PROBA "SPACECRAFT FAMILY"
SMALL AUTONOMOUS SATELLITES - A BELGIAN INNOVATIVE EXPORT PRODUCT

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ABSTRACT *– After the successful realisation of Proba 1, a 100 kg small autonomous satellite for ESA technology demonstration purposes now generating for more then 2,5 years splendid earth observation images, and the first steps set in the development of its successor PROBA 2, Verhaert and Spacebel teamed for the further worldwide commercialisation of this innovative Belgian product.*
In PROBA 1, Verhaert was the prime contractor and acted as the small systems integrator, where Spacebel was responsible for the on-board software development.
Verhaert and Spacebel offer now a complete small satellite system solution to the user community. The combined company team deals with the system aspects, while Verhaert is responsible for the satellite platform realisation and the launch procurement. Spacebel realizes the control and exploitation ground segment and is responsible for all data management aspects (on board and ground software). Other elements, such as payload development and operations, are covered by other companies on a case-by-case basis in function of the client's wishes.

1 - INTRODUCTION

Verhaert Design & development is a Belgian SME company active in the space business since 1984 and is located in Kruibeke (near Antwerp). The company is part of the Verhaert Consultancies holding, a group containing several companies dealing with innovative product development projects for third parties and was founded in 1969 by Mr. Paul Verhaert. Today, Verhaert Design & Development has two Space Business Units: Space Instruments, mainly dealing with the development of micro-gravity instruments, payloads and facilities, and Satellites & Platforms, dealing with the development of small satellites and mechanism & structures. Through the years, Verhaert built up the skills to deal successfully with multidisciplinary projects (e.g. fluid physics facility Fluidpac and small satellite PROBA 1) and is today one of the few and seasoned Small Systems Integrators in Europe. Verhaert has as well the infrastructure to integrate and functionally test space hardware in the required clean conditions.

Spacebel, a Belgian IT company established in 1988 and located in Brussels and Liege, draws its actual success upon its core business mainly located in the space industry. Today, the company is well recognised as a partner of choice within the space industry when software solutions have to be produced. It has acquired a leadership position in the development of satellite data handling software (DHS), satellite operational simulator and mission control centre. The unique combination of advanced technology knowledge, dynamism, expertise and innovation allows Spacebel to convert today's technical challenge into their customer's competitive advantage.

2 - PROBA 1

Project

Mid nineties, ESA initiated the idea for building a small satellite for technology demonstration purposes, called PROBA (Project for On-Board Autonomy). With the financial support from the Belgian Science Policy Office to ESA's General Support Technology Programme (GSTP), Verhaert finally could win a contract for a small conceptual study in 1996 and a the phase C/D contract which started in February 1998.

PROBA 1 is the first Belgian small satellite and is developed by Verhaert as prime contractor. The satellite was realised in about 3 years and a lot of Belgian and European subcontractors / suppliers participated to the project, amongst them Spacebel, which was responsible for the On-Board software development. The payload instruments were provided to the industrial team under ESA's responsibility.

Satellite

The satellite weighting only 94 kg with dimensions 80 x 60 x 60 cm, is built for an ESA technology demonstration mission. The main objective is to demonstrate the autonomous operation of the spacecraft. The strong features of the PROBA platform lie in the field of autonomous operation, its simplicity in operation, its performant attitude control system and its strong SPARC–ERC 32 based computing capability. PROBA's 3-axis attitude control system provides fine-pointing capabilities, resulting in precise snapshot images (e.g. HRC instrument) and has agility to execute demanding mapping and push-broom scanning scenarios (e.g. CHRIS instrument).

The satellite was launched as piggyback passenger on October 22nd 2001 with the Indian Polar Satellite Launch Vehicle (PSLV) from the launch site SHAR (now called Satish Dhawan Space Centre (SDSC)), at Sriharikota in South East India. It was injected directly into its final polar, sun-synchronous orbit slightly elliptic (about 560 km x 650 km). The orbital drift (away from sun-synchronism) is compatible with the PROBA mission requirements. There is thus no need for on-board propulsion. Navigation of the spacecraft is performed autonomously on-board by the Attitude Control and Navigation Subsystem (ACNS) with a combination of GPS measurements and orbit propagation. The spacecraft is kept three-axis stabilised by means of attitude measurements provided by an autonomous star tracker and by on-board control through a set of reaction wheels and magneto-torquers. PROBA is operated via a small ground station (S-band 2,4 m dish) located at the ESA Redu site in the Belgian Ardennes.

