The Mitigation of Multipath Errors by Strobe Correlators in GPS/GLONASS Receivers

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An effective method of decreasing multipath errors in GPS or GPS/GLONASS receivers by changing delay lock loop correlator reference signal is discussed. Unlike other approaches, this method does not lead to apparatus complication, power consumption increase, or augmentation of digital processor load. This method eliminates the multipath error completely if the difference in delays of direct and reflected signal is more than 30 m, and decreases this error for smaller delays. The cost of such decrease is that the noise error is increased. However, the noise error is much less dangerous than the multipath one because of its smaller value and much shorter correlation interval. Calculated and experimental data for the method are given for multipath and noise errors.

INTRODUCTION

The multipath error is currently the main limiting factor of differential GPS positioning accuracy. Strobe correlators improve accuracy. Since 1975 (Zhodzishsky, 1975) work on this issue has been conducted by the scientists of the Moscow State Aviation Institute. Some results were published (Zhodzishsky, 1978; Zhodzishsky, 1980; USSR patent grant 1367815; Zhodzishsky, 1990; Veitsel, Zhdanov, and Zhodzishsky, 1997). Additional results are being published for the first time.

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At the present, strobe correlators and their refinements are built into Ashtech navigation receivers, which operate with signals from both GPS and GLONASS navigation systems (Zhodzishsky et al., 1997; Garin et al., 1996; Garin and Rousseau, 1997; Garin et al., 1998).

SOME TYPES OF STROBE SEQUENCES USED AS REFERENCE SIGNALS IN CORRELATORS

The term *strobe correlator* refers to an accumulator of the product of an input mixture of a satellite signal with an interfering signal and a reference signal. The latter represents a strobe sequence. A single strobe is characterized by its full duration D and shape. Particularly, a strobe may consist of several pulses of various lengths and values. A reference signal in the form of a strobe sequence is phase locked with the pseudorandom noise (PRN) signal generated in the receiver [Figures 1(a) and 2(a)]. In Figure 1(a) PRN signal chip duration is denoted as Δ. There are two possible variants of locking:

- locking with a moment of PRN signal sign change [Figure 1(b)],
- locking with a PRN signal chip edge [Figure 1(c)].

A strobe shape is of great importance. A strobe may be simple, in the form of single pulse [Figure 2(b)] or complex, that is, formed of several pulses [Figures 2(c)–2(f)]. Complex strobes may be bipolar symmetrical [Figure 2(c)], antisymmetrical [Figures 2(d) and 2(e)], asymmetrical [Figure 2(f)], et cetera. In any case, when a chip changes polarity, the strobe is inverted [Figures 1(b) and 1(c)].

Strobe correlators generate the component dI for

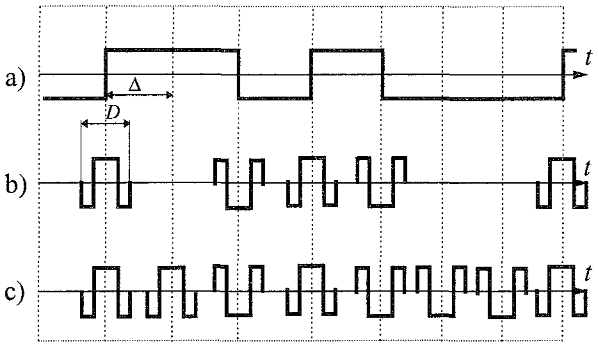

FIGURE 1. Reference signals.

