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Multipath Suppression of Radio Navigation Transmitter Signal Based on Linear Sweep Carrier

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ABSTRACT Multipath interference is the main error source for radio navigation system high-precision positioning in complex environments. Multipath suppression and elimination are critical for radio navigation systems. A linear sweep carrier signal system is proposed to improve the multipath mitigation performance of radio navigation systems, and a TDMA+CDMA technique is adopted to avoid cross-correlation interference between transmitter signals and solve the near-far effect problem. Hardware simulation and actual environment experiment are carried out, and the results show that the proposed sweep carrier signal system can improve the ranging precision greatly compared with the traditional fixed frequency signal system.

INDEX TERMS Multipath, radio navigation system, linear sweep carrier, TDMA+CDMA, near-far effect.

I. INTRODUCTION

In radio navigation systems, multipath error is difficult to be eliminated by differential technique or model correction because it has no temporal and spatial correlation. It is the main error source to realize high precision application in complex environments, and multipath suppression and elimination is very important [1], [2].

The current multipath suppression technologies are mainly processed in receivers and can be divided into three categories: antenna side multipath suppression, baseband signal processing and measurement domain processing technology. The antenna side multipath suppression technology mainly include right hand circular polarization, choke ring antenna and antenna array [3]–[5]. However, the antenna location can be applied only when the carrier is stationary and engineering applications are limited due to the high cost. The multipath mitigation algorithms in measurement domain are mainly focused on carrier phase smoothing pseudo-range algorithms and multi-frequency code multipath combinations [6]. The performance of these methods is determined by measurement redundancy and noise magnitude, and they are suitable for a long term observation application, such as a monitoring station, which has a fixed position. The multipath suppression in baseband signal processing stage contains nonparametric and parametric approaches. The nonparametric multipath suppression methods reduce the multipath effect on pseudorange measurements by changing the shape of phase discrimination curves, such as Narrow correlation technique [7], early and late code slope technique [8], Strobe technique [9], [10], Fast Iterative Maximum Likelihood Algorithm (FIMLA) [11], [12], Reduced Search Space Maximum Likelihood (RSSML) [13], Multiple Gate Delay(MGD) [14]–[16], Double–delta and its transformational algorithms. These algorithms have advantages of low complexity and good real-time performance. The parametric multipath suppression techniques mainly estimate and separate direct and multipath signals, such as Multipath Estimating Delay Lock Loop (MEDLL) [17], Multipath Mitigation Technique (MMT) [18], Vision Correlator (VC) [19], Teager Kaiser Multipath Estimating Delay Lock Loop (TK-MEDLL) [20], Coupled Amplitude Delay Lock Loops (CADLL) [21] and so on. These methods require large hardware resources and have high complexity.

Although the multipath suppression algorithms in receivers can suppress multipath to some extent, multipath effect is closely related to signal structure, and the design of anti-multipath signal system is the first step to suppress multipath. Different modulation signals have different multipath mitigation performance under the same code loop discriminator, and the same signal has different multipath mitigation performance under different code loop discriminators [22]–[25]. However, high rate pseudorandom code and good correlation characteristics can reduce the multipath effect. For example, the P code rate in GPS system is 10 times that of the C/A code and can suppress multipath with less than 10 times delay [3]. Sweep-Spread Carrier has a good multipath mitigation effect in underwater acoustic system [26], and multipath suppression method based on sweep carrier can suppress the static multipath error of BDS geosynchronous satellites [27]. In addition, the complementary code keying (CCK) in 802.11b standard and the cyclic code shift keying (CCSK) coding in Joint Tactical Information Distribution System (JTIDS) are equivalent to an increase in code rate and spread spectrum gain, correspondingly improving the multipath suppression performance. Based on the analysis of the above techniques, the multipath can be suppressed to the greatest extent if the transmitters transmit anti-multipath signals and multipath mitigation algorithms are applied in receives simultaneously.

In order to solve problems of near-far effect and severe multipath interference in pseudolite systems, a TDMA+CDMA signal system based on linear sweep carrier is proposed in this paper. This system can improve the multipath pseudorandom code correlation characteristics and effectively suppress multipath. Using narrow correlation technique at the receiver, multipath interference can be further suppressed. In addition, TDMA technology can fundamentally eliminate the near-far effect. Software and hardware simulation and actual environmental test prove that the TDMA+CDMA linear sweep signal system of radio navigation system has good multipath mitigation performance.

This paper is organized as follows: Section 2 introduces the architecture of radio navigation system. Section 3 analyzes the multipath mitigation performance of linear sweep carrier. In Section 4, a TDMA+CDMA signal system based on linear sweep carrier is designed. In Section 5, hardware simulation and actual environment test are carried out to verify the multipath suppression performance of the linear sweep carrier. Finally, conclusions are given in Section 6.

II. GROUND-BASED RADIO NAVIGATION SYSTEM

The navigation system designed in this paper is a radio navigation system with GNSS system as a space-time reference. This section introduces the architecture of the system, the functions of each part and the problems of the system.

