ISSN 2075-1087, Gyroscopy and Navigation, 2018, Vol. 9, No. 3, pp. 227–232. © Pleiades Publishing, Ltd., 2018.
Original Russian Text © V.G. Peshekhonov, 2018, published in Giroskopiya i Navigatsiya, 2018, No. 2, pp. 95–104.

Short Age of Radiosextant

V. G. Peshekhonov*
Concern CSRI Elektropribor, JSC, St. Petersburg, 197046 Russia
**e-mail: office@eprib.ru*

Received March 12, 2018

Abstract—The paper presents brief history of development of new autonomous navigation equipment, a radio astronavigation system (radiosextant), and discusses new technological solutions implemented in the radiosextant, as well as the reasons for stopping its further development.

DOI: 10.1134/S2075108718030070

INTRODUCTION

Astronavigation, a method of determining the observer's location and the true meridian direction by measuring the angular position of astronomical sources of light emission, was already used by ancient travelers, especially out at sea where there are no specific local landmarks. A tool for astronavigation measurements, optical sextant, was invented by J. Gadley about three hundred years ago, and, having undergone some small improvements, is still used by seamen. A radiosextant was created much later, and its age turned to be short: less than forty years.

The development of radiosextant began in the middle of the last century, when the problem of ships navigation in the World's water was raised. The USSR Navy started navigating in the oceans, but only in a short-range maritime zone where the radionavigation systems were effective, and where highly precise navigation could be provided without any limitations by the time of the day and season, and in any weather conditions. In the long-range maritime zone the radionavigation estimations were not accurate enough, and the satellite navigation systems were just under discussion.

In remote areas of the World Ocean, only astronavigation equipment could be helpful in correcting the navigation data. However, due to hydrometeors (continuous clouds, rain, snow, fog), the average probability of astrooptical estimations is 0.2–0.3 all over the world, and in the regions important for the Russian Navy (the North Atlantic, northern part of the Pacific Ocean) this value is much lower.

It was necessary to create an astrocorrection system which would not depend on weather conditions, and such an opportunity was opened up by a new discipline which was developing rapidly in astronomy, namely radioastronomy. Space sources (the Sun, the Moon, stars) radiate in a wide range of frequencies, including radio-frequency band. At the same time, there are so-called atmospheric "radio windows", i.e. frequency bands in which the radiation from space sources reaches the Earth surface with minimal damping under any hydrometeorological conditions. From 1955, based on the radioastronomy achievements, the possibility of radio astrotrackers development for air navigation was studied by researchers from the Mozhaiskiy Leningrad Air Force Engineering Academy (now Mozhaiskiy Military Space Academy, St. Petersburg) headed by V.S. Shebshaevich, and for marine navigation—by scientists from naval research institutes B.M. Gelman, R.P. Loshakov, and L.S. Vaisman. This idea was enthusiastically supported by researchers from the Pulkovo Observatory of the Academy of Sciences, the Leningrad State University, and the Research Institute of Radiophysics of the Academy of Sciences (Gor'ky city, now Nizhny Novgorod).

Research Institute NII-303 (CSRI Elektropribor since 1966) under the Ministry of Shipbuilding Industry took up the radiosextant development. In opinion of the institute management, it was the only chance to ensure all-weather correction of navigation data generated by the first Soviet all-latitude integrated navigation system (NS) Sigma which was designed by the NII-303 at that time (chief designer V.I. Maslevskii).

However, the NII-303 specialized in high-precision mechanics and electromechanics, and was not competent in radio engineering, radiophysics, physical optics, and television, which was essential for radiosextant development. For this reason, the institute organized a laboratory (which has grown into a large department) and employed young specialists from the city's leading universities. Head of the laboratory M.K. Petushkov[1] and leading specialist I.F. Kon'kov established cooperation with academic institutes and university, encouraged the enthusiasm of young employees, and the results were quite impressive.