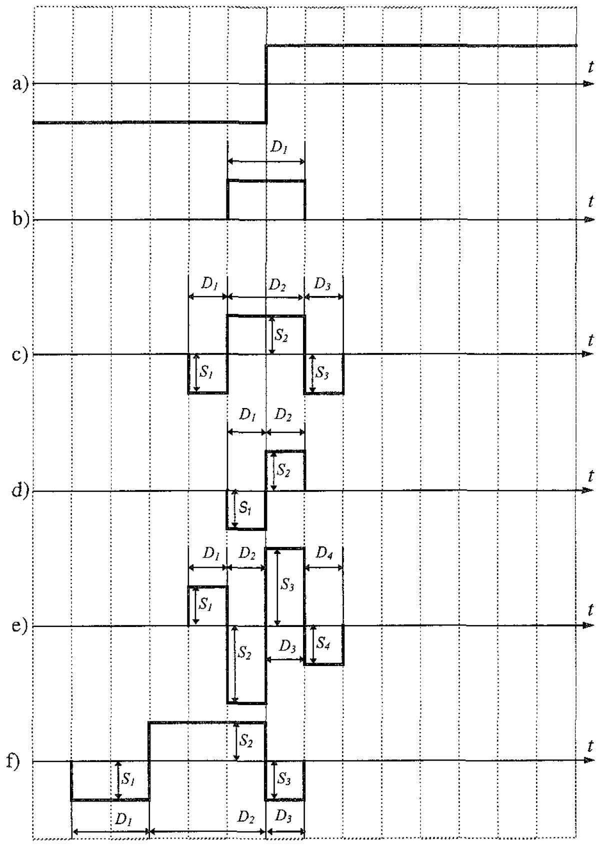

FIGURE 2. Strobes.

the coherent delay lock loop (DLL). In addition to component dI, the in-phase I and quadraphase Q components are generated by conventional correlators. Note that a DLL with a simple strobe of duration D_1 is equivalent an early–late DLL with spacing D_1.

DLL DISCRIMINATOR CHARACTERISTIC

The strobe shape actually controls the DLL discriminator characteristic $\overline{Z}_d(\varepsilon)$ (relation of the mean error signal Z_d on the time shift ε between an input and a reference PRN signal), which in turn controls the main quality characteristics of DLL, such as accuracy, reliability, et cetera. By varying the strobe shape one may build a DLL with various characteristics to match with various extraneous conditions.

In the case of locking the strobe with a PRN signal sign change and a DLL algorithm $Z_d = dI$, the discriminator characteristic for strobes consisting of rectangular pulses (Figure 2) is determined by the following equation:

$$\overline{Z}_d(\varepsilon) \sim \sum_{i=1}^{n} S_i \int_{-D_i/2}^{D_i/2} [2h(t+\varepsilon_i) - h(t+\varepsilon_i - \Delta) - h(t+\varepsilon_i + \Delta)]\, dt, \qquad (1)$$

where

~ denotes proportionality,
n is a number of strobe rectangular pulses,
S_i is the value of strobe pulse number i (with regard to the sign),
D_i is the duration of a strobe pulse number i,
$\varepsilon_i = \varepsilon + \nu_i$,
ν_i is the time shift of a center of strobe pulse number i relative to the first pulse,
$h(t)$ is a receiver filter response to a voltage jump.

It should be noted that often the discriminator algorithm is made more complicated to avoid the influence of signal amplitude and information symbols (algorithms $Z_d = dI/I$, $Z_d = dI \cdot \text{sign } I$, etc.). Here sign ( ) is the signum function. For these cases Eq. (1) must be corrected accordingly.

If $h(t)$ is given by an analytical function [for the purposes of theoretical analysis the trapezoidal $h(t)$ function corresponding to a frequency response function (FRF) of a $\sin(\omega T)/\omega T$ filter prevails] an analytic expression for $\overline{Z}_d(\varepsilon)$ can be obtained. However, to solve specific problems it is necessary to take into account the more detailed characteristics of $h(t)$ of real filters. In these cases $h(t)$ is given by a data array obtained experimentally from a real filter. The possible shapes of discriminator characteristics are shown in Figure 3.

