CONCEPT of ELECTRODYNAMIC PROPULSION SYSTEM for STATION KEEPING of LARGE SPACE STRUCTURES

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Abstract

The given paper presents the concept of the electrodynamic propulsion system (EDPS) for station keeping of the projected International Space Station (ISS) "Alpha" where the current driven by on-board power supply, is allowed to circulate along the horizontal transversal lattice girder in order to produce thrust due to interaction with the Earth magnetic field.

The expected EDPS performance were estimated and analyzed for the task of atmospheric drag make-up with some critical assumption concerning the possibility to run large current through the ionospheric plasma

The analyses performed suggests that the expected advantage of the EDPS as compared to other propulsion systems, is possibility to use light weight working substance like hydrogen or easily ionizable Lithium, offering to obtain extremly high "effective" specific impulse up to 70000 s and relatively low mass flow rates. As a result the EDPS being used instead of any conventional electric propulsion system, is capable to save at least a few tons of cargo which is to be launched into the orbit during 10-year flight of the ISS "Alpha".

The obtained estimations look promising, but reality of the EDPS concept extremely depends on solution of the problem of the ionospheric current closure path and other considerations including available onboard power capability and all aspects of compatibility.

Introduction

Due to the interaction between the Earth magnetic field and large space structures (e.g. of ISS "Alpha" class) the latters are expected to become polarized and electrically biased of a few tens of Volts relative to the ambient ionospheric plasma. These effects are discussed elsewhere concerning electrodynamic tethers in space. The polarization effect may greatly increase energy of ionospheric ions bombarding outer surfaces of the station with subsequent enhancementof their electrization and danger of arcing and other undesirable events resulting in more intense ageing of sensitive surfaces, especially solar panels.

On the other hand the electrodynamic effects may be used for station keeping of large space structures. The priciple of operation of electrodynamic propulsion system (EDPS) is based on interaction between the Earth magnetic field and electric current circulating in a properly long conductor due to available electromotive force of the on-board power supply with closure path through immobile ambient ionospheric plasma. The thruster mode of operation is well discussed and estimated for long vertical tethers (see Ref. 1, for instance).

The given paper presents the concept of EDPS where the current is allowed to circulate along the horizontal transversal lattice girder of the ISS "Alpha".

Priciple of Operation of Electrodynamic Propulsion System

To have got electrodynamic effect of proper magnitude this transversal structural conductor must be elongated from both ends using, for instance, flexible booms with closed elastic profile. The boom of this kind is in use on OS "MIR" since 1987. However these booms must be rigid enaugh unlike the classical vertical tethers stretched and stabilized by gravitational forces. The resulting geometry is shown in Fig. 1.

The accelerating Ampere force may be applied to the horizontal conductor if the latter curries the current with closure path through immobile ambient ionospheric plasma. This current interacts with vertical component of the Earth magnetic field unlike the vertical tethers. It is believed that good electrical contact with the ambient ionosphere at both ends of the conductor may be provided with plasma contactors.

Fig. 2. shows the relative orientation of of the Earth magnetic field components and the transversal horizontal conductor orbiting with inclination i. It is assumped here, that the magnetic and the geographic poles coincide. Accounting for the real 11 degrees offset of the poles does not sufficently impact conceptual evaluations presented below. It is also assumped that the Earth and co-rotating ambient ionospheric plasma are both immobile.

In the LEO the Earth magnetic field is approximated as a dipole with horizontal and vertical components [1]:

$$B_h = B_0 * \sin(90^o-\varphi)*(r_e/r)^3 = B_0*\cos\varphi*(r_e/r)^3 ;$$

$$B_v = -2B_0*\cos(90-\varphi)*(r_e/r)^3 = 2B_0*\sin\varphi*(r_e/r)^3 ,$$

where B_0 = 0.35 Gauss = $3.5*10^{-5}$ Tesla, r_e is the Earth's radius and φ is the latitude.

