PAFERM, THE ULISSES PARTICLES AND FIELDS ENVIRONMENT REFERENCE MISSION

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The paper discusses a small satellite mission that was proposed to the European Space Agency (ESA) and to the German Space Agency (DARA). The idea is to support the Ulysses mission by conducting reference measurements in the ecliptic plane, particularly during the time periods of Ulysses' polar passages. The scientific objectives, the instrumentation, and the impact on the Ulysses mission are discussed. The mission scenario is described, the mission constraints are given, and a preliminary spacecraft concept is shown.

1. INTRODUCTION

The Particles and Fields Environment Reference Mission (PAFERM) is a result of a response to a Call for Ideas that was issued by the European Space Agency (ESA) on 18 June 1990. This Call for Ideas was initiated by a recommendation of the Science Programme Review Team. The recommendation was that small missions should be implemented into the science programme. As a guideline for the scientific community some technical information on the characteristics of the small mission where given by the review team as follows.

- total mass below 200 kg
- payload mass between 10 to 50 kg
- stabilization, either spin or 3-axis
- launcher: Scout II, Pegasus or Apex
- orbit, low Earth or GTO
- operations of about 1 year duration
- development time less than three years
- cost to ESA, between 10 to 20 MAU

The proposal for PAFERM was submitted in due time to ESA. As a response ESA received a total of 52 proposals. Quite obviously, the scientific community has a pronounced interest in small missions. This interest was confirmed by a survey conducted by the Science Applications International Corporation; 91% of space physicists surveyed believe that NASA should plan more frequent smaller missions, even at the expense of large missions /1/.

The PAFERM mission is related to the Ulysses mission; the idea is to conduct in-ecliptic reference measurements for Ulysses. The period of utmost interest is the time of the spacecraft's passage of the polar regions of the Sun. Between June and October 1994 the heliographic latitude of the spacecraft exceeds 70 degree; this south polar pass will be followed by a north polar pass between June and September 1995. Therefore, the planned launch for PAFERM is dated April 1994.

The evaluation process within the European Space Agency (ESA) will continue on for some time. Subsequently, the PAFERM proposal was submitted to the German Space Agency (DARA) and found considerable interest. At the time of the writing of this paper, the evaluation process within ESA and DARA is still going on.

2. SCIENTIFIC BACKGROUND

2.1 Introduction

Scientific aim of the Particle and Field Environment Reference Mission (PAFERM) is to complement and support the scientific goals of the Ulysses mission, in particular of its polar passages. During the past decade it has become evident, that new fundamental results concerning interplanetary particle and field physics as well as conclusions on solar or galactic phenomena are only possible with sufficient accuracy if multi-spacecraft measurements are used.

2.2 The Solar Wind

The solar wind originates from the very hot corona of the Sun. Some solar radii away from the Sun, the solar wind is observed as a continous stream of hot plasma reaching out far into the heliosphere. On average, it consists of 95% hydrogen ions (protons), 4% helium ions (a-particles) and different ions of other elements with an appropriate charge-equalizing number of free electrons. The velocity of the solar wind varies widely, in general between about 300 km/s (slow solar wind streams) and about 900 km/s (fast solar wind streams).

The radial expansion of the solar wind determines the structure of the interplanetary medium which is e.g. important for propagation processes of energetic particles. The solar wind plasma flows radially away from the Sun, carrying the solar magnetic field lines as frozen in fields out into space. The field lines generally, remain attached to the solar surface. Its roots follow the rotation of the Sun, and consequently the field lines in consecutive plasma volumes are forming an Archimedian spiral around the Sun.
Figure 1 displays the magnetic field in the plane of the solar equator and shows a marked sector structure, extending into the plane of the ecliptic as well. Regions with magnetic fields predominantly pointing towards the Sun alter with regions of opposite direction.

