

MODELING OF PILLAR MAGNETIC FIELD DISTRIBUTION AT MAGNETIC OBSERVATORY

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Abstract: Based on the analytical model of the magnetized parallelepiped magnetic field, a model of the pillar magnetic field was created. Comparison of the model with the magnetic survey at the Kurchatov station variational pavilion made it possible to determine the pillar magnetic susceptibility. The anomalous field distribution of the pit near the Paratunka observatory was studied. It was shown that the field distribution is consistent with the two-layer soil magnetic properties model with a magnetic susceptibility of 0.0066 for the upper layer with a thickness of 70 cm and 0.0087 for the lower layer. Models of the magnetic field distribution at the dIdD and POS-4 pavilions at Paratunka geophysical observatory have been created. The anomalous field amplitude in the dIdD pavilion can reach 30 nT at the height of 40 cm. Compensation of the pit magnetic moment and the base plate one in the POS-4 pavilion leads to a relative uniformity of the model field, which is – not more than 0.5 nT at the magnetometer installation height.

Keywords: magnetic anomaly field, magnetic susceptibility, soil magnetic properties, simulation, analytical model, Kamchatka

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1. Introduction

A pillar is an integral part of every magnetic observatory. In some cases, magnetic anomalies occur during pillar construction due to the use of magnetic materials or the magnetic properties of the underlying rocks [Gvozdev *et al.*, 2023; Krasnoperov *et al.*, 2023]. In this case it is useful to have a model of the magnetic field distribution in the pillar vicinity. On the one hand, this allows us to evaluate the possible effect of the pillar field on measurements results, and on the other hand, to assess the magnetic characteristics of the materials used. In 2005, an analytical solution for the magnetized parallelepiped field distribution was published [Engel-Herbert and Hesjedal, 2005]. This solution was used to describe iron magnet [Kuleznev *et al.*, 2018]. This paper describes the magnetic field models based on this solution and applied for the pillars installed at the Kurchatov magnetic station (MS) and at Paratunka geophysical observatory.

2. Magnetic field of a parallelepiped-shaped pillar at the Kurchatov magnetic station

In 2012, during the survey at the new magnetic station Kurchatov in Kazakhstan, we detected pillar magnetic anomalies in the variation and absolute pavilions [Belyashov *et al.*, 2012]. They were caused by the use of lime-cement mixture with a rather high cement content for the pillars.

Based on the method of fictitious magnetic charges [Parkinson, 1983; Tamm, 1976], the magnetic field generated by a parallelepiped-shaped pillar can be represented as a sum of magnetic fields generated by four surfaces, on which fictitious magnetic charges with

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surface densities σ_H and σ_Z are uniformly distributed (Figure 1). The surface densities depend on geomagnetic field components: vertical Z and horizontal H

$$\sigma_H = \chi H, \sigma_Z = \chi Z,$$

where χ is the magnetic susceptibility. Here we neglect a demagnetization coefficient [Parkinson, 1983] for parallelepiped because χ is small.

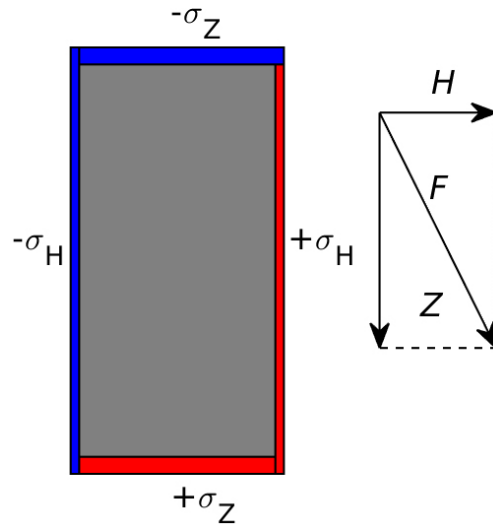


Figure 1. Fictitious magnetic charges location scheme for the pillar in geomagnetic field.

According to the article [Kuleznev et al., 2018], the field generated by vertical magnetization χZ is described as

$$\begin{aligned} \Delta H_Z &= \frac{\sigma_Z}{4\pi} \ln |v + (u^2 + v^2 + w^2)^{1/2}| \Big|_{u=-a/2-x}^{u=a/2-x} \Big|_{v=-b/2-y}^{v=b/2-y} \Big|_{w=-c/2-z}^{w=c/2-z}, \\ \Delta Y_Z &= \frac{\sigma_Z}{4\pi} \ln |u + (u^2 + v^2 + w^2)^{1/2}| \Big|_{v=-b/2-y}^{v=b/2-y} \Big|_{u=-a/2-x}^{u=a/2-x} \Big|_{w=-c/2-z}^{w=c/2-z}, \\ \Delta Z_Z &= -\frac{\sigma_Z}{4\pi} \frac{v}{|v|} \frac{w}{|w|} \operatorname{arctg} \frac{u|v|}{|w|\sqrt{u^2 + v^2 + w^2}} \Big|_{v=-b/2-y}^{v=b/2-y} \Big|_{u=-a/2-x}^{u=a/2-x} \Big|_{w=-c/2-z}^{w=c/2-z}, \end{aligned} \quad (1)$$

where $u = x' - x$, $v = y' - y$, $w = z' - z$; x', y', z' are the coordinates of the fictitious charges, x, y, z are the coordinates of the field measurement point, a, b, c are the sizes of the pillar along the axes.

