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To cite this article: Qingzhong Cai *et al* 2016 *Meas. Sci. Technol.* **27** 105001

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Analysis and calibration of the gyro bias caused by geomagnetic field in a dual-axis rotational inertial navigation system

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Received 1 April 2016, revised 13 July 2016

Accepted for publication 26 July 2016

Published 16 August 2016



Abstract

A rotational inertial navigation system (RINS) has been widely used in long term marine navigation. In a dual-axis RINS, with all constant biases averaged out, the errors which can not be averaged out become the main error source. In this paper, the gyro geomagnetic biases of a dual-axis RINS are modelled, analysed and calibrated. The gyro geomagnetic biases are proved unable to be averaged out, but can be modulated to be a constant value in the navigation frame. A slope error term of longitude error is found to be caused by gyro geomagnetic biases in north and upward directions, which increases linearly with time and is remarkable in long term navigation. Thus, a calibration method based on least square regression is proposed to compensate the slope error term. Laboratory and sailing experimental results show that the divergence speed of longitude error can be effectively slowed down by the compensation of gyro geomagnetic biases. In long term independent navigation, the position accuracy of dual-axis RINS is improved about 50% by the calibration method proposed in this paper.

Keywords: inertial navigation, rotational initial navigation system (RINS), gyro geomagnetic bias, error modelling, calibration method

(Some figures may appear in colour only in the online journal)

1. Introduction

A rotational inertial navigation system (RINS) has been widely used in marine navigation, as it can bring a much better performance in long term navigation without using higher-level inertial sensors. By rotating an inertial measurement unit (IMU) using a single-axis indexing mechanism every few minutes, the constant biases of the inertial sensors perpendicular to the axis can be averaged out in a single-axis RINS,

such as MK39 and WSN-7B (Lahham *et al* 2000, Tucher and Levinson 2000). Moreover, all constant biases of inertial sensors can be averaged out in a dual-axis RINS, such as MK49 and WSN-7A (Lahham and Brazell 1992, Levinson *et al* 1994).

With the benefit of having high precision without using costly inertial sensors, the RINS has become hot issue in recent years. Not only a ring laser gyro (RLG) (Ishibashi *et al* 2006, 2007), but also a fibre optic gyro (FOG) (Yin 2012) and micro-electromechanical systems (MEMS) (Renkoski 2008, Wang 2013) were all attempted to be used in RINS by researchers. More and more rotation schemes for single-axis (Ishibashi 2006, 2007) or dual-axis RINS (Yuan *et al* 2012,



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Zhang *et al* 2012) are studied in both theory and experiments. To improve the accuracy, various errors in RINS are analysed, calibrated and compensated. The stochastic errors which can't be averaged out by rotational technology are analysed by simulation (Lv *et al* 2014) and compensated by a twice position-fix reset method (Zheng *et al* 2016). Some IMU errors are self-calibrated by rotating the indexing. A total least squares (TLS) method is utilized for identification of the error parameters in self-calibration for dual-axis RINS (Ren *et al* 2014). A backward working calibration method based on velocity error observation is proposed by Zhang *et al* (2015). A gyro g-dependent bias can be calibrated by introducing two more positions into a conventional six-position method (Zheng *et al* 2015). Some additional errors caused by the indexing are also investigated. An optical angle encoder calibration method using accelerometers are proposed by Liu *et al* (2013). The mounting errors between the IMU and the indexing in dual-axis RINS is analysed and calibrated by Song *et al* (2013). A self-calibration method for nonorthogonal angles between gimbals of RINS is proposed by Wang *et al* (2015).

When all constant biases of inertial sensors are averaged out in a dual-axis RINS, the errors which can't be averaged out became the main error source, such as the gyro g-dependent bias (Zheng *et al* 2015) and the stochastic errors (Lv *et al* 2014, Zheng *et al* 2016). The calibration and compensation of these errors becomes a key issue. The gyro bias caused by geomagnetic field (Wang *et al* 2010 and Zhang *et al* 2013), named gyro geomagnetic bias in this paper, is also an unable averaged out error, whose effect on RINS has not been analysed in existing researches. The gyro geomagnetic bias is generated from the Faraday Effect (Saida 1999), and its range of optical gyro can still reach $0.0001\text{--}0.001^\circ \text{ h}^{-1} \text{ G}^{-1} \text{ s}^{-1}$ after double-layer magnetic shielding. In strapdown INS, the gyro geomagnetic bias is difficult to model or compensate because the directions of the three gyros are changed randomly with the maneuver of the carrier. A commonly used method for decreasing the errors caused by the gyro geomagnetic bias is magnetic shielding (Rong 2015). The gyro geomagnetic bias after magnetic shielding is much smaller, thus it is usually ignored in strapdown INS. However, in dual-axis RINS, the const gyro biases are averaged out except the gyro geomagnetic bias because the magnetic induction intensity detected by each gyro changes with the rotation of the IMU in geomagnetic field with an intensity of about 0.5 Gs. The navigation errors caused by gyro geomagnetic bias can not be ignored in dual-axis RINSs especially during long-term navigation, which has not been discussed in previous studies. In this paper, the gyro geomagnetic bias of dual-axis RINS is modelled, then by analysing the effect on the long term navigation precision, a calibration method based on least square regression is proposed.

The present paper is organized as follows. In section 2, the gyro geomagnetic bias of the dual-axis RINS is modelled and analysed. In section 3, the effect of the gyro geomagnetic bias on long term navigation is deduced and simulated. In section 4, a calibration method for the gyro geomagnetic bias in dual-axis RINS is proposed and

elaborated. In section 5, the calibration and compensation results of the gyro geomagnetic bias in laboratory and sailing experiments are presented. Finally, section 6 is the conclusions.

