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Contribution of the Russian Academy of Sciences to the Development of Navigation

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Abstract: The paper traces the outstanding role of the Russian Academy of Sciences in the formation and development of science in the country by the example of navigation.

Keywords: Russian Academy of Sciences, navigation, gyroscopes.

1. INTRODUCTION

Three hundred years ago, one of the most important events in the history of Russia took place – the Academy of Sciences and Arts in St. Petersburg (hereinafter referred to as the Academy) was founded. Since then, science has become the basis for the development of our country.

Peter the Great, who set out to make Russia a world power, during the Grand Embassy (diplomatic mission) to European countries realized that this plan could only be executed with the help of science. The Academy he conceived was to become a national research center as in leading European countries. But there were also important differences from the foreign academies.

The Academy was to become a state institution. Its members received a state salary and had to solve the scientific problems for the benefit of the state, i.e., conduct both fundamental and applied research. In the 18th century, the word "arts" in the Academy title was interpreted exactly in this sense. Another difference from the foreign academies was that a university and a gymnasium were established within it. In this way, in a country missing the layer of educated people, which provided the development of science, a "scientific elevator" for training the scientists was created, to use modern terminology. Russian students were admitted to the gymnasium, and academicians, adjuncts of the Academy, and even university students were recruited abroad; teaching at the university was conducted in Latin.

The Academy was divided into ten departments, the second being the department of astronomy, geography, and navigation. Development of the navigation science became one of the main focuses of the Academy. This article briefly traces the development of navigation methods and aids by the Academy members throughout its 300-year history.

2. THE GREAT FOUNDERS OF THE ACADEMY AND THEIR CONTRIBUTION TO THE DEVELOPMENT OF NAVIGATION

The history of the Academy was created by the works of many prominent researchers and organizers of scientific activities. However, three of them made fundamental contributions to the development of this world-famous organization, including the navigation field. Their names in chronological order are: the founder of the Academy Peter the Great, the great mathematician and mechanic Euler, and the universal Russian genius Mikhail Vasilyevich Lomonosov.

Peter the Great (1672 – 1725)

The Tsar intensively prepared for the establishment of the Academy of Sciences. The problems of preparing for this event were consistently resolved.

It started with personnel training. Boyar children were sent to study abroad. Then the country's first secular educational institution, the "School of Mathematical and Navigational Sciences, that is, teaching the nautical and sophisticated sciences" was organized (1701) in the famous Sukharevskaya Tower in Moscow. The important thing is that capable students of all classes were admitted to the School. After graduating

Fig. 1. Peter the Great.

from the School, noble children were sent for internship on ships in England and Holland, after which they were awarded officer ranks and went to the Navy. The School graduates from other classes were sent to the civil service.

In 1715, the Naval Guard Academy, training the officers for the Navy, was organized on the basis of the senior classes of the School in St. Petersburg. The graduates were awarded the newly introduced rank of midshipman (garde-marine). This is how the elite of the Navy was formed, possessing the knowledge of ship steering and navigation necessary for long sea voyages.

Well-trained Russian officers led the naval expeditions to explore, develop, and map the new lands, including (Fig. 2)

- expedition of V.V. Atlasov, which described Kamchatka (1697 – 1699);
- expedition of I.M. Evreinov and F.F. Luzhin, which constructed the map of the Sea of Okhotsk with the Kuril Islands (1719);
- the first Kamchatka expedition of V. Bering, followed by the construction of the map of the north-eastern coast of Russia, which was included in all international atlases (1725 – 1730).

