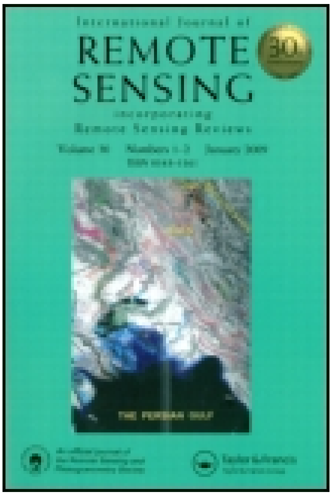

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The PROBA-V mission: the space segment

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PROBA-V (Project for On-Board Autonomy – Vegetation) is an ESA (European Space Agency) mission developed within the framework of the Agency's General Support Technology Programme (GSTP) devoted to the observation of the Earth's vegetation, providing data continuity with the SPOT (Satellite pour l'Observation de la Terre) 4 and 5 VEGETATION payloads as a gap-filler to the ESA Sentinel-3 mission. The PROBA-V space segment is based on a three-axis stabilized PROBA small-satellite platform of about 140 kg equipped with a state-of-the-art compact 4-band multi-spectral imager with a large field of view. The instrument's optomechanics is based on three very compact TMA (three mirror anastigmat) telescopes placed on an optical bench. At an altitude of 820 km, the instrument is able to provide daily coverage of the Earth in three VNIR (visible and near-infrared) bands and one SWIR (short-wave infrared) spectral band, with a spatial resolution of up to 100 m × 100 m at nadir for the VNIR. The instrument raw data will be downlinked with an X-band transmitter to the ground reception station in Kiruna, Sweden. The mission control centre is located in Redu, Belgium. The image processing centre, the so-called 'user segment', automatically accesses the raw data and is responsible for the processing and the dissemination of the data products towards the user community. The PROBA-V spacecraft was launched on board the new European launcher Vega on 7 May 2013. It is designed for a nominal mission lifetime of 2.5 years with a possible extension to 5 years.

1. Introduction

In the last decade, it has been demonstrated that small spacecraft can achieve specific mission objectives. Examples in Europe are PROBA-1 with the Compact High Resolution Imaging Spectrometer (CHRIS) hyper-spectral instrument (Bernaerts, Teston, and Bermyn 2000), the Disaster Management Constellations (DMC) for disaster monitoring, RapidEye for applications including agriculture (Jung-Rothenhäusler, Weichelt, and Pach 2006), and TopSat for high-spatial resolution (2.5 m) imaging (Price 2002), among others. Advanced technology and miniaturization for platform and payload make it possible to implement high-performance missions fulfilling a single focused objective on spacecraft weighing around 150 kg.

Time series analysis, used to monitor trends in vegetation change, has improved significantly our understanding of intra- and inter-annual variation in vegetation from a regional to global scales. To be able to detect trends in land-cover change, sufficiently long time series of remote-sensing data are of utmost importance. The VEGETATION (VGT) programme has been providing relevant products on an operational basis for the monitoring of continental biosphere since 1998 with the launch of the first instrument, VGT1 on board SPOT 4. The second instrument, VGT2 on board SPOT 5, ensures continuity until the end of 2013.

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With the decision not to pursue the VEGETATION programme on board the next SPOT (Satellite pour l'Observation de la Terre) platform, ESA investigated, internally, with industry, and the CNES (Centre National d'Etude Spatiale), whether the VEGETATION mission could be fulfilled with a small spacecraft. Since the design of the first VGT instrument back in the 1990s, spacecraft technology has progressed considerably, in particular in the fields of optical design and miniaturization. These preliminary studies have demonstrated that a PROBA-like satellite (Bermyn et al. 2008) can implement a mission capable of providing products of a similar quality to that of the VGT mission from the SPOT satellites, and with significantly fewer resources. The PROBA-V mission was born.

