GEOMAGNETIC FIELD PERTURBATION BY A PLASMA PLUME

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Abstract

The EPICURE complex space experiment[1] study of the Earth's magnetic field perturbation by a plasma plume is the subject of the paper. The EPICURE plasma generator operated on board a spacecraft and produced a flow of Cs^+ ions with the flow rate of $N=2\cdot 10^{20}$ sek^{-1} and flow velocity $u=2\cdot 10^3$ $m\cdot sek^{-1}$. The geomagnetic field perturbations were registered with two 3-component detectors, mounted at 4.5 m and 7m from the plasma generator. The measured disturbance of the geomagnetic field ***B*** corresponds to the diamagnetic displacement of the field out of the volume of a conductive jet. The 3D picture of the geomagnetic field ***B*** perturbations coincides with a 3D model of a plasma petal[2], any expansion in which across the field ***B*** causes generation of a system of electric currents. On the one hand, the obtained results provide numerical assessment of the disturbance effect of a plasma plume and, on the other hand, they represent an example of diagnostics of a plasma flow during an on-board operation of a thruster.

Introduction

Expansion of a plasma plume, injected into the circumterrestrial space by an onboard generator, is under essential effect of the Earth 's magnetic field ***B***. It is connected with that magnetic pressure $B^2/2\mu \leq 10^{-3}$ J/m^3 is comparable to plasma pressure at $T_e \sim 1$ eV, $n_e \sim 10^{10}$ cm^{-3}. At the initial stage of expansion gas kinetic pressure is higher than the magnetic one $\beta = 2\mu n_0 T_0 / B^2 > 1$. The magnetic field is being displaced out of the volume of plasma. Starting from some distance, the inequality $\beta \leq 1$ becomes valid for the parameter of magnetic interaction; so, dynamic pressure becomes comparable to magnetic pressure. The magnetic field penetrates partially into plasma and deforms the configuration of a plume. The plume transforms into a petal having its plane parallel to vectors ***B*** and ***U***, the velocity of a plume [1].

Lines of force of the magnetic field are distorted by diamagnetic currents ***j*** that arise in a jet during its expansion in an external magnetic field.

The system of currents generated in plasma compresses the plasma plume along $\pm y$ direction across the magnetic field. Pressure gradient along OX axis (that is along the velocity of a plume) and force $f_x = j_y B$ balance each other and thus, the velocity of a plume expansion along OX axis does not vary, $u=u_0$..

In case the velocity of a plume expansion is directed along the external magnetic field $U \parallel B$, annular currents arise in the plasma and they flow around the direction of injection.

In case the velocity of a plume expansion is normal to the lines of force $U \perp B$, the picture of currents in that plume represents itself a toroidal segment having an oval cross-section. The diamagnetic structure of currents was validated by the EPICURE experiment.

Experiment Arrangement

The EPICURE plasma generator of end-Hall thruster- type was mounted on board a *Cosmos*-type satellite. The generator produced a flow of Cs^+ ions with the flow rate of $N=2\cdot 10^{20}$ s^{-1} and flow velocity $u=2\cdot 10^3$ m s^{-1}. Registration of the Earth magnetic field disturbance arising due to injection of a plasma plume was the object of work. The velocity of a plume was in the orbital plane and directed to the spacecraft velocity at the angle of 150° as shown in fig. 1. Two sensor units of MME (Magnetic Measuring Equipment, IZMIR RAN development) were mounted on a boom at the distances of 4.5 m and 7 m. Each of the detectors measured three components of the geomagnetic field.

