

High-precision inertial measurement unit IMU-5000

Yu.N. Korkishko, V.A. Fedorov, V.E. Prilutskiy, V.G. Ponomarev, I.V. Fedorov, S.M. Kostritskii,
I.V. Morev, D.V. Obuhovich, S.V. Prilutskiy, A.I.Zuev, V.K.Varnakov

Optolink RPC LLC,
Moscow, Russia
opto@optolink.ru

Abstract—Today interferometric fiber-optic gyroscopes (FOGs) reach ultimate theoretical performance and surpass well-established competitor, the ring laser gyroscopes. Due to its inherent low random noise and its scalability, FOG technology is one of the very few technologies able to cope with the applications requiring the highest performance. Recently, Optolink has presented new fiber-optic gyroscope SRS-5000 with bias performance, amongst the best closed loop fiber-optic gyroscope performance published to date. The aim of the current work was to produce and to estimate the performance of inertial measurement unit (IMU) and strapdown inertial navigation systems (SINS) pilot series on the basis of SRS-5000 FOG - IMU-5000 and SINS-5000, correspondingly. Measured device parameters (ARW around 0.000069 deg/ \sqrt{h} with a bias stability of better than 0.00008 deg/h) allow to assess these kind of devices as the highest-precision strategic grade fiber-optic gyroscopes' based IMU, commercially available. Pilot units of SINS-5000 show alignment accuracy limit down to RMS 0.005° in series of 9-minute alignments. Static tests show coordinates drift of ~10 Nm over 7 days of operation. We believe the performance of these strategic-grade IMU and SINS may be useful in a range of high precision navigation, metrology, seismology, and structural sensing applications, as well as calibration of inertial test equipment.

Keywords— *fiber-optic gyroscope, inertial measurement unit, strategic grade*

I. INTRODUCTION

At present time interferometric fiber-optic gyroscopes (FOGs) are becoming widely used in inertial navigation systems. In high precision closed-loop configuration of FOG the feedback mechanism keeps the zero signal level by compensating the Sagnac phase shift with additional phase counter-shift. The value of the phase counter-shift allows one to obtain information about the angular rate of the device rotation [1]. Today the fiber-optic gyroscopes reach ultimate theoretical performance and surpass well-established competitor, the ring laser gyroscopes [2]. Due to its inherent low random noise and its scalability, FOG technology is one of the very few technologies able to cope with the applications requiring the highest performance. The FOG technology is seen by US experts as the only technology in the future able to replace the mechanical gyroscopes used for SSBN (Sub-Surface Ballistic Nuclear). Up to date, the highest performance FOGs are space grade FOGs - Honeywell HPFOG [3-7], AlliedSignal FOG [8], Litton FOG [9], L-3com Cirus [10], Airbus (former Astrium) Astrix-200 [11], as well as iXblue Marins [12], and iXBlue FOG-prototypes [14,15].

Research & Production Company Optolink has so far developed and produces series of single-axis FOGs SRS-2000, SRS-1000, SRS-501 and SRS-200 with different fiber coil lengths and diameters, as well as three-axis FOGs TRS-500 and inertial measurement units IMU-500, IMU-501 and IMU-1000 [16-22]. Space grade gyroscopes VOBIS are also produced and operate successfully on satellites at GEO [*]. To achieve great flexibility, Optolink has developed Interferometer-FOG that follows strictly the well-known Reciprocal Configuration. In order to take all the benefits of this configuration, it is combined with an original PM fiber, a high performance Integrated Optical Circuit (IOC), and a powerful All-Digital Signal Processing. Optolink's expertise in those 3 elements allowed us to develop high performance FOGs. Detailed passive thermal design, coil winding and gyro assembly techniques, methods for rejecting light source intensity noise, and light source wavelength control are critical features that have been developed to produce a FOG with low noise, stable bias, and a stable and linear scale factor.

Recently, Optolink has presented new fiber-optic gyroscope SRS-5000 with bias performance, amongst the best closed loop fiber-optic gyroscope performance published to date [23].

The aim of the current work was to produce and to estimate the performance of inertial measurement unit (IMU) and strapdown inertial navigation systems (SINS) pilot series on the basis of SRS-5000 FOG - IMU-5000 and SINS-5000, correspondingly.

