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Strapdown Inertial Navigation Systems Based on Fiber-Optic Gyroscopes

Yu. N. Korkishko, V. A. Fedorov, V. E. Prilutskii, V. G. Ponomarev, I. V. Morev, S. F. Skripnikov, M. I. Khmelevskaya, A. S. Buravlev, S. M. Kostritskii, I.V. Fedorov, A. I. Zuev, and V. K. Varnakov

Research & Production Company Optolink , Moscow
e-mail: fedorov@optolink.ru

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Abstract— Strapdown inertial navigation systems (SINS) are basic parts of modern integrated navigation systems in various vehicles. Currently, fiber-optic gyroscopes (FOGs) with closed-loop feedback are finding increasing use for inertial navigation systems. The paper presents SINS-500K, SINS-500M and SINS-501 developed and produced by the Russian Research & Production Company Optolink with Optolink FOGs. The test results are discussed. Optolink FOGs and SINS's are compared with similar devices of world leading manufacturers.

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INTRODUCTION

Strapdown inertial navigation systems (SINS) are widely used in navigation in navigation of mobile vehicles [1–10]. They provide comprehensive data on navigation motion parameters: heading, roll and pitch angles, acceleration, speed, and vehicle coordinates. Using minimum of external information, they are almost autonomous. Owing to the capability of determining angular positions of objects with high accuracy within any range of angles and with high output rate, at present time, SINSs have no alternatives. Currently, FOGs with closed-loop feedback are finding increasing use as sensitive elements for SINSs [10–15].

There are no more than a dozen manufacturers of navigation-grade FOGs in the world. These companies also produce SINSs. The world leading manufacturers of FOGs and FOG-based SINSs are iXSea (iXBlue) (France) [15, 16], Northrop Grumman (USA) [17], Honeywell (USA) [18], and KVH (USA) [19]. They have significantly pushed back the companies producing SINS on laser gyroscopes in the market, for example, Sagem (Safran) (France). Northrop Grumman has produced more than 25000 tactical-grade LN-200 FOGs. In Russia, Fizoptika, which was the first to start manufacturing FOGs, has been producing low-grade and tactical-grade open-loop FOGs since the early 1990s [20]. The researches into the FOG development are conducted by Perm Scientific Production Instrument Engineering Company, known as PNPPK in Russia, [21], and Concern CSRI Elektropribor, JSC, St. Petersburg [22, 23]. However, Optolink remains a leading manufacturer of tactical- and navigation-grade FOGs [24–32] and FOG-based SINSs [33–35] in Russia today.

In this paper, we compare the FOGs and SINS's manufactured by Optolink with those produced by the world leading companies.

FIBER-OPTIC GYROSCOPES

All closed-loop FOGs produced by *Research & Production Company Optolink* have the so-called minimum configuration with digital signal processing. Minimum configuration ensures the reciprocity of optical paths for two beams, counter-propagating in a fiber loop.

The block diagrams of single-axis (SRS) and three-axis (TRS) FOGs with digital signal processing (DSP) are shown in Figs. 1 and 2, respectively.

The FOG includes a light source with the central emission wavelength of 1550 nm, one or three photodetectors, one or two fiber couplers (1 : 1 and 1 : 2) to divide the light wave, one or three ring interferometers to sense orthogonal angular rates, and signal processing circuits. The ring interferometer consists of a multifunction integrated optic chip (MIOC) and light polarization maintaining fiber coil 200, 500 1000 and 2000 meters long, also produced by Optolink. The MIOC is an integrated optical chip fabricated on lithium niobate wafer [36, 37]. TRS-500 (and IMU-500) have one light source for three channels. Three photodetection units provide simultaneous processing of signals from three channels with independent DSP units. Each DSP unit generates voltage for sawtooth light modulation in order to compensate for Sagnac phase shift and make a constant $\pi/2$ phase shift between the counter-propagating waves with the use of additional modulation. As a result, each channel operates in the closed-loop mode [24–32].

