Miniature Inertial Measurement Units IMU200 and IMU400 Based on FOG with MEMS-Accelerometers: Development and Studying of Characteristics

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

Viktor Prilutskiy
Optolink RPC LLC,
Moscow, Russia

Vasiliy Varnakov
Optolink RPC LLC,
Moscow, Russia

Vyacheslav Fedorov
Optolink RPC LLC,
Moscow, Russia

Vladimir Ponomarev
Optolink RPC LLC,
Moscow, Russia

Sergei Kostritskii
Optolink RPC LLC,
Moscow, Russia

Stanislav Prilutskiy
Optolink RPC LLC,
Moscow, Russia

Igor Fedorov
Optolink RPC LLC,
Moscow, Russia

Ivan Morev
Optolink RPC LLC,
Moscow, Russia

Dmitriy Obuhovich
Optolink RPC LLC,
Moscow, Russia

Aleksandr Zuev
Optolink RPC LLC,
Moscow, Russia

***Abstract*—Nowadays interferometric fiber-optic gyroscopes (FOG, IFOG) are extensively used in strapdown INS, and in broad range of applications they have replaced their main competitor and predecessor - ring laser gyroscopes (RLG). To cover the new perspective applications with demands for low-cost and compact but precise inertial sensors, Optolink developed new products: most compact inertial measurement units IMU200 and IMU400. The aim of the current work was the development of pilot IMU200 devices and the estimation of the performance of IMU200 and IMU400 with direct measurements and also with SINS simulation methods. IMU200 SWaP properties are as follows: 75×75×60mm, <0.5kg, 1/3 l, ≤6W. The main IMU200 Gyro/Accelerometer accuracy parameters: Angle Random Walk (ARW) = 0.015°/√hour, Bias Instability (BI) = 0.02°/hour; Velocity Random Walk (VRW) = 40μg/√Hz, BI = 6μg. For IMU400, developed before IMU200, SWaP properties are: 80×95×62 mm, <0.7kg, ½ l, ≤7W. The main IMU400 accuracy parameters are: ARW = 0.007°/√hour, BI = 0.01°/h; Velocity Random Walk (VRW) = 40μg/√Hz, BI = 6μg. SINS expected performance (1σ, 10 min alignment time): for IMU200 heading 0.4°×sec(lat), for IMU400 ~ 0.2°×sec(lat).**

Keywords*—fiber-optic gyroscope, inertial measurement unit, C-SWaP, MEMS-accelerometer, compact, miniature

I. INTRODUCTION

Currently, interferometric fiber-optic gyroscopes (IFOG) are broadly used in strapdown inertial navigation systems (SINS). In closed-loop configuration of IFOG the feedback maintains zero signal by compensating Sagnac phase shift with additional counter-shift, this shift value is used for the angular rate quick calculation [1-4]. Due to its inherent low random noise and its scalability, FOG technology is able, as a unique technology, to meet the demands of the applications requiring the highest performance combined with c-SWaP (cost with SWaP: Size, Weight and Power) [1, 4].

Research & Production Company Optolink has developed and produces series of single-axis FOGs SRS5000, SRS2000, SRS1000, SRS501 and SRS200 with various fiber coil lengths and diameters, as well as three-axis FOGs TRS500 and inertial measurement units (IMU) IMU400C, IMU500, IMU501, IMU1000 [5], and IMU5000 [6], based on three FOG channels and three precise quartz pendulum accelerometers. Space grade gyroscopes VOBIS are produced, which operate successfully onboard the GEO satellites [7].

II. IMU200 & IMU400 DESIGN

To cover the contemporary perspective applications requiring low-cost and compact but precise inertial sensors, Optolink has launched the new products: most compact inertial measurement units IMU200 and IMU400. The aim of the current work was the development of pilot IMU200 devices and the estimation of the performance of IMU200 and IMU400 with direct measurements and also with SINS operation modelling technique, the indirect but representave way of performance observation.

IMU200 (Fig. 1) has the following SWaP characteristics: 75×75×60 mm, <0.5 kg, 1/3 l, ≤6 W. The IMU was designed with coils of circular shape, and its housing is made entirely of magnetic-shielding material. FOGs are fed with single light source. To reduce the size and cost, quartz pendulous accelerometers were substituted by MEMS, the IMU has two 3-axis MEMS accelerometers: altogether, 6 low-noise channels. Acceleration along each axis is composed of 2 low-noise signals, and while the temperature compensation of scale factors and biases is performed in a composite way, misalignment corrections are performed separately for each of 2 effective triads before mixing. Also, the combination of 2 signals in each channel enables us to mutually compensate bias and scale factor instabilities and temperature dependences, while effective accelerometer (ACC) size effect arms do not exceed 5mm. Current scheme was first used in IMU400, now it is already checked and approved. IMU200 chassis is fully made of magnetically soft material (shielding from external magnetic field).