II. FIBER-OPTIC GYROSCOPES SRS-5000

The SRS-5000 fiber-optic coil is made of specially made by Optolink polarization maintaining (Panda-type) optical fiber. PM-fiber coil length and winding radius of 5000m and 12cm, respectively. To reduce Shupe error, coils for FOGs are produced in a octupole pattern packed with glue to achieve high performance. Allan variance plots for SRS-5000 ground tests are shown in Fig. 1 with respect to Allan variance results for the most advanced iXBlue FOGs: MARINS FOG [12], 5000m-coil FOG [13], and FOG for rotational ground motions measurement [14] with ARW = 38 and 180 $\mu^\circ/\sqrt{\text{hour}}$, respectively. According to measurement results, the main SRS-5000 parameters are: dynamic range $\pm 12^\circ/\text{s}$; angle random walk (ARW) $< 70 \mu^\circ/\sqrt{h}$ ($< 20 \text{ nrad}\times\text{s}^{-1}/\sqrt{\text{Hz}}$); bias instability (BI) $< 8\times 10^{-5}^\circ/\text{hour}$ with characteristic averaging time of BI shelf $> 5000\text{s}$; scale factor repeatability $\leq 3\text{ppm}$ (1σ). Bias and scale factor (SF) stability and repeatability (run-to-run) tests were also conducted. Statistics of bias (mean values in each consequent launch) in the run-to-run test can be observed in Fig. 2., launch mean values RMS value was $6\times 10^{-4}^\circ/\text{hour}$.

Figures 3 and 4 shows the results of SF stability test results in single launch (Fig.3) and run-to-run (Fig.4) tests. The resulting SF RMS value in launches sequence (run-to-run) was only a little higher than single-launch error: 2.5-2.8 ppm RMS compared to 1.2-1.4 ppm RMS, which indicates very good SF repeatability in short-term tests.

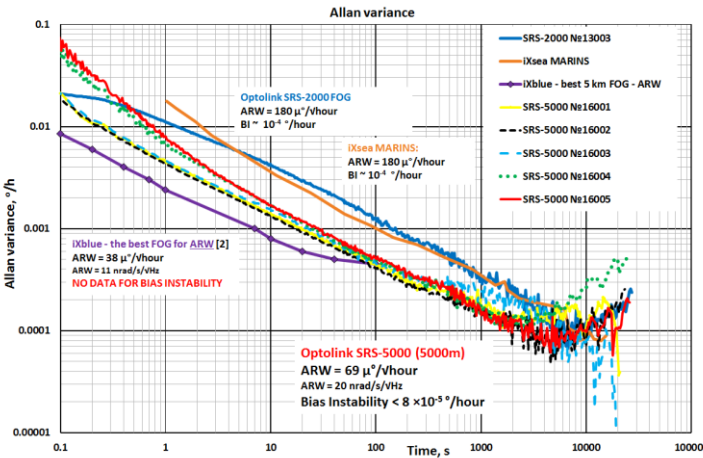


Fig. 1. SRS-5000 Allan variance plot, compared with IxBlue best FOG results presented [12-15]

