Journal of Southeast University (English Edition) Vol. 24, No. 2, pp. 197 - 200 June 2008 ISSN 1003—7985

Multipath mitigation method for tracking Galileo signals

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Abstract: In order to improve the performance of multipath mitigation in tracking Galileo signals, a new multipath mitigation method named early-late strobe correlator (ELSC) is proposed. By applying the strobe correlator used widely in global positioning system (GPS) scenarios to Galileo E1 signals, it can be found that the strobe correlator has an undesirable level of performance when the delay of multipath signals is about 0.5 chip. Combining several strobe correlators, the ELSC can effectively mitigate the multipath effect especially for the multipath signals with the 0.5 chip delay. The multipath error envelopes between the strobe correlator and the ELSC are compared for Galileo E1 signals. The simulation results indicate that the ELSC performs excellently on multipath mitigation, and can be applied in both Galileo scenarios and GPS scenarios.

Key words: Galileo signal; global positioning system (GPS); multipath; delay-locked loop; strobe correlators

GPS is the best-known satellite navigation system in the world. Besides GPS, a Russian system, GLONASS, is in operation, and a European system, Galileo, is in its construction phase. The second Galileo satellite has been launched in April, 2008. The whole Galileo system should start regular operation in 2012. Many studies on tracking Galileo signals have been done, of which the study on multipath mitigation is an important part. A conventional method to mitigate multipath errors in GNSS receivers is the strobe correlator, which achieves discriminator function shaping by combining two different narrow correlator discriminators[1-2].

Similar to the GPS receiver, by tracking the satellite code signals and decoding them into ranges from the satellites to the receiver, the Galileo receiver can compute the position coordinates of the user by observing more than four satellites at the same time. But there are various sources of errors corrupting the code measurements. Among them, multipath propagation is a major source of degradation in the performance of so-called pseudorandom noise (PN) code tracking loops. The mean-square tracking error of a conventional delay-locked loop (DLL) exhibits an irreducible floor due to the presence of closely spaced multipath components[3].

In this paper, it is first introduced how multipath signals distort the autocorrelation function (ACF) of the PN code and induce a nonnegligible tracking error in DLL. To highlight the emphasis of this paper, only the single-reflected-path case is taken into account, while the multiple-reflected-path case can be easily deduced. Owing to different signal modulation techniques, the GPS and Galileo codes present different autocorrelation functions. Unlike the GPS signals adopting the binary phase-shift keying (BPSK) modulation scheme, Galileo signals are modulated using the binary offset carrier (BOC), AltBOC and BPSK techniques[2]. BOC modulation is a distinct characteristic of Galileo which is different from GPS, so, for Galileo, only the E1 signals applying BOC(1, 1) modulation are discussed in this paper. The multiple peak nature of the BOC autocorrelation function allows for lower tracking ambiguity and better performance under thermal noise; but this will result in a more complicated tracking process for BOC modulated signals[1,4]. Then this paper discusses the performance of the strobe correlator used in Galileo scenarios. Finally, the ELSC scheme is presented for Galileo signals.

1 Generation of Multipath

In Galileo, multipath signals can distort the ACF of the PN code and induce a nonnegligible tracking error in DLL[3]. Multipath refers to the phenomenon of a signal reaching an antenna via two or more paths[5]. Typically, an antenna receives the direct line-of-sight (LOS) signal and one or more of its reflections from structures in the vicinity and from the ground (see Fig. 1). The reflected signals are the delayed and usually weaker versions of the direct signal. The subsequent code measurements are for the sum of the received signals. So, the code measurement in Galileo positioning is affected by multipath[4].