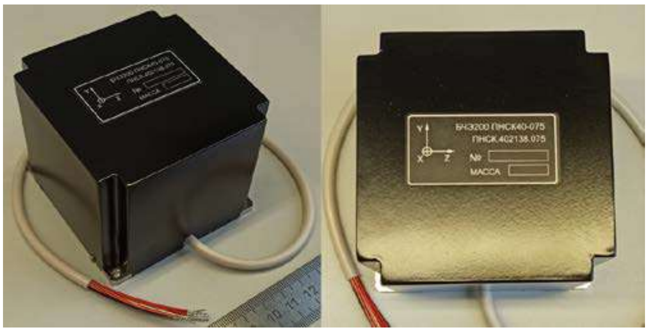

Fig. 1. IMU200 external view.

IMU400 (Fig. 2) has SWaP characteristics: 80×95×62 mm, 0.7 kg, 0.5 l, ⩽7 W. FOGs are fed with single light source, coils are designed in a shape of rectangle with rounded corners. In future, additional IMU400 versions with circular fiber coils might appear, with slightly increased (worse) ARW but with less (better) temperature instability (down to 0.1°/hour, 1σ, in temperature range).

Both IMU200 and IMU400 are available in version of three-axis gyro, with NO accelerometer channels installed.

Fig. 2. IMU400 external view.

Each IMU400 has 3 triads (physical) of MEMS accelerometers, with 6 low-noise (composing 2 effective triads) and 3 high-noise acceleration channels which are neglected. Acceleration value along each axis is composed of 2 low-noise signals from different physical triads. Effective accelerometer lever arms do not exceed 10 mm.

III. IMU CHARACTERISTICS

Pilot IMU200 units performance: FOG - ARW 0.015°/√h, bias instability 0.02°/h, run-to-run 0.03°/h, scale factor error 100 ppm; Accelerometer channels are similar to previously developed IMU400, with performance values presented below.

Regular IMU400 units performance (more than 100 devices produced and delivered to customers so far): FOG - ARW 0.007°/√h, bias instability 0.01°/h, run-to-run 0.02 °/h, scale factor error 100 ppm; Accelerometers - VRW 40 μg/√Hz, bias instability 6 μg, run-to-run 20 μg, scale factor error 150 ppm.

Allan variance plots of pilot IMU200 units and regular IMU400 units are shown in Fig. 3. IMU400 shows 2 times lower (better) ARW than IMU200, with same results for Accelerometer channels, due to identical channel models and scheme used. Gyro and Accelerometer channel bias temperature behavior of IMU200 is shown in Figure 4. Plots of similar sense for IMU400 are show in Figure 5.

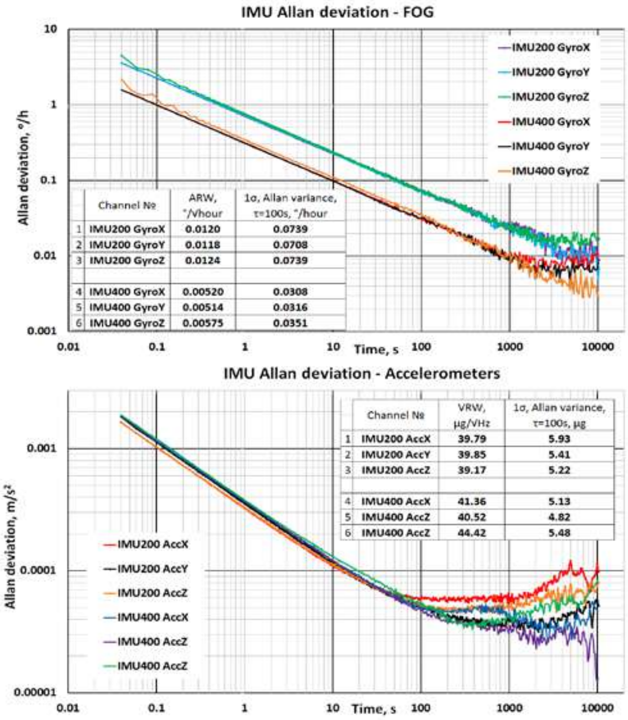

Fig. 3. IMU200 & IMU400 Allan deviation curves.