2. Analysis of gyro geomagnetic bias

2.1. Error model of gyro geomagnetic bias

In the IMU frame, which is defined by three gyro axes and denoted by m (Song *et al* 2013), gyro geomagnetic bias can be written as

$$\boldsymbol{\varepsilon}_M^m = \mathbf{M}\mathbf{H}^m \quad (1)$$

where, $\boldsymbol{\varepsilon}_M^m = [\varepsilon_{Mx} \ \varepsilon_{My} \ \varepsilon_{Mz}]^T$ is the gyro geomagnetic bias vector of three-axis gyros; $\mathbf{M} = \begin{bmatrix} M_{xx} & M_{xy} & M_{xz} \\ M_{yx} & M_{yy} & M_{yz} \\ M_{zx} & M_{zy} & M_{zz} \end{bmatrix}$ is the matrix of gyro magnetic induction coefficients; \mathbf{H}^m is the magnetic field intensity in m -frame.

Since common-used north-slaved local-level INSs always work in mid and low latitudes, where the geomagnetic field can be regarded as a parallel magnetic field pointing to north, the geomagnetic field intensity can be simplified in the geographic frame (defined by East, North and Upward and denoted by n) as

$$\mathbf{H}^n = [0 \ H_G \ 0]^T \quad (2)$$

In dual-axis RINS, because the rotation of the vehicle is isolated by the indexing mechanism, the IMU only rotates according to the designed rotation modulation scheme in n -frame. The indexing mechanism rotation matrix is equivalent to the IMU attitude matrix \mathbf{C}_n^m , and the gyro geomagnetic bias of RINS is obtained as

$$\boldsymbol{\varepsilon}_M^m = \mathbf{M}\mathbf{C}_n^m\mathbf{H}^n \quad (3)$$

2.2. Analysis of averaging results

Based on the gyro geomagnetic bias model of RINS, the averaging results of gyro geomagnetic bias in dual-axis RINS can be analysed in Z-axis rotation type and X-axis rotation type.

In the Z-axis rotation type with an angle of φ , the indexing mechanism rotation matrix can be written as

$$\mathbf{C}_n^m = \begin{bmatrix} \cos \varphi & \sin \varphi & 0 \\ -\sin \varphi & \cos \varphi & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (4)$$

When the Z-axis rotates 360° , the averaging result of gyro geomagnetic bias can be written as

$$\bar{\boldsymbol{\varepsilon}}_M^n = \int_0^{2\pi} (\mathbf{C}_n^m)^T \mathbf{M}\mathbf{C}_n^m \mathbf{H}^n d\varphi \quad (5)$$

where, $\bar{\boldsymbol{\varepsilon}}_M^n = [\bar{\varepsilon}_{ME} \ \bar{\varepsilon}_{MN} \ \bar{\varepsilon}_{MU}]^T$ is the vector of equivalent gyro geomagnetic bias in three axis directions of n -frame.

The calculation result of equation (5) is

$$\begin{bmatrix} \bar{\varepsilon}_{ME}^n \\ \bar{\varepsilon}_{MN}^n \\ \bar{\varepsilon}_{MU}^n \end{bmatrix} = \begin{bmatrix} \pi M_{xy} H_G - \pi M_{yx} H_G \\ \pi M_{xx} H_G + \pi M_{yy} H_G \\ 0 \end{bmatrix} \quad (6)$$

Similarly, the averaging result of gyro geomagnetic bias in the X-axis rotation type is

$$\begin{bmatrix} \bar{\varepsilon}_{ME}^n \\ \bar{\varepsilon}_{MN}^n \\ \bar{\varepsilon}_{MU}^n \end{bmatrix} = \begin{bmatrix} 0 \\ \pi M_{yy} H_G - \pi M_{zz} H_G \\ \pi M_{yz} H_G + \pi M_{zy} H_G \end{bmatrix} \quad (7)$$

The results show that the gyro geomagnetic bias can't be averaged out by dual-axis rotation, but it can be modulated to be a constant value in n -frame when the vehicle rotation is isolated by indexing mechanism. It should be pointed out that, the result is appropriate for all dual-axis rotating modulation schemes because all schemes are designed based on strict symmetrical rotation periodically around two axes.

3. Error analysis of long term navigation

3.1. The solution of error equation

By introducing gyro geomagnetic bias into the error equation of traditional strapdown INS, a complete error equation of a RINS can be written as

$$\begin{aligned} \dot{\psi} &= -\psi \times \omega_{in}^n + \delta \omega_{in}^n - C_m^n \delta \omega_{im}^m - \bar{\varepsilon}_M^n \\ \delta \dot{v}^n &= f^n \times \psi - (2\omega_{ie}^n + \omega_{en}^n) \times \delta v^n - (2\omega_{ie}^n + \omega_{en}^n) \\ &\quad \times v^n + C_m^n \delta f^m \\ \delta \dot{L} &= \delta v_N^n / (R_N + h) - \delta h \cdot v_N^n / (R_N + h)^2 \\ \delta \dot{\lambda} &= \delta v_E^n \sec L / (R_E + h) + \delta L \cdot v_E^n \tan L \sec L / (R_E + h) \\ &\quad - \delta h \cdot v_E^n \sec L / (R_E + h)^2 \\ \delta \dot{h} &= \delta v_U^n \end{aligned} \quad (8)$$

where, C_m^n is the direction cosine matrix for transforming the measured specific force vector from the IMU frame to the navigation frame; $\psi = [\delta\alpha \ \delta\beta \ \delta\gamma]^T$ is the attitude error vector on the mathematical platform; $\delta\alpha$, $\delta\beta$ and $\delta\gamma$ are the three attitude error elements, which can be replaced by the roll, pitch and yaw Euler errors for small angle misalignments; v^n represents the vector defined by the velocity directions of east, north and upward in the navigation frame; $\delta v = [\delta v_E \ \delta v_N \ \delta v_U]^T$ is the velocity error vector; L , λ and h are the latitude, longitude and height; δL , $\delta\lambda$ and δh stand for the latitude, longitude and height error, respectively; R_N and R_E are the meridian and transverse radius of curvature, respectively; ω_{im}^m represents the angular velocity vector with respect to the inertial space measured by the gyro triad in the IMU frame; f^m is the specific force vector measured by the accelerometer triad; ω_{ie} and g are the self-rotation angular velocity and the gravity acceleration of the earth; $\delta\omega_{ib}^b$ and δf^b are the error vectors of gyro and accelerometer triad respectively.