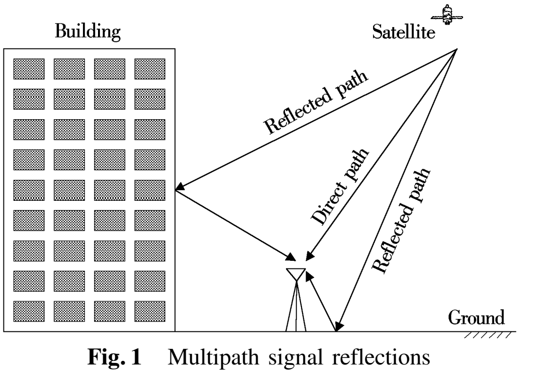

Fig. 1 Multipath signal reflections

To highlight the emphasis of this paper, without considering the carrier wipe off, the baseband-equivalent received signals of Galileo are directly analyzed. Under the multipath environment, Galileo baseband signals can be expressed as

$$C_r(t) = \sum_{i=0}^{k} a_i A c(t - \tau_i) \tag{1}$$

where $c(t)$ is the PRN code of Galileo systems; A is the signal amplitude; a_0 and τ_0 represent the coefficient and delay of the LOS signal, respectively; a_i and $\tau_i (1 \leqslant i \leqslant k)$ are the coefficient and delay of the reflected signals, respectively; and k is the number of the reflected signals. Generally,

Received 2007-10-19.

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Foundation item: The National Key Technology R&D Program of China during the 11th Five-Year Plan Period (No. 2008BAJ11B05).

Citation: Zhao Yi, Wang Qing, Zeng Qingxi. Multipath mitigation method for tracking Galileo signals[J]. Journal of Southeast University (English Edition), 2008, 24(2): 197 - 200.

$m_0 = 1$ and $a_i < a_0 (1 \leqslant i \leqslant k)$. Obviously, when $k = 0$, Eq. (1) expresses the case without the reflected signal. If $k = 1$, the typical single-reflected-signal case is expressed. For simplicity of analysis, this paper only takes the single-reflected-path case into account, while the multiple-reflected-path case can be easily deduced. Then Eq. (1) can be rewritten as

$$C_r(t) = Ac(t - \tau_0) + a_1 Ac(t - \tau_1) \qquad (2)$$

2 Code Tracking to Galileo Signals

The Galileo user segment consists of Galileo receivers, which are used to determine the user position, velocity, and precise time from the satellite signals. As the satellites are always in motion, the receiver has to continuously track the satellite signals to generate an uninterrupted solution, as desired in most applications. The code and carrier tracking loops in a receiver form the core of the signal processing and they continuously track the incoming satellite signals to generate pseudorange and carrier phase measurements[6].

To measure the code phase, the delay lock loop places one correlator on the leading edge of the correlation peak, and the other is placed on the falling edge. The correlators are called the early and late correlators, respectively. They are complex correlators. The real part is the inphase sample and the imaginary part is the quadrature sample. The outputs from these correlators are processed by a discriminator function. The discriminator forms a sensible output despite certain nuisance parameters that are also presented. For the DLL, these nuisance parameters are the unknown carrier phases and navigation data bits[7–9].

The delay lock loop operates on a baseband signal and strives to null the difference between the outputs of the early and late correlators. Without the underlying carrier signal, this baseband correlator has no need to use complex correlators. It only needs the real correlators, and the quadrature correlators are not needed. Even with the carrier, such an approach is feasible if the carrier phase and data bit are well known. Such a delay lock loop is called a coherent DLL, because the receiver's replica of the carrier is assumed to be coherent with the received carrier. In order to pay attention to the DLL, only the coherent DLL is discussed in this paper.

3 Influence of Multipath on DLL

As shown in Fig. 1, multipath arises when multiple paths exist from the satellite to the user antenna. The primary path is usually a direct, unobstructed path from the satellite to the antenna, and the secondary paths usually include a reflection off a nearby object or the ground. These reflections confound the receiver by distorting the correlation peak. After all, previous analysis has assumed that this peak is a pristine triangle. If additional signals arrive, they will contribute secondary peaks and early and late correlator samples may not be centered on the true arrival time of the direct ray. The Galileo coherent DLL discriminator output as a function of a path delay τ can be expressed as

$$D(\tau) = \sqrt{\frac{A}{2}} \left[R_C\left(\tau + \frac{\tau_d}{2}\right) - R_C\left(\tau - \frac{\tau_d}{2}\right) \right] \qquad (3)$$