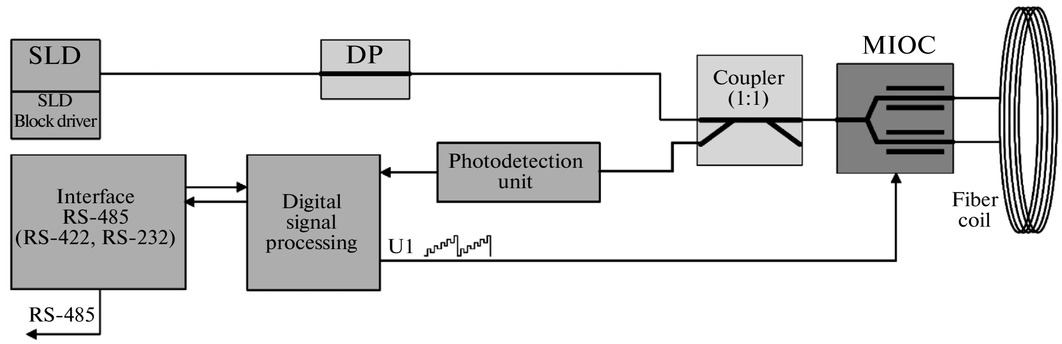

Fig. 1. A block diagram of a single-axis (SRS) FOG with digital signal processing: SLD—superluminescent light emitting diode; DP—depolarizer; MIOC—multifunctional integrated optic chip; RS-485—serial interface.

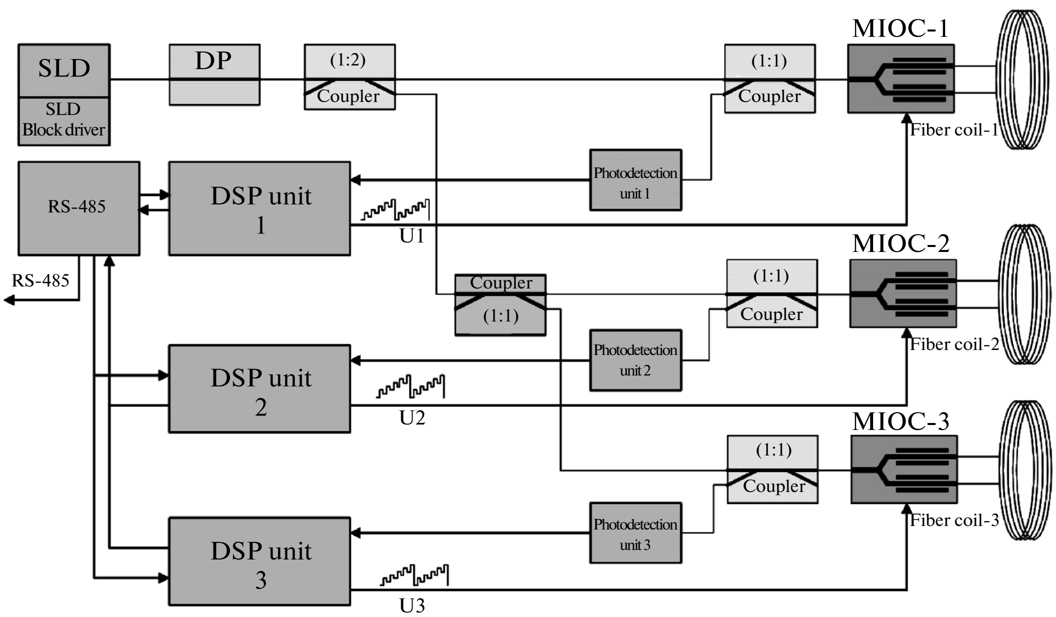

Fig. 2. A block diagram of a three-axis TRS-500 FOG.

So far, Optolink has developed and produces a series of single-axis FOGs SRS-2000, SRS-1000, SRS-501, and SRS-200, different in the fiber coil lengths and diameters, as well as three-axis FOGs TRS-500 and inertial measurement units IMU-500 and IMU-501 [24–32].

The accuracy and performance characteristics of Optolink navigation-grade FOGs and those of the world leading FOG manufacturers are shown in Table 1. The accuracy parameters for the Optolink FOGs, bias drift and noise power spectral density (angle random walk) have been calculated in accordance with the international standard, using Allan variance. The FOG parameters calculated by Russian and international standards are compared in [32].

STRAPDOWN INERTIAL NAVIGATION SYSTEMS

Strapdown inertial navigation systems SINS-500 (SINS-500K, SINS-500M) and SINS-501 are designed to form and output flight navigation data to customers in the autonomous (inertial) mode. They are also used in the GNSS-aided mode.

SINS-500K and SINS-500M are based on IMU-500, which consists of a three-axis fiber- optic angular rate sensor TRS-500 and three orthogonally mounted accelerometers (AT-1104, INN-203, or others). Digital data is output via RS-422 channel (optionally, RS-485, MIL-STD-1553B, and others).