The GNSS system provides space-time reference information for the ground-based radio navigation system transmitter, and the navigation system transmitter provides a new navigation signal with strong penetration and ability to resist near-far effect and multipath for the urban environment. The system schematic is shown in Fig. 1. The radio navigation system includes a master base station and a plurality of mobile stations. The working process of the radio navigation system is as follows:

1) The GNSS signal provides a space-time reference for the transmitter of ground-based radio navigation system;

2) After receiving the GNSS signal, the base station obtains a high-precision space-time reference by PPP technology, and then broadcasts differential information to the mobile stations;

3) After receiving the GNSS signal and the differential information broadcasted by the base station, each mobile station obtains high-precision relative spatiotemporal information through RTK differential resolution;

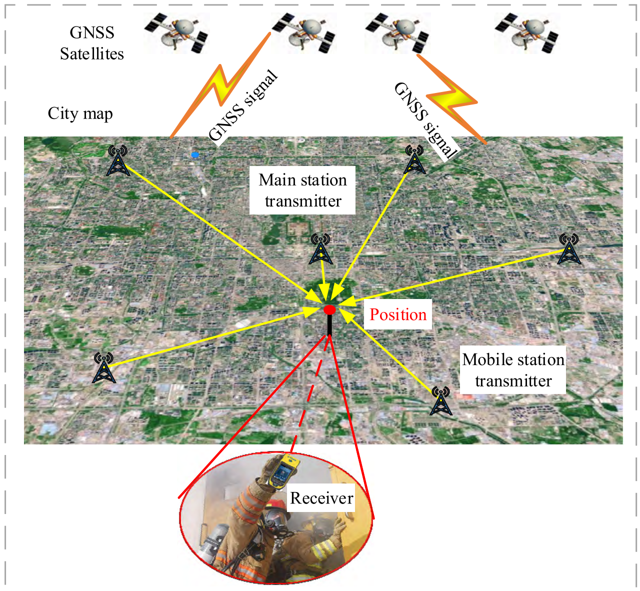

FIGURE 1. Schematic of radio navigation transmitter system.

4) Each station broadcasts a radio navigation modulation signal which contains its own spatiotemporal information;

5) The receiver receives the transmitter signal of the radio navigation system to achieve high precision positioning.

Multipath interference and near-far effect are main factors affecting receiver positioning. When the ground-based radio navigation systems are used for positioning in urban environments, the multipath interference is severe, which brings serious impact on receiver positioning results. In addition, the difference of each station signal power received by the receiver in different places may be large, resulting in cross-correlation interference, which is the near-far effect. To solve the problems, linear sweep carrier is used in radio navigation transmitter signal system to improve the multipath mitigation performance, and time-division and code division mechanisms are applied to solve the near-far effect problem.

III. LINEAR SWEEP CARRIER TECHNIQUE FOR MULTIPATH MITGATION

Carrier sweep signal consists of periodic linear frequency modulation (LFM) signals. In this section, a carrier linear sweep signal model is established, and the narrow correlation technique and Strobe technique are used to analyze its multipath mitigation performance.

A. LINEAR SWEEP CARRIER SIGNAL MODEL

In this section, a carrier linear sweep method is used to change the carrier frequency. There is a fixed ratio k between the carrier frequency and the pseudorandom code rate, as shown in Fig. 2. In order to make the frequency continuous, the carrier frequency adopts a linear change method of increasing T/2 first and then decreasing T/2. The function relation

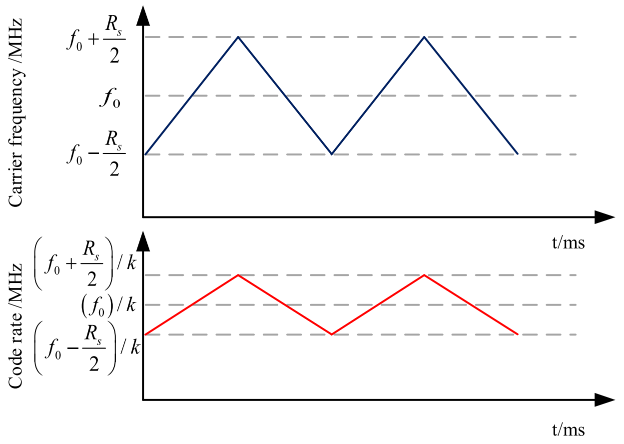

FIGURE 2. Linear sweep signal.

between frequency f and time is as follows:

$$f(t)=\begin{cases}\frac{2R_s}{T_s}t+f_0-\frac{R_s}{2}, & T_s n<t\leq T_s\left(n+\frac{1}{2}\right)\\ \frac{-2R_s}{T_s}t+f_0-\frac{3R_s}{2}, & T_s\left(n+\frac{1}{2}\right)<t\leq T_s(n+1),\end{cases} \tag{1}$$

where f_0 is carrier center frequency, R_s is sweep bandwidth, and T_s is sweep period:

Based on sweep carrier, the multipath mitigation performance of BPSK spread spectrum modulation signal is analyzed. Assuming that the multipath signal has a delay of $\Delta\tau$ relative to the direct signal, the expression of the received signal with a single multipath is as follows:

$$\begin{aligned}r(t)&=AP(t)\cos\left[2\pi\int_0^t f(t)dt+\varphi_0\right]+\alpha AP(t-\Delta\tau)\\&\quad\times\cos\left[2\pi\int_0^{t-\Delta\tau} f(t)dt+\varphi_0+\Delta\varphi\right]+n(t),\end{aligned} \tag{2}$$

where A is signal amplitude; P is pseudorandom code; α is amplitude ratio of multipath signal to direct signal; φ_0 is direct signal phase; $\Delta\varphi$ is multipath phase change; $n(t)$ is channel noise.

Assuming that the receiver steadily tracks the received signal, the local sweep carrier signal is as follows:

$$l(t)=\cos\left[2\pi\int_0^t f(t)dt+\varphi_1\right], \tag{3}$$

The carrier can be stripped by multiplying the received signal with the local signal:

$$\begin{aligned}s(t)&=[r(t)\cdot l(t)]_{LPF}=d(t)+m(t)+n'(t)\\&=n'(t)+AP(t)\cos(\varphi_1-\varphi_0)+\alpha AP(t-\Delta\tau)\\&\quad\times\cos\left[2\pi\int_{t-\Delta\tau}^t f(t)dt+\varphi_1-\varphi_0-\Delta\varphi\right],\end{aligned} \tag{4}$$