As a satellite orbits with inclination i and angular velocity ω, its latitude follows the simple low:

$$\sin\varphi = \sin i \sin \omega t,$$

where time, t, is counted from the ascending node, so that theEarth magnetic field components with time change as:

$$B_h = A\, B_0 *(1 - \sin^2 i \sin^2\omega t)^{0.5},$$

$$B_v = 2A\, B_0 * \sin i \sin\omega t,$$

where the multiplier $A = (r_e/r)^3$ is taken 0.784.

The Faraday emf, *E*, will be induced in the thin horizontal conductor of L meters long orbiting with orbital velocity, v, due to the only interaction with the vertical component of the Earth magnetic field:

$$E = [vB]L = 2ALB_0vL \sin i \sin\omega t.$$

If the current, I, is allowed to circulate in the horizontal conductor, the latter experiences the Ampere force, F = [*IB*]L. This Ampere force will be the accelerating one if direction of the current circulation in the horizontal conductor is opposit to the Faraday emf,*E*. Assume that the current also changes harmonically, $I = I_0 \sin \omega t$. Then the horizontal component of the Ampere force:

$$F_t = -2ALB_0I_0 \sin i \sin^2 \omega t ,$$

produces thrust being permanently aligned with vector v and so far accelerating the satellite. The vertical component of the Ampere force:

$$F_l = -0.5A\, LB_0 I_0 \sin i \sin 2\omega t$$

produces the lifting force changing its sign during the orbital period, so that the average lift is zero. The thrust with the average value of

$$< F_t > = ALB_0I_0 \sin i$$

may be used for the atmospheric drag make-up or/and for the orbital altitude rise. As a result the on-board supply power may be transformed in the increased orbital energy.

It is worth noting that as far as the accelerating Ampere force depends on sin i, the EDPS with the horizontal current currying conductor serves no purpose in the equatorial orbit and it is the most effective in the polar orbit since the thrust is here maximal.

The accelerating Ampere force must be applied to the structural center of mass in order to prevent arising of disturbing torques, or somewhere ahead this center where the thrust would inhibit the torques produced by the lift.

On the other hand the torques produced by the components of the accelerating Ampere force, principally may be used for the satellite orientation. Additional δL elongation of either arm of the horizontal current currying conductor will provide the torque $F_t\delta L$ for the yaw control. The same δL elongation with the current regulation " in tact"rather with horizontal than vertical component of the Earth magnetic field will provide the torque $F_l\, \delta L$ for the roll in control. If the point of the Ampere force application is δL shifted ahead the structural center of mass (the opposit situation is intolerable), the arising torque $F_l\delta L$ will provide the pitch control. The pitch control may be also provided if the horizontal current currying conductor is made dual as a vertical frame with back sides of $2\delta L$ long and the frame center coincides with the structural center of mass. Then allowing the current to circulate either along the upper or the lower frame side one may produce the torque $F_t\, \delta L$. This version looks preferable since it may provide rather accurate satellite orientation relative to the local vertical direction with no penalty for the thrust mode of the EDPS operation.

Therefore the EDPS with the horizontal current currying conductoris is able to provide all kinds of the satellite movement control with the exeption of orbital plane change.

End Plasma Contactors

For good electrical contact with the outer branch of the EDPS circuit, both ends of the current currying conductor must be provided with plasma contactors - devices injecting electrons from the cathode end and injecting ions and/or collecting electrons from the ambient ionospheric plasma at the anode end. It is believed that the role of plasma contactors could play plasma sources of the hollow cathode or arcjet type. Impedances of the end plasma contactors and the current closure path through ambient ionospheric plasma characterize energy losses of the EDPS operation.

The expected impedance of the EDPS current loop is not still properly evaluated. The general opinion from available publication on electrodynamic tethers in space is that the bulk of potential drop in this current loop belongs to the double electric layer apppearing between each contactor and ambient ionosphere and that the impedance of the latter is negligible since it is treated as a conductor of practically infinite dimensions.

Analytical evaluations of the plasma contactors operation suggest that at great currents in the EDPS circuit the mechanisms of electron collection from the magnetized ionospheric plasma are not effective enaugh. With this suggestion let us assume that the current closure at the anode end is provided only due to ion injection into the ambient media with no electron collection. This assumption corresponds to the worth operating mode of the anode end plasma contactor from the view point of the mass consumption as it was discussed in Ref. [2] (Regime 3). Available wide experiences in the hollow cathodes operation suggest that the process of electron injection requires manyfold lesser mass consumption so that the latter will be further neglected.