In order to analyse the error characteristic of the dual-axis RINS in long term navigation, the traditional error equation is simplified. The earth model is simplified as a sphere with $R = R_N = R_M$. Due to the divergence and the damping of the altitude by altimeter, altitude error, vertical velocity error and other altitude coupling error terms are ignored. Because a ship's speed is slow and the angle velocity caused by a ship sailing on the surface of earth (ω_{en}^n) is much smaller than that of the earth's rotation (ω_{ie}^n), the terms of v^n and ω_{en}^n in velocity errors are ignored. Also because of the low dynamics, the sailing acceleration is much smaller than the gravitational acceleration, the specific force can be simplified as $f^n = [0 \ 0 \ g]^T$. In the gyro and accelerometer measurement errors ($\delta\omega_{ib}^b$ and δf^b), all the constant bias are averaged out by rotation; the gyro dynamic errors are restrained by rotation isolation; part of the accelerometer dynamic errors can be averaged out, and the remaining part can also be ignored because of the low dynamics of a ship. The simplified error equation is similar with the static error equation of traditional platform INS, which can be written as

$$\begin{aligned} \delta \dot{\alpha} &= -v_N^n / R + \delta\beta \omega_{ie} \sin L - \delta\gamma \omega_{ie} \cos L - \bar{\varepsilon}_{ME}^n \\ \delta \dot{\beta} &= v_E^n / R - \delta\alpha \omega_{ie} \sin L - \delta L \omega_{ie} \sin L - \bar{\varepsilon}_{MN}^n \\ \delta \dot{\gamma} &= v_E^n \tan L / R + \delta\alpha \omega_{ie} \cos L + \delta L \omega_{ie} \cos L - \bar{\varepsilon}_{MU}^n \\ \delta \dot{v}_E^n &= -\delta\beta g + 2\omega_{ie} \sin L \delta v_N^n \\ \delta \dot{v}_N^n &= \delta\alpha g - 2\omega_{ie} \sin L \delta v_E^n \\ \delta \dot{L} &= \delta v_N^n / R \\ \delta \dot{\lambda} &= \delta v_E^n \sec L / R \end{aligned} \quad (9)$$

Laplace transformation can be used to solve the simplified error equation as in traditional platform INS. When the Foucault oscillation is ignored, the time-domain solution of position error is

$$\begin{aligned} \delta L(t) &= \frac{\omega_s^2}{\omega_s^2 - \omega_{ie}^2} \left(\frac{1}{\omega_s} \sin \omega_s t - \frac{1}{\omega_{ie}} \sin \omega_{ie} t \right) \bar{\varepsilon}_{ME}^n \\ &\quad + \left[\frac{\omega_{ie} \sin L}{\omega_s^2 - \omega_{ie}^2} \left(\frac{\omega_s^2}{\omega_{ie}^2} \cos \omega_{ie} t - \cos \omega_s t \right) - \frac{\sin L}{\omega_{ie}} \right] \bar{\varepsilon}_{MN}^n \\ &\quad + \left[\frac{\omega_{ie} \cos L}{\omega_s^2 - \omega_{ie}^2} \cos \omega_s t - \frac{\omega_s^2 \cos L}{\omega_{ie}(\omega_s^2 - \omega_{ie}^2)} \cos \omega_{ie} t + \frac{\cos L}{\omega_{ie}} \right] \bar{\varepsilon}_{MU}^n \end{aligned} \quad (10)$$

$$\begin{aligned} \delta \lambda(t) &= \left[\frac{\omega_{ie} \tan L}{\omega_s^2 - \omega_{ie}^2} (\cos \omega_{ie} t - \cos \omega_s t) - \frac{\tan L}{\omega_{ie}} (1 - \cos \omega_{ie} t) \right] \bar{\varepsilon}_{ME}^n \\ &\quad + \left[\frac{\omega_s^2 \tan L \sin L}{\omega_{ie}(\omega_s^2 - \omega_{ie}^2)} \sin \omega_{ie} t - \frac{\omega_s^2 - \omega_{ie}^2 \cos^2 L}{\omega_s(\omega_s^2 - \omega_{ie}^2)} \sin \omega_s t + t \cos L \right] \\ &\quad \times \bar{\varepsilon}_{MN}^n \\ &\quad + \left[\frac{\omega_{ie}^2 \sin L}{\omega_s(\omega_s^2 + \omega_{ie}^2)} \sin \omega_s t - \frac{\omega_s^2 \sin L}{\omega_{ie}(\omega_s^2 + \omega_{ie}^2)} \sin \omega_{ie} t + t \sin L \right] \bar{\varepsilon}_{MU}^n \end{aligned} \quad (11)$$

where, ω_s is Schuler frequency.