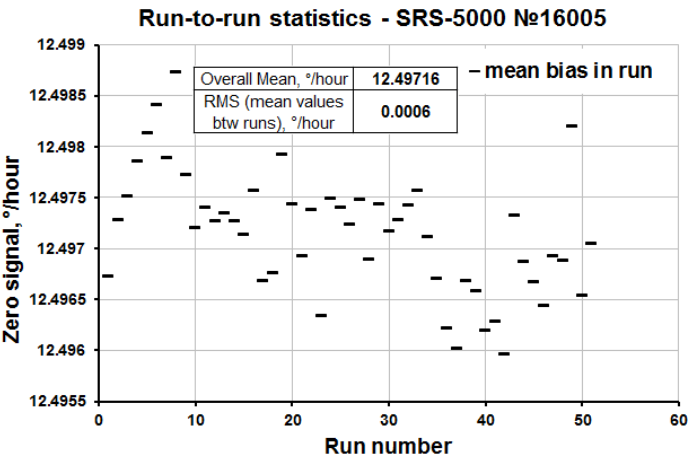


Fig. 2. SRS-5000 bias repeatability (run-to-run) test results

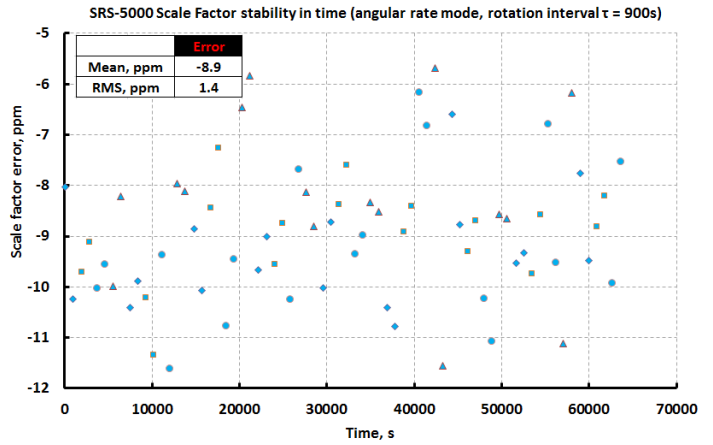


Fig. 4. SRS-5000 scale factor repeatability (run-to-run) test results

In order to examine output angle stability of SRS-5000 we also analyzed noise equivalent angle (NEA) of gyroscope's signal in ground tests, shown in Fig.5. Peak-to-peak NEA was calculated ~ 0.31 arcsec, ~ 0.37 arcsec and ~ 0.69 arcsec for time 1800 s, 3600 s and 16000 s, respectively

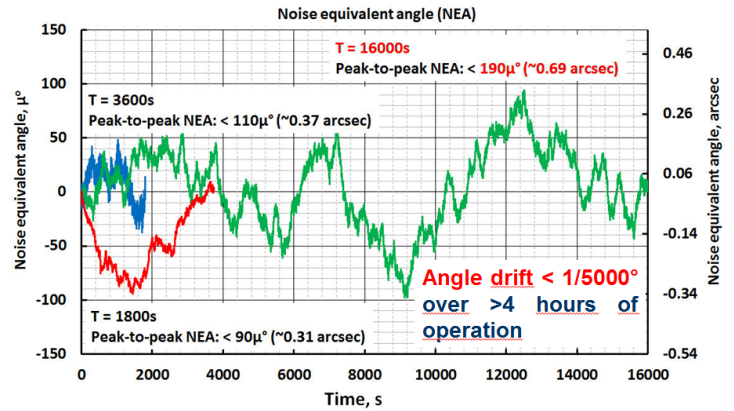


Fig. 5. SRS-5000 noise equivalent angle for 1800 s, 3600 s and 16000 s

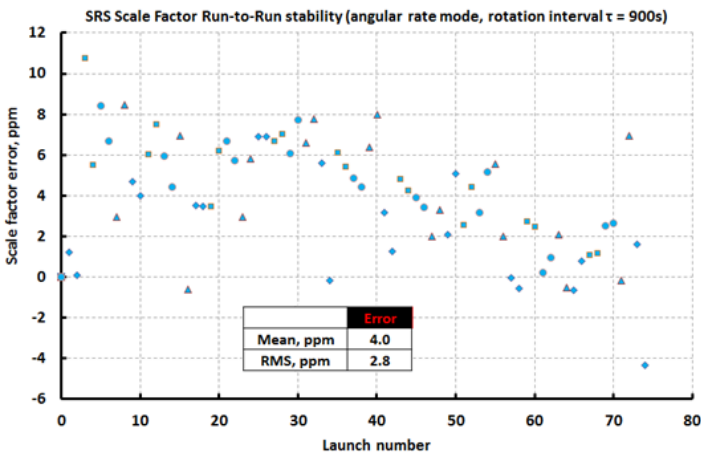


Fig. 3. SRS-5000 scale factor error at constant temperature in single launch.

III. INERTIAL MESUREMENT UNIT IMU-5000

IMU-5000 unit has initial dynamic range for input angular rates ± 12 $^{\circ}/s$, but it can be further extended to limits of ± 550 $^{\circ}/s$ via octave-switching scheme serially used in SRS-1001 fabrication [19]. To match the extraordinary performance of SRS-5000 gyro, in IMU-5000 we have installed high-precision quartz pendulous rebalancing accelerometers with noise level < 2 $\mu g/\sqrt{Hz}$, bias drift ~ 0.5 μg , scale factor error < 10 ppm. Exterior of IMU-5000 block is shown in Fig.6.

