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TOPOGRAPHIC-GEODETIC AND CARTOGRAPHIC SUPPORT OF THE ARCTIC ZONE OF THE RUSSIAN FEDERATION

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A version of the project of the concept of topographic, geodetic and cartographic support of the Arctic zone of the Russian Federation based on the use of modern means and tools is presented, including its content. The results of the development in the Arctic, carried out with the participation of the authors in 1961-1967 and 1975-1992, are presented in detail. The strategic importance and great attention of the state structures to the development of the Arctic zone is underlined. The key moments of the development of topographic, geodetic and cartographic support for this region are given. The role of leading research institutes in this process is shown. The proposed concept includes six stages. When creating a planimetric geodetic base, the authors recommend an alternative innovative algorithm for determining the height *H* without first calculating the latitude *B* and use only satellite measurements. The extremely important question of converting geodetic coordinates *B, L* into rectangular plane coordinates *x, y* is considered. For the territory of the Russian Federation new developments are proposed, they use data from satellite determinations, a new approach to the determination of normal heights and the conversion of rectangular space coordinates into rectangular plane coordinates necessary for mapping. The required regulations of reference documentation for the topographic survey of the shelf are shown. The importance of implementing the concept in connection with the definition of the outer boundary of the continental shelf of the Arctic Ocean is shown.

Key words: topographic-geodetic and cartographic support of the Arctic; concept; coordinates; conversion of coordinates; satellite determinations

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Introduction. The Arctic zone of the Russian Federation occupies a significant part of its territory, which covers both land and marine areas, including the shelf of the Arctic Ocean (AO). Despite the huge area of the Russian Arctic, it has less coverage in terms of topographic-geodetic and cartographic data than the rest of Russia. Given the strategic importance of the Arctic regions of the Russian Federation in the present and in the future (extraction and transportation of oil and gas, the route of the Northeast Passage, the establishment of the outer boundary of the continental shelf of the Arctic Ocean seas, the defense of the northern borders of Russia, etc.), the problem of developing the concept of topographic-geodetic and cartographic support of the Arctic zone of the Russian Federation and, of course, its implementation is of great importance. Without solving this problem, it is impossible to implement most of the scientific and practical projects in the Arctic. The article proposes a version of the draft concept.

Methodology. Professional geodetic support for the arctic regions of the USSR began in the 20-30s of the last century, mainly provided by the topographic and geodetic enterprises located in the Far North. Horizontal and vertical control geodetic networks were created by traditional geodetic methods (astronomical observations, triangulation, trilateration, polygonometry, geometric leveling, gravimetry). Topographic surveying was carried out by tachometric and plane-table methods, later, mainly with the help of aerial photography.

The establishment of the Northern Sea Route Authority and its «Hydrographic Enterprise» in 1932 began the active marine development of the Arctic. The enterprise created over 800 admiralty issues of nautical charts of the seas of the Arctic Ocean and hundreds of various means of navigation equipment for the Northern Sea Route [1].

Starting from the 1960s, radio-geodetic systems (RGS), in particular «Poisk» [5], were used to determine the planimetric coordinates of the aerial photographing centers. In 1960-1961, the All-Union surveying trust «Soyuzmarksh-trest» (SMT) together with the All-Union Scientific Research Geophysical Institute (VNIIgeofizika) and the All-Union Scientific Research Mine Surveying Institute (VNIIMI) developed a technique for using the «Poisk» for the mapping of terrain [5]. At the same time, an algorithm was compiled for calculating the coordinates of the target points by solving the hyperbolic intersection. The algorithm was implemented in the software product for the «Ural-1» computer. In terms of its indicators, the program was highly competitive with foreign analogues developed for the RGS «Shoran» (USA) and the RSA «Decca» (England). Aerial photography was carried out together with radio-geodetic measurements of control strips laid on the site.

Photogrammetric measurements were performed mainly on stereocomparators of the firm «Carl Zeiss, Jena». From the contour points – the «desktop survey points» of the control strips – they constructed free spatial phototriangulation networks with a length of up to 200 stereopairs (six control points per stereopair) using the analytical method of A.N.Lobanov. The network also included field vertical (barometric leveling) control points, survey control points (matching the routes). Based on the horizontal coordinates and photographing altitudes using the results of calculations of spatial phototriangulation, the horizontal coordinates and altitude control points of the «desktop survey points» of the control strips were determined. The obtained horizontal and vertical control points were used for further compilation of topographic maps according to a known technique.