The PROBA-V (Project for On-Board Autonomy – Vegetation) remote-sensing satellite mission is intended to ensure the continuation of SPOT-VEGETATION products after 2013 as a gap-filler with the ESA Sentinel-3 mission (Donlon et al. 2012). The PROBA-V micro-satellite is designed to offer a global coverage of land surfaces at four multispectral bands (blue, red, near infrared, and short-wave infrared), at spatial resolutions of 1/3 km and 1 km, with a daily revisit for latitudes from 75° N to 56° S. To support the existing VEGETATION user community, the data products for PROBA-V will continue to provide daily Top of Canopy synthesis (TOC S1) and 10-day synthesis products (TOC S10). In addition, the new Top of Atmosphere daily synthesis (TOA S1) and radiometrically corrected raw data (level 1C) products are foreseen as being accessible to scientific users (Dierckx et al. 2014).

PROBA-V will fly in a sun-synchronous circular earth orbit at a height of 820 km. This altitude will allow, with a instrument field of view of 102.6°, a swath width of about 2295 km. To ensure imaging of the Earth's surface under the same illumination conditions as those of SPOT, PROBA-V's local time at the descending node (LTDN) at orbit insertion will be 10:45 am, with a drift limited to between 10:30 am and 11:30 am during the mission's lifetime.

The pair of Sentinel-3 satellites is required to ensure the same vegetation global coverage. Considering that the first Sentinel-3 satellite is expected to launch in 2014, followed by the second in 2016, a PROBA-V nominal operational mission life of 2.5 years is foreseen, with design provisions for a possible mission extension up to 5 years.

In line with previous PROBA missions, the PROBA-V platform and its operations will be basically autonomous, thus minimizing ground involvement during nominal operations. PROBA-V can perform its routine mission with minimum ground commanding. Ground station interaction will only be needed for pass scheduling and the upload of specific user requests (e.g. calibration requests).

2. PROBA-V mission elements

The PROBA-V mission comprises three main segments, namely a flight segment, a ground segment, and a user segment, as shown in Figure 1.

The flight segment will be further detailed in this paper and consists of a PROBA platform carrying the Vegetation instrument and all the necessary hardware to meet the mission's objectives.

The PROBA-V ground segment for the operational configuration consists of two main elements: the antenna ground stations and the mission control centre (MCC), as shown in Figure 2.

Flight dynamics, operations planning, and spacecraft operations are conducted from the MCC, located at the ESA ground station of Redu, Belgium, where one antenna ground station of the PROBA-V system is also hosted. A second antenna ground station, used to