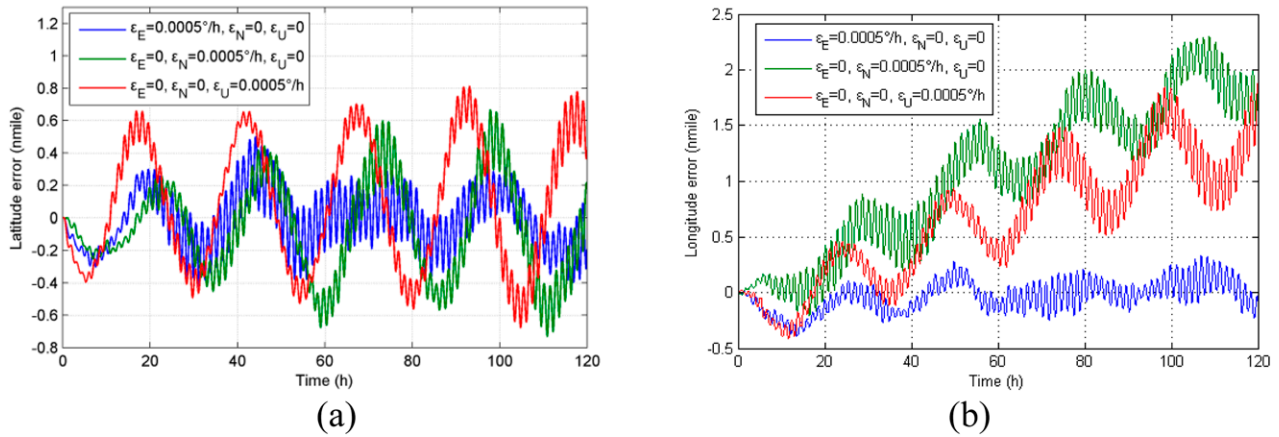


Figure 1. Test results of mathematical simulation for long term navigation. (a) Latitude error, (b) longitude error.

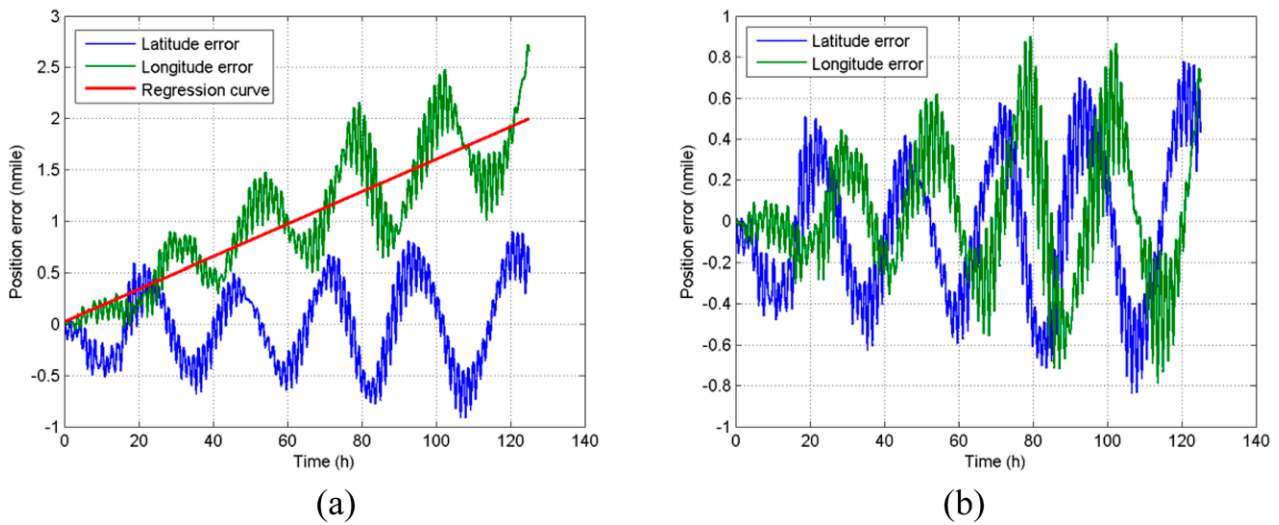


Figure 2. Results of laboratory test 1. (a) Before compensation, (b) after compensation.

When the Earth oscillation and Schuler oscillation are also ignored, the time-domain solution of position error can be further simplified as

$$\delta L(t) = -\frac{\sin L}{\omega_{ie}} \bar{\epsilon}_{MN}^n + \frac{\cos L}{\omega_{ie}} \bar{\epsilon}_{MU}^n \quad (12)$$

$$\delta \lambda(t) = t \cos L \bar{\epsilon}_{MN}^n + t \sin L \bar{\epsilon}_{MU}^n \quad (13)$$

It can be concluded that a slope error term of longitude error is caused by gyro geomagnetic biases in north and upward directions, which grows linearly with time.

3.2. Mathematical simulation

To verify the theoretical analysis in this section, a mathematical simulation test is carried out. The simulation condition is given as follow: the biases of the gyros are set as 0.01 h^{-1} with a noise of $0.1^\circ \text{ h}^{-1} \text{ Hz}^{-1/2}$ (sampled at 100 Hz); the scale factor errors of the gyros are set as 3 ppm; the misalignments of the gyros are set as $5''$. After a 10 min initial static alignment and a 30 min multi-position dynamic alignment, the system worked for 5 d in a pure inertial navigation mode. The IMU

rotates using a 16-sequence rotation scheme (Yuan 2012) for averaging out most of the constant errors. Three tests are performed with a gyro geomagnetic bias of $0.0005^\circ \text{ h}^{-1}$ in east, north and upward directions, respectively. We also assume an accelerometer geomagnetic bias of 2ug in three directions of all the three tests. The test results of latitude and longitude error are shown in figures 1(a) and (b), respectively.