The SMT Leningrad expedition achieved the best results of introducing the radio geodetic method into the practice of mapping the Arctic land regions of the USSR. The works were completed in 1961-1967 at five sites with an area of 72.8 thousand km². In total, the coordinates of over 10,000 photographic centers have been determined, and about 2,000 trapezoidal maps of 1:25,000 scale have been compiled.

The created topographic maps of the Arctic regions of Russia have been successfully used and continue to be used in the exploration and prospecting of mineral deposits (oil, gas, diamonds, gold) and other issues.

Created in 1975 the Shelf Survey Department (SSD) and the World Ocean department of the Central Research Institute of Geodesy, Aerial Survey and Cartography (CNIIGAiK) (currently the Shelf Survey Department of the Center for Geodesy, Cartography and Spatial Data Infrastructure) suggested the new activity for surveying-geodesic enterprises of Head Office of Geodesy and Cartography (HOGC) – to conduct topographic survey of the shelf aimed at creation of topographic maps of this area [12]. The difference between these maps and navigational ones is the following: instead of the projection of the Mercator, the Gauss cartographic projection is used; the relief of the bottom is mapped in horizontals, and not in the isobaths; maps are more informative and multipurpose.

The SSD was assigned the following tasks (mainly in the water area of the Arctic Ocean and its coasts): development of guidelines and regulations of topographic-geodesic survey of the shelf; participation in development of technical tools; technical management of HOGC enterprises during topographic survey of the shelf and document and technical tools follow-up for those created by CNIIGAiK. The department successfully achieved the set tasks during 1975-1991. For the first time, the normative and technical documentation necessary for topographic survey of the shelf was created (instructions, manuals, guiding technical materials (GDM), map symbols, production rates, etc.). All documents were developed in the framework of research topics and approved by HOGC.

In 1977, for the first time in our country, CNIIGAiK created an automated line for collecting and initial processing of survey information for the shelf, called Avtokoordinator [5] designed to be used in aircrafts and ships.

In 1979-1980, the North-Western Aerogeodesia software jointly with CNIIGAiK created the small-size echo-sounder ERA-1 and the sea-sound velocity meter MIS-1. At the time of creation of devices, domestic analogues did not exist. The patent search for similar equipment in leading countries (USA, England, France, Germany, Japan) showed some advantage of the ERA-1 and MIS-1 devices in comparison to equipment of that time.

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Under the guidance of the CNIIGAiK, the enterprises of the HOGC carried out a significant amount of topographic survey of the shelf in the seas of the Arctic Ocean (Barents, White, Kara, Laptev, East Siberian). The materials of the carried out topographic survey served as the basis for the creation of topographic maps of the shelf (several hundred sheets of scales 1:10,000 and 1:25,000) [7].

In addition to the development and implementation of means and methods for topographic survey of the shelf, the authors participated in the implementation of marine geophysical surveys with the help of the RGS «Poisk» at the oil fields Prirazlomnoye and Shtokmanovskoe in the Barents Sea. It is necessary to note the studies carried out to predict the shifts and faults of the earth's soil under the influence of workings (mainly coal mining), under which the coordinate base in this region deforms. The forecast allows you to optimally choose the location of the geodetic network points. The technique developed at VNIMI has been successfully introduced in several industrial regions of the Arctic, including in the Vorkuta coal basin [8, 9].

Since 1991, due to the economic situation in the country, the work of the HOGS for Topographic Survey of the Shelf has ceased, and the amount of work on hydrographic surveying has dramatically decreased. Today, hydrographic surveying is carried out mainly by private companies in the local offshore areas of the shelf (ports, offshore drilling platforms, offshore oil and gas pipelines, etc.).

A significant part of the technical means (radiogeodetic systems, radio range finders, etc.) and traditional methods (triangulation, astronomical observations, etc.) for performing topographic and geodetic work has outlived their usefulness. We need to conduct fundamental revision of the concept of topographic, geodetic and cartographic support for the territories of the Russian Federation using the modern technical means (satellite receivers, electronic tachometers, traditional and digital aerial photography, multi-beam echo sounders, etc.) and advanced technologies (creation of satellite geodetic networks, satellite leveling, electronic tachometry and etc.). This problem is especially urgent for the Arctic, which is extremely poorly covered in terms of topographic and geodetic and cartographic data.

