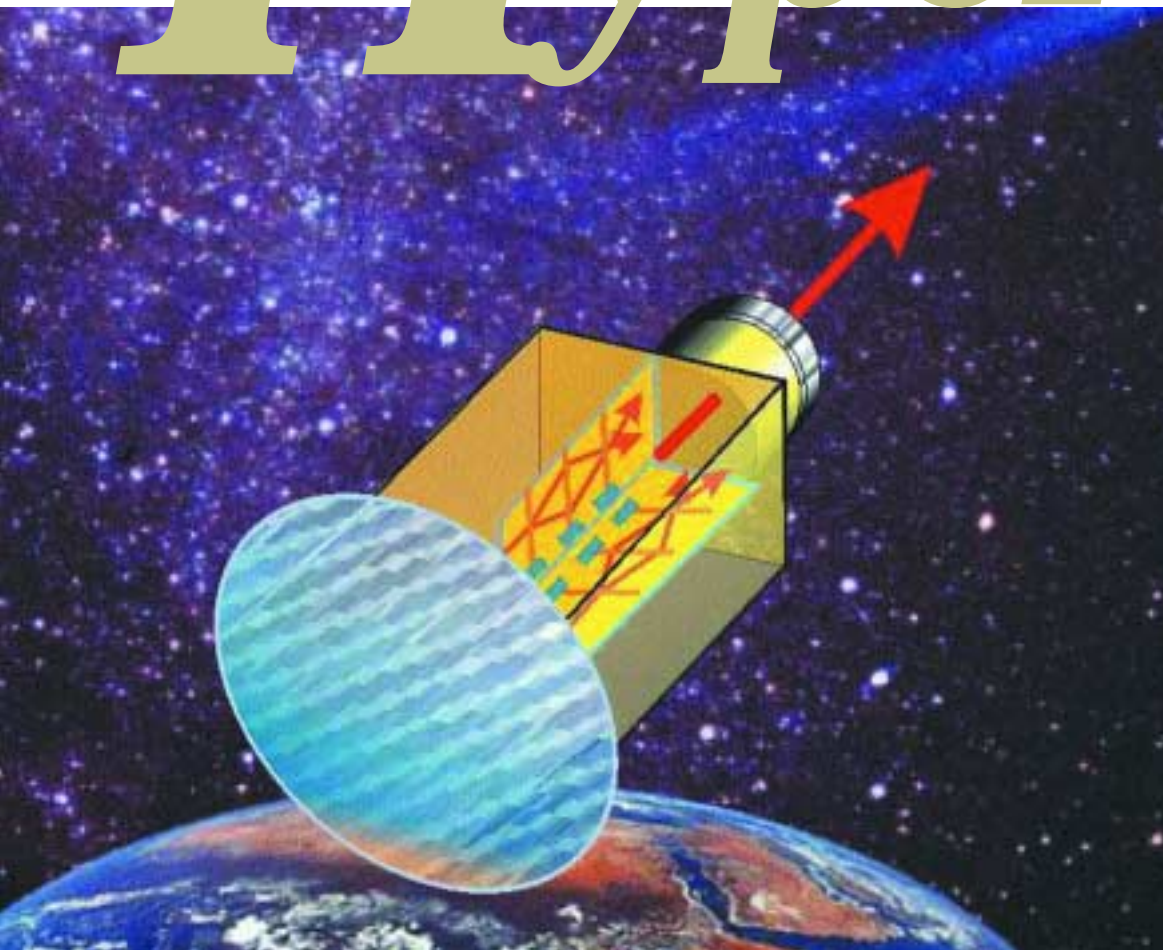


# *Hyper*

*Mission Summary*



**Hyper-precision  
cold atom  
interferometry  
in space**

*Science in perspective*

# Hyper

Cold-atom-based matter-wave interferometers provide unprecedented precision and have enormous potential. Hyper is the first satellite mission using hyper-precision atom interferometry and was recommended by ESA's Space Science Advisory Committee (SSAC) for its strong scientific impact on fundamental physics. The compact atom interferometers carried by Hyper will enable several distinct problems in fundamental physics to be addressed during one mission. The main focus of the Hyper programme is directed to;

