MAGNETOMETERS FOR SPACE MEASUREMENTS

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Introduction. — The magnetic field is defined by the magnitude and direction. Many geophysical problems, for the sake of which, magnetic measurements were carried out, need the knowledge of both the magnitude and the direction of the field.

As is generally known, a great progress was made in magnetic prospecting owing to elaborated methods of the magnetic field measurements from mobile platforms [1]. The accuracy of the measurements increased when instead of components, scalar values began to measure [2]. With proton magnetometers [3] the scalar values measurements became more attractive and exact.

At great distances from the Earth where the magnetic field is sufficiently decreased, an acceptable (at the absolute value) accuracy of the field component measurements might be achieved by much less accuracy of the mobile platform orientation. At great distances from the Earth it is possible to measure the field components of the orientation of the spacecraft is known with the accuracy at least 3° - 5° .

While choosing the optimal measurements ways it is essential to take into account the fact that the magnetometers sensors may find themselves in the influence sphere of the magnetic and electromagnetic fields of the spacecrafts. The "magnetic sanitary" requirements might be fulfilled not always, especially in the earlier years, when the spacecraft technical problems formed the conditions of experiments.

The elimination of the magnetic deviation from the readings of the spacecraft magnetometers might be reached by utilizing special design in the spacecrafts and by using definite methods.

This paper is dealt with a brief review of the magnetometers for space measurement elaborated in the Soviet Union and a short description of the methods for ensuring their normal functioning on the spacecrafts.

By the magnetometers descriptions we shall follow the next classification :

- 1) Magnetometers for measurements in the space nearest to the Earth from satellites with a low apogee;
- 2) Magnetometers for measurements in the outer magnetosphere and interplanetary space.

We shall keep the chronology of experiments because this allows to trace the evolution of the means and methods of the magnetic field measurements from spacecrafts.

1. Magnetometers for measurements from satellites with a low apogee. — Until recently at low altitudes only magnetometers for measuring the scalar value of the field were applied :

- 1) Self-oriented total field fluxgate magnetometer (1958);
- 2) Free-precession proton magnetometers (1964);
- 3) Quantum-cesium magnetometers (1970).

a) **SELF-ORIENTED TOTAL FIELD FLUXGATE MAGNETOMETER SG-45.** — This magnetometer was constructed and built in 1957 and was the first one which was mounted on board of a satellite (The third Soviet satellite, 1958).

As a scalar instrument this magnetometer, of course, yields in the accuracy the later elaborated proton and "optical pumping" magnetometers. However, in this magnetometer some solutions were realized which later found application in magnetometric systems of space apparatus :

- 1) A digit compensation system and the transmission of the data in a combination of digit and analog forms with an accuracy much better than that of the telemetry.
- 2) The determination of the satellite orientation in the space relative to the magnetic field.

The magnetometer of the third satellite measured the scalar value of the field and two angles of the field vector relative to the satellite coordinate system [4, 5]. In contrast to fluxgate magnetometers which were used in aeromagnetic prospecting the third satellite magnetometer was possible to operate at any magnetic latitude by the arbitrary orientation of the satellite. As compared with the first mentioned above it has a small weight, gabarit and low power consumption. Only semiconductors and magnetic elements were employed in the magnetometer.

A mechanical oriented unit was used to bring the system into a position where the measuring detector was set along the total field. The driving spindles of the orientation unit carried the moving contacts from two ring potentiometers, which received a voltage from a 6 v source. The voltage taken from the moving contacts depended on the orientation of the satellite relative to the magnetic field vector. The data were transmitted by two telemetric canals and were used to determine the orientation of a number of geophysical instruments of the third satellite relative to the magnetic and velocity vectors θ and also for eliminating the magnetic deviation from the magnetometer readings [7].

The measuring detector operated by the null method. A small continuously changing part (± 2400 gammas) of the field compensated by the introduction of a large negative feedback. The main part of the field compensated by means of a stable automatic digit type

field source. Information about the small continuous changing part of the field was transmitted by two analog telemetric canals and a number of the range was transmitted by the third telemetric canal. Owing to this the accuracy of the magnetometer data was irrespective of that of the telemetric system.

A detailed description of the magnetometer and the results obtained with it have been given in [4, 5, 6, 7].

b) PROTON MAGNETOMETER "PM-4". — A proton magnetometer "PM-4" of an original construction has been developed for a specialized satellite intended for the research according to the world magnetic survey program.