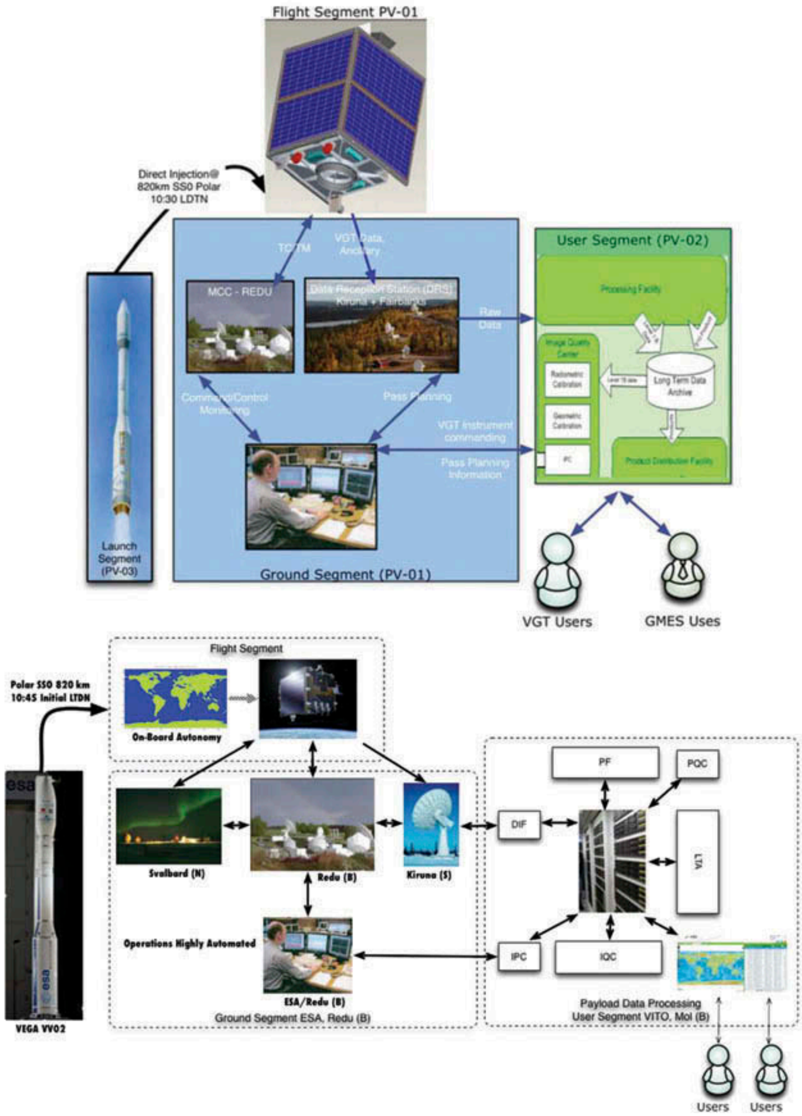

Figure 1. General architecture.

Note: IPC, Instrument Programming Centre; SSO, sun synchronous orbit; LDTN, local descending time node.

increase the satellite–ground contact time during the critical launch and early operation (LEOP) phase will be located in northern Europe.

The MCC will be used for satellite and instrument monitoring and for issuing instrument calibration requests. During nominal operations, the use of a single TTC (telemetry, tracking, and control) ground station in Redu is foreseen for telecommanding and housekeeping telemetry reception in the S-band.

The MCC is designed for a mainly automatic performance of nominal operations, including satellite pass prediction, scheduling of pass activities, processing, and uploading

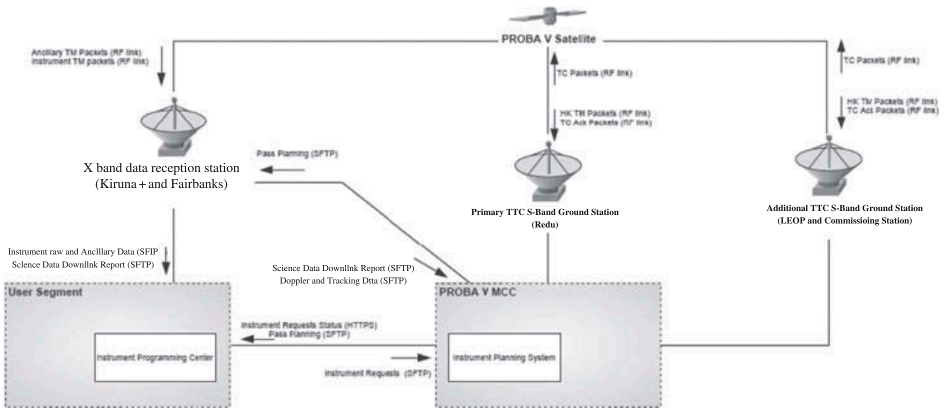

Figure 2. Ground architecture.

of received scientific observation requests, spacecraft data collection, storage and distribution, etc. Full operator intervention is needed for the preparation and execution of off-nominal activities.

During the operational phase, the Vegetation instrument will perform its data acquisition activity automatically. Image data will be dumped together with the ancillary data (orbital, attitude, and time correlation data) at a northern ground station. Then, data will be archived and transmitted to the processing facility, the so-called user segment, which is located in Mol, Belgium.