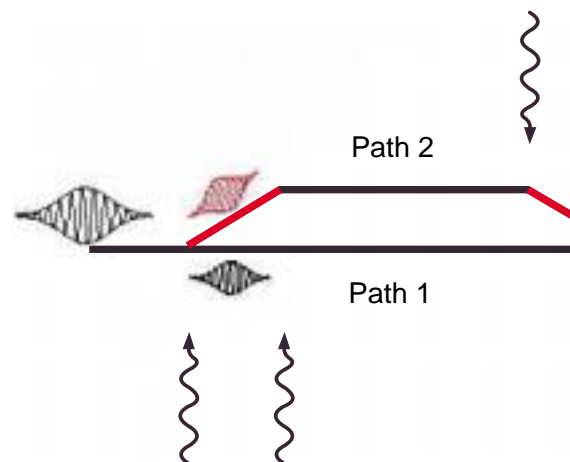
- the fine-structure constant  $\alpha$
- gravitomagnetism
- matter-wave decoherence (e.g. induced by quantum gravity).

The technology of Hyper also opens up novel tests of the equivalence principle with individual atoms instead of microscopic objects. The design selected, with four atom interferometers, makes it possible to optimise their topology for each of the scientific objectives. They may be used either as a Sagnac interferometer or as a frequency-sensitive interferometer of the Ramsey-Bordé type. All of the scientific objectives addressed are only feasible in space, where the superior potential of cold atom sensors can be fully exploited thanks to the absence of

gravity and the provision of a drag-free environment. Hyper not only has an impact on fundamental physics, but also fosters new technologies for spacecraft control, since it is the first mission in which gyroscopes based on cold atoms will be used for that purpose.

## The Fine-Structure Constant $\alpha$

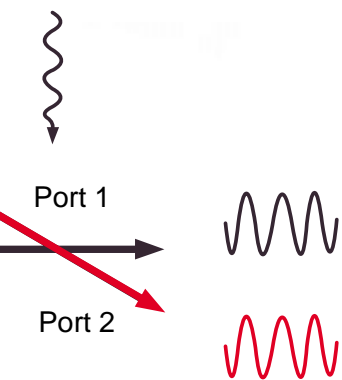
The fine-structure constant  $\alpha$  is a measure of the strength of the electromagnetic interaction and hence plays an important role in Grand Unification Theories (GUT). Presently the most precise value of  $\alpha$  is inferred from the anomaly of the magnetic moment of the electron relying on Quantum Electrodynamics (QED) theories. In contrast to this measurement, the route chosen by Hyper to determine  $\alpha$  does not rely



