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Proba-2 in orbit

→ BIG YEAR FOR SMALL SATELLITE

ESA's second in-orbit technology demonstration mission: Proba-2

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Less than a cubic metre in volume, Proba-2 is one of the smallest missions ever flown by ESA. But judged by performance per kilogram, Proba-2 can also claim to be among the most scientifically and technically productive.

Proba-2 stands for Project for On-Board Autonomy-2 and, following in the footsteps of Proba-1, its successful first year in orbit has confirmed that a microsatellite can provide the required performance for challenging missions.

This 120 kg microsatellite is the second mission in ESA's In-Orbit Demonstration (IOD) series, part of ESA's General Support Technology Programme. Proba missions offer a low-cost opportunity to prove new space technologies, equipment and techniques in the actual space environment. They also provide verification of novel operational concepts such as spacecraft autonomy, ground segment autonomy and experimental attitude control algorithms, as well as previously untried Earth observing techniques or formation flying methods.

Proba-2 has shown specifically that a small mission can combine technology demonstration with new and advanced small payloads delivering science data to users. It proved that a mission and system design which uses embedded onboard autonomy and an automated ground segment can allow reactive missions with high flexibility and fast response time; that advanced development methods (such as code generation) are cost-efficient and robust; and that an attitude control system based only on an autonomous star tracker is sufficient for the pointing and stability needs of science and Earth observation missions.

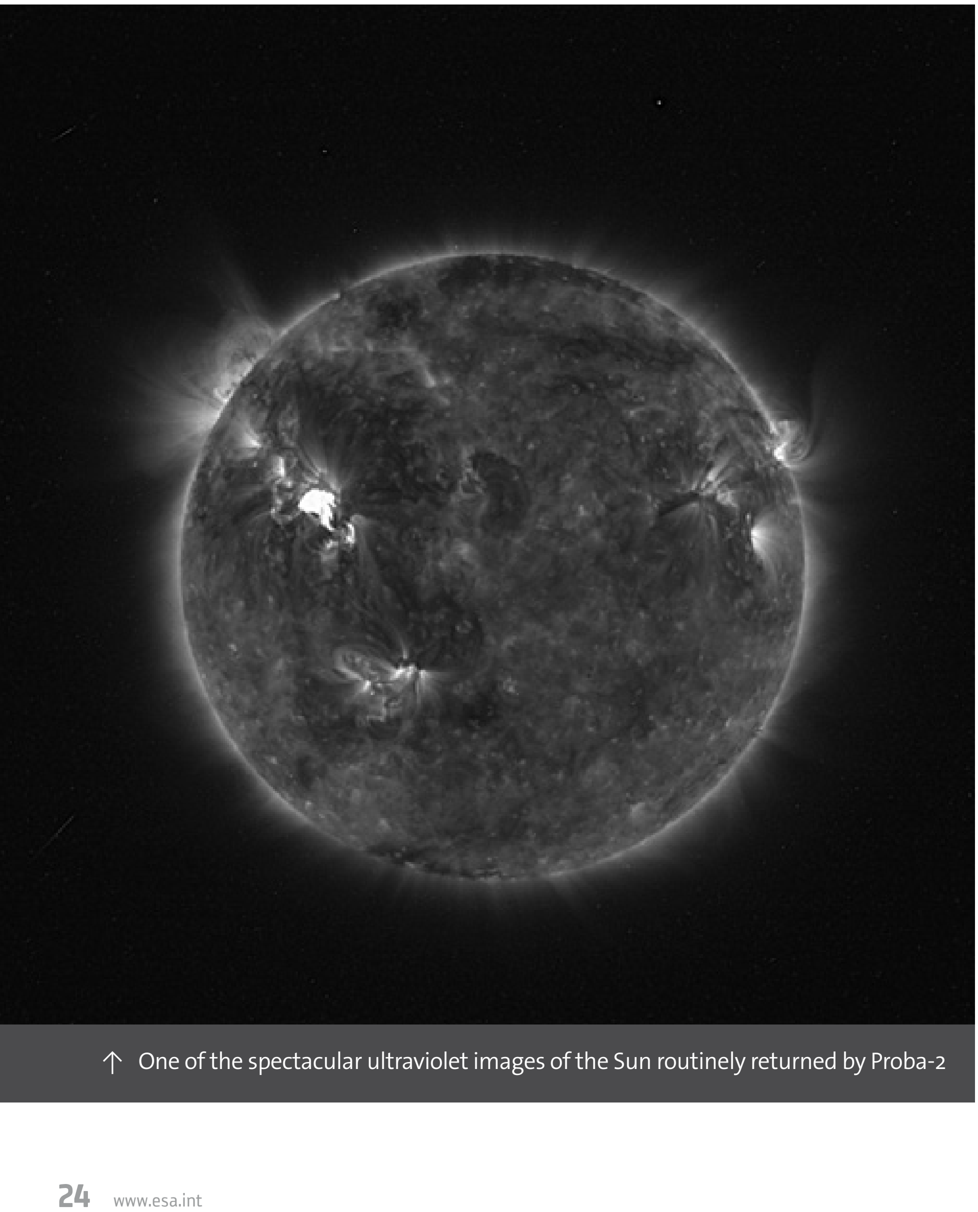
Proba-2 also hosts seventeen technology demonstrators – some of which form part of the platform and system baseline design, others being 'guest' payloads – as well as set of compact scientific instruments, monitoring the Sun and Earth's orbital plasma environment.

