Magnetic Anomaly Fields Determined from Gradient Measurements at Stratospheric Altitudes and from Magsat Satellite Data

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The magnetic anomaly fields (MAF) obtained from the data of gradient magnetic measurements at stratospheric altitudes along transcontinental routes, passing over the Russian territory, and from the Magsat satellite data are investigated. The stratospheric gradient measurements are shown to be more suitable for separating and interpreting regional magnetic anomalies of crustal sources as compared to the data obtained at aircraft and satellite altitudes. It is also shown that, at stratospheric altitudes, one should use the device for magnetic field measurements that contains three sensors spread uniformly along the vertical line within four kilometers. This allows us to obtain the rate of MAF change in the stratospheric layer, which makes it possible to study in more detail the geometry of sources and to estimate with high precision (about 1 km) the locations of positive and negative zones of the first (and second) vertical derivatives of MAF. In general, the stratospheric gradient surveys successfully supplement satellite ones.

1. Introduction

Balloon surveys of the Earth’s magnetic field are a new approach (Belkin and Tsvetkov, 1975; Cohen et al., 1986). Gradient surveys are preferable to conventional magnetic surveys, according to the results obtained by Hood and Teskey (1989), Harrison and Southam (1991), and others. The early results of stratospheric gradient surveys are shown in Tsvetkov (1993) and the recent results of balloon’s experiment are shown in Tsvetkov and Belkin (1995). In the experiment, three magnetometers were placed apart from each other along the vertical line.

The data of magnetic surveys at stratospheric altitudes along with satellite measurements are important in understanding the regularities inherent in the magnetic anomaly field (MAF) of the Earth and provide very valuable information on regional magnetic anomalies.

In order to separate the regional and long-wavelength MAF components, one usually uses surface magnetic survey data and satellite survey data. The use of the former survey data meets serious difficulties in separating crustal anomalies into the local and the regional components. In spite of some mathematic developments directed toward separating regional MAF component from the original data, the problem has not been solved yet. The satellite measurements also meet some problems which are difficult to solve. These problems are related to appropriate separation of the fields from various sources, such as the main field, the ionospheric and magnetospheric fields, and the induced field. One can hardly manage to separate the crustal field, having values of 0 to 30 nT at satellite altitudes, against the above-mentioned background (Alldredge, 1982; Arkani-Hamed et al., 1994).

The most efficient means of studying the regional magnetic anomalies are gradient magnetic surveys at stratospheric altitudes (from 30 to 40 km), where the filtration of a regional MAF component is performed in a natural manner, due to the long distance from the sources, and the gradient data are less contaminated by noises. At these altitudes, the distance to the upper and the lower edges of the sources in the lithosphere differs only as little as twice. As a result, the
influence of near-surface and deep sources is nearly balanced, and one can observe the smoothed MAF from the sources situated at depth. This MAF is presented by anomalies beginning from regional ones with transversal dimensions of about 30 km and more, up to the longest-wavelength anomalies. On the other hand, the distance of measuring devices from the sources, which is comparable with the thickness of magnetic layer, allows us to use the data of these surveys for deciphering the position of sources along the vertical line throughout the layer.

Thus firstly, magnetic measurements at stratospheric altitudes successfully supplement aeromagnetic and satellite magnetic surveys and allow us to consider the MAF as a unified phenomenon in the upper half-space. Secondary, they help us to define more precisely the MAF nature at satellite altitudes, as pointed out by Cohen and Achache (1994).

Magnetic measurements using stratospheric balloons have been carried out in a number of countries, such as France, Japan and China. One should specially mention the balloon-borne measurement made by French researchers over a long route, extending from South Africa to Australia, within the framework of the French program of balloon magnetic surveys (Achache et al., 1991), and also the flight according to the Japanese program (Tohyama et al., 1992).

The results of gradient magnetic surveys at stratospheric altitudes and magnetic measurement data obtained by the Magsat satellite are processed and analyzed in this paper. The results of processing of these data are then subject to geophysical interpretation of the regional component of magnetic anomaly fields.