The general interplanetary structure is often disturbed by non-linear processes, like e.g. shocks. Large shocks are initiated if plasma is ejected from the corona at very high velocities of about 1000 km/s upon solar flares or other dramatic, often explosion-like effects in the corona. The average solar wind velocity is about 400 km/s. The high speed plasma is pushing the normal solar wind ahead and, as the velocity is above the speed of sound in the plasma, the ambient plasma is shocked similar to an explosion shock wave. At large distances all energy of the shock is used up to accelerate the solar wind and the shock dies out.

2.3 The Interplanetary Magnetic Field

Solar wind and interplanetary magnetic field are intimately related due to the so called frozen-ion magnetic fields in the plasma. The general heliospheric magnetic field originates from the Sun's surface field. While field lines are drawn out into interplanetary space by the high electrical conductivity plasma flow of the solar wind, they also remain rooted within the photosphere. Therefore, the investigation of the heliospheric magnetic field is related to the study of solar magnetism, as well as to that of coronal structures and dynamics. Also, it is intimately related to the study of interplanetary phenomena on all temporal and spatial scales.

While direct observations have covered a large range of heliocentric distances, spacecraft orbits have been restricted to the close vicinity of the ecliptic plane. Therefore, little is known with regard to the heliolatitude dependent topology of the interplanetary magnetic field. Remote sensing of the solar surface field and of the corona indicates that it is impossible to extrapolate with sufficient confidence from in-ecliptic measurements to the third dimension of the heliosphere.

Direct observations are therefore necessary to provide an observational basis for establishing the heliolatitude dependence of the heliospheric magnetic field. These observations will be used to investigate numerous phenomena of fundamental importance for our understanding of the heliosphere.

The low-to-middle latitude regions of the Sun are dominated by sunspots and active regions. These regions are normally characterized by closed field lines in the corona. Origin and characteristic features of the solar wind and the magnetic fields over these regions are completely unknown. The measurements of Ulysses compared to PAFERM will help to resolve these questions.

At high latitudes, magnetic field lines and solar wind flow are expected to become parallel. This will strongly influence the stream-stream structure in the heliosphere at high latitude. The investigation of their extent and characteristics as a function of heliolatitude is very important and can be studied by Ulysses and PAFERM together more reliable than with one spacecraft alone.

2.4 Energetic Particles

Cosmic rays consist of electrons, protons, helium nuclei, and some very small contribution of nuclei of all other chemical elements which propagate through space with very high velocities. The high velocities imply that the charged particles have been accelerated in space very efficiently by electric fields. Meanwhile we know from many areas within the solar system that acceleration processes are typical for an extreme tenous plasma. A particle in a plasma of one million degree has an energy of 86 eV. 'Energetic' particles are those which have energies well above the thermal energy of the plasma, e.g. above 50 keV and up to several GeV.

It is known since 40 years that the Sun is able to accelerate particles, although the maximum energy of these solar cosmic rays is much smaller than the average energy of galactic cosmic rays. Solar events are relatively short intensity increases following explosive chromospheric eruptions (flares). Of special interest is the acceleration process during flares. In addition accelerated particles can be used as 'probes' which allow conclusions on magnetic structures in the solar corona and interplanetary space.

The solar wind and the heliosphere are used as a testing ground for theories of the propagation and acceleration of energetic particles in an astrophysical plasma. There are many similarities between the conditions that energetic particles find in the solar wind and those that should exist in other astrophysical plasmas. The development of reliable theories for the propagation and acceleration have been proved difficult. The result is that there are at present major discrepancies between theory and observations. As in the case of the solar wind, we wish to study the particle behaviour at different heliographic latitudes, i.e. under a variety of different plasma conditions, primarily in an effort to help delineate the various processes involved. The changing configuration of the heliospheric magnetic field with latitude should give rise to latitude variations in the nature of waves, shocks and other structures that affect energetic particles.

Solar energetic particles, i.e. energetic particles from the Sun are used as probes to monitor the conditions and physics in the solar atmosphere. These particles provide information on the chemical and isotopic composition of the solar atmosphere and also information on the transport and storage of particles in the strong magnetic fields of the corona. Observations in the ecliptic plane are difficult to interpret since the particles can originate and propagate through a variety of different regions in the corona, with the result that the composition and spectra that we observe are the products of a complicated mixture of processes.

