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System-Level Calibration for the Star Sensor Installation Error in the Stellar-Inertial Navigation System on a Swaying Base

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ABSTRACT The star sensor installation error has a great influence on the attitude accuracy of the stellar-inertial navigation system and should be precisely calibrated. However, it is difficult to realize the installation error without a proper reference on a swaying base, which becomes a limitation for operation accuracy and reaction ability improvement. In this paper, a star sensor installation error calibration method on a swaying base is proposed. The measurement equation is established using accelerometer information, gravity and direct star vector observations in the inertial frame. The state equation is deduced according to the navigation error model. The installation error can be calibrated in the inertial frame instead of the zero-velocity information with respect to the Earth. The simulations and experimental results indicate that the proposed method performs much better than the traditional method on a swaying base. The calibration accuracy can be within 1 arc-s in simulation, and the stability is approximately 5 arc-s in the experiment. High accuracy can be achieved without precise external devices and artificial references. The proposed method is very suitable for mooring ships and for readiness on duty vehicles. The on-line accuracy and rapid-response ability can be significantly improved.

INDEX TERMS Stellar-inertial navigation system, star sensor, installation error, swaying base, inertial frame.

I. INTRODUCTION

The Stellar-Inertial Navigation System (Stellar-INS) is a typical integrated navigation system [1]–[3]. With advantages of full autonomy, high accuracy and all navigation information, the system is widely equipped for ships, satellites, military and other vehicles [4]–[7]. Because the star sensor provides the attitude reference for the system, its installation relationship with respect to the Inertial Measurement Unit (IMU) has a great influence on the attitude accuracy and the calibration for the star sensor installation error has always been an important aspect of great interest [8]–[10].

In traditional, the star sensor installation error is precisely calibrated by producer. However, the true value is affected by storage, transportation and other factors, which leads to inconformity between laboratory calibration value and that under real working conditions. The undesirable working conditions also change the star sensor installation angle after long time working. For advanced applications and high navigation accuracy, the star sensor installation error calibration must be accomplished under real working conditions. A swaying base is a typical working condition [11]–[13]. On a swaying base, such as mooring ships or vehicle on duty, the body approximately stays at a fixed position on Earth-Fixed frame, and the system encounters vibrations due to sea waves, engine noise, wind or other interferences. On a swaying base, the navigation system is expected to maintain high accuracy and be able to begin functioning immediately, which is necessary for vehicle rapid-response ability.

Many methods have been proposed for the star sensor installation error calibration [14]–[19]. Yang *et al.* [20] analyzed the observability of the star sensor installation error and provided a conclusion for star vector measurements. Wang *et al.* [18] proposed a star sensor installation error calibration method based on a turntable in laboratory, and several similar laboratory calibrations have also been proposed [21], [22]. Pittelkau showed a method using a Kalman filter, which has proved to be effective for attitude sensor alignment calibration [10]. Lu *et al.* [23] also achieved installation error calibration using a Kalman filter, in which zero-velocity is regarded as the reference information. However, these methods require either accurate external devices, or zero-velocity as the reference, which are unfeasible on a swaying base.

Until now, there exist few calibration methods suitable for a swaying base. The main drawback of a swaying base is that the attitude and velocity of the system is changing with respect to both the navigation frame and the Earth-Fixed frame. Thus, the reference information of zero-velocity with respect to the Earth-Fixed frame does not exist. Without effective calibration, the star sensor performance may decline during operation. At present, calibration for the star sensor installation error on a swaying base is eagerly needed and has a great significance for navigation accuracy and vehicle rapid-response ability improvement.

In this paper, a star sensor installation error calibration method for a swaying base is proposed. The navigation and calibration are conducted with respect to the inertial frame, which avoids the swaying aspect with respect to the Earth-Fixed frame. The measurement equation is established using accelerometer and gravity information with respect to the inertial frame and direct star vector observation. With a simplified calibration rotation route, the Kalman filter is adopted for system-level calibration. The main advantages of the proposed method are as follows:

1) The on-line navigation accuracy can be guaranteed, and the rapid-response ability can be significantly improved for readiness on duty vehicles.

2) The system-level calibration does not require external references, such as a turntable, high-precision block or star simulator.

3) The calibration is conducted with respect to the inertial frame and is suitable for both a stationary base and swaying base.