It can be seen that the longitude error increases to about 2 nmiles during a 5 d pure inertial navigation when the gyro geomagnetic biases in north and upward directions are $0.0005^\circ \text{ h}^{-1}$, which is much bigger than the oscillating errors caused by the other error sources, including east gyro geomagnetic bias, accelerometer geomagnetic biases, alignment errors and random errors. Thus, the gyro geomagnetic biases in north and upward directions are the main error sources of dual-axis RINS in long term navigation, which should be calibrated and compensated.

4. Calibration method

The time-domain solution of position error caused by accelerometer geomagnetic biases and alignment errors are all

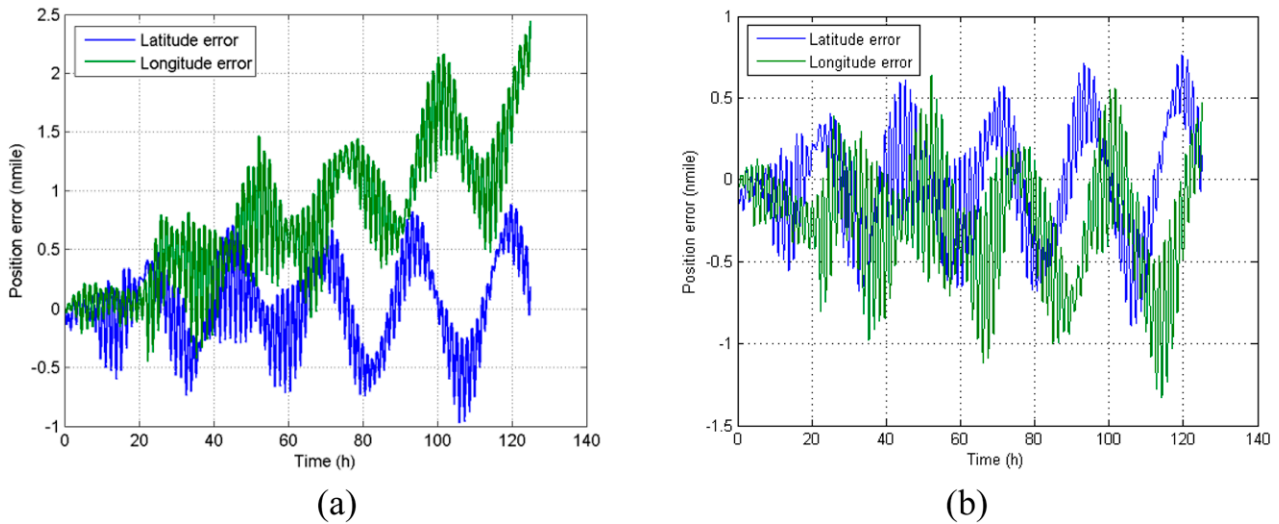


Figure 3. Results of laboratory test 2. (a) Before compensation, (b) after compensation.

oscillating or constant by the same analysis method in section 3, which is also verified by the simulation test results in section 3. Based on this, the sum of gyro geomagnetic biases in north and upward directions can be calibrated by regression analysis on the longitude error of a long term navigation result according to equation (13).

Defining the regressive equation of longitude error is $\delta\lambda(t) = \delta\lambda(0) + kt$, the traditional least square method can be used to fit the parameters as

$$k = \frac{\sum_{i=1}^n (t_i - \bar{t})(\delta\lambda(t_i) - \delta\bar{\lambda})}{\sum_{i=1}^n (t_i - \bar{t})^2} = \frac{\sum_{i=1}^n t_i \delta\lambda(t_i) - n\bar{t}\delta\bar{\lambda}}{\sum_{i=1}^n t_i^2 - n\bar{t}^2},$$

$$\delta\lambda(0) = \delta\bar{\lambda} - k\bar{t} \quad (14)$$

However, the north and upward gyro geomagnetic biases can not be decoupled by only longitude error. The latitude error can be used to evaluate the contribution of the two errors according to equation (12). This method needs more than one time offline calculation, classical dichotomy or other iterative algorithm can be used to get the contribution of the two errors close to the real situation. In practice, because the contribution of the two errors has little effect on long term navigation, the north and upward gyro geomagnetic biases are decoupled by a rule of not affecting the latitude error. The calibration equation can be written as

$$-\sin L \bar{\epsilon}_{MN}^n + \cos L \bar{\epsilon}_{MU}^n = 0 \quad (15)$$

$$\cos L \bar{\epsilon}_{MN}^n + \sin L \bar{\epsilon}_{MU}^n = k \quad (16)$$

To sum up, the gyro geomagnetic biases in north and upward directions can be calculated by equations (15) and (16) with k fitted by equation (14). It should be pointed out that, because the period of Earth oscillation is 24h and the period of Schuler oscillation is 84.4min, the calibration method need more than a 48h navigation data with

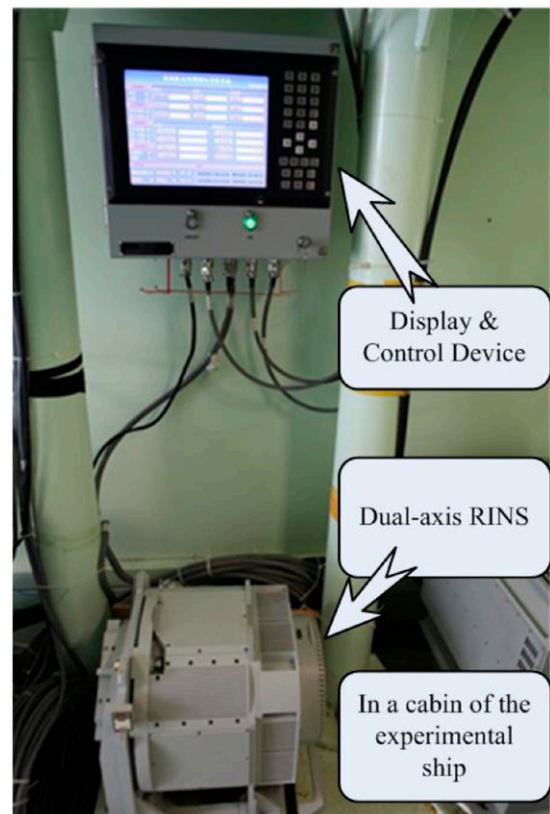


Figure 4. Sailing experiment arrangement.

a sampling interval no larger than 42.2min according to Shannon sampling theory.