In 1957, the NII-303 performed a pilot research work "Geranium" to design an on-ground solar radio astrotracker which confirmed the possibility of tracking the Sun by its radio-frequency (RF) radiation in the S-band. At the next step, three development projects "Konus", "Kupol" and "Klyuch" were carried out simultaneously in 1958–1960, in course of which the main problems of radiosextant construction were determined and partly solved. It became clear that it was possible to create a radiosextant tracking the most powerful (relative to the Earth surface) space source of radiation, i.e. the Sun. The problems to be solved with regard to the Moon, the second most powerful source of space radiation, were clarified as well.

THE MAIN PROBLEMS OF RADIOSEXTANT CONSTRUCTION

The radiosextant designers used the experience of radiotelecsopes development to the full extent, including the construction of a radiometric receiver which distinguishes weak noise signal of a space source from more intensive background of the receiver intrinsic noises.

Unlike the radiotelescope, the radiosextant is mounted on a mobile base the exact coordinates of which are unknown, and its antenna aperture size and the observation time are strongly limited. It was necessary to develop a system for searching the space radiation source and capturing it within the antenna directional pattern; to ensure the maximum possible direction-finding characteristic curvature of the antenna; and to minimize the receiving path noises.

However, a number of problems were identified which are not significant for radioastronomers. The first specific problem relates to uneven brightness of the solar disc. This leads to discrepancies between the position of the disc geographical center (relative to which the navigation problem is solved) and the Sun RF radiation center (SRFC) the position of which is detected by the radiosextant, i.e., navigational estimation error.

RF radiation of the Sun has three components: the quiet Sun with even radiation of the disc; slowly varying component with the period of 27 days (the Sun rotation period), generated by sunspots; and RF radiation bursts caused by chromospheric flare. The latter two components result in SRFC deviation from the geometrical center of the Sun disc. It is impossible to forecast the occurrence of sunspots and bursts, as well as their intensity; but their contribution in the radiosextant error can be unacceptably large, especially in the years of active Sun.

Due consideration of this factor was one of the main problems in developing the solar radiosextant. It should be noted that this problem was solved only to some extent.

Another specific problem in creating the radiosextant is associated with the influence of the environmental background noise on the accuracy of space source attitude measurements. Similarly to radiolocation, the radiosextant tracks a space source and measures its attitude by means of conical scanning of the antenna narrow-beam pattern. However, our case differs from radiolocation by the noise nature of signal. The environmental background also generates noise emissions, since, according to Kirchhoff's law, the RF radiation absorbed by the atmosphere will produce noise emission. Thanks to the antenna directivity, the noise emission from surrounding bodies (in particular, the underlying surface) can be neglected; but within the antenna radio beam the atmospheric noise must be taken into account. Atmospheric absorption and, consequently, noise emission have a vertical gradient, and while scanning, the atmospheric noises are modulated along with the useful signal.

This results in the error of the space source attitude estimation in the vertical plane. Since the noise interference is modulated, like the useful signal, with the scanning frequency, the frequency separation of signal and noise is impossible. A spatial-frequency method was proposed and developed for useful signal extraction, which was based on the difference between the spatial-frequency spectra of a tracked source with small angular dimensions, and the extensive noise background of the atmosphere. The antenna acts as a spatial-frequency filter. For the Sun, the effect of atmospheric noises leads to small errors, but in case of the Moon, a much weaker source, it is impossible to solve the navigation problem with required accuracy without spatial filtering.

Another source of error specific for a radiosextant is associated with uneven distribution of water drops on the antenna dome during rains. At that, the phase front of a wave falling on the antenna is distorted, which results in the error of estimated direction to the source. The effect of the dome uneven wetting could be reduced to acceptable levels by means of hydrophobic coating.

As a result of solving these problems, three generations of radiosextants were developed. Each succeedent generation had improved accuracy of space sources tracking and higher probability of observation.

---

[1] Mikhail Petushkov went off to war when he was a student; after the WWII he graduated from the Leningrad Electrotechnical Institute with qualification in fire control equipment. He was the chief designer of three generations of radiosextants, had the degree of candidate of engineering sciences, and was awarded the State Prize of the USSR and the State Prize of the Russian Federation.

