Research on multipath suppression performance of multiple BOC signals of navigation satellite

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Abstract. BOC (Binary Offset Carrier) signal is a kind of navigation satellite downlink signal. Compared with BPSK (Binary Phase Shift Keying) modulation signal, it can improve the multipath suppression performance of navigation system. BOC signal modulation includes a variety of extended signal modulation modes, including TMBOC (time-multiplexed BOC), AltBOC (Alternative BOC) signals, etc. It is an important subject to study the performance of multipath suppression of various BOC signals. In this paper, the multipath error model is constructed by using the noncoherent early-late processing track loop, the performance of multipath suppression of TD-AltBOC (Time Division Alternative BOC) and AltBOC signals for different front-end bandwidth of the receiver is analyzed. By studying the average multipath error and envelope value of AltBOC (15,10), BOC (1,1) and TMBOC (6,1,4/33) signals, the performance comparison results of three kinds of BOC modulation are given. In order to verify the research results of multipath suppression performance, the receiver is used to receive the signals of different BOC modulation systems transmitted by navigation satellite, the multipath error is obtained by the combination of dual frequency pseudo range and carrier phase. The experimental results show that AltBOC (15,10) has the best multi-path suppression performance, followed by TMBOC (6,1,4/33), and BOC (1,1) has the worst multi-path suppression performance compared with the others, which proves the correctness of the research results of multi-path suppression performance of various BOC signals.

1. Introduction

With the development of navigation satellite system, the navigation and positioning technology become more and more significant in national economy development and national defence day by day, and various powerful countries have engaged in the development of their own navigation satellite system. At present, there are four main established/establishing navigation satellite system: GPS (Global Positioning System), GLONASS (Global Navigation Satellite System), Galileo (Galileo Positioning System) and BDS (Beidou navigation satellite system). The more wide-spread of the navigation and positioning application, the higher requirement of its positioning accuracy, anti-interference performance and multipath mitigation capability. With the increasing of satellite number in space, the navigation frequency is more and more crowd. Using the traditional BPSK-R modulation method to improve navigation performance costs too much. Therefore, seeking a new signal modulation method may be the best way to solve the problem. BOC is a new kind of modulation method as the development of navigation technology, whose definition was first introduced in GPS modernization reformation. It was initially suggested to be the modulation method for GPS military
signal, but now it has been widely applied in modern GPS civil signal design[1]. In 2001, CNES(Centre National d’Etudes Spatiales) proposed AltBOC modulation method with four pseudocode constant-envelope, which was adopted by Galileo E5a and E5b[2].

During the establishment of Beidou global navigation satellite system, the selection of BOC is conducted as an important job. Since 2009, a plentiful of domestic scientific agencies have worked over BOC for Beidou global signal system. Tang zuping promoted TD-AltBOC modulation method, which was a time-division AltBOC modulation technology to alternately propagate 4 signal components in two time slot and each time slot propagated tow constant-envelope AltBOC signals[3]. Though this method could avoid patent issue, it also brings other problems. As indicated in reference [4], this method may reduce the affective length of the pseudocode and weaken cross-correlation between different pseudocodes. What’s more, in order to proceed time-division signal, it would force receivers to change correlator structure and add time slot switching circuit. To solve the above AltBOC shortcoming, Yao Zheng promoted ACED(Asymmetric Constant Envelope Double-sideband) multiplexing technology to improve AltBOC, increase signal power in pilot component and keep the current receiver status with good interoperability[5].

Hence, the current research in Beidou BOC modulation method is focused on compatibility, interoperability, receiver’s complexity and signal multiplexing method and efficiency, and the capability of mitigating multipath is rarely lucubrated. This paper engaged in the capability of mitigating multipath for BOC modulation signal and analyzed with simulation and actual data in Beidou navigation satellite system.

2. Multipath Error Characteristic of Beidou navigation satellite System

Multipath means the receiving of unexpected signal after being reflected and scattered. As the difference of the propagation path, there are relative phase, relative delay and scope characteristic between direct signal and reflected and scattered signal, which result in the receiving loop signal distortion and zero crossing point excursion of correlate peak discriminating curve, affecting the measurement accuracy. Normally, multipath signal is supposed to be caused by reflect and the dispersion signal model is conducted as a noise term, which has little effect to code tracking.