5. Experiments

To verify the analysis and calibration result of gyro geomagnetic bias, laboratory and sailing experiments are carried out using a dual-axis RINS. The IMU of the dual-axis RINS contains three RLGs with an accuracy of $0.008^\circ \text{ h}^{-1}$ and three

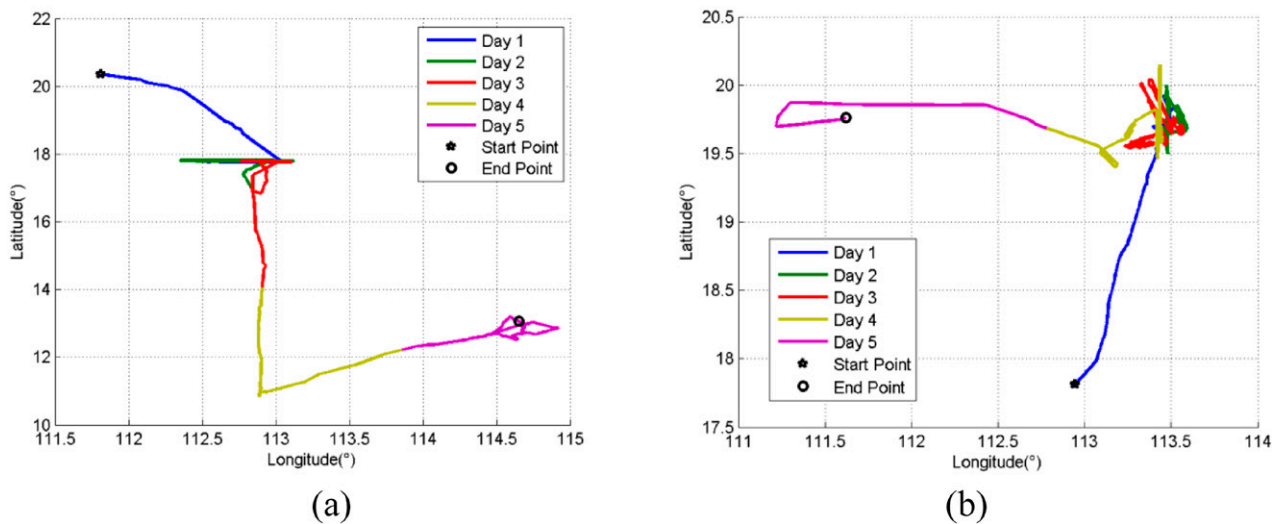


Figure 5. Sailing trajectories. (a) Sailing test 1, (b) sailing test 2.

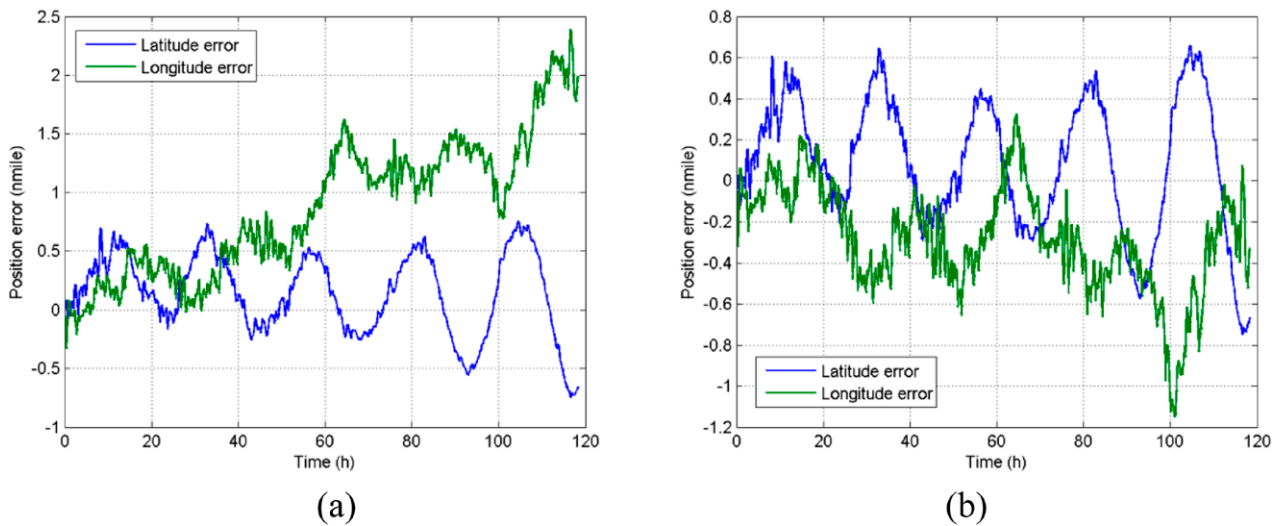


Figure 6. Results of sailing test 1. (a) Before compensation, (b) after compensation.