The discriminator characteristic of a simple strobe has a single tracking system steady balance point $\varepsilon = 0$. In contrast, the discriminator characteristic of a complex strobe generally has several zero points, each of them may be chosen as steady balance point. However, it is desirable that in the steady balance point ε_0 the discriminator gain $K_d = \partial \overline{Z}_d / \partial \varepsilon |_{\varepsilon=\varepsilon_0}$ and the mathematical expectation of component I are approximately maxi-

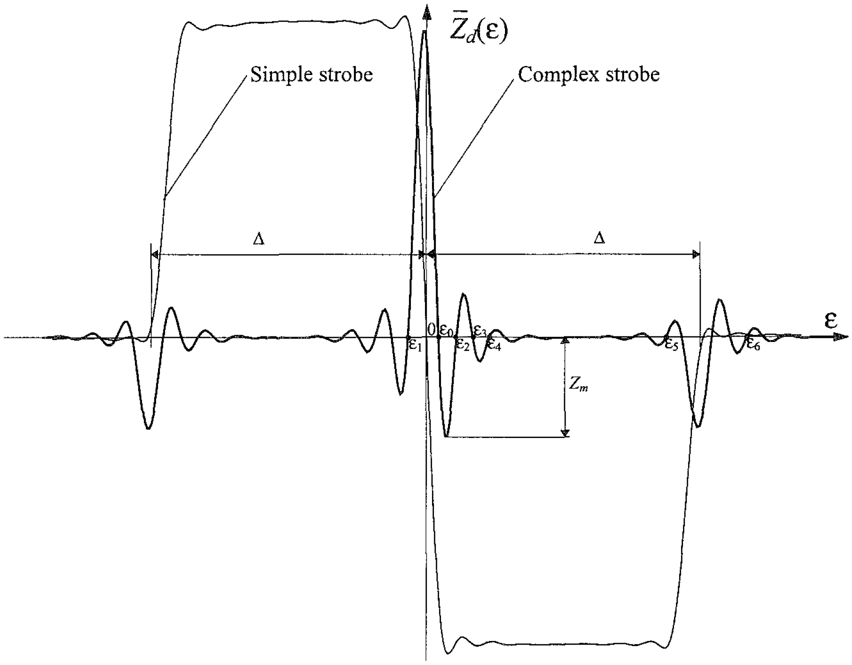

FIGURE 3. Possible shapes of discriminator characteristics.

mal. In order to make the DLL operate at the desirable point ε_0 (Figure 3) in the tracking mode (tracking error $\tau = \varepsilon - \varepsilon_0$), the initial acquisition system must provide initial shift ε within the acquisition range (from ε_1 to ε_2), and it is necessary that the gain sign in the DLL is correct. If the gain sign is not correct the point ε_0 will be an unsteady balance point and the points ε_1 and ε_2 will be steady points.

The DLL error caused by reflected signals (a multipath error) is one of the main factors determining the accuracy of a delay measurement. At a given reflected signal amplitude, a multipath error depends on the reflection delay value and consequently on the reflector location. We can estimate the maximal multipath error that occurred at the most dangerous delay value. The error is estimated as the $\alpha \cdot Z_m / K_d$ ratio, where α is the relative amplitude of the reflected signal, and Z_m is the absolute value of the discriminator characteristic maximal side peak, which is located to the right of steady balance point ε_0 (Figure 3). The latter results from the fact that the reflected signal is never ahead of the direct one. Thus we conclude that advantages can be gained from significantly asymmetrical discriminator characteristics if peaks at the right side are reduced at the expense of increased peaks located to the left of the chosen point ε_0 (Figure 3).

Another DLL quality factor, which is also related to the reflected signal effect, can be estimated by the influence zone size of the reflected signals. This size should be determined as a delay range where the multipath error for reflected signals with preset amplitude exceeds some threshold value. The influence zone of the reflected signals is also determined by the discriminator characteristic. In Figure 3 by convention this zone corresponds to the intervals ($\varepsilon_0 \div \varepsilon_4$) and ($\varepsilon_5 \div \varepsilon_6$). It is evident that the narrower the reflected signal influence zone, the weaker the DLL response to the reflected signals. In this connection the various methods of zone narrowing with the aid of specially shaped strobes are worth consideration.