2. Processing of Balloon Measurement Data and Magsat Satellite Data

2.1 Gradient magnetic surveys at stratospheric altitudes

Three transcontinental balloon flights have been performed over the Russian territory within the belt confined by $\phi_1 = 55^\circ$N and $\phi_2 = 59^\circ$N at the altitude $H = 30 \pm 3$ km and along the routes extending up to 4–8 thousand kilometers (Tsvetkov, 1993). Each balloon carried two proton magnetometers whose sensors were placed 2.5 km apart from each other along the vertical line. At the flight velocity of 40 to 60 km/hr, measurements were made every minutes. Both sensors measured the magnetic field simultaneously and as a result synchronous field differences were assumed to be the vertical magnetic field gradient. Note that the measurement baseline (the distance between the magnetic field sensors) was about one twentieth of the distance to sources. However, such measurements represent an averaged value of magnetic field's vertical gradient on the 2.5 km baseline.

The results of observations of the scalar magnetic field ($F_{30}$) and its vertical gradient ($\nabla F_{30}$) at the 30 km altitude over one of the balloon flight routes are shown in Fig. 1a, where the route of this flight is given on the topographic map. Figure 1b presents, in a larger scale, the vertical gradient $\nabla F$ (curve 1). These data were obtained during one of latest flights at the 28 km altitude over the path that originated at the point with coordinates $\phi_1 = 52^\circ$N, $\lambda_1 = 47.5^\circ$E and terminated at the point with $\phi_2 = 52.5^\circ$N, $\lambda_2 = 52^\circ$E. The same figure (curve 2) also shows the vertical gradient of the field obtained from the IGRF model.

The experiment was updated in 1994 by applying three magnetic field sensors uniformly spread along the vertical line within the distance of 4 km (Tsvetkov and Belkin, 1995). This experiment allows us to obtain the gradient and its variation in the stratospheric layer. These data, in turn, allow us to determine the characteristics of field decrease with altitude and the gradient values for any altitudes.

The experiment was carried out in October 13, 1994, from the point with coordinates $\phi = 52^\circ$N, $\lambda = 47.5^\circ$E. The scheme of balloon's suspension system with a magnetometric complex on it is shown in Fig. 2. Figure 2a demonstrates the scheme prior to the magnetometric equipment deployment process, and Fig. 2b shows the separation of balloon's suspension system from the descending part of the magnetometric complex at the final stage of flight. At the operation
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Fig. 1. a) Geomagnetic field $F_{30}$ and vertical gradient $\nabla F_{30}$ were measured at the 30 km altitude along the flight route shown by the dotted line on the topographic map. b) Vertical gradient $\nabla F_{28}$ at the 28 km altitude: 1—measured; 2—obtained from the IGRF model.

stage of flight the descending part of the complex, shown in Fig. 2b, is fastened at point M on the balloon’s suspension system by means of pyrotechnic bolt 14. Parachute 15 is placed in the chamber at this time.

The device deployment process begins when the 2-km altitude is reached. At this time pyrotechnic bolt 14 operates by a command from the barometric pressure relay. The container 3 with the first magnetometer and sensor 2 is released from fastening on truss 1, begins to fall down freely, and draws the deceleration parachute 5 out of the chamber. Then the puller is released from the puller storage unit 6 under the action of weight of a container descended with a parachute. When the puller is fully released from the puller storage unit, container 3 with sensor
Fig. 2. Scheme of the balloon's suspension system with a magnetometric complex (MC): a—prior to the magnetometric equipment deployment process, b—separation of the balloon suspension system from the descending part of an MC at the final stage of flight. At the operation stage of flight the descending part of an MC is fastened at point M on the balloon's suspension system by means of pyrotechnic bolt 14.

2 hovers on a pyrotechnic bolt's anchor. At the altitude of 4 km the pyrotechnic bolt 9 operates, and the deployment process resumes and finally terminates when the puller is fully released from the puller storage unit 11. At this time magnetic field sensors 2 and 7 occupy positions 2 and 4 km below the main suspension system of the balloon. The third magnetometer with sensor 12 remains on the main balloon's suspension system. When the flight terminates during landing, the pyrotechnic bolt 14 operates at the altitude of about 5 km, and the descending part of magnetometric complex is separated from the main balloon's suspension system and landed with
rescue parachute 15.