As is generally known [8] on board of the satellite "Avangard-3" a proton magnetometer has been mounted which contained only the units forming and amplifying a nuclear precession signal. The frequency of the precession signal has been measured on the ground. Thus, with this instrument it was possible to carry out measurements only in the zone of direct visibility of the satellite, in the districts with a limited number of ground stations.

According to the world magnetic survey program it was necessary to carry out measurements along the uniform net of points. This condition might be fulfilled by using on board a memory device.

As the frequency of free nuclear precession in the range of measured fields changes from 800 to 2 000 cps, direct memorizing of signals on board is impossible. It is necessary to have a frequency-meter on board to memorize calculated data simply and reliably. The reliable work of a board frequency-meter is possible at an advantageous signal/noise ratio.

An advantageous signal/noise ratio in the proton magnetometer is obtained if the amplifier has a narrow band and the angle between the field and the sensor axis is near to 90°. However, to make the magnetometer work along the whole orbit, the amplifier is to be enough wide-band. This contradiction could be solved by using an instrument with an automatic frequency range switch. The advantageous orientation could be obtained by using two sensors oriented at the right angle.

Among different ways of range switching that one has been preferred; namely that, in which the range switching was carried out by a logical diagram analyzing a nuclear precession signal [9].

During the period of a free nuclear precession the instrument automatically searches the optimum signal, analyzes it and if it is great enough searching it stops and allows to measure the frequency. The optimum position is being memorized and later the searching of a signal starts from that state. The measured frequency at the optimum signal is being memorized in the eight-code in the memorizing device canals of the radiotelemetry system.

The mentioned sequence of measuring operations is provided by functional elements pointed on the magnetometer "PM-4" skeleton diagram (fig. 1). On the time-program-device the instrument switches on the polarization current for 2 s and after that it feeds the sensor winding to the amplifier input. The search of the optimum signal begins. The whole measurement range is divided into subranges. An electron commutator switches them on in turn. When the commutator reaches a subrange, having a pre-

FIG. 1.

cession signal, the latter is being amplified up to the value quite enough for the electron commutator stopping by means of a search stopping diagram. The maximum search time in an unknown field is 0.6 s, and the minimum time is 0.2 s.

A special determining recounting cell may count 32 signal periods from the amplifier output. Only after that the frequency meter input opens and the measurement is being carried out.

If the cell was not filled, it may take place when the signal/noise ratio is not enough, the search goes on. With the search stopping the number of a subrange, on which the signal was detected, is being memorized. At the following measurement cycle the search begins from this subrange. The frequency-meter measured the number of impulses N of a quartz oscillator for the time equal 512 cycles of nuclear precession. The frequency-meter gives the results in the double counting system. Thus fixed number coded by step tension from 0 to 6 v is supplied to 6 channels of the telemetering system.

For determination of the scalar value T the magnetometer readings were evaluated from the eight code into decimal one. The calculation of T has been made by means of a computer according to the formula :

$$T = \frac{12\,025.25(100\,000 \pm \Delta f)}{N}$$

where Δf is the correction of the quartz oscillator for the temperature, N the number of impulses mentioned above.

Two magnetometers have been mounted on board of the satellite "Cosmos-49", the sensors of which have been oriented at the right angle. The instruments were switched on by turns from a time program device of high accuracy in the intervals of 32.76 s. The time marks gave the possibility to tie board readings out of each instrument to the absolute time.

The magnetometer sensors were sent away from the satellite centre at 3.3 m distance by means of a boom. A small magnetic influence of the satellite at this distance has been compensated by a system of permanent magnets, mounted on the bottom of the boom, creating the uniform compensating field in the places of the sensor mountings. The compensation accuracy of the magnetic and electromagnetic influence of the satellite has been verified by the absence of modulate effects in the board magnetograms when the satellite

rotated around the vertical and horizontal axes by means of a special nonmagnetic device. It was also checked by means of an outer stationary magnetometer when the satellite moved translationally relative to the magnetometer. The accuracy of compensation was about 2 gammas.

The magnetometer accuracy during the search of an unknown field was from 2 to 3 gammas. Special arrangements have been taken not to give the satellite to obtain great angular velocities at its separating from the rocket, which would be the cause of errors while measuring the nuclear precession frequency.

