Ultra-compact navigation-grade Inertial Measurement Unit IMU400

Yuri N. Korkishko[1,2], Vyacheslav A. Fedorov[1,2], Viktor E. Prilutskiy[1,2], Vladimir G. Ponomarev[1], Stanislav V. Prilutskiy[1,2], Dmitriy V. Obuhovich[1,2], Igor V. Fedorov[1,2], Aleksandr I. Zuev[1,2], Vasiliy K. Varnakov[1,2], Sergei M. Kostritskii[1,2], Ivan V. Morev[1]
[1]*Optolink RPC LLC*, Moscow, Russia, opto@optolink.ru
[2]*SIA Fiber Optical Solution*, Riga, Latvia, info@opticalsolution.lv

***Abstract*—At present time interferometric fiber-optic gyroscopes (IFOG, FOG) are widely used in inertial navigation systems (INS), and in wide range of applications have replaced its well-established main competitor ring laser gyroscopes (RLG). Recently, in order to cover the mass-market applications spectrum requiring low-cost and compact inertial sensor yet as much precise as it can be, RPC Optolink has launched new IFOG-based product: ultra-compact navigation-grade inertial measurement unit IMU400, its SWaP properties are: 80×95×62 mm, 0.7 kg, 0.5 l, ≤7 W. The aim of the current work was the production of pilot IMU400 devices batch and the estimation of the performance of IMU with direct approach and also with strapdown inertial navigation systems (SINS) simulation methods, which by sense is indirect way of performance observation. Main IMU400 Gyro and Accelerometer parameters are: Angle Random Walk (ARW) = 0.007 °/√hour, Bias Instability (BI) = 0.01°/h; Velocity Random Walk (VRW) = 40µg/√Hz, BI = 6µg. SINS expected performance (max): heading 0.2°×sec(lat) (1σ, 10 min align time).**

Keywords— fiber-optic gyroscope, inertial measurement unit, C-SWaP, navigation grade

I. Introduction

At present time interferometric fiber-optic gyroscopes (IFOGs) are widely used in inertial navigation systems (INS), and in wide range of applications have replaced its well-established main competitor ring laser gyroscopes (RLG). In high precision closed-loop configuration of IFOG 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 [1-4].

Today the interferometric fiber-optic gyroscopes reach ultimate theoretical performance that allows to surpass RLG[4]. Due to its inherent low noise and its scalability, FOG technology is one of the very few technologies able to cope with the applications requiring the highest performance combined with cost and SWaP.

II. IMU400 design

Research & Production Company Optolink and its subsidiary company "Fiber Optical Solution" (Latvia) have so far developed and produce series of single-axis FOGs SRS5000, SRS2000, SRS1000, SRS501 and SRS200 with different 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 pendulous accelerometers. Space grade gyroscopes VOBIS are also produced and operate successfully on satellites at GEO [7].

Recently, in order to cover the mass-market applications spectrum requiring low-cost and compact inertial sensor yet as much precise as it can be, Optolink has launched new product: ultra-compact navigation-grade inertial measurement unit IMU400. External and internal view (gyro coils) of IMU400 is shown in Figure 1. The aim of the current work was the production of pilot IMU400 devices batch and the estimation of the performance of IMU with direct approach and also with strapdown inertial navigation systems (SINS) simulation methods, which by sense is indirect way of performance observation.

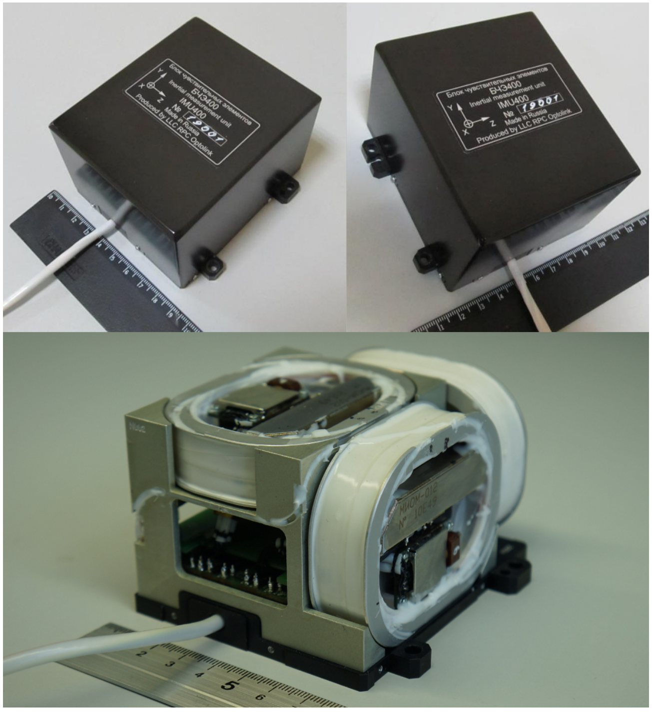

Fig. 1. IMU400 external and internal view (gyro coils).