The mission is currently in its nominal two-year operational phase. If a picture is worth a thousand words then the spectacular ultraviolet images of the Sun routinely returned by Proba-2 speak volumes on the excellent performances of the platform and its solar imaging instrument.

The spacecraft and its technology demonstrators are operated from ESA's Redu ground station in Belgium, with science operations conducted by the Royal Observatory of Belgium (ROB). Overall mission and science planning is co-ordinated and managed by ESA's Directorate of Scientific and Robotic Exploration.

Mission and spacecraft summary

Proba-2 was launched from Plesetsk Cosmodrome in northern Russia on 2 November 2009, sharing its Rockot launcher with ESA's larger SMOS satellite. Proba-2 separated from the rocket's upper stage to be placed in a circular orbit at an altitude of 730 km.



↑ One of the spectacular ultraviolet images of the Sun routinely returned by Proba-2

Because its two largest scientific payloads require continuous observation of the Sun, the orbit was selected to be 'solar eclipse-free' for most of the year, with a limited eclipse season between the middle of November and the end of January.

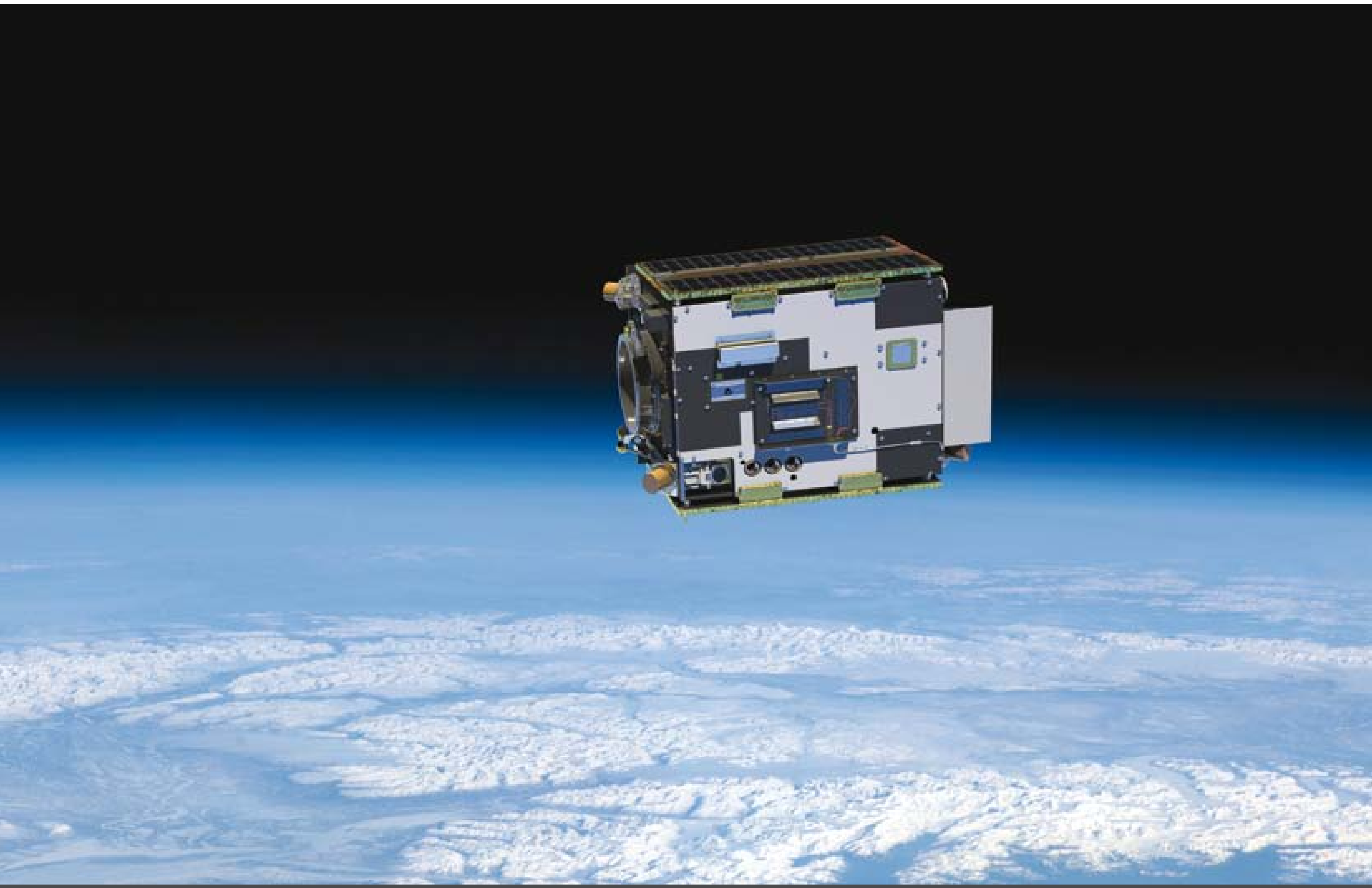
Within an overall size of 65 x 65 x 85 cm, the Proba-2 platform has full redundancy while also including a suite of technology demonstrators and various innovative aspects. Its structure comprises a combination of aluminium and carbon-fibre reinforced plastic (CFRP) honeycomb panels.

