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Research On High Precision Fiber Optic Platform System Temperature Compensation Technology

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Abstract. In a high-precision fiber optic platform system, temperature changes will have a significant impact on the start-up speed and actual application accuracy. In order to effectively improve the navigation accuracy of the system, the article analyzes the temperature characteristics of the system-level calibration error parameters and establishes a temperature error model. Finally, a temperature compensation test and a platform model calibration test are designed to verify the compensation effect. The test results show that the established temperature error compensation model is accurate and effective. The stability of error parameters has increased by an order of magnitude. The method improves the performance of the fiber optic platform at the start-up stage, and has a small amount of calculation, which has high engineering application value.

Keywords: High-precision; Fiber optic platform; Temperature error compensation; System-level calibration.

1. Introduction

With the in-depth development of the world's new military revolution, the operational objectives of long-range strategic weapons have increasingly shifted from large-scale damage to high-precision fixed-point attack [1]. Therefore, for the platform inertial navigation system, which plays a major role in the inertial navigation system of intercontinental ballistic missile, high precision, high reliability, long life, miniaturization and lightweight have become its main development trend.

As a solid-state optical gyroscope, fiber optic gyroscope has the characteristics of fast start-up, high reliability, wide frequency band range and light weight [2], which meets the new development needs of inertial navigation system [3]. With the improvement of gyro manufacturing technology, the research on optical fiber platform system has become an inevitable choice for the new generation of high-precision inertial platform system. However, as an inertial instrument very sensitive to temperature change, fiber optic gyroscope will be affected by temperature in practical using, resulting in large fluctuations of accuracy [4;5]. At the same time, the quartz accelerometer used in the optical fiber platform system is also sensitive to temperature, and the error parameters have the characteristics of temperature change. In order to solve the temperature error problem in the platform inertial navigation system, most of the previous solutions are 'temperature control' to improve the accuracy of the system, but it is not good for the rapidity of the platform system. In view of the application characteristics of the optical fiber platform, the temperature change will affect the application accuracy of the gyroscope and accelerometer from system power-on to temperature stabilization. In order to improve the application accuracy of the system under the condition of fast start, the temperature modeling of the error parameters of the system is carried out by using the method of 'temperature supplement'.

At present, most of the literature studies only focus on the temperature error modeling of a single table, and only consider the impact of temperature on the instrument, without the error of the instrument simultaneously excited [6-8]. A few literatures on temperature compensation of strapdown inertial navigation system also have the problems that the temperature compensation model is not comprehensive and the system temperature error is not compensated in essence.

The paper [9] studied the temperature characteristics of gyro in the fiber strapdown inertial system, and established a temperature error model of gyro zero deviation by two-dimensional interpolation

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method. After compensation, the stability of gyro zero deviation was significantly improved, but the temperature error modeling was not carried out for the remaining error parameters of inertial system.

The paper [10] proposed the method of wavelet neural network to establish the temperature error model of gyro bias in optical fiber strapdown inertial unit, and considered the influence of nonlinear terms of temperature and temperature change rate on gyro bias. In paper [11], in view of the current temperature compensation methods of single meter, the zero offset and the scale factor are compensated separately, a method of compensating the scale factor and the zero offset simultaneously is proposed, which can save the test time. In paper [12], based on the idea of piecewise modeling, the author uses particle swarm optimization algorithm to establish the zero bias temperature error model of fiber optic gyroscope, which can compensate the temperature error in real time, but it is easy to fall into local optimal solution in calculation. The above methods are all based on split calibration, which is difficult to meet the requirements of dynamic application environment of optical fiber platform system.

This paper presents a high precision temperature compensation method for optical fiber platform system. According to the working temperature range of the optical fiber platform, the high and low temperature test is designed, and the system level calibration is carried out at different temperatures. The system error parameters are fully excited by the rolling of the platform frame, and then the fitting model of all the system error parameters with respect to temperature is established by cubic spline interpolation method. Finally, the error parameter temperature model is substituted into the temperature error compensation model of the optical fiber platform to realize the temperature error compensation of the system. Experimental results show that the stability of system error parameters of optical fiber platform is greatly improved after temperature error compensation, and this method has high engineering application value.