At different heliographic latitudes, the mixture of processes involved is expected to be different, and perhaps simpler. Ulysses will enable us to make observations of solar particles directly over active regions, which are predominantly found at moderate solar latitudes, or directly over the magnetically open regions in coronal holes. Again the reference measurement with PAFERM is mandatory to draw conclusions on coronal and interplanetary propagation from the out-of-ecliptic data.

2.5 Interstellar Gas

Neutral interstellar gas is swept into the heliosphere as the solar system moves relative to the local interstellar medium. Most of the information about this medium is derived from indirect optical measurements of the solar Lyman-a radiation resonantly scattered by the neutral interstellar hydrogen penetrating into the heliosphere. Helium particles, being much less affected by solar radiation pressure, photo-ionisation, and charge exchange with the solar wind, provide more accurate information on the state of the interstellar gas in the vicinity of the solar system than does hydrogen. Ulysses will make the first direct measurements of neutral helium in the heliosphere; these measurements will be complemented by data taken on-board PAFERM.

3. SCIENTIFIC OBJECTIVES

The primary objectives of the Ulysses mission are to investigate for the first time as a function of solar latitude, the properties of the solar wind, the structure of the Sun / wind interface, the heliospheric magnetic field, solar radio bursts and plasma waves, solar X-rays, solar and galactic cosmic rays and the interstellar / interplanetary neutral gas and dust. The following objectives will be achieved in connection with the reference mission PAFERM:

- to provide an accurate assessment of the global three-dimensional properties of the interplanetary magnetic field and the solar wind,
- to improve our knowledge of the composition of the solar atmosphere and the origin and acceleration of the solar wind by systematically studying the composition of the solar wind plasma and solar energetic particles at different heliographic latitudes,
- to provide new insight into the acceleration of energetic particles in solar flares and into storage and transport of these particles in the corona by observing the particle emission from solar active regions and from other magnetic configurations which are more accessible for study from out of the ecliptic,
- to improve our knowledge of the internal dynamics of the solar wind, of the waves, shocks and other discontinuities, and of the heliospheric propagation and acceleration of energetic particles, by sampling plasma conditions that are expected of being different from those available for study near the ecliptic,
- to improve our understanding of the spectra and composition of galactic cosmic rays in interstellar space by measuring the solar modulation of these particles as a function of heliographic latitude and by sampling these particles over the solar poles, where low-energy cosmic rays may have an easier access to the inner solar system than near the ecliptic plane,
- to advance our knowledge of the neutral component of interstellar gas by measuring as a function of heliographic latitude the properties and distribution of neutral gas that enters the heliosphere.

Past experience with multi-spacecraft observations include the 2 German Helios spaceprobes. The twin mission of Helios 1 and Helios 2 during 1976 to 1979 provides valuable examples how two- or multi-spacecraft measurements enhance the scientific value of single point measurements.

Experience with previous missions has shown that an interdisiplinary approach is essential if the complex interactions between plasma, magnetic fields, and charged particles are to be studied on a global scale. In the case of an exploratory mission like Ulysses, this aspect is clearly of crucial importance. This includes the necessity for an in-ecliptic baseline which shall be provided by the PAFERM mission.

Secondary objectives with much lower priority are magnetospheric physics related to the parts of the PAFERM orbit inside the Earth's magnetosphere.

4. SCIENTIFIC PAYLOAD

The Particles And Fields Environment Reference Mission PAFERM is positioned to act as an interplanetary, in ecliptic, near Earth platform to continously collect data on solar, interplanetary and interstellar energetic particles, solar wind, magnetic fields, and interstellar neutral gas. It will provide baseline measurements for Ulysses. The seasonal dependence of the orbit and the excentricity allow furthermore measurements in the lobes of the magnetosphere, in the magnetosheath, and in the magnetosphere as well.

The PAFERM payload consists of four experiments with the following objectives:

COSPIN (cosmic ray and solar particle investigation) is a comprehensive solar, planetary, and interplanetary particle experiment identical to the COSPIN experiment on-board Ulysses. Its objectives are to determine intensities, spectra, and chemical and isotopic composition of galactic cosmic rays, anomalous components, and solar energetic particles.