There exist some systems which accomplish the descending of heavy containers with equipment (of mass up to 62 kg) from balloon’s “basket” down to the distance up to 12 km (Hazan and Anderson, 1984). The classic version of such a system is based on the use of windlasses, electric motors and powerful electric energy sources. An important advantage of known systems is the possibility of lifting the container with equipment back into the balloon “basket”. However, the problem of descending a load consisting of two components, each of which includes the “container-sensor” bunch, down to the earth has not been apparently solved. The main difficulty is descending and lifting of an intermediate “container-sensor” bunch. The experiment which we have carried out does not require lifting of containers with equipment back into the balloon “basket”. This allowed us to perform the experiment with the proposed version of equipment deployment technique in which, during the balloon landing, the main suspension system and the descending part of the complex were lowered down with their own parachutes.

2.2 Magnetic anomaly separation method, errors and magnetic profiles

To separate magnetic anomalies in data processing, we subtracted from the measured magnetic field the normal field, represented (except the case shown below) by the IGRF model and corrected for a secular variation. The residual field was assumed to represent the magnetic anomaly field. A similar technique was also applied to the separation of the vertical gradient of the magnetic field.

The errors of magnetic measurements on balloons were considered in Tsvetkov (1993), where the root-mean-square (RMS) error in the measurement of vertical gradient was estimated to be 0.3 nT/km. The main contribution to the gradient measurement error is that the magnetic field sensors are mounted directly on the balloon’s suspension system, that undergoes mechanical vibrations due to the action of environment disturbances. The measurement noise, which arises in this way, may be 3 to 6 times higher than the remaining components of gradient measurement error. It is not possible to estimate this noise very accurately and therefore the gradient measurement error was assumed to be equal to the RMS deviation of measured values from average ones for the weakest anomaly segment of a profile (at the 30 km altitude) over the Eastern and Central parts of the Sea of Okhotsk, for which $\sigma(\Delta F)_{a30} \approx 0.3$ nT/km.

Since the system for gradient magnetic measurements on board a balloon has been exploited in the middle of eighties, the balloon position was determined by direction-finding methods, and the flight altitude was measured by aneroid altimeters. In measuring magnetic anomalies and their vertical gradients with the same error level, the accuracy of balloon position determination for the gradient field is allowed to be as much as 30 times worse than in MAF separation (Tsvetkov, 1993). This is due to different relations between the normal and anomalous field values and the gradient values. At the current stage we can guarantee high (not worse than 0.3 nT/km) accuracy for separating the vertical MAF gradient only.

The vertical MAF gradient is little distorted by the variable magnetic field effect. It represents the information within some altitude range rather than over the surface of equal altitudes as usually adopted in a conventional magnetic survey. Therefore, in the investigation of magnetic anomalies at the stratospheric altitudes, the gradient method is recommended.

The statistical analysis of magnetic profile data was performed to estimate the RMS values of MAF. Over the route passing along $\phi = 55^\circ$N from Kamchatka to the Ural, which is about 150 km south of the route presented in Fig. 1a, the RMS value of vertical magnetic anomaly gradient was equal to $\sigma \nabla (\Delta F)_{a30} = 2.2$ nT/km, whereas for MAF $\sigma(\Delta F)_{a30} = 45$ nT. For the same profile, we calculated the RMS gradient values over the segment 600 km long. The obtained $\sigma \nabla (\Delta F)_{a30}$ values are given in Fig. 3a. The minimum value of this parameter was 0.3 nT/km; it falls on the Eastern and Central parts of the Sea of Okhotsk. This part of the profile in Fig. 3a is marked by symbol “*” and presented in Fig. 3b in current coordinates of $\nabla (\Delta)_{a30}$ gradient.
Fig. 3. Measured parameters as follows: a—mean square gradient values at the 30 km altitude over the segment 600 km long, where the minimum gradient value zone is marked by symbol "*"; b—current gradient values marked by symbol "*"; c—gradient values at the 30 km altitude given for one of high-anomaly segments of the path that intersects the Aldan shield along $\phi = 58.5^\circ$N.

Figure 3c gives the $\nabla (\Delta F)_{a30}$ values for one of the high-anomaly segments of the field path, that intersects the Aldan shield along $\phi = 58.5^\circ$N. The current data in Figs. 3b, 3c are presented in the form of averaged values taken from the results of 5 geomagnetic field measurements.

