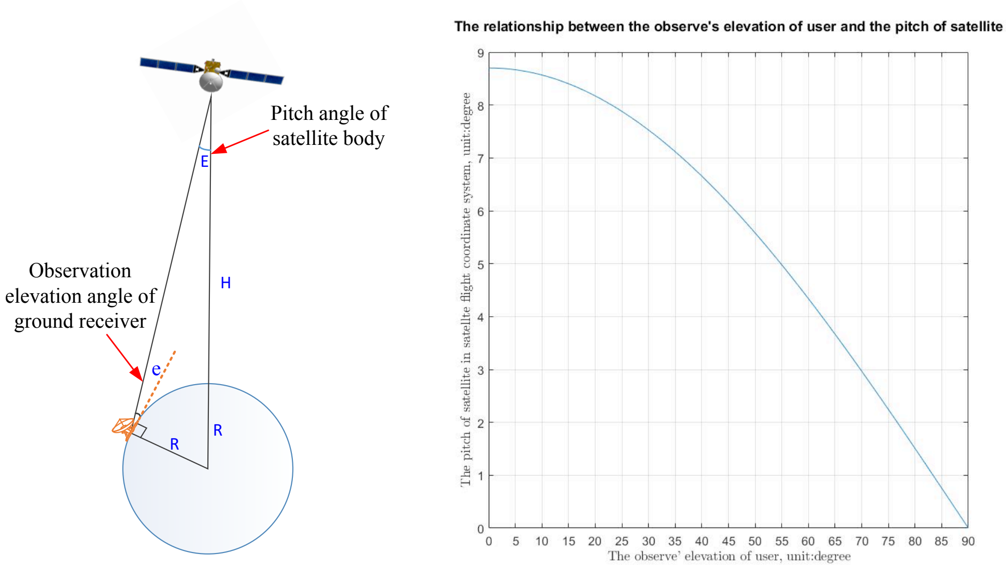


Figure 3. schematic diagram of the relationship between the elevation angle of the ground observation and the pitch of the satellite

Measures to reduce test error and risk

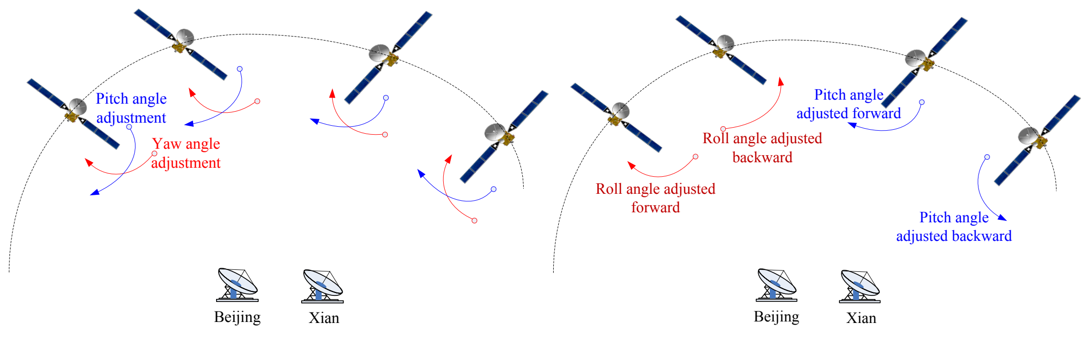
In order to reduce the measurement error and risk of the test, the following measures were adopted in the in orbit test:

a) New generation of BeiDou navigation satellite (IGSO) equipped with star sensors was selected to carry out this in orbit test to reduce the error of attitude measurement during the satellite maneuvering.

b) Chosen the time period that there elevation to the satellite was high, and the satellite adjusted its attitude according to designed plan and completed the elevation traversal in a short period of time which would ensure that there were no big differences about the orbital position of the test satellite and excluded the multipath environment of ground which would influence the test results at the same time.

c) To ensure the measurement diversity and accuracy of test data, the 40m aperture antenna of the National Time Service Center (NTSC) was selected as the main test point, and the 13m antenna of Beijing station was selected as the auxiliary test point, among which five receivers receive data at the same time.

d) Traverse along two orthogonal directions of the satellite (along the X-axis and Y-axis), without traversing omnidirectional angle of elevation, which would ensure the cooling and security of power supply of the satellite, as shown in figure 4.