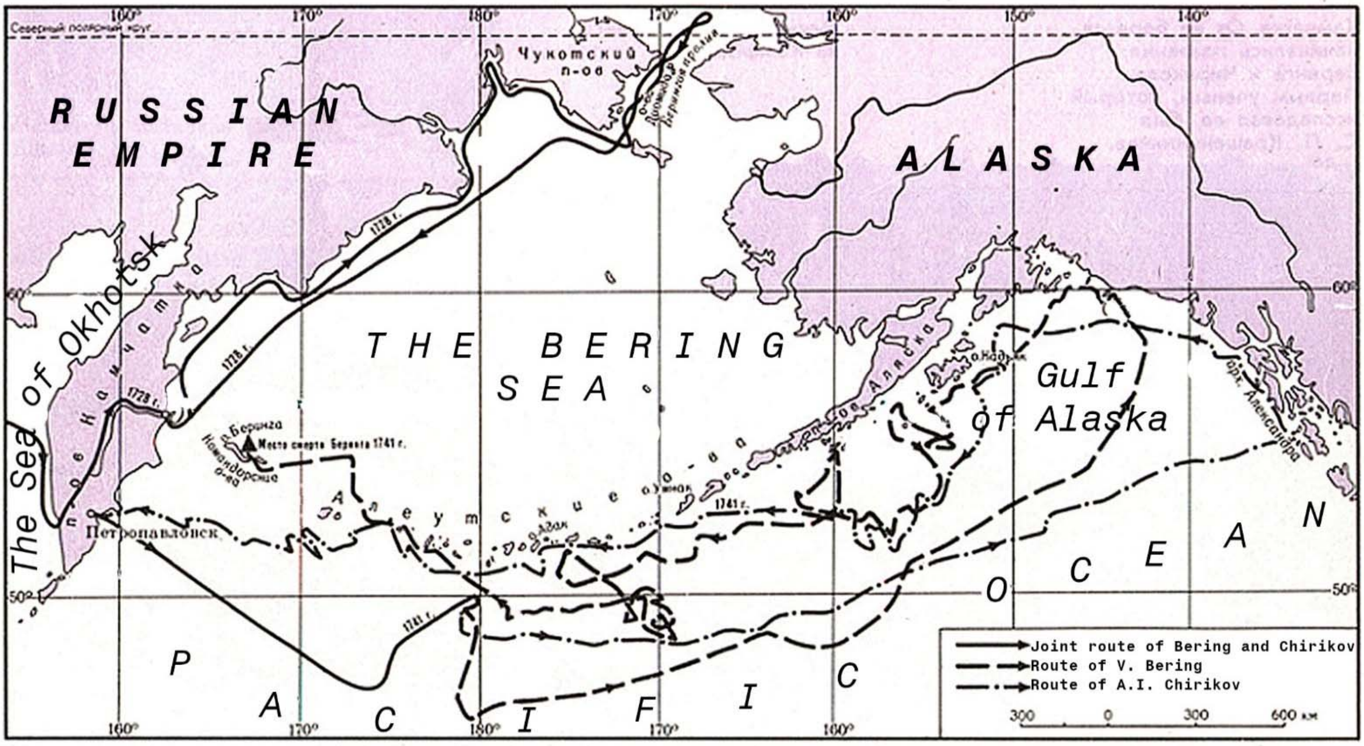

Fig. 2. Exploration of the new lands

The maps of the Baltic, Black, Azov, and Caspian seas were also compiled. Peter the Great donated the latter to the Paris Academy of Sciences, where he was an honorary member. Before this, Europe had a very vague idea of this sea.

The material facilities of the future Academy were created. Books, instruments, and exhibits from all over the world were purchased. The latter replenished the collections of the Kunstkamera. An astronomical observatory was organized; a library and a printing house were established.

Particular attention was given to navigation instruments. To repair them, a Tool Workshop was founded (1721). This organization gradually mastered the production of navigation aids and was transformed into the Naval Instruments Plant. The plant still exists today (its current name is the Navigation Instruments Plant) and, surprisingly, the range of products has changed a little.

In creating the Academy, the emperor was greatly assisted by G. Leibniz, one of the most prominent scholars of that time. Particularly, he recommended the promising scientists to become the first members of the Academy, and the Emperor selected future academicians among them.

Peter the Great did not attend the opening ceremony of the Academy in December 1725. He died on January 28 of the same year, but the ideas he laid down for the development of science in Russia were brought to life.