As it was mentioned above, the current direction must be changed during the orbital period in order to produce the permanent thrust.This requires either reversing power supply polarity and simultaneous change of operating modes of both plasma contactors. The results of experiments on ground simulation of plasma contactors operation [3,4] suggest that reversible plasma contactors may be realized using so called "ignited" mode when a contactor actually injects rather neutral gas than ready made plasma, and a plasma bridge appears as a discharge firing between the gas injector and a collector simulating the ambient ionosphere if the electrical bias is great enough.

In the experiments with the hollow cathodes [3] using Xenon, transition to the "ignited" mode with currents greater than 1 A was observed at 45 - 50 V bias for the anode plasma contactor and at 25 V for the cathode one. In the ealier experiments [4] with a good lot of plasma sources using Xenon and Argon, transition to the "ignited" mode with currents greater than 10 A was observed at 100 - 150 V bias for the anode plasma contactor under the condition of rather great mass flow rates (greater than 2 eq. Amperes). In recent experiments (with the author assistance, not published)using the Cesium plasma source EPICURE[5] the "ignited" modes with currents up to 20 A were obtained both in anode and cathode version at 30 V and 16 V bias correspondingly. For easily ionizable Cesium the "ignited" mode is characterized by greater currents and lesser biasesas compared to Xenon with its four times greater ionization potential.This is the expected feature as far as the "ignited" mode represents any specific form of the self-sustaining discharge.

In the light of the experimental results mentioned above, a conservative estimation of the maximal voltage drop, V, in the double layers at both end contactors may be taken at the level of about 10-11 values of the ionization potential V_i of the gas injected in order to be definit while further evaluating the expected EDPS performance. With assumption that the impedance of the ambient ionosphere curring the current between plasma clouds of each contactor, is negligible, the value V also characterizes the total voltage drop across the outer branch of the EDPS circuit. Let us also assume that V is sinusoidal one to drive the sinusoidal current in the EDPS circuit although actually V must change according to the Volt-Ampere characteristics for the "ignited" mode of the plasma contactor operation.

If the current is driven in the EDPS circuit only due to ion injection with no electron collection as it was assumed above, the current intensity is predomenantly determined by the mass flow rate, M_g, of the working gas from the anode plasma contactor:

$$I_0 = kM_g e/mA_g,$$

where A_g is atomic number of the working gas, k is an ionization degree, e and m are proton's charge and mass.

To provide the required current with minimal mass expences, it is reasonable to choose the most light weight working gas , e.g.hydrogen, for the plasma contactors. For hydrogen with V_i=13.5V the acquired estimation of total voltage drop across the outer branch of the EDPS circuit gives V_0 =150 V characterising energy losses in the EDPS current loop since the impedance of the ionospheric parts of the loop may be put zero for the first approximation.

Expected EDPS Performance

Let us evaluate the efficiency of the EDPS for the task of atmospheric drag make-up. The average power required for the drag compensation is

$$\langle W\rangle = \langle Ft\rangle v = ALvB_0I_0 \sin i .$$

The Ohm's law for the EDPS current loop including the metallic conductor of impedance R, the on-board power supply of output voltage U and the outer branch of the EDPS circuit, may be written as:

$$U = E + IR + V.$$

The ohmic losses may be neglected for relatively short conductor rather of a few hundreds meters long, than a few kilometers as for projected long vertical tethers, so that the average energy consumption from the on-board power supply is

$$\langle P\rangle = 0.5I_0(2ALvB_0 \sin i + V_0).$$

Then the average efficiency of the EDPS

$$\eta = \langle W\rangle/\langle P\rangle = 1/(1 + V_0/2ALvB_0 \sin i),$$

does not depend on the current and is defined by the relation of maximal values of V_0 and the induced Faraday emf, $2ALvB_0 \sin i$.To compare the EDPS with an electric propulsion system (EPS), also expending energy of the on-board power supply, let us take η = 0.5,the value generally applied for e.g. SPT or TAL thrusters. This value defines the choice of the total lengh, L, of the current currying conductor, since the value