Figure 1: PROBA 1 on PSLV (ANTRIX / ISRO)

Figure 2. PROBA complex manoeuvring capabilities

Payloads

The PROBA 1 payloads consist of a spectrometer (CHRIS), 2 Earth environment monitors (DEBIE and SREM) and 2 imagers (WAC and HRC). These instruments have been selected because they put severe requirements on the spacecraft technology in terms of ACNS, data handling and resources management in addition to scientific interest. For example, the spectrometer uses the spacecraft high accuracy slewing capabilities to perform multiple images of the same scene on Earth from different viewing angles. Also, the planning and the execution of the spectrometer and the imager's observation requests use the on-board flight dynamics function of Proba.

The main instruments are a Compact High Resolution Imager (CHRIS) developed by SIRA, generating 19 x 19 km multispectral images with a resolution of about 18 m in up to 19 selectable spectral bands at once (out of 62) and a High Resolution Camera (HRC) built by OIP, generating 5 x 5 km panchromatic snapshot images with a resolution up to 5 m.

Figure 3: PROBA / HRC Image (ESA)
20.03.2004 Pyramids Gizeh, Egypt

Figure 4. PROBA / CHRIS Image (ESA / SIRA)
19.12.2003 Three Gorges Dam, China

Applications

The design life of two years has been passed and up to date, the satellite is performing excellent and generating wonderful images, which are used by the earth observation science community on a daily basis.

After a first year used for technology demonstration purposes, the satellite is now used as an Earth Observation mission. As such, it show the potential of small satellites for earth observation purposes, demonstrated daily by the use of its images in several application fields such as but not limited to vegetation studies, coastal water studies and disaster monitoring.

Small satellites can be operated in a simple way and provide images on very short term. The image of figure 5 about the Etna eruption was delivered half a day after the event started.

Figure 5: PROBA / CHRIS Image (ESA/SIRA)
20.10.2002 Etna eruption, Sicily

The Future

By successfully realising the PROBA 1 spacecraft, Verhaert entered the small satellite business. The advanced platform has a great potential and actions are taken to commercialise the platform in the ESA and non-ESA market. The PROBA Spacecraft Family provides state-of-the-art small autonomous satellites for a wide variety of applications.

More information

More detailed information on PROBA 1 and its results can be found in the referenced papers and on following websites

www.verhaert.com
www.esa.int/estec/proba
www.chris-proba.org.uk

3 - PROBA SPACECRAFT FAMILY

This section highlights the characteristics and strong points of a typical PROBA platform.

3.1 - Typical Platform Specification

PROBA Platform Datasheet (PROBA 1 – PROBA 2 figures)		
Mission		
Orbit	Standard: Sun Synchronous **LEO**	
Mission Lifetime	Minimum **2 years**	
Launcher	Compatible with DNEPR, PSLV, ASAP5	
Mechanical		
Mass	**< 120 kg** of which at least **45 % available to payload**	Can be modified according to customer needs.
Dimensions	Typical: **60x60x80 cm^3**	Can be modified according to customer needs.
Payload dimensions	Volumes available for payloads (mm^3): 220x630x110, 210x300x110 and 250x690x325, 250x340x215 for earth observation payloads (Proba 1 figures)	Can easily be adapted according to customer needs
Avionics		
Processor	Rad-hard **LEON-FT** (SPARC V8) processor	
Processor performance	**100 MIPS, 2 MFLOPS** of which at least 70 % available for payload management and data processing	
Memory	• 4 Mb flash • **8 Mb RAM** (with EDAC protection) • **32 Mb SDRAM** (with EDAC protection)	Payload memory can be increased by the addition of a mass memory unit in the onboard computer.
Communications system	S-band, 1 Mbps downlink	Upgradeable to 10 Mbps downlink
Power		
Solar Array	Standard: **Body Mounted GaAs** solar array	Optional **deployable solar array** can be included to increase available power
Battery	**Li-ion battery**, 28V, 11 Ah	
Power interfaces	• Unregulated 21V – 31V • **Up to 7 switch-able outputs** to payloads • Max. 50W per output	
Available **payload** power	Standard configuration (based on PROBA 2): > **40 W** orbit average power > **100 W** peak power Configuration with deployable: > 200 W peak power	
Thermal		
Thermal control	• **Passive** thermal control • Payload thermal environment controlled by thermal design (MLI etc…).	Heaters or radiators can be added according to payload needs.