2. Temperature Error Model of Optical Fiber Platform

The optical fiber platform system adopts multi-level and multi parameter calibration technology. The primary calibration is the strapdown mode error calibration, which fully excites the error parameters and completes the calibration of most error parameters of the system. The primary calibration adopts the 19-position calibration method [13]. Secondary calibration is the platform mode error calibration, which mainly calibrates the error parameters of the application level of the platform, with less frame turnover position and short calibration time. The secondary calibration adopts the platform system 6 position calibration method.

During calibration, the zero bias, scale factor error, installation error of gyroscope and accelerometer will be affected by temperature. Therefore, it is necessary to establish the error parameter model related to temperature.

2.1 Temperature Error Model of Primary Strapdown Mode

2.1.1 Temperature Error Model of Gyroscope

According to the gyroscope error model of the optical fiber platform, the error parameters of the gyroscope include zero bias ω_{0x}^p, ω_{0y}^p, ω_{0z}^p, installation errors E_{zx}, E_{yx}, E_{zy}, E_{xy}, E_{yz}, E_{xz} and scale factor errors δE_x, δE_y, δE_z. Temperature error model of system-level calibration gyroscope considering the influence of temperature on error parameters:

$$\delta\boldsymbol{\omega}_{ip}^p(T)=\boldsymbol{\omega}_0^p+\left(\delta\boldsymbol{E}_g(T)+\boldsymbol{E}_g(T)\right)\boldsymbol{\omega}_{ip}^p \tag{1}$$

In the above formula：

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$\delta\boldsymbol{\omega}_{ip}^{p}(T)$ is the measurement error of gyroscope affected by temperature in three axis directions. $\boldsymbol{\omega}_0^p(T)$ is the zero position of the gyroscope related to temperature in the three axis directions. $\delta\boldsymbol{E}_g(T)$ is the gyroscope scale factor error matrix related to temperature. $\boldsymbol{E}_g(T)$ is the gyro installation error matrix related to temperature. $\boldsymbol{\omega}_{ip}^{p}$ is the rotational angular velocity of the gyroscope in the three axis directions.

2.1.2 Temperature Error Model of Accelerometer

According to the accelerometer error model of the optical fiber platform, the error parameters of the accelerometer channel include zero bias f_{0x}, f_{0y}, f_{0z}, installation errors K_{xz}, K_{xy}, K_{yz}, K_{yx}, K_{zy}, K_{zx} and scale factor errors δK_x, δK_y, δK_z. There are 12 error parameter items in total, and all error parameters are related to temperature.

Temperature error model of system level calibration accelerometer considering the influence of temperature on error parameters:

$$\delta\boldsymbol{f}_{ip}^{p}(T)=\boldsymbol{f}_0^p(T)+\left(\delta\boldsymbol{K}_a(T)+\boldsymbol{K}_a(T)\right)\boldsymbol{f}^p \tag{2}$$

In the above formula：

$\delta\boldsymbol{f}_{ip}^{p}(T)$ is the output measurement error of the accelerometer on the three axes. $\boldsymbol{f}_0^p(T)$ is the zero bias value of the accelerometer in the direction of three axes. $\delta\boldsymbol{K}_a(T)$ is the scale factor error matrix of the accelerometer related to temperature. $\boldsymbol{K}_a(T)$ is the installation error matrix of the accelerometer related to temperature. $\boldsymbol{f}^p$ is the acceleration in three axis directions in platform coordinate system.

2.2 Temperature Error Model of Secondary Platform Mode

After the off-line compensation of the primary strapdown mode, the error model of the secondary platform mode is greatly simplified.

2.2.1 Temperature Error Model of Gyroscope

$$\begin{cases}\omega_x^p=\omega_{0x}^p(T)\\ \omega_y^p=\omega_{0y}^p(T)\\ \omega_z^p=\omega_{0z}^p(T)\end{cases} \tag{3}$$

In the above formula：

ω_x^p, ω_y^p and ω_z^p are the platform drift angular rates of the three axes of the platform coordinate system respectively. $\omega_{0x}^p(T)$, $\omega_{0y}^p(T)$ and $\omega_{0z}^p(T)$ are the secondary model parameters of gyroscope zero position related to temperature in the three axis directions.

