# → AUTONOMY IN ACTION

## Ten years of Proba-1

**Sean Blair**
Communication Department, ESTEC, Noordwijk, The Netherlands

**There are times when photographers have to move their cameras: when trying to resolve objects in rapid motion for instance, or capturing a subject from a variety of angles. So it is with ESA's Proba-1 microsatellite, whose main camera is still going strong after a decade in orbit.**

At less than a cubic metre in volume, Proba-1's modest size lends it great agility and unique abilities that have seen its data used by a total of 446 Principal Investigator teams worldwide, and its camera, the Compact High Resolution Imaging Spectrometer (CHRIS), has acquired upwards of 15 560 science images of more than 3250 separate sites around the globe.

"To date Proba-1 remains the most agile and stable satellite platform in its range," explains Frank Preud'homme, Commercial Director of QinetiQ Space Belgium, the company serving as ESA's prime contractor for the development of the mission (previously known as Verhaert Design and Development).

"These attributes are a prerequisite for high-performance remote sensing missions. For Proba-1 – and the other Proba missions that have followed – the approach that has been taken has been to develop small satellites according to ESA quality standards but with specific implementation guidelines worked out between QinetiQ Space and ESA, making the platform ideally suited for operational missions at affordable costs where reliability is an important parameter."

ESA acquires, processes and distributes Proba-1 data as part of its 'Third Party Mission' data portfolio (together with international partner missions such as NASA's Landsat satellites, the Japanese ALOS satellite, the French Spot satellites or the UK-built Disaster Monitoring Constellation).

For the majority of Earth-observing missions, image acquisition is simply a matter of opening a viewing aperture, but Proba-1 is very different. A technology demonstration satellite turned Earth observation mission, the satellite's platform and payload effectively work as one. Spinning reaction wheels guided by a star tracker can roll the satellite off to 25° off-nadir in the across-track directions and 55° in the along-track direction.

To begin with, this allows Proba-1 to compensate for the effective satellite speed over Earth's surface of 7.5 km per second. This 'forward motion compensation' boosts its overall integration time per image, giving CHRIS an imaging performance and signal-to-noise equivalent to that of an instrument with an aperture area five times larger. Across-track tilts also increase the frequency with which the satellite is able to revisit areas of interest to less than a week.

## Seeing all the angles

In addition, Proba-1 can acquire different views of the same target at up to five different viewing angles: at ±55°/±36°, as well as the standard nadir view. It is this capacity in particular that has proved invaluable to many scientists investigating the 'Bi-Reflectance Distribution Function' (BRDF) of vegetation and other land cover features – meaning how the light they reflect changes with shifts in illumination or view angle.

"Say you're looking at a sunflower on the ground," explains Mike Cutter of Surrey Satellite Technology Ltd's Optical Payloads Group (formerly the Sira Space Group), which developed CHRIS and processes the data on behalf of ESA's ESRIN centre.

"You'll see a different mix of colours depending on where you're standing, as well as the growing season and time of day: the yellow canopy, green stalk and leaves, brown soil, sun glint or shadows. The same is true when observing from orbit. Quantifying this BRDF offers a way of giving much more accurate classification of vegetation and canopy covers, such as the tree species within forests."

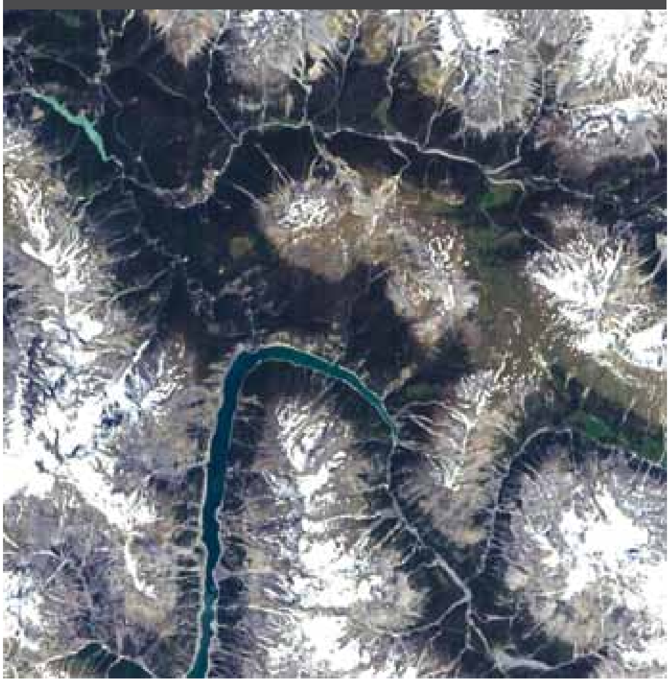
Beyond the sprightliness of its host platform, the hyperspectral CHRIS imager is well-suited to such a task in its own right, its design enabling users to fine-tune its settings as desired. Each 17 m sampled 13 sq. km image is viewed in a total of 18 visible and near-infrared spectral bands at once. Alternatively, the swath can be reduced by half, to 6.5 sq. km, to observe 34 spectral bands at a time, or 62 spectral bands observed if the spatial sampling is increased to 34 m.