This paper is organized as follows. The measurement model and calibration method using a Kalman filter with respect to the inertial frame are introduced in Section II. Section III shows the simulation and experimental results and discussion, and the results of the traditional method are also provided for comparison. Finally, the conclusion is presented in Section IV.

II. PRINCIPLE OF THE CALIBRATION METHOD

A. COORDINATE FRAME INTRODUCTION

The orthogonal coordinate frames mentioned in the calibration are as follows.

The inertial frame ($O_ix_iy_iz_i$) is fixed with respect to the stars on the celestial sphere, and its origin is at the center of the Earth.

The Earth-Fixed frame ($O_ex_ey_ez_e$) is fixed on the Earth, and its origin is at the center of the Earth.

The body frame ($O_bx_by_bz_b$) is fixed with the IMU body.

The star sensor frame ($O_sx_sy_sz_s$) is attached to the star sensor body, and the y-axis is the optical axis.

B. ERROR MODEL OF STAR SENSOR INSTALLATION AND IMU MEASUREMENT

Set $\mu^b = \left[\mu_x^b, \mu_y^b, \mu_z^b\right]^T$ as the installation error angles between the star sensor and IMU. Then, the installation error

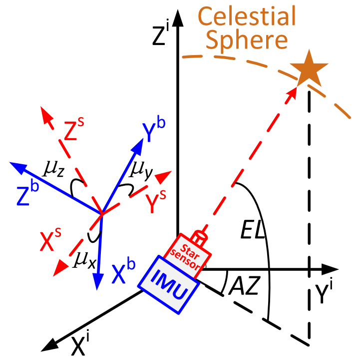

FIGURE 1. Star sensor installation error model.

matrix C_s^b can be written as:

$$C_s^b = \begin{bmatrix} 1 & \mu_z^b & -\mu_y^b \\ -\mu_z^b & 1 & \mu_x^b \\ \mu_y^b & -\mu_x^b & 1 \end{bmatrix} = \left[I - \left(\mu^b \times\right)\right] \quad (1)$$

where $\boldsymbol{I}$ is the identity matrix.

The installation relationship between the star sensor and the IMU is:

$$\begin{bmatrix} X^b \\ Y^b \\ Z^b \end{bmatrix} = C_s^b \begin{bmatrix} X^s \\ Y^s \\ Z^s \end{bmatrix} \quad (2)$$

Considering that the property of the IMU should be well realized before application, the bias is taken into consideration, and misalignment and the scale factor are ignored. The error model of the IMU consisting of three gyros and three accelerometers is described as follows.

For the gyros,

$$\delta\omega = \begin{bmatrix} \delta\omega_x \\ \delta\omega_y \\ \delta\omega_z \end{bmatrix} = \begin{bmatrix} gB_x \\ gB_y \\ gB_z \end{bmatrix} + \begin{bmatrix} \varpi_{gx} \\ \varpi_{gy} \\ \varpi_{gz} \end{bmatrix} = gB + \varpi_g \quad (3)$$

where $\delta\omega_k$ is the measurement error of the gyro on the k-axis, gB_k is the bias of the gyro on the k-axis, ϖ_{gk} is the angular random walk noise on the k-axis and $k = x, y, z$.

For the accelerometers,

$$\delta f = \begin{bmatrix} \delta f_x \\ \delta f_y \\ \delta f_z \end{bmatrix} = \begin{bmatrix} aB_x \\ aB_y \\ aB_z \end{bmatrix} + \begin{bmatrix} \varpi_{ax} \\ \varpi_{ay} \\ \varpi_{az} \end{bmatrix} = aB + \varpi_a \quad (4)$$

where δf_k is the measurement error of the accelerometer on the k-axis, aB_k is the bias of the gyro on the k-axis, and ϖ_{ak} is the angular random walk noise on the k-axis.