NOISE ERROR

The first stage in the analysis of noise errors of DLL, phase-lock loop (PLL), binary signal demodulator, and other microprocessor-based systems is to define statistical characteristics of correlator output signals *I, Q, dI*. In fact, only these values enter from the application-specific integrated circuit (ASIC) to the digital signal processor (DSP); hence their statistical characteristics entirely determine the errors of any measurements.

It may be shown that in the first (quasilinear) approximation the noise errors (as well as multipath errors in DLL and PLL) of various systems are governed only by some of the *I, Q, dI* values. For a binary signal demodulator the noise errors are governed by *I*, for PLL they are governed by *Q*, and for coherent DLL they are governed by *dI*.

Correlator outputs *I, Q, dI* are obtained as a result of accumulating over a substantial time T. Therefore these values have Gaussian distribution. In the first approximation they are independent, and consequently they are characterized only by their mathematical expectations and variances. For a DLL with a coherent discriminator the standard deviation of tracking error τ may be estimated by

$$\sigma_\tau \cong \frac{\sqrt{2 \cdot T \cdot V(dI)}}{K_d} \sqrt{B_{DLL}}, \qquad (2)$$

where

$V(dI)$ is the variance of dI at $\tau = 0$,
B_{DLL} is the DLL equivalent noise bandwidth

Hence, the problem on DLL accuracy estimation reduces to the determination of mathematical expectation $\bar{dI}$ and variance $V(dI)$. Analysis has shown that in digital systems these values depend on such parameters as time sampling frequency, number of quantization levels in analog-to-digital converter (ADC), signal-to-noise ratio at the receiver filter output, filter FRF shape, and correlator reference signal strobe shapes. The effect of sampling in digital circuits is conveniently expressed by the loss factor (to compensate for the increase of a noise error in the digital circuit as compared with the analog circuit for which the carrier power to noise spectral density ratio C/N_0 should be multiplied by a loss factor). Under the conditions of binary quantization in ADC for the case when the signal power is much lower than the noise within a filter passband (which is common to the PRN signal receivers), the loss factor lies in the range $\approx 1 \cdots 2$ dB with the proviso that the time sampling frequency is $3 \cdots 8$ times more than the filter passband. As the number of quantization levels is increased the loss factor is reduced.

In the DLL correlator with complex-shaped strobes the noise errors are generally increased. Transition from locking with moments of PRN signal sign change [Figure 1(b)] to locking with all PRN signal chip edges [Figure 1(c)] increases the noise error by an additional 3 dB.

MULTIPATH ERROR IN DLL WITH STROBE CORRELATOR

As was already mentioned, the multipath errors in the first approximation are governed by the statistical characteristic of dI and practically do not depend upon I for all DLL discriminator algorithms. This approximation is admissible if the PLL error is not large. The reflected signal distorts the discriminator characteristic $\bar{Z}_d(\varepsilon)$. We assume a mirror reflection from a single reflector and find the characteristic after distortion $\bar{Z}'_d(\varepsilon)$

$$\bar{Z}'_d(\varepsilon) = \bar{Z}_d(\varepsilon) + \alpha \cdot \cos\theta \cdot \bar{Z}_d(\varepsilon - \delta), \qquad (3)$$

where

α is the relative amplitude of the reflected signal
δ is the reflected signal delay relative to the direct one
θ is the phase shift of reflected signal carrier relative to the direct one
$\bar{Z}_d(\varepsilon)$ is determined by Eq. (1)

The multipath error $\Delta\tau$ is calculated as a root of the equation $\bar{Z}'_d(\varepsilon) = 0$ near the steady balance point ε_0.