where $R_C(\cdot)$ is the correlation function of the positioning code $c(t)$; τ_d is early-late spacing for DLL. Fig. 2 shows the Galileo discriminator function values due to a single reflected signal for a coherent discriminator using a standard correlator with early-late correlator spacing of one chip. The reflected signal is in-phase with the direct signal, and arrives quarter a chip delayed with respect to the direct signal. The discriminator values are plotted against the code tracking error. A line-type scheme is used to discriminate different "S" curves. The dashed curve corresponds to the "S" curve due to direct signal and the dot curve corresponds to the "S" curve due to reflected signal. The amplitude of the reflected signal is half of the amplitude of the directed signal. The solid curve is the resultant of the composite between the direct signal and the reflected signal. If the received signal contains only the direct signal, then the code tracking loop tracks the zero crossing of the dashed curve, which corresponds to zero tracking error. However, due to the presence of the reflected signal, the code tracking loop tracks the zero crossing of the solid curve. The intersecting point of the solid "S" curve on the X-axis within the sensitivity region moves toward the positive direction of the X-axis with respect to the intersecting point of the dashed "S" curve on the X-axis, which results in approximate 0.1 chip tracking error.

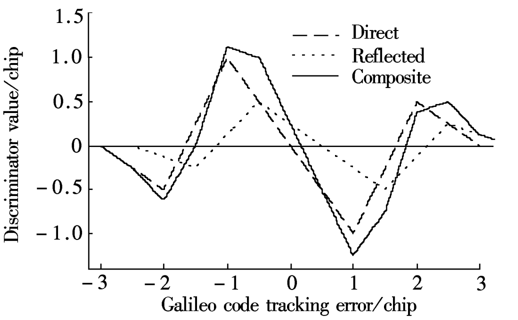

Fig. 2 Galileo DLL discriminator response using correlator spacing of 1 chip

If the reflected signal has a 180° phase offset with respect to the direct signal with other conditions being the same, the intersecting point of the solid "S" curve on the X-axis within the sensitivity region moves toward a negative direction of the X-axis with respect to the intersecting point of the dashed "S" curve on the X-axis, which results in an approximate −0.1 chip tracking error. When the phase differences between the direct and reflected signals lie between 0 and 180°, the corresponding tracking error also lies between −0.1 and 0.1 chip.

4 Mitigation of Multipath on DLL Using Strobe Correlator

The strobe correlator achieves discriminator function shaping by combining two different narrow correlator discriminators[10]. The final discriminator function is achieved as

$$D_C = (\tau_{d2}/\tau_{d1}) D_1 - D_2 \qquad (4)$$

where D_C is the final or composite discriminator function; D_1 is the discriminator function associated with narrow correlator 1; D_2 is the discriminator function associated with narrow correlator 2; τ_{d1} is the early-to-late spacing for narrow correlator 1; τ_{d2} is the early-to-late spacing for narrow correlator 2.

For example, consider the case where $\tau_{d1}=0.1$ chip and $\tau_{d2}=0.2$ chip. The strobe correlator employs two correlators in parallel to provide multipath mitigation for Galileo signals. The narrow correlator 1 generally has a chip spacing of ± 0.1 chip; the wide correlator 2, therefore, has a chip spacing of ± 0.2 chip. Code discriminators are generated by sliding a pair of correlators along the autocorrelation function and plotting the early minus late values. The "narrow" chip spacing correlator is made up of an early prompt, E1, and a late prompt, L1. The "wide" chip spacing correlator is made of an early prompt, E2, and a late prompt, L2. The discriminator function is a linear combination of the two early-late discriminators.

The two discriminator functions for Galileo are plotted in Fig. 3. The dot curve presents the output of correlator 2, and the solid curve presents the output of correlator 1. The final discriminator output is the linear combination of the output from correlator 1 and correlator 2. In order to compare the performances of the strobe correlators for Galileo and GPS respectively, the case of strobe correlators used in GPS is also presented in Fig. 3. Obviously, multipath signals with chip delays between ± 0.1 and ± 0.9 and with chip delays greater than ± 1.1 will not have any effect on the tracking error and hence these multipath signals can be rejected in GPS scenarios. Nevertheless, the results for Galileo scenarios are not so ideal. Multipath signals with about a 0.5 chip delay will not have a great effect on the tracking error in a Galileo correlator.