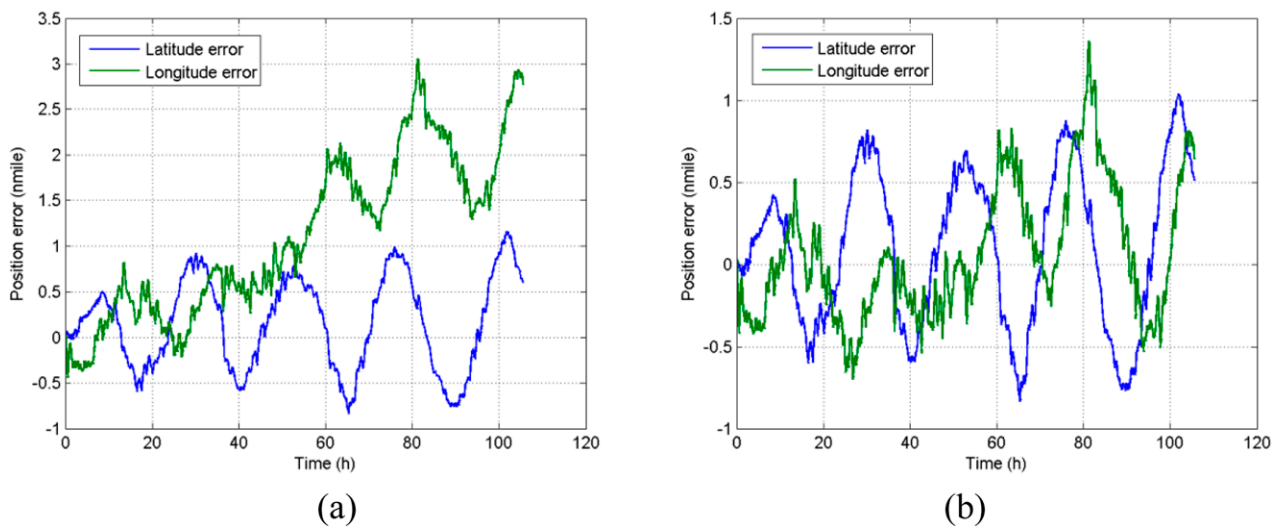


Figure 7. Results of sailing test 2. (a) Before compensation, (b) after compensation.

quartz flexible accelerometers with an accuracy of $10 \mu\text{g}$. The precision of the indexing mechanism is $5''$.

5.1. Laboratory experiment

In the laboratory experiment, two groups of static tests are carried out in different latitude regions to evaluate the applicability of the calibration method. The raw data of gyros and accelerometers are stored. One group of data is used for calibration and the other is used for verification.

The first test is carried out at 40° north latitude with a 4 h alignment and a 5 d static pure inertial navigation. The position errors before the compensation of the gyro geomagnetic bias are shown in figure 2(a). The regression curve is also shown in figure 2(a) with a result: $k = 0.000347^\circ \text{h}^{-1}$, $\delta\lambda(0) = 0.023$ nmile. The calibration result of north and upward gyro geomagnetic biases are calculated as $0.000270^\circ \text{h}^{-1}$ and $0.000226^\circ \text{h}^{-1}$ by equations (12) and (13). The calibration result lies in the range of optical gyro geomagnetic bias after double-layer magnetic shielding. The position errors after the compensation of the gyro geomagnetic bias are shown in figure 2(b).

The second test is carried out at 21° north latitude, which also contains 4 h alignment and a 5 d static pure inertial navigation. The position errors before and after the compensation of the gyro geomagnetic bias are shown in figures 3(a) and (b).

It is shown from the figures that the compensation of the gyro geomagnetic bias can slow down the divergence speed of longitude error effectively. The max longitude error is reduced from 2.7 nmiles to 1.3 nmiles, which verifies the theoretical analysis results in sections 2 and 3. The applicability of the calibration method in mid or low latitude regions is also proved by the compensation result of test 2 using the parameters calculated by test 1.

5.2. Sailing experiment

In the sailing experiment, the dual-axis RINS is mounted in a cabin of an experimental ship and the Display and Control Device is mounted on the wall (shown in figure 4).

Two groups of sailing tests are carried out at $10\text{--}20^\circ$ north latitude. Both tests contain a 6 h alignment and a 5 d horizontal-damped navigation, and the velocity information of damping is provided by the on-board log. It has to point out that Schuler oscillation error can be restrained in horizontal-damping mode, but the other errors, including the slope error caused by gyro geomagnetic bias, has the same characteristic as in pure inertial navigation. In each sailing, no fewer than three times of 360° rotation, acceleration and deceleration, ‘ ∞ -type’ maneuver and ‘S-type’ maneuver are carried out every day. Sailing trajectories of the two tests are shown in figures 5(a) and (b), respectively.

Using the high-accuracy position information of a differential Global Position System (GPS) as the true value, the position error of the dual-axis RINS before and after compensation the gyro geomagnetic bias in both sailings are shown in figures 6 and 7, respectively.

The sailing test results show that, the divergence speed of longitude error can be slowed down effectively by the compensation of the gyro geomagnetic bias. The max longitude error is restrained from 2.5 nmiles to 1.2 nmiles and from 3 nmiles to 1.5 nmiles in twice sailings, respectively. There is a little over-compensation in the result of sailing test 1, which is because the gyro geomagnetic bias drifted with the environment changed. Even then, the compensation result is acceptable because the drift is much smaller than the compensated error. It can be concluded from the four tests that the calibration and compensation of gyro geomagnetic bias can effectively retrain the divergence speed of longitude error, and improve the position accuracy of a dual-axis RINS about 50% in long term independent navigation.