fast ergodic test

slow ergodic test

Figure 4. schematic diagram of test implementation

TEST SITUATION AND DATA ANALYSIS

The in orbit experiment carried out was divided into two stages: the fast ergodic test and the slow ergodic test. In the fast ergodic test, the satellite adjusted its attitude four times along the X-axis and Y-axis, and the time of each elevation traversal was 1 minute. The aim of fast ergodic was to shorten the test time and eliminate the influence of other factors. In the slow speed ergodic test, the satellite adjusted its attitude twice along the X-axis and Y-axis, and the time of each elevation traverse was 90 minutes, in order to locate the source of the pseudorange deviation. In order to compare, we also observed GPS satellite and analyzed its MP value.

Fast ergodic test

During the experiment, six receivers in both locations obtained effective measurement data. The fluctuation of MP value was analyzed based on the measured data of different receivers. The range of fluctuation is shown in Table 1.

Table 1. MP fluctuation based on measured data from different receivers

Signal component	NTSC receiver	Beijing station				
		receiver 1	receiver 2	receiver 3	receiver 4	Receiver 5
B1I	0.28	0.70	0.38	0.43	0.70	0.15
B1Ap	0.32	-	0.73	0.22	0.23	0.24
B1Cd	0.36	0.67	0.48	0.63	0.56	-
B1Cp	0.36	0.45	0.40		0.41	0.76
B2ap	0.26	0.28	0.22	0.45	0.24	0.21
B2ad	0.20	0.18	0.26		0.23	0.21
B2bp	0.24	0.24	0.16	0.36	0.16	0.15
B2bd	0.19	0.16	0.17		0.16	0.14
B3Ap	0.23	0.21	0.32	0.32	0.29	0.20
B3Ad	0.24	0.20	0.38		0.20	0.20
B3I	0.23	0.20	0.32	0.32	0.21	0.20
Uniformity	0.17	0.54	0.57	0.41	0.54	0.62

It can be seen from Table 1 that the MP values measured at each frequency point with receiver of NTSC have better consistency and less measurement noise, so the subsequent data processing is based on data from NTSC.

When the MP value measured by NTSC is combined with the attitude data of the satellite, it is found that there is no obvious corresponding relation between the MP value and the pitch of the satellite. The MP value only fluctuates slightly with elevation angle during several ergodic operations, and the MP value of each frequency point fluctuated not more than 0.1 m (±0.05 m) as shown in figure 5. Therefore, we take the data of B3I signal measured by NTSC as an example for further analysis, as shown in figure 6.