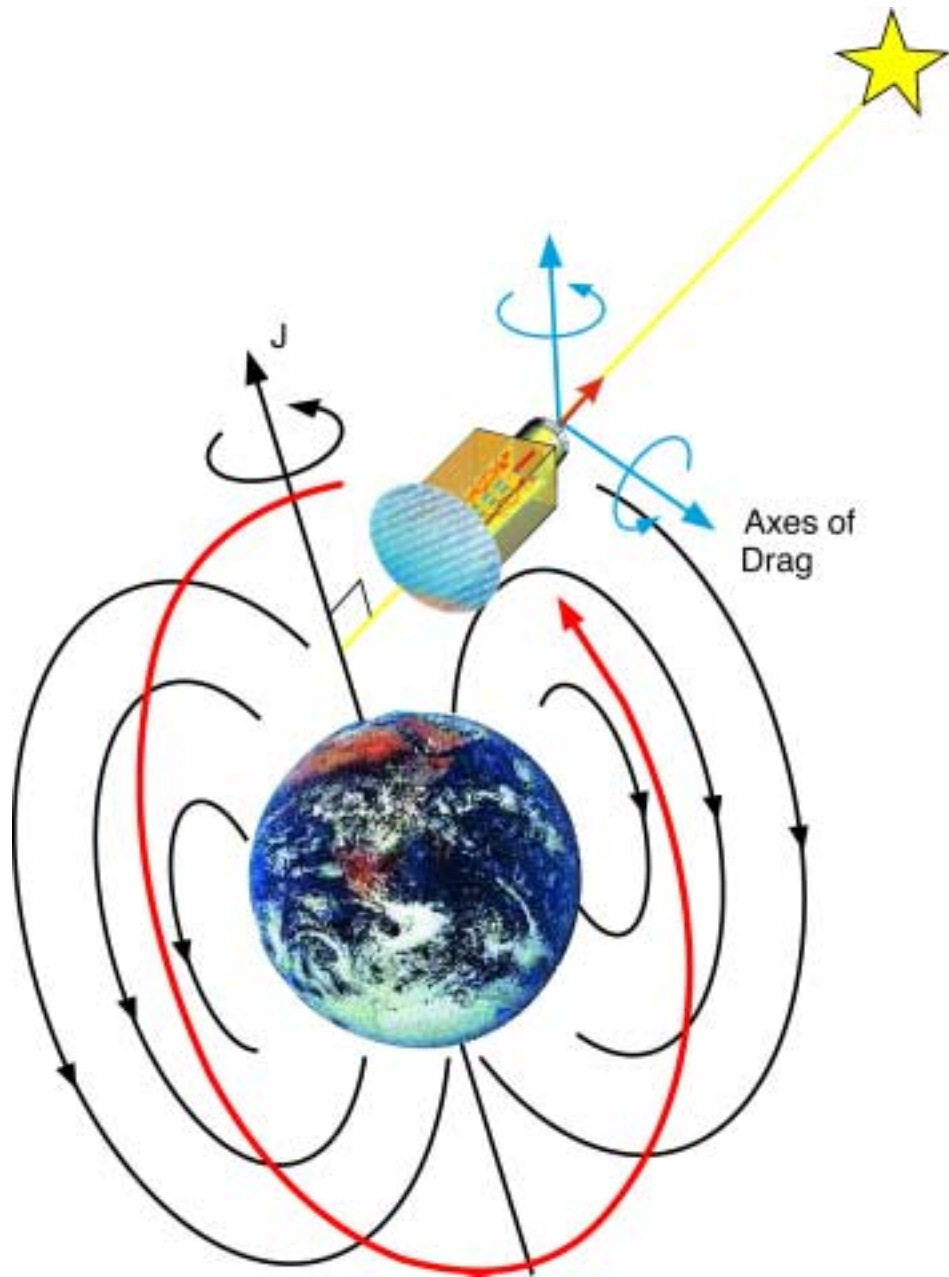
on QED and, thus, represents an independent test for these kinds of theories. The measurements performed by Hyper will help to resolve the disagreement between the results of the various distinct methods of measuring  $\alpha$ . Hyper will improve the measurement of the ratio of Planck's constant and the atomic mass by more than one order of magnitude. Combined with further ground-based experiments, this method will possibly become one of the most accurate techniques to determine the fine-structure constant. Apart from the significance for QED-theories, the fine-structure constant plays an important role in metrology and spectroscopy linking together three other fundamental physical constants: the speed of light, Planck's constant and the electric charge of an electron.

### Gravitomagnetism

Gravitomagnetism describes the general relativistic curvature of spacetime around massive bodies, like the Earth. The roots of gravitomagnetism even reach back to Mach's principle. Measurement of the gravitomagnetic effect is a long-standing goal which will test General Relativity. Hyper will make the first map of the spatial contours of the gravitomagnetic effect close to Earth. It will achieve about 1%