FOG operation (SLD operation modes, signal processing from photodetectors, phase modulation control) is controlled via a block of service boards. Analog

Table 1. Accuracy and performance characteristics of fiber-optic gyroscopes

Parameter	Optolink SRS-1000	Optolink SRS-501	Optolink TRS-500	IMU-90 iXBlue [16]	IMU-120 iXBlue [16]	LN-200 Northrop Grum-man [17]	IMU-600 Northrop Grumman [17]	DSP1750 KVH [17]
Range of measured angular rates, deg/s	±90	±250	±300	±500	±260	±1000	±750	±490
Bias drift at fixed temperature, deg/h	0.0005	0.0011	0.0025	0.001	0.0005	0.07	0.009	0.05
Scale factor repeatability, ppm	200	500	700	30	30	100–500	n/a	500
Angle random walk, deg/$\sqrt{h}$	0.0009	0.0023	0.0065	0.0025	0.001	0.056	0.0044	0.013
Weight, kg	0.8	0.35	1.2	4.8	4.0	1.25	1.47	0.14
Dimensions, mm	∅150 × 80	∅100 × 30	110 × 110 × 90	280 × 136 × 150	160 × 160 × 160	∅89 × 132	137 × 190 × 69	∅44 × 21

signals from three accelerometers, proportional to the accelerations on the orthogonal axes, arrive at the three channels of a 24-digit analog-digital (AD) converter. The latter also receives signals from the temperature sensor. The computer in the interface unit processes the data from all angular rate, acceleration and temperature sensors, and sends it via the exchange serial channel to the SINS computer, which processes them to solve the tasks of autonomous alignment, orientation and navigation. The SINS computer exchanges data with external devices via a serial line.

The GNSS receiver included in the system receives and digitally processes the signals from the visible GLONASS or/and NAVSTAR satellites, thus providing the correction data for the inertial system. If the signals from the satellites are unavailable, the system provides customers with the data in autonomous (inertial) mode [19–21].

The sequence diagram of SINS operation includes the following stages:

SINS coarse initial alignment;

SINS precise initial alignment;

SINS navigation mode.

SINS coarse initial alignment provides rough estimation of the IMU angular orientation, using the output data from the IMU sensitive elements.

SINS precise initial alignment is aimed at estimating the IMU angular orientation errors, residual drifts of the IMU sensitive elements, and parameters of their dynamic models. Analytical gyrocompassing with Kalman filtering is the main method used at this stage.

Estimation and compensation for SINS errors in the navigation mode are performed based on position and velocity inertial and satellite measurements.

STRAPDOWN INERTIAL NAVIGATION SYSTEM SINS-500K

The exterior and interior views of SINS-500K are shown in Fig. 3.

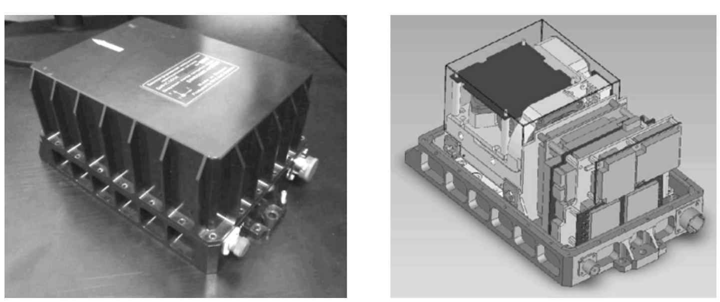

Fig. 3. SINS-500K.