The COSPIN instrumentation includes three different experiment boxes and one electronic box. The instrumentation that is foreseen for the PAFERM mission is the flight spare model from Ulysses. Therefore a detailed description of the experiments can be found elsewhere /2/3/. The instrumentation comprises five solid-state detector telescopes and a double Cherenkov / semiconductor telescope. The energy range of this particle instrument is 0.3 to 600 MeV/nucleon for nuclei, i.e. protons, helium and other elements; and 1 to 300 MeV for electrons.

Box 1 contains two anisotropy telescopes, a low energy telescope and the data-processing unit. The detector consists of a stack of three and four solid-state detectors, respectively. The low energy telescope is surrounded by a cylindrical plastic scintillator as an anti-coincidence shield.

Box 2 houses a high-energy telescope and a high-flux telescope. The high-energy telescope is comprised of a stack of Lithium-drifted silicon detectors surrounded by a plastic scintillator. The high-flux telescope incorporates a single silicon detector. The electronics for both detectors accounts for most of the volume of this box.

Box 3 consists of two separate packages. The Kiel Electron Telescope is one package. This detector incorporates a Cherenkov detector inserted between two surface barrier semi-conductor detectors, and four photomultiplier tubes. The second package houses the electronics for this instrument.

The ANGAS experiment will remotely sound the main fluid parameters of the interstellar gas (mainly helium) into which the solar system is embedded. First measurements of this kind are presently being done by the GAS (or KEP-3) instrument on the Ulysses spacecraft. The ANGAS instrument consists of a sensor incorporating the LiF-coated conversion surface and channel electron multiplier as detector elements. It also includes a tiny furnace that will be used to deposit fresh layers of LiF in the case of contamination during flight.

ANGAS is based on the GAS experiment on-board Ulysses, but is slightly modified because of the different mission-profile and interface to the spacecraft.

The TAUS instrument will perform state of the art solar wind measurements by determining 3-dimensional distribution functions of protons and alpha particles and allowing measurements of the all relevant solar wind parameters with high energy, angular and time resolution. The hardware of TAUS that will be used for PAFERM is a flight spare model from the Soviet Phobos mission.

The magnetic field experiment will measure the interplanetary magnetic field. The knowledge of the interplanetary field is very important for the scientific interpretation of the particle data (COSPIN) and the solar wind data (TAUS). The propagation of the energetic particles is mainly along the magnetic field lines, the scattering centers of the particles are provided by fluctuations of the guiding magnetic field. The second objective is the study of the magnetosphere. The orbit is partly inside the magnetosphere (actually for the larger part of the mission), therefore the magnetic field experiment will study the access of energetic particles to the different regions of the magnetosphere depending on the dynamic state of the magnetosphere.

5. MISSION-SCENARIO

Figure 2 is a sketch of the Earth and its magnetosphere. The Sun (not shown) is located far away on the left of this sketch. The magnetic field of the Earth is a dipole field that is affected by the solar wind. At the side of the magnetosphere that points towards the Sun, the field is compressed causing a bow shock; at the opposite side the field is elongated and forms the magnetotail. The most important point for the PAFERM mission is that the Ulysses reference measurements have to be conducted within the undisturbed solar wind. The distance Earth / bow shock is approximately 10 Earth radii (70,000 km).

The implication for the PAFERM orbit is, that the maximum distance (apogee) spacecraft / Earth has to exceed this 10 Earth radii. Therefore the orbit foreseen is a 400 km times 100,000 km orbit. A circular orbit with a distance of 100,000 km from the Earth has some advantage compared to the chosen high eccentric orbit, but raising the perigee from 400 km to 100,000 km takes a large amount of energy. Within the constraints given by the definition of a small mission only a high eccentric orbit can be realized. An increase of the apogee distance beyond 100,000 km needs of course additional energy, but a modest increase might be possible.