## A worldwide community of users

Researcher David Goodenough of Natural Resources Canada has found that CHRIS multi-angle observations of Canadian forests and associated land cover reduced his classification errors by more than half. Teams in Switzerland, Germany and Australia meanwhile have been using CHRIS observations to classify the leaf angle and therefore maturity of maize, wheat and cotton crops respectively (the angle of the leaves increases as the structure of the growing crops change, the stems and heads coming to dominate). A Peking University project has done the same for seasonal observations of wheat, cotton and apple orchards in the Hengshui area of China's Hebei Province.

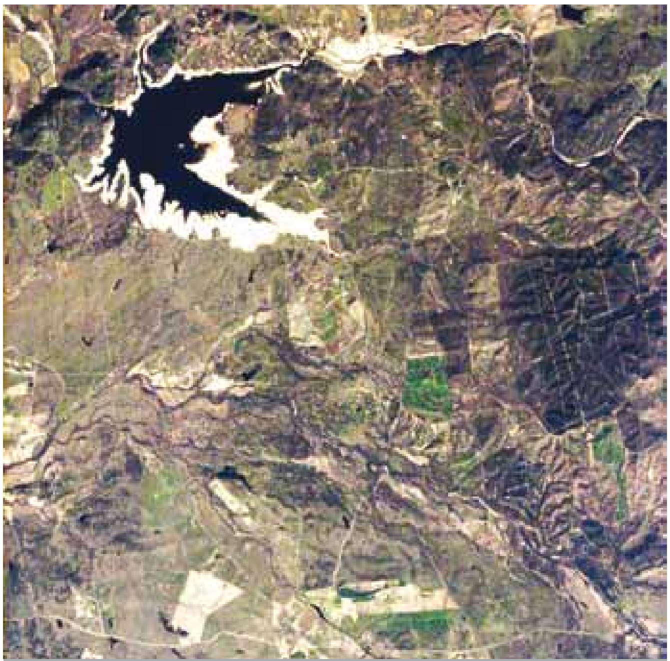
Other CHRIS users within the land cover field concentrate on spectral data alone – multi-angular views not being relevant. Bettina Weber of the University of Kaiserlautern in Germany has employed CHRIS imagery to measure the coverage and estimate the biomass of lichens and biological soil crusts

↓ CHRIS view of Swiss National Park, Switzerland



in the Namibian Desert. Such crusts play an important ecological role, anchoring soil in place, so their loss over time can flag up erosion patterns.

CHRIS data has also found favour in combination with other, lower spatial and spectral resolution imagers, such as NASA's Moderate Resolution Imaging Spectroradiometer or the Medium Resolution Imaging Spectrometer on ESA's Envisat satellite. "It can give extra detail of a local section of a larger satellite image acquired at lower spatial resolution, which is often useful," adds Mike Cutter.



↑ ↓ CHRIS views of the Rosarito Reservoir in Spain

## CHRIS over water, and imaging the air

This is true on land, but especially so over water. A community of users are using CHRIS to sample water quality, its multispectral imagery serving to derive standardised parameters such as chlorophyll content, total suspended soils and dissolved organic matter within inland water bodies such as the Rosarito Reservoir and Aracena Dam in Spain – research of growing significance due to the European Commission's Water Framework and Drinking Water Directives.