Leonhard Euler (1707 – 1783)

Fig. 3. Leonhard Euler and his book *Complete Theory of the Construction and Maneuvering of Ships, Written for the Students of Navigation*

Leonhard Euler, a great mathematician and mechanic, entered the Academy when he was only twenty years old at the invitation of Academician D. Bernoulli. With a short exception, when he worked at the Berlin Academy of Sciences, his whole creative life was connected with St. Petersburg. The works on marine navigation occupy a worthy place in the rich scientific heritage of Academician Euler. On this topic, he published Scientia Navalis (Ship Theory) (1749) and Complete Theory of the Construction and Maneuvering of Ships, Written for the Students of Navigation (1778). He proposed a solution to the most difficult navigation problem of that time – determining longitude, which had been used in marine navigation for more than a century.

When solving the problems of celestial mechanics, he derived the kinematic and dynamic equations of a solid body motion relative to the center of mass or to a fixed point. A century later, these equations formed the basis of a new branch of theoretical mechanics – the mechanics of gyroscopes.

In the field of cartography, L. Euler obtained formulas for conformal projections of a sphere onto a plane. He supervised the creation of the Russian Atlas and, according to his words, "Russian geography has been brought into a much better condition than the geography of the German land" [9].

Academician Euler laid the foundations of the Russian mathematical school, which is characterized by a rigorous solution of mathematical problems for the relevant applications.

Mikhail Vasilyevich Lomonosov (1718 – 1765)

Fig. 4. Mikhail Lomonosov.

Academician Lomonosov had a wide range of scientific interests and has greatly contributed to the development of natural sciences. A huge part of his research activities was focused on marine navigation.

In the field of navigation theory, he authored the work *Discussion of the Great Accuracy of the Maritime Route* (1759) and the dissertation *A New, Rather Easy and Accurate Method of Determining the Noon Line* (1761). In addition to the theoretical part, the dissertation contains a description of a device invented by M. Lomonosov for determining the meridian by measuring the altitudes of stars.

Lomonosov's creative activity is amazing. He invented or improved more than twenty navigation instruments for the navigational practice, including a sea current meter based on the deviation of the vertical, a sextant, a recording compass, a ship drift meter with account for pitching, an optical instrument for underwater observations, a night vision scope for detecting rocks and ships at night, and many others.

Since 1757 until the end of his life, Academician Lomonosov headed the Geographical Department of the Academy. He initiated a number of expeditions and supervised the compilation of nine land maps and a new edition of the *Russian Atlas*.

Lomonosov descended from the Pomors (an ethnographic group living on the coasts of the White and Barents seas), and his scientific interests naturally included navigation in the Arctic seas. He authored *A*

Short Description of the Various Voyages in the Northern Seas and an Indication ofthe Possibility of Passage by the Northern Ocean to Eastern India (1763), to which a circumpolar map was attached. This is how the idea of the Northern Sea Route was put forward. A year later, the *Addition on Northern Navigation to the East by the Siberian Ocean* was published, followed by the *Second Addition, Compiled Based on News from Industrials from the American Islands*.

Fig. 5. Navigation instruments developed by M.V. Lomonosov

Based on these research works, Lomonosov developed and submitted to the Admiralty Board a project of expeditions to find a way from the Atlantic Ocean to the Pacific and to the Aleutian Islands by the northern route. The project was approved and a decree was issued by Empress Catherine II. Two expeditions were organized: headed by V.Ya. Chichagov on three ships to explore the Northern Sea Route and headed by P.A. Krenitsyn and M.D. Levashov to the Aleutian Islands.

Lomonosov assumed that in June, at 80°N latitude, ice-free sea stretches for at least a thousand versts (600 miles) [2], but this assumption was not confirmed and the sailing ships of Chichagov's expedition could not pass further than Spitsbergen due to solid ice in 1765 and 1766. The visionary idea of Academician Lomonosov has been realized only in our days, when powerful nuclear icebreakers and ice-class transport ships have been created, and global warming has occurred.

Contribution of Navigators, Honorary Academy Members, to the Development of Navigation

Since the end of the 18th century, the navy sailors, who received an excellent education, had started to further the progress of navigation methods. The first books on navigation written by them were published: *Extract of Navigational Art* by F.I. Soimonov and *Complete Collection of Navigation Books* by S.I. Mordvinov.