The user segment is responsible for data archiving, processing, and dissemination to users. It consists of a soft- and hardware environment comprising several interconnected functional modules – the data ingestion facility (DIF), processing facility (PF), image quality centre (IQC), long term archive (LTA), product distribution facility (PDF), and the product quality centre (PQC). The user segment will have the tasks of processing the raw data delivered from the flight and ground segments and distributing the mission products to the Vegetation user community. The segment delivers two main products to users, which are geometrically and radiometrically corrected and projected in standard cartographic projections (Dierckx et al., 2014). The user segment will also be responsible for the calibration request to the flight segment. The calibration service ensures the 5% absolute/3% relative radiometric quality and also the geometric quality of the delivered imagery, and provides correction parameters to be implemented in the processing facility. Vicarious calibrations will be used as an in-flight calibration methodology to allow for absolute and relative radiometric calibration and performance assessment of the Vegetation instrument's output.

3. PROBA-V flight segment

3.1. Platform design

3.1.1. General

PROBA-V is a small satellite with a mass of about 140 kg and a volume of 800 mm × 800 mm × 1000 mm, as shown on Figure 3. The three-axis stabilized platform mostly uses bus elements and units with flight heritage from PROBA-1 and PROBA-2 (Vrancken et al. 2012).

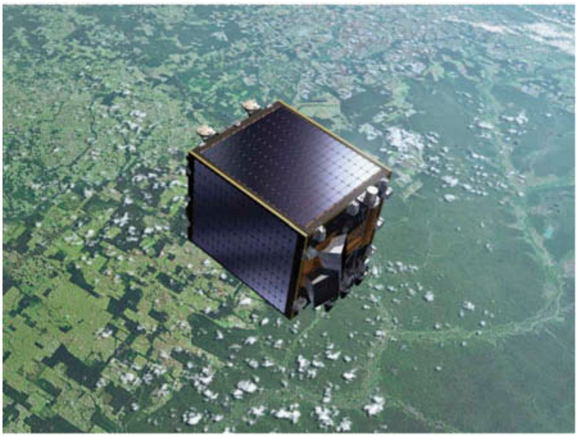

Figure 3. Platform, top view (with the courtesy of ESA).

The platform is built on a structure combining aluminium honeycomb panels for the internal, main load-carrying, core, and carbon fibre honeycomb panels for the outer body shell. Triple-junction gallium arsenide solar cells, mounted on three body panels, are capable of supplying 180 W peak power to the spacecraft. Power distribution to all platform units and instruments is done using a lithium-ion battery-regulated, centrally switched 28V bus providing 16.5 amp-hours capacity.

The overall telecommunication architecture for PROBA-V is standard and as applied in many Earth-observation satellites. It comprises an S-band Telemetry and Command fully CCSDS- (Consultative Committee for Space Data Systems)-compliant subsystem for engineering telemetry downlink and telecommand uplink. It is designed around a redundant set of receivers and transmitters, a radio frequency (RF) distribution unit, and a set of transmitting/receiving antennae providing omnidirectional coverage, to guarantee communication with the satellite in any mission mode and attitude condition. Furthermore, due to the high demand in downlink data rate for the vegetation images, it also comprises an X-band payload data transmission (PDT) subsystem for the Vegetation image and ancillary data. The X-band transmitter is a new development targeting low-cost and low-Earth-orbit missions, under cooperation between CNES and ESA.

The different elements of the PROBA-V satellite are summarized in Table 1 and shown on Figure 4.

3.1.2. Avionics

The management and control of all PROBA-V sub systems is combined in the spacecraft's 'Advanced Data and Power Management System' (ADPMS) computer based on a cold-redundant, radiation-tolerant, LEON2-FT RISC processor, providing the entire platform's computing power. (In cold-redundant configuration, the redundant unit is off when the primary unit in on. This is in contrast to hot-redundant, when both units are on and a voting mechanism between the two units is implemented.)