Proba-1 acquired a notable image of the 2010 Gulf of Mexico oil spill and has also been used to study spills within Venezuela's Lake Maracaibo, one of the most ancient, oil-rich (and hence polluted) water bodies in the world. In Germany CHRIS data has been harnessed to assess the ecological condition of abandoned open-cast mining areas, identifying impacts on vegetation, sediments and water – iron oxide tailings can not only turn water brown but also acidic. Similar techniques can be used within coastal waters, with one survey of chlorophyll and suspended particles performed off Ostend in Belgium.

↑ CHRIS view of Rupel and Schelde rivers in Belgium

But CHRIS is also being used to survey the bathymetry of coastal waters as well as their contents: Ray Merton of the University of New South Wales in Australia has developed an innovative algorithm to estimate the shallowness of coastal waters by identifying the shifting frequency of waves as they approach the coast or underlying reefs, employing the fact that the wave's spatial frequency increases as the water gets shallower. This technique can be used in highly sedimented water without needing to rely on the optical visibility through the water as typically used in bathymetry.

↓ Konakri, Guinea, seen by Proba-1's CHRIS instrument in 2002

CHRIS is also usable for atmospheric aerosol monitoring, its higher resolution offering enhanced insight into highly polluted regions. A team led by Janet Nichol at the University Polytechnic of Hong Kong adapted an algorithm originally developed by MODIS to retrieve aerosol optical thickness (AOT) over Hong Kong, with results checked against by Sun photometer and lidar measurements, as well as air quality data gathered by ground stations. They estimated an error of around 6%, compared to up to 20% from comparable MODIS data products – the entire sampling area of 11 x 11 km being only slightly larger than a single MODIS AOT pixel.

↑ Proba image of Victoria Harbour in Hong Kong

## Versatile by design

The versatility that has attracted devoted users around the world was inherent from Proba-1's very start. Its name stands for 'Project for Onboard Autonomy'. "The aim of the project, supported in particular by the Belgian Federal Science Policy Office through ESA's General Support Technology Programme, was to demonstrate as many new technologies as possible on a single platform, the resulting small satellite being able to operate itself with minimum ground control," explains Frederic Teston of ESA's In-Orbit Demonstration Programme.

Onboard innovations included what were then novel gallium arsenide solar cells, one of the first lithium ion batteries – now the longest operating such item – in low-Earth orbit, and attitude and orbit determination using only star trackers and GPS sensors, doing without the then-standard standard Earth or Sun sensors or gyros (GPS timings are also used to synchronise operations).

Navigation and attitude control software was generated through 'autocoding' to cut costs – essentially applying code to write code – with Proba-1's overseen by an ERC32 computer, a space version of a standard commercial processor, subsequently employed on projects including ESA's Automated Transfer Vehicle, the Columbus laboratory module on the International Space Station, the European Robotic Arm and the forthcoming Sentinel satellites that support Europe's Global Monitoring for Environment and Security initiative.

As part of Proba-1's technology goals, all software components in the central computer or embedded within other subsystems can be reprogrammed in flight. The satellite itself does as much work as possible: CHRIS users only have to submit the latitude, longitude and altitude of their intended target and the onboard computer navigates to the correct location, tilts, shoots and delivers the scene.

### Steering by the stars

During normal operations, Proba-1's attitude is provided with the star tracker viewing two star fields, and the orbit calculated autonomously from GPS data. Knowing the orbit and attitude allows the satellite to deduce the direction of all user-selected Earthbound targets.

Attitude is controlled using a set of four reaction wheels mounted in a tetrahedral configuration – set one spinning and the satellite spins in the opposing direction, yielding a pointing accuracy of one arc minute (one sixtieth of a degree). Momentum built up in the wheels is dumped via magnetotorquers – electromagnets that interact with Earth's magnetic field – that are also used to align the satellite in the event of it entering 'safe mode'. The satellite has no fuel, further reducing its mass and avoiding any 'sloshing' effects that might interfere with fine pointing.

### Proba-1 payloads

As this autonomous technology demonstrator underwent development, led for ESA by what is now QinetiQ Space Belgium (then Verhaert Design and Development), payloads were sought. "There were several candidates, however CHRIS found favour because it had particularly challenging requirements, so offered a good demonstration of Proba-1's onboard autonomy," recalls Mike Cutter.