V_0 has been already chosen from the condition of the expected possibility to run the "ignited" mode of the plasma contactor operation with large currents:

$2ALvB_0 \sin i = L*0,34$ V/m, $= V_0$

for the ISS "Alpha" orbit inclination i = 51.6 degrees.So 0.34 V/m is maximal value of the induced Faraday emf per meter for the given flight geometry. With the chosen value V_0 = 150 V we find L = 440 m, so that the length of each additional boom in Fig.1 is approximately 165 m. This four times increase of the transversal dimension is likely a striking surprise for the ISS "Alpha" designers.

The required maximal output voltage, U, of the power supply allowing the current to circulate is of about 2 V_0 , so not less than 300 V, the value being often chosen as the working voltage for SPT or TAL thrusters to obtain specific impulse Isp = 1600 - 2000 s.

The average thrust required for the ISS "Alpha" drag make-up, may be evaluated from

$$M_\alpha v = \langle F_t \rangle T,$$

where data, M_α = 406 500 kg and v = 485 m/s, on total impulse to be compensated during 10-year period T, are taken from Report[6] , where the concept of the EPS for the ISS "Alpha" is presented. The corresponding average thrust is 0.62 N and the required power for drag compensation is of about 4.8 kW. With the average efficiency of the EDPS, η = 0.5, the average rate of energy consumption from the on-board power supply is 9.6 kW, so that maximal current is 64 A and the average rate of current consumption is 41 A.

Such a large current, however, does not look non-realistic in the light of the ground experiments mentioned above, where currents greater than 10 A were obtained using Xenon and those up to 20 A were observed with easily ionizable Cesium in the "ignited" mode of plasma contactor operation. Surely, the question whether the high current "ignited" mode may arise under the real flight conditions of the rarefied and magnetized ionospheric plasma, is still open so that the assumption of this possibility is very critical for the analyses presented.

Approximately the same evaluation of the EDPS energy consumption scale may be obtained using data on the drag compensation for the Space Operation Center, an early large structure concept. From Ref.[1] for altitudes between 430 and 460 km the average drag is not greater than 0.5 N. The corresponding average power for drag compensation with h = 0.5 is greater than 8 kW. The level of the EDPS energy consumption up to 10 kW well falls in the concept of the solar gas-turbine power supply with two modules of 10 kW each presented in Ref.[6] in reference to the project of the EPS for the ISS "Alpha".

To provide the above calculated current of 41 A, the required mass flow rate of hydrogen with moderate ionization degree of k=0.5 at the plasma contactor exit is 0.82 mg/s. Then the total mass consumption,M_t, for 10-year flight period is approximately 260 kg.

The "effective" specific impulse, $I_{sp} = \langle F_t \rangle / M_g\, g$, of the EDPS is very high - on the level of 77 000 s. This is not surpising since the EDPS expends mass only for closing the current loop, not for producing the thrust. The latter is produced due to mutual repulsion of the mobile metallic and immobile ionospheric parts of the current loop.

Injection of partly ionized gas by the plasma contactors will produce a reactive force,F_{tp} , of the plasma flow, e.i. disturbing thrust and torques. The upper estimation of this thrust may be obtained with the assumption that the plasma flow from the plasma contactor is monoenergetic and perfectly focused:

$$F_{tp} = M_g (2e\langle U \rangle / mA_g)^{0.5}$$

With hydrogen mass flow rate of 0.82 mg/s the resulting disturbing thrust, F = 0.12 N, is well compared to 0.62 N, the usefull EDPS thrust. Since the end plasma contactors functionally replace each other every half-period of the orbital revolution these disturbing thrust and torques will be compensated in average. Never-the-less it is necessary to provide torqueless plasma injection, e.g. as it is shown in Fig. 1. If heavy gas, e.g. Xenon is used as a working substance of the end plasma contactors, the disturbing thrust may exeed the usefull EDPS thrust so that the EDPS will serve no purpose.

Therefore the only expected advantage of the EDPS as compared to other propulsion systems, is possibility to use light weight working gas offering to obtain extremly high "effective" specific impulse and relatively low mass flow rates.