IMU400 SWaP properties are: 80×95×62 mm, 0.7 kg, 0.5 l, ≤7 W. FOGs are fed with single light source, coils are designed in the shape of rectangle with rounded corners.

In future, additional versions of circular fiber coils may appear, with slightly increased (worse) ARW but with less (better) temperature instability (down to 0.1°/hour, 1σ, in temperature range).

To cut down the size and cost, regularly used in all Optolink's other IMUs quartz pendulous accelerometers were substituted by MEMS. 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. While the temperature compensation of scale factors, biases and non-linearities is performed as whole, in order to achieve better accuracies misalignment temperature corrections are performed standalone for each of 2 effective triads before mixing. Also, the combination of 2 signals in each channel enables us to mutually mitigate bias and scale factor instabilities and temperature dependences, while effective accelerometer lever arms do not exceed 10 mm. Spatial displacement of 3 physical MEMS-accelerometer triads inside the IMU400 is presented in Fig. 2. IMU effective center, which is defined by accelerometric lever arms minima, coincides with the IMU physical center with maximum shift of 1.5mm. IMU400 has both top and bottom magnetic shield.

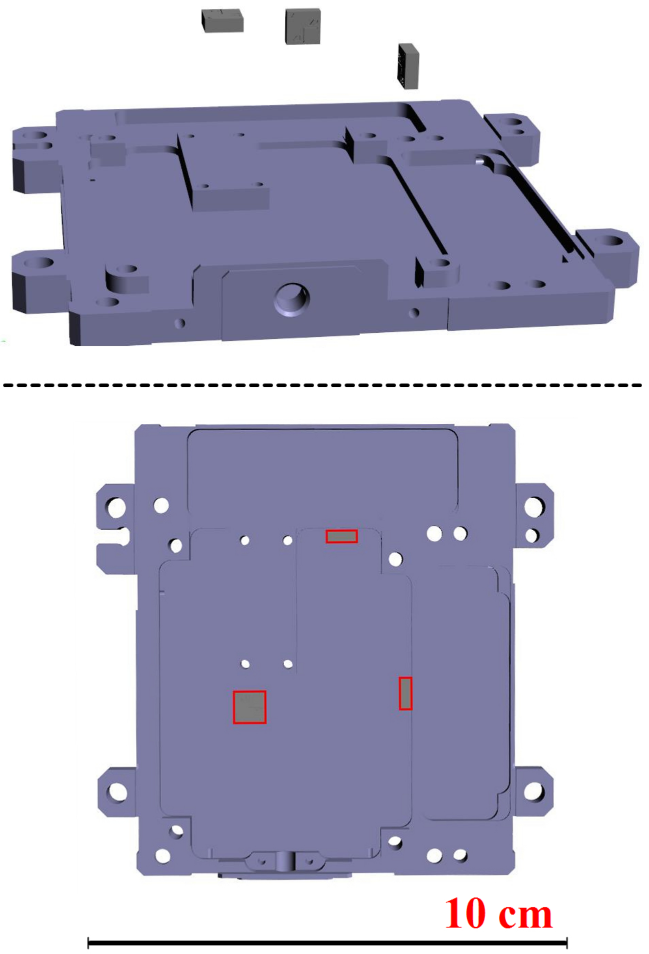

Fig. 2. Spatial displacement of 3 physical MEMS-accelerometer triads inside the IMU400. Scale bar is applicable only for the bottom drawing.

III. IMU400 CHARACTERISTICS

The Allan variance (deviation) curves of IMU400 gyroscope channels (gyros, Figure 3) and accelerometer channels (ACCs, Figure 3) are presented.

According to regular Allan Variance plot results, IMU400 performance values are:

Gyroscope axes (FOG) - ARW 0.007 °/√hour, bias instability 0.01 °/hour, run-to-run 0.015 °/hour, scale factor error 100 ppm;

Accelerometers - VRW 40 µg/√Hz, bias instability 6 µg, run-to-run 20 µg, scale factor error 150 ppm.

