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IN-FLIGHT CHARACTERIZATION OF SATELLITE ELECTROMAGNETIC SENSORS

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ABSTRACT

This paper presents the description of the inter-calibration methodology which will be used in the future flight of SICH-1M satellite to carry out the in-situ validation of new scientific instruments – Split Langmuir Probe and Rogovsky Coil – intended for the direct measurement of the spatial current density in space plasma. The transfer functions of these instruments and also this of Faraday Cup, used for the data quality estimation, are presented. Additional possibility to estimate the measurement results is provided using the simultaneously operating on-board magnetometers since these also permit to estimate indirectly the spatial current value. Other problem is that the onboard magnetometers are very sensitive to the service systems noise. An original way to overcome this problem onboard small satellites where the boom deployment is not possible to realize is discussed in the paper. It proposed to use a rotating microsatellite with flexible booms or ropes (power supply/data retrieval wires in the simplest case) at the end of which two flux-gate magnetometers are fixed, and a calibration coil fixed on microsatellite body. The given mathematical expressions and numeric example confirm the possibility to realize such a flexible construction with high metrological parameters. © 2003 COSPAR. Published by Elsevier Ltd. All rights reserved.

INTRODUCTION

The latest tendency in in-situ experimental study of the outer space is to reduce satellites dimensions and their weight. By this the performance parameters of the onboard physical sensors should be maintained as they are or even made better. The development of the satellite technique implies new requirements to the scientific instrumentation manufacturing and utilization. Special situations arise when new instruments are proposed and tested for the first time in space or when the existing instrument is used in new conditions. Both these cases are considered below.

SPATIAL CURRENT MEASUREMENTS

The physical processes in earth's magnetosphere and ionosphere are governed by the currents flowing through different conducting paths. In order to study these processes there is a necessity to measure directly the current spatial density. Till now, it was mainly executed with magnetometers measuring the magnetic signature of the spatial current which seriously reduces experimental results interpretation possibilities. If a direct measurement of the spatial current density could be realized, some new exciting opportunities could arise. For example, as it is shown below the simultaneous measurement of orthogonal components of magnetic field and spatial current density fluctuation can give the wave vector k values for a spectrum of plane waves, by which wave field in plasma reference frame can be represented [Korepanov and Dudkin, 1999]. Each spectral component of plane wave may be written in the following form:

$$\vec{A} = \vec{A}_0 \exp\left(-j\left(\vec{k}\vec{r} - \omega t\right)\right), \quad A = H, J, \tag{1}$$

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where H, J – magnetic field and electric current density respectively, $j=(-1)^{0,5}$, $\vec{r}$ - vector distance, ω - angular frequency, t – time.

Let substitute expression (1) in Maxwell's equation

$$\left[\nabla \times \vec{H}\right] = \vec{J} \tag{2}$$

(J may be the sum of displacement and conductivity currents) and assume that the space derivative of magnetic field is very small:

$$\partial H_{0i}/\partial x_l \rightarrow 0, \tag{3}$$

where i, l =1,2,3; H_{0i} – amplitude of x_i – magnetic field component, x_l – component of coordinate system. Then we can obtain from (1)-(3) the following equation

$$\left[\vec{k} \times \vec{H}\right] = j\vec{J}\,. \tag{4}$$

This system of equations allows to determine the unknown values k_m, $m=x,y,z$ by the measured values H_m, J_m.

Unfortunately, there is no instrument up to now able to measure reliably the spatial current. As early as in 1973 a method and device named Split Langmuir Probe (SLP) were proposed (Bering et al., 1973), but further abandoned because of severe theoretical and interpretation problems connected with explanation of SLP interaction with surrounding space plasma.

Its operation principle is rather simple: two conducting plates are placed in space plasma at as small distance between them as possible and they are connected with a resistor R_s. The SLP output signal U is formed as follows:

$$U = IR_s = JSR_s, \tag{5}$$

where S is the surface of one SLP plate and I – current via resistor R_s connecting two plates of the probe. Further SLP output is connected to the high impedance preamplifier and to the measuring system. So, SLP is supposed to operate as electric current density to voltage transformer. In reality, it is not so obvious. For the first approach SLP can be considered as the capacitance connected to the external plasma current source via equivalent plates resistors. More detailed operation mode investigation is under development and the experimental SLP model was already constructed. The most important noise source for SLP is sunlight which can produce very dense flux of photoelectrons, masking measured current, and the wake formation during SLP movement which can considerably distort current density distribution.

