COMPLEX SATELLITE (“SWARM”) AND STRATOSPHERIC BALLOONS GEOMAGNETIC RESEARCHES

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1. INTRODUCTION

It is offered to complete the project “Swarm” by gradient magnetic surveys at the lengthy measuring base onboard stratospheric balloons. At altitudes over 20 km there are zonal air flows together with which a stratospheric balloon can make round-the-world flights. An advantage of the method of gradient surveys consists in the fact that such method allows to localize the sources creating significant values of gradients of the geomagnetic field, in a volume of the sphere having a radius of about a tenfold size of the measuring base of the gradiometer.

Located onboard the stratospheric balloon the magnetic gradiometer, having a measuring base length of 6 km, confidently feels signals from the sources removed up to 60 km from a point of observation. Thus, in gradients magnetic signals of the removed sources are excluded. By stratospheric balloon flights at altitudes of 30-40 km, using a property of gradients, the gradient magnetic surveys with help of lengthy base enable reliably to extract in gradients the crustal magnetic field down to the most low-frequency components without use of magnetic variation stations. Hence, the data obtained in the stratospheric balloon gradient magnetic surveys bear in gradients the information only about crustal magnetic anomalies. It is important for understanding the nature of the separate magnetic components obtained aboard of " Swarm " satellites.

The extracted crustal field generated naturally can serve as a reliable database for deriving an analytical model of the magnetic field in the near Earth space. Magnetic anomalies up to altitudes of 30-40 km are formed as from 3D sources, and at altitudes above this level - as from 2D sources. Hence, for receiving an analytical model of the magnetic field in the near Earth space, the magnetic data recorded at the altitude level of about ~30 km are important.

For the realization of these problems the stratospheric balloon magnetic gradiometer is constructed and tested in the natural experiment and this equipment consists of three instrument containers suspended to a basket of a balloon one after another through 3 km (the general length of measuring base is equal 6 km).

Each of the three instrument containers holds a scalar magnetometer, the GPS-receiver, the system of data transmission by a radio channel in FTP a server of a network of the Internet.

In test flights the deviations of the measuring base of the gradiometer from a vertical line caused by the drift of the stratospheric balloon has been obtained and the technique of their evaluation has been elaborated.

Time simultaneous flights of balloons with magnetic gradiometer aboard and of the "Swarm" satellites will allow to obtain additional information for a better interpretation of magnetic data of the last, namely:

- to obtain the three-dimensional structure of magnetic anomalies in the altitude range of 20-50 km (extension of values of magnetic field in these limits is carried out by using vertical magnetic gradients) and by combining the results with the magnetic anomalies obtained from satellites and from the Earth´s surface in order to derive a model of the magnetic field in the upper half-space;
- to create a reliable map (model) of magnetic anomalies of polar areas of the Earth and to use it for control (validation) of a map of satellite magnetic anomalies of this region;
- to study processes of the formation of satellite and long-wavelength magnetic anomalies;
- to estimate the probability of additional errors of global analytical models of the main magnetic field of the Earth (IGRF) and to develop measures of their decreasing.

Thus, the stratospheric balloon is an ecologically pure object. At operation stratospheric balloon gradiometer are observed measures of full safety at all stages of a balloon flight - rise, horizontal flight, landing. This quality is reached because each container with the equipment is connected with the brake parachute.

There is an official sanction for flights of the Russian stratospheric balloons where magnetic gradiometers are installed, having a six kilometer measuring base.

2. STRUCTURE AND CONSTRUCTION OF THE GRADIOMETER

2.1. The scheme of the stratospheric balloon gradiometer is shown in Fig. 1. A gradiometer for magnetic measurements consists of three instrument containers, each of which includes a proton precession magnetometer, the GPS-receiver, the on-board computer of gathering and packing of the scientific information and the modem of the satellite radio communication «Global-Star».

With respect to the fact that, at the end of flights a landing of the stratospheric balloon with gradiometer in unfolding condition is quite admissible, the configuration of a system can be essentially simplified. In the offered construction the lifting rope loops keeps within the magazines of cellular type. Each instrument container for its descent downwards is supplied with the parachute (that also guarantees the safety of operation of gradiometer in case of breakage of a rope).