The best experimental information for studies of magnetic anomalies from the space is the Magsat satellite data. We processed the satellite data using the technique outlined in Oraevsky et
al. (1993). In order to separate magnetic anomalies and to compare them with the gradient data obtained at stratospheric altitudes, we selected the satellite data corresponding to the balloon flight route extending from Kamchatka to the Ural along $\phi = 55^\circ$N. Furthermore, the data series was subjected to filtering with about 16 points to exclude diurnal variations. Then only the passes, for which the geomagnetic activity index $K_p \leq 2$, were selected from the filtered series. Figure 4 shows the MAF values obtained over the balloon flight route passing between $\lambda_1 = 81^\circ$E and $\lambda_2 = 122^\circ$E meridians: Figure 4a gives the MAF values ($\Delta F_{a350}$) (taken from the Magsat satellite data obtained at the 350 km altitude). Figure 4b represents the MAF values ($\Delta F_{a30}$) at the 30 km altitude. Figure 4c shows the values of the vertical gradient of magnetic anomalies $\nabla (\Delta F)_{a30}$ at the 30 km altitude. (b and c represent the balloon flight data).

One can notice rather well the coincidence of anomalies at satellite and stratospheric altitudes, though some distinctions still exist. This is associated with the fact that the anomalous field at a measurement point is the superposition of fields from sources which are situated mainly in a spherical segment whose size depends on the survey altitude. At satellite altitude, the anomalies at the measurement point are formed from wider sources, than those for 30 to 40 km altitudes.

The comparison of magnetic data of some different altitudes is given in Fig. 5. This figure shows the ($\Delta F_{a25}$) values over the route that cuts the Kursk magnetic anomaly (KMA) at the 25 km altitude along $\phi = 52^\circ$N (curve 1). The figure also gives the ($\Delta F_{a9}$) values (curve 2), obtained from the results of aeromagnetic survey along $\phi = 51.5^\circ$N at the 9 km altitude, taken from the paper by Lugovenko and Matusckin (1975) and also the ($\Delta F_{a350}$) values (curve 3), obtained by Taylor and Frawley (1987) from the Magsat satellite data.
3. Results

3.1 Spectral analysis

The MAF amplitude spectra were obtained from the data of magnetic measurements in the stratosphere by using the Fourier discrete transformation method (Tsvetkov, 1993). The comparison of MAF spectra with the spectra of the vertical gradient of magnetic anomalies at the 30 km altitude shows that the amplitude characteristics are rather close in shape to each other. However, the gradient spectrum width is about 1.4 times greater than the anomalous field spectrum width, due to high-frequency domain. The significant harmonics of the vertical MAF gradient spectrum have minimum periods of about 50 km, as illustrated in Fig. 6, which shows the MAF gradient spectrum $(\Delta F)_{\alpha,30}$ and the gradient spectrum $\nabla (\Delta F)_{\alpha,30}$ for $H = 30$ km, obtained from the data measured on the continental part of a route ($\phi = 55^\circ$N, $\lambda = 75^\circ$E–138$^\circ$E). In the domain of harmonics with 1000 to 3300 km periods, the gradient spectrum is much more stable than the anomalous field spectrum. This is explained by a more reliable separation of field gradients into anomalous and normal parts. Due to small length of the selected part of the profile (about 4000 km), the harmonics with the wavelength of 2000 to 3300 km are not shown here.

In the gradient spectrum of the continental part of the route, the harmonics with periods of 200 to 240 km are most prominent. The harmonics with periods of 100 to 120 km are less prominent. These harmonics may be explained by a regmatic net, which divides the Earth’s crust by means of faults into separate blocks (Moody and Hill, 1956). Certain blocks with a typical size of about 60 km are weakly reflected in the magnetic anomaly field spectrum at the 30 km altitude. However, there also exists a larger structure, which is reflected in MAF in the
form of harmonics with 200–240 km periods. These harmonics exist in the spectrum everywhere with high intensity and characterize the basic continental crust structure. Larger lithosphere structures are reflected supposedly in lower-frequency harmonics of the spectrum. These may be deduced from the following consideration. The anomalous and weak-anomalous segments, which are often found over the flight route, have extensions of the order of 300 to 600 km. Two typical segments of this type, corresponding to the Okhotsk Sea plate and the Aldan shield, are given in Figs. 3b, 3c. The alternation of disturbed and undisturbed segments, associated with features of the tectonic structure of the region, is seen in Fig. 4 as well. Therefore, the gradient harmonics having wavelengths of 550 to 1000 km, which are shown in Fig. 6, have apparently lithospheric origin and are associated with tectonic structure of the region. Probably, the harmonics having wavelength of 1000 to 3300 km also have lithospheric origin and are associated with large tectonic structures such as the West-Siberian plate, the East-Siberian platform, the Mongol-Okhotsk folded belt (Tsvetkov, 1993).