2.2.2 Temperature Error Model of Accelerometer

$$\begin{bmatrix}N_{ax}^p\\ N_{ay}^p\\ N_{az}^p\end{bmatrix}/\Delta\mathrm{T}=\begin{bmatrix}K_{0x}^p(T)\\ K_{0y}^p(T)\\ K_{0z}^p(T)\end{bmatrix}+\begin{bmatrix}K_{1x}(T) & 0 & 0\\ 0 & K_{1y}(T) & 0\\ 0 & 0 & K_{1z}(T)\end{bmatrix}\begin{bmatrix}\mathrm{A}_x^p\\ \mathrm{A}_y^p\\ \mathrm{A}_z^p\end{bmatrix} \tag{4}$$

In the above formula：

ΔT is the sampling period. N_{ax}^p, N_{ay}^p and N_{az}^p are respectively the pulse increment of the accelerometer in the three axis directions. A_x^p, A_y^p and A_z^p are respectively the apparent accelerations in the three axis directions under the orthogonal platform system. $K_{0x}^p(T)$, $K_{0y}^p(T)$ and $K_{0z}^p(T)$ are temperature related accelerometer zero position secondary model parameters in three

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axis directions . $K_{1x}^{p}(T)$, $K_{1y}^{p}(T)$ and $K_{1z}^{p}(T)$ are the secondary model parameters of accelerometer scale factor related to temperature in three axis directions.

3. Temperature Error Modeling

3.1 Method of Temperature Error Modeling

Before compensating the temperature error of optical fiber platform system, it is necessary to establish the mathematical model of error parameters about temperature. According to the previous test analysis, the data sampled at different temperatures of the optical fiber platform fluctuates greatly after integration, and many key data points are often ignored by the polynomial modeling method [14]. The model established by spline interpolation method must contain the selected data points, and the curve is continuously derivable at the segment connection, which not only retains the characteristics of data, but also obtains a model with higher accuracy.

In order to minimize the amount of calculation on the premise of ensuring the modeling accuracy, cubic spline function is usually used for modeling. The cubic spline function $S(x)$ approximates the function $y = f(x)$ in the form of piecewise cubic polynomial. And $S(x)$ satisfies the condition of cubic spline interpolation function with $y = f(x)$ on interval $[a, b]$. Take the following interpolation points on the interval $[a, b]$: $a = x_0 < x_1 < \cdots < x_{n-1} < x_n = b$. y_i is the value of function $y = f(x)$ at each node.

The cubic spline function is:

$$S(x_i) = y_i (i = 0, 1, \ldots, n) \tag{5}$$

The following formula can be obtained from the interpolation conditions.

$$S''(x) = \frac{x - x_i}{-(x_i - x_{i-1})} S''(x_{i-1}) + \frac{x - x_{i-1}}{x_i - x_{i-1}} S''(x_i), (i = 1, 2, \ldots, n) \tag{6}$$

Take $P_i = S''(x_i)$, $h_i = x_i - x_{i-1}, (i = 1, 2, \ldots, n)$.

Combined boundary conditions: $S''(x_0) = y_0'', S''(x_n) = y_n''$,and integrated equation (6) twice to obtain:

$$\begin{aligned} S(x) = &\frac{P_{i-1}}{6h_i}(x_i - x)^3 + \frac{P_i}{6h_i}(x - x_{i-1})^3 \\ &+ (\frac{y_{i-1}}{h_i} - \frac{P_{i-1}}{6} h_i)(x_i - x) \\ &+ (\frac{y_i}{h_i} - \frac{P_i}{6} h_i)(x - x_{i-1}), \\ &x_{i-1} \le x \le x_i, (i = 1, 2, \ldots, n) \end{aligned} \tag{7}$$

According to the continuity of the first derivative at the node and the boundary conditions, the following linear equations can be obtained.

$$\begin{bmatrix} 2 & \alpha_0 & 0 & 0 & 0 \\ \gamma_1 & 2 & \alpha_1 & 0 & 0 \\ 0 & \ddots & \ddots & \ddots & 0 \\ 0 & 0 & \gamma_{n-1} & 2 & \alpha_{n-1} \\ 0 & 0 & 0 & \gamma_n & 2 \end{bmatrix} \begin{bmatrix} P_0 \\ P_1 \\ \vdots \\ P_{n-1} \\ P_n \end{bmatrix} = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_{n-1} \\ \beta_n \end{bmatrix} \tag{8}$$

