Geomagnetic Survey for Solving Ecology Problems on Aquatory Seaport with High Level of Electromagnetic Noise (Golden Horn Bay, Peter the Great Gulf, Sea of Japan)

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Abstract. The crucial task of geomagnetic survey is detecting of magnetic anomalies coming from local object with ferromagnetic properties on aquatory seaport with high level of electromagnetic noise. We developed magnetic survey and data interpretation procedure which is necessary for expanding level of results authenticity under the conditions of limited size of aquatory and high vessel traffic. We used measuring equipment and software produced in Russia. Results of magnetic anomalies quantitative interpretation certified by side-scanning sonar and diver's works.

1. Introduction
Golden Horn bay is a most polluted area in Peter the Great bay. Aquatory and seacoast present the infrastructure of biggest Pacific seaport of Russia. Seaport is a complex transport system. It includes aquatory with arrangement of cargo, passenger and subservient fleet vessels in aggregate with port terminals, shipyards and dockyards, navigational and hydrographic support services, extensive railroad network and other objects. It also includes berths of commercialiland fishery ports, dockyards and machine shops and other town factories. Along the coast of Golden Horn bay almost all shore armed with concrete walls, fitted with berths and piers. Ships sunken on aquatory in different time periods are obviously potentially hazardous, especially of those whose location was lost due various reasons. Well-developed infrastructure of operation port defines not only difficult operational environment on aquatory of Golden Horn bay but also extremely high level of electromagnetic noise which grows higher along the sea walls.

Targeted search and detection of local objects with ferromagnetic properties in water areas with a high level of electromagnetic interference is an extremely urgent task of geomagnetic research. In general, abnormal effect of these objects is comparable to the intensity level of discrete human-induced noise of various origin. Measurements made from marine magnetic gradient survey can be used to eliminate the electromagnetic noise effect [1]. Measurements made from marine towed magnetic detector and gradiometer allow to obtain data about course horizontal magnetic field gradient free from temporal variations effect [2]. This kind of research have been sussesfully used to
detect local objects representing wreckage of sunken ships in the Baltic and Mediterranean Seas [3]. Gradiometry for locating ferromagnetic objects in shallow-water aquatory can be applied by arranging measuring equipment on non-magnetic external carrier [4]. However, differential magnetic survey on operating port with limited area (the Golden Horn bay juts out into the northern shore of the Eastern Bosphorus in a narrow curved strip) and high ship traffic is inappropriate due to critical decrease in the maneuverability of a vessel towing a non-trivial structure consisting of two outboard measuring systems. Unfortunately, miniature towed devices using a complex system of spatially distributed magnetic field sensors are currently under development [5].

Using of geomagnetic-variation station on the shore of Golden horn bay for enhancement of measurement quality is of no use as port aquatory is extensive and framed by high-density development of production facilities and living quarters. This leads to high level of noise signals along the aquatory.

Purpose of the survey is to design and implement methodical procedures of geomagnetic survey on aquatory of Golden Horn bay (city of Vladivostok) to detect sunken ships located at the bottom and in bottom sediments; also, to detect and quantitatively evaluate objects of accumulated environmental damage.

Attaining the goal requires using procedures of measurement and data interpreting which provides valid detection of human-induced sources of local magnetic anomalies with ferromagnetic properties. As experience of geomagnetic survey on aquatory of Peter the Great gulf has shown, goal setting always requires the development of new approaches and measuring methods and data interpretation [6].

Hydromagnetic survey on aquatory of Golden Horn bay was never made before.

2. Technique and method of geomagnetic survey
Measurements of the geomagnetic field full vector module (T) were made by marine towed proton magnetometer MPMG-04 developed in Russia (IZMIRAN) assigned for automatic measuring of the geomagnetic field full vector module for marine magnetic survey. The geo-referencing of the measurement points was made by SPS855 GNSS Modular Receiver. The aquatory survey were made with POI FEB RAS research vessel “Malakhit” (Project VRD376 boat). The magnetic sensitive transducer (MST) was towed over the water surface. Positive buoyancy was provided by using the polystyrene winding of the MST, which is more convenient than specific towed devices [7]. A 1:2000 scale hydro-magnetic survey was carried out in the aquatory of the Golden Horn Bay. Due to limited maneuvering ability in the port waters the survey profiles were laid each 100 m. To achieve the required density of the observation network the hydromagnetic survey was made using “sliding window” method (figure 1).
To eliminate the effect of discrete electromagnetic interference, we repeated measurements for each profile twice. In some cases the number of passes was tripled. The improvement of work quality was achieved by accounting nature-based geomagnetic field variations based on synchronous magnetovariational measurements at the POI FEB RAS static observation point “Popova isl.”.