The additional booms complecting necessary length of the EDPS thrusting conductor represent net mass penalty inherent to the EDPS.For the given example a conservative estimation of this mass penalty is 500-700kg. Assuming that masses of the cabling and tubing for the EDPS and EPS are equal, one may expect that use of the EDPS instead the EPS, is capable to save at least a few tons of cargo which is to be launched into the orbit during 10-year flight of the ISS "Alpha", since the EPS with specific impulse of 1600-2000 s would totally exhaust 10000-12000 kg of the working substance whereas chemical thrusters with specific impulse of 300 s would consume up to 60 000 kg of fuel.

The thrusting mode of operation may be also realized using classical vertical tethers deployed e.g. upward and downward from the both ends of the transversal lattice girder. It may be shown that the EDPS performance like presented above may be obtained with vertical tethers not shorter than 1 km. This looks non-perspective since may pose a serious interference for docking manouvers.

The visually unpleasant feature of the given EDPS concept is necessity to build up the horisontal current currying conductor long enough to obtain an acceptable efficiency. With the analogy to the Cesium experiments mentioned above, one may expect that use of light weight and easily ionizable Lithium as the working substance for the plasma contactors will allow to reduce the electrical bias required to run large currents and hence to reduce the length of the current currying conductor. Taking for Lithium V_0 = 60 V we obtain the EDPS efficiency η=0.5 with L=176 m looking much more attractive than 440 m with hydrogen. The calculations concerning possible use of Lithium for the EDPS are presented in Table1.

Table 1.

	gas	L, m	η	<P> kW	<I> A	I_{sp} s	M_t t
EDPS	H	440	0.5	9.6	41	77000	0.26
	Li	440	0.71	6.5	39	13490	1.48
	Li	176	0.5	9.6	102	5160	3.88
EPS	Xe	-	0.5	9.6	32	2000	10.1

Table 1. suggests that expected mass saving is still attractive even with relatively short current currying conductor, but perspective to run as large currents as 100 A seems to be a subject of hesitation at least.

Conclusion

Due to action of the Earth magnetic field the orbiting large space structures (e.g. of ISS "Alpha" class) are expected to experience noteciable electrodynamic effects which may be used for station keeping. The required thrust can be obtained with electrodynamic propulsion system (EDPS) based on interaction between the Earth magnetic field and electric current circulating in a properly long conductor due to available electromotive force of the on-board power supply with closure path through the immobile ambient ionospheric plasma.

The given paper presents the EDPS concept for the projected ISS"Alpha" where the current is allowed to circulate along the horizontal transversal lattice girder which must be at least twice elongated in order to have got the electrodynamic effects of proper magnitude. For good electrical contact with the outer branch of the EDPS circuit, both ends of the current currying conductor must be provided with plasma contactors - devices injecting electrons from the cathode end and injecting ions and/or collecting electrons from the ambient ionospheric plasma at the anode end. It is believed that the role of plasma contactors could play plasma sources of the hollow cathode or arcjet type.

The expected EDPS performance were estimated and analyzed for the task of atmospheric drag make-up with some critical assumption concerning the possibility to run large current through the ionospheric plasma, based on the results of the ground experiments simulating plasma contactor operation.

The analyses performed suggests that the expected advantage of the EDPS as compared to other propulsion systems, is possibility to use light weight working substance like hydrogen or easily ionizable Lithium, offering to obtain extremly high "effective" specific impulse up to 70000 s and relatively low mass flow rates. This is not surpising since the EDPS expends mass only for closing the current loop, not for producing the thrust. The latter is produced due to mutual repulsion of the mobile metallic and immobile ionospheric parts of the current loop. As a result the EDPS being used instead any conventional electric propulsion system, is capable to save at least a few tons of cargo which is to be launched into the orbit during 10-year flight of the ISS "Alpha".

The obtained estimations look promising, but reality of the EDPS concept extremely depends on solution of the problem of the ionospheric current closure path and other considerations including available onboard power capability and all aspects of compatibility. Never-the-less it seems reasonable to proceed evaluation of possibilities offered by enhanced electrodynamic features of large space structures.