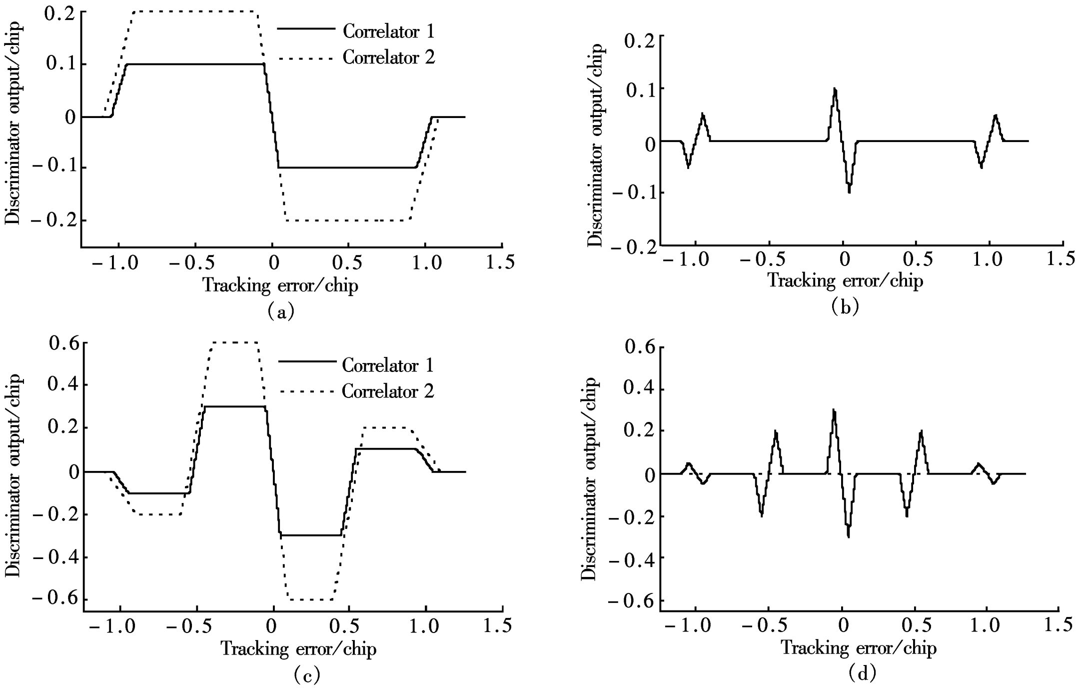

Fig. 3 Comparisons of outputs generated by using different discriminators for GPS and Galileo. (a) The output of narrow correlator discriminators used in the strobe correlator in GPS; (b) The strobe correlator discriminator output in GPS; (c) The output of narrow correlator discriminators used in the strobe correlator in Galileo; (d) The strobe correlator discriminator output in Galileo

5 Mitigation of Multipath on DLL Using ELSC

As shown in section 4, the strobe correlator has poor performance in Galileo DLL, which results in a deteriorated positioning precision. It can be found that the shapes of discriminator outputs with about ± 0.5 chip delays are similar, which can be considered as the contractible edition of the shape of discriminator outputs in about zero chip delay with a 180° phase offset. So, the linear combination of several outputs of strobe correlators is considered to eliminate the effects of multipath signals with about 0.5 chip delays. Considering combining three different strobe correlators, a novel method named as ELSC(early-late strobe correlator) is presented in this paper to mitigate multipath on Galileo DLL as well as on GPS DLL. The final discriminator function of ELSC can be written as

$$D_{ELSC}=D_{CL1}+D_{CL2}+D_{CL3}=d_1D_C+k_2D_C+(k_2+d_2)D_C \quad (5)$$

where D_{ELSC} denotes the final or composite discriminator function for the ELSC; D_C is the output of the strobe correlator denoted in Eq. (4); the magnification factor $k_2=-1$; d_1 denotes a code length delay and d_2 denotes two code length delay; D_{CL1} is the delay edition of D_C with a code length delay, D_{CL2} is the amplificatory edition of D_C, and D_{CL3} is the amplificatory and delay edition of D_C. Fig. 4 shows the corresponding block diagram for the ELSC, in