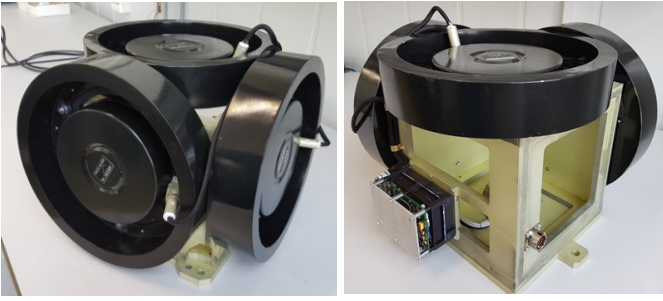


Fig. 6. Images of produced high-precision inertial measurement unit IMU-5000

During the fabrication of IMU-5000 unit, the preliminary calibration is done which includes compensation of gyro and accelerometer bias & scale factor temperature drift, all channel misalignments (non-orthogonalities) with their temperature dependence, output sampling frequency and analog electronics fine-tuning. In SINS IMU-5000 is shielded with thermostatic chassis with heating modules that enable active temperature control of SINS system.

The main technical characteristics of high-precision inertial measurement unit IMU-5000 are shown in Table 1.

TABLE I. ACCURACY AND OPERATIONAL CHARACTERISTICS OF HIGH-PRECISION INERTIAL MEASUREMENT UNIT IMU-5000

Parameter	Inertial measurement unit IMU-5000
Gyroscopes	
Bias instability (according to Allan variance plot), °/hour	$\leq 8 \cdot 10^{-5}$
Angle random walk (according to Allan variance plot), μ°/\sqrt{h}	≤ 70
Scale factor error at constant temperature, ppm	≤ 10
Scale factor repeatability at constant temperature (1σ), ppm	≤ 3
Accelerometers	
Velocity Random Walk, $\mu g/\sqrt{Hz}$	≤ 2
Bias Instability, μg	≤ 0.5
Scale factor error at constant temperature, ppm	≤ 10

This performance allows to assess this type of devices as the highest-precision strategic grade fiber-optic gyroscopes, commercially available.

The performance of IMU-5000 and SINS-5000 in tasks of inertial navigation is discussed. Pilot units of SINS-5000 show the estimated alignment accuracy limit down to RMS 0.005° in series of 9-minute alignments (Fig.7). Static tests show coordinates drift of ~ 10 Nm over 7 days of operation.