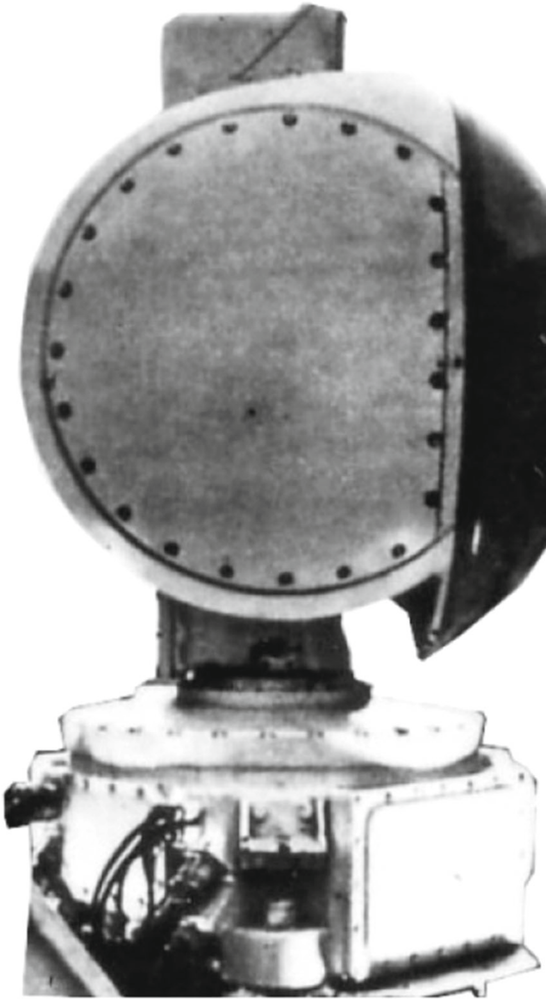

Fig. 1. Antenna post of Samum radiosextant.

SAMUM SOLAR RADIOSEXTANT

The first Soviet radiosextant Samum was designed for observations by the most powerful source of RF radiation, i.e. the Sun[2]. It was developed as a part of the all-latitude NS Sigma-M.

The main constituent parts of the radiosextant are the antenna post which is moved out of submarine enclosure by a hoisting device, and the data processing and control unit located within the hull.

The antenna post is a sealed structure; radiotransparent antenna dome is integrated in the housing (Fig. 1).

The radiosextant has a dual-reflector antenna; it is constructed according to Cassegrain scheme widely used in radioastronomy, with a large parabolic reflector and a small hyperbolic one. The original scheme of conical scanning of the antenna directional pattern was implemented. Scanning is carried out by means of the small reflector rotation about the axis inclined relative to the large reflector axis. Rotation of the small reflector with simultaneous reference voltage generation is provided by a specially designed small-sized electromechanical unit. At the same time, the waveguide remains stationary, which prevents parasitic modulation of the receiver local oscillator radiation leaking in the antenna. The scanning frequency exceeds 50 Hz in order to avoid abnormal intrinsic noises of the receiver. The waveguide comprises an optimized feed horn, a hybrid-type frequency converter of superheterodyne receiver, and a ferrite valve reducing the local oscillator signal leakage in the antenna.

The operating wavelength of the radiosextant was chosen equal to 3.2 cm, i.e. within the short-wave end of the S-band, optimal for a solar radiosextant. At that time, the waveguide elements technology was well developed only for this sub-band. The NII-303 had to learn this technology and design its own waveguide. The required accuracy of the radiosextant was ensured at the chosen wavelength and the antenna diameter of 820 mm, the largest diameter possible for a submarine.

The antenna post accommodates the waveguide, an IF amplifier, a local gyrovertical, and actuators of the tracking systems which provide the antenna pointing to the Sun and its retention during vehicle motion and pitching/rolling. Analog computer and control circuits of tracking systems, as well as the observation data displays, are installed in the instrument cabinets within the submarine hull.