Some years later a new interest to this device reappeared because of the original idea to separate spatial and temporal magnetic field variations using one satellite only (Vaisberg, 1985, Krasnoselskikh et al, 1991). The intense theoretical and technological study was made which resulted in the new current density measurement attempt using SLP onboard Soviet satellite Prognoz-10 (Vaisberg et al., 1989). The experimental results seem to be enough trustworthy to prove that it is possible to measure this value, but still, problems with their interpretation appeared to be too complicated.

Still one attempt to solve the problem of spatial current density measurement is planned to be realized in the future international VARIANT experiment onboard Ukrainian satellite SICH-1M (launch foreseen in 2003). The executed theoretical study of SLP - plasma interaction allowed to get its transfer function normalized to maximum value (Fig. 1, a).

In-flight inter-calibration of this instrument with other types of sensors is foreseen in order to facilitate the SLP operation understanding. Besides SLP, still two instruments will be installed onboard the satellite: Faraday Cup (FC) and Rogovsky Coil (RC); all three sensors will be in the same conditions and equally oriented and operating simultaneously (Korepanov and Dudkin, 1999).

Faraday Cup (FC) is the device for direct electron or ion current measurements in space plasma. Such measurements were realized, in particular, onboard some of "Prognoz" satellites and in experiment "Interball" (Safrankova et al., 1995). The principle of its operation is also rather simple. The charged particles go through the entrance window (its area is about 10 sq. cm) to collector. The current formed by these particles is transformed into voltage by current amplifier with high input resistance R (about 10^9 Ohms). Thus the FC output voltage is related to current density by the same correlation as in Eq. (5):

$$U = JSR\,, \tag{6}$$

where S is the area of the window.

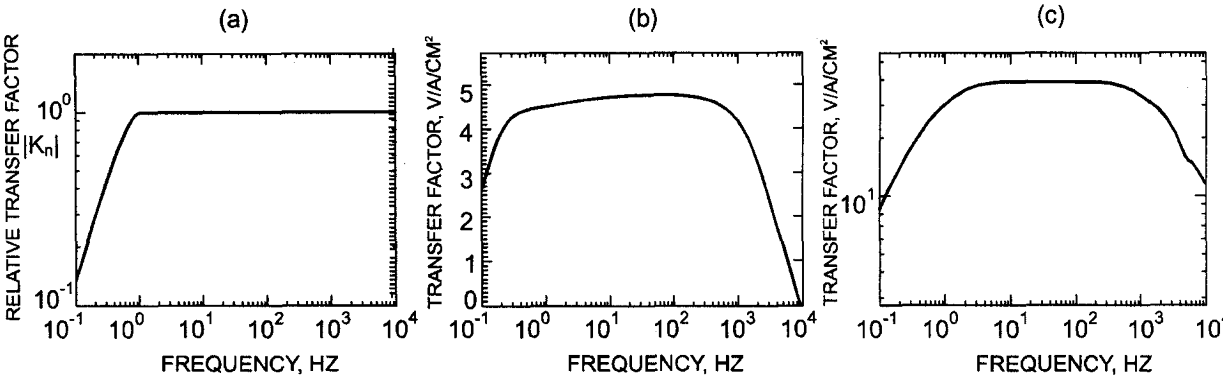

Fig. 1. Transfer functions for Split Langmuir Probe (a), Faraday Cup (b) and Rogovsky Coil (c).

Certainly it is not possible to say that FC measures total current density, but in appropriate conditions its data could be used for the current estimation. To this, FC is the only device between three ones which was successfully used in many scientific experiments and its transfer function is simple and easy to interpret (Fig. 1, b).

The third device – RC – is a recently proposed current meter and also never was used in space experiments on satellites before. The principle of RC operation is based on the following concept. The instrument itself consists of the ring core from high permeability material with the toroidal winding on it (Krasnossel'skich et al., 1996). The current with density J flowing through the core inner hole in the direction parallel to the axis of this toroid causes magnetic field intercepting the turns of the RC winding. When the current J is oscillating it provokes time varying magnetic field H and the output voltage of the sensor depends upon the time derivative of the normal component of the current density by the relation:

$$U = \frac{\mu S N \rho}{2}\,\frac{dJ}{dt} = K\,\frac{dJ}{dt}\,, \tag{7}$$

where K is the instrument's constant, S is core cross-section and μ - permeability of the material, N is the number of turns, ρ is the mean radius of the toroid.