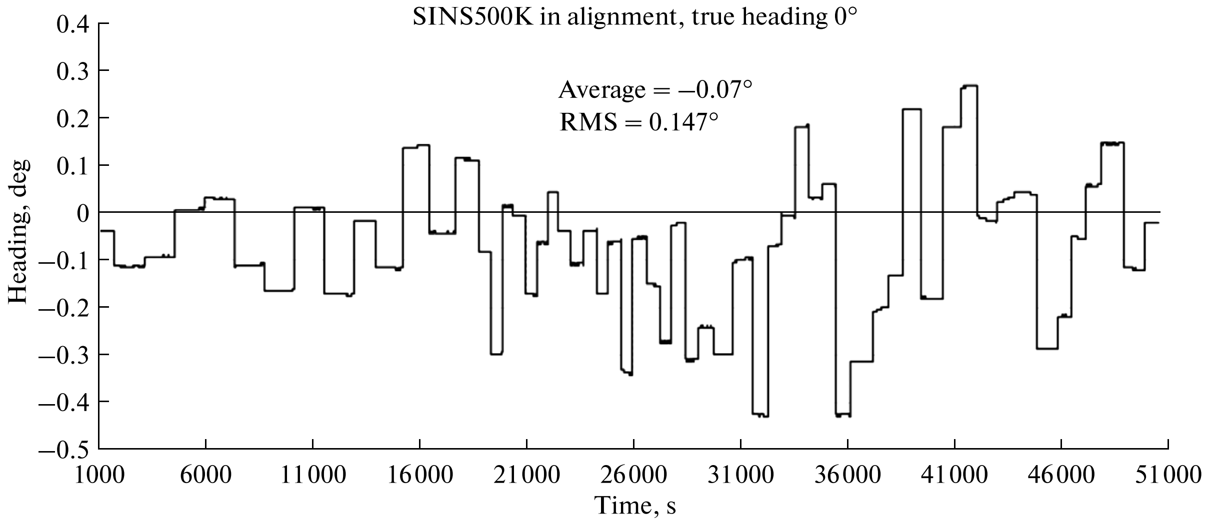

Fig. 4. SINS-500K initial alignment stability from run-to-run. Restart time is 10 minutes.

The results of series-produced SINS-500K tests in static and dynamic conditions for a wide range of external actions have been obtained. The specified accuracy characteristics have been confirmed: the heading estimation error (gyrocompassing) is less than 0.3 deg (Fig. 4); the position estimation error in the inertial mode is less than 10 km/h.

STRAPDOWN INERTIAL NAVIGATION SYSTEM SINS-501

In 2011, Optolink finished the development and began the serial production of the strapdown inertial navigation system SINS-501 (Fig. 5), designed on the basis of IMU-501 with three Optolink single-axis fiber-optic angular rate sensors SRS-501 (see Table 1) and three orthogonally mounted accelerometers by other manufacturers.

Fig. 5. SINS-501.

SINS-501 are designed for ground-based vehicles and airborne applications (alignment in static conditions). They have shown improved accuracy characteristics as compared with SINS-500K: the heading estimation error (gyrocompassing) is less than 0.1 deg (Fig. 6), the position estimation error in the inertial mode is less than 6 km/h, and improved temperature stability.

STRAPDOWN INERTIAL NAVIGATION SYSTEM SINS-500M

In 2012, Optolink finished the development of a marine strapdown inertial navigation system SINS-500M with the possibility of initial alignment in dynamic conditions (roll/pitch and motion. The system is integrated with external marine sensors (GNSS, log, etc.). As distinct from SINS-500K and SINS-501, alignment is possible both in static and dynamic conditions. SINS-500M is based on IMU-500. It is designed to form and output navigation data to customers both in the autonomous (inertial) mode and in the correction mode aided by GPS/GLONASS and log data.

The information is available for customers in digital form via RS-422 (or RS-232, MIL-STD-1553B, and Ethernet). Another possibility is 10 Hz frequency data exchange with the navigator console on a ship. The navigator console displays the main navigation data and allows setting and adjustment control of the SINS. The SINS indicators are used to visually control its operation.

Figures 6 and 7 show the exterior view and a block diagram of SINS-500M.

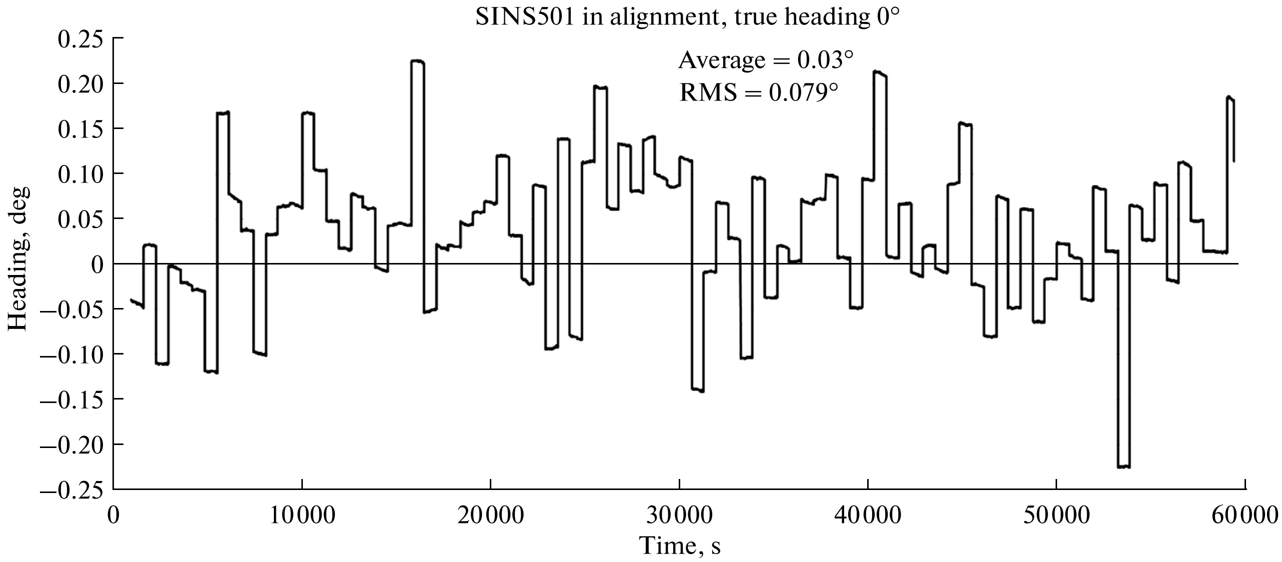

Fig. 6. SINS-501 initial alignment stability from run-to-run. Restart time is 10 minutes.