The ADPMS combines a data-handling unit and a power-conditioning and distribution unit in one box. The data-handling part of ADPMS is created from several modules, each based on the compact PCI (Peripheral Component Interconnect) standard. All

Table 1. Platform specifications.

Platform	
Subsystem	Equipment
Avionics	ADPMS (cold redundant) MPM (Main Processor Module): LEON2-E Sparc V8 processor, 50 MHz, 42 MIPS, 10 FLOPS Mass memory Module: 100 Gbit Flash, EDAC protected
Power	*Photo-Voltaic Array*: Triple junction GaAs cells (3G-28%) Cover glass CMG 100AR coating 25 strings, 18 cells per string *Battery*: 12 Ah Li-ion (7s8p) ABSL 18650HC cells
Structure	Aluminium (AA2024-T3): Face sheets t = 0.8 mm inner panels, t = 0.4 mm top and nadir panel), honeycomb core (t = 10. 8 mm) Aluminium (AA7075-T7351): edge profiles, hot inserts 3 CFRP (EX-1515/M55J + Redux 312L) outer panels
ACS	*Actuators*: 3 magnetotorquers (internally cold redundant) 4 reaction wheels (3 + 1 for redundancy) 2 magnetometers (cold redundant) *Sensors*: 2 star trackers (hot redundant heads, cold redundant electronics) 2 GPS (cold redundant) AOCS IF box (internally redundant) RW Power Supply box (internally redundant)
On board software	Operating System RTEMS
Communication	*S-band* TXRX: 5W BPSK (TC = 64 ksps, TM = 1.91 Msps or 329 ksps): hot redundant (RX), cold redundant (TX) *X-band* TX: 6 W filtered OQPSK (76.53 Msps): cold redundant
Thermal	Passive (MLI and paint)

Note: t, Tickness; ksps, kilo samples per second; msps, mega samples per second.

safety- and mission-critical functions within the PROBA-V avionics are single-failure tolerant. This is achieved either by hot or cold redundancy or by built-in tolerance to one failure, and thus the ADPMS design is fully cold-redundant. ADPMS also integrates a mass-memory module providing a data storage capability of 100 Gbit EDAC (Error Detection And Correction)-protected that is based on NAND flash technology and is used to store the Vegetation instrument's compressed raw data before downlinking by the X-Band channel.

The PROBA-V avionics architecture can be divided into several sections:

- the attitude control and navigation subsystem (ACNS), which contains all the ACNS equipment and the required additional electronics in order to adapt or convert interfaces and supply voltages;
- the ADPMS, featuring the two redundant data-handling lanes and its power section for all data handling, communications, and power conditioning and distribution;
- the main payload (the Vegetation instrument);

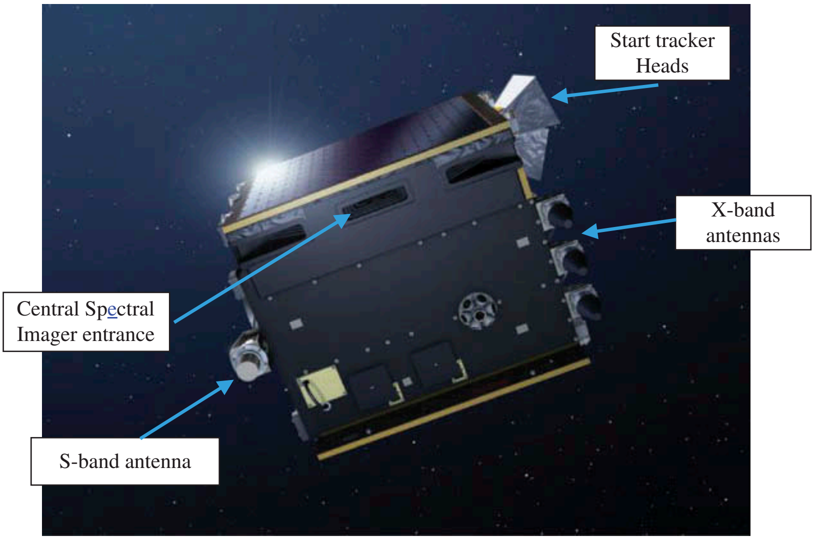

Figure 4. Platform, front view (with the courtesy of ESA).