PROBA Platform Datasheet (PROBA 1 – PROBA 2 figures)		
Attitude Control		
Attitude control	**3-axis stabilised** using extended Kalman filter	
Pointing accuracy	• Absolute error: **< 0.025°** • Stability: better than **0.003° over 10 sec**.	
Agility	• Along-track and across-track (+/- **30° off-track pointing**) • Slew rates up to **1°/sec**	
Pointing modes	• Complex attitude manoeuvring according to payload needs • Fixed Earth Target Pointing • Earth Pointing • Inertial Pointing	Examples of attitude manoeuvres: *TDI, BRDF, image paving, multiple target imaging*
Orbit Determination	• Fully autonomous orbit determination (+- 15 m) and time management based on onboard GPS • On-board Flight Dynamics including orbital navigation and computation	
Sensors	Advanced Star Tracker (dual head) Magneto-meter GPS	
Actuators	Reaction Wheels Magnetotorquers	
Propulsion	Standard: no propulsion system	Cold gas propulsion system can be added for orbit maintenance, station keeping etc…
Software		
Autonomy	• **High level payload management** • Autonomy in planning • Autonomous attitude control • Autonomous target predictions • FDIR	*For example:* *Earth Observation instrument:* *1 image = 1 command (latitude, longitude)*
Operating System	RTEMS	
Redundancy		
Redundancy	Standard: **fully redundant** platform	Non-redundant platform can be foreseen
Development time		
Typical development time	**1.5 – 3 years** depending on the applications and recurrence	
More info: www.verhaert.com	www.esa.int/proba	www.spacebel.be

3.2 - Strong Features of the PROBA satellite

3.2.1 - Modularity and flexibility in design

The PROBA concept is built up from several honeycomb panels. Internally it consists of 3 panels, each carrying a specific set of subsystems. The subsystem distribution is chosen in function of an optimised AIV approach (e.g. payload panel, avionics panel,), in fact the panels can be tested in parallel which gives a lot of flexibility. The panels are bolted together to a H-shape and panels carrying the body-mounted solar cells close the satellite. The main advantages of this concept are:

- Modularity in mechanical structure
- Easy incorporation of off-the-shelve units and instruments
- Modularity and flexibility in AIV approach
- Modularity in software architecture and design
- Flexibility towards launchers (separate I/F panel)

Figure 6: PROBA concept drawing and PROBA under integration at Verhaert

3.2.2 - Autonomy

One of the main advantages of the PROBA platform is that it has a high level of on-board autonomy and can be operated through an automated ground station, resulting in a low operational cost. Furthermore, the commanding of instruments is very simple, in fact 1 image ask for 1 command (target latitude, longitude and altitude) and an image request can simply be sent via the internet.

On-board autonomy

The Attitude & Control System (ACS) contains several functions enabling the on-board autonomy.
The navigation function has autonomous attitude and orbit determination, the prediction of orbital events & target over fly's and time management
The guidance function is performing the on-board generation of commanded attitude profiles (angle, rate, acceleration) during imaging, fixed-target pointing and "RELORB" modes
The control function is providing autonomous transition between large-angle sliding manoeuvres and state feedback fine-pointing control and autonomous management of the total spacecraft angular momentum
The fault detection & isolation function (FDI) provides the autonomous detection and identification of invalid inputs/outputs to/from ACNS functions and downstream propagation of validity and status flags for protection

Automated Ground Segment

The ground segment allows for Internet image request and image data distribution. The ground segment is operating in an automated way and thus the involvement of ground operators during nominal and routine mission phases is limited to routine maintenance tasks on (typically) weekly basis (so-called "Light-out" ground segment) . Furthermore, remote access to the ground station via a local network or via the Internet provides the operators with the capability to access the down linked spacecraft data whenever they wish.

