Analysis of Elevation-dependent Pseudo-range Variation Characteristics for GPS III New Signal in-orbit Testing Phase based on Measurements with a High Gain Antenna

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Abstract: With the launch of the first GPS III satellite on December 23, 2018，Global Positioning System(GPS) accomplished its third-step of modernization. This GPS III satellite is the very first GPS satellite with a new L1C civil signal broadcast. In this study, the characteristics of elevation-dependent pseudorange variation was investigated for the three civil signals in the L1(including L1C/A, L1CD, L1CP), L2 and L5 bands based on code and carrier phase measurements collected using monitoring receiver which is connected with 40-meters dish antenna. The analysis results show that there exist code biases in the GPS III signals and the biases are all nearly at a decimeter (dm) level. Furthermore, in order to compare with the old generation satellite, the multipath characteristics of BIIF-7 and BIIF-8 were discussed. The results show that elevation-dependent variations in code measurements of L1C/A, L2C, and L5 frequency bands still exist for BIIF-7 and BIIF-8 satellites. In the L5 band for GPS III, BIIF-7 and BIIF-8, the elevation-angle effect are readily more apparent on the measurements than that of other bands. Finally, the MP series changing regulation of GPS III signals is illustrated in details using the polynomial fitting curve.

Keywords: *GPS III, In-orbit testing phase,40 m high gain antenna, Pseudorange variation, Multipath*

Introduction

The space segment of GPS is composed of medium earth satellites of different generations. GPS constellation currently contains Block IIA, Block IIR, Block IIR-M, Block IIF. The frequency values broadcasting signals at band L1, L2 and L5 are 1575.42, 1227.6, 1176.45MHz, respectively. The GPS III system is more advanced than the current constellation. It will broadcast 4th civil signal on L1(L1C). It will provide enhanced signal reliability, accuracy, and integrity.

The first GPS III satellite was launched at the Kennedy Space Center successfully on December 23, 2018, Current Local Time in Canaveral Florida, USA. As a typical and developed satellite navigation system, especially with the first GPS III satellite launched, the characteristics of GPS get an increased public awareness and attention of the scientific community. Among these characteristics, multipath and measurement noise is the key to investigating ranging performance and positioning accuracy, because it is difficult to mitigate, e.g., by differencing technology. Moreover, severe multipath error will result in failure of signal's acquisition and tracking of GNSS receiver. The typical signal distortion due to multipath effect is the L1 signal anomaly of GPS satellite Space Vehicle Number 49(SVN-49), also known as Block IIR-20(M), which appear to be elevation-dependent and has kept the satellite from being declared healthy(S. Thoelert et al. 2009;Alexander et al. 2011).Worse yet, other Block IIR and IIR-M satellites also exhibit a similar, though much smaller anomaly(Tim Springer and Florian Dilssner 2009).

The following question naturally rises:"Does an elevation-dependent pseudo-range error also exist for GPSIII?"To answer this question, we processed the data from a high gain antenna located in Hao-Ping Radio Observatory(HRO) in Shangluo, Shaanxi, China. The paper is organized as follows. First, the models applied in the GPS III multipath are briefly presented. Then, the signal observation facilities and data for multipath analysis are introduced. The main body of the paper will be focused on multipath error of GPS III, compared with other old generation satellite, based on the observation models and measurements from HRO. Finally, some conclusions and suggestions are presented in summary.

Observation model

Code and carrier phase measurement in units of meters at frequency $L1$ can be modeled as follows respectively:

$$\rho_{L1} = R + c(\delta t_u - \delta t^s) + d_{orb} + I_{\rho L1} + T + b + B + MP_{\rho L1} + \varepsilon_{\rho L1} \quad (1)$$

$$\phi_{L1} = R + c(\delta t_u - \delta t^s) - \lambda_1 N_1 + d_{orb} - I_{\phi L1} + T + b + B + MP_{\phi L1} + \varepsilon_{\phi L1} \quad (2)$$