When the frequency of the sweep carrier signal increases, the expression of the multipath component after carrier stripping is equation (5); When the frequency of the sweep signal decreases, the expression of the multipath component after carrier stripping is equation (6):

$$\begin{aligned}&m_1(t)\\&=\alpha AP(t-\Delta\tau)\cos\left[2\pi\int_{t-\Delta\tau}^t f(t)dt+\varphi_1-\varphi_0-\Delta\varphi\right]\\&=\alpha AP(t-\Delta\tau)\\&\quad\times\cos\left[\begin{array}{l}\frac{4\pi R_s}{T_s}\Delta\tau\cdot t\\+2\pi\left(-\frac{R_s}{T_s}\Delta\tau^2+\left(f_0-\frac{R_s}{2}\right)\Delta\tau\right)+\varphi_1-\varphi_0-\Delta\varphi\end{array}\right]\\&=\alpha AP(t-\Delta\tau)\cos(\omega t+\phi_1),\end{aligned} \tag{5}$$

$$\begin{aligned}&m_2(t)\\&=\alpha AP(t-\Delta\tau)\cos\left[2\pi\int_{t-\Delta\tau}^t f(t)dt+\varphi_1-\varphi_0-\Delta\varphi\right]\\&=\alpha AP(t-\Delta\tau)\\&\quad\times\cos\left[\begin{array}{l}-\frac{4\pi R_s}{T_s}\Delta\tau\cdot t\\+2\pi\left(\frac{R_s}{T_s}\Delta\tau^2+\left(f_0+\frac{3R_s}{2}\right)\Delta\tau\right)+\varphi_1-\varphi_0-\Delta\varphi\end{array}\right]\\&=\alpha AP(t-\Delta\tau)\cos(\omega t-\phi_2),\end{aligned} \tag{6}$$

where

$$\begin{aligned}\omega&=\frac{4\pi R_s\Delta\tau}{T_s};\\\phi_1&=2\pi\left[-\frac{R_s}{T_s}\Delta\tau^2+\left(f_0-\frac{R_s}{2}\right)\Delta\tau\right]+\varphi_1-\varphi_0-\Delta\varphi;\\\phi_2&=2\pi\left(\frac{R_s}{T_s}\Delta\tau^2+\left(f_0+\frac{3R_s}{2}\right)\Delta\tau\right)+\varphi_1-\varphi_0-\Delta\varphi.\end{aligned}$$

It can be seen from the above equations that the multipath component of the pseudorandom code has the characteristics of a sinusoidal envelope after being demodulated. If the signal frequency monotonicity is constant in the integral time T, the integral result is as follows:

$$\begin{aligned}IR(\tau)&=\int_0^T d(t)\,dt+\int_0^T m_1(t)\,dt\\&=AT\cos(\varphi_1-\varphi_0)R(\tau)\\&\quad+\frac{\alpha A}{\omega}[\sin(\omega T+\phi_1)-\sin\phi_1]R(t+\Delta\tau)\end{aligned} \tag{7}$$

$$\begin{aligned}IR(\tau)&=\int_0^T d(t)\,dt+\int_0^T m_2(t)\,dt\\&=AT\cos(\varphi_1-\varphi_0)R(\tau)\\&\quad+\frac{\alpha A}{\omega}[\sin(\omega T-\phi_2)+\sin\phi_2]R(t+\Delta\tau),\end{aligned} \tag{8}$$

where $R(\tau)$ is code autocorrelation function.

The above formulas show that the integral result of multipath component is related to the sinc(x) function and exists some zero points.

B. ANALYSIS OF MULTIPATH SUPPRESSION OF SWEEP CARRIER SIGNAL

The nonparametric multipath suppression technology is easy to implement and has good real-time performance. In this section, Narrow correlation technique and Strobe technique are used to analyze the multipath mitigation performance of the sweep carrier signal.

1) NARROW CORRELATION TECHNIQUE

Narrow correlator is obtained by reducing the early and late correlator spacing based on the standard correlator. The standard correlator spacing is 1 chip while the narrow correlator spacing can be up to 0.1 chips. The distance between the early or late correlator of the narrow correlator and the prompt correlator is d, and the distance between the early and the late correlator is 2d.

The narrow correlation phase discrimination function of multipath sweep carrier signal is constructed as follows:

$$\begin{aligned} D(\tau) &= IR_E(\tau) - IR_L(\tau) \\ &= AT\cos(\varphi_1 - \varphi_0)\left[R(\tau - d) - R(\tau + d)\right] \\ &\quad + \frac{\alpha A}{\omega}\left[\sin(\omega T + \phi_1) - \sin\phi_1\right] \\ &\quad \times \left[R(\tau - d + \Delta\tau) - R(\tau + d + \Delta\tau)\right], \end{aligned} \tag{9}$$

As seen from equations (7), (8) and (9), the discrimination result of the multipath component has the form of sinc(x) function. $\omega = 4\pi R\Delta\tau/T$ can be obtained from formula (6), and when the integral time T is the zero of the sinc(x) function and satisfies $\omega = 4\pi R\Delta\tau/T$, namely carrier sweep range, sweep period and multipath delay satisfies $\omega T = 2k\pi$, the integral result of multipath component is 0.

According to the mechanism of the multipath code phase error, the relationship between code tracking error, correlator spacing d and multipath parameter k is as follows:

$$\tau_e = \begin{cases} \dfrac{k\Delta\tau}{1+k}, & 0 < \Delta\tau \le \tau_a \\ dk, & \tau_a < \Delta\tau \le \tau_b \\ \dfrac{k}{2-k}(d + 1 - \Delta\tau), & \tau_b < \Delta\tau \le \tau_c \\ 0, & \Delta\tau > \tau_a, \end{cases} \tag{10}$$

where $k = \frac{\alpha A}{\omega}\left[\sin(\omega T + \phi_1) - \sin\phi_1\right]$ is related to multipath amplitude, phase and delay, $\tau_a = (1+k)d$, $\tau_b = 1 - d + dk$, $\tau_c = 1 + d$.

