A0.2-0024

SMALL SATELLITES EMC STUDY

V. Korepanov[1], F. Dudkin[1], O. Melnik[1], and K. Pajunpää[2]

[1]Lviv Center of Institute of Space Research (LCISR), 5-A Naukova St., 79000 Lviv, Ukraine
[2]Nurmijarvi Geophysical Observatory, FIN-05100 Röykkä, Finland

ABSTRACT

The decreasing of weight and dimensions of the new generation of space vehicles – micro- and nanosatellites – allows us to place the sensors of scientific payload on short and simple booms or even on the satellite body. By this the electromagnetic cleanliness (EMC) of these satellites becomes a first priority question. The investigation methodology and special theoretical approach were developed, which allow determination the parameters and location of the magnetic source inside the tested body with high enough sensitivity and precision. The EMC test system composition is described as well as developed theoretical basis is discussed.

INTRODUCTION

One of the greatest advantages of small satellites (SS) is their electromagnetic cleanliness (EMC), which allows realizing very accurate electromagnetic measurements in space. Besides the corresponding SS construction design, it is very important to execute its EMC study when all payloads is already assembled. The attempts to investigate the state of this problem showed that, according to the existing publications, it is rather poorly developed and neither special instrumentation nor corresponding theoretical basement and software exist for exact determination of SS inner interference sources parameters and location. The special problem is how to estimate EMC in very low frequency band and at DC. One of the first instrumentation intended to solve this problem is the calibration system of Nurmijarvi Geophysical Observatory. Recently it is equipped with all necessary hardware to realize the measurements of low magnetic fields produced by the studied object.

EMC STUDY METHODOLOGY

The determination of presence of a weak magnetic field source in very low frequency (VLF) or direct current (DC) band is very complicated procedure because of many industrial and natural interference. If it is necessary to evaluate the magnetic source parameters then a complexity of this task considerably increases (Korepanov et al, 1997; Dudkin and Korepanov, 2000). To solve the electromagnetic cleanliness (EMC) problem these parameters must be measured in order to take in account a possible influence of such a source on another sensitive equipment.

In VLF-DC band the corresponding procedure and instrumentation are much more complicated because of the following:

- low efficiency of short electric antennae in VLF band because of very high reactance and very low curl component of electric field (Dudkin and Gough, 1999);
- necessity to use the complicated combinations of magnetic dipole systems as magnetic field sensors;
- very high level of industrial and natural noises;
- influence of residual magnetic fields of surrounding metallic bodies and the Earth’s magnetic field.

In spite of this the practice requires the more and more accurate determination of possible magnetic interference source parameters. One of these applications is the development of the satellites with very low level of own electromagnetic radiation for space research that needs exact measurements and compensation of stray sources of magnetic interference (Klimov et al., 1993). In this case two main methods are used:

- rotation of the satellite with simultaneous magnetic field variations measurement by three component magnetometer (Arnold et al., 1998);

- displacement of magnetic sensors relatively satellite and measurement of magnetic field distribution in near space (Primdahl, 1990; Korepanov et al., 1997; Auster et al., 1998; Dudkin and Korepanov, 2000).

The first method is used mostly for small satellite (nanosatellite, for example) certification.

THEORETICAL APPROACH

The main task of the present study is to improve this method for small satellite magnetic moment estimation and localization of such a moment within the satellite body. Here the term "magnetic moment" means the vector value with dimensions $A \times m^2$. Usually this term is applied to small magnets or the loop with electric current when the distance to the loop is 3-5 times more than its diameter. Thus we may consider such a moment as a magnetic dipole.

Let us assume that magnetic moment $\vec{M}$ has arbitrary direction in space and rotates along circular orbit in plane $x'0'y'$ (Fig. 1). The point of observation P is on x axis of coordinate system $x0y$. The axes y'' and z'' of local coordinate system in point P are parallel to axes y, y' and z respectively. The axes x'' and x, z' and z coincide. Also r_0 is the distance between points $0''$ and 0, h_0 is the distance $0'0$.