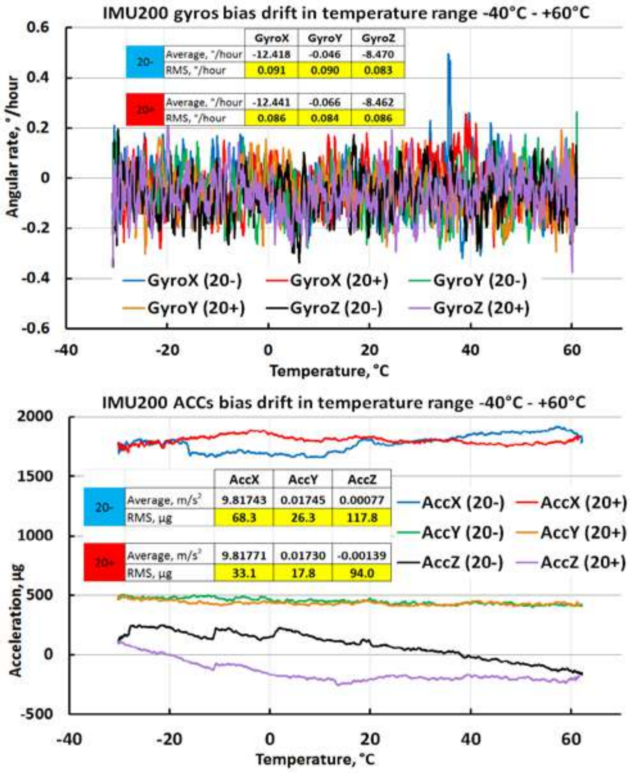

Fig. 4. IMU200 Gyroscopes & Accelerometers bias stability (drift) plots in temperature range -40°C - +60°C with constant temperature change rate (ramp) +20°C/hour (20+) and -20°C/hour (20-). Absolute values are shifted.

In general, due to conventional fiber coil design IMU200 possess more stable temperature profile for gyro bias and scale factor dependences, compared with IMU400. Shown in Fig.4 plots for gyroscope biases represent that IMU200 can successfully meet regular IMU400 results [9] of RMS < 0.1°/hour over the device temperature range. Meanwhile, best IMU400 coils give results of RMS < 0.04°/hour over the temperature range, however it is difficult to guarantee from coil to coil.

For reader's convenience, in order to represent all temperature test data in one plot with single scale of magnitude, Gyro and ACC plots were shifted by constants: -12.4, 0, -8.4°/hour for Gyros X,Y,Z, respectively, and 9.8, 0.013 m/s^2 for accelerometers X,Y in Fig.4; -12.4, 7.7, 3.4 °/hour for Gyros X,Y,Z in Fig.5. Real Average/STD data for each channel is presented in captions in Fig. 4, 5.

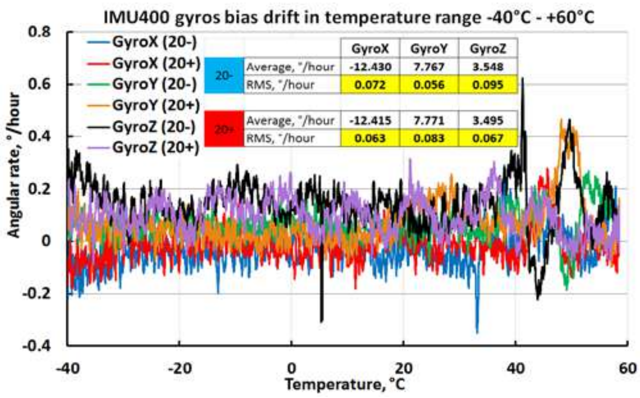

Fig. 5. IMU400 Gyroscopes bias stability (drift) plots in temperature range -40°C - +60°C with constant temperature change rate (ramp) +20°C/hour (20+) and -20°C/hour (20-). Absolute values are shifted for convenience.

IV. SINS Simulation Tests

At Optolink, various test procedures [8] are carried out in order to qualify SINS accuracy level. One of key SINS performance parameters is the heading accuracy during successively performed initial alignments via gyrocompassing. Each SINS runs series of alignment tests, which consist of alignment statistics accumulation over 4 or more cardinal directions. This test is significant because in addition to sensor noise (RMS of yaw with respect to its mean value), it shows the mean heading errors for each direction. These heading errors represent mainly gyro absolute bias errors and their stability in time [9].