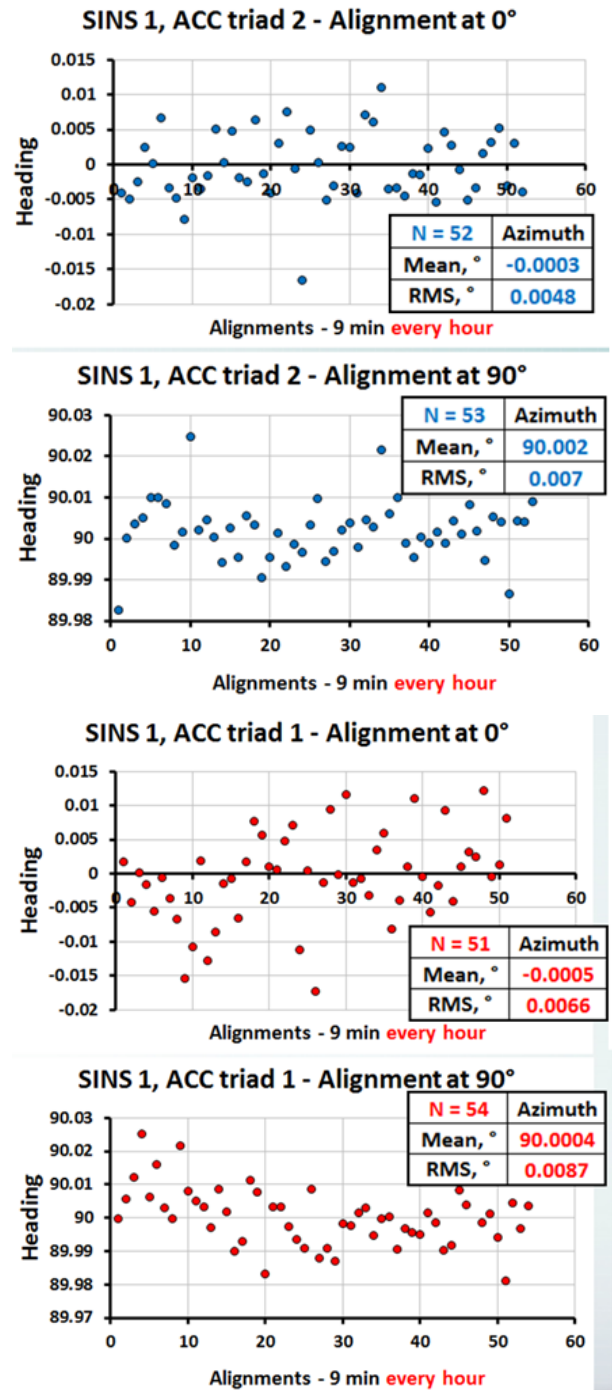


Fig. 7. Alignment stability of SINS-5000 (~50 hours) fabricated on the basis of IMU-5000

Hence, company Optolink RPC has developed and manufactured the new high-precision inertial measurement unit and strapdown inertial navigation systems pilot series on the basis of SRS-5000 fiber-optic gyro - IMU-5000 and SINS-5000, correspondingly. Measured device parameters allow to assess these kind of devices as the highest-precision strategic grade FOG-based IMU, commercially available. We believe the performance of these strategic-grade IMU and SINS may

be useful in a range of high precision navigation, metrology, seismology, and structural sensing applications, as well as calibration of inertial test equipment.