The marine system SINS-500M was subjected to tests on a car, rotary test bench, and ships. The task was to test the onboard software and study the accuracy characteristics at the stage of SINS initial alignment and in the navigation mode. Also tested were different algorithms for the SINS.

The tests checked the following parameters: position and heading errors (on a car); alignment errors and roll and pitch angle errors (on a test bench); coordinates, velocity and heading errors (on a ship), and SINS alignment in real rolling and pitching motions (ship). Tests were also performed to check generation of roll/pitch and vertical motions. The SINS errors were determined both when the ship was steady on course and in maneuvering.

The plots of pitch and roll angles are given in Fig. 9a. Fig. 9b shows the plots of pitch and roll angles during initial alignment, and Fig. 10, the heading angle. Rolling and pitching motions were imitated in a rotary test bench (Fig. 11). The plots indicate the SINS operability in rolling and pitching. The ampli-

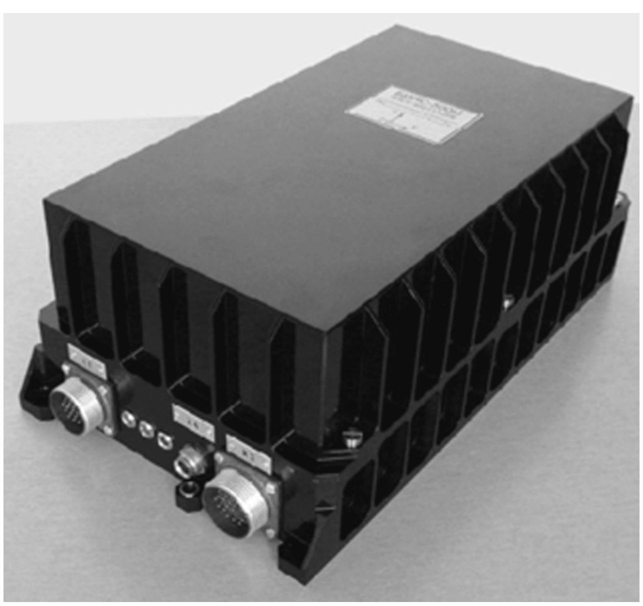

Fig. 7. SINS-500M

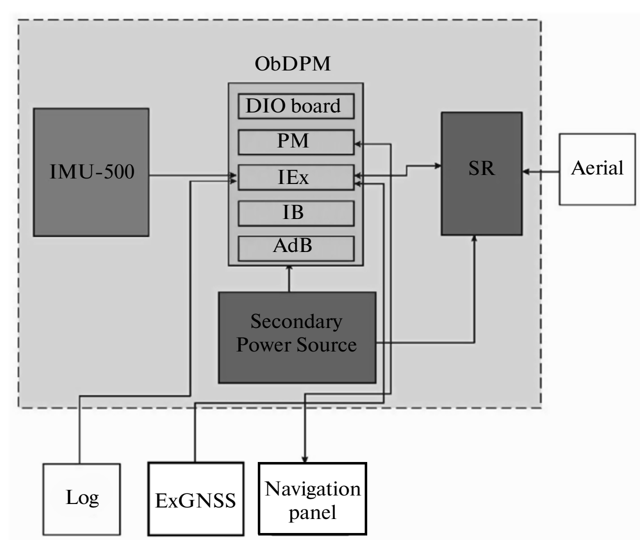

Fig. 8. A block diagram of SINS-500, where ObDPM—onboard digital processing module, DIO board— board of digital input-output, PM—processor module, IEx—interface expander, IB—interface board, AdB—adjustment board, SR—satellite receiver, ExGNSS—external satellite navigation system.