One of the possible variants of the concept is proposed to include the following elements:

• creation of a planimetric satellite geodetic base;
• conversion of geodetic coordinates into plane coordinates in a wide coordinate zone;
• determination of vertical anomalies by the satellite method in the sea ice survey;
• cartographic support for the Arctic;
• reference documentation update;
• studies to determine the outer border of the continental shelf within the polar zone of the Russian Federation.

Creation of planimetric satellite geodetic base. Planimetric satellite geodetic base is created according to the fundamental document «Basic Provisions on the State Geodetic Network of the Russian Federation». GKINP (Moscow: CNIIGAiK, 2004, p. 14).

At each defined point of the satellite geodetic network we measure the space rectangular coordinates X, Y, Z [11], to use them for mapping they should be converted into geodetic coordinates: B (latitude), L (longitude), H (altitude). The easiest value to determine is longitude L, and the most difficult one is latitude B. In this case, as a rule, it is necessary to perform several iterations. The altitude H is calculated after finding the latitude B.

The authors developed an alternative innovative algorithm for determining the altitude H without previous calculation of the latitude B using only satellite measurements X, Y, Z [4, 10]:

$$H = \left[D - \frac{b}{\sqrt{1 - e^2 \left(\frac{S}{D} \right)^2}} \right] \cos\left(e^2 \rho \frac{SZ}{D^2} \right), \qquad (1)$$

where $D = \sqrt{S^2+Z^2}$; b – semi-minor axis of used earth ellipsoid; e^2 – eccentricity square of ellipsoid; $S = \sqrt{X^2+Y^2}$; ρ = 57,29577951° (const).

There are no domestic and foreign analogues of the algorithm (1). Taking into account the obtained altitude H, we calculate the latitude:

$$\mathrm{tg}B = \frac{Z - He^2 \sin B_0}{(1-e^2)S},$$

where $\mathrm{tg}B_0 = \dfrac{Z}{(1-e^2)S}$.

Longitude L is determined using the formula $L = \mathrm{arctg}Y/X$. For further calculations a longitude difference is required: $l = L - L_0$ (here L_0 – longitude of the axial meridian).

Conversion of geodetic coordinates B, l in plane rectangular x, y, required for mapping was suggested in 1820-1830s by a German mathematician C.F. Gauss [4]. Until now, the formulas for calculating plane rectangular coordinates, in spite of the many invariants, have practically remained unchanged and rather cumbersome. The following alternative Gaussian algorithms are proposed for calculating rectangular coordinates in a 6-degree zone from known geodetic coordinates:

$$x = X + \Delta x;\quad X = \frac{R_э}{\rho^0}\mathrm{arctg}\left[\frac{R_э\sqrt{1-e^2}}{a}\cos\left(\frac{1}{6}\cos B\right)\mathrm{tg}B\right]q;$$

$$\Delta x = \frac{N}{\rho}\left[\mathrm{arctg}\left(\frac{\mathrm{tg}B}{\cos t}\right) - B\right]t;$$

$$y = \frac{N}{\sqrt{V}}\mathrm{arth}\left(\sqrt{V}\cos B \sin l\right),$$

where X – axial meridian arc length; $\Delta x = (x - X)$ – latitude difference; $R_э = \frac{3}{4}(a+b) - \frac{1}{2}\sqrt{ab}$ – equivalent radius of ellipsoid curvature [4]; e^2, e'^2 – squares of the first and second eccentricities of the ellipsoid; a, b – large and small semi axes of ellipsoid; $q = \cos[0.003\sin^2 B]$; $N = \dfrac{a}{W}$ – radius of curvature of the first vertical; $t = 1.000014\cos^4 B$; $V = \sqrt{1-e'^2\cos^2 B}$ and $W = \sqrt{1-e^2\sin^2 B}$ – basic spheroidal functions [4] (functions W, V were introduced by C.F. Gauss).

Conversion of geodetic coordinates into plane coordinates in a wide coordinate zone. In the Arctic zone of the Russian Federation, a significant part of strategic line communications (main land and subsea oil and gas pipelines, the Northern Sea Route, etc.) have a longitudinal extent, i.e. pass through several 6-degree coordinate areas of the Gauss map projection. Russia is situated in twenty-six 6-degree coordinate areas – from V area (western geodetic longitude L = 24°) to XX area (eastern geodetic longitude L = 180°). That is why the line can be in different coordinate zones. To get plane rectangular coordinates of different points of the line required for mapping, it is necessary to make quite labor-intensive conversion from one 6-degree zone to another.

On this basis, the question of converting the geodetic coordinates B, L, currently obtained from the satellite coordinates X, Y, Z, into plane rectangular coordinates x, y n a single coordinate zone is extremely urgent.

