Research on Phase-Control Technology of Recovery Terminal by Two-Way Optical Fiber Time Frequency Transfer Method

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Abstract: Optical fiber time-frequency transmission technology is one of the key technologies of satellite navigation system for global service. With the application background of the construction of time-frequency system in satellite navigation field, the phase consistency control technology of two-way time-frequency transmission of optical fiber is studied, and the experimental analysis is carried out. The results show that the phase consistency control accuracy is better than 100ps when the optical fiber transmission distance is within 10km, which provides a solution for engineering application of remote time-frequency technology with high precision.

1 INTRODUCTION

Global Navigation Satellite System (GNSS) is new generation of radio navigation system, which has the advantages of global, all-day and all-weather navigation, positioning, timing and speed measurement to meet supply urgent demand for space-time information in many fields in today's information society (Gang Xie, 2013). Due to the complex structure and signal propagation environment of the satellite navigation system and scattered locations (Rong Qiang, 2011), It is very important to realize the high-fidelity time-frequency signal transmission between the front-end equipment and the terminal equipment during the time-frequency signal transmission between the ground stations of the large-scale satellite navigation system, which requires the time-frequency signal transmitted to the terminal to achieve impedance matching within a long distance and provide a low amplitude Degree loss, low noise insertion loss, maintain high fidelity signal quality, especially the demand for signal phase consistency and time signal synchronization accuracy.

Optical fiber two-way time-frequency transmission technology is an ideal transmission means because of its small transmission attenuation, less stability insertion loss, low implementation cost, simple configuration, convenient and flexible (Zhu X, 2015). According to the relevant literature (Schnatz H - Lopez O), it can be seen that the current optical fiber frequency transmission method can reach or exceed the stability of 1×10^{-14}/s, 2×10^{-16}/day, and the phase noise of -120dBc/Hz@1Hz, and the accuracy of frequency transmission can maintain the same order of magnitude as the input. However, for the requirement of phase consistency, this index (Schnatz H - Lopez O), is not mentioned in the relevant literature of optical fiber time-frequency transmission method at present, and there is a lack of engineering application guidance, so it is difficult to achieve and needs to be analyzed and studied.

Optical fiber two-way time-frequency transmission technology needs to solve the phase synchronization problem of terminal recovery signal. At the end of the signal recovery, phase noise purification and distribution after amplification, the phase between all signals is arbitrary, which is to obtain the time difference between them and the front-end signal through phase measurement technology, and control them to maintain phase consistency with the front-end signal through phase adjustment.

Aiming at the difficulty of restoring terminal phase consistency control by optical fiber time-

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frequency transmission method, this paper proposes and discusses the design and implementation of a phase consistency control method for optical fiber time-frequency signal transmission, and verifies its feasibility and performance through experimental analysis.

2 BASIC PRINCIPLE OF FIBER TWO-WAY TRANSMISSION METHOD

Optical fiber time-frequency transmission technology has been studied in foreign countries for more than 30 years. From the initial unidirectional time-frequency transmission method to the widely used optical fiber two-way time-frequency transmission method (Xiaohui LI, 2010), the synchronization accuracy has entered the sub-nanosecond order, which is an important means to realize time synchronization between stations.

The basic principle of fiber two-way time frequency transmission technology is: station A and station B send and receive time signals each other (such as 1PPS), signals generally through multiplexing technology coupled in A fiber transmission, because station A and station B send and receive signals at the same time, two-way transmission path is basically the same, its propagation delay can be effectively cancelled; In addition, if station B can't independently generate the time-frequency reference, it can also be combined with one-way time-frequency transmission method to pass the frequency reference of station A to station B. Its implementation principle block diagram is shown as Figure 1:

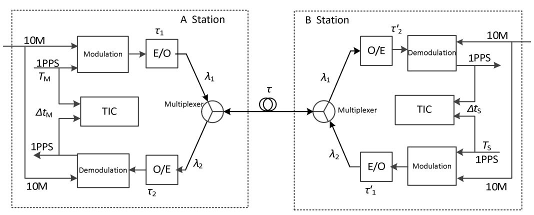

Figure 1: Principle of fiber optic two-way time frequency transmission method.