In equation(8):

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$$\alpha_i = \frac{h_{i+1}}{h_i + h_{i+1}}, \gamma_i = 1 - \alpha_i,$$

$$\beta_i = \frac{6}{h_i + h_{i+1}}\left(\frac{y_{i+1} - y_i}{h_{i+1}} - \frac{y_i - y_{i-1}}{h_i}\right)$$

Thus, P_i can be obtained from equation (8). The coefficients of cubic spline function $S(x)$ are obtained by substituting it into equation (7).

3.2 Temperature Error Compensation Model

When modeling the temperature error of the optical fiber platform system, it is necessary to select a set of effective data calibration results obtained at the specified temperature as the benchmark for modeling. The temperature error model is as follows:

$$f^{'} = f_i + \left[f(T_0) - f(T) \right] \tag{9}$$

In the above formula, $f_i (i = 1 \cdots N)$ is the error calibration results for each group of sampled data. $f(T_0)$ is the error reference value. $f(T)$ is the corresponding temperature error fitting result at any temperature. $f^{'}$ is the compensated error value.

4. Test Design and Verification

The test adopts high-precision FOG stabilization platform system, temperature box and other test equipment.

4.1 Test Design

4.1.1 The First Round of Heating Process

Combined with the characteristics of optical fiber platform system, the experimental design is carried out. Set 4 temperature stable points, keep the optical fiber platform in the 19 position or 6 position system level calibration state at the temperature rise and insulation stages of the incubator, and record the sampling data. The following are the specific test steps.

(1) Checking the product status and powering off the product after confirming that there is no problem.

(2) Adjusting the temperature box to 5°C for insulation for 4 hours. The insulation time shall be calculated from the time when the temperature box reaches 5°C .

(3) After the heat preservation time, power on the product and start to increase the temperature. After 15 minutes of power on, start the rapid calibration of position 19, and use the automatic click test software for continuous calibration. One temperature point calibration 12 groups.

(4) After the 12th group of calibration is completed, the product continues to be calibrated automatically. Set the temperature of the incubator to 20°C and the heating rate to 1°C/min . Start timing when the incubator reaches the specified temperature, and take this time as the starting time of the second temperature point test.

(5) After the second temperature point is tested for 12 groups, set the incubator to 30°C and the heating rate to 1°C/min . Start timing when the incubator reaches the specified temperature, and take this time as the starting time of the third temperature point test.

(6) After the third temperature point is tested for 12 groups, set the incubator to 40°C and the heating rate to 1°C/min . Start timing when the incubator reaches the specified temperature, and take this time as the starting time of the fourth temperature point test. Power off the product after measuring 12 groups at the fourth temperature point. Close the temperature box and open the door of the temperature box to let the product dissipate heat naturally.

(7) Removing the product from the incubator. By processing the test results, the temperature coefficients of parameters other than gyro zero are obtained. Burn the temperature coefficient into the product.

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(8) Powering on the product after the above steps. After power on for 15 minutes, starting 19-position calibration and calibrating three groups to verify the correctness of temperature compensation.

4.1.2 The Second Round of Heating Process

(1) The test is the same as the first round of test, except that the process is switched to 6-position fast calibration process.

(2) After the test, power off the product, close the incubator, and open the door of the incubator for natural heat dissipation.

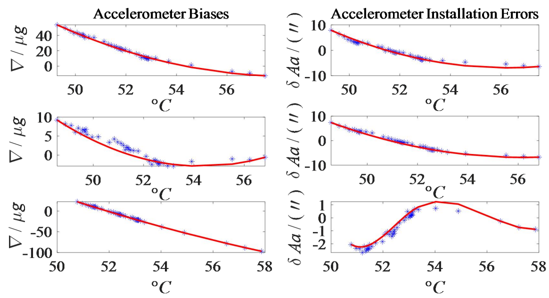
After the test is completed, another test with completely consistent test process is carried out, which is mainly used to assess the repeatability of the change trend of system parameters with temperature under the same temperature conditions.