The second mission constraint is given by the Earth's orbit around the Sun. If PAFERM is initially launched with the apogee pointing towards the Sun, than six months later the apogee is in the opposite direction, far down the magnetotail. During the polar passages of Ulysses, PAFERM has to have an apogee within the solar wind and not down the magnetotail. The time periods for the two polar passes are separated by close to a year, therefore a correct initial orbit ensures that the PAFERM mission can deliver the Ulysses baseline measurements within these two time periods. In Figure 2 the orbit for June (any year) and October is given.

The launch window for PAFERM is an approximately 30 minutes time period everyday, just at a certain local time at the launch site. The mission duration should at least cover the two time periods of the polar passes of Ulysses, this means a mission duration of at least 16 months.

6. SATELLITE CONCEPT

The design baseline of the PAFERM mission is the low cost approach of developing and launching a relatively complex scientific mission within three years. This can be achieved by using existing hardware. Most instruments to be flown on PAFERM are spares from Ulysses.

In addition to the instruments some spares of spacecraft subsystems are available at ESA. Different forms of support for small missions are under consideration at ESA; one is that ESA could make appropriate spare parts left-overs from flown projects,(e.g. Ulysses, Giotto) available at no charge including some limited manpower for advise on specific issues. Usage of existing hardware would be helpful in keeping the costs low and the development times within the three years frame. Further a compromise of choosing a high excentric orbit but without full time coverage by the ground station and the limited ability of spacecraft control will keep costs relatively low.

The PAFERM spacecraft (Figure 3) can be launched by a Scout II and must therefore fulfill the requirements of its useable volume and interfaces. Consideration of the Scout II eliptical orbit performance (launch site San Marco) determines the maximum available spacecraft mass of about 100 kg for the 400 km times 100000 km high eliptical orbit. A payload mass of 25 kg would leave for the spacecraft a total mass of about 75 kg, including the adapter ring for the launcher. Other launchers, like Delta, have a better performance and could provide a higher apogee or perigee thereby increasing the time spent in the solar wind or increasing the mission life-time, respectively. Analyses of the proposed experiments (Table 1) give the basic requirements concerning volume, mass, power, and data rate. An additional requirement of the experiments is to scan the ecliptic plane with 5 to 6 rpm with 1 degree pointing accuracy and 0.1 degree/s pointing stability.

The mechanical structure of PAFERM (Figure 4) consists of two major components, a central tube with two platforms and an outer shell. The diameter and the length of the spacecraft outer shell were designed to provide a mounting area for the solar cells, delivering about 100 W solar power. All instruments are located in the payload compartment between the two platforms with the subsystems on the upper one.

The outer shell can easily be dismounted from the central structure to ensure accessibility to all components. For thermal reasons the battery pack is located inside the central tube.

Since the spacecraft does not have to be in spin mode below altitudes less than geostationary orbit, a nadir orientation with the antenna pointing towards the Earth can be easily achieved using momentum exchange between the momentum wheel and the spacecraft. As an option, two smaller platforms can be used for telemetry and telecommand (TM/TC) components and a steerable high-gain antenna. This antenna will be Earth pointing to ensure the required data rate of 10 kbps over 100,000 km apogee altitude.

In order to reduce the spacecraft costs without reducing the reliability, the spacecraft subsystem design will be mainly based on already existing hardware and improved technology. The interfaces between the experiments and the on-board data-handling (OBDH) system should be very similar to the Ulysses system. Therefore the OBDH interface to the instruments will be designed to be as close to the Ulysses OBDH system as convenient. Additional tasks, like housekeeping, attitude stabilization and control, mass memory, pseudo sun-pulse for the instruments during eclipse times and the management of TM/TC can be improved using existing technology (hard- and software) which are partly implemented in the small satellites BremSat and SAFIR.

The solar array will generate 100 W average power. Appropriate design of the panel current and voltage will enable the use of BremSat power control electronics with a minimum of modifications. A battery is used to supply power during eclipse phases and peak power needs. To demonstrate the feasibility of the PAFERM spacecraft with 100 kg total mass, an estimated budget breakdown for mass and power has been done (Table 2).