REFERENCES

- [1] H. Lefevre, *The Fiber-Optic Gyroscope*, Artech House, 1993.
- [2] H. C. Lefèvre, “The fiber-optic gyroscope: Achievement and perspective”, *Gyroscopy and Navigation*, 2012, Vol.3, pp.223-226.
- [3] G.A. Sanders, B. Szafranec, L. Strandjord, R. Bergh, A. Kaliszek, R. Dankwort, and D. Kimmel, “Progress in high performance fiber optic gyroscopes”, in *Optical Fiber Sensors*, Optical Society of America, 1997, p. OWB1.
- [4] S. Divakaruni and S. Sanders, “Fiber optic gyros: a compelling choice for high precision applications”, in *Optical Fiber Sensors*, Optical Society of America, 2006, p. MC2.
- [5] S. Divakaruni, G. Keith, C. Narayanan, and J. Keener, “Strategic interferometric fiber-optic gyroscope for ballistic missile inertial guidance”, *AIAA Guidance, Navigation and Control Conference and Exhibit*, 18 - 21 August 2008, Honolulu, Hawaii, paper 2008-7301.
- [6] S. Sanders, A. Taranta, S. Mosor, M. Alden, L. Hendry, R. DeMaio, N. Giere, and J. Sewell, “Fiber optic gyros in a high-performance, high-reliability inertial reference unit for commercial satellites”, *Proc. SPIE*, 2012, vol.8421, OFS2012 22nd International Conference on Optical Fiber Sensors, pp.842106; doi: 10.1117/12.975535.
- [7] https://aerocontent.honeywell.com/aero/common/documents/Fiber_Optic_Gyro_Based_Inertial_Reference_System.pdf
- [8] K.M.Killian, M. Burmenko, and W. Hollinger, “High-performance fiber optic gyroscope with noise reduction”, *Proc. SPIE*, 1994, vol.2292, *Fiber Optic and Laser Sensors XII*, pp. 255-263; doi: 10.1117/12.191838.
- [9] A. Cordova, R.A. Patterson, J. Rahn, L.K. Lam, and D.M. Rozelle, “Progress in navigation-grade IFOG performance”, *Proc. SPIE*, 1996, vol.2837, *Fiber Optic Gyros: 20th Anniversary Conference*, pp. 207-217; doi: 10.1117/12.258181.
- [10] <http://www2.l-3com.com/spacnav/pdf/datasheets/cirius-a.pdf>
- [11] <https://spaceequipment.airbusdefenceandspace.com/avionics/fiber-optic-gyroscopes/astrix-200/High-Performance FOG IMU>
- [12] Y. Paturel, V. Rumoroso, A. Chapelon, and J. Honthaas, “MARINS, the first FOG navigation system for submarines”, in *Symposium Gyro Technology*, 2006, p. 17.
- [13] F. Guattari, C. Moluçon, A. Bigueur, E. Ducloux, E. de Toldi, J. Honthaas, and H. Lefèvre, “Touching the limit of FOG angular random walk: Challenges and applications”, in *Proc. DGON Inertial Sensors and Systems (ISS)*, September 20-21, 2016, Karlsruhe, Germany, pp.1-13.
- [14] F. Bernauer, J. Wassermann, F. Guattari, and H. Igel, “Portable sensor technology for rotational ground motions”, *Geophysical Research Abstracts*, 2016, Vol. 18, pp. EGU2016-13345.
- [15] Yu.N.Korkishko, V.Fedorov, V.Prilutskii, V.Ponomarev, I.Morev, S.Kostritskii, A.Zuev, and V.Varnakov, “Closed loop fiber optical gyroscopes for commercial and space applications”, in *Proc. DGON Inertial Sensors and Systems - Symposium Gyro Technology 2012*, Karlsruhe, Germany, 18-19 September 2012, pp.P14.1-P14.15.
- [16] Yu.N. Korkishko, V.A.Fedorov, V.E.Prilutskii, V.G.Ponomarev, I.V.Morev, and S.M.Kostritskii, “Interferometric closed-loop fiber-optic gyroscopes”, *Proc. SPIE*, 2012, Vol.8351, *Third Asia Pacific Optical Sensors Conference*, 83513L.
- [17] Yu.N.Korkishko, V.A.Fedorov, V.E.Prilutskii, V.G.Ponomarev, I.V.Morev, S.M.Kostritskii, A.I.Zuev, and V.K.Varnakov, “Interferometric closed loop fiber optical gyroscopes for commercial and space applications”, *Proc.SPIE*, 2012, vol.8421, OFS2012 22nd International Conference on Optical Fiber Sensors, 842107.
- [18] Yu.N.Korkishko, V.A.Fedorov, V.E.Prilutskiy, V.G.Ponomarev, I.V.Morev, D.V. Obuhovich, I.V.Fedorov, and N.I.Krobka, “Investigation and Identification of Noise Sources of High Precision Fiber Optic Gyroscopes”, in *Proc. 20th Saint Petersburg International Conference on Integrated Navigation Systems*, Saint Petersburg, May 27-29, 2013, pp.59-62.
- [19] Yu.N.Korkishko, V.Fedorov, V.Prilutskii, V.Ponomarev, I.Morev, D. Obuhovich, and S.Prilutski, “High-precision fiber optical gyro with extended dynamical range”, in *Proc. DGON Inertial Sensors and Systems - Symposium Gyro Technology 2014*, Karlsruhe, Germany, 16-17 September 2014, pp.P09.1-P09.14.
- [20] 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, “Strapdown Inertial Navigation Systems Based on Fiber Optic Gyroscopes”, *Gyroscopy and Navigation*, 2014, Vol. 4, No. 4, pp. 195–204. (doi: 10.1134/S2075108714040154)
- [21] Yu.N.Korkishko, V.A.Fedorov, V.E.Prilutskiy, V.G.Ponomarev, I.V.Morev, A.I.Morev, D.V.Obuhovich, S.M.Kostritskii, A.I.Zuev, V.K.Varnakov, A.V. Belashenko, E.N.Yakimov, G.V.Titov, A.V.Ovchinnikov, I.B.Abdul'minov, and S.V.Latyntsev, “Space grade fiber optic gyroscope: R&D results and flight tests”, in *Proc. 2016 DGON Inertial Sensors and Systems (ISS)*, Karlsruhe, Germany, 20-21 September 2016, pp.21.1-21.19.
- [22] Yu.N.Korkishko, V.A.Fedorov, V.E.Prilutskiy, V.G.Ponomarev, I.V.Fedorov, S.M.Kostritskii, I.V.Morev, D.V.Obuhovich, S.V. Prilutskiy, A.I.Zuev, and V.K.Varnakov, “Highest bias stability fiber-optic gyroscope SRS-5000”, in *Proc. 2017 DGON Inertial Sensors and Systems (ISS)*, Karlsruhe, Germany, 19-20 September 2017, pp.P03.1-P03.23. (doi: 10.1109/InertialSensors.2017.8171490).