Figure 2a shows the calculations results for a pillar with height $c = 2m$, horizontal dimensions $a = b = 1m$ and $\chi = 0.002$ (in SI unit). Here H is the magnetic north component, Y is the magnetic east one, Z is the vertical component, F is the total field intensity. The positive anomaly of the vertical component ΔZ_Z above the pillar and negative anomaly beyond it are clearly visible. In the first case, the field lines of anomalous field coincide with the vertical component Z , while in the second case, they are directed against it. An anomalous field in the magnetic north and eastern components is observed where the field lines turn from the direction along the vertical magnetic moment to the opposite direction. Since Figure 2a shows a section above the pillar, the field lines tend to converge towards its upper surface. Therefore, to the north of the pillar, the field lines are directed southward and the anomalous component ΔH_Z is negative, while to the south of the pillar, the opposite pattern is observed. As a result, we can see that the total field F increases to the south of the pillar and decreases to the north.

The field generated by horizontal magnetization χH is described as

$$\begin{aligned}\Delta H_H &= \frac{\sigma_H}{4\pi} \ln \left| w + (u^2 + v^2 + w^2)^{1/2} \right| \Bigg|_{u=-a/2-x}^{u=a/2-x} \Bigg|_{v=-b/2-y}^{v=b/2-y} \Bigg|_{w=-c/2-z}^{w=c/2-z}, \\ \Delta Y_H &= -\frac{\sigma_H}{4\pi} \frac{v}{|v|} \frac{w}{|w|} \operatorname{arctg} \frac{u|w|}{|v|\sqrt{u^2 + v^2 + w^2}} \Bigg|_{v=-b/2-y}^{v=b/2-y} \Bigg|_{u=-a/2-x}^{u=a/2-x} \Bigg|_{w=-c/2-z}^{w=c/2-z}, \\ \Delta Z_H &= \frac{\sigma_H}{4\pi} \ln \left| u + (u^2 + v^2 + w^2)^{1/2} \right| \Bigg|_{u=-a/2-x}^{u=a/2-x} \Bigg|_{v=-b/2-y}^{v=b/2-y} \Bigg|_{w=-c/2-z}^{w=c/2-z}.\end{aligned}\quad (2)$$

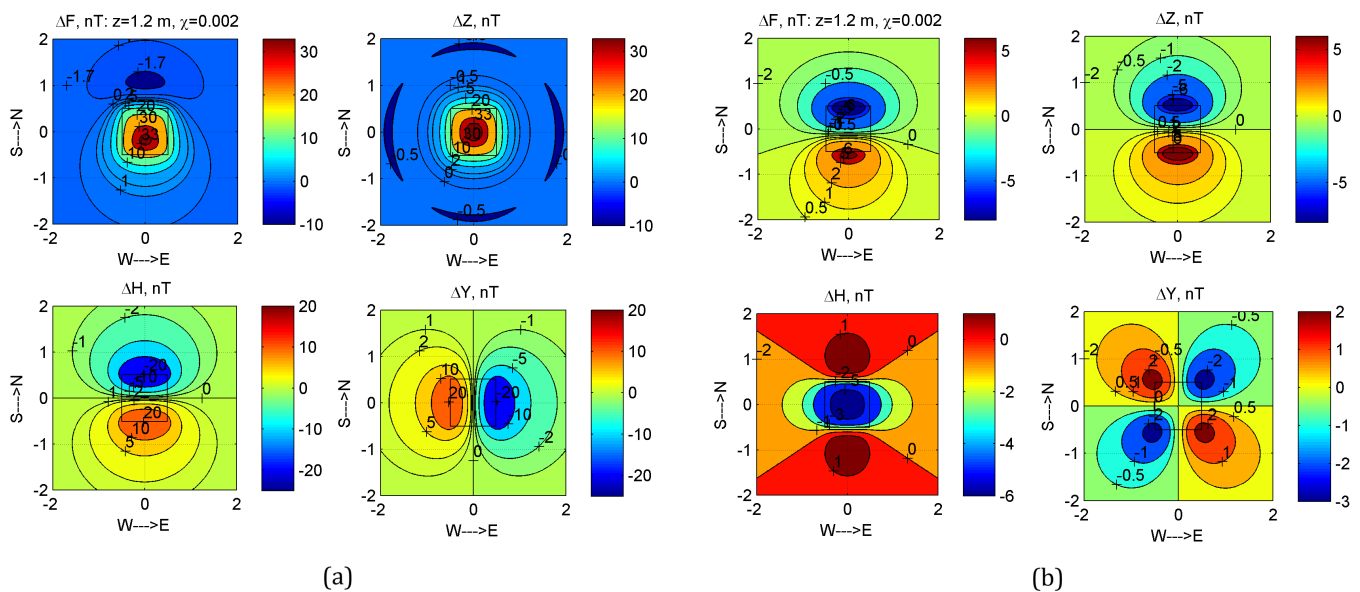


Figure 2. The simulated anomalous field distribution generated by vertical (a) and horizontal (b) components of pillar magnetization at a height of 0.2 m above the upper pillar surface. $a=b=1$ m, $c=2$ m and $\chi=0.002$.