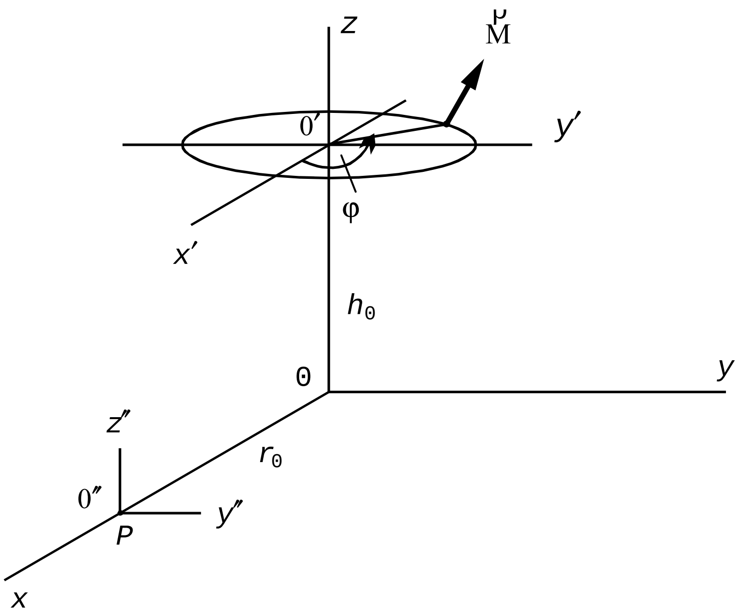

Fig. 1. Schematic diagram of measuring arrangement.

It is clear that the rotation of magnetic moment along circular trajectory of radius R will cause the magnetic field components changes in point *P*. The dependence of magnetic field components of magnetic moment $\vec{M}$ in point *P* against angle of rotation φ may be written in form:

$$H_x = \left(4\pi\left((r_0 - R)^2 + 2r_0R(1-\cos\varphi) + h_0^2\right)^{2,5}\right)^{-1} \times$$
$$\times \begin{pmatrix} \left(2(r_0 - R\cos\varphi)^2 - R\sin^2\varphi - h_0^2\right)(M_r\cos\varphi - M_t\sin\varphi) + \\ 3(r_0 - R\cos\varphi)R\sin\varphi(M_r\sin\varphi + M_t\cos\varphi) + \\ 3(r_0 R\cos\varphi)R\sin\varphi M_z \end{pmatrix}, \qquad (1)$$

$$H_y = \left(4\pi\left((r_0 - R)^2 + 2r_0 R(1-\cos\varphi) + h_0^2\right)^{2,5}\right)^{-1} \times$$
$$\times\begin{pmatrix} \left(3(r_0 - R\cos\varphi)^2 - R\sin^2\varphi - h_0^2\right)(M_r\cos\varphi - M_t\sin\varphi) + \\ \left(2R^2\sin^2\varphi - (r_0 - R\cos\varphi)^2 - h_0^2\right)(M_r\sin\varphi + M_t\cos\varphi) + \\ 3h_0 R\sin\varphi M_z \end{pmatrix}, \qquad (2)$$

$$H_z = \left(4\pi\left((r_0 - R)^2 + 2r_0 R(1-\cos\varphi) + h_0^2\right)^{2,5}\right)^{-1} \times$$
$$\times\begin{pmatrix} 3(r_0 - R\cos\varphi)^2 h_0(M_r\cos\varphi + M_t\sin\varphi) + \\ 3Rh_0\sin\varphi(M_r\sin\varphi + M_t\cos\varphi) + \\ \left(2h_0^2 - (r_0 - R\cos\varphi)^2 - R^2\sin^2\varphi\right)M_z \end{pmatrix}, \qquad (3)$$

where M_r, M_t, M_z are radial, tangential and vertical components of the moment vector respectively.

The Eqs. (1) – (3) are derived from known expressions for magnetic field of dipole moment in spherical coordinate system [*Ramo et al.*, 1984]:

$$H_r = |\vec{M}|\cos\theta\left(2\pi r^3\right)^{-1}(1 + jkr)\exp(-jkr),, \qquad (4)$$

$$H_\theta = |\vec{M}|\sin\theta\left(4\pi r^3\right)^{-1}\left(1 + jkr + k^2r^2\right)\exp(-jkr),, \qquad (5)$$

at condition $\omega \to 0$, where ω is circular frequency of field, k – wave number, r – distance from moment to observation point, θ – angle between the vectors $\vec{M}$ and $\vec{r}$.

Eqs. (1) – (3) connect magnetic parameters M_r, M_t, M_z of moment and its coordinates R, h_0, φ with field values in point P. In the case when the coordinates of the moment location are known the system of Eqs. (1) – (3) has solution relatively to the magnetic moment components M_r, M_t, M_z.