*Ramsey-Bordé-type atom interferometer used for the determination of the fine-structure constant.*



precision over a one-year measurement time. As they move in their orbit, atom gyroscopes with high sensitivity for rotation rates ( $10^{-12}$  rad/s at 1 Hz) will trace the latitudinal variation of the Earth's drag with respect to an inertial reference provided by a guide star monitored by a high-performance star tracker. In an atom interferometer, the Earth's rotation affects the trajectories of the coherently split matter waves differently and thus causes a Sagnac-like phase shift at the exit ports of the interferometer. Proposals to precisely track satellites with lasers, like the LAGEOS Project, and the even more ambitious Gravity Probe B, to survey the precessions of free-falling gyroscopes over the course of one year, will only be sensitive to the mean effect and cannot resolve the latitudinal shape of the gravitomagnetic effect.

*The gravitomagnetic effect. The Earth's rotation  $J$  leads to a drag (black field lines) varying over the satellite's orbit (red). The contour of the vector field of the Earth's drag resembles a magnetic field of a dipole. On account of this formal similarity, this effect is called 'gravitomagnetic'.*

### Quantum Gravity

Hyper will search for possible evidence of spacetime granularity reducing the coherence of matter waves. One of the biggest unsolved problems in fundamental physics is the unification of quantum mechanics and gravity. A consequence of the unification could be the existence of so-called 'incoherent conformal waves' in gravitational fields due to quantum mechanical zero-point fluctuations. New theories have been developed predicting changes in the first-order correlation function of matter-waves due to such fluctuations as functions of parameters such as atomic mass and the geometry of the atomic trajectories. The outstanding performance of the atom interferometers on Hyper will set an upper boundary for these predictions and, thus, will have a strong impact on this new field in quantum gravity.

### Atomic Gyroscope

Hyper will be the first mission where atom interferometers act as sensors for accelerations and rotations to control a spacecraft. The four atom interferometers carried by Hyper can be combined to form two atomic Sagnac units to measure rotations and accelerations in two orthogonal directions. The two atomic Sagnac units can work in two different modes for coarse (sensitivity  $10^9$  rad/s at 1 s

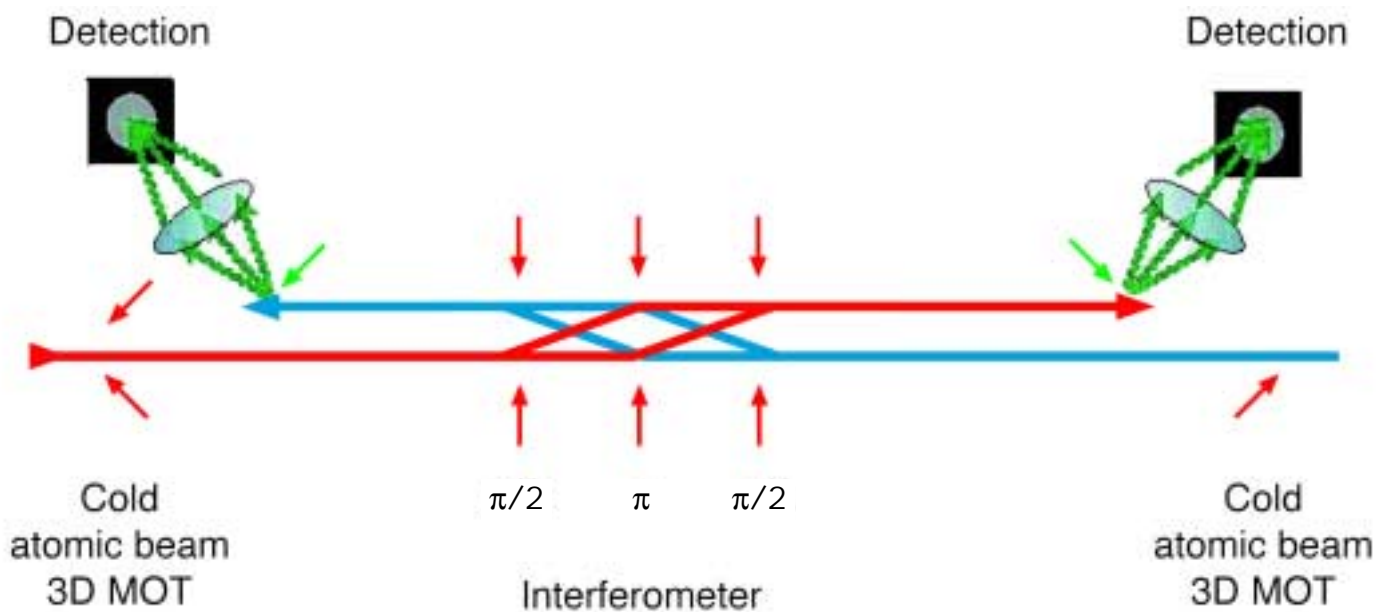
integration time) and fine (sensitivity  $10^{-12}$  rad/s at 1 s integration time) sensing depending on the atomic velocity, which is adjusted by lasers. While the fine-sensing gyroscope is measuring the gravitomagnetic effect, the coarse gyroscope will support the Attitude and Orbit Control System (AOCS) and keep the star tracker directed to the guide star.