Figure 2b shows the calculation results of this field. In this case, the magnetic moment is directed towards the magnetic north, so the field lines are directed towards the south above the pillar, and the anomalous field ΔH_H is negative at the plane center. To the north and south of the pillar, the field lines are directed along the horizontal magnetic moment, and the anomalous field ΔH_H is positive. In the northern part of the plane, the field lines cross it from bottom to top, so the anomalous vertical field ΔZ_H is negative, while the opposite pattern is observed in the southern half of the plane.

Figure 3a is the sum of (1) and (2):

$$\begin{aligned}H_a &= H + \Delta H_Z + \Delta H_H, \Delta Y = \Delta Y_Z + \Delta Y_H, \\ Z_a &= Z + \Delta Z_Z + \Delta Z_H, F = \sqrt{H^2 + Z^2}, \\ F_a &= \sqrt{H_a^2 + Z_a^2 + \Delta Y^2}, \Delta F = F_a - F\end{aligned}$$

Here H, Z, F are horizontal, vertical components and the total intensity of the external uniform field, while H_a, Z_a, F_a are the same characteristics of the sum of the external and anomalous fields. When the fields created by horizontal and vertical magnetization are added together, the symmetry between the northern and southern parts of the plane is broken for the vertical anomalous field ΔZ , as it seen in Figure 3a. There is a negative anomaly to the north of the pillar, and the maximum of the positive anomaly is shifted to

the south of the pillar center. For the full vector anomaly ΔF , these trends are even more pronounced. The distribution of anomalous magnetic fields for the magnetic northern component ΔH and magnetic eastern one ΔY is generally similar to the distribution created by horizontal magnetization χH , but it also loses symmetry between the northern and southern parts of the plane.

Comparison with the measurement results at the Kurchatov (Figure 3b) shows the presence of common features. The maximum of the field is shifted to the south. A negative anomaly is observed to the north of the pillar.

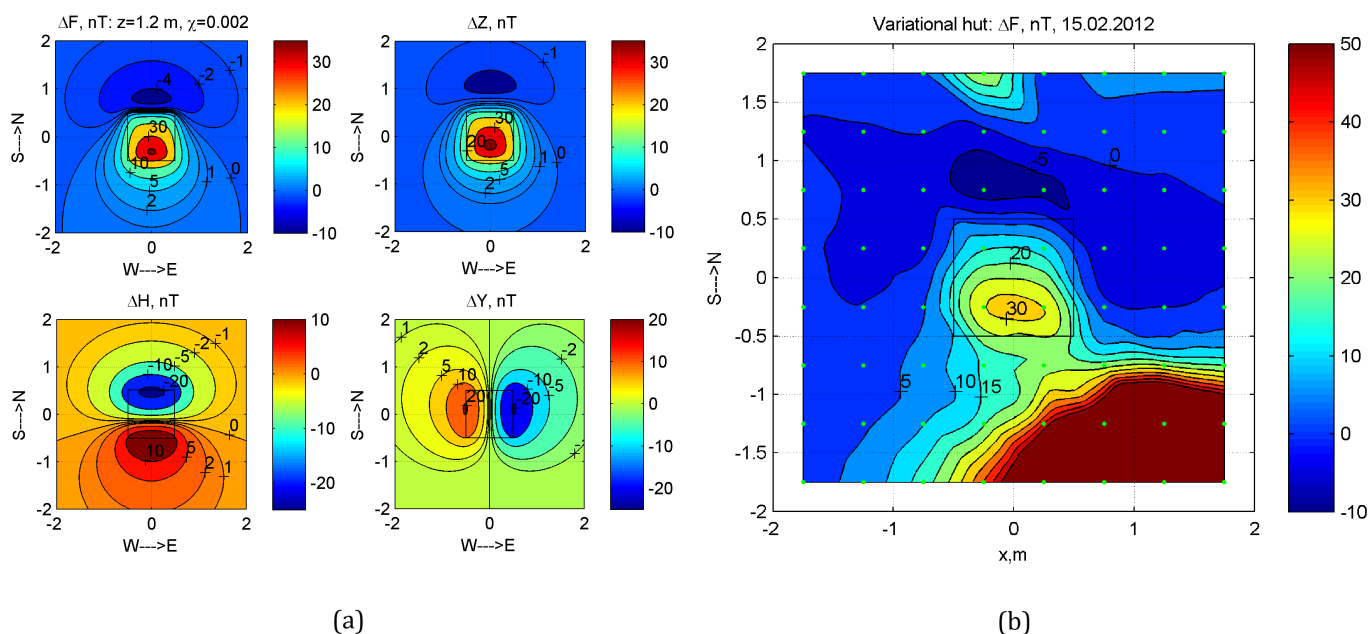


Figure 3. Results of calculation of the anomalous field of the total magnetization (a) and measured total field intensity distribution at the variation pavilion of the Kurchatov magnetic station [Belyashov *et al.*, 2012] (b).