The results of error of module ($\delta|\vec{M}|$ (%)) and direction ($\delta\alpha$ (°)) of magnetic moment estimate at $M_r = 1$ A·m^2, $M_t = 1$ A·m^2, $M_z = 1$ A·m^2 , $r_0 = 0.3$ m, $R = 0.1$ m, $h_0 = 0.3$ m for different signal to interference ratio and 36 points of measurement with angle step 10° are shown in Table 1. Here it was supposed that interference magnitude satisfies the normal distribution law.

Table 1. Interference Influence on Measurement Error (Simulation Results)

Signal/interference ratio	3	5	10	20	50	100	∞
$\delta\lvert\vec{M}\rvert$ (%)	8.8	5.4	1.5	0.24	0.15	0.17	0
$\delta\alpha$ (°)	20	10	5.4	2.5	1.3	0.6	$3.3\cdot10^{-6}$

The problem becomes significantly complicated at unknown R, h_0, φ, M_r, M_t, M_z. In this case it is necessary to solve the system of 6 equations with six unknown values for two vector $\vec{M}$ positions on circle with radius R. (Obviously the distance r_0 from point of field measurement to axis of rotation is supposed to be known).

Then the systems of equations for magnetic moment parameters determination may be written in the form:

$$\begin{cases} r_1^5 b_{1,1} b_{2,1}^{-1} + r_2^5 b_{1,2} b_{2,2}^{-1} = 0 \\ r_1^5 b_{3,1} \left(a_{1,1} b_{2,1}\right)^{-1} + r_2^5 b_{3,2} \left(a_{1,2} b_{2,2}\right)^{-1} = 0 \\ r_1^5 b_{4,1} \left(a_{1,1} a_{2,1} b_{2,1}\right)^{-1} - r_2^5 b_{4,2} \left(a_{1,2} a_{2,2} b_{2,2}\right)^{-1} = 0 \end{cases} \tag{6}$$

$$\begin{cases} M_r = 4\pi r^5 \left(a_1 b_2\right)^{-1} \left(a_1 b_1 \cos\varphi + b_3 \sin\varphi\right), \\ M_t = 4\pi r^5 \left(a_1 b_2\right)^{-1} \left(-a_1 b_1 \sin\varphi + b_3 \cos\varphi\right), \\ M_z = 4\pi r^5 b_4 \left(a_1 a_2 b_2\right)^{-1}, \end{cases} \tag{7}$$

where: r_j ($j=1,2$) – distances from point P to two opposite positions of magnetic source on the circle during rotation, a_{ij}, b_{lj} ($i=1,2$; $l=1 \div 4$) are the functions of magnetic moment's coordinates and magnetic field components in point P. The system of Eqs. (6) allows calculating the values R, h_0, φ_0. (Angle φ_0 corresponds to the initial magnetic moment's position). The components of magnetic moment M_r, M_t, M_z are calculated by substituting values R, h_0, φ in the system Fqs. (7), where a_i, b_l are the functions of R, h_0, φ.

SIMULATION RESULTS

The system of Eqs. (7) is too complicated to find its analytic solution. But it may be solved by means of computer numerical methods.

The results of error of magnetic moment parameters estimation against signal to interference ratio and 10 full rotations of moment with step 10° are shown in Fig. 2 (normal distribution of interference). Vertical lines show the errors range for ten cycles of rotation. The values averaged for ten cycles are shown.

The presented study shows that EMC problem for small satellites can be solved with good precision for high enough signal to noise ratio. It implies the special requirements to the test site and the best possible one seems to be the magnetic observatory. These are placed in specially selected places with as low as possible magnetic interference level.

The described system was realized at Nurmijarvi Geophysical Observatory (Finland). Taking into accounts very favorable surrounding the calibration system successfully operating already some years (Pajunpää et al., 1997) was completed last year by a new magnetic cleanliness measuring system. Its application was supposed to serve both to the local and European satellite instrumentation manufacturers. An existing reference coil system and electronic equipment for vector magnetometer's calibration were utilized as basic components for the new instrument. A non-magnetic rotating table with both manual and pecker gear and a high-sensitive three-component flux-gate magnetometer were installed there additionally. Such a combination allows executing the EMC test with very high sensitivity, practically limited by the reference magnetometer noise.