Instrument containers, everyone with a mass of 20-30 kg, in the flight are suspended to "basket" of the stratospheric balloon and at unfolding one behind another are separated from it, decreasing on parachutes, remaining consistently connected with the stratospheric balloon with an interval of 3 km by means of a lifting synthetic rope.

The course of the unfolding process for the gradiometer is obvious from Fig. 1 and its caption signatures. The beginning of unfolding of the first lifting rope occurs at the rise of the stratospheric balloon and is caused by short circuit of barorelay contacts, entering in the control system of unfolding and tuned for operation at achievement by the stratospheric balloon of 3 km altitude, and the beginning of the unfolding of the second lifting rope - from another barorelay, tuned at the altitude of 6 km. The barorelay develop a command for operation of pyrolocks 4 and 9 accordingly.

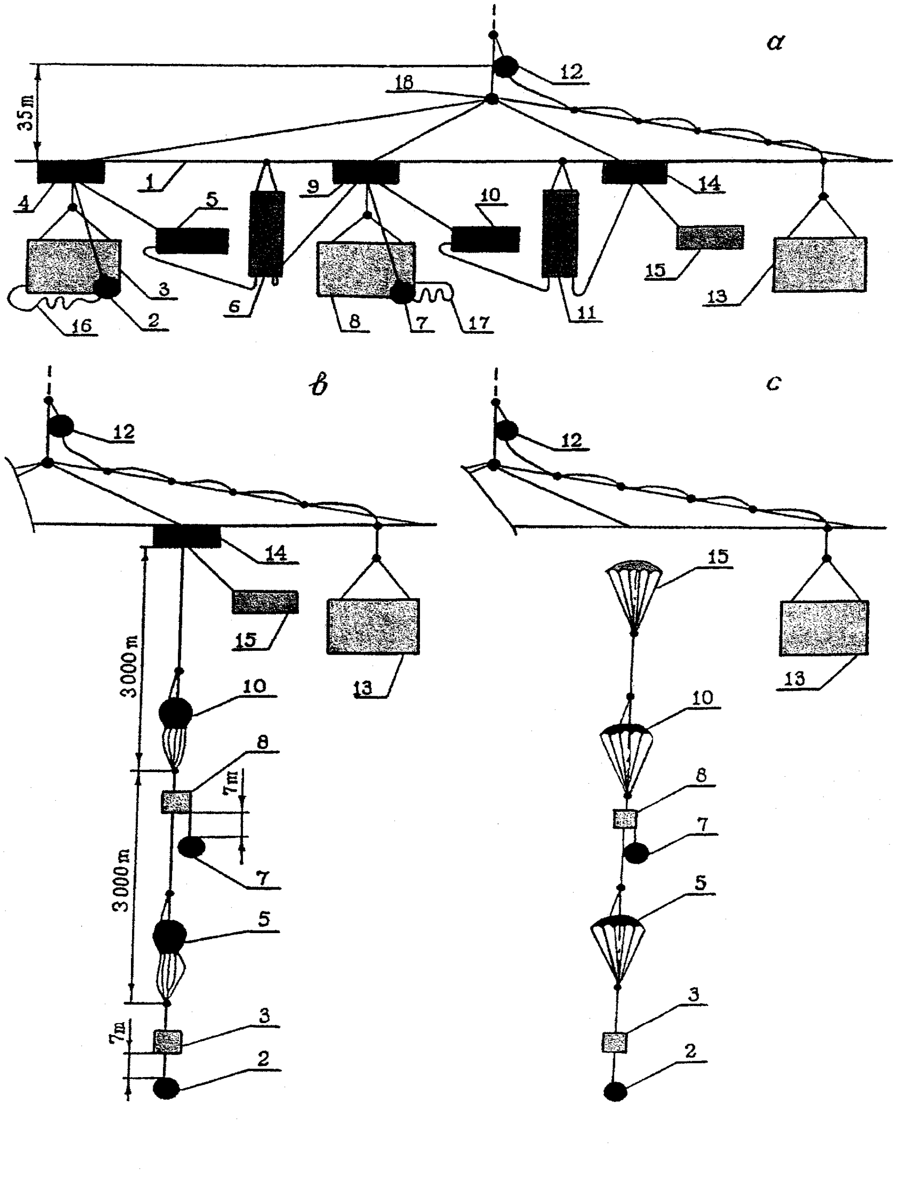


Fig. 1. Scheme of the magnetic gradiometer system in the starting (a), working (b) positions and at the final stage (c) of the flight.