- the five technology demonstrators;
- the communication section, featuring full redundancy for the S-band TTC and the X-band data downlink subsystems;
- the power section, containing the solar arrays, battery, and dump resistor (to dissipate excess current).

The PROBA satellite's on-board software is designed and implemented to provide the system with extremely high levels of on-board autonomy. PROBA-V is capable of handling its routine mission completely on board, only interacting with the ground station for downlinking of the acquired scientific data and the acquisition of new observation requests. Besides the nominal mission's management under complete autonomy, many potential on-board anomalies can be handled without ground intervention, due to integrated failure detection, isolation and recovery (FDIR) capabilities, allowing the system's automatic reconfiguration, to allow continuity in scientific data acquisition, providing a minimum set of required units is available.

3.1.3. Attitude control and navigation subsystem

An ACNS is essential for autonomous mission and platform management and the scheduling of on-board activities as it allows a completely autonomous satellite attitude, position and orbital event determination, satellite guidance, attitude control and manoeuvring, and on-board time management.

The PROBAV ACNS hardware set comprises four reaction wheels (one in cold-redundancy), two cold-redundant magnetometers, one cold-redundant miniaturized μ-advanced stellar compass star tracker with two hot-redundant camera heads to improve measurement accuracy, one cold-redundant GPS receiver, and three internally cold-redundant dual-coil magnetotorquers.

For the complete implementation of the PROBA-V mission, six operational guidance laws (also called ACNS modes) have been implemented in the ACNS software. Transition between any of these modes is possible either by manual command from the ground station or, in an autonomous fashion, by command from the on-board software's mission manager.

The PROBA-V ACNS guidance law most relevant for the payloads' nominal operations is 'Geodetic mode', so called since in this mode the spacecraft attitude is controlled with respect to a reference frame, having one axis perpendicular to the Earth's ellipsoid surface (i.e. geodetic pointing). An extra steering compensation (i.e. yaw steering) is added to minimize the image distortion caused by the rotation of the Earth during imaging.

Furthermore, the PROBA-V mission focuses on the observation of land. It is generally considered that only one-third of the world consists of land. Removing all sea pixels would thus result in a threefold data flow reduction. However, this approach would lead to a complex image format. The approach selected for PROBA-V is the use of a land–sea mask on board which allows the satellite software to autonomously activate the adequate spectral imager(s) viewing land areas while keeping the spectral imager(s) currently viewed sea areas switched off.

3.2. Instrument design

3.2.1. General layout

As the design of the Vegetation instrument is highly influenced by the requirement to fit the small PROBA platform, the vegetation instrument is significantly smaller and lighter, and it uses a very limited amount of power compared with its predecessor on board SPOT 5: the dimensions are 200 mm × 812 mm × 350 mm, it weighs around 35 kg, and consumes 43.2 W at maximum load.

In order to reach the large 102° field of view (FOV), the instrument comprises three distinct spectral imagers (SIs), each based on highly aspherical mirrors in a TMA (three mirrors anastigmat) configuration and with a 34° FOV across track, as shown in Figures 5 and 6.