The spacecraft was on a circular orbit with inclination of 65° and 800 km altitude, orbital period of ~100 min and had a strong orbital orientation and stabilisation. The flight trajectory was computed to provide a

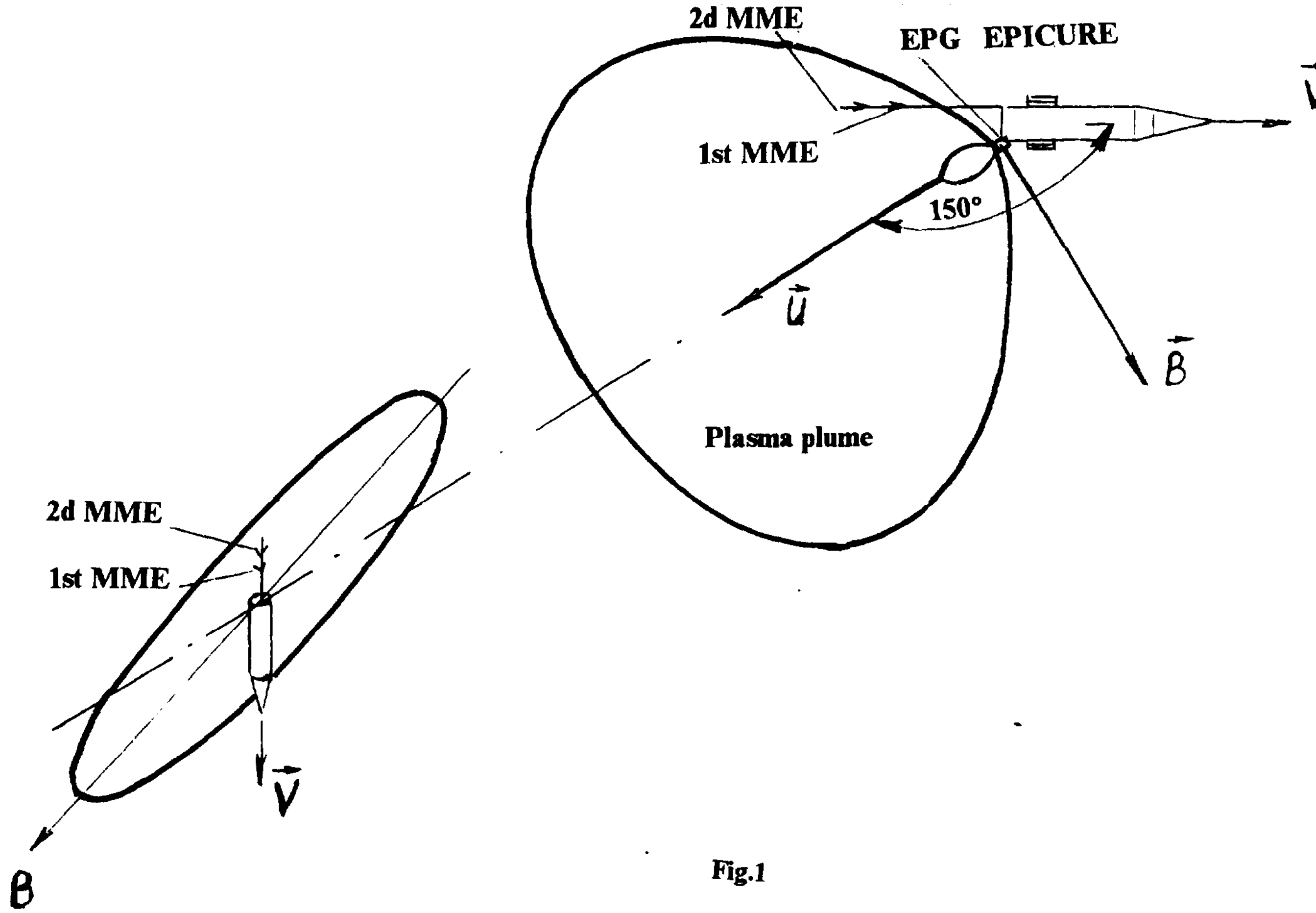

2d MME
EPG EPICURE
1st MME
150°
u
V
B
Plasma plume