where ρ_{L1} represents a code measurement, R is the geometric distance between receiver and satellite, c is light speed, δt_u is users' receiver clock errors, δt^s is satellite clock errors, d_{orb} represents orbit errors, $I_{\rho L1}$ and T are ionosphere and troposphere errors respectively, satellite and receiver hardware- and software-induced delays are written as b and B , $MP_{\rho L1}$ is code multipath errors and $\varepsilon_{\rho L1}$ is code measurement noise in units of meters at frequency $L1$, $\lambda_1 N_1$ is ambiguity. The subscript ϕ corresponds to phase measurements. The carrier phase multipath $MP_{\phi L1}$ and measurements noise $\varepsilon_{\phi L1}$ are much smaller than those of code measurements and are neglected here. Troposphere, clock, orbit, satellite, receiver delay and relative effects is independent on frequency and these effects on code and carrier phase are the same. On the contrary, ionosphere refraction and multipath effect are relative with frequency. Except for multipath and measurement noise, all the other errors can be eliminated in code and carrier phase difference value (code minus carrier，CMC) based on code and carrier phase measurements observed by dual-frequency receiver(Rocken and Meerens,1992). Simsky (2006) and Wanninger et al.(2015)proposed an extended version in which multi-frequency combinations are applied in analysis . But, for the convenience of comparison with the SVN-49 multipath analyzed by Grace Xingxin Gao et al.(2010) , dual-frequency combinations are adopted in the following calculation and analysis.

Code multipath and measurement noise MP_{L1}, MP_{L2} and MP_{L5} at frequency $L1$, $L2$ and $L5$ can be calculated using the following equation(3), (4) and (5),respectively.

$$MP_{L1} = \rho_{L1} - \frac{f_{L1}^2 + f_{L2}^2}{f_{L1}^2 - f_{L2}^2}.(\phi_{L1}) + \frac{2f_{L2}^2}{f_{L1}^2 - f_{L2}^2}.(\phi_{L2}) + K_1 \quad (3)$$

$$MP_{L2} = \rho_{L2} - \frac{2f_{L1}^2}{f_{L1}^2 - f_{L2}^2}.(\phi_{L1}) + \frac{f_{L1}^2 + f_{L2}^2}{f_{L1}^2 - f_{L2}^2}.(\phi_{L2}) + K_2 \quad (4)$$

$$MP_{L5} = \rho_{L5} - \frac{2f_{L1}^2}{f_{L1}^2 - f_{L5}^2}.(\phi_{L1}) + \frac{f_{L1}^2 + f_{L5}^2}{f_{L1}^2 - f_{L5}^2}.(\phi_{L5}) + K_5 \quad (5)$$

where the unknown carrier phase ambiguities and measurements noise are attributed to K_1 , K_2 and K_5 .If there is no cycle slip in carrier phase data, K_1 , K_2 and K_5 are hypothetically constant. Therefore, the average can be obtained by multiple epoch in the entire data period and the sequence containing ambiguities parameters subtract this average. Then, the code multipath can be obtained and this code residuals is our main concern to detect the elevation-dependent pseudo-range characteristics in this research.

Observation data collection

GNSS signal-in-space quality assessment system built by the National Time Service Center of the Chinese Academy of Sciences is located in HRO ,which is in the Tsinling Mountains of Shaanxi Province, China. It can realize continuous monitoring of navigation signals in space of GNSS satellite navigation systems, and achieve precise and accurate performance evaluation of GNSS signal quality. In China, it is the first signal quality assessment system based on high gain and large aperture antennas and has played an significant role in the process of BeiDou Global Navigation System construction. The core facility of the assessment system is a 40-meter-diameter parabolic antenna with a main surface diameter of 40 meters, and a minor surface diameter of 4 meters. It works in the L-band (1.10-1.75 GHz) and has an antenna gain of 51.2 dBi@1.1 GHz. The tracking mode is a single-pulse self-tracking system, and receives a right-circularly-polarized navigation signal(see Fig.1).

The data acquisition mainly uses a multi-band multi-constellation GNSS monitoring receiver, which can receives GPS L1,L2 and L5 signals at the same time. Its Pre-correlation bandwidth is 20 MHz, chip spacing between correlators used for tracking is 1/4 chip for L1CA/L1CD BOC(1,1) /L2C/L5 and 1/6 for

L1CP TMBOC(6,1,4/33), data frequency is 1Hz and narrow correlation technique is used to mitigate multipath. Because of these characteristics of this system mentioned above, low-noise and low-multipath code and phase measurements can be obtained at HRO. It is noted that receiver connected with 40m antenna is only able to collect data sets sequentially for each satellite in view due to a narrow beam-width of 40 m antenna.