The time of station A is denoted as T_M, the time of station B is denoted as T_S, the comparison and measurement result of station A is Δt_M, and the comparison and measurement result of station B is Δt_S. It is assumed that the delay of the transmitting device at station A is τ_1, the delay of the receiving device at station A is τ_2, and the delay of the transmitting device at station B is τ'_1, the delay of the receiving device at station B is τ'_2, the optical fiber path transmission delay is τ, then:

$$\Delta t_M = T_M - (T_S + \tau'_1 + \tau + \tau_2) \quad (1)$$

$$\Delta t_S = T_S - (T_M + \tau'_2 + \tau + \tau_1) \quad (2)$$

let station A and station B use the same transmitting and receiving technology, it is considered that $\tau_1 = \tau'_1$, $\tau_2 = \tau'_2$, then the time difference between station A and station B is:

$$T_M - T_S = (\Delta t_M + \Delta t_S) / 2 \quad (3)$$

In formula (3), the circuit delay of station A and station B at the receiving and transmitting ends is not equal, and the delay of the device must be measured and calibrated. At this time, the time difference between station A and station B is:

$$T_M - T_S = \frac{\Delta t_M - \Delta t_S + \tau'_1 - \tau_1 + \tau_2 - \tau'_2}{2} \quad (4)$$

In Formula (4), station A and station B use high-precision phase measurement technology to measure Δt_M and Δt_S, and adjust the time-frequency reference of the recovery terminal of station B using high-precision phase control technology according to the comparison measurement results, so as to realize the time-frequency transmission and time synchronization of station A and station B.

3 PHASE CONTROL METHOD OF OPTICAL FIBER RECOVERY TERMINAL

When the time frequency signal of the optical fiber time frequency transmission recovery terminal is recovered, multiple types of local time frequency signals will be generated, and the delay of multiple PLL and frequency division circuit will be inconsistent in the design, and each time the device is started, reset or PLL relock will cause large delay uncertainty, resulting in non-synchronization between multiple types of time frequency signals. Therefore, a local high-resolution phase regulation method is needed to regulate the local signal according to the time difference between stations calculated by the two-way time and frequency transmission method of optical fiber, so that the phase consistency of the multi-class time and frequency signals generated locally in real time is constrained within a reasonable index range, and high-precision services are provided for the back-end time-used frequency equipment.

3.1 Principle of High-Precision Phase Adjustment Method

High-precision phase adjustment can be achieved by controlling the output phase of the frequency synthesizer. PLL (Phase Locked Loop) based on DDS (Direct Digital Synthesis) The frequency synthesis technology of Loop is a high-precision phase adjustment method, which has the advantages of simple structure, convenient control, high phase control accuracy and resolution (<lps), unrestricted phase control range, and low cost. The principle of the specific design and implementation method is shown as figure 2:

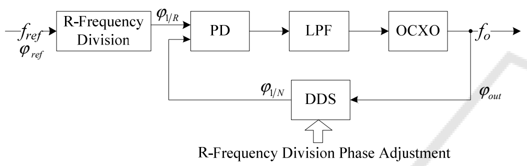

Figure 2: A high-precision phase adjustment method for PLL based on DDS.

Figure 2 PLL high-precision phase adjustment method of DDS schematic block diagram. The above is a closed-loop phase negative feedback control system. In the basic PLL structure shown in the schematic diagram, PLL is used to realize frequency synthesis. In order to ensure the phase noise index of the output frequency signal, OCXO is selected as VCO; Loop phase is automatically controlled by DDS negative feedback, PLL loop output phase is realized by controlling 1N in the output phase of DDS, and at the same time, the N frequency divider is matched with the input reference R frequency divider for phase identification: PLL output is used as the clock of the post-stage time-frequency reference regeneration. Considering the phase control relationship of PLL, in the PLL loop, the phase discriminator thinks that the output phase of the N divider is the output phase of the VCO, that is, the final output phase of the PLL loop. When the VCO output phase changes, the N frequency divider phase changes, the phase discriminator output adjustment voltage control VCO to adjust the phase, and finally the phase discriminator two input phase equal to reach a steady state. R divider and N divider will introduce phase delay when realizing frequency division, respectively recorded as IR and IN, loop steady state phase divider R divider and N divider output phase equal, then PLL output phase 0out and reference input phase n has the following relationship:

$$\varphi_{out} = \varphi_{ref} + \varphi_{1/R} - \varphi_{1/N} \tag{5}$$

According to formula (5), the PLL output phase is determined by the phase delay of the R divider and the N divider. Changing the phase delay of the N/R divider will also change the output phase of the PLL, and then realize the delay adjustment of the back-end time-frequency reference signal. In this scheme, phase adjustment is carried out by changing the N frequency divider of DDS. The formula of res of DDS phase control resolution can be obtained by referring to (Gong Hang, 2008):

$$\varphi_{res} = \frac{T_{out,DDS}}{2^{N_p}} = \frac{1}{2^{N_p}} \cdot \frac{N_D}{f_{clk,DDS}} \tag{6}$$

In formula (6), where N is the phase control word length and $f_{\mathrm{clk,DDS}}$ is the DDS output frequency. As can be seen, the resolution is not only related to the phase control word length, but also directly related to the output frequency of DDS, the greater N, the higher $f_{\mathrm{clk,DDS}}$, the higher resolution.

3.2 Local Time-Frequency Signal Phase Control Method

For the phase alignment of local time-frequency signal, a phase control method of local time-frequency signal based on optical fiber two-way comparison measurement data, DDS phase lock adjustment and ARM automatic control is proposed. The implementation principle is shown in FIG3. Set the reference input signal f, the measured signal f is also the feedback signal of the local output time-frequency signal, and fou is the local output time-frequency signal.

If f_r is completely synchronized with station A through the method in Section 2, then when f_r is aligned with the phase of f_{out}, the phase comparison result measured by the external high-precision phase comparator (PCO) is T_r, assuming that the time delay between the two measuring channels of PCO is equal to the cable time delay, then $T_r \approx 0$,

It can be considered that the phase of the recovery terminal time-frequency signal at station B has been completely synchronized with that at station A. Set the real-time phase difference of the measurement of two-way comparison at this time to $\varDelta T$, then through real-time monitoring of the difference between the measurement value of two-way comparison and the zero value $\varDelta t = \varDelta\ T - T_1$ you can achieve real-time control and alignment of the phase of the local time-frequency signal, set the threshold of real-time phase adjustment toΦ, then:

$$\begin{cases} \Delta\tau=\Delta T\text{-}\ T_{1}\leq\Phi\ , & \text{turn off} \\ \Delta\tau=\Delta T\text{-}\ T_{1}>\Phi\ , & \text{turn on} \end{cases} \tag{7}$$

Through the real-time monitoring of formula (7) decision conditions by ARM microprocessor, the phase of the local time-frequency signal can be aligned in real-time self-closed loop phase to achieve local phase consistency control.

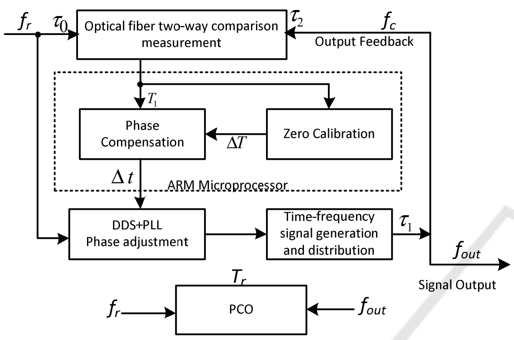

Figure 3: Principle of local time-frequency signal phase alignment method.