Such an instrument was constructed and showed rather good sensitivity: having diameter 2ρ equal to 30 cm the obtained minimal noise level was about 10^{-12} A/cm^2 Hz$^{1/2}$ (Krasnossel'skich et al., 1996). The RC frequency dependence allows to use it in rather limited frequency band; its transfer function shape is presented on Fig. 1, c. But good results of RC intercalibrations with FC in plasma chamber with imitation of ionospheric conditions (Meyer et al., 2001) give hope to its proper operation onboard the satellite too.

Still one hope to have good intercalibration results gives the fact that two types of magnetometers – flux-gate and search-coil – covering the frequency band from DC to 40 kHz with enough high sensitivity also are included into VARIANT payload (Korepanov et al., 2000). It will allow also to make spatial current density estimation by known method of measuring its magnetic signature. So, it seems that everything is done in order to provide as reliable as possible direct current density measurements data in VARIANT experiment and to find in experimental way the possibilities and limitations of every of three instruments.

FLUX-GATE MAGNETOMETER

Flux-gate magnetometers (FGM) are present on the board of practically every spacecraft that allows collecting important information about physical processes in space. At earlier experiments their sensitivity threshold seldom surpassed 0.1 nT and long booms used to take the FGM sensor far enough from satellite body for realization of the measurements with such a sensitivity (Klimov et al., 1997). As it was already stated, modern tendency in space research is drastic reducing of satellite dimensions: nano- and even pikosatellites are the present reality. It becomes not possible to use long booms and even to use booms at all. To this, the sensitivity threshold or FGM noise level was considerably decreased and recently the level of ~1 pT was already obtained (Fig. 2).

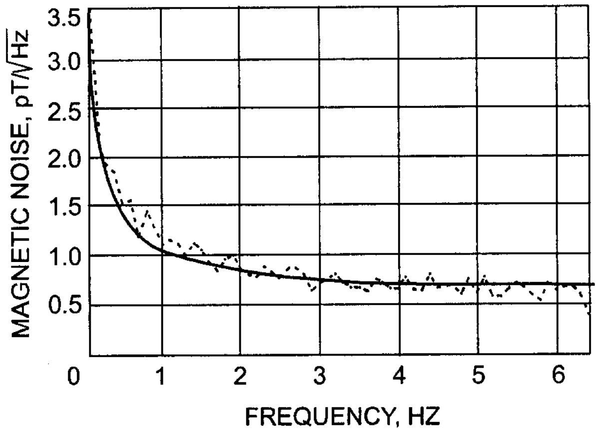

Fig. 2. Advanced FGM magnetic noise density (experimental plot and fit function).

The attempts to realize this very high sensitivity level of modern flux-gate magnetometers during the space experiments lead to the confrontation because even in the best cases of electromagnetically clean design the satellite service systems noise (including this of DC-DC converters obligatorily present on every board) will be much greater.

A new approach to the solution of this problem is proposed based on the use of tethered space system with flexible booms (ropes or wires, Fig. 3).

This idea can be realized by a rotating satellite with tethered FGM at some fixed distance between satellite and magnetometer, and one of the magnetometer's axis has to be perpendicular to the satellite axis of rotation. The system may be symmetrical (two magnetometers symmetrically connected by the ropes with the satellite body – possibility of differential measurements) or asymmetrical (magnetometer and satellite rotate around common center of mass). The details of realization are given below.

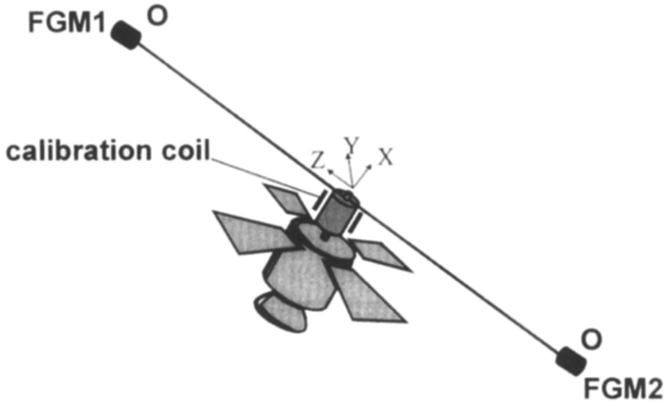

Fig. 3. Flexible boom structure for super-sensitive magnetic field measurement.