3. Pit magnetic field at Paratunka observatory

The article [Gvozdarev *et al.*, 2023] shows that the soil at Paratunka geophysical observatory has relatively pronounced magnetic properties. Thus, a pit under the pillar basement can create a magnetic anomaly with an amplitude up to 100 nT. To study this phenomenon, a pit with a depth of 1 m and a width of 0.9 m was dug at the distance of 30 meters to the east of the absolute pavilion. The soil samples were taken at different depths in the pit and their magnetic susceptibility was measured using the MS3 Magnetic susceptibility meter [Bartington Instruments *...*, 2022]. The measurements were taken on samples taken from the pit, which were dense for clay and loose for sand. Measurements were performed at fifteen points for each sample, followed by averaging. The measurements results are presented in Table 1. It shows that there is a layer of clay at the depth of 70 cm with the higher magnetic susceptibility than the layers of sand and loam above it.

A magnetic survey was also carried out near the pit before and after the digging on an area of 4×4 m at heights of 0.15 and 1.0 m. Measurements were carried out using a magnetometer GSM-19W, natural geomagnetic variations were removed using the records of the stationary scalar magnetometer GSM-90. The total field intensity difference of these surveys is shown in Figure 4. The circles in the figure show the measurement points, and the field distribution between them was calculated using interpolation.

A negative anomaly is clearly visible in the pit area, and a weak positive anomaly is visible to the north of it. The field distribution at the height of 1 m clearly shows the shift

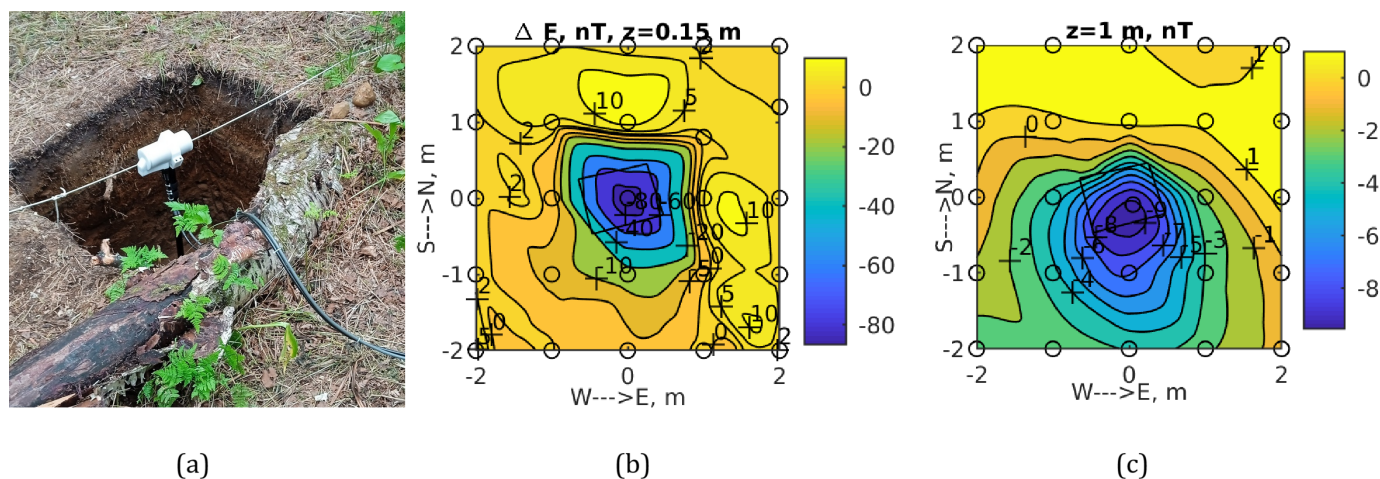
Table 1. Magnetic susceptibility of soil probes taken at different depths

	Depth, cm	Rocks	Magnetic susceptibility $\chi, 10^{-3}$
1	0	sand	3.2 ± 0.1
2	20	sand	4.0 ± 0.1
3	40	sandy loam of ochre color	4.7 ± 0.4
4	60	sandy loam of ochre color	4.0 ± 0.2
5	80	light yellow clay	9.0 ± 0.5
6	80	light yellow clay	8.3 ± 0.8

of the negative anomaly to the south. In general, the field distribution resembles the pillar field discussed in the previous section, but with the opposite sign of magnetization.

The magnetic field of the pit is calculated as the field of the pillar, but with opposite signs of the surface fictitious charges densities (Figure 5). The values of the magnetic susceptibility $\chi = 0.0072$ were calculated based on the condition of minimum for the standard deviation of the model values with the experimental ones. The value of the residuals standard deviation was equal to 2.0 nT. The model residuals range was 12 nT.

However, since the magnetic susceptibility increases at a depth of 70 cm, a two-layer model was developed. In this model, one parallelepiped with a length of 70 cm and magnetic susceptibility $\chi = 0.0066$ was placed on another parallelepiped with a length of 30 cm and magnetic susceptibility $\chi_1 = 0.0087$. The residuals standard deviation of this model was 2.1 nT, but the range of deviations between the experimental and model values did not exceed 10 nT. The latter value is approximately equal to the survey positioning error (2 cm) near the pit. In this case, the average value of the magnetic susceptibility calculated over the entire depth of the pit $\langle \chi \rangle = 0.7\chi + 0.3\chi_1 = 0.0072$ was the same as that obtained in the single-layer model.