3.2 Characteristics of anomalies decreasing with altitude

One important problem in the magnetic anomaly investigation is the determination of the rate of intensity change with altitude.

The observed MAF values, obtained at various altitudes for KMA, are presented in Fig. 5. Since the balloon flight route actually intersected the satellite anomaly maximum, the decreasing rate was considered for the satellite KMA center, where the value of anomalies was 36 nT. To determine the anomaly decrement with altitudes we used the formula:

$$Y(h) = K \frac{1}{h^n}$$  \hspace{1cm} (1)

where $K$ is the proportionality factor determined from the initial conditions, $h$ is the distance to the source, and $n$ is the magnetic anomaly decrement factor.
The KMA source is known to have the form of a stratum, whose upper boundary coincides with the Earth's surface and the lower one reaches the depth of 10 km. Therefore, we took the depth to the source center as 5 km. The KMA value on the Earth's surface along the balloon flight path within the segment under consideration, estimated from the magnetic map, varied from 500 to 10000 nT. Using formula (1) for near-earth and stratospheric altitudes, we obtained $n = 1$. For $n = 1$ the maximum anomaly values were found to be 8400 nT for $h = 5$ km (on the Earth's surface, 3000 nT for $h = 14$ km, and 1400 nT for $h = 30$ km). These values are close to the measured ones, and the latter value was used in determining factor $K$ in expression (1). The value of satellite anomaly does not correspond to the case for $n = 1$. This should be expected, since the source zone on the satellite KMA and the shape of the source which is situated in this zone, will differ from the zone and the shape for stratospheric altitudes. In the first approximation, one may assume that the decrement factor varies with increasing altitude according to the linear law. Then the approximating function will be as follows:

$$Y(h) = K \frac{1}{h^{n+mh}}$$

(2)

where $m$ is the coefficient that takes into account the linear increase of the factor with growing $h$. For the satellite KMA having a value of 36 nT, $m = 0.0006$, and for $h \cong 400$ km, $n = 1.24$.

So, the shape of a source influences the anomaly decrement factor; hence, parameter "$n" may be used for determining geometry characteristics of a source. This parameter may be obtained for each large-scale anomaly from the magnetic survey data at stratospheric and satellite altitudes. The initial anomaly decrement factor may be rather accurately determined, if one uses the magnetic field data for three stratospheric altitudes. These data can be obtained using three magnetometers spread along the vertical line. In this case, searching for a law of type (2) is essentially simplified, and the results may be more accurate. According to the data of the experiment, in which three magnetic field sensors were used in the measurement system, the positive anomaly was separated in the gradient data, as shown in Fig. 1b. In the magnetic field data, the anomaly was separated with the use of the normal field model MGST 3/80. Its value is $(\Delta F)_{a28} = 180$ nT. The magnetic source depth was determined as about 17 km. The magnetic anomaly decrement factor was calculated by formula (1) and found to be $n = 1.3$ for the altitude of 28 km ($h = 45$ km) (Tsvetkov et al., 1996). Furthermore, by comparing the experimental dependence $Y(h) = Kh^{-1.3}$ with theoretical ones, calculated for magnetic bodies of various shapes, we came to the conclusion that the shape of an anomaly-forming body under consideration is most close to a vertically extended body. Using the data obtained above, the possibility arises, as was shown in the examples, to develop a new technique of studying magnetic anomalies and their sources.