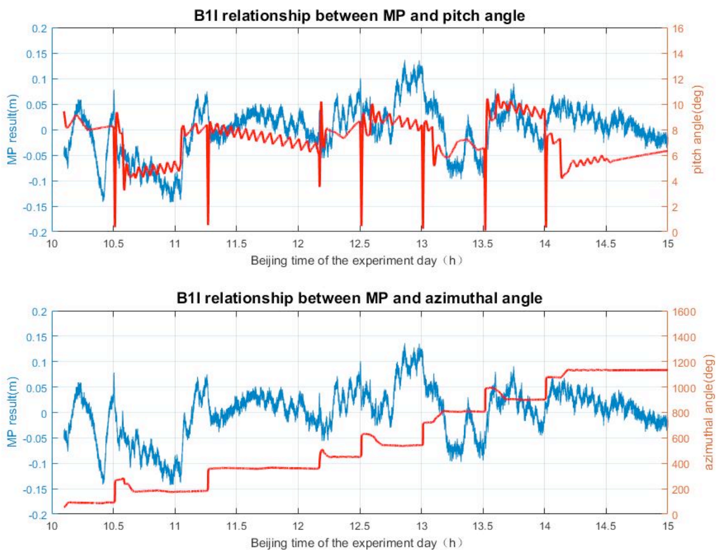


Figure 5. relationship of MP with the pitch and the azimuth of B1I

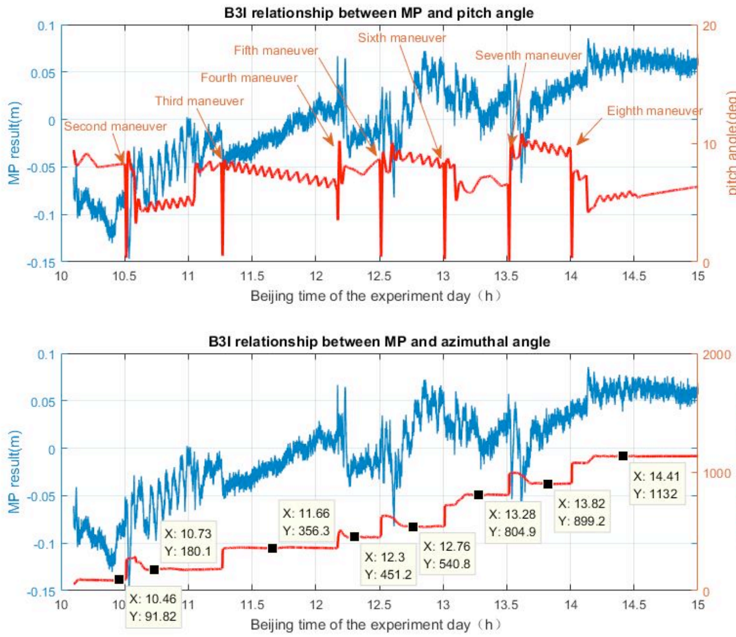


Figure 6. relationship of MP with the pitch and the azimuth of B3I

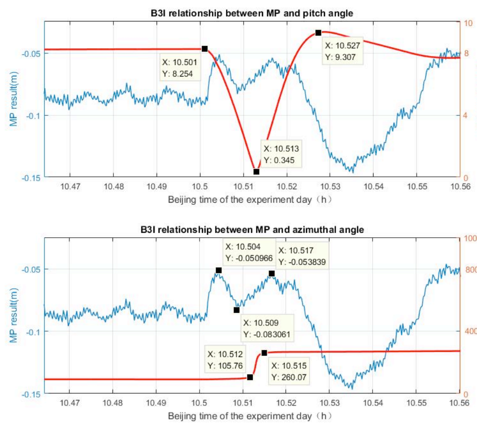


Figure 7. result of the second maneuver

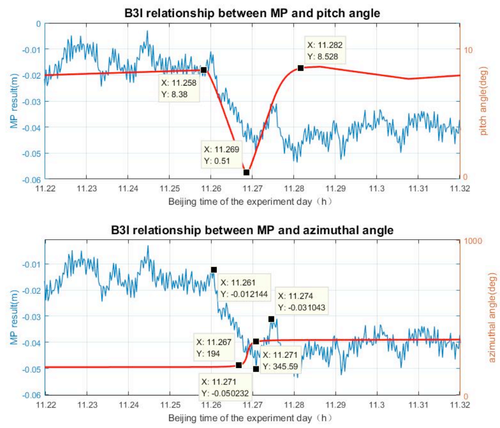


Figure 8. result of the third maneuver

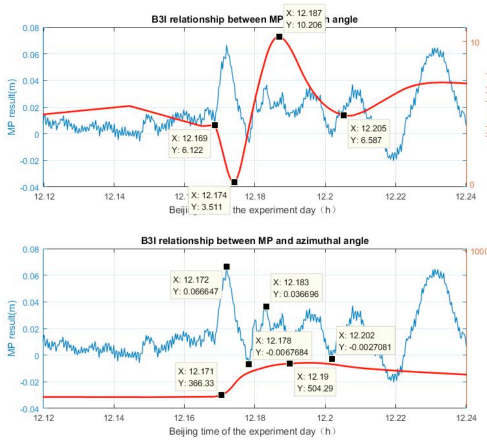


Figure 9. result of the fourth maneuver

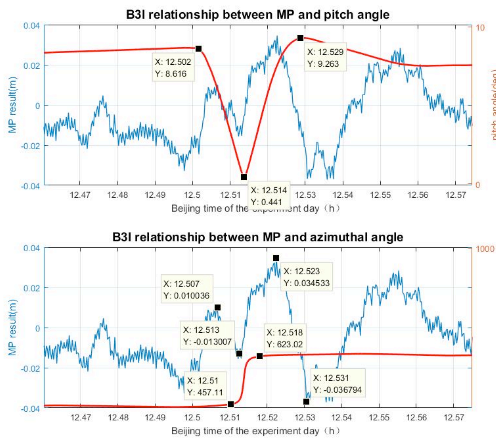


Figure 10. result of the fifth maneuver

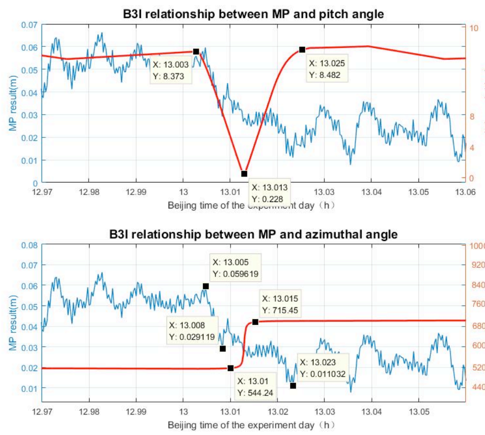


Figure 11. rusult of the sixth maneuver

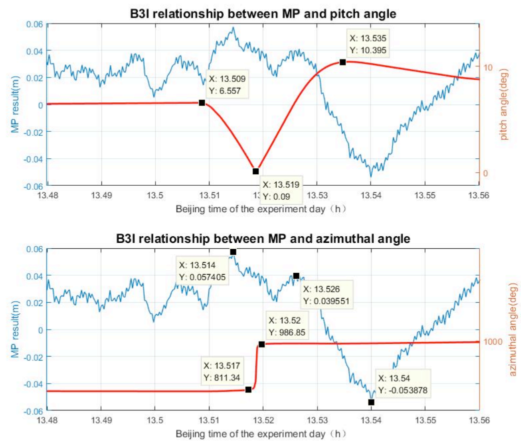


Figure 12. result of the seventh maneuver

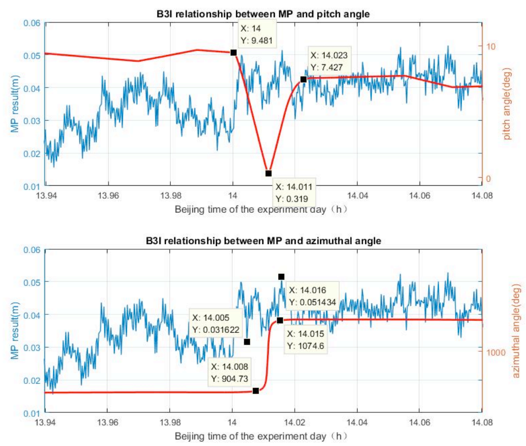


Figure 13. result of the eighth maneuver

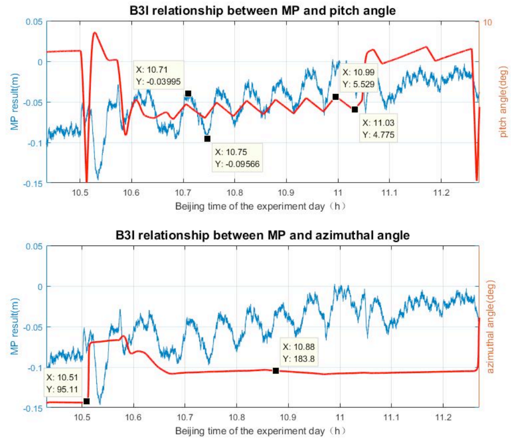


Figure 14. result of little attitude maneuver periodically

As shown in figure 7-13,there is no obvious correspondence between the fluctuation of MP value and the change of the pitch.

During the traversal period of the pitch, the pitch is adjusted periodically by a small margin when the azimuth is specified. It is found that the MP value of the B3I signal also fluctuates in the same period, and the law is consistent with the law of the change of the pitch. The observed fluctuation of MP is 0.07 m (±0.035 m), as shown in figure 14.

In the fast ergodic test, the relationship between the MP value of each signal at the three frequency points of B1,B2 and B3 and the elevation angle of the earth station relative to the satellite are shown in figure 15. It can be seen that the fluctuation between the MP value of each signal component and the pitch is within 0.1 m.