The ground station provides the following functions:
1. Automatic link acquisition based on Norad elements and spacecraft navigation data;
2. Communications set-up protocol for the types of data (and their bit-rates) to be received;
3. Automatic uplink of previously screened observation requests and spacecraft planning commands;
4. Automated call of ground staff in case of detection of on-board anomalies;
5. Automated data filing, notification of users and data distribution.

3.2.3 - Fine pointing and stability

The PROBA platform is 3-axis stabilised and equipped with a very performant attitude control system (combination of star tracker and set of reaction wheels). It provides along and cross-track agility (+/- 30° off-track pointing), Position knowledge up to 20 m accuracy, sufficient stability for snapshot imaging (10 arcsec stability over 10 sec and) scanning functions for push-broom imaging (Slew rates up to 1°/sec) and allows complex manoeuvres to image a certain target from several viewing angles.

The several pointing and imaging modes are shown in following scheme

Figure 7: PROBA imaging modes

3.2.4 - Advanced on-board computer - ADPMS

The PROBA platform is equipped with an advanced state-of-the-art computer called ADPMS (Advanced Data and Power Management System). Verhaert is currently developing the unit under an ESA GSTP contract and the flight unit will be available in 2005. ADPMS will be flight qualified on the PROBA 2 mission (planned 2006).

The ADPMS is a logic step in the on-going process of further miniaturizing the small satellite subsystems in order to improve the available mass / volume for payloads. The ADPMS is combining in a single box the data handling system, power control system and has extension possibilities for additional boards as mass memory, payload processing, GPS and ACS interface board. It has a modular concept based on a compact PCI standard, which gives a lot of flexibility in design, testing and configuration (redundant or not). Compared to PROBA 1, where we had 3 boxes for these functions and had about 30 % of the total mass available for payloads, we have for PROBA 2 about 40 % of payload mass available. Furthermore, this unit is based on the Single Chip LEON version, giving very performing computing power needed for complex autonomous missions. The miniaturized concept also drastically reduces the power consumption of ADPMS, which is about half of PROBA 1..

3.2.5 - ESA Quality label

The PROBA platform is developed under an ESA contract, thus compliant with the ESA PA and quality standards but tailored to a small satellite mission. This “quality label” should give confidence to potential customers.
On component level, a mix of Space Qualified, MIL and Commercial parts is used. Components for critical systems are tested and the complete Parts list was screened and approved by ESA PA. On unit and component level, qualification is based on flight heritage (e.g. similar unit; component from same batch). Furthermore, the platform has redundancy for critical systems.

Given the short development time (typical 2-3 years) and the complex on-board software inherent to autonomous small satellites, not everything can be tested towards 100% guarantee before launch. As such a "safe-in-orbit" approach is followed, where the satellite is launched when sufficient confidence is built up on the correct functioning of the basic elements to guarantee in-orbit survival. Uplink and software patch possibilities should allow for corrective actions when needed.

3.2.6 - Short development time – low cost

Two important advantages of small satellites are they can be developed in a reasonable short time (typical 2-3 years) and are low cost products, compared to large missions. These advantages open possibilities to new markets and users (seen next point).

3.3 - Summary of potential future missions and concept studies

While PROBA 1 is continuing its successful operation, Verhaert performed several concept studies and signed the contract with ESA for its second small satellite PROBA 2.

3.3.1 - PROBA 2 – Technology demonstration

PROBA 2 is the second satellite in ESA's "PROBA series". The contract for the realisation of this mission was awarded to Verhaert in July 2004, Spacebel is involved for the on-board software and the ground segment and operations aspects.

PROBA 2 is again a technology demonstration mission, thus carrying several technology demonstration elements from all over Europe and payloads. In contrary to PROBA 1, where the main instruments where for earth observation, PROBA 2 is equipped with two Belgian sun observation instruments (SWAP and LYRA).

PROBA 2 shall be build according the small satellite philosophy as successfully demonstrated on PROBA 1. It shall also further improve the capabilities of the platform, such as increased mass available to payloads, miniaturized and advanced computer ADPMS, propulsion system, deployable solar panels, .. ….