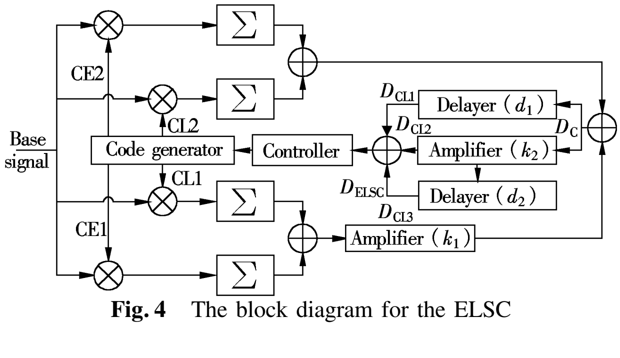

Fig. 4 The block diagram for the ELSC

which the magnification factor $k_1 = \tau_{d2}/\tau_{d1}$.

Fig. 5 shows the multipath error envelopes for the Galileo scenarios by using a strobe correlator and the ELSC, respectively. By comparing the simulation result between the strobe correlator and ELSC, it is easy to find that the ELSC performs well for Galileo signals. The relatively small path delay will result in notable multipath errors. That is to say, like a strobe correlator, the ELSC cannot effectively eliminate the impact of the multipath with no more than 0. 1 chip path delay, but it still possesses a better performance than the strobe correlator. The multipath with about a 0. 5 chip path delay has no effect on signal tracking, which is one of the advantages of the ELSC with respect to the strobe correlator. Actually, ELSC also performs well in a GPS scenario, which is predominantly due to the ELSC ability to apply in the receivers that can receive and dispose of both GPS and Galileo signals synchronously.

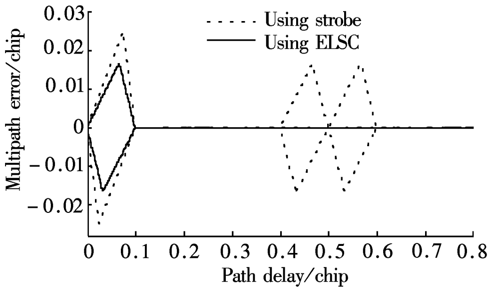

Fig. 5 Comparison of multipath error envelope between the strobe correlator and the ELSC for Galileo

6 Conclusion

Multipath is the dominant error source in high precision Galileo applications and is an important error source in non-differential applications as well. Although the strobe correlator can mitigate the effects of multipath to GPS signals, it performs poorly in Galileo when Galileo signals are patched by the multipath signals with an approximate 0. 5 code length delay with respect to the direct signals. When the ELSC is used, the situation can be improved greatly. The multipath signals with an approximate 0. 5 code length delay have hardly any effect on the ELSC. The results indicate that the performance of the ELSC is more excellent than that of the strobe correlator for the multipath signals with no more than 250 m delay. Nevertheless, the performance of the ELSC is not so good for the multipath signals with longer delay. So, further studies need to be made for mitigating the effects of multipath signals with longer delays, even though such multipath may be present infrequently.

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一种伽利略信号跟踪的多路径消除方法

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摘要:针对伽利略信号调制的特点,提出了一种基于滤波相关器法的多路径消除方法 ELSC(early-late strobe correlator). 通过对滤波相关器法应用于伽利略 E1 信号的跟踪情况进行分析,发现滤波相关器法不能消除延迟为 0. 5 个码片附近的多路径信号影响. ELSC 方法通过对几个滤波相关器的叠加,能有效消除 0. 5 个码片附近的多路径信号影响. 通过仿真比较了 ELSC 方法和滤波相关器法对于伽利略信号的多路径误差包络. 结果表明 ELSC 方法优于传统的滤波相关器法,不仅适用于伽利略信号的跟踪,同时也适用于 GPS 信号的跟踪.

关键词:伽利略信号;GPS;多路径;延迟锁相环;滤波相关器

中图分类号:V249. 36