**Figure 4.** The pit view (a) and the difference in the total magnetic field intensity before and after pit digging at the heights of 15 cm (b), 1 m (c).

Note that, the magnetic susceptibility of the upper layer in the model is significantly higher than that obtained using the magnetic susceptibility meter. This is due to the decompaction of the loose soil during the digging of the pit, resulting in underestimated values of its magnetic susceptibility. When trying to use the model of the average values of magnetic susceptibility in sand and clay layers, obtained by direct measurements $\chi = 0.0042$, $\chi_1 = 0.0087$, the amplitude of the negative anomaly in the pit was 30 nT less than in the experiment, and the model residuals standard deviation reached 5.5 nT.

Thus, by measuring the magnetic field of the pit, we were able to obtain more accurate values of the soil magnetic susceptibility, which were underestimated in [Gvozdev et al.,

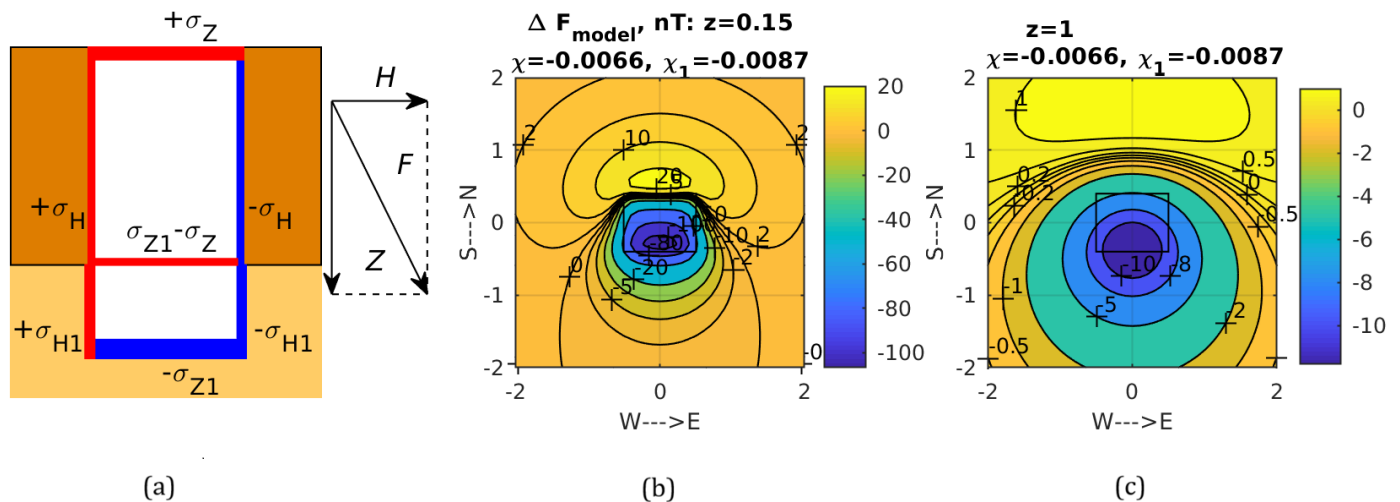


Figure 5. The two-layer magnetic field model of the pit: the scheme of fictitious charge location (a), the anomalous total field intensity distribution at the heights of 15 cm (b) and 100 cm (c)

2023]. Of course, such high magnetic susceptibility of clay and sand at Paratunka is need to discuss. However, the problem is not that our predecessors chose an unsuccessful location for the magnetic observatory in the 1960s, but rather the widespread development of volcanism in Kamchatka.

The Paratunka River valley, where the observatory is located, is a graben filled with Quaternary sediments. The sediments thickness is between 115 m and 230 m near observatory according to drilling data and the upper layer consists of glacial sediments [State ..., 2000]. The right side of valley is composed of Neogene andesite rocks. There is also Holocene basaltic volcanism with area about 100 km² (Barkhatny volcanic complex). A magnetic anomaly of up to 1000 nT is associated with these rocks. The left valley side is composed of tuffs, tuff-sandstones, sandstones, andesites and diorite-porphyrites. A magnetic anomaly of up to 1000 nT is associated with the left side. The Vilyuchinsky volcano, composed of andesites and basalts, rises above the upper reaches of the valley, and a magnetic anomaly with an amplitude of up to 500 nT is associated with it [State ..., 2000].

We do not have data on the magnetic properties of the rocks that make up the valley sides, but for the tuffs of the Mutnovsky volcanic area, located 50 km to the south, the magnetic susceptibility ranged from 0.0002 to 0.046 [Frolova and Ladygin, 2008]. The magnetic susceptibility of andesites in the same area varied from 0.0002 to 0.070, with an average value of 0.017 [Frolova and Ladygin, 2008]. The magnetic susceptibility of basalts from the Verhnyaya Avacha volcanic complex, which is similar in chemical composition to Barkhatny volcanic complex ones, varied between 0.010 and 0.026 [State ..., 2000]. Thus, the primary materials for Quaternary sediments in Kamchatka (as well as in other areas of volcanic activity) often have strong magnetic properties.