2d MME
1st MME
V
B

Fig.1

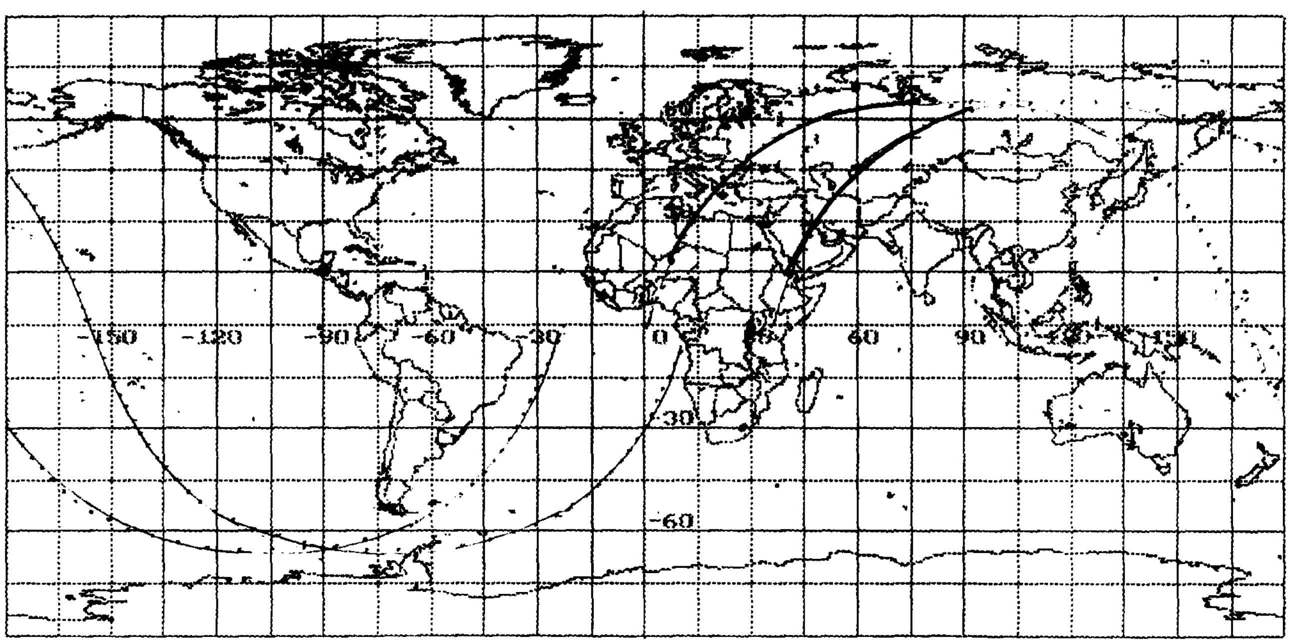
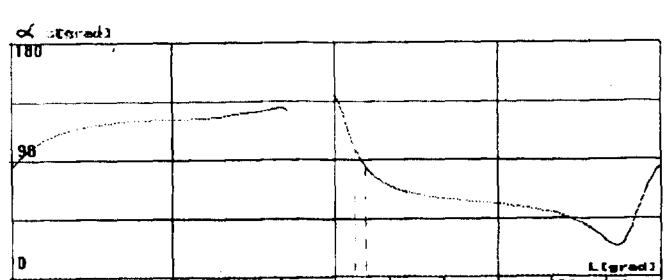
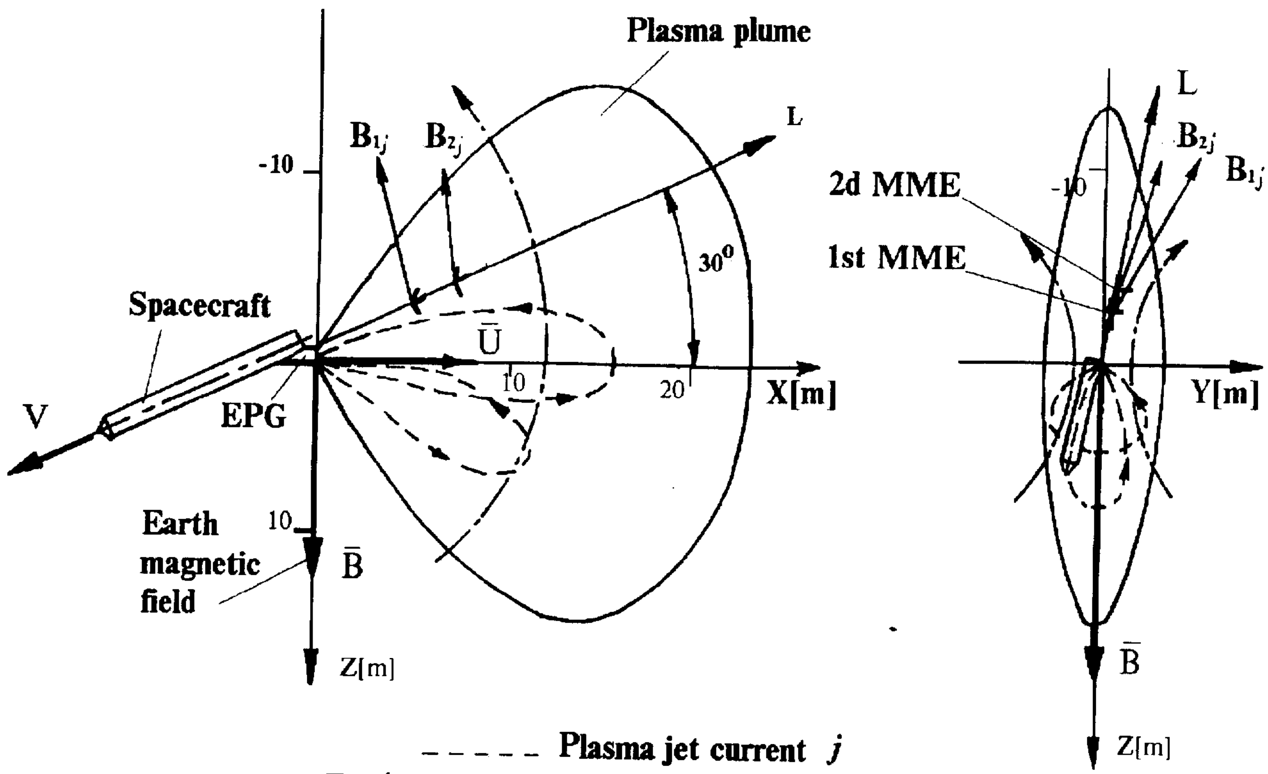