In 1964, the first Samum radiosextant passed the official tests as a part of the NS Sigma-M on the lead strategic nuclear-power submarine (SNPS) of 658M project. Later, over twenty products were installed on the SNPS of this project and 667A project. Even the first experience of Samum radiosextant operation showed that in the conditions of the North Atlantic and the Arctic Ocean this device is a valuable means of navigation data correction, and the navy highly appreciated this new navigation instrument. In the daytime, the probability of radiosextant use was 0.9 under any weather conditions (it was not 1.0 because of limited minimum solar angle due to increased tracking error near the horizon, caused by abnormal refraction).

Following the submarines, the radiosextant began to be used on surface vessels, such as space control monitoring ships which estimated the motion parameters of spacecraft and missiles outside the country territory. The space control monitoring ship Cosmonaut Vladimir Komarov was equipped with an NS Sozh-595 with a solar radiosextant Sura-595 which was based on the Samum radiosextant and adapted for operation on surface ships.

---

[2] The USA also designed solar radiosextants AN/SAN-1 (marine) and AN/SAN-25 (airborne), but no further development followed in this area. The reason was probably in the fact that the US created marine inertial and satellite navigation systems earlier than the USSR did.

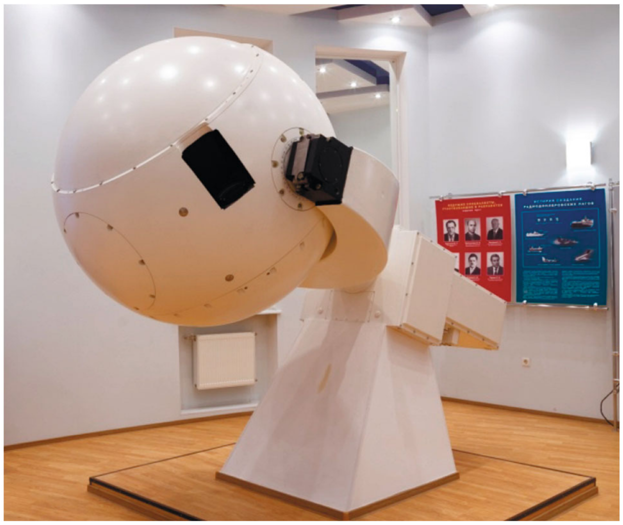

Fig. 2. Station Dreif for estimating the Sun radio frequency center displacement.

As was mentioned above, solar radiosextants have a specific error caused by mismatching SRFC and the solar disc geographical center. The attempts (onboard) of autonomous estimation of SRFC displacement were not successful, and it was decided to estimate SRFC at an onshore station and transmit the obtained data to the vessels.

A special on-ground station Deviatsia for SRFC estimation was developed and located in the Crimea in 1964. Operation of this station showed that it provided the required accuracy of SRFC displacement estimation. The only problem was that the measurements were taken only during the period of the day when the Sun was above the horizon in the station area. To increase the time of observation, an improved station Dreif was developed (Fig. 2), and it was planned to place four such stations along one parallel so that 24-hour monitoring of SRFC displacement could be performed; however, these plans never came true.

PERISCOPE RADIOSEXTANTS

Further development of radiosextants was focused on overcoming the limitations typical for Samum radiosextant. One of those limitations consisted in the necessity of submarine surfacing to perform the observations. Therefore, a periscope version of radiosextant was designed, which allowed observations from submerged submarine when only the antenna post of the radiosextant was lifted above the water surface (Fig. 3).

The other important limitation was the possibility to perform observations only at daytime, when the Sun was above the horizon. Average annual probability of solar radiosextant use was 0.4, and during the polar night the observations were impossible at all for a few months.