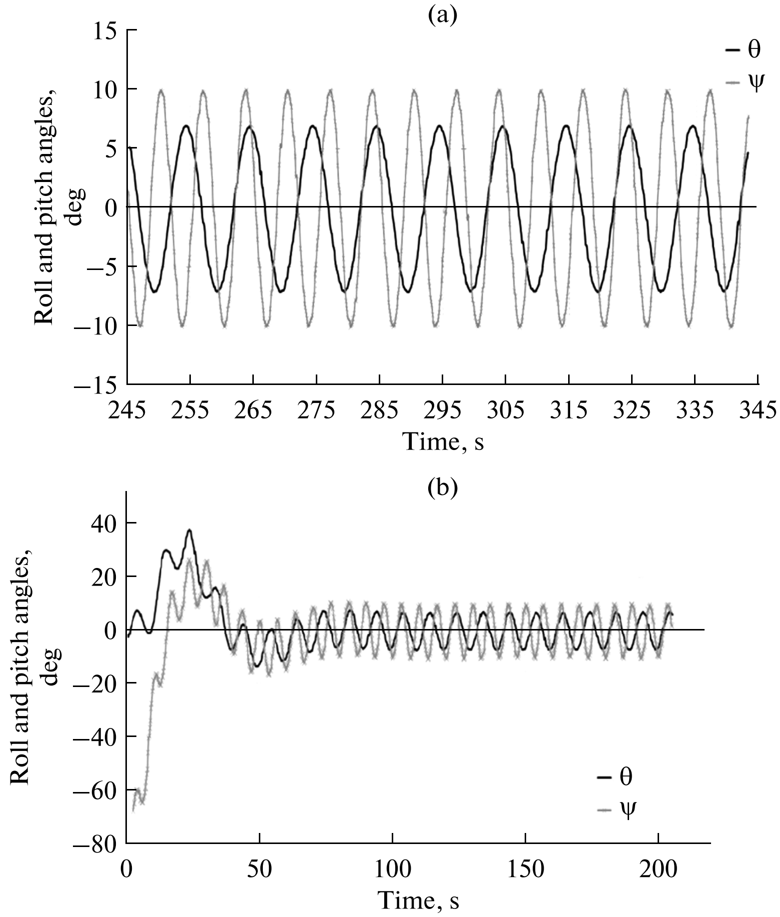

Fig. 9. Roll (ψ) and pitch (θ) angles (a) and alignment (b) under rolling and pitching motions on a rotary test bench.

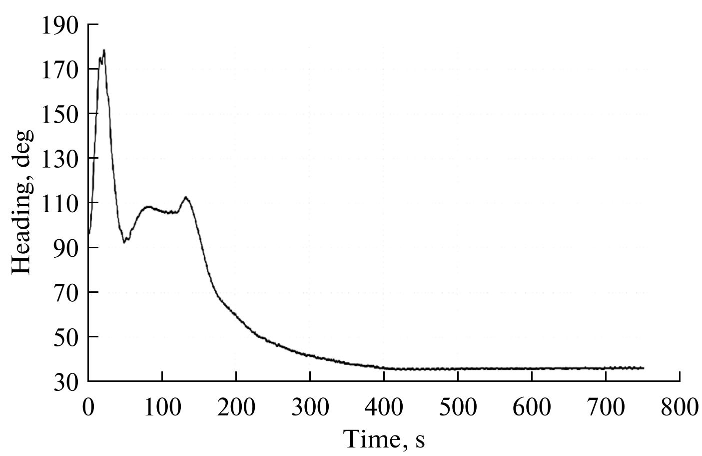

Fig. 10. Heading angle at alignment under rolling and pitching motions.

tude and period of angles are equal to the predetermined values with the following errors: pitching—10 s period (10.00299s, error ~3 ms), amplitude—7° (6.9918°, error ~0.5 arc min); rolling—6.6666 s period (6.6687 s, error ~2 ms), amplitude—10° (10.015°, error 0.6 arc m–1.2 arc m).

SINS-500M was tested for operability and accuracy characteristics under roll and pitch in the open

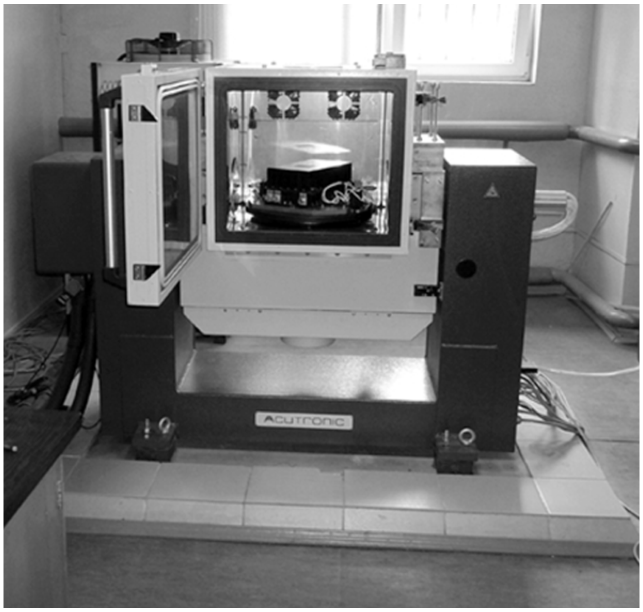

Fig. 11. SINS-500M test on a two-axis rotary test bench.

waters of Lake Ladoga (the test base of the Concern TsNII Okeanpribor Karelian affiliate) aboard an 18 ton-displacement ship and on a towboat RB-394 project 90600 (304-ton displacement) at the Leningrad Pella shipyard (Otradnoe, Leningrad oblast).