-150
-120
-90
-60
-30
0
60
90
-30
-60

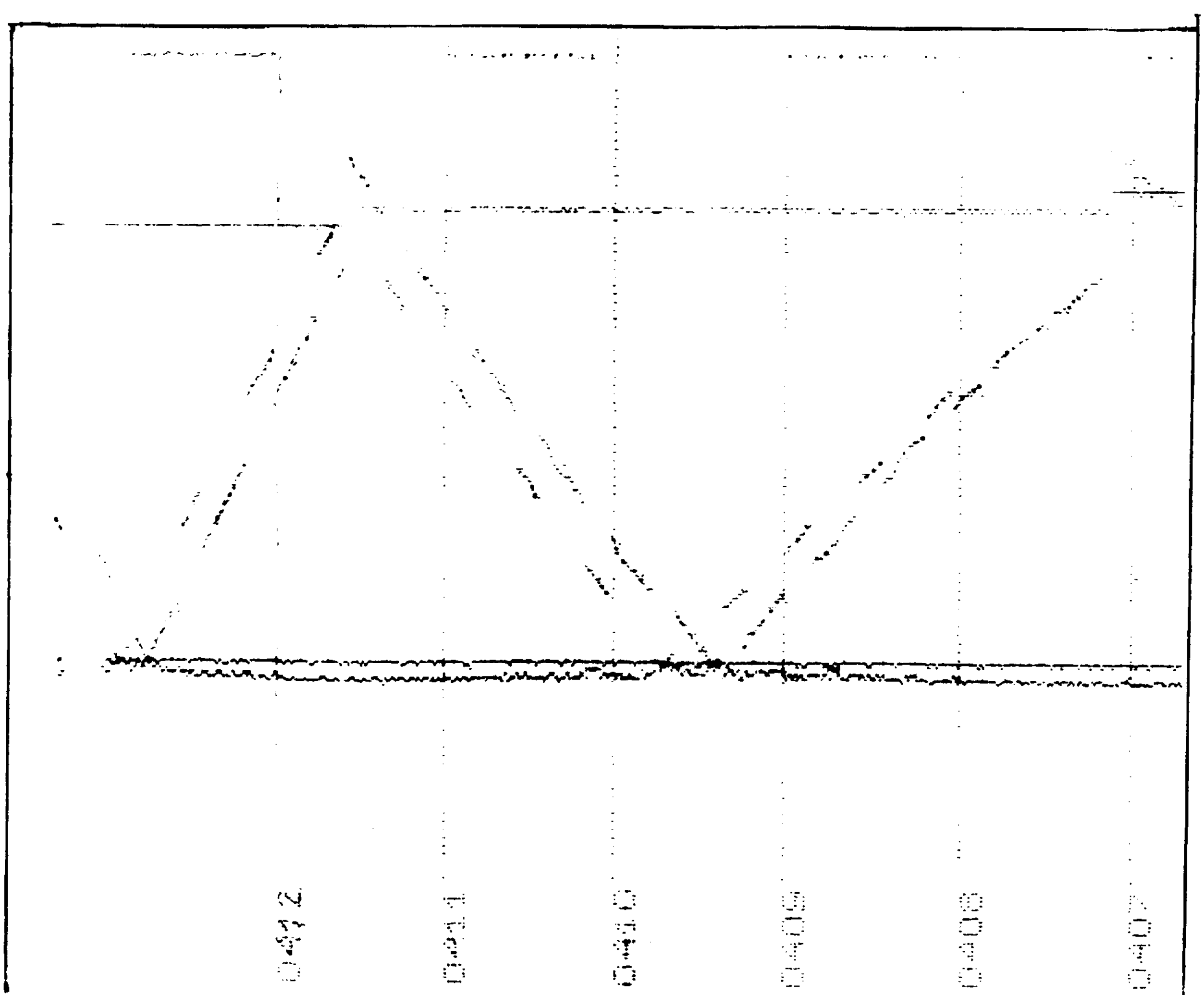
Fig.2


α (grad)
180
0
L (grad)
-180
-150
-120
-90
-60
-30
0
30
60
90
120
150



- - - - - Plasma jet current j

Fig.4 — — — Magnetic induction B_j of plasma jet current



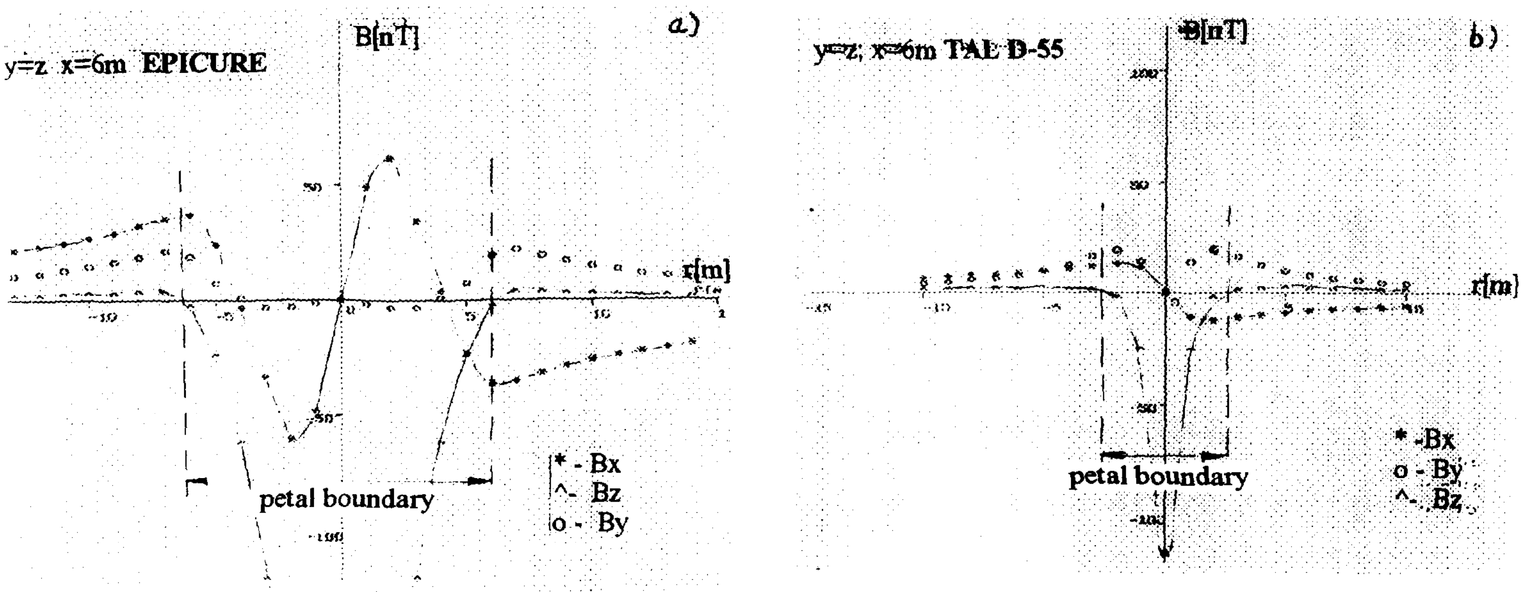


Fig.6

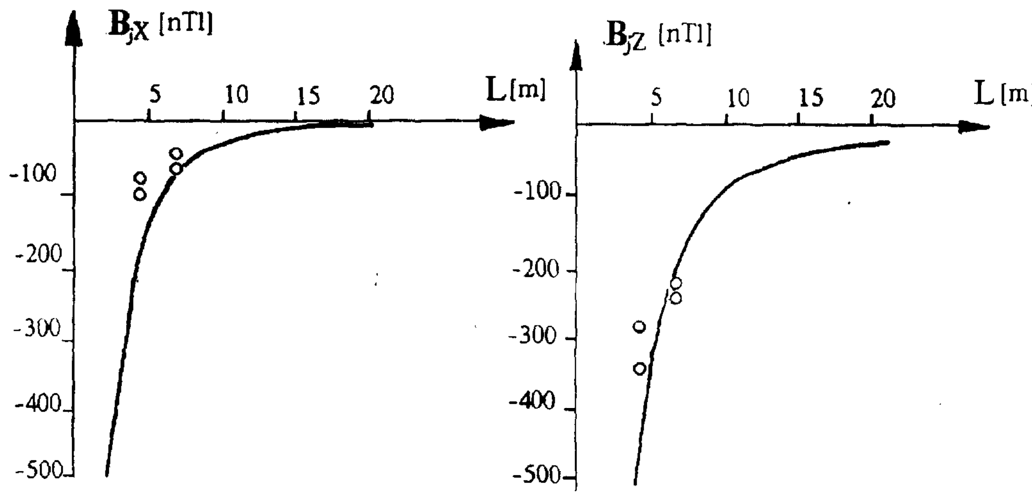


Fig.7 Comparison of experimental and theoretical data

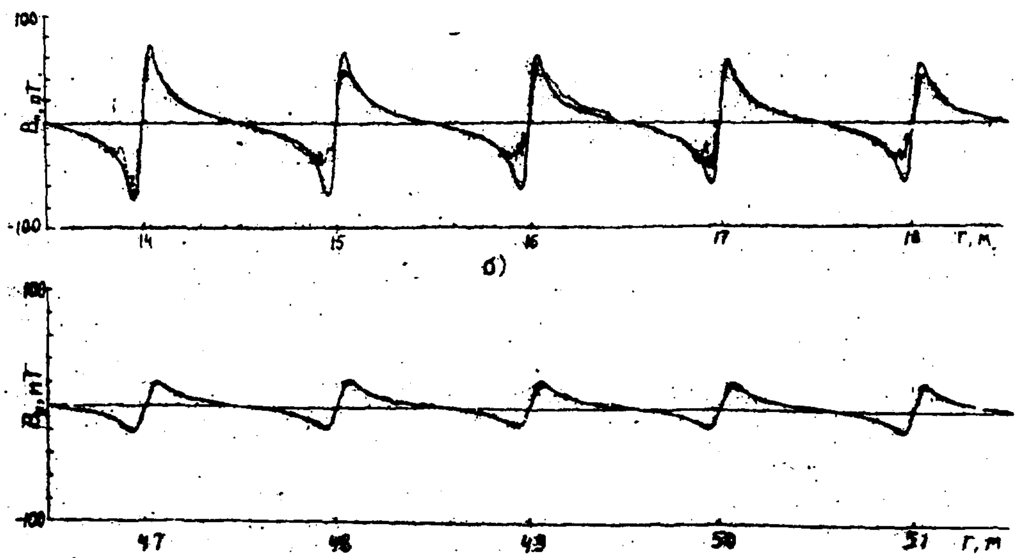


Fig.8 Longitudinal component of magnetic field
a) at distance 14-18m

path circle with the period of 99 revolutions. It means that each 100-th orbital pass overlaid the 1-st one. The plasma generator operated for 20...30 minutes in the visibility zone of the equipment (bold lines on fig.2) according to the periodic operation mode with the cycle: 16-sec operation / 8-sec pause.