C. KALMAN FILTER DESIGN FOR STAR SENSOR INSTALLATION ERROR CALIBRATION

As described in the introduction, interferences such as sea waves and engine noise cause the base to sway. In addition, zero-velocity with respect to the Earth-Fixed frame cannot be used as the calibration reference. However, there still exist references in the inertial frame. The gravity vector in the inertial frame is only decided by the Earth's rotation; the star vector in the inertial frame that remains steady in

$$C_b^i = \begin{bmatrix} \cos\gamma\cos\varphi - \sin\gamma\sin\theta\sin\varphi & -\cos\theta\sin\varphi & \sin\gamma\cos\varphi + \cos\gamma\sin\theta\sin\varphi \\ \cos\gamma\sin\varphi + \sin\gamma\sin\theta\cos\varphi & \cos\theta\cos\varphi & \sin\gamma\sin\varphi - \cos\gamma\sin\theta\cos\varphi \\ -\sin\gamma\cos\theta & \sin\theta & \cos\gamma\cos\theta \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix} \quad (7)$$

the celestial sphere is constant. The two types of information cannot be influenced by a swaying base and can be regarded as the reference for calibration. In addition, when changing the sampling time, the location of the swaying base should be constant after integrating over a span of time. According to the analysis above, the state equation and measurement equation of the Kalman filter for system-level calibration are established with respect to the inertial frame.

In the system-level calibration, the navigation information is also included in the system state. Accompanied with the parameters of the star sensor and IMU, the state vector $\boldsymbol{X}$ is expressed as:

$$\begin{aligned} X &= [\delta v_x^i, \delta v_y^i, \delta v_z^i, \psi_x^i, \psi_y^i, \psi_z^i, \\ &\quad gB_x, gB_y, gB_z, aB_x, aB_y, aB_z, \mu_x^b, \mu_y^b, \mu_z^b]^T \\ &= [\delta v^i, \psi^i, gB, aB, \mu^b]^T = [X_1, X_2, \ldots, X_{15}]^T \end{aligned} \quad (5)$$

where δv_k^i is the velocity error δv^i on the k-axis and ψ_k^i is the attitude error ψ^i on the k-axis.

According to the navigation error model [24], the state equation is described as:

$$\begin{cases} \delta\dot{v}^i = g^i \times \psi^i + C_b^i \cdot \delta f \\ \dot{\psi} = -C_b^i \cdot \delta\omega \\ \dot{X}_j = -1/\tau_j X_j + \eta_j (j = 7, 8, \ldots 15) \end{cases} \quad (6)$$

where the sensor parameters follow the first order Gauss-Markov process; τ_j is the correlation time and η_j is white noise; C_b^i is the transformation matrix from the body frame to the inertial frame and can be written using Euler angles of pitch θ, roll γ and azimuth φ using Eq. (7), as shown at the top of this page.

Combining the sensor error model and the state equation, the velocity error and attitude error can be expressed as:

$$\begin{cases} \delta\dot{v}_x^i = -g_z^i\psi_y^i + g_y^i\psi_z^i + C_{11}aB_x + C_{12}aB_y + C_{13}aB_z \\ \delta\dot{v}_y^i = g_z^i\psi_x^i - g_x^i\psi_z^i + C_{21}aB_x + C_{22}aB_y + C_{23}aB_z \\ \delta\dot{v}_z^i = -g_y^i\psi_x^i + g_x^i\psi_y^i + C_{31}aB_x + C_{32}aB_y + C_{33}aB_z \\ \dot{\psi}_x = -(C_{11}gB_x + C_{12}gB_y + C_{13}gB_z) \\ \dot{\psi}_y = -(C_{21}gB_x + C_{22}gB_y + C_{23}gB_z) \\ \dot{\psi}_z = -(C_{31}gB_x + C_{32}gB_y + C_{33}gB_z) \end{cases} \quad (8)$$

The measurement information of the proposed method includes the velocity error with respect to the inertial frame and star vector.

1) The velocity error in the inertial frame is the first part of measurement information $\boldsymbol{Z_1}$:

$$Z_1 = \int (\widehat{C}_b^i \widehat{f}^b - g^i) = \delta v^i \quad (9)$$

where $\widehat{C}_b^i$ is the computed body attitude and $\widehat{f}^b$ is the measured information of the accelerometers.