Triple junction gallium arsenide solar cells (mounted onto one body panel and across two deployable panels) can supply 120 W end-of-life (EOL) peak power. A battery-regulated, centrally switched 28 V bus distributes this power to all platform units and instruments, while a new type of lithium-ion battery provides 16.5 Ah of energy storage. Proba-2's S-band telecommunication subsystem is based on a redundant set of receivers, transmitters and omnidirectional coverage.

Proba-2's platform and instrument management and control, data handling and processing and power management and distribution functions are combined in the platform's Advanced Data and Power Management System (ADPMS) computer based on ESA's standard radiation-tolerant processor, the LEON2-FT.

The satellite's onboard software provides a high level of autonomy. Proba-2 is capable of handling all its routine operations, only interacting with the ground station to downlink science data and obtain new observation requests. Its software can compress, process and prioritise images of interest, automatically adjusting spacecraft attitude as required.

In addition, a large quantity of potential onboard anomalies can be handled if needed without ground intervention, because of Proba-2's integrated Failure Detection, Isolation and Recovery (FDIR) capabilities.



↑ Artist impression of Proba-2 leaving the Rockot launcher adapter after reaching orbit in 2009

Autonomous navigation, guidance and control functions

Proba-2's Attitude, Control and Navigation Subsystem (ACNS) hardware is based on four reaction wheels, two magnetometers, a redundant miniaturised µ-ASC star tracker with two hot-redundant camera heads to improve measurement accuracy, a cold-redundant GPS receiver and internally redundant magneto-torquers.

The satellite's main ACNS guidance law is known as 'Sun mode', and used routinely during operations for the SWAP and LYRA payloads' nominal pointing. The payload stays pointed at the Sun while the satellite performs four rotations of 90° around the payload's line of sight per orbit (avoiding the star trackers being blinded by Earth).

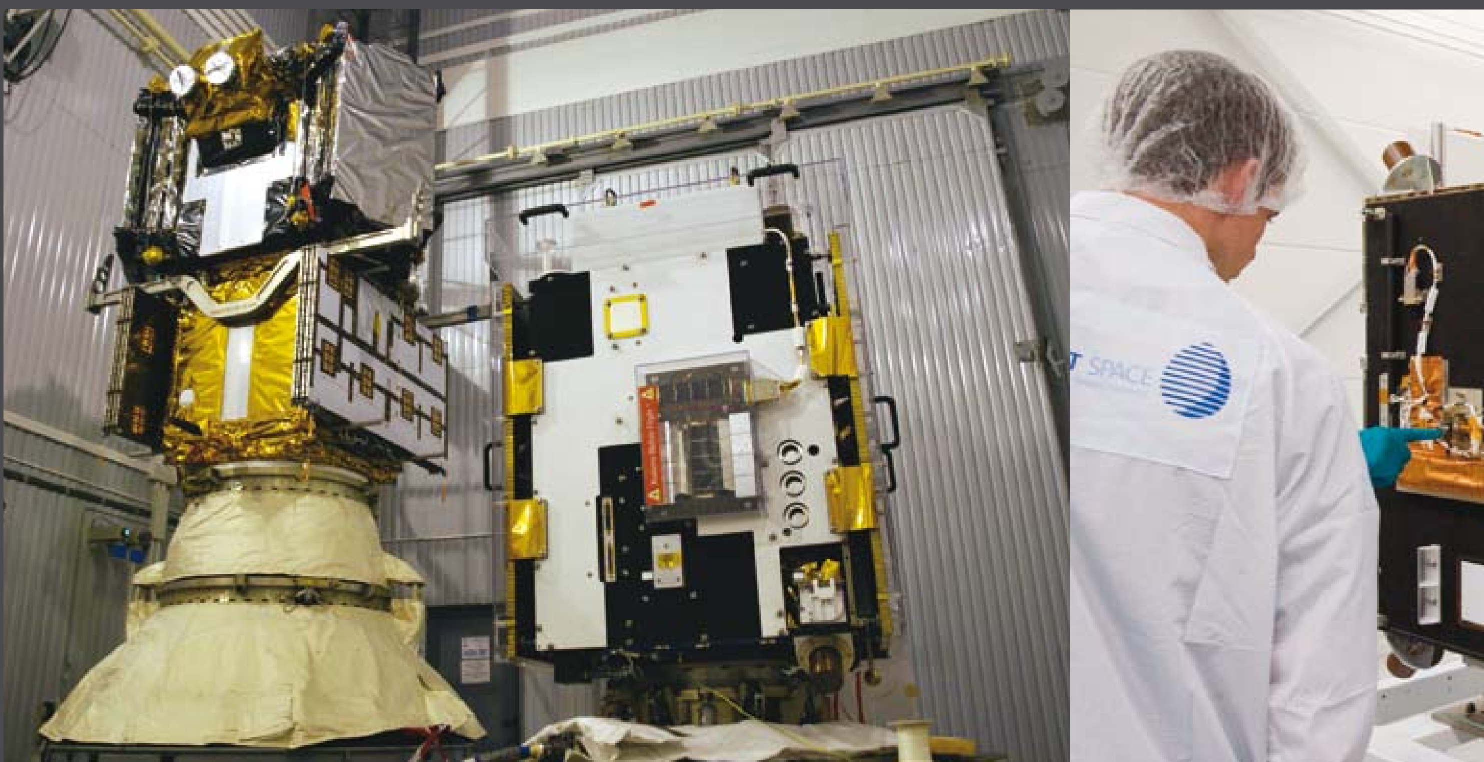
Proba-2's ACNS capabilities are not only limited to the Sun-pointing mode, but also support most of the pointing modes required by any Earth observation or science mission (such as 'inertial', 'Earth target point and stare', etc.)