6. Conclusions

The gyro geomagnetic bias is one of the main error sources in the dual-axis RINS with all constant biases averaged out. By the analysis of the gyro geomagnetic bias in this paper, we found that it can not be averaged out, but can be modulated to be a constant value in the navigation frame. Theoretical derivation and simulation indicate that a slope error term of longitude error is caused by gyro geomagnetic biases in north and upward directions, which increases linearly with time and is remarkable in long term navigation. Based on this, a calibration method based on least square regression is proposed. Laboratory and sailing experimental results show that the divergence speed of longitude error can be slowed down effectively by the compensation of gyro geomagnetic bias. In a 5 d long term independent navigation, the position accuracy of the dual-axis RINS is improved about 50% by the proposed calibration method. The analysis, calibration and compensation of the gyro geomagnetic bias in this paper apply to the long term navigation of all kinds of RINS or other high accuracy INS.

References

- Ishibashi S, Aoki T, Yamamoto I, Tsukioka S, Yoshida H and Hyakudom T 2006 The Method to improve the performance of an inertial navigation system using a turntable *Proc. of the Sixteenth Int. Offshore and Polar Engineering Conf. (San Francisco, CA, USA, 28 May–2 June 2006)* pp 229–38
- Ishibashi S, Tsukioka S, Yoshida H, Hyakudome T, Sawa T, Tahara J, Aoki T and Ishikawa A 2007 Accuracy improvement of an inertial navigation system brought about by the rotational motion *Oceans 2007—Europe (Aberdeen, UK, 18–21 June 2007)* pp 1–5
- Lahham J I and Brazell J R 1992 Acoustic noise reduction in the MK49 Ship’s inertial navigation system (SINS) *IEEE Position Location and Navigation Symp. 1992 (Monterey, CA, USA, 23–27 March 1992)* pp 32–9
- Lahham J I, Wigent D J and Coleman A L 2000 Tuned support structure for structure-borne noise reduction of inertial navigator with dithered ring laser gyros (RLG) *IEEE Position Location and Navigation Symp. 2000 (San Diego, CA, USA, 13–16 March 2000)* pp 419–28
- Levinson E, Horst J and Willcocks M 1994 The next generation marine inertial navigator is here now *IEEE Position Location and Navigation Symp. 1994 (Las Vegas, NV, USA, 11–15 April 1994)* pp 121–7

- Liu F, Wang W, Wang L and Feng P 2013 Error analyses and calibration methods with accelerometers for optical angle encoders in rotational inertial navigation systems *Appl. Opt.* **52** 7724–31
- Lv P, Lai J, Liu J and Nie M 2014 The compensation effects of Gyros' stochastic errors in a rotational inertial navigation system *J. Navig.* **67** 1069–88
- Ren Q, Wang B, Deng Z and Fu M 2014 A multi-position self-calibration method for dual-axis rotational inertial navigation system *Sensors Actuators A* **219** 24–31
- Renkoski B 2008 The effect of carouseling on MEMS IMU performance for gyro compassing applications *Master Thesis* Massachusetts Institute of Technology
- Rong C and Yao X 2015 Design of a three-axis magnetic field measurement system for the magnetic shield of the ring laser gyroscope *AOPC 2015: Optical Test, Measurement, and Equipment (Beijing, China, 8 October 2015)* (DOI: [10.1117/12.2199871](https://doi.org/10.1117/12.2199871))
- Saida T and Hotate K 1999 General formula describing drift of interferometer fiber-optic gyro due to Faraday effect: reduction of the drift in twin-depo-i-fog *J. Lightwave Technol.* **17** 222–8
- Song N, Cai Q, Yang G and Yin H 2013 Analysis and calibration of the mounting errors between inertial measurement unit and turntable in dual-axis rotational inertial navigation system *Meas. Sci. Technol.* **24** 115002
- Tucher T and Levinson E 2000 The AN/WSN-7B marine gyrocompass/navigator *Proc. of the 2000 National Technical Meeting of The Institute of Navigation (Anaheim, CA, USA, 26–28 January 2000)* pp 348–57
- Wang B, Ren Q, Deng Z and Fu M 2015 A self-calibration method for nonorthogonal angles between gimbals of rotational inertial navigation system *IEEE Trans. Ind. Electron.* **62** 2353–62
- Wang L, Lu Y, Xu Y, Yang Z and Zhao L 2010 Error characteristics of magnetic field in depolarized interferometric fiber optic gyroscope *Opt. Eng.* **49** 064402
- Wang X, Wu J, Xu T and Wang W 2013 Analysis and verification of rotation modulation effects on inertial navigation system based on MEMS sensors *J. Navig.* **66** 751–72
- Yin H, Yang G, Song N, Jiang R and Wang Y 2012 Error modulation scheme analyzing for dual-axis rotating fiber-optic gyro inertial navigation system *Sensor Lett.* **10** 1359–63
- Yuan B, Liao D and Han S 2012 Error compensation of an optical gyro INS by multi-axis rotation *Meas. Sci. Technol.* **23** 025102
- Zhang D, Zhao Y, Shu X, Liu C, Fu W and Zhou W 2013 Magnetic drift in single depolarizer interferometric fiber-optic gyros induced by orthogonal magnetic field *Opt. Eng.* **52** 054403
- Zhang L, Lian J, Wu M and Hu X 2012 An improved computation scheme of strapdown inertial navigation system using rotation technique *J. Cent. South Univ. Technol.* **19** 1258–66
- Zhang Q, Wang L, Liu Z and Feng P 2015 An accurate calibration method based on velocity in a rotational inertial navigation system *Sensors* **15** 18443–58
- Zheng Z, Han S, Yue J and Yuan L 2016 Compensation for stochastic error of gyros in a dual-axis rotational inertial navigation system *J. Navig.* **69** 169–82
- Zheng Z, Han S and Zheng K 2015 An eight-position self-calibration method for a dual-axis rotational inertial navigation system *Sensors Actuators A* **232** 39–48