CHRIS was the largest of five payloads. A second, smaller imager, the High Resolution Camera (HRC) developed by Belgian company OIP Sensor Systems provides monochrome 5–10 m resolution images across an approximately 25 sq. km field of view.

And with Proba-1's approximately 600 km polar orbit taking it through the polar 'horns' of Earth's radiation belts, it also carries two radiation monitors: the Standard Radiation Monitor (one of a family of monitors flown on various ESA missions, building up radiation maps across the inner Solar System) and a smaller Miniaturised Radiation Monitor. Finally, a space-debris detector, the Debris In-Orbit Evaluator, was also flown – another version of this detector was later attached to the ISS.

### A decade in orbit

Proba-1 was designed to be compatible with several launchers, including Ariane 5, to help find a cheaper 'piggyback' launch opportunity (launch costs can amount to a considerable proportion of a mission's final price tag), finally riding to orbit on 22 October 2001 on an Indian Polar Satellite Launch Vehicle (PSLV), from the launch station at Shriharikota, a small island about 100 km from Madras.

## → Proba-1

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|---|---|
| Spacecraft mass | 94 kg |
| Instrument mass | 25 kg |
| Technology payload mass | 30 kg |
| Shape | 60 x 60 x 80 cm box-shaped aluminium honeycomb structure |
| Launch date | 22 October 2001 |
| Launch site | Sriharikota, India |
| Launcher | Antrix/ISRO PSLV-C3 |
| Orbit | LEO Sun-synchronous |
| Orbital parameters | 681 x 561 km |

Proba-1 remains in orbit, all its technology goals long since accomplished but still fully functional and its imaging services in steady demand. Funded by ESA's Earth Observation Programme since 2004, the scientific data exploitation is overseen from ESA's Earth observation centre in ESRIN. CHRIS acquires an average of three sets of five multi-angle images daily, with the HRC high-resolution black-and-white camera also returning a steady stream of imagery.

The satellite is commanded from ESA's Redu ground station in Belgium with a dedicated 2.4 m antenna, with Kiruna in Sweden serving as an additional data downlink. The onboard autonomy and the ground-segment automation elements allow the control of satellite passes with no operator attendance. This approach proved to be very successful in terms of operational efficiency and has been reiterated for the coming Proba satellites.

The user segment operations of Proba-1 are spread across ESA's Member States, overseen by the ESRIN team. A company called RSAC Ltd (UK) compiles a schedule of upcoming CHRIS targets based on Principal Investigator (PI) requests gathered by ESRIN. This process is guided by NORAD 'two-line elements' feeding an orbital model compiled every fortnight by Jeff Settle and his colleagues at the University of Reading, forecasting which sites will be visible per given day, along with a 48-hour cloud prediction product (initially provided by the UK Met Office but lately by weather.com).

# → Disaster monitoring

North Sentinel Island in the Indian Ocean – seen here in this 2005 CHRIS image – was one of the more obscure victims of the 2004 Asian tsunami, with geological uplift leading to formerly submerged coral reefs rising above the waves. The shift represented a big environmental change for the island's inhabitants, the Sentinelese, one of the last uncontacted indigenous human tribes on Earth.

The image shows how CHRIS images can be employed for detailed disaster monitoring, one of more than 500 acquired to date on behalf of the International Charter 'Space and Major Disasters', an agreement between global space agencies under which satellite imagery is supplied freely to emergency responders on a best-effort basis.

The resulting target coordinates are then transferred to Redu by SSTL together with the payload configuration for the specific PI requested spectral and spatial observation conditions. The acquired image data is then processed to Level 1b by SSTL and delivered to ESRIN for downlink by the PIs.

There are currently a total of 42 262 CHRIS data sets available for scientific users in the ESRIN data archive, each set comprising between one and five images of the same target. The archive also contains more than 13 000 HRC images.

## Effects of time

The only noticeable ageing effect experienced by the satellite comes from a combination of cumulative radiation damage and higher seasonal temperatures (counter-intuitively for us in the Northern hemisphere, Earth comes closest to the Sun in January, leading to an effective 10% increase in solar flux). After 10 years in orbit (and a design life of only two years) Proba-1's star tracker shows sensitivity to the resulting change in temperature.