The authors proposed an algorithm for the conversion of geodetic coordinates:

$$x = \frac{R_{1э}}{\rho}\mathrm{arctg}\left(\frac{\mathrm{sh}\,q}{\cos t}\right) + \frac{R_{2э}}{2\rho}\left[\mathrm{arctg}\left(\frac{2k\,\mathrm{sh}\,q\cos l}{1-t^2}\right) + \frac{0°}{180°}\right];$$

$$y = R_{1э}\mathrm{arth}\left(\frac{\sin l}{\mathrm{ch}\,q}\right) + \frac{R_{2э}}{2\rho}\mathrm{arth}\left(\frac{2k\,\mathrm{ch}\,q\sin l}{1-t^2}\right),$$

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where $R_{1э}$ = 3430583.135 m (for SK-42); $R_{2э}$ = 2936973.362 m (for SK-42) (here $R_{1э} + R_{2э} = R_э$ = = 6367558.497 m); q = arth(sin$B$) – $e$arth($e$sin$B$); e = 0.081813334 (const); k = 1.003638604 (Krasovsky ellipsoid); $t^2 = k^2(\text{sh}^2 q + \sin^2 l)$.

For the territory of the Russian Federation, using the proposed algorithm, we have chosen the average axial meridian with a longitude

$$L_0 = \frac{1}{2}(24° + 180°) = 102°.$$

The advantages of using a single zone for the entire territory of the Russian Federation are:

• no need to converse coordinates x, y from one area to another;

• the algorithm, unlike the known ones, is non-iterative and does not require the expansion into series;

• the proposed algorithm can be used in circumpolar areas (to $B \le 89.9°$);

• the simplicity of the algorithm; its implementation is not difficult when using a 9-bit engineering and scientific micro calculator (with hyperbolic functions), which is impossible for other rather complex algorithms that require only personal computers and expensive domestic and especially foreign software products;

• to determine the coordinates x, y of some remote objects (including objects on the islands of the Arctic Ocean) it is advisable to use the proposed algorithm, especially for the purposes of the RF Ministry of Defense.

Determination of vertical anomalies by the satellite method in the sea ice survey. As is well known, the vertical anomaly ζ is the height of the quasigeoid over the surface of the ellipsoid [11]:

$$\zeta = H - H^{\gamma},$$

here the value of ζ ranges from –107 to +85 m.

The determination of vertical anomalies in the sea, especially in the high latitudes of the Arctic shelf, is quite relevant. It should be noted that in the seas and oceans the surface of the geoid coincides with the surface of the quasi-geoid. One of the types of marine mapping is ice surveying.

Taking into account that $H = h + \zeta$, where h – antenna height, i.e. distance from the center of reception of satellite measurements to the water surface (geoid), does not exceed ~ 100 m, instead of formula (1) without loss of accuracy, we can use a simpler expression

$$H = D - \frac{b}{\sqrt{1 - e^2\left(\frac{S}{D}\right)^2}}. \qquad (2)$$

In this case the normal height H^{γ} equals to the measured antenna height, hence

$$\zeta = D - \frac{b}{\sqrt{1 - e^2\left(\frac{S}{D}\right)^2}} - h.$$

The proposed approach is innovative and has no domestic or foreign counterparts. It is especially promising for use in the Arctic regions of Russia on the coast of the Arctic Ocean. With the help of satellite leveling, it is possible to create and thicken a network of normal heights with an accuracy not lower than the leveling of Class IV. In this case, it is necessary to take into account the average level of the seas of the Arctic Ocean according to the methodology for accounting for sea level fluctuations with the help of level posts, as described in [12]. It is advisable to determine the coordinates of the level posts on the entire coast by the satellite method. In the airborne mode, the application of this technique will significantly reduce costs, in the absence of gravimetric measurements.

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Thus, in this case, the coast of the Arctic Ocean is used as the initial level surface, since the level fluctuations of water under ice are negligibly small, especially in the seas (White, Kara, Laptev, East Siberian). From the coast of the AO a network of the IV class of leveling develops, which ensures the accuracy of determining the normal heights of points, sufficient for creating topographic maps on a scale of 1:10,000 and 1:25,000.

Cartographic support for the Arctic. After the creation and bridging, the aerial photo-topographic survey of the terrain is carried out, the zones of the coastline of the shelf of the AO, domestic cameras with the «Russar» lenses.