The weight of the magnetometer is 4 kg, the weight of the sensor is 1 kg. The average power consumption on the orbit by switching once in 32 s is 2.4 W. The measurements once in 8 s are possible.

More detailed description of the magnetometer has been given in [9]. The results of measurement by this instrument on the satellite "Cosmos-49" have been presented in [10, 11, 12, 13]. Figure 2 represents the world map of magnetic "Cosmos-49" prospecting.

FIG. 2.

c) QUANTUM-CESIUM MAGNETOMETER "QCM-1". — The quantum-cesium magnetometer "QCM-1" is designed to measure spatial and temporary changes of the scalar value of the Earth's magnetic field by means of an unoriented satellite.

"QCM-1" is a self-generated magnetometer [14, 15] (fig. 3). It differs by its diagram from those used on board of the spacecrafts OGO-2 [16].

FIG. 3.

Cesium is employed as its working substance. The frequency change effect of the centre of the magnetic resonance line at the field sign, replacing, inherent all the magnetometers with alkali metals, has the lowest value in cesium. This orientating effect in cesium at those limits of the light flow and radio-frequency field, which are being applied in the magnetometer sensor for providing the necessary signal/noise ratio, reaches 1 to 2 gammas in the field of 0.5 e [17, 18]. It gave the possibility to refuse the using of two chambers usually employed for eliminating of an error in orientation [19].

For eliminating "dead" zones connected with the signal amplitude change versus the angle of the sensor optical axis, two absorption chambers oriented at the angle of about 135° have been employed. The optical orientation of cesium atoms is being conducted by means of a single spectral cesium tube.

The magnetometer has absorbent cells with paraffin covers [20] without buffering gas. It gave the possibility to exclude from the optical part of the sensor an interference filter on to the line D₁ of cesium duplex radiation. The real signal/noise ratio in the band of 250 kc exceeds 50. It is determined in general by the photoreceiver noises. The measurement range in the limits of 15 000 to 66 000 gammas is being overlapped by a single amplifier having a block filter up to 50 kc. The amplifier provides an automatic adjustment of amplification with the initial coefficient for the ring feedback equal 700 to 900.

The absorbent chamber structures made it possible to extend temperature range by employing cesium-potassium solutions instead of pure cesium [21]. Without the system of thermal regulating the range lies in the limits of 17 to 40 degrees (according to the limit of one half of a signal). The magnetometer is supplied with a thermoregulating system for extending the temperature range up to the lower temperature range.

The construction of a cesium spectral lamp makes possible the work in the vacuum. By means of a feedback diagram the stabilization of the given light limit is provided through the light flow [21].

The normal functioning of a magnetometer on the rotating platform is provided with a diagram of the signal automatic phasing in the ring of the feedback field which changes the current direction in the radio-frequency coils at the instrument orientation change relative to the magnetic field. The optimum signal is being supplied to the frequency meter input from one of the sensors.

The field measurements are carried out once in 2 s during 0.17 s. The measurements once in 1 s, 4 and 8 s are possible. The time counting intervals are formed of quartz standard high stability generator signals. Magnetometer readings are being handed into 6 channels of the telemetering system in eight-code. Each measurement accuracy is 1.7 gamma. Correspondence to the absolute values in the measurement range is ± 2 gammas. The magnetometer sensor in a special unhermetic container leans back from the satellite body by means of a boom of 3.6 m length.

II. Magnetometers of satellites with high apogee and of space rockets. — In 1959 on board of the automatic stations "Lunic-1" and "Lunic-2" a portable

three component magnetometer was mounted for the first time [22]. The instrument, having the index SG-50, consisted of three independent fluxgate sensors of the second harmonic type, oriented at the right angle to each another (the sensors will be called Z, X, Y later). Mutual position of the sensors corresponded with one of the possible positions which excluded principally the influence of one ferropole upon another (fig. 4). With that magnetometer it was possible to measure three field components at the arbitrary orientation of a satellite.

FIG. 4.

The skeleton diagram of three component magnetometers was kept unchangeable while only separate elements of the principal diagram changed on different spacecrafts ("Electron-2", "Electron-4") [23].