About fifty expeditions were carried out, led by naval officers and almost always including the Academy scientists. More than a thousand members including academicians, adjuncts, and students of the academic university took part in the Second Kamchatka expedition (the Great Northern Expedition) led by V. Bering. From 1733 to 1743, the expedition teams explored the coasts and shelf of the Arctic Ocean, determined the astronomical coordinates of the most important points – the mouths of the great Siberian rivers, Kamchatka, the Kuril and Aleutian Islands, and Alaska. The names of the expedition team leaders – Captain-Commander V. Bering, Lieutenants Laptevs, Navigator S.I. Chelyuskin – are commemorated in the geographical names.

In the first Russian circumnavigation of the world commanded by I.F. Kruzenstern and Yu.F. Lisianski on the sloops *Nadezhda* and *Neva* (1803 – 1806) participated the Corresponding Members of the Academy Tilesius von Tilenau, G.I. Lansdorf, and astronomer Johann Caspar Horner. During the circumnavigation of the world on the sloop *Predpriyatie* under the command of O.E. Kotzebue (1823 – 1826), observations were carried out by astronomer Ernst Wilhelm Preuss and physicist E.H. Lenz (later academician). F.F. Bellingsgauzen and M.P. Lazarev discovered the Antarctic on the sloops *Vostok* and *Mirny* (1821). The astronomer I.M. Simonov, who worked in the expedition, later became a Corresponding Member of the Academy.

Fig. 6. Fyodor Litke.

For their scientific merits, naval commanders I.F. Kruzenstern, P.V. Chichagov, A.S. Greig, F.F. Veselago, N.S. Mordvinov, D.N. Senkevich, F.P. Wrangel, P.I. Rikord, P.Ya. Gamoleya, and F.P. Litke became the Honorary Academicians or Corresponding Members of the Academy [2]. Moreover, Admiral Fyodor Petrovich Litke was the President of the Academy from 1864 to 1880.

As a young man, he took part in the circumnavigation of the world on the sloop *Kamchatka* (1817 – 1819) and even then headed the hydrographic party. Then four expeditions on the brig *Novaya Zemlya* (1821 – 1824) followed, where he already commanded the expedition. The White and Barents Seas were explored, and a cartographic survey of the coasts of Novaya Zemlya was carried out. Based on the results of the expedition, F. Litke published the work *Four Voyages in the Arctic Ocean on the Warship Novaya Zemlya*.

During Litke's second trip around the world (1826 – 1829), he commanded the sloop *Senyavin*. He presented his scientific results in the three-volume book *A Voyage around the World on t he Warship Senyavin* (1834 – 1836), as well as in the books *Experiments on the Invariable Pendulum Conducted during the Voyage around the World* (1833), *On High and Low Tides in the North Atlantic Ocean* (1843) and in two articles in the academic *Memoirs*.

In 1845, F.P. Litke became one of the initiators of the establishment and the First Vice-Chairman of the Imperial Geographical Society (later the Russian Geographical Society).

The First Institutes of the Academy

As the scientific activity developed, the range of addressed problems expanded and more accurate results were required. This has already become a task for research teams rather than for individual scientists. Research institutes began to be established.

In the field of navigation, the first research institution in Russia was the Pulkovo Observatory (Fig. 4). The observatory project was developed by a commission of Academicians consisting of V.K. Vishnevsky, I.Ya. Parrota, V.Ya. Struve, and P.N. Fuchs (1833). In accordance with the project, the observatory was equipped with the most modern equipment; it was even called the "astronomical capital of the world". The Pulkovo Observatory determined the annual parallax of stars with high accuracy, and on this basis annual catalogs of their positions were compiled.

From the early days of the Pulkovo Observatory (1839), its director, Academician V.Ya. Struve organized the solution of problems in the interests of the Navy. The navigators received training at the Observatory before the long trips, studying the methods and technologies for astronomical navigational determinations. In 1844 – 1884, the Pulkovo meridian ($30^0$19.7'E longitude) was the reference meridian for the Russian navy. The longitudes of the ship's positions were measured and the maps were drawn relative to it. The Navy started to use the Greenwich meridian for longitude determination as late as in in 1884.