The tests included:

1. Alignment of the system aboard the ship moored at the pier—15 min. Start of data recording.

2. Moving to the Ladoga open water area—40–60 min.

3. Moving on tacks at 8 main rhumbs with constant speed and heading at least for 20 min on each rhumb–200 min.

4. Ship maneuvering including at least 3 full circulations in clockwise and counter-clockwise directions changing each 5 minutes, legs of acceleration and deceleration—60 min.

5. Restarting the system software under roll and pitch conditions in the absence of motion—40 min.

6. Restarting the system software under roll and pitch conditions while moving with constant heading and speed—40 min.

7. Returning to the pier—40–60 min.

Speed and coordinates accuracy characteristics in the sea tests were determined by comparing the SINS data output with the data from the built-in GPS/GLONASS receiver 1K-161-42 (Russian Institute of Radionavigation and Time). The system was mounted approximately on the ship's centerline plane. Correction and damping were also carried out based on the satellite data. The accuracy of the estimated speed and coordinates were determined from the comparison with the satellite data. Heading estimation accuracy was calculated using the course over ground. The data from the SINS and GNSS were recorded into the technological PC in the same file. By GNSS data we mean the coordinates, speed, and course over ground.

The ship maneuvering trajectory is shown in Fig. 12, whereas the plots of heading, course over ground and northern speed in circulations during the test are given in Fig. 13. Initial alignment was performed on the move. The tests lasted 8 hours. The average ship speed was about 10 knots. The position estimation accuracy (difference in SINS and GNSS data) for speed estimated by the built-in GPS/GLONASS receiver was 50 m and 100 m for latitude and longitude over a time period of 2–5 hours.

The characteristics of FOG-based SINSs produced by Optolink and the leading world manufacturers are given in Table 2.

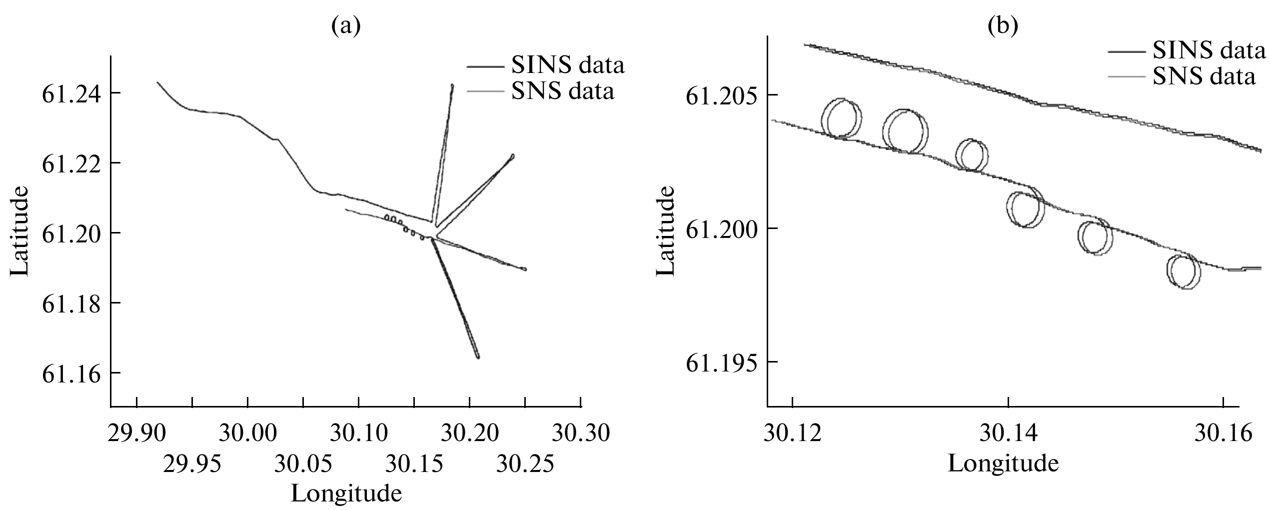

Fig. 12. Trajectory of ship maneuvering during the tests (a) and in circulations (b).