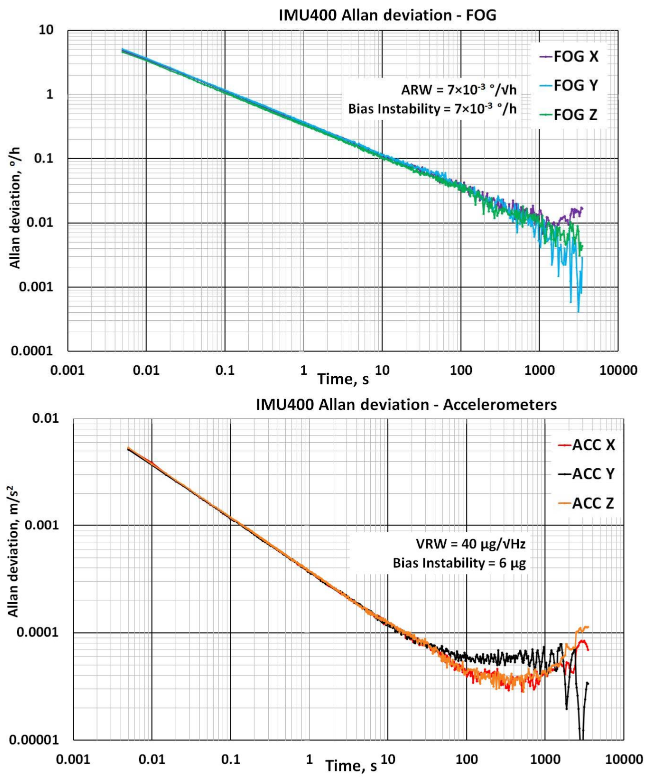

Fig. 3. IMU400 Gyroscopes & Accelerometers Allan deviation plots.

In temperature range IMU400 pilot units also shows stable behavior (shown in Figure 4), with gyro and ACC bias drift (100s-averaging RMS, 1σ) of <0.1°/hour and <100µg.

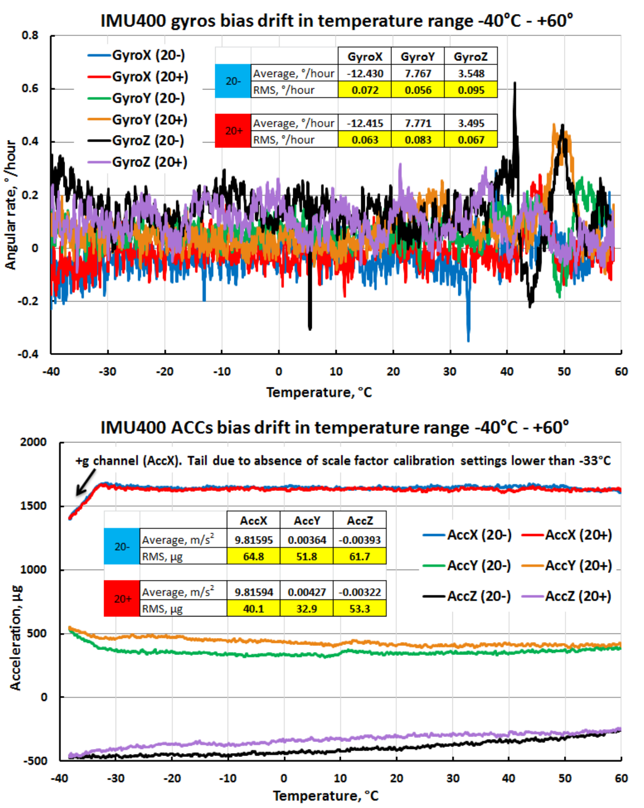

Fig. 4. IMU400 Gyroscopes & Accelerometers bias stability (drift) plots in temperature range -40°C - +60° with constant temperature change rate (ramp) +20°C/hour (20+) and -20°C/hour (20-). Absolute values are shifted.

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, 7.7, 3.4 °/hour for Gyros X,Y,Z, respectively, and 9.8 m/s^2 for accelerometer X. Real Average/STD data for each channel is presented in captions for each plot in Fig. 4. For ACC X one can see a tail of temperature drift below temperature -33 °C, which is due to the absence of Scale factor calibration settings (points) below this temperature. If needed, it can be compensated further.

The performance of IMU400 units after full calibration cycle, temperature dependencies and major biases, was investigated using indirect way of measurements - by SINS modelling software.