Besides the nominal Sun-pointing mode, the satellite can be put in a stand-by mode that only uses a limited set of ACNS units, is simpler to control and guarantees stable incoming power and coverage of Earth. As in the case of Proba-1, this mode is based on the 'Bdot algorithm', a tried and tested method that employs magnetometers to sense Earth's magnetosphere and magnetotorquers to control the satellite.

In addition, the ACNS software allows full onboard autonomous orbital and attitude navigation, and onboard time management and correlations, for autonomous predictions of all manoeuvres' execution times, and of all relevant Sun or Earth-related events (eclipse entry and exit times, node crossing and target flyby times).

It also allows estimation of environmental perturbation torques and remnant spacecraft magnetism for improved pointing. The control module is based on a state-feedback controller for fine control and on a sliding mode controller for large manoeuvres.

Developing such a complex ACNS system within such a small mission was only made feasible by high-level modelling tools and advanced autocoding techniques. These allowed very efficient generation and testing of the ACNS software and integration and validation with the onboard software.



↑ Bigger than SMOS? From this perspective view, Proba-2 in the foreground seems bigger than its much larger cousin, the SMOS satellite, seen mounted on its launcher adapter (Proba-2 fits inside this structure)

Project organisation and development flow

Small low-cost missions offer access to space to smaller companies, providing them with the essential experience for European industry to stay competitive and innovative. The Proba-2 industrial consortium therefore mainly consisted of small and medium-sized enterprises from ten European countries and Canada.

Belgium-based prime contractor QinetiQ Space (formerly Verhaert) had broad responsibility for mission and spacecraft design, platform development and manufacturing and platform technologies selection (such as batteries, reaction wheels, star tracker, solar cells, on-board computer). They also conduct the integration, assembly, integration and testing of the complete spacecraft and overall system-level testing, ground segment development, as well as the Launch and Early Orbit Phase, commissioning phase and operational activities completion.

Proba-2 subcontractors included Spacebel (BE), developing the mission's onboard software as well as its System Verification Facility (SVF) and its ground segment, NGC Aerospace (CA) developing the ACNS algorithms and Dynacon (CA) developing the reaction wheels.

The solar panels came from Selex Galileo (IT), the CFRP structural elements were from APCO (CH), the batteries from SAFT (FR) and the star tracker was from DTU (DK).

As with Proba-1, an innovative approach was taken to the development and assembly, integration and verification of the satellite and ground segment, with the same system and tools being used incrementally for ground verification and system-level testing and for operations. This approach increased the cost efficiency, avoided duplication of development and validation activities and provided a more extensive validation coverage.

Software validation was performed across all project phases, using incremental versions of the flight software and SVF, including accurate models of the onboard computer and processor, as well as all platform units.

↑ Proba-2 in the cleanroom at Verhaert (now QinetiQ Space), in Belgium, just before shipping for launch

→ Laser-tagging Proba-2

Among its 17 technology payloads, Proba-2 carries two innovative GPS receivers: the Topstar 3000 (specifically developed by Thales under an ESA/CNES contract for Earth observation and telecom satellites) and the highly miniaturised Phoenix, developed by the German Aerospace Center (DLR).

Another advanced onboard technology provided the opportunity to assess performance of these receivers: Proba-2 has a laser retro-reflector (the Russian LRR) on its underside to support highly accurate laser ranging measurements.

In a dedicated campaign conducted by the International Laser Ranging Service, Proba-2 was tracked by 15 laser stations around the world for a two-week period in March and April. Some 2000 observation points were collected during 120 passes.

Using these results, it was demonstrated that GPS-based precise orbit determination processed on the ground achieved an accuracy of 0.5 m – smaller than the satellite itself. Even on board, a remarkable 1–2 m positioning accuracy could be achieved with advanced real-time navigation filters embedded into the GPS receivers. This was a major milestone in the art of spaceborne navigation, and has proven these technologies for future European missions.

The SVF was then extended into a complete system simulator, including interfaces with the ground operations system.