The IMU performance under precise calibration option is regularly tested with the same approach as to SINS, with the use of SINS modeling software. The statistics of alignments shows heading RMS 0.5° for IMU200 and RMS 0.3° for IMU400 (latitude φ=56°N, Figures 6 & 7, respectively). Minimum achievable heading RMS due to gyro noise level is 0.2°×sec(lat) for IMU200 and 0.1°×sec(lat) for IMU400, not accounting for biases.

Gyro bias changes from test to test were at most 0.043°/hour and 0.027°/hour for IMU200 and IMU400, respectively.

After precise accounting for biases, IMU200 at 4 cardinal directions test shows position drift of ~8 nautic miles over 5 hours in pure inertial mode (no aiding, no Schuler oscillations damping), with a 30-minute alignment (Fig. 8). Schuler velocity amplitude reaches 2.7 m/s and 5 m/s for the East and North velocities.

Heading °	1	2	3	4	5	6	Average for	Dispersion for	RMS for Heading, °
0	-0.374	0.300	0.279	0.388	0.077	0.108	0.1296	0.0793	0.282
90	89.315	89.669	89.358	90.038	89.444	89.343	89.5277	0.2889	0.537
180	179.961	179.503	180.123	179.465	179.766	179.861	179.7797	0.1042	0.323
270	270.489	271.323	270.342	270.973	270.405	270.703	270.7061	0.6189	0.787
0	0.834	0.481	0.181	0.006	-0.226	0.731	0.2560	0.1957	0.442

Total disp.	Total RMS
0.3019	0.549

	Bias, °/hour		
	X	Y	Z
test1	-0.071	-0.026	-0.052
test2	-0.029	-0.036	-0.047

	Cardinal direction					
	0°	90°	180°	270°	0°	Average
RMS (Mean-shifted), °	0.274	0.281	0.258	0.380	0.386	0.316

Fig. 6. IMU200 alignment statistics (10 minutes alignment time), 4 cardinal directions. Total RMS = 0.549° (Moscow latitude 55.97°). Estimated gyro bias errors are shown. Estimated alignment limit 0.316° ~ 0.2° × sec(lat°).

Heading °	1	2	3	4	5	6	Average for	Dispersion for	RMS for Heading, °
0	0.195	0.034	0.380	0.002	0.098	0.279	0.1647	0.0452	0.212
90	90.339	90.513	90.541	90.276	90.051	90.398	90.3531	0.1514	0.389
180	179.857	179.605	179.770	179.926	179.778	179.731	179.7779	0.0594	0.244
270	269.555	269.798	269.531	269.476	269.569	269.804	269.6221	0.1597	0.400
0	0.011	-0.192	-0.278	-0.023	0.145	0.115	-0.0226	0.0211	0.145

Total disp.	Total RMS
0.0979	0.313

	Bias, °/hour		
	X	Y	Z
test1	0.028	0.054	-0.019
test2	0.036	0.040	0.008

	Cardinal direction					
	0°	90°	180°	270°	0°	Average
RMS (Mean-shifted), °	0.147	0.179	0.110	0.142	0.153	0.146

Fig. 7. IMU400 alignment statistics (10 minutes alignment time), 4 cardinal directions. Total RMS = 0.313° (Moscow latitude 55.97°). Estimated gyro bias errors are shown. Estimated alignment limit 0.146° ~ 0.1° × sec(lat°).

After bias trimming, IMU400 in alignment test run shows 5 nautic miles position drift over 8 hours in pure inertial mode with 20 minutes start alignment (Fig. 9, no aiding, no ZUPT, no Schuler oscillations damping). Velocity error reaches 2 m/s and 4 m/s for East and North velocities.

In addition to modeling of IMU400 drifts in static over time, real navigation data of IMU are presented (Fig. 10). IMU device was being recorded standalone along the track on a vehicle. For each test, IMU record starts with 10 minutes of static required for initial alignment, then the movement starts. No data source is used for aiding or fusion - IMU is the only device in tests. GPS data for the true track plotting (blue in Fig. 10 plots) is available before the IMU tests as the tracks that we use are fixed.