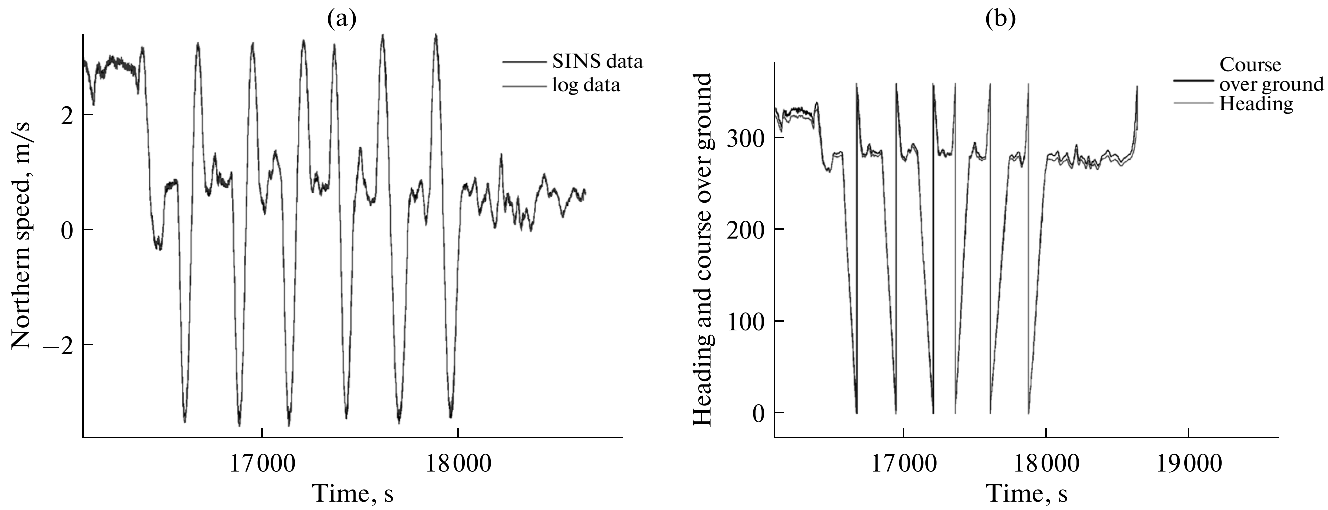

Fig. 13. The plots of northern speed (a) and heading and course over ground (b) in circulations during the test.

CONCLUSIONS

Thus, strapdown inertial navigation systems based on navigation-grade fiber-optic gyroscopes manufactured by leading Russian and foreign companies demonstrate high precision and performance characteristics sufficient enough for a wide range of airborne, ground-based, underground, water surface, and underwater applications.

Table 2. Characteristics of FOG-based strapdown inertial navigation systems

Characteristics	SINS-500K	SINS-500M	SINS-501	Quadrans IxBlue [16]	Octans IxBlue [16]	LISA-200 Northrop Grumman [17]
Inertial mode:						
Coordinate estimation error	10 km/h	8 km/h	4 km/h			
Speed estimation error	2.5 m/s	2 m/s	1 m/s			
Heading estimation error	0.5 s(lat)°	0.4 s(lat)°	0.1 s(lat)°	0.23 s(lat)°	0.1 s(lat)°	0.8°
Pitch and roll estimation error	0.1°	0.1°	0.05°	0.1°	0.01°	0.3°
Readiness time, min	10	5–15	10	5	15	2
FOG bias drift (1σ)	<0.1°/h	<0.1°/h	<0.03°/h	<0.1°/h	<0.05°/h	<0.5°/h
Accelerometer bias drift (1σ)	$<5 \times 10^{-4}$ g	$<5 \times 10^{-4}$ g	$<1 \times 10^{-4}$ g	$<5 \times 10^{-4}$ g	$<5 \times 10^{-4}$ g	$<3 \times 10^{-4}$ g
Power supply, V DC	27	27	27	12–36	24	28
Power consumption, W	14	20	20	13	12	40
Dimensions, mm	240 × 160 × 110	343 × 185 × 120	286 × 163 × 124	160 × 160 × 113	275 × 136 × 150	190 × 102 × 114
Weight, kg	3.4	6.4	4.8	2.8	4.6	2.0
Application conditions:						
Angular rates, °/s	<300	<300	<250	<500	<260	<1000
Temperature range, °C	–40°C...+60°C	–40°C...+60°C	–40°C...+60°C	–20°C...+55°C	–20°C...+55°C	–50°C...+70°C

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