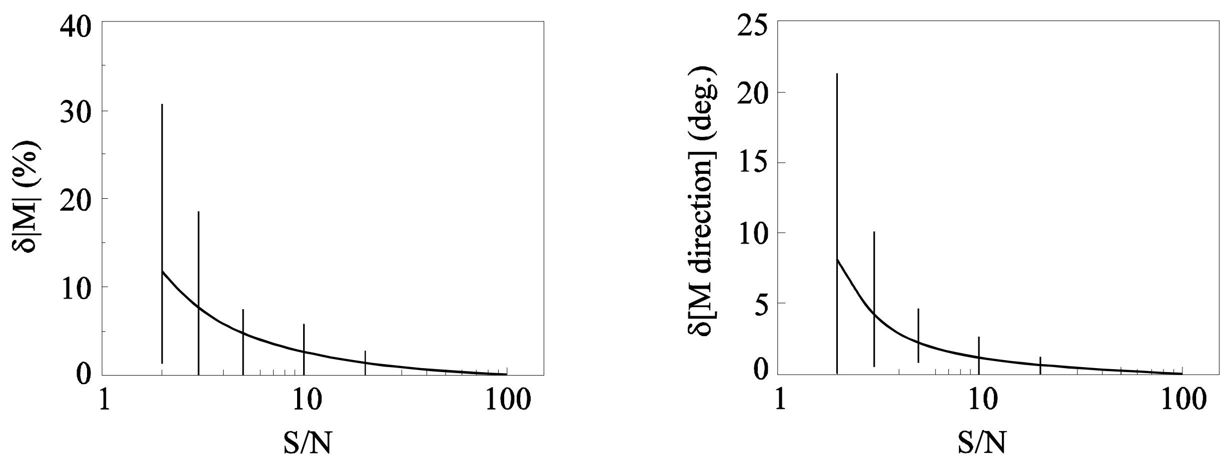

Fig. 2. Measurement errors estimation.

To increase the system performances, a special super-low noise LEMI-004 magnetometer (vector flux-gate type) was used. The rms noise level at uniform part of the noise spectrum of LEMI-004 reaches only few picoteslas in 1 Hz band.

The reference coils allow to suppress the influence of the Earth's magnetic field during the tests and to create the magnetic field of any amplitude and direction, making the external conditions close to those in which the satellite is designed to operate.

ACKNOWLEDGMENTS

These works were partially supported by NSAU contract No 1221 and STCU grant No 862.

REFERENCES

Arnold, H., G. Berghofer, K. Schwingenschuh, and M. Stachel, Description of the Magnetic Cleanliness Measurement Unit, private communication, 1998.

Auster, H.-U., V. Auster et al., Description of the Gradiometer Unit (GU), private communication, 1998.

Doudkin, F. L. and M. P. Gough, The Feasibility of Studying the Solar Wind – Magnetosphere Interaction by Active Electromagnetic Sounding from Outside of the Magnetosphere, *Radio Science,* **34**, No. 5, 1299-1320, 1999.

Dudkin F., and V. Korepanov, EMC Study in Space Systems, *Proceedings of the 4th European Symposium on Electromagnetic Compatibility* (September 11-15, 2000), Brugge, Belgium (in print).

Klimov, S. I., Yu. V. Lissakov et al., In-Flight Monitoring of the Electromagnetic Conditions on Phobos-1 and –2 Spacecrafts with the PWS and FGMM Instruments, *Proceedings of 3rd ESA European Workshop on Electromagnetic Compatibility and Computational Electromagnetics* (Pisa, Italy, October 26-28, 1993), 127 1993.

Korepanov, V., R. Berkman, and F. Doudkin, Low Frequency Gradientometer for EMC Certification, *Proceedings of 12th Intern. Zurich Symp. on Electromagnetic Compatibility* (Zurich, Switzerland, February 18-20, 1997), 207, 1997.

Pajunpää, K., V. Korepanov, and E. Klymovych, Calibration System for Vector DC Magnetometers, in *New measurements – challenges and visions,* XIV IMECO World Congress, Tampere, Finland, **IVA**, 97, 1997.

Primdahl, F., *A Pedestrian Approach to Magnetic Cleanliness*, Danish Space Research Institute, Lingby, March, 1990.

Ramo S., J. R. Whinnery, and T. Van Duzer, *Fields and Waves in Communication Electronics*, 2nd ed., New York, Wiley, 1984.