Equipment: **1** - balloon suspension girder; **2, 7, 12** - magnetic field sensors; **3, 8, 13** – containers with magnetometers, GSP-receiver, modem and antenna "GlobalStar"; **4** – pyrolock, ensuring beginning of process of descent of container 3 and a magnetic field sensor 2; **5, 10** - bracke parachutes; **6, 11** – rope-magazines; **9** – pyrolock, ensuring beginning of process of descent of container 8 and magnetic field sensor 7; **14** – pyrolock, ensuring division of system at landing; **15** – saving parachute; **16, 17** – convolution with cable-rope to magnetic field sensors 2 and 7; **18** – starting lock.

2.2. The important requirement to such construction of gradiometer is maintenance of durability of a lifting rope at dynamic loadings, maximal at the end of the unfolding process. In calculations of the unfolding process of the system a movement of two parts of a lifting rope is considered at their consecutive going-out from magazines. It is considered, that a movement of the stratospheric balloon does not depend on dynamics of unfolding of the suspension system; in the horizontal direction the stratospheric balloon moves together with an air flow, and in vertical - with some known speed.

The problem is solved in the flat statement. Lifting ropes are approximated by the system of the discrete masses connected with each-other by weightless elastic elements. The initial moment of unfolding is shown in Fig. 2.

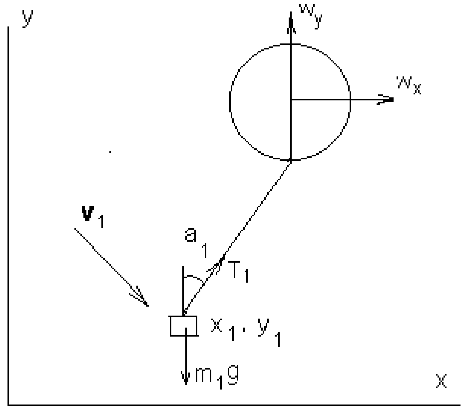


Fig. 2.

Here m_1 – mass of the lower container; w_x, w_y – horizontal and vertical speed of the stratospheric balloon; T_1 – a tension of a rope; α_1 – a corner of a rope with a vertical; $\mathbf{v}_1$ – a vector of relative speed of the wind, equal:

$$\mathbf{v}_1 = (w_{1x} - dx_1/dt)\,\mathbf{i} - dy_1/dt\,\mathbf{j}, \tag{1}$$

i, **j** – units of coordinates axes; x_1, y_1 – coordinates of the lower container; w_{1x} – speed of a wind at altitude of an arrangement of the container. The beginning of coordinates is located at ground level.

Tension T_1 up to a going-out of the second discrete mass is considered equal to effort T_0 of the draw of a rope from magazine; after a going-out of the second mass it is calculated by formula:

$$T_1 = C_{rop}\,(L_1 - L_0), \tag{2}$$

where L_1 - length of the deformed first element; L_0 – length of not deformed element of the rope, equal $L_0 = L_{rop/N}$; N - number of the discrete masses approximating a rope; C_{rop} - a rigidity of a rope at a stretching.

The equations of movement of the first (lower) container can be written down in the form of:

$$\begin{gathered} m_1\, d^2x/dt^2 = C_{XP}\, q_X\, S_P + T_1 \sin\alpha_1 \\ m_1\, d^2y/dt^2 = C_{YP}\, q_Y\, S_P + T_1 \cos\alpha_1 - m_1 g \end{gathered} \tag{3}$$

Here C_{XP}, C_{YP} – factors of resistance of the parachute, depending on size of relative speed of environment; S_P – the area of a parachute; q_X, q_Y projections of a high-speed pressure of a wind q, acting on the container with a parachute and equal:

$$q = \rho\, v_1^2/2 \tag{4}$$

ρ - density of an environment at altitude Y_1.

Considering (1) and (4), we shall receive for q_X, q_Y:

$$\begin{gathered} q_X = 0.5\,\rho\,(w_{1X} - dx_1/dt)\,[(w_{1X} - dx_1/dt)^2 + (dy_1/dt)^2]^{0.5} \\ q_Y = -0.5\,\rho\,(dy_1/dt)\,[(w_{1X} - dx_1/dt)^2 + (dy_1/dt)^2]^{0.5} \end{gathered} \tag{5}$$

Similarly, we receive the equations of movement of the intermediate (middle) container at a going-out of its lifting rope.