The following results were obtained for the acoustic surface-wave intermediate frequency filter SAWF CTI-1652, which determines the analog channel frequency response. Here the equivalent noise bandwidth at intermediate frequency $B_{IF} \approx 11$ MHz.

DLL discriminator characteristics (Figure 4) and associated multipath error envelopes (Figure 5) for the reflected signal with parameters $\alpha = 0.5$, $\theta = 0$, and π; $0 \leqslant \delta \leqslant 1.36\Delta$ were computed for the C/A code of GPS for the following preferable strobes:

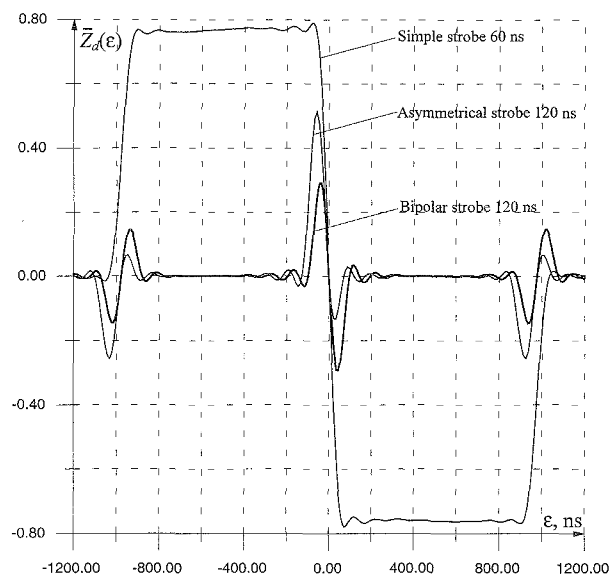

FIGURE 4. Discriminator characteristics of simple, bipolar, and asymmetrical strobes.

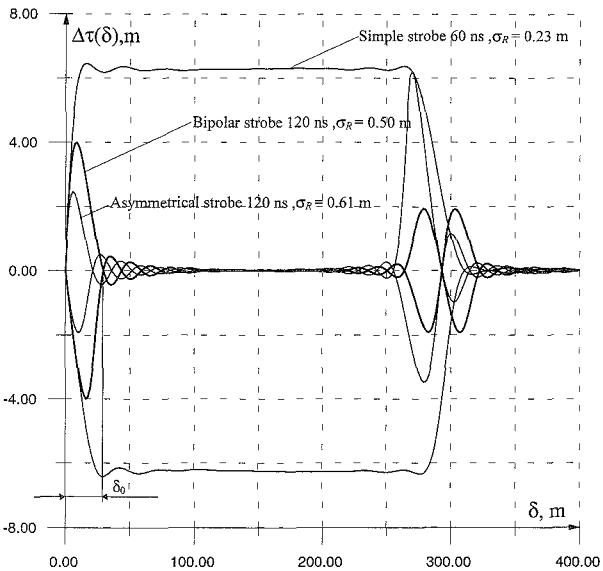

FIGURE 5. Multipath error envelopes of simple, bipolar, and asymmetrical strobes.

- Simple strobe as shown in Figure 2(b) (for pulse duration D_1 = 60 ns),
- Bipolar strobe as shown in Figure 2(c) (D_2 = 60 ns; D_1 = D_3 = 30 ns; $S_1 = S_3 = -1$; $S_2 = 1$),
- Asymmetrical strobe as shown in Figure 2(f) (D_1 = 40 ns; D_2 = 60; D_3 = 20 ns; $S_1 = S_3 = -1$; $S_2 = 1$).

Full strobe duration D in Figure 5 is indicated after the strobe designations. Additionally, there are range standard deviations $\sigma_R = 3 \cdot 10^8 \cdot \sigma_\tau$ for the DLL bandwidth B_{DLL} = 1 Hz and binary quantization in ADC. Here the time sampling frequency and carrier power to noise spectral density (single sideband) ratio C/N_0 at a receiver input are set to be equal to 33 MHz and 50 dB Hz, respectively.