The only kind of corrections that we used in post-processing of IMU400 test laps was zero velocity update (ZUPT) and Kalman filtration on the basis of velocity errors during ZUPT. In Figure 10, navigation of two data sets is shown, heading is obtained via gyrocompassing alignment (10 minutes). First record is collected over track of ~30 km (30 minutes of vehicle movement). Second record is collected over track of ~110 km (100 minutes of vehicle movement). The presented plots show IMU400 navigation results of ~1km position error for the 1st track and ~10km error for the 2nd track. These results are incomparably better than any MEMS or open-loop FOG for the same task (they are not even measured in pure inertial mode).

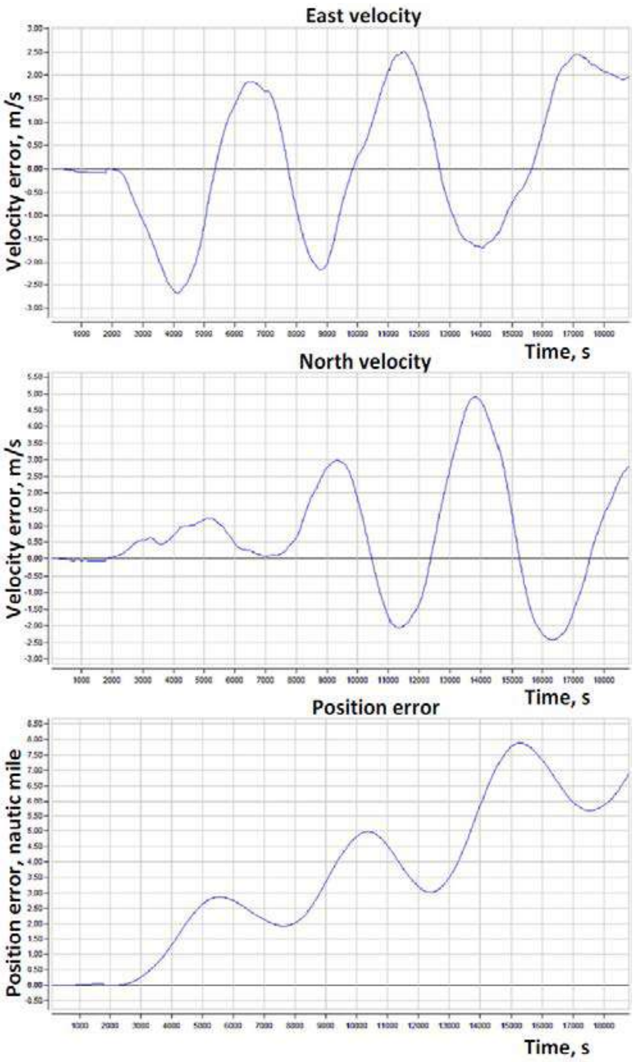

Fig. 8. IMU200 drift in pure inertial mode (static), 5 hrs, no aiding, 30 min. alignment, 4 cardinal directions.