The equations of movement of intermediate j-th point:

$$\begin{aligned} m_j\, d^2x/dt^2 &= c_N\, q_x\, d_{TR}\, L_{j-1} - T_{j-1} \sin\alpha_{j-1} + T_j \sin\alpha_j - \\ &\quad - c_X\,(dx_j/dt - w_j)\times \mathrm{abs}(dx_j/dt - w_j); \\ m_j\, d^2y/dt^2 &= c_N\, q_y\, d_{TR}\, L_{j-1} - m_j\, g - T_{j-1} \cos\alpha_{j-1} + T_j \cos\alpha_j - \\ &\quad - c_y\,(dy_j/dt)\times \mathrm{abs}(dy_j/dt). \end{aligned} \tag{6}$$

Here c_N – coefficients of normal aerodynamic resistance of a rope; c_x, c_y – coefficients of damping chosen from conditions of stability of the account; d_{rop} – diameter of a rope. Efforts T_{j-1} and T_j are determined by formulas similar (2).

In that case when the intermediate point j coincides with the intermediate container, the equation (6) is supplemented by members containing resistance of a parachute (it is similar (3)).

The equations (6) are fair as well for last going-out mass. In this case effort T_j is determined differently depending on, whether mass last element of a rope has left magazine.:

$T_j = T_0$ at $L_j \le L_0$; $T_j = C_{rop} (L_j – L_0)$ - after a full going-out of an element.

Thus, the process of unfolding of the system is described by the equations of movement (3), (6). These equations were solved by Euler's numerical method for various variants of initial data. The computer model has been created. Coefficients of damping, an effort of the draw of rope, a horizontal speed of wind, a vertical speed of the stratospheric balloon, a flight altitude of beginning of unfolding of the system, a step of integration for this model were set. Results of calculations were shown on the display of the computer for the analysis.

As an example in Fig. 3 the diagram from the display of the computer for one of the variants of the task of initial parameters is resulted. In Figure the saggings a lifting rope are visible. This effect by selection of values of forces of resistance to the going-out of lifting ropes is eliminated. An adjustment of forces of resistance is carried out by fastening of each loop of the rope laid in magazine, a string of the set durability to walls of magazine.