4. Conclusions

1. The balloon gradient surveys represent a new type of geomagnetic measurements, whose results successfully supplement the satellite and aeromagnetic survey data and allow us to jointly consider the magnetic anomaly field on the earth and in near-earth space. The gradient data interpretation demonstrated the importance of stratospheric gradient magnetic measurements for solving fundamental problems related to crustal magnetic anomalies.

2. The magnetic anomaly spectrum harmonics in the wavelength range of 200 to 3300 km, obtained from the data of gradient measurements in the stratosphere, reflect the tectonic structure of the lithosphere.

3. To obtain the law of magnetic anomaly intensity decrease in the stratospheric layer, it is sufficient to have a measurement system containing three magnetic field sensors uniformly spread along the vertical line within 4 km.
4. Using the data obtained in the stratosphere layer, one can evaluate, with high accuracy (about 1 km), the position of zones of positive and negative values of the first (and second) vertical derivatives of the magnetic anomaly field.

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REFERENCES

Achache, J., Y. Cohen, and G. Unal, The French program of circumterrestrial magnetic surveys using stratospheric balloons, EOS, Trans. Amer. Geophys. Union, 72, 97–101, 1991.

Alldredge, L. R., Long wavelength components in high degree spherical harmonics, J. Geomag. Geoelectr., 34, 547–550, 1982.

Arkani-Hamed, J., R. A. Langel, and M. Purucker, Scalar magnetic anomaly maps of Earth derived from POGO and Magsat data, J. Geophys. Res., 99, 24075–24090, 1994.

Belkin, V. A. and Yu. P. Tsvetkov, Absolute geomagnetic field measurements at 20 to 40 km altitudes, in The Analysis of Space-Time Geomagnetic Field Structure, pp. 224–235, Nauka, Moscow, 1975.

Cohen, Y. and J. Achache, Contribution of induced and remanent magnetization to long-wavelength oceanic magnetic anomalies, J. Geophys. Res., 99, 2943–2954, 1994.

Cohen, Y., M. Menvielle, and J. L. Le Mouel, Magnetic measurements aboard a stratospheric balloon, Phys. Earth Planet. Inter., 44, 348–354, 1986.

Harrison, C. G. A. and J. R. Southam, Magnetic field gradients and their uses in the study of the Earth’s magnetic field, J. Geomag. Geoelectr., 43, 585–599, 1991.

Hazen, N. and J. Anderson, Reel down: A balloon-borne winch system for stratospheric sounding from above, AIEE 84-0027, American Institute of Aeronautics and Astronautics, New York, 9 p., 1984.

Hood, P. J. and D. J. Teskey, Aeromagnetic gradiometer program of the Geological Survey of Canada, J. Geophys., 54, 1012–1022, 1989.

Lugovenko, V. N. and B. A. Matushkin, About dimensions of block's structures of the Earth's crust continents, in Proceedings of the U.S.S.R. Academy of Sciences, Geological Series, 9, 139–142, 1975.

Moody, J. D. and M. L. Hill, Wrench-fault tectonics, Bull. Geol. Soc. Amer., 67, 1207–1246, 1956.

Oraevsky, V. N., N. M. Rotanova, A. L. Kharitonov, and O. D. Pugacheva, Anomalous magnetic field over Russian-Indian region determined from the Magsat satellite data, Geomagn. Aeron., 33, 132–141, 1993.

Taylor, P. T. and J. J. Frawley, Magsat anomaly data over the Kursk region, U.S.S.R., Phys. Earth Planet. Inter., 45, 255–265, 1987.

Tohyama, F., Y. Tonegawa, T. Takahashi et al., Observation of the geomagnetic field by polar patrol balloon (PPB), Journ. Solar Terrestrial Environmental Research in Japan, No. 16, 60, 1992.

Tsvetkov, Yu. P., Study of the anomalous magnetic field of the Earth at stratospheric altitude, Geomagn. Aeron., 33, 159–163, 1993.

Tsvetkov, Yu. P. and V. A. Belkin, Magnetic measurements in the stratospheric layer, Doklady of Russian Academy of Sciences, 345, 397–400, 1995.

Tsvetkov, Yu. P., N. M. Rotanova, V. N. Oraevsky, and S. A. Serkerov, Interpretation of the magnetic anomaly field in the results of stratospheric balloon experiment data in 1994, Geomagn. Aeron., 36, 183–187, 1996.