The regularly visited ISS "Alpha" with its horizontal transversal lattice girder over 100 meters long and projected high onboard power capability, represents an excellent test-bench for thorough experimental study of the electrodynamic effects under the conditions of real flight. These experiments may be a good addition to the well known TSS program since offer the possibility to test different types of plasma contactors and to scan in detail the flow field of the ionospheric current closure path.

From the physical point of view the most critical question for the EDPS concept is whether high currents of 50-100 Amperes level may be really run through the rarefied and magnetized ionospheric plasma. Of course, this question is also a common head ache of the whole electrodynamic tether community with no special reference to the concept here presented.

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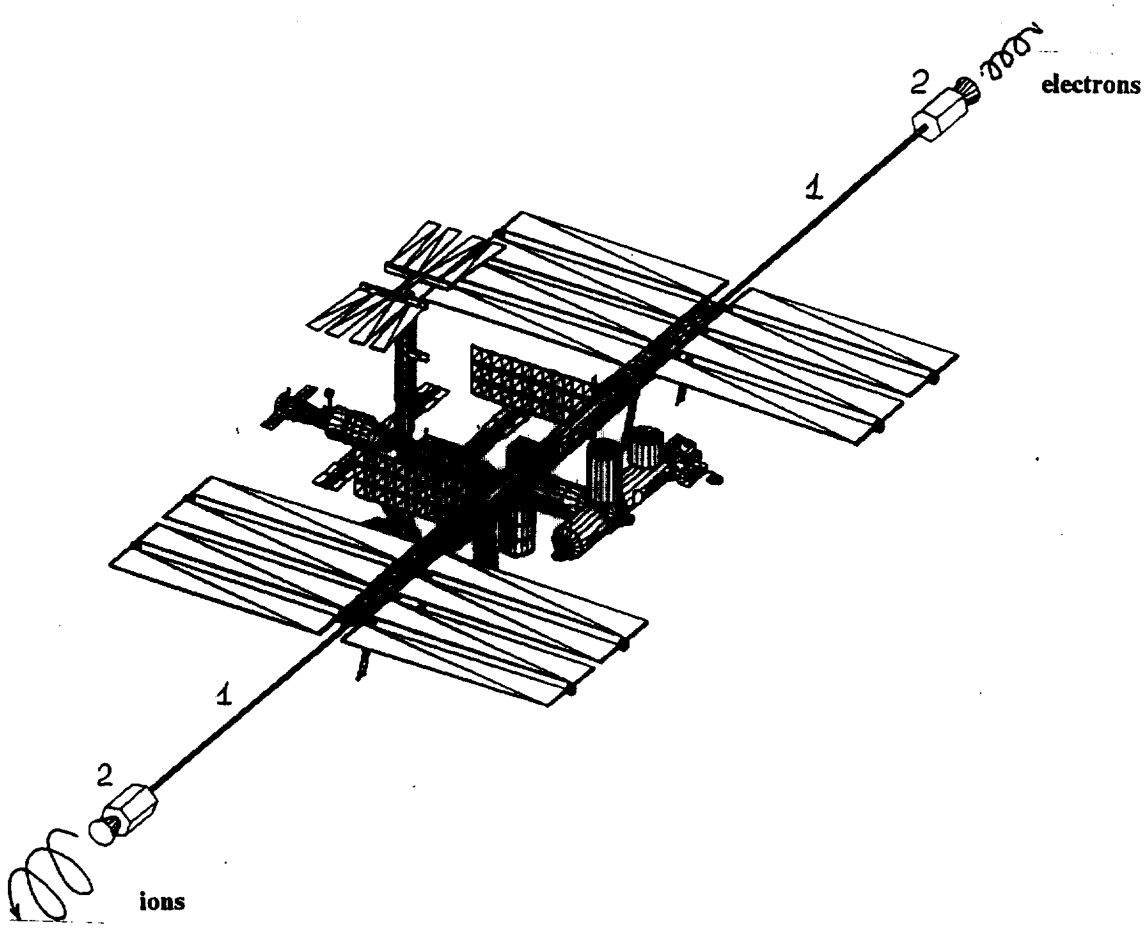