At Optolink [8], for SINS certain test procedures are carried out in order to qualify their accuracy level. One of the main and peculiar SINS parameters is the obtained heading accuracy during straightforward alignment in gyrocompassing mode. At Optolink, each SINS runs series of alignment tests, which consist of alignment statistics accumulation over 4 cardinal directions (or more). This test is of importance as it shows not only the noise of sensors (heading RMS with respect to its mean value), but the mean heading errors for each direction, which also represent mainly gyro absolute bias errors and their stability in time. For example, mean values of obtained heading statistics at directions 0° and 180° allow to identify absolute bias error of sidewinder Gyro of IMU in SINS, as it points East and West in those tests and has thus near-zero angular rate value. And, mean values of heading at directions 90° and 270° allow to identify the absolute bias error of forward Gyro of IMU in SINS. Thus, these tests also can help in precise calibration of gyro biases.

Alignment tests were carried out with IMU400, alignment statistics accumulated over 4 cardinal directions is presented in Figure 4. Duration of each alignment in statistics is 10 minutes, no overlapping, 4 cardinal directions, 6 alignments per direction. Statistics show heading alignment true error (gyro bias + IMU noise) of **0.3°** (at latitude 56°N). Obtained mean heading values at each direction indicate gyro bias errors of: X 0.03°/h, Y 0.05°/h, Z 0.02°/h. Minimal achievable heading RMS due to only gyro noise level: Estimated alignment limit is 0.146° ~ 0.1°×sec(lat°). Gyro bias changes from test to test comprised at most 0.03°/hour.

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. 5. IMU400 alignment statistics (10 minutes acquisition 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°).

Accelerometer biases according to error propagation theory play minor role in the current test, as their influence is an order of magnitude lower than gyros:

- 0.01 °/hour bias error b_ω (small) of gyro pointing East/West corresponds to mean heading error of ~ *arctan* $(b_\omega / (15.041\times\cos(lat°)))$ = **0.068°**; *15.041* °/hour is the value of Earth rotation rate, *lat* = 55.98° (Moscow).

- 100 μg bias error b_a (moderate) of East ACC corresponds to seeming East gyro deflection by $\arcsin(b_a/g)$ = 0.0057° in vertical plane and effectively adds $\sin(0.0057°)\ \times 15.041\times\sin(lat°)$ = *0.00125* °/hour to gyro bias b_ω, resulting into heading error of **0.0085°**, according to formula above. Other ACCs biases have almost zero impact.