The method principle of phase consistency control of local time-frequency signal by using optical fiber two-way comparison of real-time measurement data and initial calibration zero value is discussed above. The implementation process is shown as figure 4:

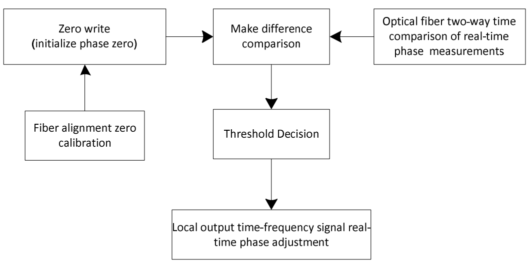

Figure 4: Phase alignment method implementation flow chart Specific.

Implementation steps are:

1) When measuring for the first time, calibrate the zero value ΔT of the output time-frequency signal by the local reference time-frequency reference, and store the initial calibration zero value in the phase control register;
2) the optical fiber time ratio is compared with the phase comparison result T_1 of real-time measurement and the zero value ΔT, and the result is Δt;
3) When Δt exceeds the threshold, turn on the output signal Real-time phase adjustment of f_{out};
4) Stop real-time phase alignment when Δt reaches within the threshold.

4 TEST ANALYSIS

4.1 The Design of Test

Test scheme combined with the phase control method of the optical fiber recovery terminal in the upper section, the two-way optical fiber two-way comparison method and DDS phase modulation technology were used to verify the method through the test design, and the test design scheme was connected with the block diagram is shown as figure 5:

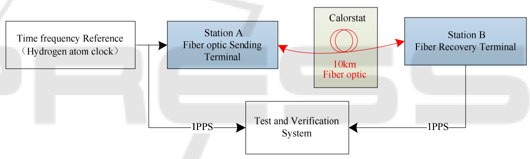

Figure 5: Block diagram of the test design scheme.

The time-frequency reference in the figure above is a hydrogen atom clock. The homologous hydrogen clock in the reference source of the test and verification system has passed the metrological inspection, proving that its indicators are accurate and reliable; The time-frequency transmission terminal and time-frequency recovery terminal are self-developed prototypes; The test system is composed of phase noise analyzer, time interval tester and other measuring equipment, and the test fiber is 10km. The temperature control box is used for temperature regulation and constant temperature control of the test optical fiber.

In the two-way time comparison method, the positive pseudo-code ranging result is Δt_M,,the positive pseudo-code ranging result is Ats, the time of the main station is recorded as T_M, the terminal time is recorded as T_S, the link delay of optical fiber transmission is τ, the time difference between the central node IPPS and the distribution node 1PPS is T_{MS}= T_M,-T_S,and according to formula (1) and formula (2), then:

$$\begin{cases}\Delta t_M = T_M - (T_S + \tau) = (T_M - T_S) - \tau = T_{MS} - \tau \\ \Delta t_S = T_S - (T_M + \tau) = -(T_M - T_S) - \tau = -T_{MS} - \tau\end{cases} \quad (8)$$

For the control of the phase consistency between the central node 1PPS and the distributed node 1PPS, the phase difference that the distributed node 1PPS needs to compensate is T_{MS}, and the phase consistency can be regarded as that the amplitude of T_{MS}, T_{MS} can be controlled within the range of the phase consistency index by compensating T_{MS} in real time.

4.2 Analysis of Results

During the test and verification, the output phase consistency under two typical application scenarios is analyzed.

1) When the central node is the same origin as the distributed node, and the link delay t has no fluctuation and is A constant, then:

$$\begin{cases}T_{MS} = 0 \\ \tau = A \\ \Delta t_M = T_{MS} - \tau = -A \\ \Delta t_S = -T_{MS} - \tau = -A\end{cases} \quad (9)$$

Formula (9) can be understood as that under ideal conditions, the delay of one-way frequency transmission is fixed, and the clock difference of two-way time comparison is about zero. At this time, for distributed nodes, it is necessary to compensate the fixed zero value of the frequency transmission system and align the internal phase to realize the phase consistency control between stations A and B. The test results in this scenario are shown as figure 6:.