The SVF included a complete dynamic model of the orbital environment, incorporating perturbing forces and torques acting on the spacecraft, illumination conditions, sensor performance and attitude-dependent blinding, and so on, allowing mission performance to be realistically evaluated.

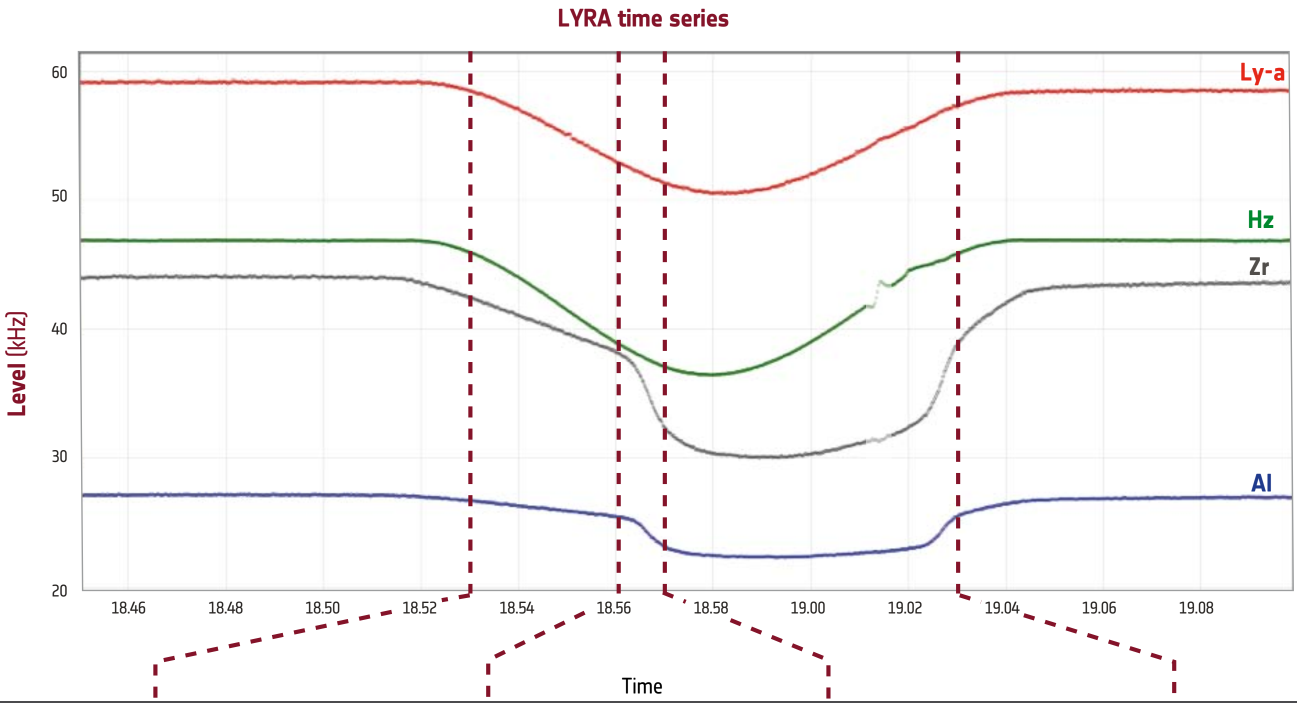
Compatibility of the hardware and of the whole system was verified using a mixture of simulator tests, 'hardware-in-the-loop' tests and system validation exercises. This development approach needed close collaboration between industry teams and the ESA project members across all levels and disciplines.

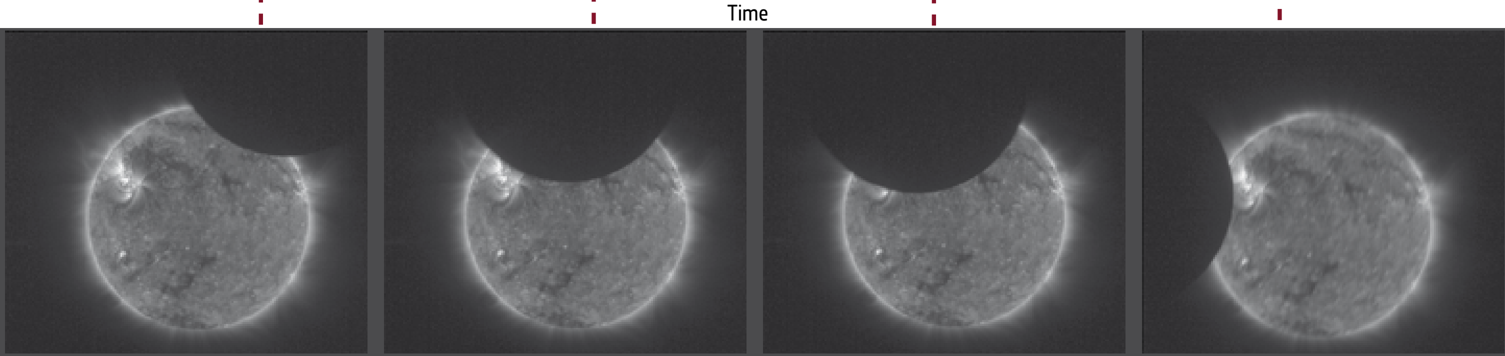
Scientific payload

SWAP

SWAP is a telescope for observing the solar corona in the extreme ultraviolet (EUV), corresponding to an emission temperature of around one million degrees. The instrument was developed and tested under the supervision of the Centre Spatial de Liège (BE) for the Royal Observatory of Belgium, and builds on the heritage of the Extreme-ultraviolet Imaging Telescope (EIT) on the ESA/NASA SOHO solar observatory.