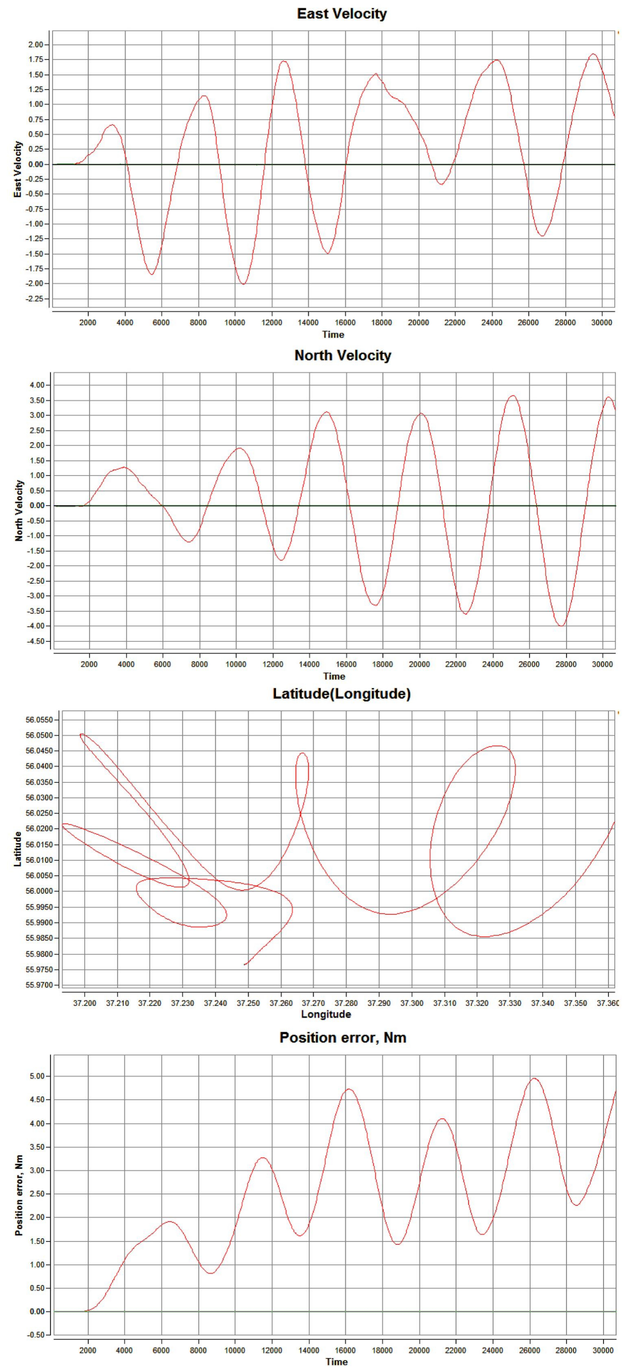

Fig. 6. IMU400 navigation performance in pure inertial mode (static), 8 hrs, no aiding, 20 min. alignment, 4 cardinal directions. East & North Velocities in m/s.

Alignment-to-alignment stability of Pitch/Roll angles was found to be 0.0017° and 0.0016°, respectively, showing performance enough for low-accuracy SINS demands.

After precise accounting for biases, IMU400 at 4 cardinal directions test shows coordinates drift of ~5 Nm over 8 hours in pure inertial mode (no aiding, no Schuler oscillations damping), with 20 minutes alignment (Fig. 6). Schuler velocity amplitude reaches 2 m/s and 4 m/s for East and North velocities.

Another SINS test is real navigation performance test. In order to perform these tests with IMU not involving SINS equipment, IMU device was being recorded standalone along the track on a vehicle, after that with the post-processing software we are able to run the navigation simulation of SINS on the basis of IMU. Each track, IMU data set starts with 10 minutes of static position needed for initial alignment, then the vehicle starts the movement. No aiding data sources are present as IMU is the only data recorded in tests. GPS data for the true track plotting (blue in Figure 7 plots) is available before the IMU tests as the tracks that we use are fixed. GPS data is not synchronized with IMU data thus cannot be used for any kind of IMU aiding or tailoring its path along the way. The only sort of corrections that we used in post-processing was zero velocity update (ZUPT) and Kalman filtration on the basis of velocity errors during ZUPT.

In Figure 7 Navigation performance in two data sets is shown, heading is obtained in true gyrocompassing alignment (10 minutes). First data set is recorded over track of ~30 km (30 minutes of vehicle movement). Second data set is recorded over track of ~110 km (100 minutes of vehicle movement). The presented plots show navigation performance of IMU400 ~1km CPE error and ~10km CPE error, which is several orders of magnitude better than any MEMS or open-loop FOG for the same task (not even measured in pure inertial mode).

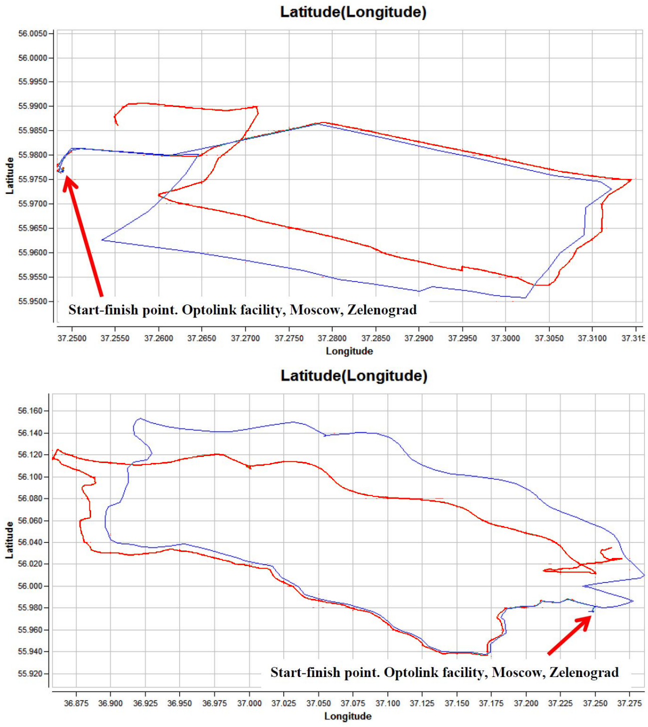

Fig. 7. IMU400 navigation performance in compensated inertial mode (ZUPT) in two data sets on tracks: ~30 km (~1km CPE error), ~110 km (~10km CPE error). Blue is GPS plot, red is IMU postprocessing track.

The observed performance values allow to assess IMU400 type of devices as navigation or near-navigation grade IMU with unique combination of performance / cost / SWaP characteristics.

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.

[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.

[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).