The situation where chip duration is much longer compared to the transient process time of the $h(t)$ function is typical for C/A code. Then (Figure 5), for a simple strobe the multipath error rises as the delay δ increases from 0 to some value δ_0, and then it is held near constant until δ approaches Δ. At the further increase of δ the error drops to zero. The value of δ_0 is determined by the strobe duration D_1 or by the front duration $1/B_{IF}$, whichever is longer. Accordingly, the multipath error for the most dangerous delays is determined by D_1 if $D_1 > 1/B_{IF}$ or by $1/B_{IF}$ if $D_1 < 1/B_{IF}$. In this case the reflected signal influence zone size is practically equal to the chip duration Δ.

For approximate calculations the maximal multipath error can be estimated according to the formula

$$\Delta\tau_{max} \approx \begin{cases} 0.5 \cdot \alpha \cdot D_1, & at\, D_1 > 1/B_{IF}, \\ 0.5 \cdot \alpha / B_{IF}, & at\, D_1 < 1/B_{IF}, \\ 0.59 \cdot \alpha \cdot D_1, & at\, D_1 = 1/B_{IF}. \end{cases} \quad (4)$$

More accurate numerical estimates show that Eq. (4) determines $\Delta\tau_{max}$ with an accuracy of 15%; the accuracy increases as the difference between $1/B_{IF}$ and D_1 increases and α is reduced.

The application of the bipolar strobe [Figure 2(c)] in the reference signal results in considerable reduction of the multipath error for C/A code. If the strobe positive pulse area is equal to the total area of the strobe negative pulses, the reflected signal influence zone size is reduced significantly. The error $\Delta\tau$ begins to decay toward zero once a delay δ has exceeded δ_0 (Figure 5). At the same time the maximal error is reduced approximately by 30%. For the strobe sequence of the type shown in Figure 1(b), the multipath error occurs also at delays of order Δ. The maximal error in this range is reduced by half as compared with that in the small delay range. The error does not occur at great delays if we use a sequence of the type shown in Figure 1(c). But then, as was already mentioned, the noise error σ_τ is increased on 3 dB.

The bipolar strobe gives the discriminator characteristic (Figure 4), which has the steady balance point $\varepsilon = 0$, provided the gain sign is chosen correctly (if the gain sign is not chosen correctly the steady balance points will be $\varepsilon = \pm\Delta$). The corrected acquisition zone length is determined by the strobe full duration ($\pm D$ at $D > 1/B_{IF}$) or by the front length ($\pm 1/B_{IF}$ at $D < 1/B_{IF}$) and is narrow. Hence a two-stage procedure of coming into synchronism may become a necessity. At the first stage the simple strobe provides a wide acquisition zone but introduces a relatively large error in the presence of a reflected signal. Then, after completion of the transient process the switching to a bipolar strobe is performed to reduce the multipath error. Studies revealed that in first-order DLL for simple strobe duration $D_1 = 50 \cdots 100$ ns (and for about the same $1/B_{IF}$) the initial error resulting from the first stage is reasonably small to ensure the reliable acquisition at the second stage. The transient process due to the parametric disturbance from the switching proceeds rather smoothly.

To further reduce the multipath error, the asymmetrical strobe of the type shown in Figure 2(f) may be used. The corresponding discriminator characteristic is shown in Figure 4. The plot of multipath error via delay δ (Figure 5) shows that in this case the most dangerous are large delays (at multipath with $\delta \approx \Delta$) rather than small ones. Hence to eliminate these errors, it is necessary to form strobes locked with the chip edges.