The three SIs are identical in both design and performance. Their optics are based on an all-reflective design, in TMA telescope telecentric configuration (two mirrors are

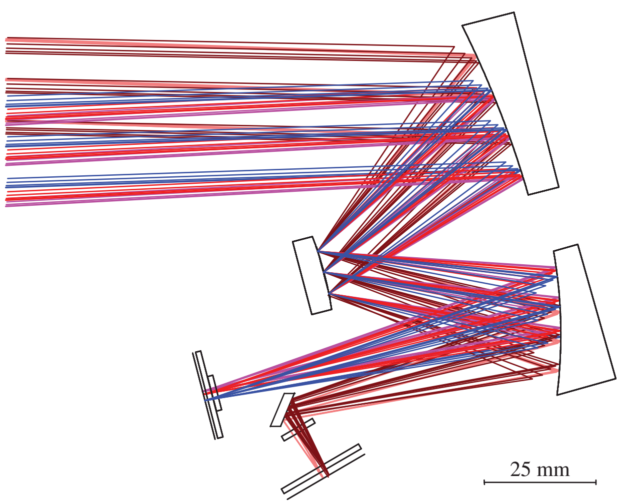

Figure 5. TMA optical layout (with the courtesy of OIP Sensor Systems).

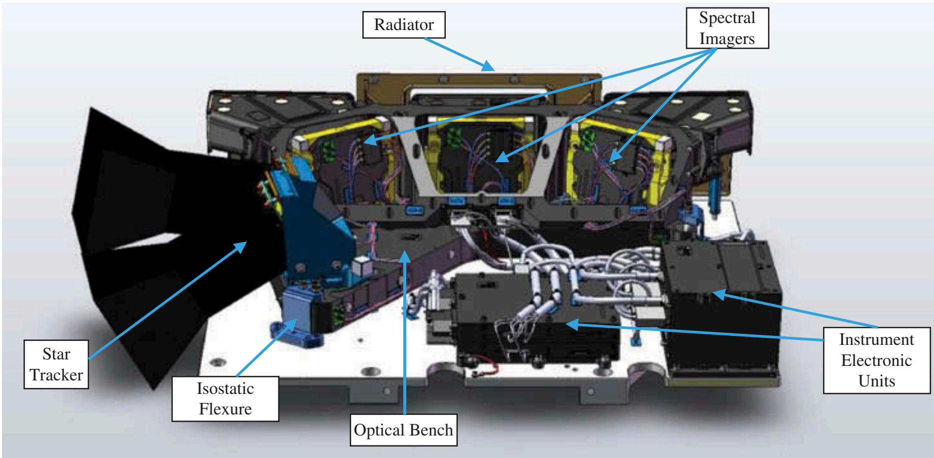

Figure 6. Instrument, general layout (with the courtesy of OIP Sensor Systems).

aspheric, one is spherical) with 110 mm focal length. Each TMA has two focal planes (see Figure 5): one for the visible and near infrared (VNIR) bands and one for short-wave infrared (SWIR), respectively equipped with one linear 6000-pixel VNIR detector and three linear SWIR detectors with 1024 pixels, mechanically butted to one large detector. The spectral bands are centred at 460 nm for blue, 655 nm for red, 845 nm for NIR, and 1600 nm for SWIR.

To minimize thermal gradients (and resulting thermo-elastic deformations), all elements are constructed completely of aluminium: this includes the optical bench, star trackers, and the TMA's structure and mirrors. The three TMAs and the star tracker's optical heads are fixed together on the aluminium optical bench, thus allowing precise co-alignment (see Figures 6 and 7). The optical bench, connected to the platform panel by means of three isostatic flexures, is passively cooled through a radiator facing the Earth. In addition, all power-dissipating electronics, apart from the front-end electronics and detectors, are thermally separated from the optical bench, to maintain it passively in a stable thermal environment (Versluys et al. 2012).

The instrument includes the electronics necessary to control and process the three spectral imagers. It includes a data handling unit, which performs compression of the incoming image data as per CCSDS standard; packetizing of the image data before sending to the satellite mass memory; collection and transmission of the available housekeeping data; and processing of command data sent from the on-board computer over the serial communication link. It also includes a power supply unit, which conditions the incoming 28V to the different voltage references required.

3.2.2. *Spectral imager*

The design of the spectral imager is shown in Figures 6 and 7. The principal optical parameters, the dimensions of the optics (excluding mounts), and the main features of the detectors are given in Table 2.