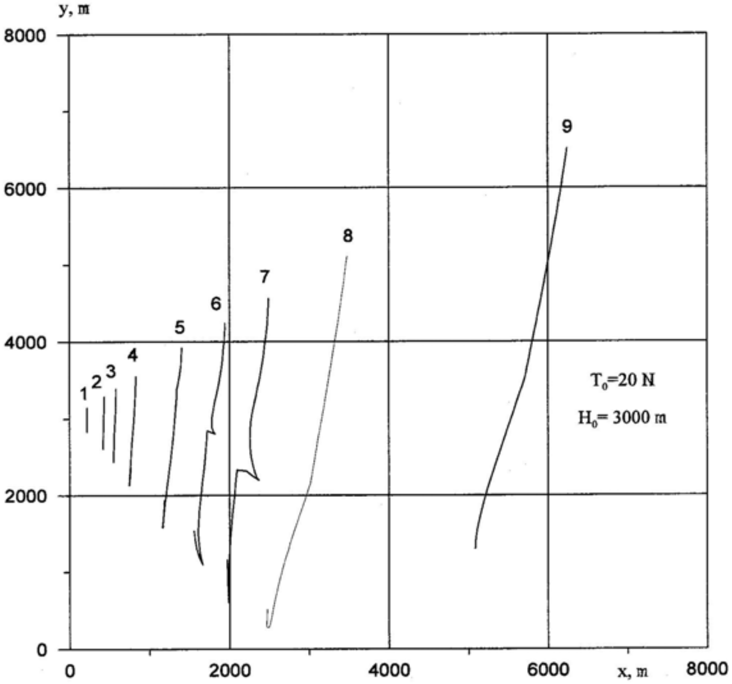
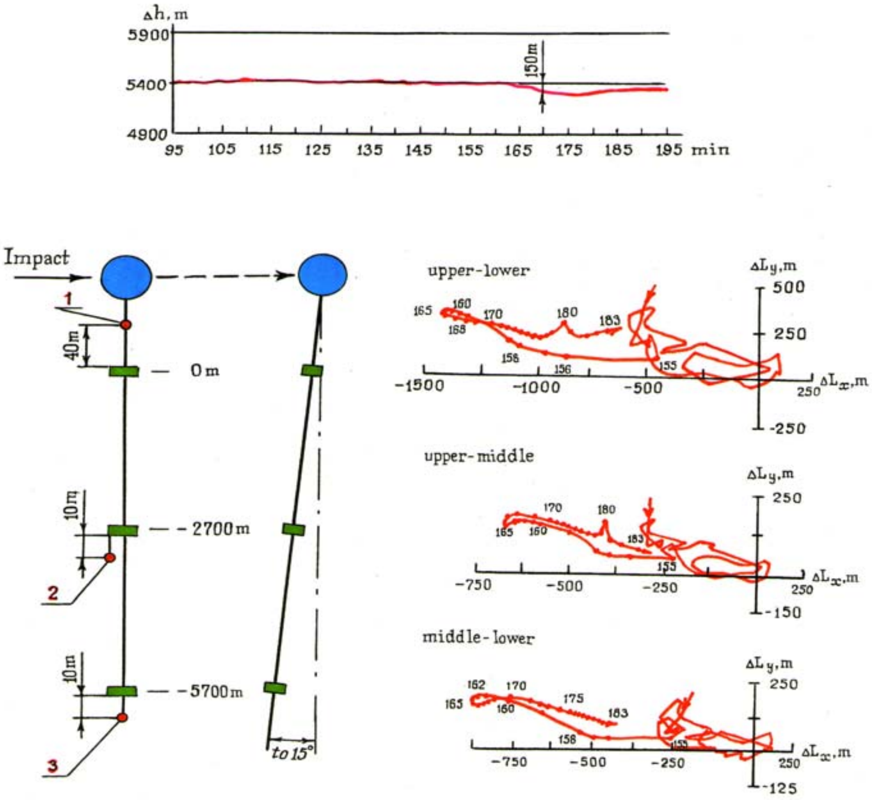


Fig. 3. Change of a configuration of system during expansion where forms 1-9 correspond to the moments of time after the beginning of unfolding.

3. DISTURBANCE OF THE SUSPENSION BASKET OF THE STRATOSPHERIC BALLOON BY ASCENSION AND DRIFT BALLOON

For measuring vertical gradients of any physical field it is necessary to know the position of the measuring instruments in space during the drift of the stratospheric balloon. Thus deviations of the lower containers of measuring gradiometer instruments from the vertical line which are passing through the upper container were studied.

The stratospheric balloon is also influenced by fluctuations of lifting air flow therefore the position of the measuring base concerning the vertical can be broken. It leads to a reduction of the accuracy of measurements of vertical gradients. In Fig. 4 the position of a triad of instrument containers with magnetic gauges of gradiometer during the drift of the stratospheric balloon is given. The position of an axis of measuring base of the gradiometer with respect to a vertical line by the drift of a balloon has been checked up experimentally during the most adverse, cold period of the year by means of navigating GPS-receivers. The field experiments took place on November, 3rd, 2007 and on December, 23rd, 2008. Speeds of drift of the stratospheric balloon in these flights made ~170 km/hours.



A wind speed impact influence on the stratospheric balloon envelope
1, 2, 3 – magnetic sensors

Fig. 4. Deviations of position of measuring base gradiometer in space at drift of the stratospheric balloon during the winter period of the year (flight in 2007)

During the flight of the stratospheric balloon spatial coordinates of the position of all scientific containers and the operating length of measuring base of the gradiometer, where a projection of the measuring base to the vertical line were determined while synchronous measurements are performed. For GPS-receivers errors of the coordinates are estimated by values of ~10 m.

In Fig. 4-6 current differences of altitudes of the position between the upper and the lower containers are shown. The values of the projections to a horizontal plane of deviations of containers from each other (hodographs of vectors of measuring base) resulted.

The stratospheric balloon experiment has shown, that the value of a mutual deviation of the containers at length of measuring base is equal to 6 km, i.e. basically within the limits of 500 m (corresponds ~5º of deviations of base from the vertical line), but during the separate periods reached 1300 m (~15º) due to fact that the operating length of measuring base was reduced. In Fig. 5 the appreciable trend of differences of the altitude levels of a position of gauges of the gradiometer is observed. This trend is probably connected with the relaxation of processes in lifting ropes according to influences of starting disturbances.