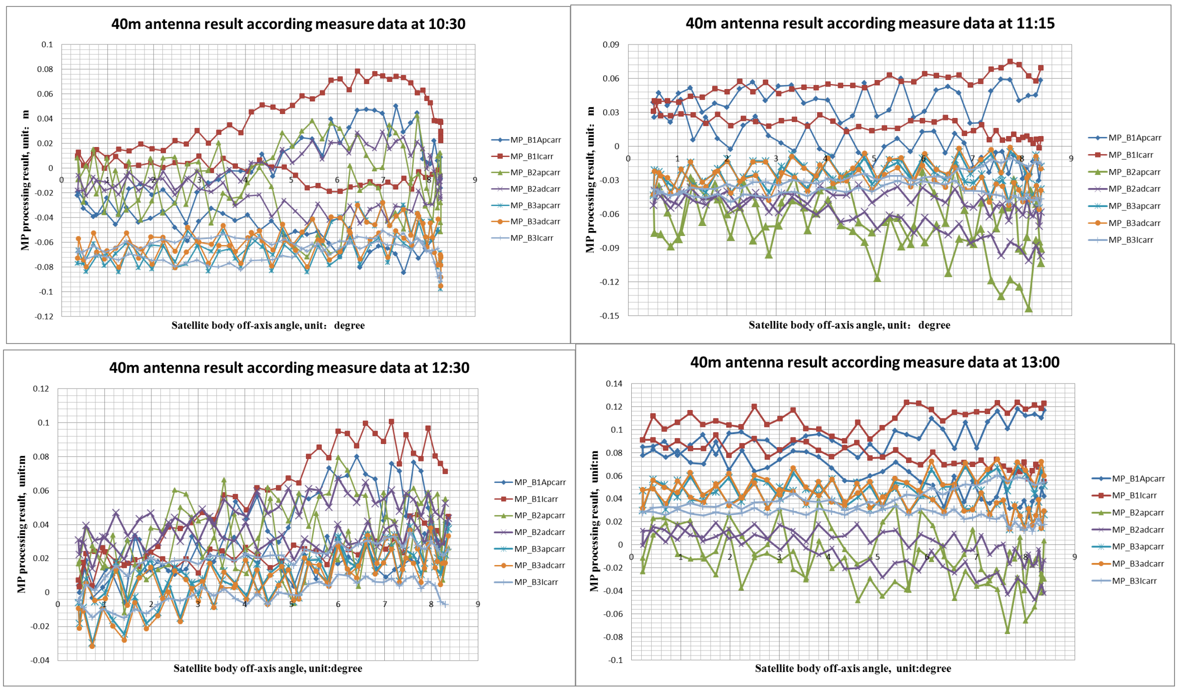


Figure 15 Relationship between MP of B1/B2/B3 signal and off-axis angle of satellite

The relationship of the MP value with the azimuth and the pitch of the satellite to the ground station is shown in figure 16.

It can be seen from the diagram that there are multiple MP values at the same azimuth and pitch angle, and the cross locus in the polar center is the most obvious, which indicates that the fluctuation of MP value is not entirely caused by multipath of the satellite body.

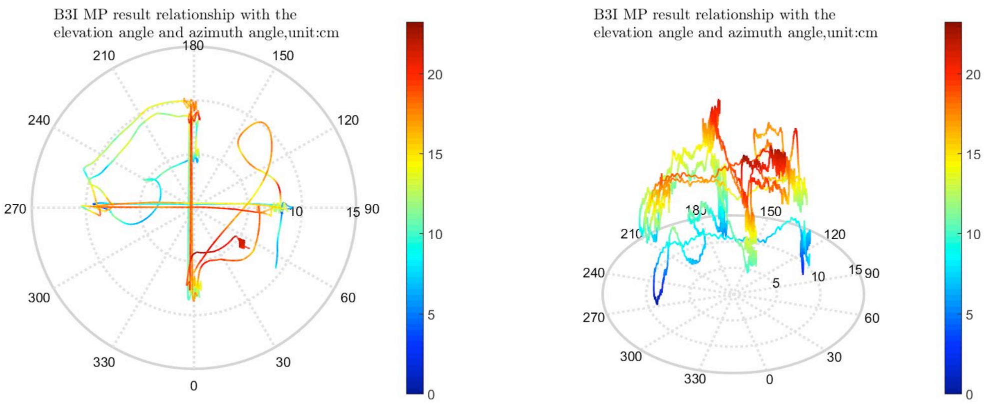


Figure 16 relationship of MP with the elevation and azimuth

Slow ergodic test

The angular velocity of satellite attitude maneuver is faster during the fast ergodic test, so in order to eliminate the measurement error caused by the narrow loop bandwidth of the monitoring receiver of the earth stations , a slow ergodic test of elevation angle was carried out.