The attitude control and stabilization subsystem (Figure 5) consists of a fixed momentum wheel, magnetic rods, magnetometer, Sun and star sensors. Two attitude stabilizations are designed: spin and 3-axis stabilization at momentum vector perpendicular to the ecliptic. The closed loop pitch control achieves a pitch pointing accuracy of less than 1 degree and a pointing stability of about 0.1 degree/s. Additionally, any required spacecraft spin-rate can be achieved by using momentum transfer between the momentum wheel and the spacecraft. The spin-rate will be sensed by the Sun and star sensors. The fixed momentum wheel should be preferably run-up to the nominal rate shortly before separation, avoiding in-orbit running up using magnetic rods. The magnetic rods are used for nutation dumping, wheel desaturation and to control the precessing of the momentum vector.

7. CONCLUSIONS

The rationale for demanding the PAFERM mission as Ulysses baseline was explained by summarizing the scientific objectives and giving specific examples where a reference is mandatory to achieve the objective at all.

The mission requirements, the experiments and the spacecraft foreseen for the mission were summarized (Table 3). Spare models or partially built models of the experiments and spacecraft subsystems are on the shelf waiting to be refurbished for the PAFERM flight. A detailed spacecraft description was not given here because the spacecraft definition is not finalized yet.

We hope that the evaluation process within ESA and DARA will result in realistic plans to implement such a mission. Ulysses is on its way to Jupiter and towards its passages of the polar regions of the Sun. We need the go-ahead for the PAFERM project quite soon, otherwise we will run out of time; and time is really running fast, actually, with the velocity of Ulysses, which is at the moment the fastest operating man-made object in space.

REFERENCES

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2/ ESA bulletin, European Space Agency, Volume 63, August 1990, 'Ulysses Launch Issue'.

3/ K.-P. Wenzel and R.G. Marsden, The International Solar Polar Mission - Its Scientific Investigations, ESA SP-1050, European Space Agency, July 1983.

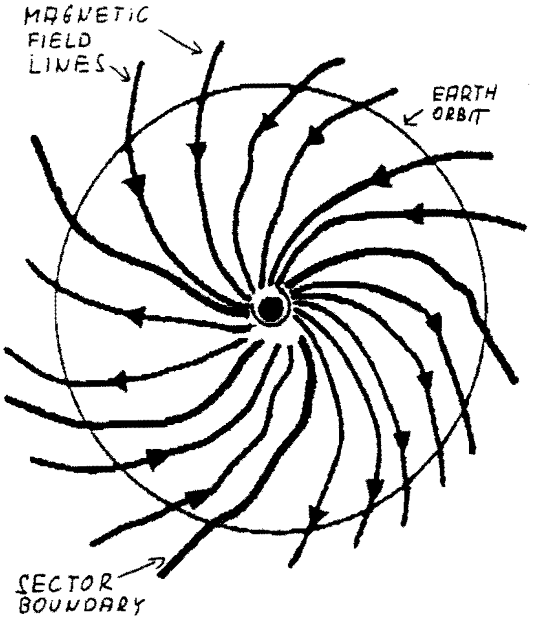

Figure 1: Interplanetary structure in the inner heliosphere. The figure shows the average large scale structure of the interplanetary magnetic field between Sun and Earth.