To determine the rectangular space coordinates X, Y, Z of the aerial photographing points, the GPS /GLONASS satellite navigation systems are used. The integrated navigation systems of IMU type are used, they define the values of six elements of external orientation of each aerial photo (linear and angular).

Conversion of rectangular space coordinates into plane rectangular and normal heights x, y, H^{γ}, required for mapping is carried out according to the scheme

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \Rightarrow \begin{bmatrix} B \\ L \\ H \end{bmatrix} \Rightarrow \begin{bmatrix} x \\ y \\ H^{\gamma} \end{bmatrix}.$$

Topographic maps and plans are compiled according to a known method. If it is necessary to create a digital topographic map of the terrain, photogrammetric processing of the aerial survey results should be carried out using the PHOTOMOD photogrammetric station. This method was introduced by the Federal State Unitary Enterprise «Aerogeodesia» in 2000-2003 on the territory of the Norilsk industrial region (the Arctic) when creating digital topographic maps of scale 1: 1000 [6].

Reference documentation update. The previously developed reference documentation on the topographic survey of the shelf outlived its usefulness. For the renewal of topographic mapping of the shelf, we need to revise this process taking into account the modern technical means and methods.

GPS receivers of GPS/GLONASS satellite systems are mainly used as technical means of determining the ship's planned coordinates. Multi-beam echo-sounders and a modern hydroacoustic equipment are used as technical means of height survey [3, 13, 14].

The reference documentation for topographic survey of the shelf should include the following:

- basic provisions for the creation of cartographic maps of the shelf;
- instruction for topographic survey of the shelf;
- guidelines for topographic survey of the shelf;
- samples of topographic maps of the shelf;
- reference specification documents;
- software units, etc.

As a basis for the development of reference documentation, it is possible to use similar documentation created in CNIIGAiK and FSUE «Aerogeodesia» in 1975-1992.

Studies to determine the outer border of the continental shelf within the polar zone of the Russian Federation. From the geological point of view, the outer boundary of the continental shelf is confined to the shoulder line of significant inflection of the surface of the shelf relief, where the boundary between the shelf and the continental slope runs. In this case, the depth of the shelf shoulder line is different and does not coincide with any of the isobaths. According to the American scientist F. Shepard, the average depth of the shelf is 132 m, its average width is 78 km, and the average slope is 0.1 [12]. However, the depth and width of the shelf vary considerably. In some regions the shelf extends to a depth of over 2 km, and its width in places, for example in the Arctic Ocean, reaches 1.5 thousand km.

According to the legal definition of the International Convention on the Continental Shelf (Geneva, 1958), the shelf zone is usually limited to a 200-meter isobath or a greater depth at which bottom resources can be developed. In some states, however, there are other definitions of the outer

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shelf boundary: a 500-meter isobath, a 200-mile (370 km) distance from the coast, and so on. At present, the concept of an extended shelf has been introduced into practice. More detailed information on the shelf boundaries is presented in [2]. In this connection, the issue of delimitation of the shelf zones of the Arctic Ocean between Russia, the USA, Canada, Norway, Denmark, and Sweden is extremely topical. One of the important documents of the Application in the United Nations is the result of an on-site bathymetric survey of the AO, designed in graphic and digital form [2, 8, etc.]. The authors take an active part in the preparation of this Application. An important contribution to the solution of this issue is the participation of the SSD in the expert group of the Russian delegation in the protection of the revised partial applications for the outer boundary of the continental shelf of the Arctic Ocean for their transfer to the Commission on the Limits of the Continental Shelf at the United Nations

Conclusion. In this paper the authors present the review of studies conducted with their participation in the field of research and development on topographic, geodetic and cartographic support of the land zone of the Arctic and the continental shelf of the seas of the Arctic Ocean within the territory of the Russian Federation. New developments and ways of their practical use are described. The variant of the project of topographic-geodetic and cartographic support of the Arctic zone of the Russian Federation is outlined based on the use of modern technical means and methods.

A significant part of the work was carried out within the framework of state orders: the technical and economic report «State and objectives of the enterprises of the HOGS for the mapping of the Russian shelf», themes 07.962, 07.963, 07.911, 07.912, 07.914, etc.

The testing of satellite technology was carried out at two points of the fundamental astronomical and geodetic network, functioning of which are provided by JSC «Aerogeodeziya» and SSD and at the points of satellite networks: a high-precision geodetic network and SGS-1 (satellite geodetic network) in St. Petersburg (Pulkovo), its surroundings and in the Leningrad Region.

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