The Quaternary sediments of Kamchatka are also characterized by high values of magnetic susceptibility. For example, the lake clay sediments at the Polovinka paleomagnetic section have an average specific magnetic susceptibility of $4.1 \cdot 10^{-6}$ m³/kg [Naumov et al., 2017b]. If the density of clay is taken to be 1800 kg/m³ [Soil density, 2017], their magnetic susceptibility can be estimated as $\chi = 0.0074$. For the glacial deposits at the same section, the magnetic susceptibility estimates are varied in range of up 0.008 to 0.014. Finally, the upper layer of sandy loam with 1600 kg/m³ density has a magnetic susceptibility estimates range of 0.001 to 0.050. The magnetic properties of these sediments are caused by magnetite and titanomagnetite. The lepidocrocite is found in ochre-colored sandy loams [Naumov et al., 2017b]. The specific magnetic susceptibility of volcanic ashes in this section (about 20 layers) varied between 0.6 and 14.8, 10^{-6} m³/kg [Naumov et al., 2017a].

Hydrothermal clays formed as a result of the andesites argillitization also have a magnetic susceptibility of about 0.005–0.010 [Frolova *et al.*, 2019]. It should be noted that the Paratunka River valley contains a hydrothermal water deposit, and the observatory is heated by these waters.

Thus, our estimates of the magnetic susceptibility of the Quaternary sediments in the vicinity of the observatory are consistent with the results of magnetic susceptibility measurements at other sites in Kamchatka. The source of their strong magnetic properties is magnetic minerals from volcanic rocks. It should be noted that the separation of magnetic minerals in Quaternary sediments can lead to a stronger manifestation of their magnetic properties. For example, the black sands of the Halaktyrsky Beach marine sediments near Petropavlovsk-Kamchatskiy are considered as promising source of iron and titanium [State ..., 2000].

4. Magnetic field of dIdD pedestal at Paratunka observatory

The magnetometer dIdD is located in a separate unheated wooden pavilion — about 1 m wide and 2 m long. The pillar base is cast from lime-cement mixture, the pillar is made of glass blocks (Figure 6a). The dIdD pillar model differs from the pit model by introducing surface densities of fictitious charges on the pillar basement surface (Figure 6a): $\sigma_{Hb} = \chi_b H$, $\sigma_{Zb} = \chi_b Z$. The difference in the magnetic susceptibility of lime-cement mixture χ_b and soil χ was estimated based on the magnetic survey results carried out after constructing the base: $\Delta\chi = \chi_b - \chi = 0.01$. Figure 6b shows the calculation results at the magnetometer installation height (0.4 m). It can be seen that the maximum of the anomalous total field ΔF distribution (31.4 nT) is shifted to the southern edge of the pillar and ΔF changes within it by 22.8 nT. The magnetic northern and eastern components change within the pillar by 23.5 and 24.0 nT, respectively. Magnetic field gradient is up to 82.5 nT/m above the pillar center.