According to the above formula, the multipath error envelope of sweep signal under narrow correlation technique can be obtained. The sweep carrier changes the multipath signal code phase relation, which is related to the sweep period, sweep range and multipath delay. Therefore, the relationship between the multipath error and the carrier phase is no longer deterministic.

The multipath mitigation performances of BPSK (1), BPSK (1) + sweep bandwidth 4.092MHz and BPSK (1) + sweep bandwidth 8.184MHz are analyzed. The signal center frequency is set to 51.15MHz, and the pseudorandom code reference frequency is 1.023MHz. The ratio of multipath signal amplitude to direct signal amplitude is 0.5, and the data sampling rate is set to 250MHz. The correlator spacing of narrow correlation technique is 0.1 chips. The multipath error curves under the narrow correlation technique are shown in Fig. 3.

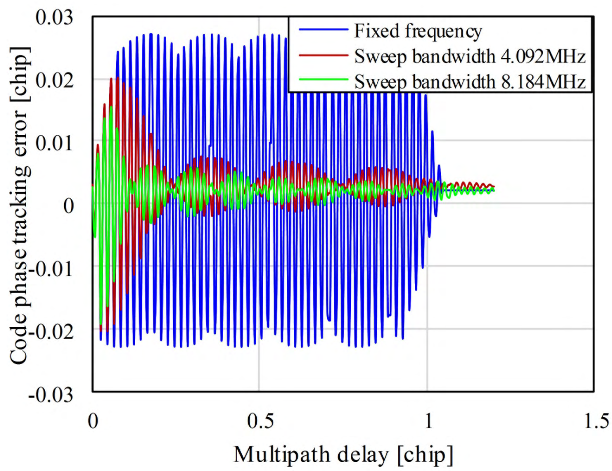

FIGURE 3. Multipath error curves under the narrow correlation technique.

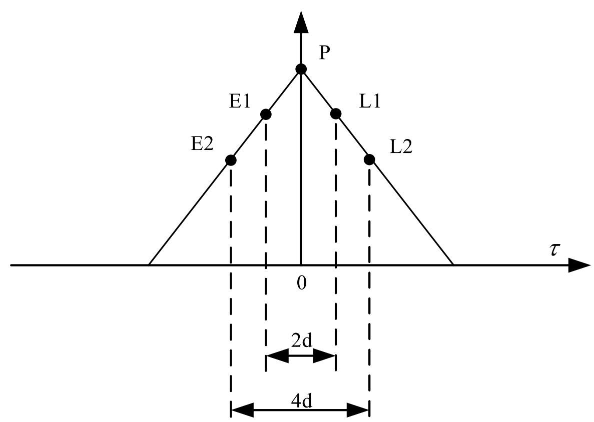

FIGURE 4. The correlator configuration of Strobe technique.

In Fig. 3, the multipath error envelope decreases with the increase of sweep bandwidth, and the multipath error curve envelope presents the form of sinc(x) function between two zeros. The experiments show that the carrier sweep signal reduces the multipath error.

2) STROBE TECHNIQUE

Narrow correlation technique only involves a pair of early and late correlators, while Strobe technique adds a pair of wide correlators to narrow correlation. If the distance between the two correlators is d, the distance between the narrow correlators E1 and L1 is 2d, and the distance between the wide correlators E2 and L2 is 4d. The correlator configuration of Strobe technique is shown in Fig. 4.

The phase discrimination function of Strobe technique is expressed as $S = 2(E_1 - L_1) - (E_2 - L_2)$, and then the phase discrimination function of multipath sweep carrier

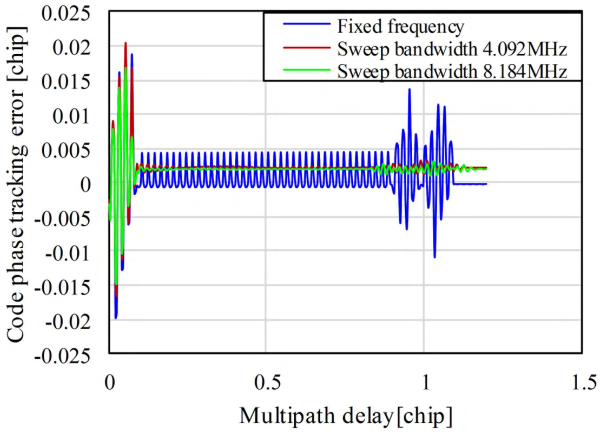

FIGURE 5. Multipath error curves under the Strobe correlation technique.

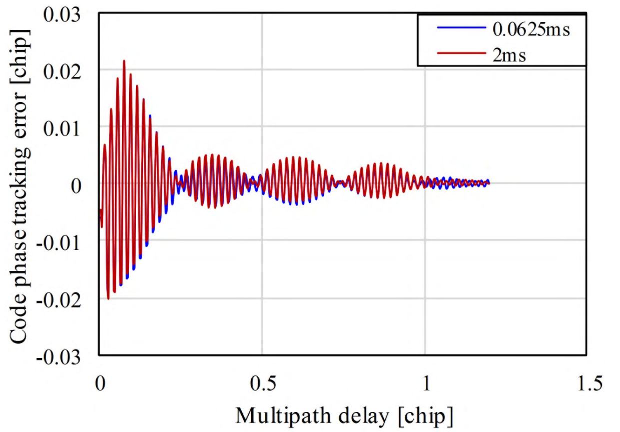

FIGURE 6. Multipath error curves under the narrow correlation technique.

signal is:

$$D(\tau) = 2\left[IR_{E_1}(\tau) - IR_{L_1}(\tau)\right] - \left[IR_{E_2}(\tau) - IR_{L_2}(\tau)\right]$$
$$= AT\cos(\varphi_1 - \varphi_0)\begin{bmatrix} 2\left[R(\tau - d) - R(\tau + d)\right] - \\ \left[R(\tau - 2d) - R(\tau + 2d)\right] \end{bmatrix}$$
$$+ \frac{\alpha A}{\omega}\left[\sin(\omega T + \phi_1) - \sin\phi_1\right]$$
$$\times \begin{bmatrix} 2\left[R(\tau - d + \Delta\tau) - R(\tau + d + \Delta\tau)\right] \\ -\left[R(\tau - 2d + \Delta\tau) - R(\tau + 2d + \Delta\tau)\right] \end{bmatrix}, \tag{11}$$