Thus, among the all interesting parameters of the experiment there was only one - induction of the geomagnetic field ***B***- that varied. At every point of the orbit both features of the vector ***B*** changed - its value and its direction. The change of the latter one was more considerable. In figure 3 the behaviour of pitch angle α (the angle between vectors of a plume velocity and geomagnetic induction ***B***) during one orbital pass is depicted. The geographical latitude of a point is *x*-coordinate. A part of the orbital pass went above Moscow. One can see from the figure that at the orbital point over the earth region with 10°÷20°W.L. the pitch angle was ~90°. It means that a plasma jet was perpendicular to the geomagnetic field ***B***. In this case of orientation of a plume the geomagnetic field disturbances are maximum. There was found one more region where conditions of such kind could be realised.
The geometry of the problem is shown in plume-referenced coordinates in figure 4. In that coordinate system OZ axis is directed along the earth magnetic field vector ***B*** (OZ||***B***) at every point of the orbit. OX axis coincides with the plume velocity ***U*** (OX || ***U***). ***L*** is the distance along the cantilever where two MME sensor units were mounted. In the picture the line of equal density (*n=const*) is plotted for the case of $2.8 \cdot 10^{8}$ cm^{-3} concentration. It should be noted that for the taken case of geometry the both MME sensors were inside the plasma petal. The detectors registered components of the geomagnetic field ***B*** every second (during pause in the operation cycle) and components of the total field $\Delta B+B$ (during operation phase of the thruster's cycle).
An example of the telemetry record of a MME sensor's signal is represented in fig. 5.
On the record one can see a jump in the total magnetic field after the plasma generator activation. The same pattern of disturbances was observed for all the three components registered both by the first and the second MME detectors.