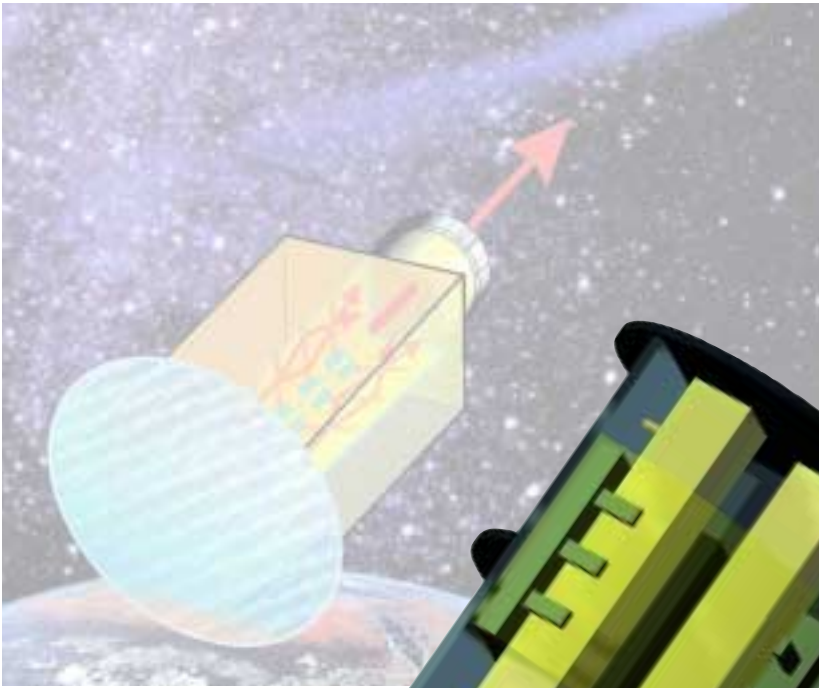
### The Payload Module

The Payload Module (PLM), with a mass of 240 kg and 200 W power consumption, consists essentially of two elements:

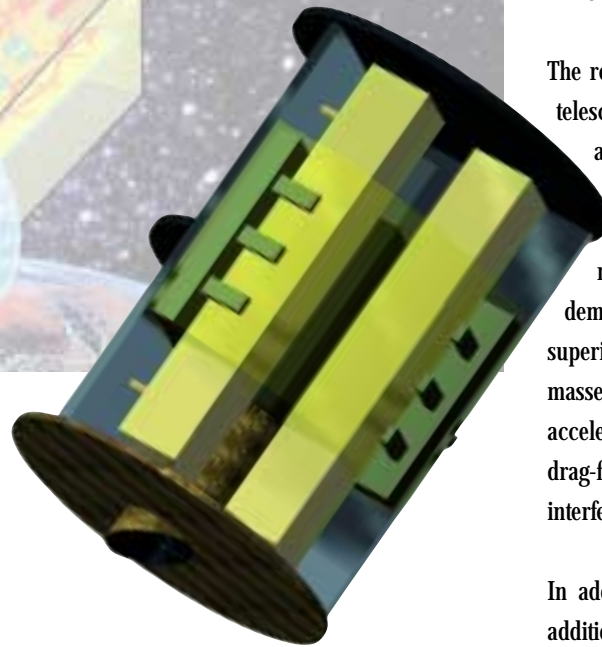
- *Atom Preparation Bench:* Two magnetically-shielded vacuum chambers are rigidly held by a very stable CFRP structure. On the vacuum chambers are mounted the atomic oven and the optics for the preparation and detection of the atoms.
- *Optical Bench:* An ultra-stable, monolithic Zerodur structure which comprises the high-precision star tracker (200 mm-diameter telescope) and two drag-free proof masses. It also carries the optical elements which control the beam splitting and recombination in the atom interferometer. With this arrangement all of the critical elements are rigidly mounted with very high thermo-mechanical stability.

*The Atomic Sagnac Unit (ASU). Two counter-propagating atom interferometers (red and blue) discriminate between rotations and accelerations. The ASU is sensitive only to one axis for both accelerations and rotations.*





*The Hyper Payload Module configuration. The two magnetically-shielded vacuum chambers (constituting the four interferometers) are mounted alongside the central telescope and Optical Bench structure.*



The PLM is housed in a 1m-diameter CFRP cylinder, which also constitutes the interface to the launcher, and provides the main path for launch structural loads. It is thermally and structurally de-coupled from the spacecraft Service Module (SVM). Extensive use of CFRP gives superior stiffness and minimises mass and thermal distortions. Perturbations on the PLM are further reduced by excluding any moving parts or liquids on the spacecraft. The thermal stability of the PLM is achieved by a combination of passive isolation (Multi-Layer Insulation, conductive de-coupling with titanium mounts), and active temperature control by heaters. The layout of the PLM is driven by the science requirements:

- The relative pointing error of the PLM to the guide star has to be less than  $10^{-9}$  radians within the frequency range of 0.3 to 3 Hz.
- Maximum temperature variations of the Optical Bench of 20 mK over 20 minutes in order to

guarantee a thermo-mechanical pointing stability better than  $10^{-9}$  radians with respect to a guide star.

- Residual acceleration levels at the PLM below  $10^{-10}$  g at 0.3 Hz.

The required inertial reference is established by the telescope, pointing to a guide star with  $10^{-7}$  radian accuracy at 10 Hz readout frequency, together with a high-frequency operation mode of the cold-atom interferometer itself. The measurement strategy for Hyper is less demanding on long-term stability, but requires a superior short-term stability. The drag-free proof masses act as inertial sensors to control the residual acceleration level on the PLM in order to maintain drag-free conditions over a designated area of the interferometer.