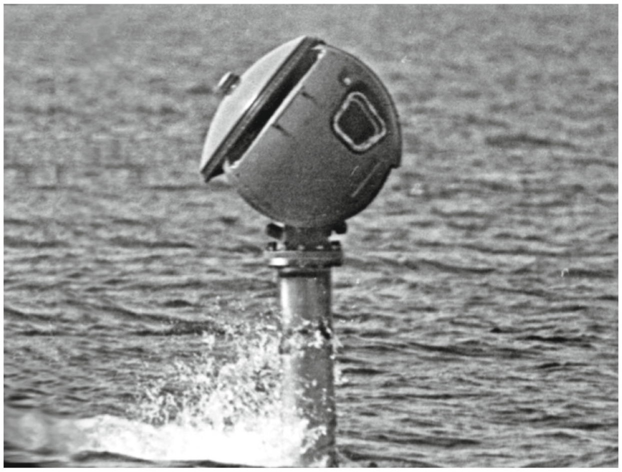

Fig. 3. Periscope radiosextant during observation.

This problem could be solved by increasing the number of astronomical markers. At the first step, a periscope radiosextant Saiga was developed, which was able to track the Moon along with the Sun by their RF radiation; also, it allowed the observation of stars in the optical band at night. Due to this, the average annual probability of radiosextant Saiga use reached 0.74.

The density of the Moon's RF radiation flux at the Earth surface is about 70 times lower than that of the Sun. In order to provide an acceptable signal-to-noise ratio during the Moon tracking, the following technical solutions were implemented in Saiga radiosextant: the antenna aperture diameter was increased to the maximum possible (1200 mm), which resulted in three-fold increase in the direction-finding characteristic curvature compared to Samum radiosextant. The band of received radiation was optimized, and the superheterodyne receiver was improved. The studies showed that the optimal band lies close to 2 cm, and thus provides two-fold increase in the signal-to-noise ratio compared to the 3.2 cm band. These measures did not compensate in full the reduced signal-to-noise ratio when tracking the Moon, compared to the Sun. This ratio was additionally raised by increasing the minimum angle of the Moon height above the horizon. As a result, it became possible to perform observations by the Moon, but with lower accuracy than by the Sun, and with limited minimum height of the Moon above the horizon.

The technical solutions that allowed the Moon tracking also resulted in better accuracy of the Sun tracking due to increased curvature of direction finding characteristic, reduced error caused by mismatching SRFC and the solar disc geographical center, and higher gyrostabilization accuracy. The error associated with SRFC displacement decreased due to the fact that the intensity of radiation flux from chromospheric flare reduces while the wavelength is shortening. Gyrostabilization became more accurate thanks to the periscopic structure of the radiosextant, where the gyrovertical is located on the lower flange of periscope tube, i.e. much closer to the ship pitching/rolling center than in Samum radiosextant.

The periscope solar and lunar radiosextant Saiga became the second generation of radio astronavigation systems. It was included in the NS Tobol (designed by CSRI Delfin, chief designer O.V. Kishchenkov) onboard the SNPS of two projects, and in the NS Altair and Antares onboard the space control monitoring ships Academician Sergei Korolev and Cosmonaut Yurii Gagarin (designed by CSRI Elektropribor, chief designer V.I. Maslevskii).

The third generation of radiosextants was developed in 1970-s. Two new channels, optical-television and satellite ones, were added to the radiosextant, and its radiometric channel was upgraded.

The task of creating the optical television channel in a radiosextant was performed by the team of O.M. Nikonchuk. Due to the useful signal accumulation on the receiver matrix elements, this channel allowed observations under the conditions of discontinuous clouds and twilight. The optical television channel was tested in an experimental radiosextant Simvol (modification of Saiga radiosextant) and then included in the third-generation radiosextants Snegir' and Salyut.

The radiometric channel parameters were considerably improved by means of a specially designed low-noise parametric amplifier on a packageless semiconductor epitaxial structure. It was the country's first 2 cm parametric amplifier, and thanks to its development, CSRI Elektropribor became a quite reputed designer among the superhigh-frequency engineering institutions. The parametric amplifier made the accuracy of the Moon tracking almost similar to that of the Sun tracking.