The relationship between the ideal body attitude and computed attitude is:

$$\widehat{C}_b^i = [I - (\psi\times)]C_b^i \quad (10)$$

The relationship between gravity and the measured information of the accelerometers is:

$$\widehat{f}^b = g^b + \delta f \quad (11)$$

Combining Eq. (9) $\sim$ Eq. (11), $\boldsymbol{Z_1}$ is deduced as:

$$\begin{aligned} Z_1 &= \int (\widehat{C}_b^i \widehat{f}^b - g^i) \\ &= \int ([I - (\psi\times)]C_b^i \widehat{f}^b - g^i) \\ &= \int (C_b^i(g^b + \nabla^b) - g^i - (\psi\times)C_b^i(g^b + \nabla^b)) \\ &= \int (C_b^i\nabla^b + ((g^i + C_b^i\nabla^b)\times)\psi) \\ &\approx \int (C_b^i\nabla^b + (g^i\times)\psi) \end{aligned} \quad (12)$$

2) The star vector observation error is the second part of the measurement information, and $\boldsymbol{Z_2}$ is expressed as:

$$Z_2 = \widehat{C}_b^i l^s - l^i \quad (13)$$

The relationship between the star vector in the body frame and the measured star vector in the star sensor frame is:

$$l^b = (1 - \mu^b\times)l^s \quad (14)$$

Combining Eq. (10), Eq. (13) and Eq. (14), Z_2 can be deduced as follows:

$$\begin{aligned} Z_2 &= \widehat{C}_b^i l^s - l^i \\ &= (1 - \psi\times)C_b^i(1 - \mu^b\times)l^b - l^i \\ &= (1 - (\psi + \mu^i)\times)l^i - l^i \\ &= -(\psi + \mu^i) \times l^i \\ &= l^i \times (\psi + C_b^i\mu^b). \end{aligned} \quad (15)$$

Then, the measurement information is:

$$Z = \begin{bmatrix} Z_1 \\ Z_2 \end{bmatrix}. \quad (16)$$

According to the state equation, the measurement matrix is:

$$Z = HX \quad (17)$$

where

$$H = \begin{bmatrix} I(3) & 0_{3\times3} & 0_{3\times6} & 0_{3\times3} \\ 0_{3\times3} & l^i\times & 0_{3\times6} & (l^i\times)C_b^i \end{bmatrix}_{6\times15}$$

where $\boldsymbol{I}(3)$ is a 3×3 identity matrix.

Thus far, the design of the Kalman filter is accomplished. The principle scheme of the star sensor installation error calibration is shown in Fig. 2. Before the calibration procedure, the coarse alignment can be achieved using self-alignment methods or using star sensor measurement information C_s^i as the initial attitude [11], [13], [25]. The principle scheme of the calibration is shown in Fig. 2.

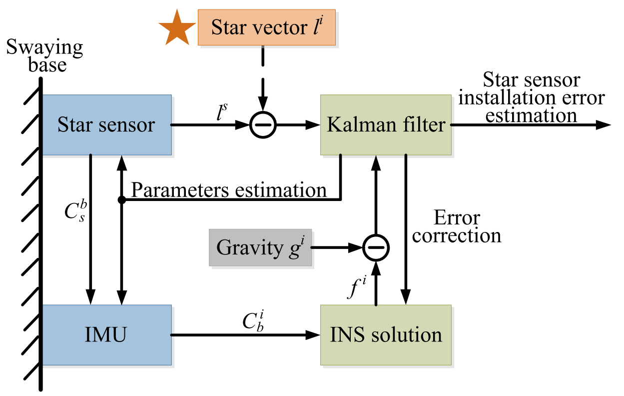

FIGURE 2. Principle scheme of star sensor installation error calibration on a swaying base.

III. SIMULATION AND EXPERIMENT

To verify the performance of the proposed method, simulations under swaying working conditions are conducted. Laboratory experiments using a turntable and star simulator are also conducted on both a stationary base and swaying base for further verification. The Stellar-INS used in the simulation and experiment are as follows: three fiber optic gyroscopes (FOGs), three quartz flexible accelerometers (QFAs) and a star sensor.

According to the observability analysis of the star sensor installation error, at least three star observations are required for three axis installation error calibration [20]. In this paper, a simplified and time-saving rotation sequence is designed for calibration. The star location in the field of view (FOV) of a star sensor after 3 observations during calibration is shown in Fig. 3. In each position, the star observation lasts 10 seconds.

In addition, any rotation sequence that satisfies the observability is suitable for star sensor installation error calibration with the proposed method [20].

A. SIMULATION

Simulations in a PC are first conducted for verification. The traditional method using the Kalman filter with respect to the navigation frame is also reproduced for comparison [20], [23]. The error sources are listed in Table. 1.