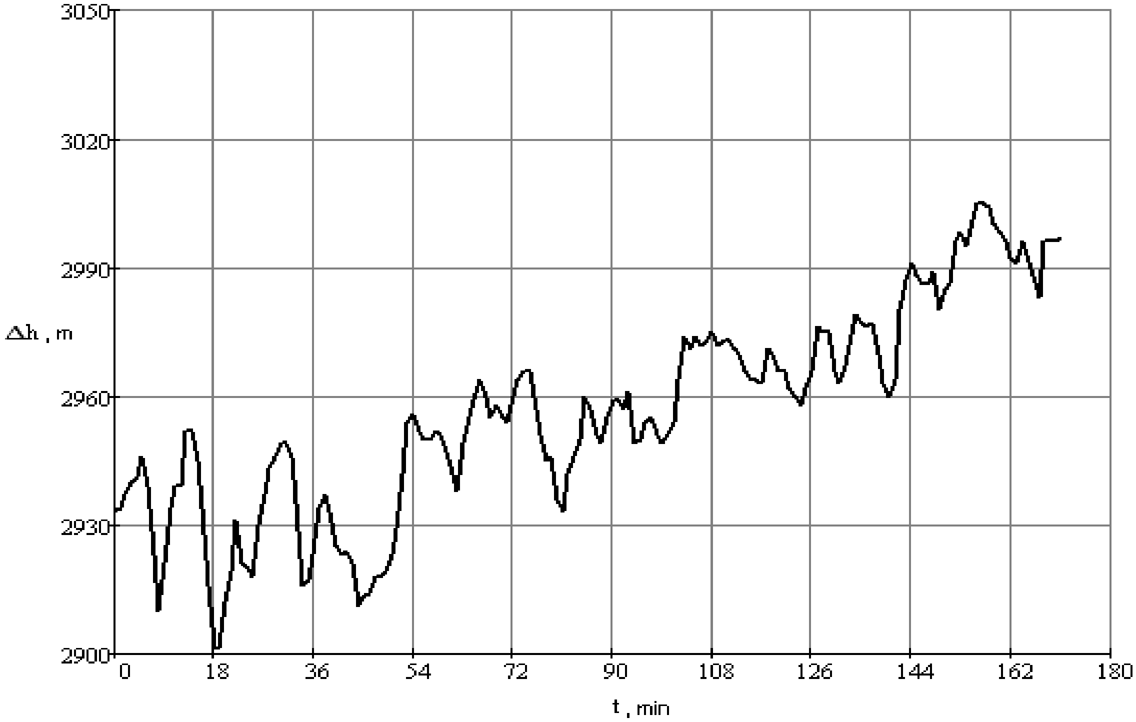


Fig. 5. Current differences of altitudes between upper and middle containers (23 December 2008) achieved as ceiling of flight by the stratospheric balloon. Extent of a line of flight is of ~500 km.

A slowing restoration of length of a lifting rope after influence of the loadings connected with the process of expansion magnetic gradiometer and the process of emersion of a balloon is visible.