Formula (11) is also related to the sinc(x) function, where the result of the multipath component integral is zero. The relationship between code tracking error, correlator spacing d and multipath parameter k is as follows:

$$\tau_e = \begin{cases} \dfrac{k\Delta\tau}{1+k}, & 0 < \Delta\tau \leq \tau_a \\ \dfrac{k(\Delta\tau - 2d)}{k-1}, & \tau_a < \Delta\tau \leq \tau_b \\ 0, & \tau_b < \Delta\tau \leq \tau_c \\ \dfrac{k(\Delta\tau - 1 + 2d)}{2+k}, & \tau_c < \Delta\tau \leq \tau_d \\ \dfrac{k(1 - \Delta\tau)}{2-k}, & \tau_d < \Delta\tau \leq \tau_f \\ \dfrac{k(\Delta\tau - 1 - 2d)}{2+k}, & \tau_f < \Delta\tau \leq \tau_g, \end{cases} \tag{12}$$

where $\tau_a = (1+k)d$, $\tau_b = 2d$, $\tau_c = 1 - 2d$, $\tau_d = 1 - (2-k)d/2$, $\tau_f = 1 + (2-k)d/2$, $\tau_g = 1 + 2d$.

According to the formula (12), the multipath error envelope of the sweep carrier signal under the Strobe technique can be obtained, thereby obtaining the multipath mitigation performance.

The signal parameters is the same as narrow correlation. The narrow correlator spacing of Strobe technology is 0. 1 chip. The multipath error curves under the Strobe correlation technique are shown in Fig. 5.

In Fig.5, as the sweep bandwidth becomes larger, the Strobe technique can completely suppress the large-delay multipath and has a certain suppression effect on the short-delay multipath. Fig. 4 is compared with Fig. 5, the Strobe technique has better multipath mitigation performance than the narrow correlation technique at the same sweep bandwidth.

C. FACTORS INFLUNCING MULTIPATH SUPPRESSION

Carrier center frequency, sweep bandwidth and sweep period are three parameters of carrier sweep signal. In this section, the effects of these three parameters on multipath suppression performance are analyzed under narrow correlation technique.

1) SWEEP BANDWIDTH

The effects of different sweep bandwidths against multipath performance are analyzed at the same carrier center frequency and sweep period. As can be seen from Fig. 4 and Fig. 5, as the sweep bandwidth increases, the multipath error envelope becomes smaller, and the multipath suppression effect is better.

2) SWEEP PERIOD

The effects of different sweep periods against multipath performance are analyzed at the same carrier center frequency and sweep bandwidth. The sweep bandwidth is set to 4.092MHz, and the sweep periods are 2ms and 0.0625ms respectively. The code phase multipath error curve is shown in Fig. 6.

As shown in Fig. 6, under the same integral time, the multipath error envelopes of two signals with different sweep periods are almost the same, so the frequency sweep period has no effect on multipath suppression.

3) CARRIER CENTER FREQUENCY

The carrier sweep bandwidth is set to 4.092MHz, and the sweep period is 2ms. Under the same sweep bandwidth and period, the effects of multipath suppression with different carrier center frequencies are analyzed, as shown in Fig. 7.

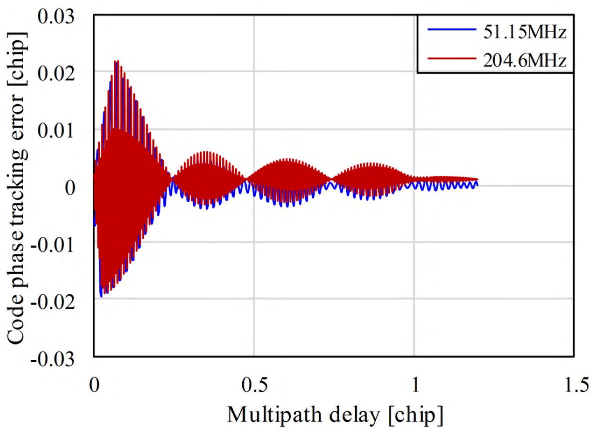

FIGURE 7. Multipath error curves under the narrow correlation technique.

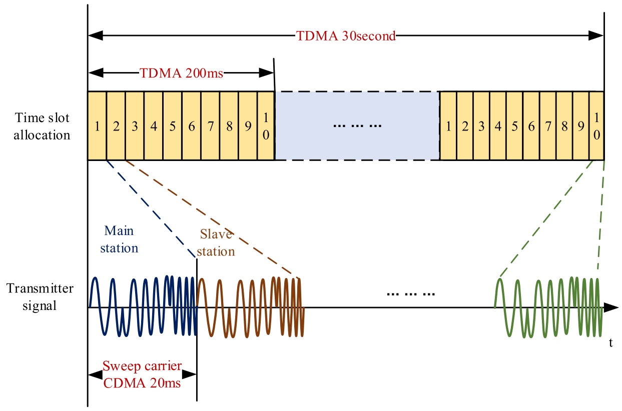

FIGURE 8. TDMA+CDMA signal structure based on linear sweep carrier.

In Fig. 7, comparing the multipath error curves with two different center frequencies, the envelopes are basically the same. Therefore, the signal center frequency has little effect on multipath suppression.

In summary, the sweep bandwidth is the main factor that affects multipath suppression performance, while the sweep period and the carrier center frequency have little effect on multipath suppression.