There are ways to overcome the effect, such as reorienting the satellite between imaging acquisitions to decrease the solar flux reaching the star tracker. But still, CHRIS has been forced into taking 'winter holidays' these last few years.

Time is gradually running out for Proba-1 in another way, nothing to do with its design but resulting from stern laws of orbital mechanics. Like most Earth observation missions, Proba-1 was placed into a Sun-synchronous orbit, meaning it keeps pace with the Sun so that it crosses the equator northward at a fixed local time, helping to keep lighting conditions constant for comparing images.

At launch, this local time was 10:30 a.m., the orbit chosen so it would advance up to 10:46 within the first three years and then gradually drift back earlier. "This gave us very good local times for about eight years," adds Frederic. "Bear in mind that the original mission lifetime was set at two years originally. It's becoming more of a problem as we get past 9:00 a.m., and there will come a point it simply gets too dark."

Orbital geometry aside, having sufficient funds to support missions that considerably exceed their nominal lifetime is always a challenge. "We are happy that through the past eight years our national delegations have supported


us in extending the mission and thus enabling the variety of applications to expand further every year," says Bianca Hoersch, the Proba-1 Mission Manager.

"The funding from Third Party Missions and the current Earth Observation Envelope Programmes has ensured the mission operations until the end of 2012. It would be great to have CHRIS around even longer until national hyperspectral instruments such as the Italian PRISMA or the German EnMap missions become available, currently foreseen for 2013."

## The Proba family

The success of Proba-1 has inspired a family of follow-on technology demonstrator missions, aimed at providing more frequent flight opportunities to new European technologies. Proba-2 has been in orbit since November 2009, carrying 17 technology demonstrations and four science payloads focused on the Sun and space weather.

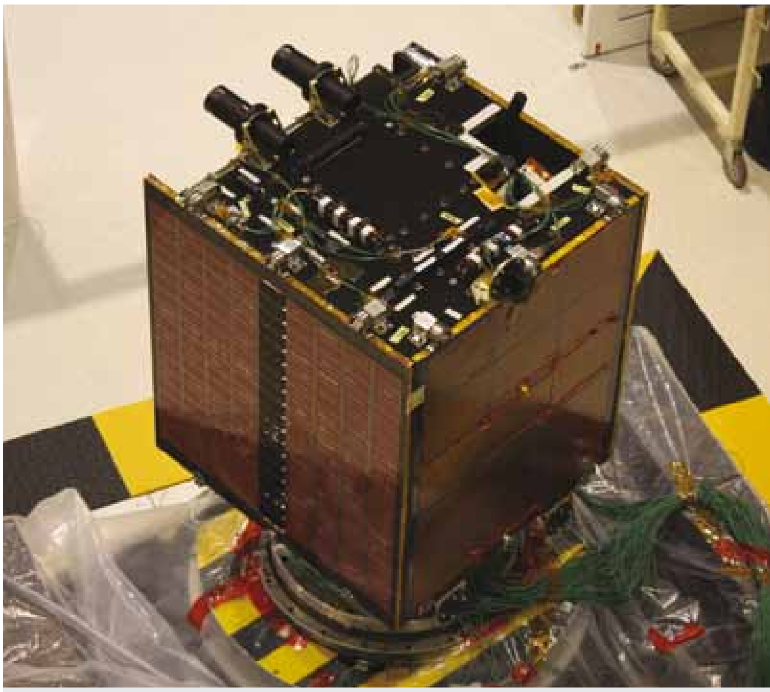
Proba-V is due for launch next year, providing daily maps of global vegetation cover in order to ensure data continuity between the end of the 'Vegetation' series of sensors flown on France's Spot-4 and -5 satellites and the launch of a compatible sensor on ESA's Sentinel-3.

Its novel technologies include a compact telescope and short-wave infrared detectors, the first X-band gallium nitride transmitter, as well as an energetic particle monitor and an experimental automatic dependent surveillance-broadcast receiver, used for aircraft tracking.

Also under study is Proba-3, a double satellite mission to demonstrate close formation-flying techniques, with one satellite casting the other in an artificial solar eclipse to reveal hidden features of the inner solar corona.