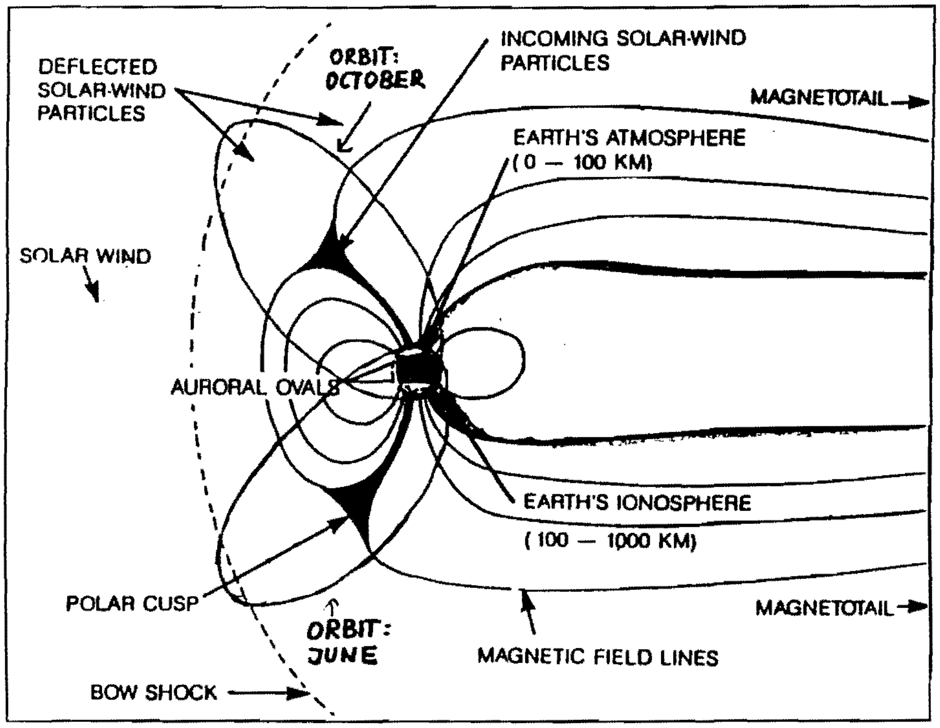

Figure 2: The magnetosphere of the Earth and the orbit of PAFERM.