In Beidou regional system, there are 5 GEO(Geosynchronous Earth Orbit) satellites to cover the most area of China. According to the research of satellite based augmentation system abroad, there was “inherent multipath error” in GEO pseudorange measurement, meaning GEO trajectory characteristic had remarkable affection to pseudorange multipath error. The moving trajectory satellite, such as IGSO(Inclined GeoSynchronous Orbit) and MEO(Medium Earth Orbit), does not have obvious and inherent multipath error and their multipath error may only increase for low observation elevation during inbound and outbound[6].

According the current Beidou global blueprint, the Beidou global satellites will all be moving trajectory satellites, which composes of IGSO and MEO, and trajectory characteristic will not be the major factor to pseudorange multipath as the signal modulation structure is the major factor. During the experiment segment of Beidou global system construction, downlink signal system will be one of the key chain-link. In order to realize compatibility and interoperability with GPS and Galileo, in Beidou navigation satellite system, TMBOC, AltBOC and TD-AltBOC had been chosen. Therefore, the research of the three modulation methods for pseudorange multipath is an urgent and essential work.

3. Simulation and Analysis on Multipath-mitigating Capability of BOC Singal

3.1. Model Choosing and Estimating Criterion of Multipath Mitigation

As mentioned in chapter 2, the major factor affecting user positioning accuracy is reflected signal. The multipath mathematical model is normally expressed as:

\[ r(t) = D(t) \cdot C(t) \cdot \sin(\omega_0 t) + \sum_{i=0}^{N-1} \alpha_i \cdot D(t) \cdot C(t + \delta_i) \cdot \sin(\omega_0 t + \theta_i) \]  

(1)
Where $D(t)$ is base-band modulation signal, $C(t)$ is satellite spreading code, $\sin(\alpha_\ell t)$ is the intermediate frequency after down-conversion, $\alpha_\ell$ is multipath signal gain compared to direct signal. Usually, the amplitude of multipath signal is less than the direct signal. Hence, $\alpha_\ell < 1$. $\delta_\ell$ is the phase delay of spreading code, $\theta_\ell$ is the effect of multipath to carrier phase. The multipath signal in base-band of receiver is equivalent discribed as following.

\[
r(t) = \alpha_0 e^{j\phi_0} x(t - \tau_0) + \sum_{n=1}^{N} \alpha_n e^{j\phi_n} x(t - \tau_n)
\]

(2)

Where $\alpha_0$ is amplitude of direct signal, $\phi_0$ is the phase of direct signal, $x(t)$ is the complexing envelope of receiving signal, $\tau_0$ is the propagation delay of direct signal, $N$ is the path number of reflecting multipath singals; $\alpha_n$, $\phi_n$ and $\tau_n$ repectely mean the amplitude, phase and propagation delay of reflected multipath signal.

The receiving of the reflected multipath signal leads the balance point offseting the zero point of receiver discriminating curve and produces pseudorange tracking deviation which means pseudorange multipath error. Therefore, the multipath error analysis should be engaged on the ouput function of discriminator. In order to realise convenient analysis and possessing generality, the analysis model with single reflected path is widely applied during the design of navigation signal. Under the condition of one reflected path considered, the envelope model of multipath error for loop discriminator is established. Then, the non-coherent early-late processing track loop is chosen, whose loop discriminator is shown as following.

\[
D(\varepsilon_\ell) = \alpha_0 \left[ R \left( \varepsilon_\ell - \frac{d}{2} \right) - R \left( \varepsilon_\ell + \frac{d}{2} \right) \right] + \alpha_1 \left[ R \left( \varepsilon_\ell - \tau - \frac{d}{2} \right) - R \left( \varepsilon_\ell + \tau + \frac{d}{2} \right) \right]
\]

(3)

Where, $R(\tau)$ is the correlation function, $\varepsilon_\ell$ is delay error estimation of direct signal, $\tau$ is multipath delay, and $d$ is the interval of early-late correlator.