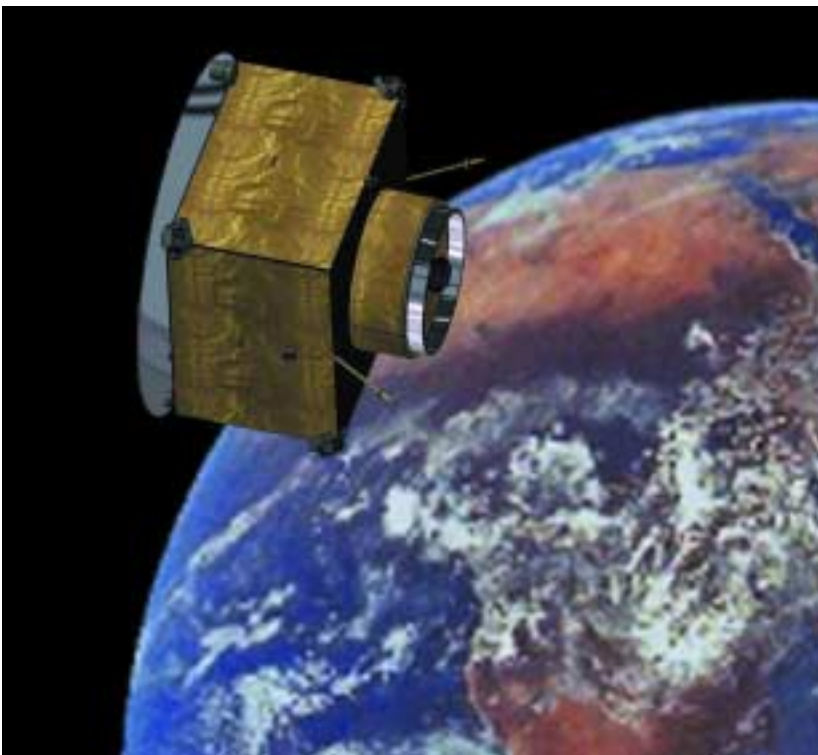
In addition to the PLM, a Laser Bench and some additional payload components are accommodated on the SVM. The Laser Bench contains less sensitive, mainly optical components for the atom interferometer (lasers, power supplies, control electronics). The light is guided via optical fibres to both the Atom Preparation Bench and the Optical Bench.

#### **The Spacecraft, Launcher and Orbit**

The spacecraft, of mass 770 kg, is launched by a low-cost Rokot vehicle from Plesetsk, which yields a large launch mass margin. A 700 km-altitude Sun-Synchronous Orbit (SSO) inclined at  $98^\circ$  has been selected, in order to meet the science requirements (low-altitude, near-polar orbit) as well as to minimise eclipse-induced thermal variations. A set of about 10 guide stars in the local anti-Sun direction, and roughly orthogonal to the orbital plane of Hyper, is used over a year of science operations; each star provides a pointing reference for up to 25 days, after which the spacecraft is slewed over 2 days to the next guide star. A lifetime of 2 years is baselined, but an extension of the mission is in principle possible.

The attitude and orbit control system of Hyper comprises:

- The primary AOCS, an SVM responsibility, which performs all operations except the error generation during the science mode.
- The secondary AOCS, provided by the PLM, which generates the required torque and thrust demands about each axis by using the information delivered by the drag-free masses, the high-performance star tracker and the cold atom interferometers.



*The Hyper spacecraft overall configuration.*

Actuation is carried out by a set of 16 Field Emission Electric Propulsion (FEEP) 500  $\mu$ N thrusters located on the SVM. A set of 4 additional pairs of 40 mN cold-gas thrusters is employed for off-launcher rate reduction in the initial phase of the mission.

The required total power of 520 W is provided by a fixed circular array with 3.4 m<sup>2</sup> of GaAs solar cells. This design gives a maximum bus power of 320 W even when the solar array is pointing up to 30° away from the Sun, in accordance with the mission and science requirements. A 6 Ah lithium-ion battery is

sized to cover the peak demand and the seasonal eclipses, which have a maximum length of 20 minutes. Science data are downlinked in S-band during 8-minute passes over the 15 m-antenna Kiruna station, at a data rate of 500 kbit/s. A 2 Gbit mass memory is provided on board, which is able to store up to 10 days of science data.

### Programmatics

The drag-free control system (proof masses, FEEP thrusters, and control loop) required for Hyper have first to be demonstrated by the SMART-2 mission, expected to be launched in 2005 or 2006. Consequently, manufacturing and integration of the PLM will not start before early 2007. Cold atom interferometer components exist at breadboard level (with a technology heritage from PHARAO), while the telescope mechanical stability requirements are comparable to those of the LISA mission, for which a dedicated technology R&D programme on high-stability structures will be carried out in 2003-2004. On that basis, a Hyper launch would be feasible in early 2010, requiring a Phase-B start around mid-2003. The cost to completion of the mission (procurement of the SVM, overall integration, launch and operations, but excluding development and procurement of the PLM) is within the F2/F3 budgetary allocation.