Its development was driven by the accommodation on Proba-2, and it had strict limits on mass, power and size: it weighs 10 kg, it measures 570 x 150 x 110 mm in size and has a power consumption together with the LYRA instrument of 6 W.





↑ A set of images taken by the SWAP telescope and corresponding LYRA signals for one lunar transit of the solar disc at about 19.00 on 7 July 2010. The signal drops in the four wavelengths, and they are not always symmetric. During these transits in particular, the aluminium and zirconium channels (Al in blue, Zr in black) show a very asymmetric drop in signal. This is caused by the fact that these channels are sensitive to the shortest EUV wavelengths and thus highest temperature plasma. The active regions on the Sun radiate in these wavelengths. The steepest drop and rise in the Zr and Al signal is found when the one and only active region disappears and then reappears. The long-wavelength channels Lyman-alpha (Ly-a) and Herzberg (Hz) show the overall radiation of the 'quiet' Sun (more interesting for long-term variations). They show a symmetric drop at the times of lunar transits, directly related to the size of the solar disc area being obscured

SWAP demonstrated that it is possible to build a small reliable telescope for space weather monitoring with limited power and thermal requirements.

To save power, the detector is an Active Pixel Sensor (APS) detector – the first used for in-orbit solar physics – with special coatings enhancing its EUV sensitivity. To minimise SWAP's electronics, the mission's main ADPMS computer oversees onboard data processing including image compression, solar event detection and image prioritisation.

SWAP's scientific goal is to monitor all 'space weather' relevant phenomena in the solar corona, taking pictures at a rate of one image per minute, an order of magnitude faster than its EIT predecessor, and with a larger 54 arcmin field of view.

The spatial resolution of SWAP is complementary to the high temporal resolution of the LYRA instrument.

More than 130 000 images have been taken since launch until August 2010, and SWAP remains in excellent health. Although a compact instrument on a small platform, SWAP has demonstrated promising results when used for space weather forecasting activities.

It can be used for detection of CMEs and the study of weak, dim structures in the corona (such as dimming, coronal holes and so on). SWAP's higher rate of imaging also provides more dynamic information on birth of active regions, flares, prominences, jets, EIT-waves, off-limb eruptions and inflows.

↑ Artist's impression of Proba-2 fully operational in its final orbit

↑ The ESA Redu ground station

→ Highly automated ground segment

Proba-2's ground segment consists of three main elements: antenna ground stations, the Mission Operation Centre (MOC), including the Mission Data Server (MDS) and the Science Operation Centre (SOC).

Flight dynamics, operations planning and spacecraft operations are conducted from the MOC at Redu in Belgium, which also hosts one antenna ground station. A second station is at Svalbard in Norway, used to increase the satellite/ground contact time and to maximise scientific data return.

The MOC is designed to perform routine automated operations, including satellite pass prediction, pass activity scheduling, scientific request processing, spacecraft data collection and distribution. Operator intervention is only needed for 'off-nominal' activities, such as specific test requests for any of the technology demonstrators. The facilities at the MOC (such as ground antennas, pass planning system, web server) are shared between Proba-1 and Proba-2.

The SOC is hosted by the Royal Observatory of Belgium in Ukkel, near Brussels. Planning requests for the two main payloads (SWAP and LYRA) are sent from there to the MOC where they are automatically taken into account by the pass planning system. Scientific data from the spacecraft are automatically transferred to the SOC for further processing, allowing the flexible and fast interactions of solar specialists with their payloads.

→ In-orbit performances

Pointing accuracies	Position accuracy:	Power budget:	CPU usage:
Well within mission and payload requirements - End-to-end (SWAP instrument) measured Absolute Pointing Performances (APE): 87 arcsec (2σ). Requirement 100 arcsec (2σ) - Measured Relative Pointing Performances (RPE): 2 arcsec/5 s (2σ) and 5 arcsec/60 s (2σ).	Kinematic navigation solution (used for autonomous onboard navigation by the ACNS software): 2 m (position) and 5 cm/s (velocity) (3D rms) Real-time navigation filter (embarked as technology demonstration item): 1 m (position) and 4 mm/s (velocity) (3D rms).	Demonstrated sufficient margin at beginning of life between consumption during the nominal platform and payload operations (<80 W) and the total incoming power (>120 W) providing a lot of flexibility for the operation of the onboard technology demonstrators.	About 40% for all the nominal platform activities, more than 60% is available for onboard payload processing and data compression.
Although there were no data availability requirements in view of the experimental nature of the mission, the overall mission design (spacecraft and ground segment) has proven that it is capable of acquiring and delivering science data on a continuous daily basis, (about 70 SWAP images per contact, delivered within 30 minutes to the SOC).			
In addition, thanks to the ground segment automation, the SOC is able to interact in an almost direct way with the payloads and can submit modifications to payload operations up to 20 minutes before each contact.			