IV. TDMA+CDMA SIGNAL SYSTEM BASED ON LINEAR SWEEP CARRIER

Aiming at solving the multipath effect and near-far effect of ground-based radio navigation transmitter system, a time-division and code-division signal system based on linear sweep carrier is designed.

Linear sweep carrier can improve the multipath pseudorandom code correlation characteristics and effectively suppress multipath interference. Applying a linear sweep carrier to CDMA modulated signal can increase multipath suppression ability; Near-far problem is a cross-correlation interference issue, and the fundamental solution is to adopt TDMA signal system. The TDMA+CDMA signal structure of the radio navigation transmitter based on linear sweep carrier is as follows in Fig. 8.

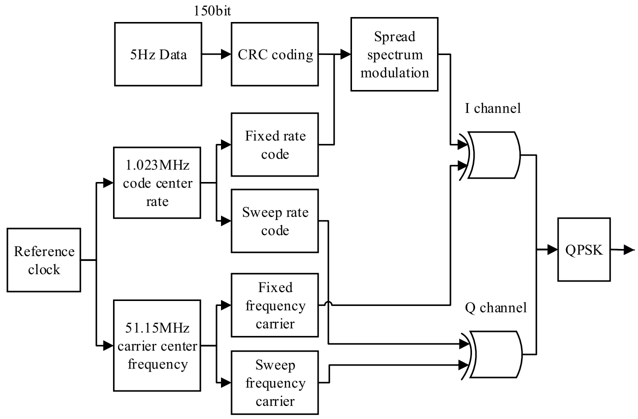

FIGURE 9. Sweep carrier modulation flow.

A. STRATEGY OF TIME SLOT ALLOCATION

In order to solve the near-far effect, TDMA signal system is adopted in the system. This section introduces the strategy of time slot allocation.

One day of 86400s is divided into 2880 superframes and each superframe is 30s. Each superframe is divided into 150 time frames, and each time frame is 200ms. Each time frame is divided into 10 time slots, and each station occupies a fixed time slot. CDMA linear sweep carrier signal system is adopted in each time slot. Each time slot includes 1-bit message of 18ms and transmission protection time of 2ms. The transmission protection time takes into account the signal overlap caused by long-distance signal transmission time, crystal frequency drift and other factors, completely avoiding cross-correlation interference.

B. LINEAR SWEEP CDMA SIGNAL

This section designs a linear sweep CDMA modulated signal to improve the multipath mitigation performance of the radio navigation system. The overall structure is similar to QPSK modulation, that is, the data channel adopts a fixed carrier frequency while the pilot channel adopts a linear sweep carrier. The carrier sweep bandwidth is 4MHz and the sweep period is 2ms, during which carrier frequency increases 1ms and then decreases 1ms. The signal modulation flow is shown in Fig. 9.

V. EXPERIMENTS AND RESULTS

This section is mainly about the multipath mitigation verification and analysis of the designed TDMA+CDMA sweep carrier signal system, and the verification experiment includes two parts: hardware multipath simulation test and actual multipath environment test.

A. HARDWARE MULTIPATH SIMULATION TEST

The verification of the signal multipath mitigation performance can be quantitatively analyzed using direct signal and multipath signal generated by the navigation transmitter.

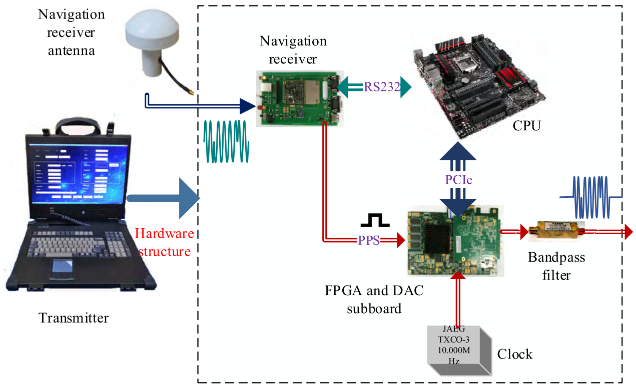

FIGURE 10. Hardware structure of the navigation transmitter.

The hardware structure of the navigation transmitter is shown in Fig. 10.

The parameters of the navigation transmitter to generate analog signal are as follows: the amplitude ratio of multipath signal to direct signal is 0.5 and the multipath delay is 0.2 chips; Carrier center frequency is 51.15 MHz with carrier sweep bandwidth of 4.092 MHz and sweep period of 2ms. The analog signal is collected under the sampling rate of 125MHz and processed by correlation and phase discrimination. The correlation and phase discrimination curves are shown in Fig. 11.

In Fig. 11, the correlation curve of the fixed frequency signal is distorted, proving that there are multipath components in the signal. The correlation curve and phase discrimination curve of sweep carrier signal are normal, indicating that the sweep carrier signal has obvious suppression effect on multipath. In Fig. 11 (a), the S-curve of the sweep carrier signal has 6 sampling points less than that of the fixed-frequency carrier signal (namely 14.39m); In Fig. 11 (b), the S-curve of the sweep carrier signal has 2 sampling points less than that of the fixed-frequency carrier signal (namely 4.80m).

Under the two different correlator spacings, the S-curves of the sweep carrier signal almost have no distortion, and the zero point is almost unchanged, while the multipath component is basically suppressed.

B. ACTUAL MULTIPATH ENVIRONMENT TEST

The actual multipath environmental testing site is the narrow corridor on the third floor of a high building. The distance between the transmitter and the receiving antenna is about 80 meters. A narrow environment can make multiple multipaths reaching the receiving antenna, which could clearly verifies the multipath mitigation performance of the signal using TDMA+CDMA sweep carrier system. The scenario is shown in Fig. 12.

The signal received by the antenna is collected and processed at a sampling rate of 125MHz. With a narrow correlator spacing of 0. 1 chip, code correlation and phase discrimination curves of I and Q channels are shown in Fig. 13.