The answer of the equation which makes the $D(\varepsilon_\ell) = 0$ is the multipath error. With the signal bandwidth being considered, the final output of multipath error is described as following.

\[
\varepsilon = \frac{\pm \alpha_1^{\beta_0/2} \sin(2\pi f \tau) \sin(\pi f d) df}{2\pi \alpha_1^{\beta_0/2} \int_{-\beta_0/2}^{\beta_0/2} \left| S(f) \sin(\pi f d) \right| [1 \pm \alpha \cos(2\pi f \tau)] df}
\]

(4)

Where, $\alpha = \alpha_1/\alpha_0$ is MDR, meaning the signal amplitude rate of multipath signal and direct signal, $\beta_0$ is signal bandwidth, $d$ is the interval of early-late correlator, and $\tau$ is multipath delay. When the phase difference between multipath signal and direct signal is 0°, + is selected in above equation; when the phase difference between multipath signal and direct signal is 180°, - is selected in above equation, which means minimum and maximum influence to multipath signal respectively. Hence, the above equation shows the envelope of multipath error. Besides, the average of the multipath error can be obtained with the following equation.

\[
\varepsilon(\tau_1) = \frac{1}{\tau_1} \int_0^{\tau_1} \left| \frac{\left| \varepsilon(\tau) \right|_{\tau=0} + \left| \varepsilon(\tau) \right|_{\tau=180}}{2} \right| d\tau
\]

(5)

Where $\vartheta$ is relative phase of multipath signal, respectively corresponding with the + and – condition. When the multipath delay $\tau 1$ is known, the average of the multipath error can be obtained.

TD-AltBOC(15,10) is one of the modulation methods used in Beidou navigation satellite system, whose power spectrum density can be described as following.

\[
G_{TD-AltBOC} = \frac{10.23}{\pi^2 f^2} \cos^2 \left( \frac{\pi f}{6 \times 10.23} \right) \left( \sin^2 \left( \frac{\pi f}{10.23} \right) - 2 \cos \left( \frac{\pi f}{3 \times 10.23} \right) \right)
\]

(6)
AltBOC(15,10) is another modulation method used in Beidou navigation satellite system, whose power spectrum density can be described as following.

\[
G_{\text{AltBOC}}(f) = \frac{4 \times 10^{2.3}}{\pi f^2} \cos^2 \left( \frac{\pi f}{10^{2.3}} \right) \left\{ \cos^2 \left( \frac{\pi f}{2 \times 10^{2.3}} \right) - \cos \left( \frac{\pi f}{2 \times 10^{2.3}} \right) \right\} \\
2 \cos \left( \frac{\pi f}{2 \times 10^{2.3}} \right) \cos \left( \frac{\pi f}{4 \times 10^{2.3}} + 2 \right)
\]

Putting equation (6) and (7) into (4) and (5) respectively, the multipath error envelope and its mean value can be gained with two different BOC modulation methods.

3.2. Capability Comparison of Mitigating Multipath between AltBOC and TD-AltBOC modulation method

Set MDR= -6 dB, \( d = 24.4 \text{ ns} \), and the frontend signal bandwidth \( \beta_r = 30 \text{MHz} \). According to equation (4), the multipath error envelope with TD-AltBOC and AltBOC modulation method can be gained and the comparison result can be seen in figure 1. According to equation (5), the mean value of multipath error with TD-AltBOC and AltBOC modulation method can be gained and the comparison result can be seen in figure 2.

![Figure 1. AltBOC and TD-AltBOC multipath error envelope comparison (frontend bandwidth 30MHz)](image1)

![Figure 2. AltBOC and TD-AltBOC mean multipath error comparison (frontend bandwidth 30MHz)](image2)

It can be seen that the capability of mitigating multipath with AltBOC and TD-AltBOC was approximate when the front bandwidth of receiver was 30MHz.

Keep other parameters unchanged and increases the signal bandwidth to 40MHz, the multipath error envelope could be seen in figure 3 with mean value showed in figure 4. Seen from the figure 3 and 4, the capability of mitigating multipath of TD-AltBOC was better than AltBOC.
In conclusion, the front bandwidth of receiver could affect the capability of mitigating multipath with two modulation methods. Under the condition of larger front bandwidth, the capability of mitigating multipath with TD-AltBOC was superior to AltBOC.