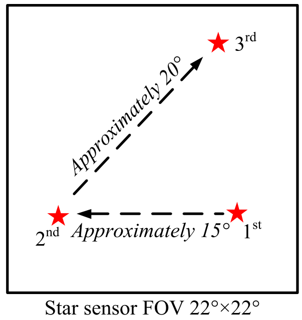

FIGURE 3. Star location in FOV during calibration.

TABLE 1. Error sources added in simulation.

Component	Parameter	Value
Gyroscope	Bias ($°/h$)	0.01
	Scale factor (ppm)	100
	Misalignment ($''$)	100
	Random white noise w_g ($°/h/\sqrt{Hz}$)	0.003
Accele-rometer	Bias (μg)	10
	Scale factor (ppm)	100
	Misalignment ($''$)	100
	Random white noise ($\mu g/\sqrt{Hz}$)	5
Star sensor	Measurement accuracy ($''$)	3

Considering that both angular and lineal movements exist on a swaying base, the swaying condition is set as follows.

The angular movement expressed using Euler angles is:

$$\begin{cases} \varphi = 3\cos(\frac{2\pi}{10}t + \frac{\pi}{3}) \\ \theta = 4\cos(\frac{2\pi}{8}t + \frac{\pi}{4}) \\ \gamma = 2\cos(\frac{2\pi}{6}t + \frac{\pi}{5}), \end{cases} \tag{18}$$

and the unit is degree.

The lineal movement on the three axes is set as:

$$\begin{cases} V_x = \frac{1}{2}\cos(\frac{2\pi}{6}t + \frac{\pi}{8}) \\ V_y = \cos(\frac{2\pi}{7}t + \frac{\pi}{7}) \\ V_z = \frac{3}{2}\cos(\frac{2\pi}{8}t + \frac{\pi}{6}), \end{cases} \tag{19}$$

and the unit is m/s.

The simulation results are listed in Table 2. The typical calibration processes of group 1 in Table 2 are shown in Fig. 4 for the proposed method and the traditional method. In Table 2 and Fig.4, the corner mark "P" and "T" represent the proposed method and traditional method respectively.

Considering the results of the proposed method, the estimation process in Fig. 4 converges stably after the star observation, proving the correctness and feasibility of the method