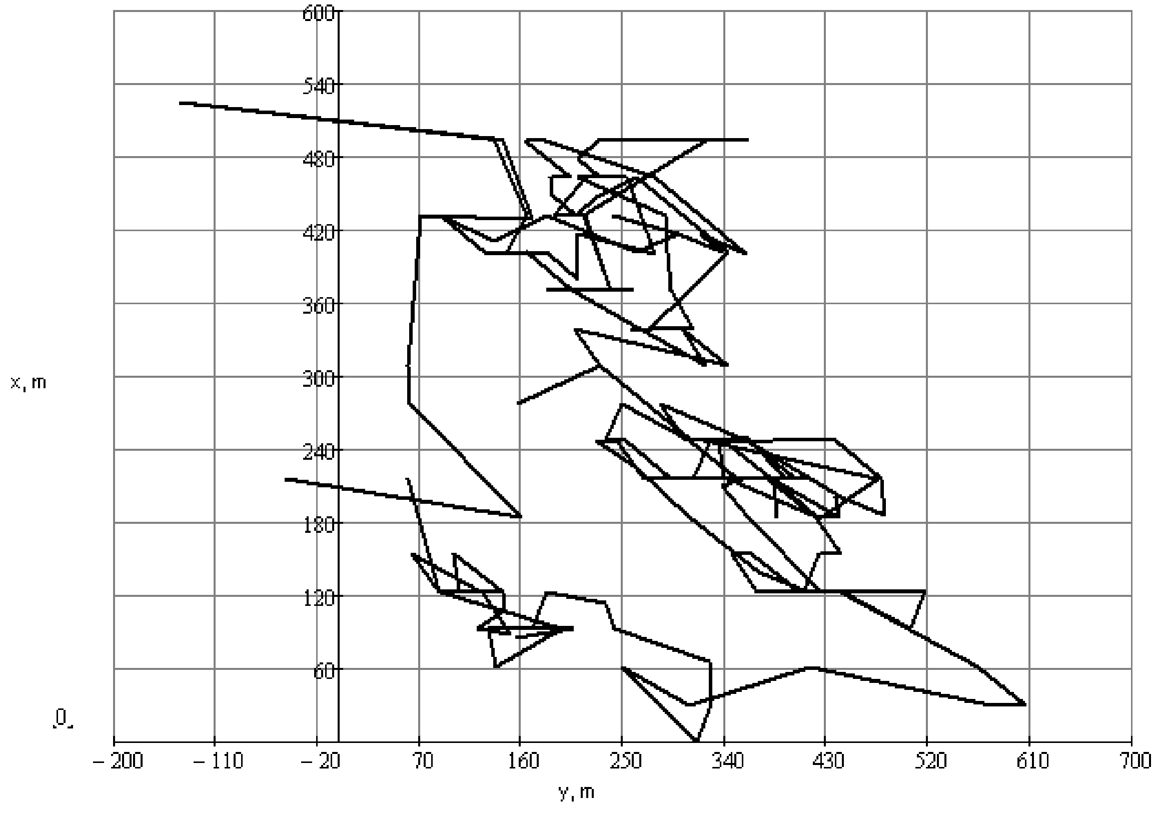


Fig. 6. For the pair "upper-middle" containers the size of projections of position of the middle container to a horizontal plane and concerning the vertical line which are passing (are taking place) through the upper container as they are received from the flight of the stratospheric balloon on December, 23rd, 2008.

So, for the first time experimental estimations of deviations of an axis of measuring base of the gradiometer from the vertical line are obtained at disturbances by lifting air flow and the dynamics of the difference of altitudes between containers during drift of the stratospheric balloon. Both experiments have shown identical results. For a warm season these deviations – as necessary – are expected to be 3-4 times smaller. As result of the development of the new direction of aeronautics by constructing stratospheric balloons of superpressure for which the flight can last many months, for the use of a gradiometer with long base, alternations of winter and summer conditions for the flights with corresponding variants of deviations of containers are possible.

If for processing magnetic data that are obtained in experiments on deviations of position received in experiments of gradiometers during drift of the stratospheric balloon, on values of the measured gradients are not considered then there will be errors. Errors will arise because of the influence of the main magnetic field on the measured magnetic gradients caused by deviations of the position of magnetometers from the vertical line, passing through the upper magnetometer. These errors are eliminated for the calculation of values of the crustal fields if the data of GPS-receivers are used for determining the position of magnetometers during the moments of synchronous magnetic measurements. These data are entered into the IGRF model.

4. ON THE OPPORTUNITY TO USE GRADIOMETER DATA FOR DERIVING SPECIFIED ANALITICAL MODELS OF THE GEOMAGNETIC FIELD

The conditions of the drift of a balloon in air current and at use of rope systems as measuring base of gradiometers have been shown. The gradiometer tests gave significant mechanical disturbances of the elements and its construction. These disturbances do not allow to use vector magnetometers as measuring equipment, but the use of scalar (proton precession) magnetometers is quite admissible. Hence, the use of offered experiments concerns the scalar models of the field. The error of measurement of the magnetic induction of the field of the Earth by proton (precession) magnetometers usually is at the level of ~0.1 nT. An accuracy of the measurement of proton magnetometers aboard a stratospheric balloon can be quite realized, as aboard the stratospheric balloon there are places for the accommodation of sensors of magnetometers where its own magnetic field of the stratospheric balloon (deviation) has an induction less, than 0.1 nT. Considering an opportunity of correction of deviations of measuring base of gradiometer at processing magnetic data, it is possible to ascertain, that the measuring device has an accuracy of measurement of gradients ~0,5 nT/km as created.