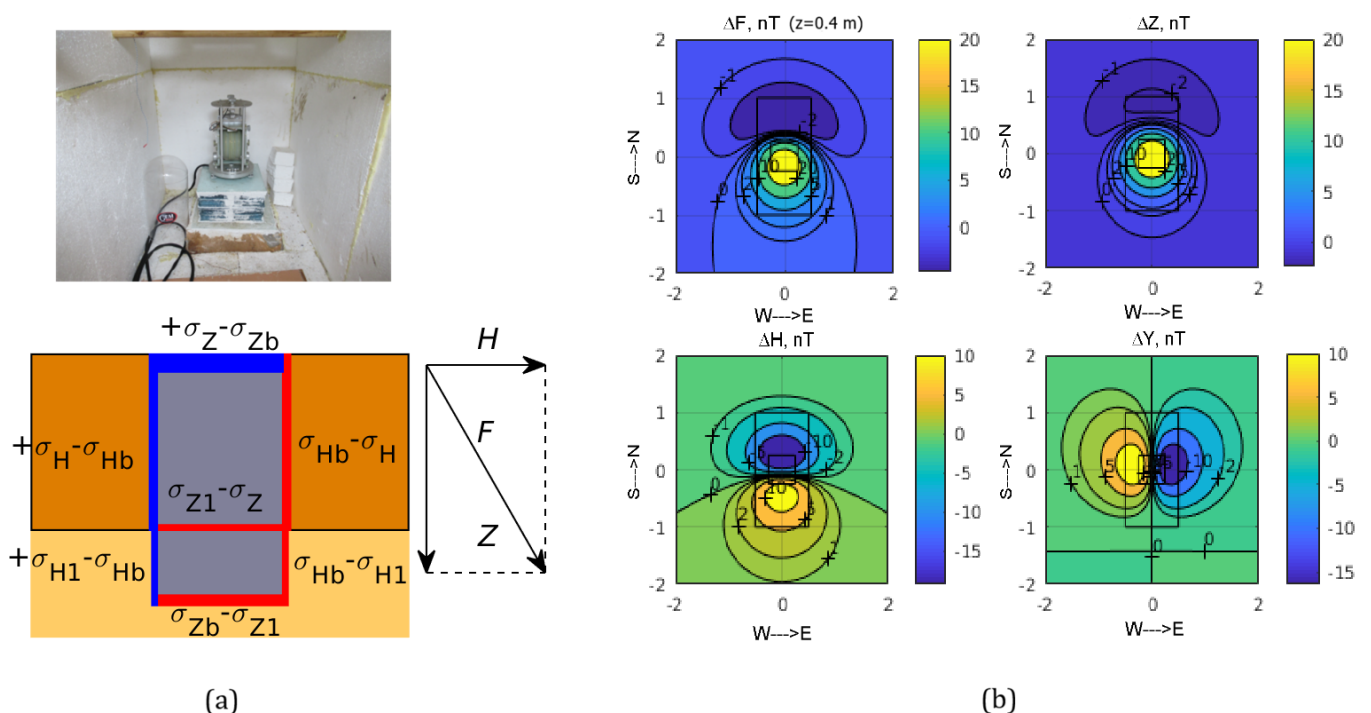


Figure 6. dIdD pavilion magnetic field model: the scheme of fictitious charge distribution (a), the field distribution at the height of 0.4 m in the dIdD pavilion taking into account the pillar and soil magnetization: $\chi = -0.0062$, $\chi_1 = -0.0087$, $\Delta\chi = 0.01$ (b). The rectangles show the boundaries of the pillar and the pavilion. Isolines correspond to levels of 0, ± 1 , ± 2 , ± 5 , ± 10 , ± 20 nT.

The anomaly field component values at this point are presented in Table 2. The anomalous total field at this point can be described by formula

$$\Delta F = \frac{H}{F} \Delta H + \frac{Z}{F} \Delta Z$$

therefore the vertical component anomaly ΔZ exceeds the total field anomaly ΔF .

The presence of an anomalous field leads to a systematic error in determining the magnetic inclination

$$\Delta I = \cos^2 I \cdot \frac{Z \Delta H - H \Delta Z}{H^2} = -1.33 \text{ arcmin}$$

In addition, the field inhomogeneity causes the field to vary at different points within the sensor volume. The model allows calculation of the magnetic field at all points inside the volume of the Overhauser dIdD magnetometer sensor (a 7.5 cm radius sphere [Hegymegi *et al.*, 2004]). The standard deviations of this field components are shown in the Table 2 as the error of the field components. However, the field gradient can only affect the accuracy of the total field intensity measure, as the D-I components are measured in artificially created fields with a gradient of about 1000 nT/m. It is shown in [Hegymegi *et al.*, 2004] that in a region with a diameter of 10 cm inside dIdD coil system, the field inhomogeneity does not exceed 5% of 2000 nT.

Table 2. Anomaly components values above the pillar center and components standard deviation inside the sensor volume for two heights

z, m	$\Delta H, nT$	$\Delta Z, nT$	$\Delta Y, nT$	$\Delta F, nT$	$\text{grad } F, nT/m$
0.4	-7.4 ± 2.6	32.6 ± 4.5	0 ± 2.4	26.6 ± 4.6	82.5
1.2	-0.7 ± 0.1	3.1 ± 0.2	0 ± 0.1	2.5 ± 0.2	3.8

The similar calculation results for height of 1.2 m are presented in Table 2. It can be seen that anomaly field amplitude is smaller to one magnitude order here. Accordingly, component accuracies are about 0.1–0.2 nT. The magnetic inclination systematical error at this height is $\Delta I = -0.13$ arcmin.

However, since the dIdD magnetometer is used as a variometer that is controlled by absolute observations, the constant deviation from the “true field” is not so important. What is important is how stable this deviation is over time and/or how accurately it can be tracked by the baseline values. The presented model can be used to analyze small seasonal variation of these baseline levels.

5. POS-4 pedestal magnetic field at Paratunka observatory

The POS-4 magnetometer is also located in a separate unheated wooden pavilion about 2×2.5 meters in size. The underground base of the pillar is cast from lime-cement mixture, the pillar is 1 m high and made of glass blocks. However, in the winter months, the pillar is tilted strongly due to the soil freezing. To avoid these tilts, a 90 cm wide pit was made around the base, and a lime-cement mixture slab was constructed at its bottom. The magnetic field model of the POS-4 pillar is formed from 4 parallelepipeds. Two of them describe the upper and lower soil layers in the pit, and the remaining two describe the lime-cement mixture slab and the pillar base. Figure 7a shows surface densities of fictitious charges on these parallelepipeds surfaces and calculation results. The model field is relatively uniform. There is no more than 0.5 nT field difference at the magnetometer installation height at the pavilion area (Figure 7b). The total field, horizontal and vertical components change within the pillar at this height by 0.09, 0.11 and 0.05 nT, respectively.