In Fig. 13, the correlation curve of the fixed frequency channel is distorted, which demonstrates the existence of

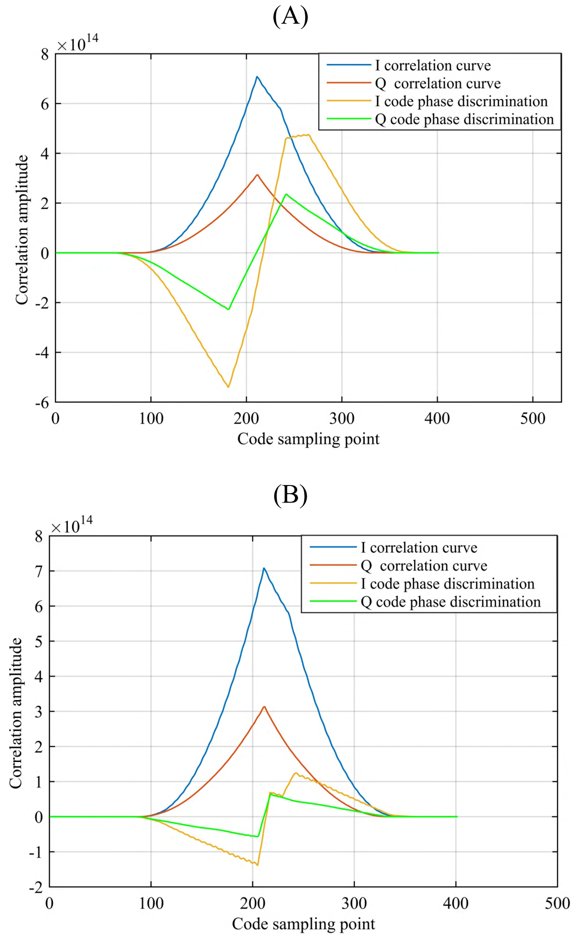

FIGURE 11. Correlation curve and phase discrimination. A: Correlator spacing of 0.5chip. B: Correlator spacing of 0.1chip.

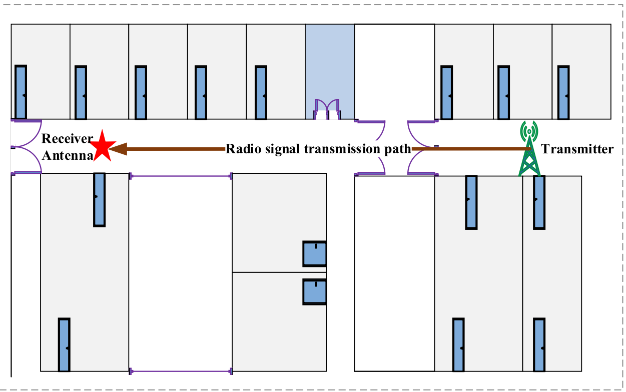

FIGURE 12. Actual multipath test environment.

severe multipath in the received signal. The correlation curve of the sweep carrier signal is less distorted than that of the fixed frequency signal, and the phase discrimination error of the sweep carrier signal is 17 sampling points (namely 39.848 m) less than that of the fixed frequency signal. It can be concluded that the sweep carrier signal significantly improves the code phase discrimination accuracy.

The hardware signal simulation test and the actual environment signal test prove that the correlation curve distortion of

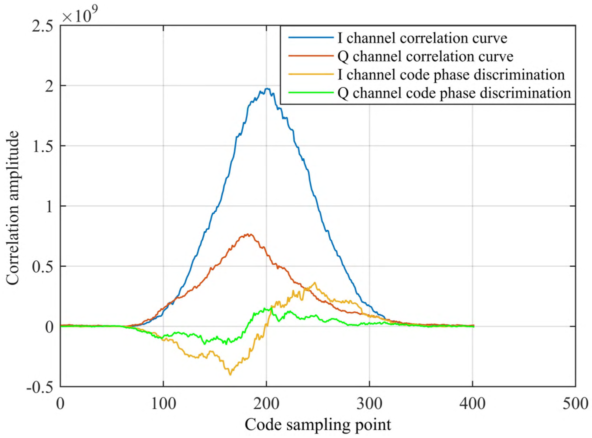

FIGURE 13. Code correlation curve and phase discrimination.

sweep carrier signal is smaller than that of fixed frequency signal, and sweep carrier signal can effectively suppress the multipath error and greatly improve the ranging precision.

VI. CONCLUSION

A ground-based radio navigation system with GNSS system as the space-time reference is designed in this paper. Aiming at the multipath problem and the near-far effect in the system, a TDMA+CDMA mixed signal system based on linear sweep carrier is proposed. Linear sweep carrier can improve the correlation characteristics of multipath signal pseudorandom codes, and the multipath error envelope is small. The time slot allocation strategy proposed in this paper fundamentally solves the problem of near-far effect. The paper completes the design of a new signal system with multipath mitigation and anti-near-far effects, and realizes the verification under the hardware multipath simulation and the actual multipath environment. The results show that the correlation curve distortion of the sweep carrier signal is smaller than that of the fixed frequency signal, and the ranging accuracy can be greatly improved.