In that situation, significant contribution in the Moon tracking error began to be made by the above-mentioned vertical gradient of the atmospheric natural noise emission. Two algorithms of spatial filtering were implemented based on the known fact that the atmospheric radiation azimuth gradient is not large. Both algorithms can be used for measuring the atmospheric radiation gradient at a small azimuth angular distance from a tracked source, but at different time. Simultaneous tracking and gradient measurement can be carried out by means of a special directional pattern. There was also a less complicated scheme which did not require any changes in the antenna directional pattern; the gradient could be measured after tracking a space source at a small angular distance from it. It was the scheme that was made use of.

The probability of radiosextant use close to 1.0 made it possible to create a satellite channel. At the first stage of a low-orbit navigation satellite system development, two methods of navigational estimations were applied: a Doppler method, and a bearing-and-distance method. The Doppler method provided the estimation of position coordinates and the speed components of the vehicle on which the satellite data consumer equipment was installed. The bearing-and-distance method provided the estimation of both position coordinates, and the true meridian direction, i.e., it solved the same problems as a radiosextant tracking the Sun and the Moon did.

The bearing-and-distance method was developed at the Research Institute NII-195 (now the Russian Institute of Radionavigation and Time, RIRT), under the supervision of the chief designer A.F. Smirnovskii. The key point of the development was to solve the problem of oscillator frequencies convergence in the navigation satellite and in the navigation data consumer.

CSRI Elektropribor was assigned to develop the onboard equipment for the bearing-and-distance channel. The Institute managed to complete this task in a short time, because the design was based on the antenna post of Samum radiosextant. The main challenge was to develop an antenna receiving the emission in two bands with different polarization, and to replace the analog processing of signals with digital processing. The prototype system Tsezii developed by CSRI Elektropribor (chief designer M.K. Petushkov) in 1968–1970 was tested at sea onboard the oceanographic research ship Nikolai Zubov. When working on the first navigation satellite Cosmos-192 (launched in 1967), the obtained accuracy of heading and position coordinates was comparable to the accuracy of radiometric channel of radiosextant.

In 1972, pilot operation of space navigation and communication system Parus started (lead developer Experimental Design Bureau OKB-10, now Information Satellite Systems JSC, Krasnoyarsk, chief designer M.F. Reshetnev). By that time, CSRI Elektropribor had completed the development of radiosextant Snegir' which had a radiometric channel of the Sun and the Moon tracking, a satellite bearing-and-distance channel and an optical-television channel. Snegir' system was mounted in the NS Tobol-B on an SNPS of 667B project, and Tobol-M on an SNPS of 667BD project. The subsequent system Salyut was used in the NS Simfonia on an SNPS of 941 project (NS chief designer V.G. Peshekhonov).

Concurrently, a radio astronavigation system (call name Narva, chief designer V.A. Vasil'ev) was developed for large surface ships, such as aircraft carriers of 1143 project and heavy nuclear-powered guided-missile cruisers of 1144 project (Fig. 4).

The Narva system had the same channels as in Snegir' system, but, unlike the submarine systems, it ensured tracking of space sources at large pitch/roll angles. Another important difference from previous versions of radiosextants was the radio-transparent dome mounting onto the antenna post body instead of antenna, which removed the external mechanical

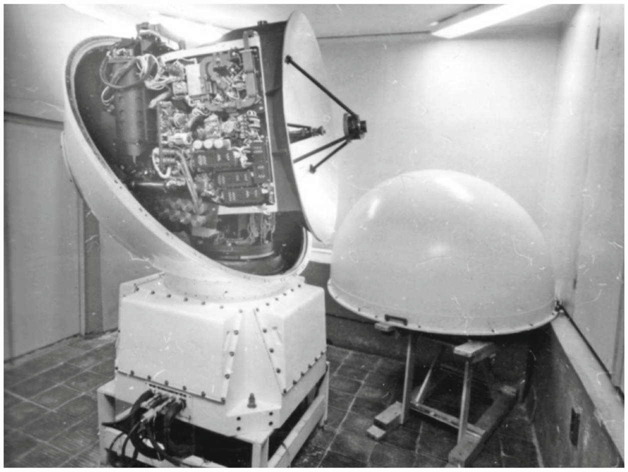

Fig. 4. Antenna post of Narva radiosextant with removed dome.

effects on the drives, but required high electrical uniformity of the dome.