At the same time, the astronomer A.N. Sienkiewicz, the Academy member, developed new applied astronomical methods for determining the site latitude and longitude.

Along with the astronomical method, magnetic compass was the most important aid for determining the ship's heading, which indicated the direction of the magnetic meridian. Russian academicians actively participated in the studies and use of the Earth's magnetic field for the marine navigation [4].

Academician L. Euler made the first attempt to calculate the Earth's magnetic field. Academician M. Lomonosov noted that magnetism is the most complex branch of physics and it is necessary "to establish a theory from observations, and to correct observations through theory". He was the first to explain the terrestrial magnetism by the presence of tiny magnetized particles that provide nonhomogeneous magnetic declinations in different regions of the Earth. Academician F.U. Aepinus published his work *An Attempt at* a *Theory of Electricity and Magnetism* (1759). Academician D. Bernoulli received a prize from the Paris Academy of Sciences for creating the theory of an inclinometer – a device measuring the inclination of the Earth's magnetic field. The Corresponding Member of the Academy I.M. Simonov published the article *An Experience in the Mathematical Theory of Terrestrial Magnetism* (1835).

To study the variations of the Earth's magnetic field, Academician A.Ya. Kupfer organized the Magnetic Observatory in the Peter and Paul Fortress (1849). Later it was transformed into the Normal Observatory, and then into the Main Geophysical Observatory (1849) in Pavlovsk near St. Petersburg. The Observatory conducted systematic observations of the magnetic field in different water areas, and participated in the First International Polar Year in 1882 – 1883.

Based on this, the compass technology was developed in the country. The Naval Instruments Plant mastered the production of magnetic compasses [3]. The mariners refined the magnetic declination and inclination in various areas of the World Ocean and worked on improving the compass accuracy. I.F. Kruzenshtern conducted a special experiment to determine the heading deviation of the compass. I.P. Belavenets improved the method for refining semicircular and quadrant deviations, developed the methods for determining heeling deviation, compensating for local sources of deviation, and reducing compass errors in high latitudes.

Captain 2nd rank I.P. de-Kolong (later a Corresponding Member of the Academy) invented the deflector – a device for measuring and eliminating deviation, which found its application in the navy all over the world – and received the highest award of the Academy, the Lomonosov Prize. Under his supervision, a young officer Alexei Nikolaevich Krylov, a future famous academician, studied the compass technology, researched the deflector, and improved the compass by determining that the optimal position of the magnetic needle on the compass card in the nonhomogeneous magnetic field of the ship (this became the subject of his first scientific publication). A.N. Krylov invented the dromoscope, a device for automatic calculation of deviation depending on the ship's heading. Later, he published the monographs *On Terrestrial Magnetism* (1921) and *Fundamentals of the Theory of Compass Deviation*, and the article *The Disturbance of Compass Measurements due to Ship Rolling in Rough Seas* (both, 1933).

Generally, due to the efforts of the Academy scientists and naval sailors, the compass technology in Russia was based on a solid scientific foundation, and in this part, marine navigation was equipped in the best possible way.

The Pulkovo and Main Geophysical Observatories became the first academic organizations in Russia to solve navigation problems.

Fig. 7. Pulkovo Observatory.

Development of Gyroscopy

Remarkable scientific events of the late 19th and early 20th century affected the field of navigation, too. Achievements in physics, mechanics, and mathematics led to the formation of new branches of navigation, which dominate up to date: radio navigation and inertial navigation. Today, radio navigation is first of all the satellite navigation systems, global, available, and precision, which form an integral part of the life and activity of modern people. The journal *Gyroscopy and Navigation* mostly focuses on autonomous navigation, so radio navigation is not discussed below.

We will speak about gyroscopy, science and technology, which at that time was based on the achievements of mechanics. Leonhard Euler derived his equations of solid body motion relative to the center of mass or a fixed foundation in the interests of the celestial mechanics, whereas the concept of gyroscopy did not exist then. But the mechanics of gyroscopes was developed based on these Euler equations. A century later, S.V. Kovalevskaya, the first Russian woman being an Honorary Member of the Academy, found the case, when a solution to the Euler equation can be obtained under arbitrary initial conditions, and the Corresponding Member N.E. Zhukovsky produced a geometrical interpretation of this case. The theory of stability of mechanical systems, created by Academician A.M. Lyapunov, became the basis for solving relevant problems in the mechanics of gyroscopes.