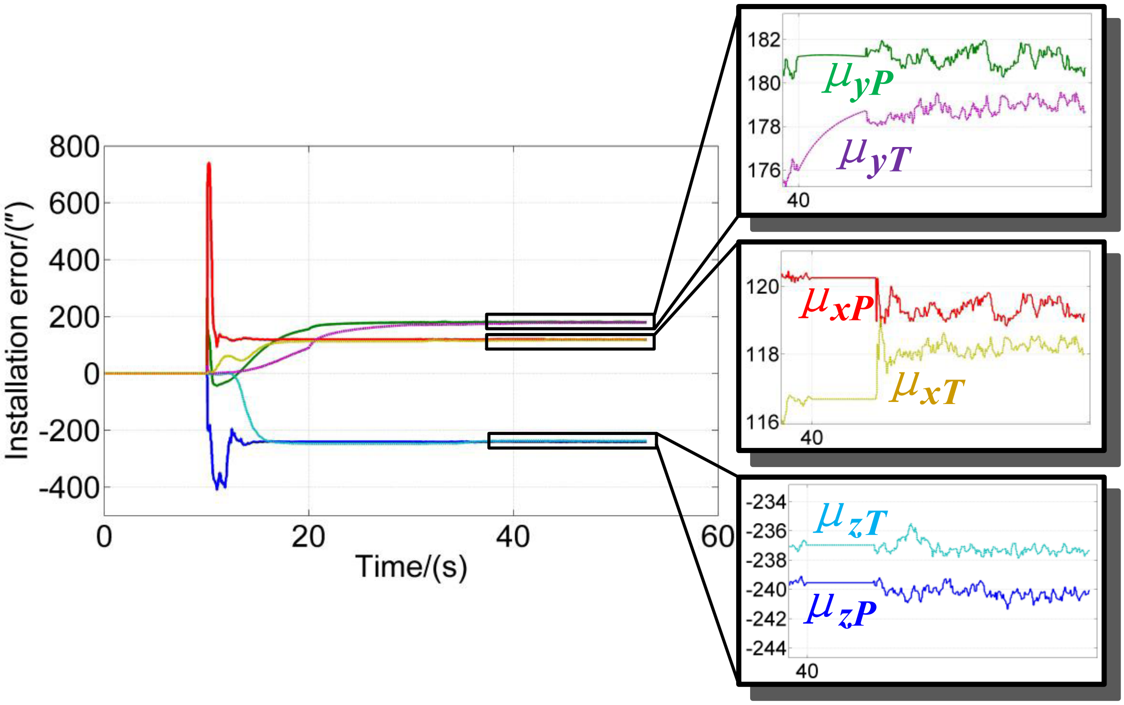

FIGURE 4. Simulation results of group 1 using the proposed method and traditional method. (μ_{xP}, μ_{yP}, μ_{zP}) and (μ_{xT}, μ_{yT}, μ_{zT}) represent the estimation values of proposed method and traditional method respectively.

TABLE 2. Simulation and comparison results of estimated values for the star sensor installation error on a swaying base.

Test group	True value (arc-sec)	Proposed method $(\mu_{xP}, \mu_{yP}, \mu_{zP})$ (arc-sec)	Traditional method $(\mu_{xT}, \mu_{yT}, \mu_{zT})$ (arc-sec)
1	120	119.27	117.72
	180	180.68	178.60
	-240	-240.19	-237.31
2	-200	-198.50	-202.45
	160	159.22	165.09
	90	89.49	86.33
3	100	99.83	97.55
	100	100.12	98.17
	100	99.41	96.28
4	-200	-200.79	-204.21
	-200	-200.88	-203.46
	-200	-199.37	-196.63
5	60	59.78	58.48
	-220	-219.48	-223.79
	150	149.87	155.22

on a swaying base. The final errors for the 3-axis installation error calibration are at the same level and are all less than 1 arc-sec, showing the excellent accuracy and stability of the proposed method.

With the traditional method, the performance declines, as shown in Fig. 4. The estimation results also converge at the end, however, the converging time is longer than that of the proposed method. The final error is approximately 2∼5 arc-sec, which is much larger than that of the proposed method. The main reason for the decline in accuracy is the unstable reference of the traditional calibration in the navigation frame.

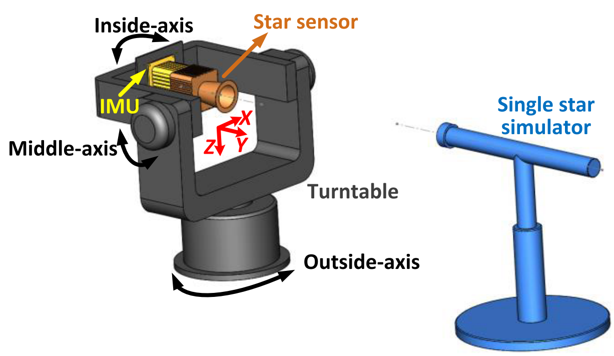

FIGURE 5. Experimental setup.

B. EXPERIMENT

A laboratory experiment is conducted for further verification. The Stellar-INS, a turntable, and a single star simulator are included, and the experimental setup is shown in Fig. 5. The parameters of the IMU and star sensor are equivalent to those in the simulation. The star simulator is fixed on the ground, and the pointing accuracy is better than 0.5 arc-second. The star sensor installation error in the experiment should be less than 240 arc-second according to the fixture provided by the manufacturer.

Calibrations with the proposed method under both stationary and swaying conditions are conducted. The traditional method using the Kalman filter with respect to the navigation frame is also reproduced for comparison. Five experiments are repeated under each condition, using each method. Because the duration of each experiment is relatively short, and all the experiments are conducted within 2 hours, the installation error is regarded to be constant in the experiment. The angular movement condition is the same in the simulation. There is also lineal movement because the Stellar-INS is not at the rotating center of the turntable.

Considering that the true value of the star sensor installation error is unknown, the stability of the calibration result is given. The experimental results are listed in Table. 3.

TABLE 3. Experimental results for star sensor installation error calibration.