4.2 Test Results

4.2.1 First Round Test Results

After the first round of complete test, 42 groups of effective test data can be obtained. In the calibration range of each group, the temperature change is small, so multiple groups of error parameters are used to calibrate the results. Integrate the gyroscope temperature in the optical fiber platform system and the internal and external temperature values of the accelerometer to obtain the temperature value corresponding to each group of data. Then the cubic spline interpolation model (7) and temperature error model (9) are used for modeling. Due to the low identification accuracy of gyro zero position in the 19-position system level rapid calibration process, and the temperature compensation of other error parameters, all the gyro output errors caused by temperature change under static conditions come from zero position error. Therefore, this paper uses the zero bias temperature error model constructed under the static state of the system to compensate the zero bias of the gyro. Since the modeling is relatively simple, it will not be introduced.

The interpolation model of error parameters with respect to temperature is as follows:



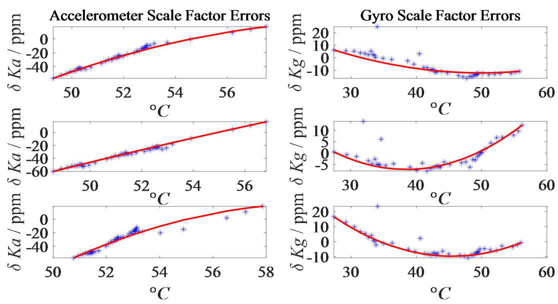


Fig. 1. Accelerometer bias and installation error curve

Fig. 2. Gyro and accelerometer scale factor error curve

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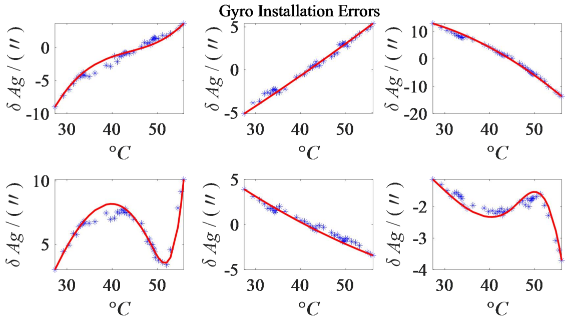

Fig. 3. Gyro installation error curve

It can be seen from Fig.1 to Fig.3 that the model curve established by cubic spline interpolation for each error parameter of Strapdown mode can better describe the data characteristics. The maximum error of each parameter model is shown in Table.1.

Table.1. Strapdown mode temperature compensation error

Parameter	f_{ox}(μg)	f_{oy}(μg)	f_{oz}(μg)	K_{xz}(")	K_{xy}(")	K_{yz}(")
Error	3.18	2.72	2.47	1.41	1.17	0.62
Parameter	δK_x(ppm)	δK_y(ppm)	δK_z(ppm)	δE_x(ppm)	δE_y(ppm)	δE_z(ppm)
Error	5.76	6.48	9.79	5.02	4.89	3.37
Parameter	E_{xy}(")	E_{xz}(")	E_{yx}(")	E_{yz}(")	E_{zx}(")	E_{zy}(")
Error	1.31	0.78	1.22	0.67	0.73	0.26

According to table 1, after temperature error compensation in strapdown mode, the zero-bias error of accelerometer is less than $4\mu g$. The installation error of the accelerometer is less than $2''$, and the scale factor error of the accelerometer is less than $10ppm$. The gyro installation scale factor error is less than $6ppm$, and its installation error is less than $2''$. The accuracy of error parameters is significantly improved compared with the original data in the figure.

4.2.2 Second Round Test Results

After the second round of test, 114 groups of valid data were obtained. After the first stage strapdown mode compensation, the temperature error modeling of the platform application stage error parameters is carried out. Including accelerometer zero bias and accelerometer scale factor error. The static temperature error model is also used to compensate platform drift.