At the large length of measuring base of gradiometer the received value of a difference of signals of magnetometer, carried out by the length (b) of real measuring base of the complex ($\Delta F/b$), is not the gradient in its strict sense of this term and can noticeably differ from a vertical derivative of the first order ($\Delta F/dr$) - the true gradient of the field. The use of three sensors of the magnetic field allows to determine by three points the laws of change of the field along a vertical line and to calculate a true gradient for any point within the limits of length of the measuring base. Let's note also, that the alternative attempts of other researchers based on plane magnetic gradiometer with the necessary sensitivity and studying the structure of deep horizons of the Earth's crust, have not been successful. The modern methods using the most precision and high-sensitivity measuring instruments, do not allow determine magnetic gradients with respect to their small sizes as caused from the sources located on the lower horizons of the Earth's crust. In case of stratospheric balloon magnetic gradiometer this problem is solved due to very long measuring base. As presented above this balloon equipment allows derive a three-dimensional model of the magnetic anomalies in a range of altitudes of 20-50 km, using the received magnetic gradients. The geomagnetic field up to altitude levels of 30-40 km is formed from 3D sources, and above, as from 2D sources. Hence, the altitude level of flights of stratospheric balloons is important for the development of analytical models of the magnetic field. Principles of construction of such model are stated below.

In [1] it has been discussed that the global SHA field models up till now use commonly internal magnetic field data from the Earth´s surface and from satellite altitudes. Consequently, on this supposition the models of the crustal anomaly fields are derived. These global internal magnetic field models are a first approximation for a 3D model.

When global internal magnetic field models of higher quality shall be calculated then the mathematical assumptions to apply the global SHA field model do not allow to use commonly these different data sets of the internal magnetic field in the usual SHA algorithm because of the fact that SHA series expansions have significantly different convergence properties in dependence on their used reference surfaces. Furthermore, it is shown that data sets of internal magnetic field recorded at the Earth´s surface and at satellite altitudes, respectively, shows different physical properties.

From both arguments in [1] it is proved that for an essentially better global SHA field model and for the derived crustal anomaly models the altitude dependence of the internal magnetic field has to be considered and practically introduced by 3D data. Therefore, recorded internal magnetic field data are necessary and have to be used for calculating separate internal magnetic field models but simultaneous in time. For this also satellites of different orbits and

different orbit altitudes are to be used. The altitude dependence of the internal field data can be completed by balloon gradient data from altitudes below the satellite orbits.
In [1] the author introduced a mathematical algorithm for a reasonable approximation of a downward field continuation so that the different internal magnetic field models are compared for their mathematical and physical properties. Furthermore, this continuation procedure gives the tool to derive global SHA field models of different altitudes.
The magnetic field data recorded from satellites and balloons of different altitudes enable to check the field data and the models that had been calculated by the continuation procedure of [1] and to evaluate the quality and discuss errors.
Finally, to combine the data recorded at different altitudes with the mathematical downward continuation procedure enable to calculate altitude dependent global internal magnetic field models. Herewith, also 3D crustal anomaly field models are available for the regions of special interests.

These principles make obvious that satellite as well as balloon data are necessary to complete a 3D magnetic field data set as suppositions for a 3D field model of high quality.

5. CONCLUSION

The device, measuring vertical magnetic gradients from sources, placed in all vertical thickness of the Earth's crust and having an accuracy of measurement of gradients ~0,5 nT/km, is created:

- To receive the three-dimensional structure of magnetic anomalies in a range of altitudes of 20-50 km. The use of these data in combination with satellite and aeromagnetic data will enable to create the improved 3D model of the crustal magnetic field;
- To study the nature of separate components of the geomagnetic field in satellite data, including long-wavelength anomalies;
- To create the reliable map (model) of magnetic anomalies of polar areas of the Earth and to use it for validation of maps of satellite magnetic anomalies of this area;
- To estimate probable additional mistakes of global analytical models of the main magnetic field of the Earth (IGRF), to study their reasons and to offer measures of their reduction.

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