3. Method of survey results processing

The observed geomagnetic field ($T$) is the sum of the normal field ($T_n$), abnormal field ($T_a$) and the field of variations ($\delta T$):

$$T = T_n + T_a + \delta T$$  \(1\)

The normal geomagnetic field ($T_n$) was calculated using the spherical coefficients The International Union of Geodesy and Geophysics (IUGG) recommends for calculating the normal geomagnetic field (model IGRF-2017) [8].

For the entire observation period the magnetic field was not troubled by storms, and the magnitude of $\delta T$ did not exceed 80 nT per day. However, in some periods the variation gradient was 20–25 nT/h and have to be accounted while identifying weak anomalies in the slightly noisy part of the Golden Horn bay aquatory.

The “local” component of the investigated aquatory is the nature-based first-level anomalous magnetic field ($T_a_r$). Human-based (ferromagnetic) objects are the sources of local second-level anomalies $\Delta T a$. Thus, the human-based anomalous magnetic field can be presented as:
\[ T_{ar} = Ta - Tr \] (2)

Division of anomalies is based on the idea that anomalous objects of a various origin differ in size, magnetization and depth. The selection of the local component \( (Tr.) \) under task conditions was made by averaging magnetic field profiles using the “sliding window” method.

The influence of magnetic masses of moving and stationary objects with ferromagnetic properties during the time is included as unavoidable interference. Anomalies made by these objects were excluded from calculation.

Further transformations of the abnormal magnetic field were determined by the work task and represented the neutralization of noise anomalies of different origin \( (Tc) \):

\[ \Delta Ta = Tr - Tc \] (3)

Random noise anomalies are highlighted in all measurement profiles. These are sign-alternating anomalies of small size (recorded by 1, rarely by 2 points) characterized by a wide range of amplitudes -6 ÷ 6 nT. Such anomalies are associated with random measurement errors, changes in distance between the magnetosensitive transducer and bottom surface due to sea waves, etc. The elimination of these anomalies is based on low-frequency filtering.

Unfortunately, it is impossible to calculate the influence of high-amplitude, high-frequency electromagnetic interference of port facilities operations.

As a result of the performed transformations we obtained \( \Delta Ta \) data array which allowed to construct maps of the abnormal magnetic field (AMF) and quantitative interpretation of local anomalies aimed to identify human-based objects with ferromagnetic properties. To construct the maps we used two \( \Delta Ta \) datasets obtained from the same profiles with measurements performed at different time periods.

The construction of maps of the \( \Delta Ta \) anomalous magnetic field was performed by the network method [9]. The distance between the network nodes corresponds to the scale of the survey. The calculation of the network for constructing AMF maps was performed using kriging method, which has optimal statistic properties.

4. Quantitative interpretation of magnetic anomalies

The magnetic field (2) can be structurally divided into two types: type along the quay walls it is high-intensive and type at the central part of the Golden Horn bay has low-amplitude positive values. Moreover, along the coastline negative anomalies are identified near the quay walls; they are associated with high-amplitude positive magnetic anomalies located closer to the fairway. It was impossible to identify “useful” anomalies [10] in these areas due to "overwhelming" intensity of anomalies created by constant interference sources (reinforced concrete berth walls). The low-amplitude magnetic field in the central part of the bay is troubled by high-gradient dipole local anomalies. The sources of such magnetic anomalies are highly probably the objects with ferromagnetic properties. To distinguish local search-objects based anomalies, we excluded “false” magnetic anomalies created by moving vessels in the aquatory.

The quantitative interpretation of local magnetic anomalies in dipole form is a solution of a simple task: can there be a local source of abnormal magnetic field with ferromagnetic properties in a known depth, which creates this magnetic anomaly, or is the source of anomaly electromagnetic interference.

The quantitative interpretation of magnetic anomalies was performed in a two-dimensional version. Solving the inverse problem of magnetic prospecting the sources of magnetic anomalies are approximated by layers of limited thickness and strike.

The calculation of the estimated sizes of local magnetic anomalies sources made on the assumption of magnetic moment \( M \) for each ton of massive iron or steel object in the range of \( 10^2 \text{ to } 10^3 \text{ A/m}^2 \).

Abnormal effect \( (A) \) of the geomagnetic field full vector module\( (T) \) measured by the formula [11]:

\[ A = M/r^3 \] (4)

where \( r \) is the distance to the magnetic anomaly source in meters.
Calculations were made using ZondMAG2d software for two-dimensional interpretation of magnetic survey data (figure 2).

![Figure 2](image)

**Figure 2.** An example of a quantitative interpretation of local magnetic anomaly in the dipole form.

Experimental and methodological studies were made in a shallow water area. The object is located at 2.6 m depth, has a high magnetization characteristic of iron and weighs about 100 kg.

In the Golden Horn bay within an abnormal magnetic field of the form (3) we identified 7 local magnetic anomalies in total which sources can be ferromagnetic objects comparable in size to the search objects. These magnetic anomalies are characterized by locality, high intensity, dipole shape (positive and negative poles) and significant distance between the poles.