3.3. Capability Comparison of Mitigating Multipath with BOC Modulation Method

For Beidou navigation satellite system, data component BOC (1,1) and pilot component TMBOC (6,1,4/33) are combined with MOC (6,1,4/33), realizing the compatibility and interoperability with GPS L1. The power spectrum density of the pilot component is shown as equation (8).

$$G_f(f) = \frac{29}{33} G_{BOC(1,1)}(f) + \frac{4}{33} G_{BOC(6,1)}(f)$$  \hspace{1cm} \text{(8)}$$

The power spectrum density with BOC (1,1) and BOC (6,1) are shown as equation (9) and (10).

$$G_{BOC(1,1)} = 1.023 \times \left[ \tan(\frac{\pi f}{2 \times 1.023}) \sin(\frac{\pi f}{1.023}) \right]^2$$  \hspace{1cm} \text{(9)}$$

$$G_{BOC(6,1)} = 1.023 \times \left[ \tan(\frac{\pi f}{2 \times 6 \times 1.023}) \sin(\frac{\pi f}{1.023}) \right]^2$$  \hspace{1cm} \text{(10)}$$

Putting the equation (9) and (10) into (8), the power spectrum density of pilot component can be gained and shown as equation (11).

$$G_f(f) = \frac{\sin(\frac{\pi f}{1.023})}{(\pi f)^3} \left[ \frac{29 \times 1.023}{33} \tan(\frac{\pi f}{2 \times 1.023}) + \frac{4 \times 1.023}{33} \tan(\frac{\pi f}{2 \times 6 \times 1.023}) \right]$$  \hspace{1cm} \text{(11)}$$

The power spectrum density of data component is shown in equation (9). Putting the equation (11) and (9) into (4) and (5) respectively, the multipath error envelope and its average value can be obtained in data component and pilot component.

Set MDR = -6 dB, d = 24.4 ns, and the signal bandwidth $\beta_r = 40$ MHz. The figure 5 showed the comparison result of pseudorange multipath error envelope with AltBOC (15,10), BOC (1,1) and TMBOC (6,1,4/33). According to equation (5), the mean value of multipath error with AltBOC (15,10), BOC (1,1) and TMBOC (6,1,4/33) could be gained. The comparison result was shown in figure 6.
Figure 5. multipath error envelop comparison of three BOC signals (frontend bandwidth 40 MHz)

Figure 6. mean multipath error comparison of three BOC signals (frontend bandwidth 40 MHz)

In conclusion, when the delay of multipath signal was small, the average of multipath error with three modulation methods was rather approach; when the delay of multipath signal was large enough, the average of multipath error with AltBOC (15,10) was lower than MBOC (6,1,4/33) and the average value with BOC (1,1) was largest.

4. Analysis of Test Data

The RMS(Root Mean Square) of pseudorange multipath error was gained as receivers in two ground monitoring stations received down-link signal of Beidou global system and proceeded pseudorange measurement when satellites could be observed within 24hours. The result of pseudorange multipath error in BOC (1,1) and TMBOC(6,1,4/33) was obtained with two ground station observing two satellites S1 and S2.

The RMS statistics results of the two satellites was shown in Table 1.

Table 1. Multipath error statistics results of two monitoring stations

| Satellite | Monitoring station | TMBOC | BOC | AltBOC |
|-----------|-------------------|-------|-----|--------|
| S1        | Sta1              | 0.187 | 0.243 | 0.123  |
|           | Sta2              | 0.335 | 0.408 | 0.156  |
| S2        | Sta1              | 0.186 | 0.214 | 0.118  |
|           | Sta2              | 0.171 | 0.215 | 0.095  |

Seen from the Table 1, the statistics results of pseudorange multipath error were consistent with the simulation results in chapter 3 as the comparison result is AltBOC> TMBOC>BOC.

5. Conclusion

Global navigation satellite system adopts various BOC modulation signals. Based on noncoherent early-late processing track loop, the paper simulated the capability of mitigating multipath with TD-AltBOC and AltBOC modulation methods under different front bandwidth conditions, compared the capability of AltBOC and TMBOC under the same front bandwidth, and analyzed pseudorange measurements with two ground monitoring stations observing two Beidou global satellites, calculating the RMS of the pseudorange multipath error. The simulation results showed: when the front bandwidth was 30MHz, the capability of pseudorange multipath error with TD-AltBOC (15,10) and AltBOC (15,10) was similar; when the front bandwidth was 40MHz, the capability of pseudorange multipath error with TD-AltBOC (15,10) was better than AltBOC(15,10); The capability of pseudorange multipath error with AltBOC(15,10) is superior to TMBOC(6,1,4/33) and the capability of TMBOC(6,1,4/33) is better than BOC(1,1). The analysis results with actual data was consistent with the simulation results.
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