LIMITING FACTORS FOR RADIOSEXTANTS APPLICATION

As the NS were improving, the contribution of radiosextants reduced. For the first-generation NS Sigma-M which generated heading by processing the data from a gyrocompass and a directional gyro, and position—by navigational dead-reckoning, Samum radiosextant became an extremely important instrument for navigation data correction in remote regions of the World Ocean.

The NS Tobol initially had poor accuracy characteristics, and when the satellite navigation was unavailable, the second-generation radiosextant Saiga was widely used.

When the low-orbit navigation satellite system was created, and, at the same time, the accuracy characteristics of marine NS were improved, the role of radiosextants reduced dramatically. In Snegir' radiosextant, the accuracy characteristics of radiometric and satellite bearing-and-distance channels were identical, but it was already evident that the accuracy of position coordinates estimation by satellite Doppler channel has all the chances to significantly excel the accuracy of these channels.

This forecast was implemented in developing a high-precision medium-orbit navigation satellite system GLONASS. At the first phase, this system generated the coordinates with an accuracy that was by one, and later by two orders better than the accuracy of radiometric channel. At the same time, heading generation by the third-generation NS reached such a level of accuracy that its correction based on radiosextant data became ineffective. For this reason, Salyut radiosextant was only used as a redundant correction instrument, and also for correcting the azimuth drift when the NS was operated in a quasi-geographical system of coordinates.

The functions of radiosextant were decreasing, while its design became more and more complicated as the number of channels increased, and, finally, it became one of the most sophisticated radioelectronic devices in terms of manufacturing and operation onboard a ship. Besides, the problem of SRFC displacement accounting was still unsolved, so it becomes clear why in late 1980-s the NS designers finally decided that further development of radiosextants would be unfeasible.

CONCLUSIONS

Development of radiosextants was a short, but bright episode in the centuries-old history of navigation technology. The experience gained in these works can still be used nowadays. It was not an experience of evolutionary, and much less of pursuing development. The set problem was absolutely new, and the methods of its solution were also to be novel.

Such an approach provided a vast opportunity for creative research, and the team of radiosextants designers attracted active people who were focused on finding new ways. When the work on radiosextants was over, their high potential was quite valuable for a number of new developments at CSRI Elektropribor, including the NS, automated control systems, and new types of gyroscopes.

The contribution of radiosextant designers was the key factor in the development of a new-generation periscope system Parus-98, including the first Russian multifunctional optronic mast (system chief designer V.E. Yanushkevich, one of the leading experts in radiosextants).

Unfortunately, after decades, the new generation of navigation engineers does not know much of a radiosextant and its contribution in the navigation development, the more especially as the scarce publications on this topic are very difficult to find. The author of this brief review worked in the team of radiosextant designers for fifteen years, and he felt called upon to tell about this prominent team and its scientific and technical achievements.

REFERENCES

1. Peshekhonov, V.G., *Antennye sistemy radiosekstanov* (Antenna Systems of Radiosextants), Doctoral (Engineering) Dissertation, St. Petersburg: Concern CSRI Elektropribor Library, 1972.
2. Bogomazov, K.Ya., *Osvoenie navigatsionnykh kompleksov na podvodnykh lodkakh Severnogo flota* (Learning to Handle the Navigation Systems onboard Submarines of the Northern Fleet), St. Petersburg: Concern CSRI Elektropribor, JSC, 2011, 318 p.
3. Suvorov, E.F., *Letopisi zarozhdeniya, razvitiya i pervykh shagov realizatsii idei otechestvennoi sputnikovoi sistemy* (Idea of Russian National Satellite System: Chronicles of Birth, Development and First Steps of Implementation), Moscow: Kulikovo pole, 2014, 232 p.