All the other Proba missions to come follow the first one's example, incorporating demanding science payloads to serve as the best possible demonstration of the experimental technologies integrated aboard. If the results are good enough then the scientific end users will come – challenging Proba's engineers to do their very best to make it happen. ■

Sean Blair is an EJR-Quartz writer for ESA



↑ Proba-V Structural and Thermal Model during testing in Toulouse, France, in 2010 (Intespace)

↑ A mosaic of four black and white images taken by Proba-1's High Resolution Camera in September 2011, showing massed camper vans and tents gathered for the desert-based Burning Man festival at Black Rock, Nevada, USA

## → Proba-1: lessons learned

The Proba-1 experience has proved remarkably successful in demonstrating the potential of small satellites in space, first, for flight-testing new technologies and going on to serve scientific end-users.

Small satellites – their mass measured in the tens of kilograms, rather than tonnes – take months instead of years to develop and are much cheaper and simpler to build and launch. In the case of Proba-1, it succeeded in its aim of being launched within two years of the start of its Phase-B design study phase.

Spending less money per mission means a somewhat increased level of risk becomes acceptable, and experimental systems that the (understandably) risk-averse mission manager of a full-sized satellite might flinch at can find a berth in space.

This opens up new opportunities for European companies to prove novel technology in space. In-orbit demonstration is the last step on the technology development ladder: flight heritage is essential for market acceptance.

The satellite itself represented an experiment – Proba-1's name also derived from the Latin word *probare* – 'to test', or 'to try'. Autonomy was seen as a highly desirable attribute for future missions, but also it tends to drive up development costs and threaten, in the worst case, the loss of control of the satellite. But this mission was small enough to take the risk.

Autonomy also required more complex onboard software – which meant a lot of time taken to write it, at least traditionally. Autocoding reduced the time taken to compile and validate Proba-1's flight software by a factor of nearly two.

The project proceeded in other novel ways for ESA: mission control system development became an integral part of the overall mission programme, along with associated operations. Development occurred incrementally, with progressive validation taking place throughout activities ranging from software development, spacecraft integration and system testing to in-orbit operations.

For ESA's industrial partners, the experience proved an extremely valuable one. For what was then Verhaert Design and Development, Proba-1 provided the opportunity for them to oversee a high-profile space project by themselves, rather than work on a subcontracted slice of another company's work.

"Proba-1 was a milestone in developing our prime contractor capabilities. Despite prime contractorship of other important large projects, it was Proba-1 that marked QinetiQ Space as a small system integrator," comments Frank Preud'homme, Commercial Director of QinetiQ Space.

"This allowed QinetiQ Space to acquire larger projects in turn, and to attract motivated young engineers to further develop these capabilities. New young engineers were trained on the Proba projects. And once Proba-1 was adopted by ESA's Earth Observation Directorate for operations, providing high-quality images daily, the opportunity was opened up for us to show interested customers the advantage of the automated operations concept, further enhanced by the advances made in the follow-up Proba missions."

The Optical Payload Group of Surrey Satellite Technology Ltd (SSTL) recount a similar experience: "Our staff became extremely enthusiastic about having full control of a satellite instrument, rather than supplying subsystems to prime contractors and it helped give consideration to the approach to take when developing low-cost missions," said Mike Cutter of SSTL.

"CHRIS helped put us on the map as a small satellite instrument supplier. It also helped to build up our relationship with SSTL, which led to the joint bid for the NigeriaSat-2 Very High Resolution Imager and the subsequent acquisition of the Sira Space Group by SSTL. NigeriaSat-2 was launched in August 2011 and is providing 2.5 m imagery. Expertise and heritage in payload development for small satellites can also drive new business opportunities, as seen by the recent award to SSTL to build the 1 m resolution spacecraft under contract to its subsidiary, DMC International Imaging Ltd."

↑ The Pyramids of Giza in Egypt, taken by Proba-1's High Resolution Camera in March 2004. The three main pyramids stand on the edge of Greater Cairo at the verge of the desert

↑ Uluru, also known as Ayers Rock, in Australia as taken in April 2004 by the High Resolution Camera on Proba

↑ Proba-1 took this image of Liberty Island and Ellis Island, New York, from 600 km altitude in 2006. Liberty State Park is to the left, and New Jersey is at the top left. Manhattan is top right, and Governor's Island is bottom right