↑ Proba-2 commissioning confirmed that the mission is well within its anticipated performance requirements

It is capable of imaging and tracking of erupting prominences above the solar limb using its larger field of view and the platform three-degree off-pointing capability, beyond the regions that are imaged by comparable missions such as SOHO, TRACE and the Solar Dynamics Observatory (SDO).

It can be used in the generation of high-resolution 3D images of solar events outside the solar disk, with SWAP serving as a 'third eye' for the twin STEREO satellites, which are now too far apart to continue stereoscopic viewing without Proba-2's assistance.

It complements the data from solar imagers on other missions, providing context images of the corona at one million degrees for the JAXA Hinode satellite and off-disc context image information for SDO's Atmospheric Imaging Array images. Its images of coronal structures during solar eclipse events in the EUV also complement visual data gathered on the ground.

LYRA

LYRA is a solar ultraviolet radiometer manufactured by a Belgian/Swiss/German consortium including the Royal Observatory of Belgium, the Centre Spatiale de Liège and the World Radiation Centre in Davos. It monitors solar radiation intensity in four ultraviolet pass bands. The channels have been chosen for their relevance to solar physics, aeronomy and space weather. The instrument contains three units which each possess four channels for redundancy and calibration.

LYRA makes use of novel 'wide bandgap' detector technology, based on diamonds. Diamond sensors have a high 'radiation hardness', useful in making instruments tougher against EUV as well as ionising radiation. LYRA's demonstrates technologies that are important for future missions, such as ESA's Solar Orbiter, which is intended to go closer to the Sun than any other mission.

→ Proba-1 operating for ten years

Launched in November 2001, and originally designed for only one year of life, Proba-1 is now entering its tenth year of operations. The platform and instruments are still in good health. So far there has been no need to use redundant units and there has been very limited degradation of its solar cells and battery.

Constructed as a technology testbed, Proba-1 is being operated by ESA today as an Earth Observation 'Third Party' mission. A dedicated user community has grown, with 18 m resolution multispectral imagery being produced by Proba-1's main Compact High Resolution Imaging Spectrometer (CHRIS) instrument on a daily basis. Even higher-resolution 5 m imagery comes from the monochromatic High Resolution Camera (HRC). Controllers specify the latitude, longitude and altitude of their desired target and the largely autonomous and highly agile satellite does the rest itself.

↑ Proba-1, Project for On Board Autonomy, demonstrates the potential and feasibility of small satellites for advanced scientific and Earth Observation missions

→ Technology demonstrations payloads

Payload	Company	Notes
Digital Sun Sensor	TNO (NL)	Both Star Tracker and Sun Sensor are digital attitude sensors based on APS technology, as well as micro-mechanical devices and folded optics. The latter design is a demonstration model for ESA's forthcoming mission to Mercury.
BepiColombo Star Tracker	Selex Galileo (IT)	
Fibre sensor demonstrator	MPB (CA)	Fibre optics interfacing with the propulsion module to measure temperature and pressure levels
Science Grade Vector Magnetometer	DTU (DK)	Directly controlled by the μ-ASC electronics, delivering real-time magnetic field components with a very high precision. This prototype is paving the way for an operational version to be flown on ESA's Swarm mission.
Experimental Solar Panel	CSL (BE)	With a solar flux concentrator, studying temperature behaviour and ageing effects resulting from concentrated solar flux. In-flight results show a 55% increase in cell efficiency, with measurements being repeated to monitor solar cell degradation.
Dual-frequency GPS receiver	Thales Alenia Space (FR)	Radiation-hardened and dual frequency, intended for use on many future missions
Exploration Micro-camera	SpaceX (CH)	A powerful miniaturised micro-camera with a large optical field of view
Laser Retro-Reflector (LRR)	Federal Unitary State Enterprise (RU)	
ZMM set of magnetometers	ZARM (DE)	
Credit Card Magnetometer	Lusospace (PT)	This and the Zarm set are new developments in high-precision, high-rate three-axis magnetometers
Additional innovative Guidance, Navigation & Control algorithms	NGC (CA)	
TDM	QinetiQ Space (BE)	Measuring radiation effects, featured inside an additional ADPMS board
Lithium ion battery	SAFT (FR)	
Advanced Data and Power Management System	Verhaert Space (BE)	Containing many new technologies, including the LEON processor
Structural panels	Apco Technologies SA (CH)	Combined carbon-fibre and aluminium panels
Reaction wheels, star trackers and GPS receivers	Dynacon (CA), DTU (DK), DLR (DE)	
Telecommand system	SST-SystemTechnik GmbH (DE)	Upgraded with a decoder largely implemented with software
A PROPULSION MODULE CONSISTING OF:		
Cold gas 'resistojet' thrusters	SSTL (UK)	Using xenon as propellant
Cool gas generator experiment	Bradford Engineering/ TNO (UK/NL)	A solid-state gas generator that produces nitrogen to repressurise the propulsion module tank. This COGEX system contains four solid-state cartridges which, when ignited, repressurise the propulsion tank of the resistojet system and squeeze out more performance.