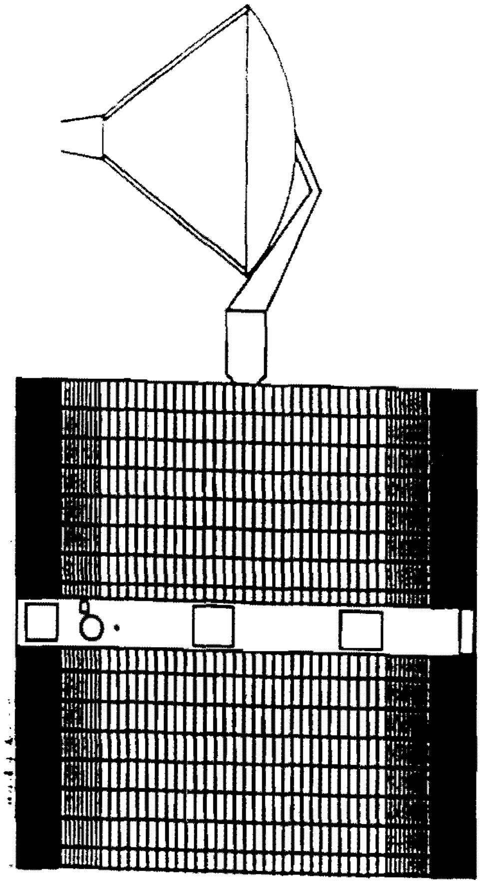

Figure 3: The PAFERM spacecraft

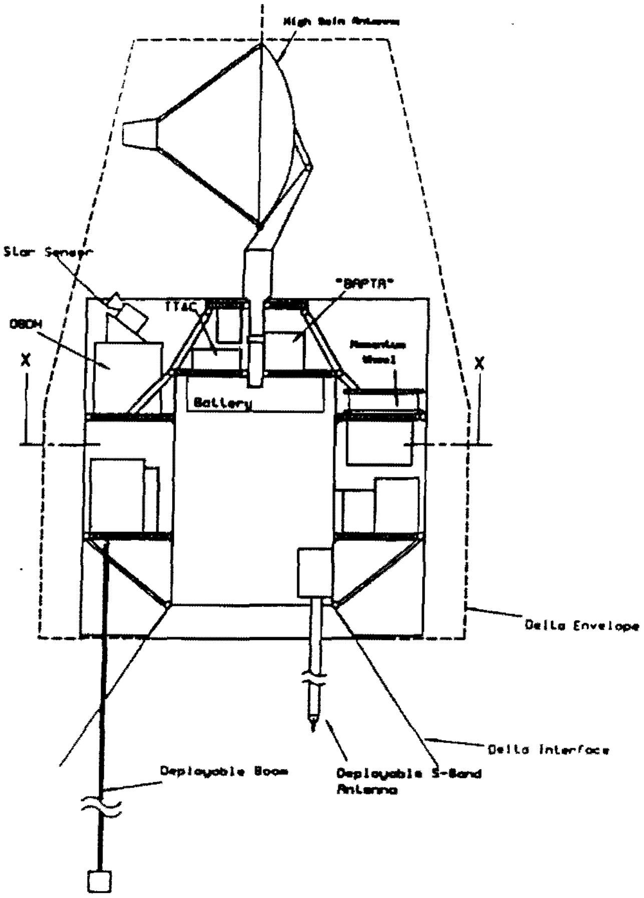

Figure 4: Structure of PAFERM

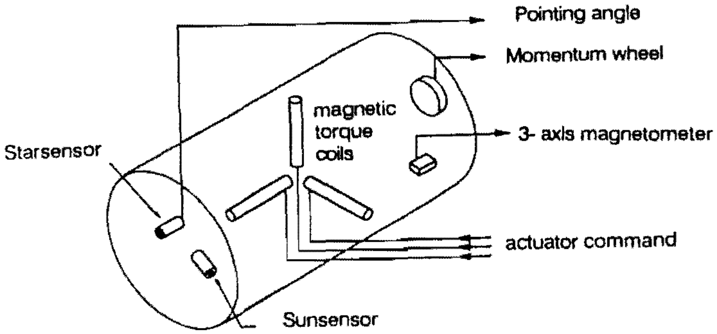

Figure 5: Attitude control and stabilization subsystem.

	COSPIN	ANGAS	TAUS	MAGNET	TOTAL
PI	H. Kunow	H. Rosenbauer	H. Rosenbauer	A. Balogh	
Objectives	solar, planetary, interplanetary particles	neutral gas	solar wind	magnetic field	
Data Rates/kbps	0.2 aver 0.2 peak	0.05 aver	0.01 aver 0.05 peak	0.1 aver 0.5 peak	0.36 aver 0.8 peak
Mass/kg	13.02	2.2	4.2	1.8	21.22
Power/W	14.7 aver 17.2 peak	3.0	4.5 aver 5.5 peak	1.5 aver 2.0 peak	23.7 aver 27.7 peak
Size/m	0.20 x 0.19 x 0.23 0.29 x 0.28 x 0.19 0.25 x 0.26 x 0.11 0.17 x 0.14 x 0.19 0.16 x 0.10 x 0.061 5 boxes	0.2 x 0.2 x 0.2	0.22 x 0.15 x 0.18 0.13 x 0.13 x 0.15 2 boxes	0.25 x 0.25 x 0.25 0.13 x 0.13 x 0.15 2 boxes	72.5 dm^3

Experiments Analyses Matrix

SUBSYSTEM	MASS (kg)	POWER (W)
Payload	25	28
OBDH	2	3
Batteries	8	–
Electronics	2	2
FMW	3	5
Torquer	3	5
Sun/Star Sensors	1.5	3
Structure (incl. solar panels and adapter)	30	–
TM/TC	10	80
Harness	3	–
Thermal Control	3	–
Margin	9.5	–
TOTAL	100	86

Table 2: Budget breakdown for mass and power.

orbit:	highly excentric
apogee / perigee:	100.000/400 km
mission duration:	May 94 - Oct. 95
ground station coverage:	6 hours/day
downlink data rate:	10 kb/s
uplink data rate:	64 b/s
spin stabilized spacecraft:	5 rmp
spin axis:	perp. to ecliptic
pointing accuracy:	1°
pointing stability:	0.1°/s
spacecraft mass:	100 kg
spacecraft power:	120 W
experiment mass:	22 kg
experiment power average:	24 W
experiment power peak:	28 W

Table 3: Mission requirements