Fig.1

Concept of electrodynamic propulsion system for station keeping of ISS "Alpha"
1 - boom, 2 - plasma contactor

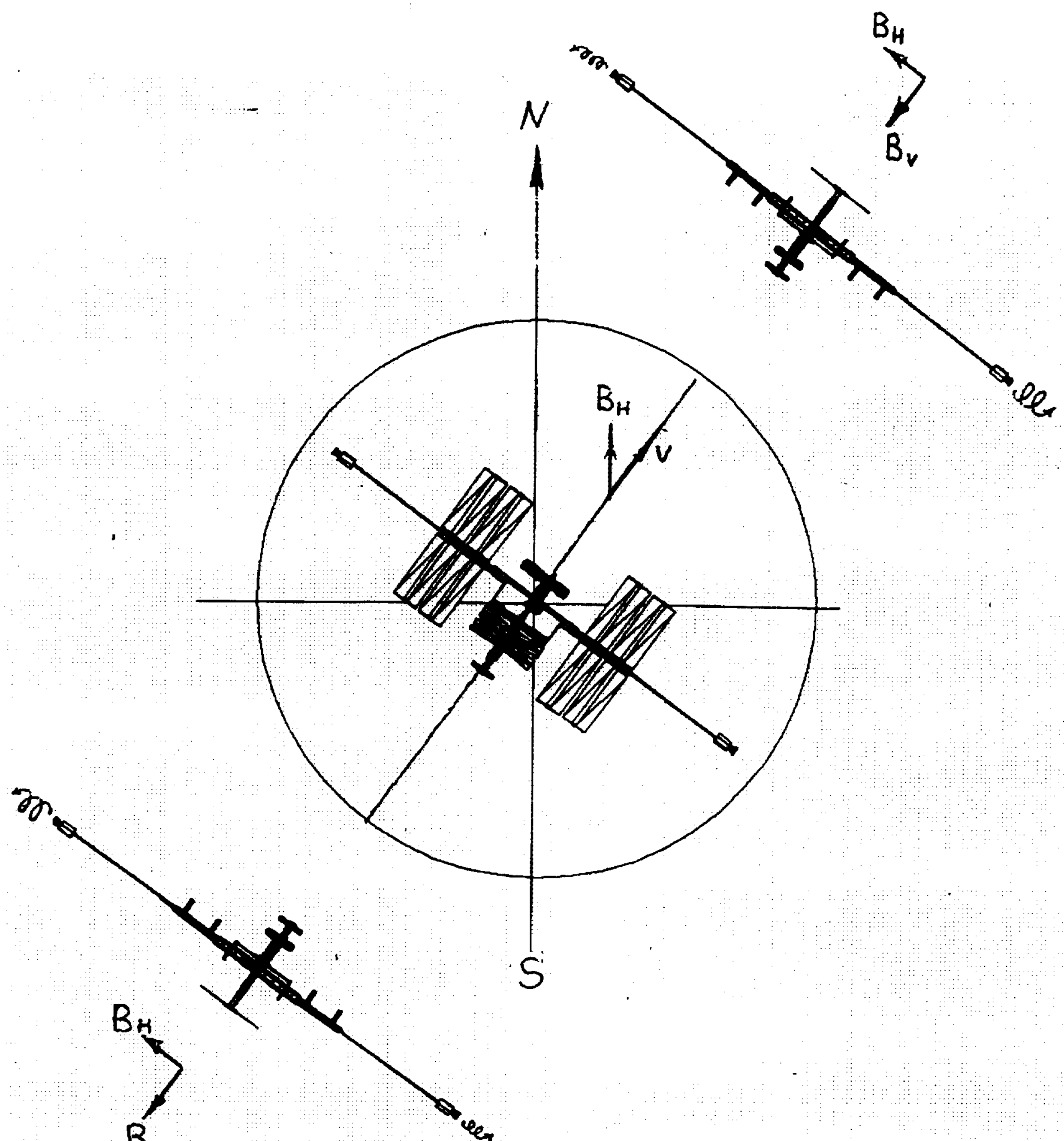

Figure 2

Orientation of the JSS «Alpha» relative to the Earth magnetic field