Unfortunately, as has already happened in the history of Russia, the deep theoretical works of Russian authors were not followed by applied research, which led to the dominance of the companies Anshütz (Germany) and Sperry (USA)* in gyroscopy in the first decades of the last century. During the First World War, the Russian Navy used Sperry gyrocompasses.

Only the first navy construction program in the USSR created the conditions for the start of research and development in the field of marine gyroscopic technology. In 1931, the Naval Instruments Plant under the scientific supervision of Rear Admiral Prof. B.I. Kudrevich (responsible for servicing gyrocompasses in the pre-revolutionary navy) developed the experimental samples of GU-1 gyrocompass based on Sperry

*The only exception was the individual inventor Pyotr Petrovich Shilovsky, a high-rank official (governor of the Kostroma province), who received a patent from Russia and other countries for the gyrostabilization of vehicles "A device for maintaining the balance of carts or other bodies in an unstable position", designed a monorail train and a two-wheeled car, but these works were not developed. In 1922 he emigrated to England, where he published two books on gyroscopy in 1924 and 1935 [5].

gyrocompass design. Tests onboard a torpedo boat destroyer and an icebreaker in high latitudes did not satisfy the Navy, and this direction was not developed.

On the recommendation of Academician A.N. Krylov, the development of the gyrocompass was entrusted to the Maritime unit of the Elektropribor plant. In 1932, the Maritime unit began developing the gyroscopic technology. The *Gazon* and *Shar* vertical reference systems for naval artillery fire control systems (the prototype was the *Hudson* vertical reference gyro by Sperry) and gyrocompasses of the *Kurs* type (the prototype was the *New Anschütz* gyrocompass by Anschütz) for solving the navigation problems were created.

Academician A.N. Krylov played a huge role in creating the gyroscopic technology at Elektropribor. His monography *The General Theory of Gyroscopes and Some of Their Technical Applications* coauthored by Yu.A. Krutkov, the Corresponding Member of the Academy, became a manual for the first generation of gyroscopic engineers. Krylov willingly advised the engineers and beginning researchers, especially if problems of interest to him were discussed. Once a week he came to the Elektropribor gyroscopic laboratory and asked if there were any questions. They always were, and many of them were resolved by the Academician on the spot. If the problem had to be worked on, he took some time, and sometimes it ended with a research article. He initiated the establishment of the first gyroscopic departments: at the Leningrad Institute of Precision Mechanics and Optics (1937) and at the Leningrad Electrotechnical Institute (1938). The Russian scientific gyroscopic school began to form under his supervision.

Fig. 8. Alexei Krylov

The life path of Academician A.N. Krylov ended in 1945. At the same time, a new stage in the development of gyroscopy began – the creation of inertial navigation systems (INS). The idea of INS design was actually put forward as early as in 1905. It was as follows: the readings of accelerometers, stabilized in space with the gyroscopes, are integrated to determine the linear velocity, and the readings of gyroscopes are used to find the heading and angular velocity. Based on this data, the coordinates of the traveled path are calculated. However, the accuracy of gyroscopes and accelerometers at that time was three orders of magnitude lower than the required accuracy, and the idea of INS was not developed.

The first simplest INS was developed in the USSR at the Central Aerohydrodynamic Institute (TsAGI named after Zhukovsky) by V.S. Vetrov and N.A. Pilyugin (future academician, member of the famous Board of Chief Designers headed by S.P. Korolev) for the experimental studies of aircraft spin (1934).

The situation changed radically when after the Second World War it turned out that INS had been created in Germany for the V-2 ballistic missile control system. A race began to create a fully fledged INS, mainly between the USSR and the USA. The success depended primarily on the country's scientific potential, and the role of the Academy was paramount.