The reason for the field uniformity is the compensation of pedestal elements field and that of the pit. A Table 3 shows surface fictitious charges of pedestal construction elements caused by the vertical magnetization $\sigma_{Zb} S = \chi_b Z S$ and by the horizontal magnetization

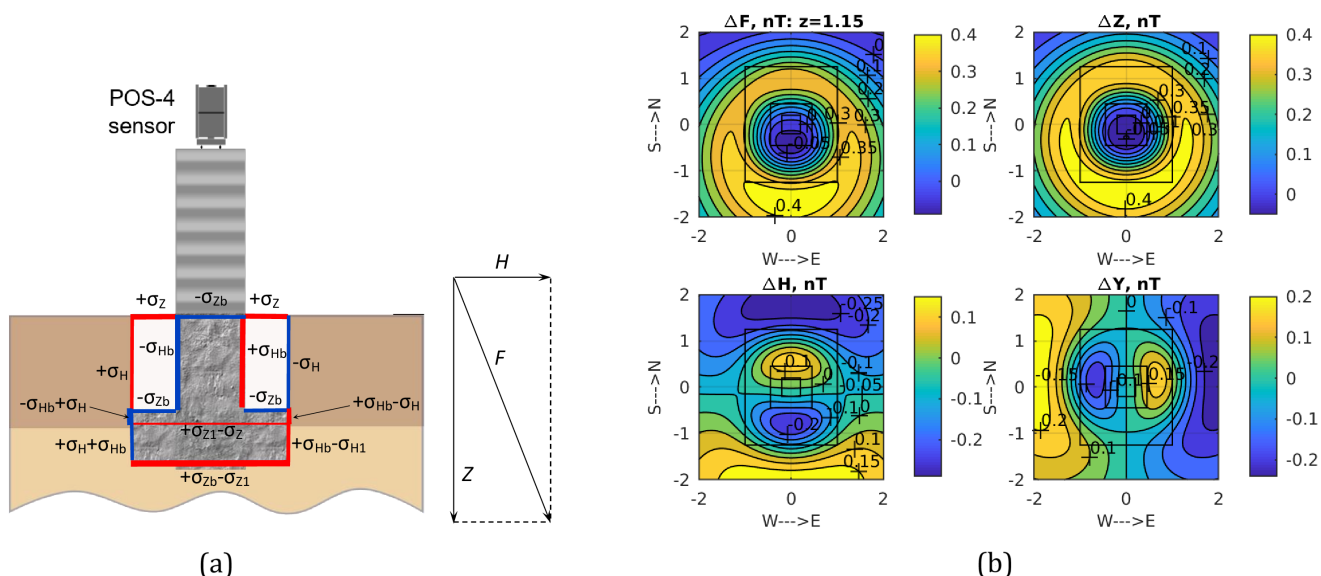


Figure 7. POS-4 pavilion magnetic field model: the scheme of fictitious charge distribution (a), the results of the field distribution calculation at a height of 1.15 m in POS-4 pavilion (b). The rectangles show the position of the pillar, pit and pavilion boundaries.

$\sigma_{Hb}S = \chi_b HS$ and the same characteristics for the pit: $\sigma_z S = \chi ZS$, $\sigma_H S = \chi HS$. Also there are their magnetic moments P_m (to within a constant) $\mu_0 P_{mZb} = \sigma_{Zb} V$, $\mu_0 P_{mHb} = \sigma_{Hb} V$ for pedestal elements, $\mu_0 P_{mZ} = \sigma_Z V$, $\mu_0 P_{mH} = \sigma_H V$ for the pit. Here S and V are the surface area and the element (or the pit) volume, $\mu_0 = 4\pi \cdot 10^{-7} \text{H/m}$ is the magnetic constant. Mutual compensation of the pit magnetic moment and that of the slab leads to the model field relative uniformity.

Table 3. Surface fictitious charges and magnetic moments of pedestal construction elements

Pedestal element	Element sizes, m	Magnetic susceptibility χ	Surface fictitious charge σS , nT · m ² H/Z	Magnetic moment σV , nT · m ³ H/Z
slab	$0.9 \times 0.9 \times 0.4$	0.017	133/654	119/262
pillar base	$0.4 \times 0.4 \times 0.6$	0.017	88/129	35/78
pit	$0.9 \times 0.9 \times 1$	-0.007	-136/-269	-123/-269

6. Conclusions

Based on the analytical model of the magnetized parallelepiped magnetic field, a model of the pillar magnetic field at the Kurchatov magnetic station was created. The comparison of the model with measurements in the variational pavilion allows us to determine the lime-cement mixture magnetic susceptibility of the pillar ($\chi = 0.002$).

The change in the field distribution before and after digging a model pit at Paratunka observatory was studied. It was shown that the field change is consistent with the model of the two-layer soil magnetic properties distribution with a magnetic susceptibility of 0.0066 for the upper layer with a thickness of 70 cm and 0.0087 for the lower layer. The obtained values are in the order of magnitude consistent with the results of the magnetic susceptibility measurements of the Quaternary sediments in other places of Kamchatka. Their relatively high magnetic susceptibility is caused by the impurities of magnetic minerals of volcanic origin.

The magnetic field distribution models at the dIdD and POS-4 pavilions of Paratunka geophysical observatory have been created. It shows that the anomalous field amplitude at the dIdD pavilion can reach 30 nT at the magnetometer installation height (40 cm). Magnetic field gradient is 82.5 nT/m above the dIdD pillar center. Compensation of the

magnetic moments of the pit and the base plate in the POS-4 pavilion leads to the model field relative uniformity, which is – no more than 0.5 nT at the magnetometer installation height (1.15 m) at the pavilion area. The total field, horizontal and vertical components change within the pillar at this height by 0.09, 0.11 and 0.05 nT, respectively.

Thus, it is shown that due to natural conditions or an unsuccessful selection of pedestal materials, magnetic anomalies with an amplitude of up to 10–30 nT can be observed in the vicinity.

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