TEST OF STROBE CORRELATORS

For this test two Ashtech GG-24 receivers were used. In the DLL of the first receiver there was the simple strobe; in the second receiver, the bipolar strobe. The input signals came from an antenna installed on the roof of a building in Moscow. The roof has severe multipath conditions: Borders and banisters are metallic; there is additional metallic roofing 20 m from the antenna. The Ashtech GG-24 tracked C/A signals from both GPS and GLONASS. The measurements were recorded with frequency 2 Hz for 23 min. For the separation of the code multipath error the full carrier phase was subtracted from the range. With the help of this subtraction the satellite motion and the receiver's and satellite's (including selective availability) reference oscillator fluctuations were removed. At the same time the steady component (caused by phase ambiguity), thermal Gaussian noise, code multipath error (in comparison with it the phase multipath error is negligible), and time float ionosphere bias were kept. However, the code multipath error is major. For instance, such code-phase is shown in Figure 6 for GPS space vehicle (SV) No. 27 for both first (with simple strobe) and second (with bipolar strobe) receivers over a short interval of 400 s. For ionosphere bias compensation a quadratic polynomial is subtracted from the code-phases. Figure 7 shows momentary power spectral density (single sideband) of this code-phase. Standard deviations of this and other code-phases are shown in Table 1. Here the GLONASS satellite number equals the sum of the system number plus 32.

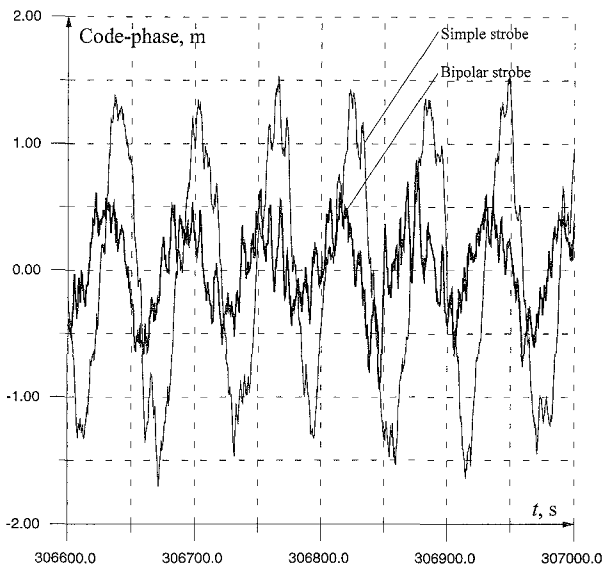

FIGURE 6. Behavior of multipath errors for simple and bipolar strobes (GPS, SV No. 27).

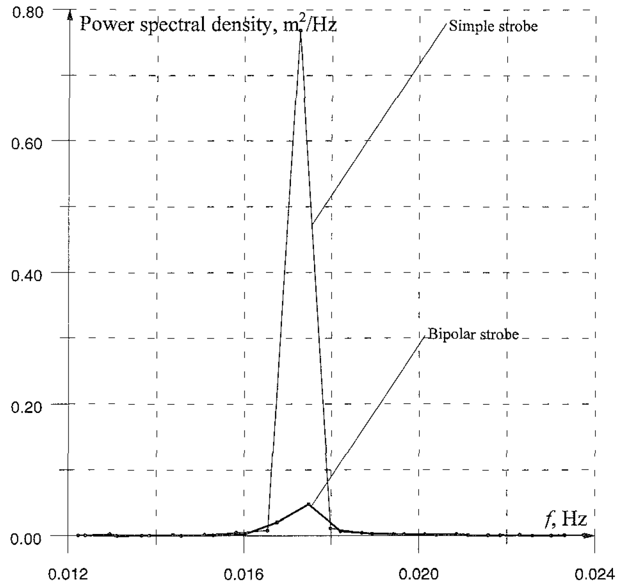

FIGURE 7. Power spectral densities of multipath errors for simple and bipolar strobes (GPS, SV No. 27).