Fig. 9. Alexander Ishlinksky

Academician Alexander Yulievich Ishlinsky became the scientific leader in the field of inertial navigation. Back in 1940, being a young candidate of sciences who had achieved first success in theoretical mechanics, he was invited by N.N. Ostryakov, the first Chief Designer of Gyroscopic Devices at Elektropribor, to cooperate with marine gyroscopists. This cooperation lasted 25 years and was very fruitful. The contribution of A.Yu. Ishlinsky to the creation of gyroscopic aids of the first two generations of marine integrated navigation systems (further, navigation systems) cannot be overestimated.

The development of navigation systems started in connection with the construction of nuclear submarines. Nuclear power provides practically unlimited underwater navigation of the submarine without surfacing. The core of the navigation system is formed by the gyroscopic systems, however, the drift of the gyroscopes leads to the system error accumulation. To correct the gyroscope drift, observation is required, which involves the submarine surfacing. At the early stage of navigation system development, the gyroscopes featured large drift, and frequent surfacing of the submarine was required. The reduction of gyroscope drift occurred in stages and continued for several decades. Each stage of this work gave rise to a new generation of navigation systems.

Academician Ishlinsky showed that a navigation system, lowly disturbed by the submarine maneuvers, can be based on a stabilized gyrocompass and a directional gyroscope [5], and this scheme can be approached by supplementing two available types of gyroscopic navigation devices (gyrocompass and vertical reference gyroscope) with a third one – gyroazimuth. The Central Scientific Research Institute Elektropribor has developed the gyroazimuth and created the first-generation navigation system.

The first-generation navigation systems provided the first under-ice voyages of the Soviet nuclear submarines to the North Pole, transpolar voyages, and voyages to many other earlier inaccessible areas of the World Ocean [6].

The second-generation navigation system, based on classical INS with a horizontally held platform with the installed accelerometers, was designed by the Moscow Central Research Institute Delfin. Academician Ishlinsky demonstrated that using an azimuth-free platform was preferable for this system and designed an algorithm for its ideal operation. He also showed that the scheme did not impose high requirements on the accuracy of accelerometers, and commercially available accelerometers could be applied. The problem of the still insufficient accuracy of gyroscopes was resolved by periodically turning on the hydroacoustic log.

The third generation of navigation systems was based on high-precision INS, designed on the principle known since the beginning of the last century [6]. It consisted in simulating the celestial navigation method, where two free gyroscopes set to stable directions relative to the stars were used instead of a sextant.

In these conditions, the decisive role was played by technology, which was developed mostly by applied research organizations. By that time, the leaders who have mastered the theory of gyroscopes, engineering sciences, and had outstanding organizational skills, appeared in the applied institutes. They took the lead in creating a new generation of gyroscopic technology and also joined the Academy. Academician Viktor Ivanovich Kuznetsov, who began working at Elektropribor before the war and then headed the development of gyroscopic technology in the rocket and space industry, was a prominent representative of this generation of scientists [8].

The development of gyroscopic technology continues. Gyroscopes on new principles are being created. These are, first of all, the gyroscopes on the relativistic Sagnac effect and the hemispherical resonator gyroscopes (HRG), the operating principle of which is based on the inertia of elastic waves excited in a resonator cavity. Laser and fiber-optic gyroscopes, in which the Sagnac effect is realized, have been mastered in production, are mass-produced and constantly improved. The institutes of the Academy actively participate in this work. HRGs are also mass-produced, but their properties are being further developed, in our country by Academicians D.M. Klimov, V.F. Zhuravlev, and Professor Yu.K. Zhbanov.

The problems of developing gyroscopes on atomic physics effects – nuclear magnetic resonance and matter waves – are to be solved by marine navigation designers. At the initial stage of the new cycle of work, the role of academic science will be decisive.

3. CONCLUSIONS

The Russian Academy of Sciences, which conducts the fundamental research, has made and continues to make an important contribution to the development of applied sciences, including navigation. At the initial stage, the navigation methods and aids were based on mechanics, astronomy, and the studies of the Earth's magnetic field. Today they are supported by optics, electronics, gravimetry, and tomorrow, by atomic physics.

High-level fundamental research in the country guarantees that in the future the navigation science in Russia will maintain its internationally advanced position.

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CONFLICT OF INTEREST

The author of this work declares that he has no conflicts of interest.

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