Fig.1 40-meters parabolic antenna appearance

Because of SVN49 satellite has been out of work, in order to verify elevation-dependent pseudo-range variation characteristics of this new GPS generation and compare resulting multipath errors with old satellites, the signals of BIIF-7 and BIIF-8 satellites, whose transmitted signals contain triple-frequency (L1/L2/L5) ,are observed and analyzed. Table 1 describes satellites observation time and elevation range observed by 40 m antenna at HRO to collect the observation data.

Table1 Satellites observation time and elevation range at HRO

Satellite name	PRN	Observation time（UTC）	Elevation range （degree）
GPSIII	**4**	2019.1.22 09:36~13:29	12~38~10
		2019.1.29 09:07~12:59	12~38~10
BIIF-7	**9**	2019.1.28 08:26~12:34	12~44~12
BIIF-8	**3**	2019.1.31 05:27~08:56	12~33~10

Data analysis and discussion

On Jan. 22, 2019, observables of a near full span of elevation for the very first GPSIII satellite collected by monitoring receiver at HRO were used to compute the multipath time series. Both code and carrier phase measurements with 1 s sampling interval were available at three frequencies. The multipath error for each frequency was calculated at each epoch using(3),(4)and(5) to detect the code-carrier divergence between pseudo-range and carrier phase measurements.

Shown in Fig.2 are the multipath time series with respect to elevation angles, of L1,L2 and L5 for GPSIII satellite. There is no obvious difference of multipath error; that is, it ranges from about -0.2 m to nearly 0.2 m for L1C（subdivided into L1CD and L1CP）and L2C（subdivided into L2CM and L2CL）signals，and±0.1 m for L1C/A and L5(subdivided into L5I and L5Q). It is noted that multipath error in each signal does not randomly vary with elevation，but appears to be a code bias correlated with the satellite elevation. The multipath error of L1C/A and L5 signals decrease along with the arise of elevation angel, and increase along with the elevation down. The multipath error trend almost appears to be V-shaped and an obvious negative elevation-dependent bias exists in the L1C/A and L5 measurements. Signals of L1CD and L1CP, which are the data and pilot component of GPSIII new L1C signal respectively, have a similar multipath trend: there is almost a slow monotonous increasing trend with the change of elevation. The L2 multipath curve appears to be a W-shaped trend and the center of the W shape almost corresponds to the highest point of elevation angel curve. The results were further verified by checking the data from another observation period in view on Jan. 29 at the same site, and the bias are similar and not shown here.

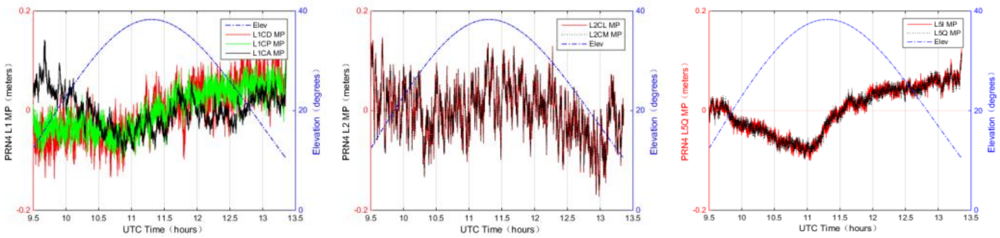

Fig.2 GPSIII multipath versus satellite elevation for L1(left), L2 (middle) and L5(right) (Monitoring receiver and 40-meters antenna at HRO, Jan. 22, 2019)

Elevation-dependent multipath verification compared with BIIF satellite

Grace Xingxin Gao et al.(2010) analyzed code-minus-carrier measurements, also named as multipath error and pseudo-range variations, for the L1 and L2 signals on BIIF-1(SVN-62) and BIIR-20(M)(SVN-49), using the same method and combination in this analysis. The code-minus-carrier (CMC) with ionosphere correction for BIIR-20(M) has a bias highly correlated with the satellite elevation. The bias of L1C/A has a relative shift of 1.5 meters from a low elevation of 15 °to a high elevation of 77 ° and L2CMC is about 0.4m in the opposite direction. No apparent elevation-dependent bias exists in either L1 or L2 measurements for BIIF-1.