The magnetometer principal diagram was chosen according to requirements of the minimum difference of zero from the absolute zero, high stability and low temperature coefficient. Generator and amplifier two-cycle diagrams, high negative feedback after phase-sensitive signal rectification, low enough ohm output resistance of each channel [24] favoured the above-mentioned fact. But all this did not exclude the necessity to make corrections relative to the absolute zero, to check temperature coefficients according to electronics and sensitive sensors, and to verify the sensitivity stability by calibrating in the flight [25].

Three component fluxgate magnetometer acquires optimum metrological characteristics on board of a rotating spacecraft [22]. The readings of X sensor, for instance, mounted at the angle α_x to the spacecraft rotation axis is given by means of the formula :

$$X = T \cos \alpha_x \cos \beta + T \sin \alpha_x \sin \beta \cos (\omega t + \varphi_x) + X'_0 + X''_0$$

where T is the field intensity, β is an angle of the field with a rotation axis, ω is an angular rotation velocity, X'_0 is a correction to the absolute zero, X''_0 is an influence of the spacecraft magnetic details. In a regular far cosmic field " β " changes slowly and magnetometer readings are presented as a modulated component with an amplitude $T \sin \alpha_x \sin \beta$ and a constant component $T \cos \alpha_x \cos \beta$, which may not be separated from the interferences $X'_0 + X''_0$. If $\alpha_x = \alpha_y$ is equal to the right angle, then $X'_0 + X''_0$ may be excluded from the magnetometer readings. The changeable component $T \sin \beta$ does not depend on the spacecraft deviation and "correction" to the absolute zero. The third sensor Z is not free from these corrections. At

arbitrary sensor orientation relative to the rotation axis both components are present on the sensors. But in this case too the error related with the deviation influence and corrections to the absolute zero are possible to detect. If these errors take place, the scalar value of the measured field $T = (x^2 + y^2 + z^2)^{1/2}$ has the modulation with the rotation frequency of a spacecraft [22].

The range extending of the magnetometer type SG-50 was reached by making the device rough, by introducing higher negative feedback. At this the absolute error on transmission the data by means of a telemetering system increased by the same value.

III. Three-component magnetometer SG-59 K. —

In 1965 a universal three-component magnetometer SG-59 K was developed. It consisted of two units : a typical three-component magnetometer SG-59 itself with a measurement range of ± 50 gammas along each channel and an automatic field compensator with three autonomous channels. SG-59 switching with its compensator expanded the measurement range up to $\pm 3\,000$ gammas along each channel and excluded hardening of the instrument SG-59 (fig. 5).

FIG. 5.

The data are being transmitted by analog telemetering channels in the magnetometer SG-59. The compensator readings are being transmitted by digital telemetering channels.

The magnetometer SG-59 K has the following characteristics :

- 1) The measurement range along the magnetometer channels (without compensator) is ± 50 and 200 gammas;
- 2) The measurement range with a compensator is $\pm 3\,000$ gammas along each channel;
- 3) The temperature coefficient on the sensor is 0.002-0.01 gamma/degree at the scale of 50 gammas, in the temperature range $\pm 70^\circ$.

It is 0.05 gamma/degree at 50 gammas, in the range 0 to 40° on electronics. The compensator temperature coefficient is 0.01 %/degree. In this combination the instrument SG-59 K is designed for measurements in the outer magnetosphere from 2.5 radii of the Earth and higher. In the combination without any compensator the instrument is used for measurements in the interplanetary space and near other planets.

The measurements by means of the magnetometers SG-59 without any compensator have been performed on board of the stations "Lunic-10" and "Venus-4" [26, 27].