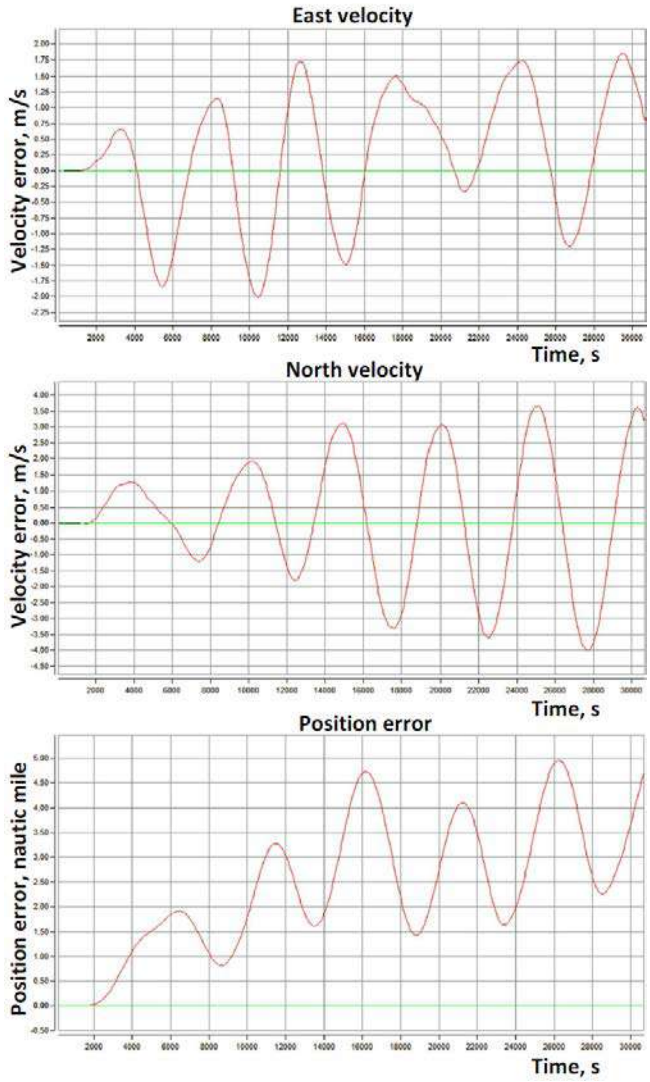

Fig. 9. IMU400 drift in pure inertial mode (static), 8 hrs, no aiding, 20 min. alignment, 4 cardinal directions.

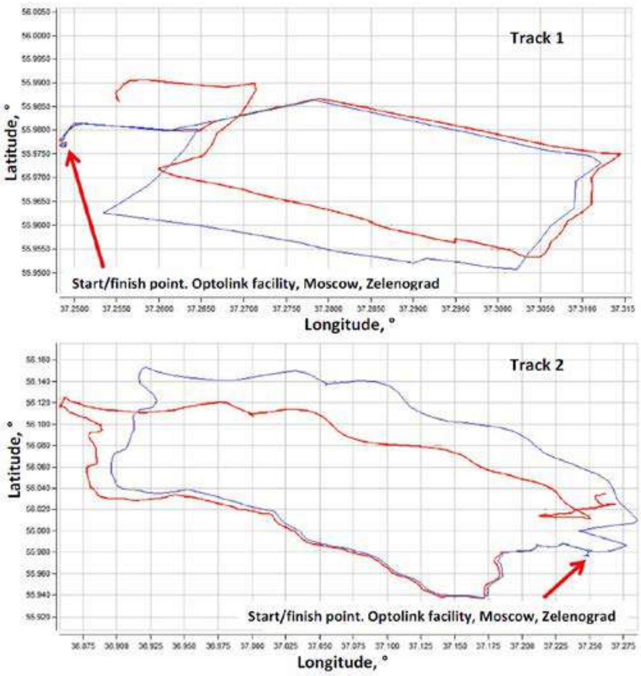

Fig. 10. IMU400 navigation results in compensated inertial mode (ZUPT) in two records: ~30 km (1km CPE error), ~110 km (10km CPE error). Red is the IMU postprocessing results, Blue is GPS plot collected for the track.

V. Conclusion

Obtained performance characteristics and results allow us to consider IMU200 as tactical and IMU400 as near-navigation grade IMUs suitable for various applications, especially aeronavigation and UAV. While accelerometer channels in these two kinds of devices are virtually same, gyro channels differ in terms of noise and bias stability; IMU400 has two times lower (better) ARW ~ 0.007°/√hour, IMU200 ARW ~ 0.015°/√hour.

References

[1] H. C. Lefevre, The Fiber-Optic Gyroscope, Second Edition. Boston, Artech House, 2014

[2] W. K. Burns, Ed., Optical Fiber Rotation Sensing, Boston, Academic Press, 1994.

[3] E. Udd and M. Digonnet, Eds., Design and Development of Fiber Optic Gyroscopes, Bellingham, Washington, SPIE Press, 2019.

[4] H. C. Lefevre, “The fiber-optic gyroscope: Achievement and perspective”, Gyroscopy and Navigation, 2012, Vol.3, pp.223-226.

[5] Yu. N. Korkishko, V. A. Fedorov, V. E. Prilutskii, V. G. Ponomarev, I. V. Morev, S. M. Kostritskii, A. I. Zuev, 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.

[6] 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, “High-precision inertial measurement unit IMU-5000”, in Proc. 2018 IEEE International Symposium on Inertial Sensors and Systems, pp.111-114. (doi: 10.1109/ISISS.2018.8358121)

[7] 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, 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. (doi: 10.1109/InertialSensors.2016.7745682)

[8] 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, 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)

[9] Yu. N. Korkishko, V. A. Fedorov, V. E. Prilutskii, V. G. Ponomarev, S. V. Prilutskiy, D. V. Obuhovich, I. V. Fedorov, A. I. Zuev, V. K. Varnakov, S. M. Kostritskii, I. V. Morev, “Ultra-compact navigation-grade Inertial Measurement Unit IMU400”, in Proc. 2020 IEEE International Symposium on Inertial Sensors and Systems. (doi: 10.1109/INERTIAL48129.2020.9090072)