In order to compare with the old generation satellite, the following analysis further discuss the multipath characteristics of BIIF-7 and BIIF-8, which broadcast the navigation signals in the L1, L2 and L5 bands.

Fig.3 shows the elevation-dependent multipath effects for all signals at three frequencies for BIIF-7 and BIIF-8. In the left column are BIIF-7 satellite results and there exists a similar bias at three frequencies, whose shape like an "M" along with elevation angel and especially in the L5 band is obviously clear. The pseudo-range variations magnitude of L1/L2/L5 is 0.1 m, 0.2 m and 0.2 m, respectively.

However, this regular pattern doesn't apply to the results of BIIF-8 satellite in the right column. Multipath error in the L1 band of BIIF-8 satellite over the full range of observation appears to be a downward trend. L2 multipath curve is much flatter in the first half span of elevation when it varies from a low elevation to the top， moreover the multipath error begin to fluctuate nearly at the highest elevation and there exists pseudo-range variations in a range of 0.4 m. A negative elevation-dependent bias is seen in the L5 band, which is V-shaped, and its magnitude is appropriately 0.3 m.

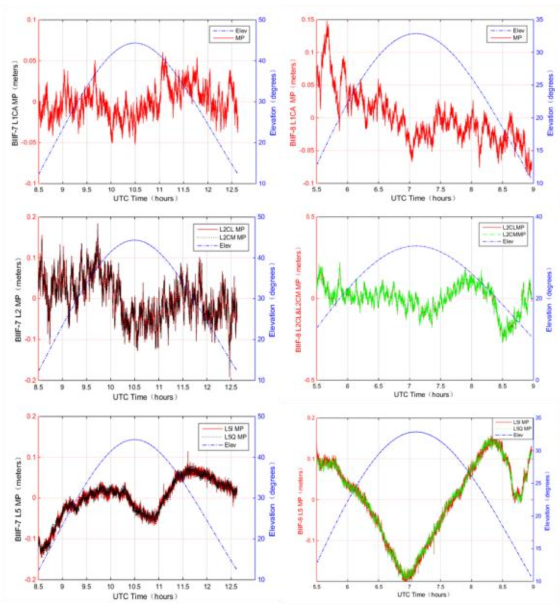

Fig.3 BIIF-7 (left column) and BIIF-8 (right column)multipath versus satellite elevation for L1 (top),L2(middle) andL5(bottom) (Monitoring receiver and 40-meters antenna at HRO, BIIF-7:Jan. 28, BIIF-8: Jan. 31,respectively)

Elevation-dependent multipath analysis in details

We further analyzed the change regulation of multipath curve with the elevation using the polynomial fitting curve based on observations of Jan. 22 and 29,2019, which were shown in Fig.4. The trend of Jan. 22 is comparable of that in Jan. 29.

Analysis of the MP series curve of the L1CA frequency on January 22 shows that when the satellite elevation angle rises from 19.85° to 37.64°, the corresponding MP value decreases from 0.04 m to -0.02 m. The MP curve is concave and the elevation angle corresponding to the lowest point -0.04 m is 37.14°. In the stage of the satellite elevation angle drop, the MP value shows a gentle change trend. In the entire observation period, MP value of the L1CA frequency varies by about 0.08 m.

The change trend of L1C frequency is completely different from that of L1CA. The MP value of L1C has no obvious bumps, and it shows an upward trend in the whole observation period. Taking L1CD on January 22 as an example, when the satellite elevation angle rises from 33.01° to the highest point and drops to 25.23°,the MP value increases faster, which increases from -0.05 m to 0.04 m. The trend of the two components of L1CD and L1CP is similar. In the entire observation period, MP value of the L1C frequency varies by about 0.09 m.

The MP change trend of the L2C frequency shows a "W" shape. Taking the L2CL on January 22 as an example, in the rising stage of the elevation angle, the MP value drops from 0.05 m to -0.01 m and then rises to 0.03 m, corresponding to the elevation angle of 12.6°,30.19° and 36.36°,respectively. In the descending stage of the elevation angle, the MP value decreases from 0.03 m to -0.06 m and then rises to -0.004 m, corresponding to the elevation angles of 36.36°,16.79° and 10.59°. The trend of the two components of L2CL and L2CM is similar. In the entire observation period, MP value of the L2C frequency varies by about 0.11 m.