REFERENCES

- [1] LOGATCHEV (A. A.), *Rasvedka Nedr.*, 1936, **17**, 40.
- [2] MUFFLY (G.), *Geophys.*, 1946, **II**, 321.
- [3] PACKARD (M.) et VARIAN (R.), *Phys. Rev.*, 1954, **93**, 941.
- [4] DOLGHINOV (Sh. Sh.), JUZGOV (L. N.) and SELIOU-TIN (V. A.), *Iskustvienniyé sputniki Ziemli*, 1960, **4**, 135.
- [5] DOLGHINOV (Sh.), *A.R.S. Journ.*, 1329, **31**, 9.
- [6] BELETSKII (V. V.) and ZONOV (Iu. V.), *Iskustviemiye sputniki Ziemli*, 1961, **7**, 32.
- [7] DOLGHINOV (Sh. Sh.), JUZGOV (L. N.), PUSHKOV (N. V.), TIURMINA (L. O.) and FRIAZINOV (N. V.), *Gheomagnetism i aeronomiya*, 1962, **2**, 6, 1061.
- [8] HEPPER (J. D.) *et al.*, *Space Res.*, 1960, **I**, 982.
- [9] DOLGHINOV (Sh. Sh.), NALIVAÏKO (V. I.), TIURMIN (A. V.) and TSHINTCHEVOÏ (M. M.), *Issledovanié kosmitsheskovo prostranstva*. Isd. Nauka, 1965, p. 606.
- [10] Katalog ismeriennik'h i V'itshislennik'h znatshenii moduliya napryajennosti gheomagnetitno polya vdol' orbit sputnika « Kosmos-49 », Moskva, 1967, **I**, **II**, **III**, 644.
- [11] TIURMINA (L. O.) and TSHEVKO (T. N.), *Gheomagnetism i aeronomiya*, 1967, **2**.
- [12] ADAM (N. V.), BEN'KOVA (N. P.), TIURMINA (L. O.) and PORTNOVA (V. P.), *Gheomagnetism i aeronomiya*, 1967.
- [13] BEN'KOVA (N. P.), DOLGHINOV (Sh. Sh.), TIURMINA (L. O.) and TSHEREVKO (T. N.), *Doklad na XIV gheeneralnoi assemblee MAGA*.
- [14] BLOOM (A. L.), *Appl. Opt.*, 1961, **I**, 61.
- [15] KOZLOV (A. N.), NALIVAÏKO (V. I.), FASTOVSKII (U. V.), TIURMIN (A. V.), DASHEVSKAÏA (E. I.) and BORISOVA (Iu. P.), *Kvantovskii tsezivii magnetometr KTSM-I*, *Doklad na VII Sessii seminaru po problemam postroeniya i ispol'zovaniya magnetometritsheskoï apparaturi*, Leningrad, 1968.
- [16] FARTHING (W. H.) and FOLZ (W. C.), *Review of Scientific Instruments*, 1967, **38**, 1023.
- [17] GRIVET (P. A.) and MALNAR (L.), *Advances Electronics and Electron Physics*, Academic Press, 1967, **23**, 39.
- [18] KOZLOV (A. N.), DASHEVSKAÏA (E. I.) and PESTOV (E. N.), *Izmerieniya Magnitnikh pol'iei* *Sbornik izd. « ILIM »*, 1968.
- [19] BORISOVA (Iu. P.), DASHEVSKAÏA (E. I.) and KOZLOV (A. N.), *Gheofisicheskaia apparatura*, *Izd. Nedra*, 1965.
- [20] DEHMELT (H. A.), *Phys. Rev.*, 1957, **105**, 1924.
- [21] BORISOVA (V. P.), DASHEVSKAÏA (E. I.), KOZLOV (A. N.) and PESTOV (E. N.), *Sbornik izd. « ILIM »*, 1968.
- [22] DOLGHINOV (Sh. Sh.), EROSHENKO (E. G.), JUZGOV (L. N.), PUSHKOV (N. V.) and TIURMINA (L. O.), *Iskusstviennii sputniki ziemli*, 1960, **5**, 16.
- [23] ALEXANIAN (L. M.), EROSHENKO (E. G.) and JUZGOV (L. N.), *Kosmitsheskie issledovaniya*, 1966, **IV**, 302.
- [24] AFANAS'IEV (Iu. V.), LIULIK (V. P.) and ALEXEEVA (G.), *Kosmitsheskie issledovaniya*, 1966, **IV**, 302.
- [25] DOLGHINOV (Sh. Sh.), EROSHENKO (E. G.) and JUZGOV (L. N.), *Issledovaniya Kosmitsheskovo prostranstva*, 1965, *Izd. Nauka*, **342**.
- [26] DOLGHINOV (Sh. Sh.), EROSHENKO (E. G.) and JUZGOV (L. N.), *Kosmitsheskie issledovaniya*, 1966, **IV**, 6.
- [27] DOLGHINOV (Sh. Sh.), EROSHENKO (E. G.) and JUZGOV (L. N.), *Kosmitsheskie issledovaniya*, 1968, **IV**, 4.