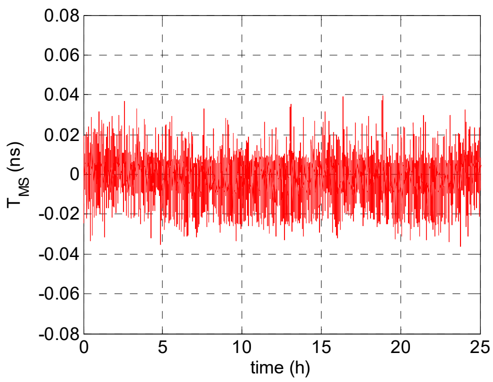

Figure 6: 1PPS phase difference between Station A and Station B(S1).

2) When the central node is the same origin as the distributed node, the link delay rfluctuates and is a variable value, then:

$$\begin{cases}T_{MS} = 0 \\ \Delta t_M = T_{MS} - \tau = -\tau \\ \Delta t_S = -T_{MS} - \tau = -\tau\end{cases} \quad (10)$$

Formula (10) can be understood as the real-time phase alignment adjustment is enabled when the optical fiber is subjected to the temperature regulation delay fluctuation in the temperature control box, the delay fluctuation of one-way frequency transmission is effectively compensated, and the forward delay and reverse delay change laws of two-way comparison are consistent. At this time, the delay fluctuation of the time frequency transmission of the recovery terminal of station B is dynamically compensated, and the fixed zero value of the system is also compensated to realize the phase consistency control of station A and station B. The test results in this scenario are shown as figure 7:

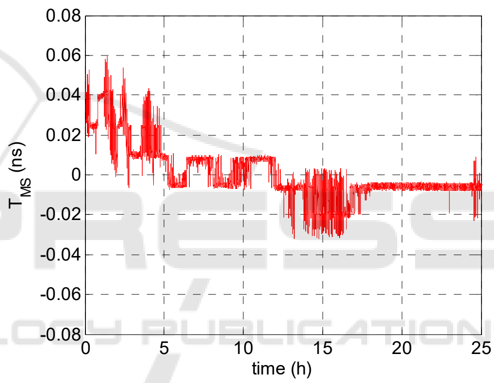

Figure 7: 1PPS phase difference between Station A and Station B(S2).

4.3 Test Summary

In the two test groups, due to the homology test, the clock difference between station A and station B is zero, and the 1PPS phase difference between station A and station B is significantly affected by the fluctuation of link delay. The T_{MS} values of the two scenarios were statistically analyzed, and the maximum value of each group of TMs in the table was defined as the phase consistency measurement results of the group of experiments. Details are shown as Table 1:

Table 1: Statistics of phase consistency test results.

Experimental Scenario	Phase difference consistency control results
S1	0.05ns(50ps)
S2	0.09ns(90ps)

Based on the above analysis, under the condition of 10km indoor optical fiber, the phase-consistency control accuracy of the time-frequency signal transmission method designed in this paper is less than 100ps.

5 CONCLUSION

In summary, we have come to the following conclusion:

1) High precision time-synchronization within and between stations can be achieved.

Using fiber two-way time-frequency transmission can effectively eliminate the asymmetric error of delay, but the accuracy of two-way comparison with drastic change of delay is worse than that of stable change of delay. Through the phase control of terminal recovery signal, the phase synchronization accuracy of recovery signal can reach sub-nanosecond or even higher.

2) It is completely feasible to use the measurement data of optical fiber two-way time frequency method to carry out phase consistency control on the recovery terminal.

The phase consistency test of two-way optical fiber comparison under different scenarios is analyzed. The results show that the phase consistency control method of optical fiber time-frequency signal transmission designed in this paper, by realizing phase consistency control, recovers the phase consistency control of the time-frequency signal output by the terminal (station B) and the 1PPS signal output by the main station (station A). At the transmission distance of 10km optical fiber, the time comparison measurement accuracy of the two scenarios is better than 100ps, which is further verified the proposed phase control method of optical fiber recovery terminal is feasible in engineering application.

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