The MP change trend of the L5 frequency shows a "V" shape. Taking the L5I on January 22 as an example, the MP value decreases from 0.004 meters to -0.067 m and then rises to 0.049 m, corresponding to an elevation angle rising from

16.95° to 34.6 ° and then falling to 23.13° . In the entire observation period, MP value of the L5 frequency varies by about 0.12 m.

Table 2 lists the elevation angle at which the MP is lowest of all GPSIII signals. In the stage of elevation rises, there exist the lowest MP value in signal components of L1CA, L1C, L2, L5. Wherever, MP time series of L2C signal has the lowest value when the elevation is dropping.

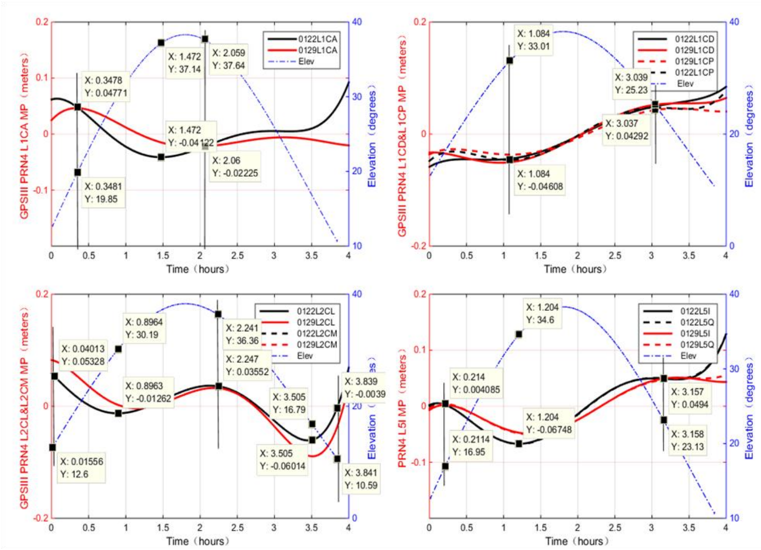

Fig.4 GPSIII multipath using the method of polynomial fitting versus satellite elevation for L1C/A (top and left), L1C(top and right),L2(bottom and left) and L5(bottom and right) (Monitoring receiver and 40-meters antenna at HRO)(Jan. 22 and 29,2019)

Table2 GPSIII satellite MP series change regulation

Signal component	The elevation angle at which the MP is lowest		Remarks
	Stage of elevation rises	Stage of elevation drops	
L1CA	37.14°	---	The highest elevation is 38°
L1CD/L1CP	33.01°	---	
L2CM/L2CL	30.19°	16.79°	
L5I/L5Q	34.6°	---	

Summary and conclusions

Based on observations collected by 40-meters dish antenna at HRO, the MP time and elevation series analysis of all signal components of GPSIII were carefully investigated. With substantial signal design and navigation unit assembly improvements, pseudo-range variation of the first new civil signal L1C for GPSIII is flatter than those of the other band. However, in the L5 band for GPSIII, BIIF-7 and BIIF-8, the elevation-angle effect were readily more apparent on the measurements than that of other bands. This is may be caused by a L1 signal reflection on the L5 payload via the auxiliary antenna where the L5 payload is connected, which is the reason of GPS SVN49-L1 anomaly.

It is important to note that the lowest MP value in all signal components of GPSIII do not correspond to the highest point of elevation. The lowest point of the other signals all appear when the elevation is rising and it is nearly up to the highest angle, except for L2C signal whose MP curve has two bottoms which happen in the stage of elevation rises and drops, respectively. The reason about this phenomenon remains unclear for GPSIII signals in-orbit testing phase.

Although the pseudo-range variations in the L1,L2 and L5 band all nearly at a decimeter (dm) level, which was dramatically reduced with respect to those of the BIIR-20(M), there exist code bias in the GPSIII signals. Whether this magnitude of about 0.2 m would affect high-precision positioning applications still needs to be investigated further in the future when the GPSIII signals are formally put into use and participate in locating calculation.

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