↑ Proba-2 is demonstrating a several new technologies in orbit

From January, LYRA provided a stream of solar irradiance measurements, taken every 20 milliseconds, or more or less continuously. LYRA is the only detector in space with such a high time resolution. LYRA serves to confirm all flares observed by other space sensors. For some very energetic flares, an extra component of activity in longer wavelengths has been discovered.

LYRA is currently used for continuous flare detection (since May all flare events are reported and Level 5 data for flare events can be found online), Earth atmosphere studies, reconstructing atmospheric ozone distribution during the yearly eclipse season (December to February), and temporal analysis of magnetic reconnection and the investigation of potential millisecond UV structures as known from solar radio bursts.

The latest SWAP and LYRA data can be found on the Proba-2 science web pages at **http://PROBA2.sidc.be/index.html/**

DSLP/TPMU

The Double Segmented Langmuir Probe (DSLP) experiment measures plasma around the satellite. This instrument was developed by the Institute of Atmospheric Physics, part of the Czech Republic Academy of Sciences. The DSLP is based on a novel development of classical electrostatic probes, comprising two identical spherical sensors mounted with short booms on tips of one of Proba-2's deployable solar panels. The main scientific objective is to identify the response of ionospheric plasma response to variable solar activity and space weather.

After commissioning, the DSLP sensors have been used on a continuous basis, providing measurements along Proba-2's orbit.

The Thermal Plasma Measurement Unit (TPMU) contains three experiments that measure the total ion density and electron temperature, ion composition and temperature, and the floating potential of the satellite body.

This instrument was also developed by the Czech Institute of Atmospheric Physics. The TPMU field of view is aligned with the flight direction of the spacecraft as far as the satellite's Sun-pointing attitude allows. ■

Acknowledgements

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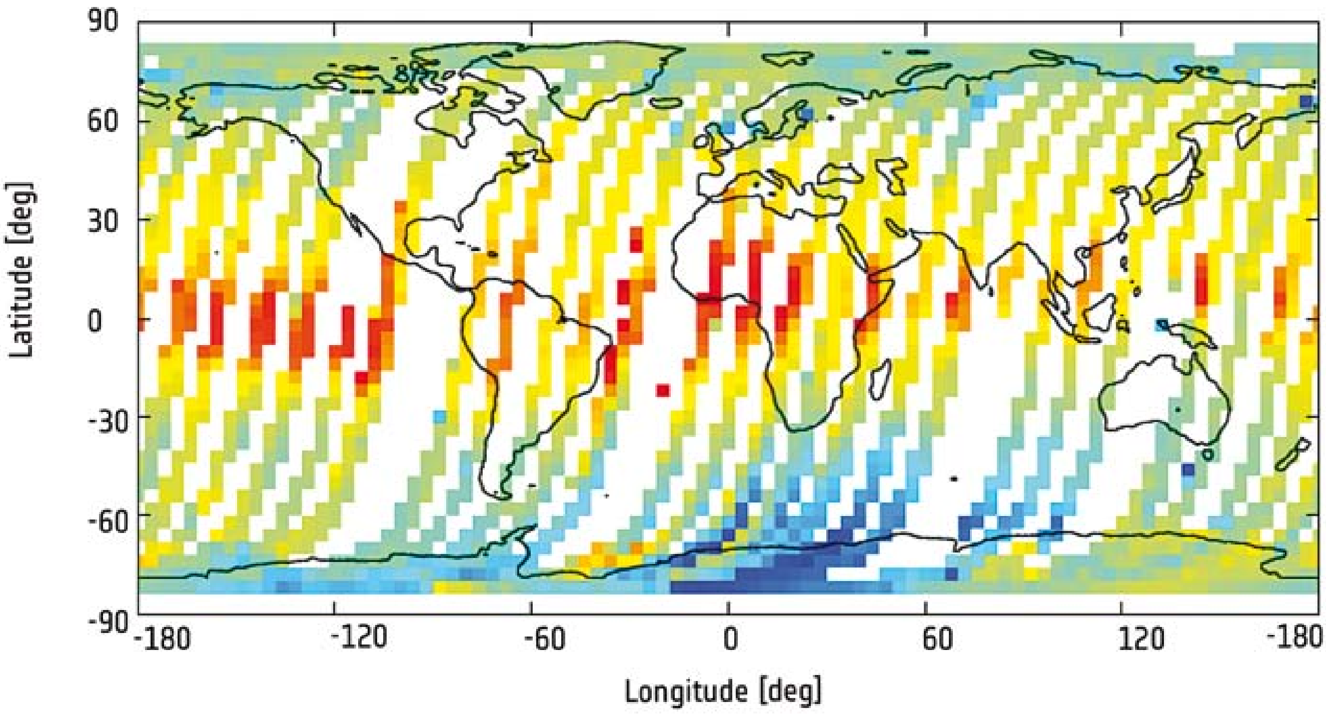

↑ Electron density map based on DSLP measurements