REFERENCES

[1] Z. Mengyang, L. Baowei, and S. Wenmiao, "Analyses of multipath effects in the GPS system," *Acta Electron. Sinica*, 1998.
[2] L. Cheng, M. F. Ren, and G. Xie, "Multipath estimation based on centered error entropy criterion for non-Gaussian noise," *IEEE Access*, vol. 4, pp. 9978–9986, 2016.
[3] G. Xie, *Principles of GPS and Receiver Design*. Beijing, China: House of Electronics Industry, 2009.
[4] J. Malmström, "Robust navigation with GPS/INS and adaptive beamforming," Swedish Defence Res. Agency, Sci. Rep., 2003, pp. 1650–1942.
[5] S. M. Amjadi, M. Hoque, and K. Sarabandi, "An iterative array signal segregation algorithm: A method for interference cancelation and multipath mitigation in complex environments," *IEEE Antennas Propag. Mag.*, vol. 59, no. 3, pp. 16–32, Jun. 2017.
[6] R. D. J. van Nee, "Multipath effects on GPS code phase measurements," in *Proc. 4th Int. Tech. Meeting Satell. Division Inst. Navigat. (ION GPS)*, Albuquerque, NM, USA, Sep. 1991, pp. 915–924.
[7] A. J. van Dierendonck, P. Fenton, and T. Ford, "Theory and performance of narrow correlator spacing in a GPS receiver," *Navigation*, vol. 39, no. 3, pp. 265–283, Sep. 1992.
[8] M. Irsigler and B. Eissfeller, "Comparison of multipath mitigation techniques with consideration of future signal structures," in *Proc. Int. Tech. Meeting Satell. Division Inst. Navigat.*, Portland, OR, USA, 2003, pp. 2584–2592.
[9] L. Garin and J.-M. Rousseau, "Enhanced strobe correlator multipath rejection for code & carrier," in *Proc. 10th Int. Tech. Meeting Satell. Division Inst. Navigat. (ION GPS)*, Kansas City, MO, USA, 1997, pp. 559–568.
[10] Z. Liu, L. Huang, X. Tang, and F. Wang, "Multipath mitigation strobe for global navigation satellite system receivers," *Electron. Lett.*, vol. 52, no. 11, pp. 962–963, May 2016.
[11] S. Attia, K. Rouabah, D. Chikouche, and M. Flissi, "Side peak cancellation method for sine-BOC(m,n)-modulated GNSS signals," *EURASIP J. Wireless Commun. Netw.*, vol. 2014, no. 1, p. 34, 2014.
[12] N. Sokhandan, J. T. Curran, A. Broumandan, and G. Lachapelle, "An advanced GNSS code multipath detection and estimation algorithm," *GPS Solutions*, vol. 20, no. 4, pp. 627–640, 2016.
[13] M. Z. H. Bhuiyan, J. Zhang, E. S. Lohan, and W. Wang, "Analysis of multipath mitigation techniques with land mobile satellite channel model," *Radioengineering*, vol. 21, no. 4, pp. 1067–1107, 2012.
[14] H. Hurskainen, E. S. Lohan, X. Hu, J. Raasakka, and J. Nurmi, "Multiple gate delay tracking structures for GNSS signals and their evaluation with Simulink, SystemC, and VHDL," *Int. J. Navigat. Observ.*, vol. 2008, no. 5, Feb. 2008, Art. no. 785695.
[15] Y.-M. Gan and Y.-L. Zhou, "Multipath suppression performance analysis of multiple gate delay structure for GNSS signals," *Telecommun. Eng.*, vol. 54, no. 7, pp. 905–909, 2014.
[16] Y. Gan, "Performance analysis of multipath mitigation for BOC modulated signals based on multiple gate delay structure," in *Proc. 12th Int. Conf. Signal Process.*, Oct. 2015, pp. 1709–1712.
[17] B. R. Townsend, P. C. Fenton, K. J. V. Dierendonck, and D. J. R. Van Nee, "Performance evaluation of the multipath estimating delay lock loop," *Navigation*, vol. 42, no. 3, pp. 502–514, 1995.
[18] L. R. Weill, "Multipath mitigation using modernized GPS signals: How good can it get?" in *Proc. 15th Int. Tech. Meeting Satell. Division Inst. Navigat. (ION GPS)*, Portland, OR, USA, 2002, pp. 493–505.
[19] P. C. Fenton and J. Jones, "The theory and performance of NovAtel Inc.'s vision correlator," in *Proc. 19th Int. Tech. Meeting Satell. Division Inst. Navigat. (ION GPS)*, Long Beach, CA, USA, 2005, pp. 2178–2186.
[20] Q. Yang, H. Qin, and H. Yuan, "Multipath analysis of GNSS measured data based on TK-MEDLL," *J. Navigat. Positioning*, 2017.
[21] X. Chen, F. Dovis, S. Peng, and Y. Morton, "Comparative studies of GPS multipath mitigation methods performance," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 49, no. 3, pp. 1555–1568, Jul. 2013.
[22] H. Chengyan, G. Ji, L. Xiaochun, and L. Jun, "Multipath performance analysis of GNSS navigation signals," in *Proc. IEEE Workshop Electron., Comput. Appl.*, May 2014, pp. 379–382.
[23] E. S. Lohan and M. Renfors, "Correlation properties of multiplexed binary offset carrier (MBOC) modulation," in *Proc. Eur. Wireless*, 2007, p. 7.
[24] A. Pirsiavash, A. Broumandan, and G. Lachapelle, "Performance evaluation of signal quality monitoring techniques for GNSS multipath detection and mitigation," in *Proc. Int. Tech. Symp. Navigat. Timing*, 2017, pp. 14–17.
[25] H. Xiong, S. Wang, S. Gong, M. Peng, J. Shi, and J. Tang, "Improved synchronisation algorithm based on reconstructed correlation function for BOC modulation in satellite navigation and positioning system," *IET Commun.*, vol. 12, no. 6, pp. 743–750, 2018.
[26] L. Marchetti and R. Reggiannini, "An efficient receiver structure for sweep-spread-carrier underwater acoustic links," *IEEE J. Ocean. Eng.*, vol. 41, no. 2, pp. 440–449, Apr. 2016.
[27] Y. Xie, C. Xu, X. Tang, and F. Wang, "A multipath mitigation method based on carrier frequency sweeping for satellite navigation signal," *J. Navigat. Positioning*, vol. 5, pp. 38–43, 2017.

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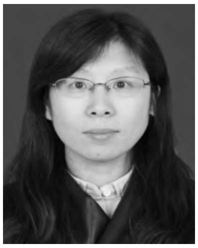

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