Following is a summary of the technology elements and payloads for PROBA 2

PROBA 2 Technology experiments:

- o Bepi Colombo Star Tracker from Galileo Avionica(I)
- o Digital Sun Sensor from TNO (NL)
- o GPS Receiver from Alcatel (F)
- o Cool Gas Generator (NL)
- o Propulsion subsystem from SSTL (UK).
- o Solar Array concentrator experiment from CSL (B)
- o Science Grade Vector Magnetometer

Apart from this there are also platform critical technology demonstrators such as:

- o Li-Ion Battery from SAFT (F)
- o ADPMS from Verhaert (B)
- o Advanced Stellar Compass from DTU (DK)
- o Reaction Wheels from Dynacon (CAN)

PROBA 2 payloads:

- Thermal Plasma Measurement Unit (TPMU): space environment
- Dual Segmented Langmuir Probe (DSLP): space environment
- Sun Watcher using APS detectors and image processing (SWAP) from CSL: sun observation
- Lyman alpha Radiometer (LYRA) from Royal Observatory (B): sun observation

Figure 8: PROBA 2 Artist's Impression

3.3.2 - ARGUS – High resolution mission

The PROBA platform has high pointing accuracy capabilities and is sufficient stable to take sharp snapshot images. Through an ESA feasibility study (2000) and internal Verhaert concept studies, we defined a concept for high resolution missions (1 – 5 m) based on a PROBA platform, called ARGUS (Advanced Resolution Generated Using Small Satellites).

The most challenging concept can provide 1 m panchromatic resolution with a PROBA platform of about 170 kg and dimensions of roughly 70 x 100 x 130 cm. Challenges are the thermal stability needed for the payload, the micro vibrations generated by the reaction wheels and the need for a very performant gyro for pointing stability..

3.3.3 - µG server – micro gravity mission

The autonomous features of the PROBA platform allow for its use as free flying microgravity platform, providing high quality microgravity levels (< 10^{-4}, much better then ISS levels).

Currently, Verhaert finalised an ESA phase A study under the STEP program "Wakeshield Type of Facility for Very Low Microgravity". The study analysed the user needs, the problems related to flying around the ISS (safety issues) and defined a concept for a PROBA based microgravity platform and the operational scenario.

The major challenges are coming from safety concerns in flying in the vicinity of the ISS and the servicing of the system through Docking. This finally result in platform of about 400 kg and a size of 1,5 m cube.

Figure 9: Concept drawing PROBA / micro gravity platform

3.3.4 - Wonder – disaster monitoring mission

Together with the Russian Institute IZMIRAN, Verhaert did an assessment of using PROBA platforms for an earthquake early warning system. The project was called WONDER (Warning and Observation for Nuclear Disaster and Earthquake Readiness).

The system allows predicting earthquakes 1 to 3 days before occurrence by analysing measurements from the ionosphere. It consists of in total 4 PROBA satellites located in two orbital planes, which are equipped with a set of instruments for ionosphere measurements. Further developments are waiting for the results of the Russian Kompass and the CNES Demeter missions.

4 - GROUND SEGMENT AND OPERATIONS

Figure 10: PROBA GS Overview

The main elements of the PROBA ground segment are a fully steerable S-band antenna, a baseband equipment, a main control system based on the ESA SCOS 2000 system used also during the ground test and integration phase, a mission planning system and a Web server.

An operational language allows to interface with the telemetry and the telecommand server of the control system and to control all the pass activities and most of the ground segment units. It is the key element of the automation of the ground segment. It allows also the automatic email generation in case of any warning message. It is completed by the mission preparation and product generation responsible from the schedule of the payload activities based on the user requests to the processing and delivery of the acquired images.

The NORAD Two Lines Elements automatically retrieved from the Web, are used to predict with a COTS software the ground station visibilities, as well as the target fly-by times. The antenna pointing angles are also derived from the TLEs.

The PROBA GS is based on a scaleable architecture that can be easily extended to future missions and completed with new antennae resources (local or remote).

5 - CONCLUSION

The platforms of the PROBA spacecraft family are highly modular and tuneable towards the customer needs (missions up to a few 100 kg).

State-of-the-art on-board processing and advanced attitude control functionality handle the most complex mission demands.

The high level of spacecraft autonomy combined with ground segment automation results in an extremely user friendly system minimising the operational costs.

Verhaert - Spacebel can offer you low-cost turn key autonomous small satellite solutions all the way from concept definition up to in orbit commissioning.

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