In the slow ergocic test, the satellite controlled its pitch to NTSC at a lower angular velocity. Also taken the B3I data received by the NTSC as an example, the MP values obtained after data processing are shown in figure 17 with the change of the elevatio angle to the satellite.

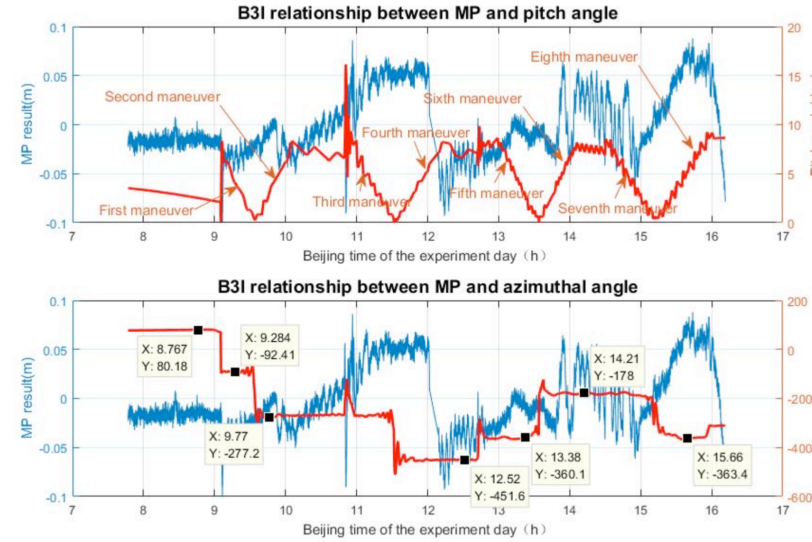


Figure 17. relationship of MP with the pitch and the azimuthal of B3I in slow ergodic test

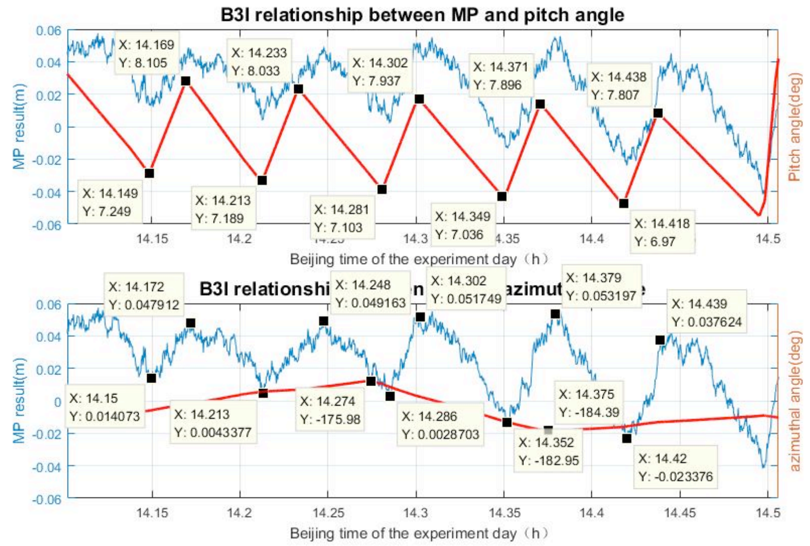


Figure 18. result of little attitude maneuver periodically in slow ergodic test

It can be seen from the diagram that during the four pitch traversing, there is no obvious rule that MP value changes with the pitch.

In the process of attitude adjustment, when the attitude has a fixed periodical fluctuation with small angle range and small change rate, the MP value has the fluctuation of the same fixed period with the maximum amplitude of 0.05m , as shown in figure 18, which seems to be related to the multipath on board.