In the western part of the Golden Horn bay we identified three magnetic anomalies which representative for the search objects (I, II, III) - figure 3. The magnetic anomaly I is characterized by the presence of negative and positive poles shifted to the northwest and southeast and high amplitudes \(-220 \div 515\) nT. Positive and negative poles have heterogeneous internal structure. The positive part of the anomaly consists of two maxima spaced along the submeridian strike.

The negative part is also characterized by two maxima spaced sublatitudinally. Inhomogeneous shape of anomaly indicates either complex contours of object or lack of integrity. The calculated length of the ferromagnetic source lying about 30 m depth in the northwest and about 20 m in the southeast should be about 32 m.
Figure 3. Local magnetic anomalies in the western part of the Golden Horn Bay.

Magnetic anomaly II is characterized by the dipole shape with poles located along the north-west-south-east strike. The intensity of the anomaly is $-154 \div 115$ nT. The length of the ferromagnetic source lying diagonally at a 22 m depth along a line passing through the centers of the poles is about 35 m. The width of the object is 10-12 m. The source of the magnetic anomaly is characterized by its integrity and simple form. The object lies parallel to the bottom surface.

Magnetic anomaly III identified near berth No. 2a between the signal buoy and the quay wall. The anomaly is characterized by a dipole structure and a significantly high intensity $2200 \div 3400$ nT. Such a high intensity of the anomaly indicates a small distance to the source. The negative and positive poles are characterized by several high-amplitude maxima. The length of the source is about 50-40 m, width is about 12 m. The integrity of the object has been violated. According to the information received from the harbor master and confirmed by sonar survey, Figure 4 is a tugboat 46 m long and 15 m wide rising above the bottom to a depth of 3 m that was sunk near berth 2a. Magnetic anomaly III highly probably reflects the influence of this particular ferromagnetic source magnetic masses.

Figure 4. Side-scan sonar data. The localization of the sunken ship at the bottom of the Golden Horn Bay (berth No. 2a) is shown in red.
Local magnetic anomalies IV, V, VI are located in the eastern closure of the Golden Horn Bay (Figure 5).

Figure 5. Local magnetic anomalies of the eastern closure of the Golden Horn Bay.

Magnetic anomaly IV is characterized by the dipole shape oriented by the poles along the north-south line with a slight deviation to the west. The intensity of the anomaly is quite high, -200 ÷ 1250 nT. A dipole is characterized by a non-uniform pole structure. The intensity of the positive pole is much higher. Most likely, an elongated object is located in the ground at an angle with the southern part closer to the surface. The length of the object is no more than 20 m, the width is no more than 9 m. The depth to the source is about 14 m.

Magnetic anomaly V is characterized by the dipole shape oriented by the poles along the north-south line. A dipole has regular shape with a well-defined homogeneous pole structure. The object is characterized by ferromagnetic properties, integrity and regular shape. The length of the object is about 10 m. The intensity of the anomaly is rather high -359 ÷ 656 nT. The depth to the source is 8-9 m.

Magnetic anomaly VI is located in the eastern closure of the Golden Horn Bay, near the northern side. Anomaly has the dipole form with a poorly expressed positive pole. The intensity of the anomaly is -215 ÷ 1300 nT. The ferromagnetic source is characterized by a shallow burial depth (8 m), about 10 m long, and almost vertical position in the ground. The object’s negative pole is closer to the surface.

Thus is the anomaly sources based of quantitative interpretation, their shape, sizes and position in space have been restored. Subsequently, the existence of all identified objects and the peculiarities of their occurrence in the ground suggested by the results of the interpretation of geomagnetic data were confirmed by diving operations.

5. Conclusion
The paper presents current geomagnetic research in the aquatory of an operating seaport with a high level of electromagnetic interference aimed at identifying magnetic anomalies which sources are local objects with ferromagnetic properties.

We develop the technique for geomagnetic measurements and data interpretation necessary to increase the reliability of the results obtained in the conditions of limited water area and high vessel traffic. All measuring equipment and software that we used were developed in Russia.

Based on the material obtained we made the zoning of the abnormal magnetic field in research area accounting the magnetic anomalies morphology, performed transformation of the anomalous magnetic field and obtained the data allowing a quantitative interpretation of local magnetic anomalies which sources are human-based ferromagnetic objects. Abnormal magnetic field near the quay walls is determined by sources of stationary and electromagnetic magnetic anomalies of port facilities and mechanisms. The intensity of these anomalies does not allow to distinguish local anomalies in the
abnormal magnetic field, reflecting the influence of submerged ferromagnetic objects possibly located in aquatory. According to the measurement results, the rest of the research area reveals a high level of high-frequency interference. The methods we used made it possible to identify local magnetic anomalies in the aquatory of the Golden Horn bay sourced from sunken ships.

The results of the quantitative interpretation of magnetic anomalies have been verified by side-scan sonar and diving operations. Geomagnetic studies of this direction in the water area of the Golden Horn have been performed for the first time.

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