Theoretical Analysis

The picture of currents in a plume represents itself a toroidal segment of an oval cross-section[3] (see fig. 4). Inside a plasma formation (PF) the direction of the magnetic field ΔB generated by this structure of currents is opposite to the external magnetic field ***B***, and near the boundary of a PF the resulting field exceeds B: $(\Delta B+B) > B$.
To calculate magnetic field ΔB of a plume as a function of coordinates a code has been developed. The algorithm uses integration of the current density *j* equations under the Biot-Savarra law

$$\vec{B} = \frac{\mu}{4\pi}\iiint_V \frac{[\vec{j}\times\vec{l}\,]}{r^2}dV ,$$

where r - a distance from an element of current to a point; $\vec{l}$ - a unit vector along r.
In figures 6a,b examples of the own (natural) magnetic field of a plume for two types of thrusters are represented. Figure 6a shows calculations of the magnetic field of the EPICURE plasma generator plume, and Figure 6b represents the same results in case of a SPT-100 or DAS D-55 plume. In the figure there are distributions of the all three components of magnetic field ΔB along the line $y=z$ in the cross-section of a plume $x=6m$. The behaviour of the curves demonstrates that due to existence of closed currents inside a PF diamagnetic effect appears. However, in case of a SPT-100 or DAS D-55 plume the magnitude of the magnetic field induction is lower.
Comparison of calculations and the EPICURE experiment data is represented in figure 7. Distance along the boom ***L*** where the MME sensors were mounted, is measured along x-axis. Vectors ΔB_1 and ΔB_2 in figure 4 correspond to the magnetic field of a plume constructed also on the base of experimental telemetry data of the MME's 1st and 2nd sensor units .
The obtained experiment data validate the correctness both of the system of currents inside a plasma plume of an electric thruster and of the model of interaction between a dense low-temperature plasma and an external magnetic field.

Comparison with Other Experiment Results

The mentioned above distribution of current in a plasma plume differs from the one described previously [4] in case of Porcupine experiment. In that experiment a plasma plume was generated by SPT-70 at the altitude of ≥200km. Transverse electric field damped itself at the distance of ~ 1m. Therefore at the distances of 15..50 m from the nozzle exit section (where sensitive probes were mounted), sensors registered a conical expanding flow of ions. As a result of that the coordinate function of the magnetic field of a plume is different. The curve of that dependence taken from [4] is shown in fig. 8.

The above was caused by the fact that in the Porcupine experiment a rather rarefied plasma plume transformed itself in a conical flow of ions surrounded with a current of ionosphere electrons.

The influence of external magnetic field appeared through the deflection of the conical plume axis in the direction ***U*** x ***B*** with radius of ions $R_L = m_i U / eB$.

In the EPICURE experiment, in a dense plasma plume injected at the altitude of 800 km diamagnetic currents appeared. Short circuit currents through the ionosphere plasma were inessential. The distance of the transverse electric field damping was greater by hundred times and was about 200 m.

On the graph of the geomagnetic field ***B*** disturbances one can see the effect of diamagnetic displacement of the field ***B*** out of the plasma volume (see fig. 6a).

Influence of the external magnetic field appeared through limiting of a plume expansion in the direction of ***U*** x ***B*** that caused formation of a petal .

Conclusion

1. Configuration of plasma formations (PF) generated in the vicinity of a spacecraft during operation of a thruster is under the geomagnetic field influence.
2. The geomagnetic field affects upon the flows of substances and energy inside the PF.
3. Exhausted plasma plumes of typical thrusters such as TAL or SPT cause disturbances of the geomagnetic field $\Delta B \sim 1000$ nT at the distances of 1...5 m along the plumes.
4. If parameters of a plume have a jumping change (e.g., turn-on/turn-off or pulse mode) the disturbances cause generation of a correspondent electro-magnetic impulse.

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