However, during the slow attitude adjustment, the phenomenon disappears when the satellite adjusted its attitude at the same rate of attitude change with large angles.

We analyzed that the phase centers at different frequency points do not coincide. In the case of small angle fluctuation, when the error is within the wavelength range of the carrier , the corresponding variation law is presented. While in the large angle fluctuation, when the carrier wave length is crossed, the ambiguity occurs and the rule disappears.

The relationship of the MP value with the azimuth and the pitch of the satellite to the ground station are shown in figure 19. It can be seen from the diagram that during the slow traversal test, there are still many MP values at the same azimuth and pitch of the earth station relative to the satellite. So,the fluctuation of MP value is not only caused by the multipath environment of satellite, and the error of pseudorange introduced by satellite is less than 0.1 m (±0.05 m).

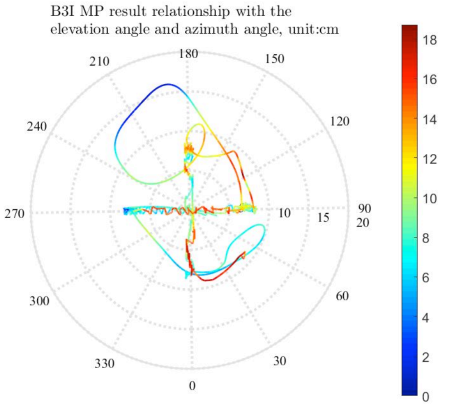


Figure 19 relationship of MP with the pitch and the azimuth in slow ergodic test

The result of slow ergodic test shows that the fluctuation of MP value still has no obvious correspondence with the observation elevation angle of the satellite to the ground station.

MP analysis of observation data of GPS

In order to verify the results of in orbit experiment with BeiDou satellite, the GPS satellite is observed and the MP value is compared and analyzed on August 26. During the verify test, we implemented a complete arc tracking to a GPS satellite SVN6 , and data processing shows that the SVN6 satellite also has the similar phenomenon of pseudorange fluctuation with elevation angle of the observation station. The range of pseudorange fluctuations in the visible arc of 7 hours is 0.2m~0.25m. The data processing results are shown below.

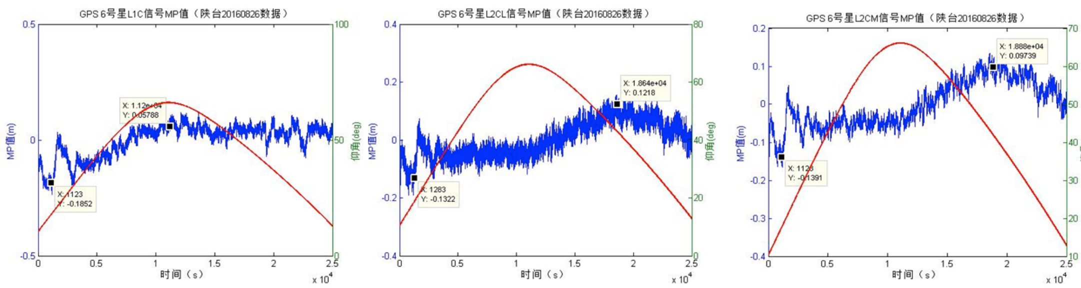


Figure 20. data processing of GPS satellite SVN6

CONCLUSION

By adjusting the satellite attitude several times orthogonally in a tracking arc, every satellite attitude adjustment is equivalent to a complete tracking process under the normal attitude of the satellite, and then we could observe the presence of colored noise components related to satellite elevation angle. During the in orbit test, fast attitude adjustment was used to reduce the possible influence of ionospheric time-varying, and slow attitude adjustment was used to reduce the processing error caused by the unsteady measurement loop of the receiver. In both experiments, there is no direct relationship between the colored component of the noise of ground measurement data and the elevation angle of the satellite observation.

According to the test results, amplitude of the MP fluctuation introduced by BeiDou test satellite of global system is less than 0.1 m, which is equivalent to the GPS satellites, and is a great improvement over the MEO satellite of BeiDou regional system. So, the pseudorange variation with the satellite elevation angle fluctuations is not caused by satellite only, and what causes the colored noises in the measured data is the focus of the further analysis.

ACKNOWLEDGMENTS

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