The calibration coil is fixed to the satellite, by this its magnetic axis is collinear to the axis of the satellite rotation and the coil is mounted in such a way that its center was in the plane of ropes' rotation. Thus initial (location) point of corresponding magnetic dipole moment will be in plane of rotation and aligned with the axis of rotation. The coordinate axis in the point of magnetometer location (*O*) that is parallel to the axis of rotation we denote as *x*. At ideal orientation of magnetometer only the B_x component of calibration coil magnetic field is observed. At rope torsion the B_y component additionally appears. At any deflection of magnetometer main axis (which is collinear to the rope and is denoted as *z*) from the plane of rotation (this deflection may be only small because the rotating system is very stable) the B_z component of magnetic field also appears.

Thus we may use calibrated field for transformation of the magnetic field data of tethered FGM to the known satellite axes coordinate system *x, y, z*. The calibrated magnetic field B_c in the point *O* has only *x* component and equals to:

$$B_{c,x} = 10^2 M_c / r^3, \tag{8}$$

where B_c is in nanoteslas; M_c is a magnetic moment of the calibration coil in A×m^2; *r* is rope length in meters. Also the maximal interference field B_s of an own magnetic moment of satellite M_s in the FGM location point is assumed to be collinear to the rope and has only *z* component that equals:

$$B_{s,z} = 2 \cdot 10^2 M_s / r^3, \tag{9}$$

where B_s and M_s have the same dimensions as in Eq. (8). If we assume that B_s must be equal or less than the sensitivity threshold value $B_{s,t}$ then from Eq. (9) we can calculate the length of the rope:

$$r = (2 \cdot 10^2 M_s / B_{s,t})^{1/3}. \tag{10}$$

From Eqs. (8), (10) we get the simple relation between necessary calibration coil magnetic moment M_c and available M_s value:

$$M_c = 2M_s (B_c / B_{s,t}). \tag{11}$$

We can get the relation for power dissipated in calibrated coil with copper wire from evident formulas $M_c = I_c S_c$, $S_c = w\pi d_c^2/4$, $R = l_w/(\sigma S_w)$, $m_c = \rho S_w l_w$, where I_c is a current in the calibrated coil, S_c is equivalent area of coil's winding, *w* is number of coil's turns, d_c is the coil diameter, *R* is resistance of the winding, l_w, S_w are the length and cross-section area of wire in winding, σ, ρ are the specific conductivity and density of the wire material, m_c is the mass of coil's winding:

$$P_c \approx \left(0.1 M_s B_c / (B_{s,t} d_c)\right)^2 / m_c \tag{12}$$

The numeric example gives realistic number: for $B_{s,t}$=10^{-3} nT, B_c=0.02 nT, M_s=0.1 A· m^2, d_c=0.2 m, m_c=0.25 kg from Eq. (12) we get P_c=4 W. Taking into account relative stability of the rotating system, such a calibration coil can be switched on rather seldom.

Such configuration will allow to solve two problems. First, the sensitive FGM will be taken enough far from the satellite body in order do not feel interference from it. The second problem appearing in this case because the rope is not rigid as a boom and can not provide exact orientation of the sensitive FGM relative to the satellite axes and even more, this orientation may change in time by known reasons, will be overcome also.

CONCLUSION

The present paper shows the efficiency of in-flight calibration of sensitive scientific instruments. This can especially help in the case when a new scientific sensor never used in space before has to be tested. The permanent inter-comparison of its data with simultaneously operating device having proved technical parameters will allow unambiguously determine the performances of the new instrument operating in space plasmas. This is namely the goal of VARIANT experiment, which is under the preparation to the launch. Using the sensitive magnetometer example other in-flight intercalibration application area is described, which helps to solve the interference influence problem when super-sensitive device has to be used for scientific experiment and no possible to deploy a rigid enough boom for it.

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