Test group	Stationary base (arc-sec)		Swaying base (arc-sec)	
	Proposed method	Traditional method	Proposed method	Traditional method
1	218.3	218.3	215.5	211.2
	102.8	102.9	104.0	109.8
	155.4	155.3	156.7	147.3
2	216.0	215.9	218.9	204.0
	106.9	106.9	105.7	110.5
	154.8	154.7	153.9	164.9
3	218.1	218.1	218.4	209.7
	103.8	103.7	107.1	93.4
	154.6	154.4	154.6	142.8
4	215.5	215.5	217.3	223.1
	105.7	105.6	103.1	110.7
	158.6	158.9	159.1	167.0
5	219.1	219.0	214.8	214.6
	105.8	105.9	102.2	114.1
	157.2	157.5	158.2	150.6
Max-min	3.6	3.5	4.1	19.1
	4.1	4.0	4.9	20.7
	4.0	4.5	5.2	24.2
Mean	217.4	217.4	217.0	212.5
	105.0	105.0	104.4	107.7
	156.1	156.2	156.5	154.5

For experiments on a stationary base, the calibration using the two methods obtains nearly the same results. The mean value of the proposed method is (217.4, 105.0, 156.1) arc-sec, and the max-min value is approximately 4 arc-sec. Because the working condition is steady with respect to the Earth, the results, in theory, should be equivalent when using both methods. The experimental results are in accordance with the assumption, showing the correctness and proving that the proposed method is suitable for a stationary base.

For experiments on a swaying base, the mean value of the proposed method is (217.0, 104.4, 156.5) arc-sec, and the max-min value is approximately 5 arc-sec. The mean values of the proposed method are almost the same between the stationary base and the swaying base. The accordance proves the robustness and accuracy of the proposed method on a swaying base. The main technical improvement of the proposed method includes system-level calibration and gravity measurement with respect to the inertial frame and direct star observation.

However, the mean value of the traditional method is (212.5, 107.7, 154.5) arc-sec and the max-min value is (19.1, 20.7, 24.2) arc-sec. The stability of the traditional method declines severely on a swaying base, leading to declined calibration accuracy. The main reason is because zero-velocity with respect to the Earth-Fixed frame is unsuitable for a swaying base. The result is influenced by the swaying condition and is not reliable for each calibration case.

Considering the computational complexities, the DSP in our experiment is TMSV320C6727B, 350MHz. Since the matrix dimensionality of Kalman filter in the proposed method is less than 15, the calculation time for each time interval is less than 3 ms. It can be concluded that our DSP has sufficient processing power for the real-time calibration operation.

To further show the superiority of proposed method, the on-line navigation with our Stellar-INS is conducted in laboratory using turntable and star simulator. The calibration result of group 1 in Table.3 is adopted. The star sensor installation error calibration is conducted on swaying base firstly, and then the system turns to navigation mode. With a typical ballistic trajectory, in which the flying time is about 25min, the attitude accuracy can be better than 10 arc-sec (3σ) with the calibration results of proposed method, and the attitude accuracy using traditional method is about 20~30 arc-sec (3σ). The results show that the accurate star sensor installation error calibration results of proposed method have significantly improved the navigation accuracy. The attitude accuracy of the Stellar-INS can be improved.

It can be concluded from the experiments that the star sensor installation error can be estimated precisely using the proposed method on a swaying base, which is beyond the ability of the traditional method.

IV. CONCLUSION

A swaying base is a typical working condition for the Stellar-INS. The star sensor installation error has a great influence on system attitude accuracy and should be calibrated precisely. A system-level calibration method for the star sensor installation error on a swaying base is proposed. The system state equation and measurement equation are established using the information of gravity and the star vector with respect to the inertial frame; the Kalman filter is adopted for system level calibration. The calibration can avoid the effects of swaying due to sea waves or engine vibration, for example. Simulations and laboratory experiments have shown the effectiveness and stability of the proposed method, and high accuracy calibration results have been achieved. The calibration method on swaying base is very suitable for Stellar-INS in mooring ships or readiness on duty vehicles, such as missile lunching vehicle and rockets at lunch site. The on-line navigation accuracy and rapid-response ability can be significantly improved.

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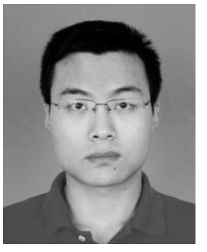

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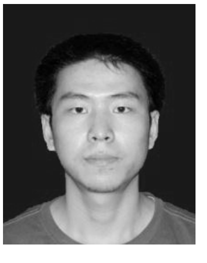

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