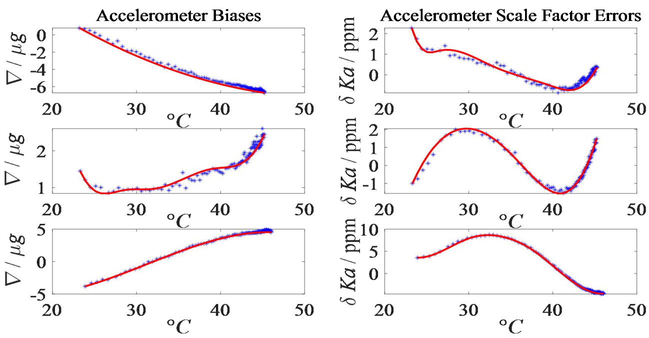

Fig. 4. Accelerometer bias and installation error curve

Fig. 4 shows that in the platform mode, the cubic spline interpolation model of accelerometer zero bias and scale factor error is more accurate. The maximum error of the model is shown in Table 2.

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Table.2. Platform mode temperature compensation error

Parameter	K_{0x}(μg)	K_{0y}(μg)	K_{0z}(μg)	K_{1x}(ppm)	K_{1y}(ppm)	K_{1z}(ppm)
Error	0.75	0.28	0.37	0.28	0.46	0.34

Platform mode is the practical application mode of optical fiber platform. It can be seen from Table. 2 that the model has high accuracy after temperature error compensation. The zero-bias error of the accelerometer is less than $1\mu g$, and the scale factor error is less than $1ppm$ .The compensation effect is obvious.

4.3 Experimental verification

In order to verify the accuracy and effectiveness of the temperature compensation model, the system level calibration test needs to be carried out for the optical fiber platform system after temperature error compensation. The results of platform mode 6 position calibration are shown in Table. 3.

Table. 3. Platform mode six times calibration results

Calibration parameters		Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Mean	3σ
Platform Drift	ω_{0x} $(^{(o)}/h)$	-0.0743	-0.0726	-0.0723	-0.0724	-0.0734	-0.0718	-0.0728	0.0029
	ω_{0y} $(^{(o)}/h)$	-0.0723	-0.0710	-0.0724	-0.0690	-0.0698	-0.0712	-0.0708	0.0038
	ω_{0z} $(^{(o)}/h)$	-0.0710	-0.0721	-0.0733	-0.0716	-0.0712	-0.0724	-0.0725	0.0026
Acceleration Channel Zero Bias	$K_{0x}(g_0)$	-1.32E-06	-3.97E-07	5.16E-07	1.08E-07	-1.99E-07	-6.21E-07	-3.19E-07	1.90E-06
	$K_{0y}(g_0)$	-1.48E-06	-5.78E-07	-3.40E-07	-1.31E-07	-2.73E-07	-1.40E-07	-4.91E-07	1.54E-06
	$K_{0z}(g_0)$	-9.24E-07	5.58E-07	-1.92E-07	3.21E-07	5.56E-07	1.14E-06	2.44E-07	2.15E-06
Acceleration Channel Equivalent	K_{1x} $(\wedge/(g_0 \cdot s))$	49669.13	49669.22	49669.26	49669.20	49669.24	49669.24	49669.23	0.1268
	K_{1y} $(\wedge/(g_0 \cdot s))$	49670.88	49670.90	49670.94	49670.91	49670.92	49670.91	49670.90	0.0490
	K_{1z} $(\wedge/(g_0 \cdot s))$	49670.42	49670.50	49670.47	49670.49	49670.50	49670.49	49670.49	0.0918

It can be seen from Table.3 that the effect of temperature error compensation is obvious. The calibration accuracy of platform drift is better than $0.004°/h$ and the calibration accuracy of accelerometer channel zero is better than $3\mu g$. The equivalent error of accelerometer channel is better than $3ppm$. The calibration accuracy of error parameters of the platform system after temperature compensation in the process of temperature change in the start-up stage meets the application requirements of high precision of the system, which proves the effectiveness of the temperature compensation scheme.

5. Summary

This paper presents a full parameter temperature error compensation method for high-precision optical fiber platform system. The temperature error compensation of the system is realized by modeling the temperature error of the two-stage calibration error parameters. The experimental results show that the stability of error parameters has been significantly improved after temperature

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error compensation. This method effectively improves the calibration accuracy of the platform in the start-up stage, and the amount of calculation is small, so it has high engineering application value.

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