Additionally, in this table the percent difference (improvement) between 1 and the ratio of standard deviations of code-phase with bipolar and simple strobe is shown. In the last column the percent difference between 1 and the square root of the ratio of spectral density maximums is shown.

One can see that on average the standard deviation is decreased by bipolar strobe by 47% (by about two times). However, at spectral density the code multipath error really is suppressed more—by 62% (about three times). The difference is explained by the influence of Gaussian noise on standard deviation.

CONCLUSIONS

The results show that a strobe correlator is a rather flexible tool for adaptation of DLL to the various extraneous

TABLE 1

Standard deviations and spectral density maximum improvement of code phase for different SVs

SV Number	Elevation (deg)	Standard Deviation for Simple Strobe (m)	Standard Deviation for Bipolar Strobe (m)	Standard Deviation Improvement (%)	Spectral Density Maximum Improvement (%)
02	52	0.30	0.26	13	29
03	09	1.72	0.94	45	76
10	28	1.35	0.68	50	61
17	62	1.79	1.18	34	46
19	37	0.96	0.40	58	73
26	25	1.76	0.71	60	75
27	81	0.94	0.37	61	75
31	28	1.14	0.50	56	74
38	21	2.38	1.56	34	43
41	12	2.54	1.01	60	85
47	50	1.02	0.45	56	69
49	53	0.85	0.59	31	46

conditions by choice of a strobe shape in a correlator reference signal.

Short simple strobes locked with the moment of reference PRN signal sign change make it possible to minimize the noise tracking error.

Strobe correlators with low sensitivity to reflected signals can be made. Complex-shaped strobes reduce the space where dangerous reflectors may be located, and mitigate the multipath errors from reflectors located within this space.

Increase of DLL noise error, which often accompanies the multipath error mitigation, limits the level of an achievable effect. However, because the multipath error controls the real DLL accuracy, the application of complex-shaped strobes have substantial advantages when operating on C/A code of GPS and GLONASS. ■

REFERENCES

Garin, L., F. Van Diggelen, and J.M. Rousseau. 1996. Strobe and edge correlator multipath mitigation for code, *Proceedings of ION GPS-96,* The Institute of Navigation, Alexandria, VA, pp. 657–664.

Garin, L., and J.M. Rousseau. 1997. Enhanced strobe correlator multipath rejection for code & carrier, *Proceedings of ION GPS-97,* The Institute of Navigation, Alexandria, VA, pp. 559–568.

Garin, L., M. Zhodzishsky, V. Veitsel, S. Sila-Novitsky, and F. Kamgar. 1998. An improved signal correlation technique for a receiver of a spread spectrum signal including a pseudo-random noise code that reduces errors when a multipath is present, April 2, international application published under the Patent Cooperation Treaty (PCT) No. WO 98/13947.

Veitsel, V., A. Zhdanov, and M. Zhodzishsky. 1997. Strobe correlators in navigation receivers with pseudo-random noise signals. *Radiotekh.,* 8, 11–18 (in Russian).

Zhodzishsky, M. 1975. Digital PLL systems for video signal processing, *Proceedings of the 2nd Scientific Conference PLL Systems,* Gorky, Russia (in Russian).

Zhodzishsky, M. 1978. Digital PLL systems for video signal processing. *Radiotekh. Elektron.,* 12, 2525–253 (in Russian).

Zhodzishsky, M. (Ed.). 1980. *Digital systems of phase locking,* Moscow, Sovetskoye Radio, Moscow, Russia (in Russian).

Zhodzishsky, M. (Ed.). 1990. *Digital Radio Receiver Systems Handbook,* Radio i Svyaz, Moscow, Russia (in Russian).

Zhodzishsky, M., V. Veitsel, S. Sila-Novitsky, J. Ashjaee, and L. Garin. 1997. Multipath error reduction in a spread spectrum receiver for ranging applications, February 20, international application published under the Patent Cooperation Treaty (PCT) No. WO 97/06446.

BIOGRAPHIES

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