The focal plane assembly (FPA) consists of the spatially separated VNIR and SWIR detectors, protected by windows (see Figure 6). The SWIR channel is reflected by a flat

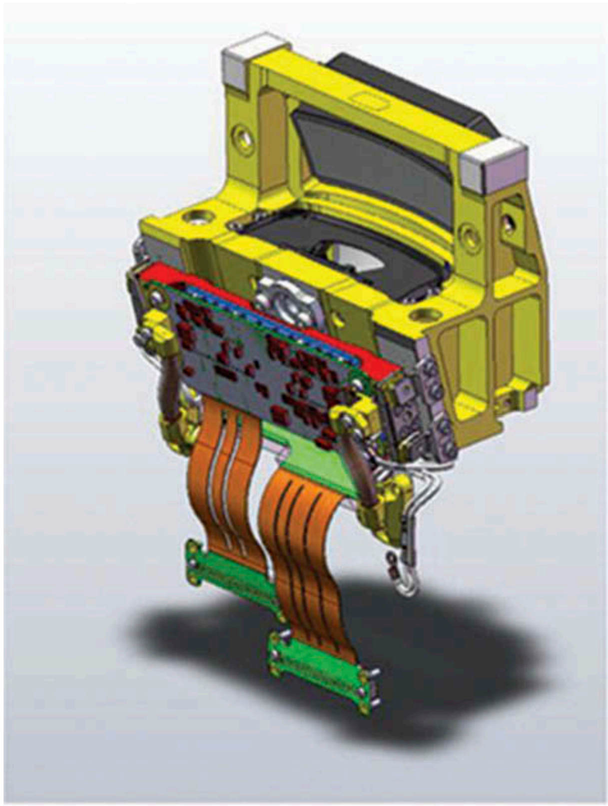

Figure 7. Spectral imager, with opto-mechanics (grey and yellow areas) (with the courtesy of OIP Sensor Systems).

Table 2. TMA and detector key features.

Geometric specifications	
Focal length	110 mm
Aperture	18.5 mm
f/#	7
Field of view (FOV)	67.6 mm × 10.8 mm 34.6° × 5.5°
Length	90 mm
Width	110 mm
Height	140 mm
Detector	3 × 6000 pixels, 13 μm (E2V)-quadric-linear TH1547 3 × 1024 pixels, 25 μm (Xenics)-mechanical butting (130 to 160 pixels overlap)
Spectral bands (μm)	VNIR: 0.435–0.490 (blue) 0.610–0.700 (red) 0.760–0.930 (NIR) SWIR: 1.520–1.670

mirror, which serves to fold the SWIR beam in order to minimize its volume, and the VNIR channels pass next to this mirror. The FPA is mounted and aligned onto the TMA interconnecting structure, which is of titanium.

3.3. Technology payloads

The PROBA-V platform will accommodate five additional ‘guest’ payloads in addition to the Vegetation instrument.

- An X-band transmitter with a gallium-nitride-based RF amplifier derived from the design of the main X-band transmitter based on gallium arsenide technology. The technology demonstrator will allow provision of a flight opportunity for European-sourced gallium nitride (GaN) technology and measurement of key parameters of the GaN RF power amplifier in orbit, validating the technology.
- An electron particle telescope. This is an innovative science class radiation spectrometer, designed to directly identify and measure fluxes of electrons, protons, and alpha and heavy particles. The flight on board PROBA-V will allow validation of the sensor technology together with the on-board treatment of the data.
- An automatic dependent surveillance broadcast (ADS-B) receiver. This is an air traffic surveillance system based on the ADS-B signals that are broadcast by an aircraft at low L-band frequency. The broadcast information includes flight-related data such as speed, position, flight number, and direction of the aircraft. Terrestrial-based ADS-B services are foreseen as being deployed in regions where a traditional air traffic management (ATM) system based on primary and secondary radar stations is not cost effective.
- A radiation monitoring system called SATRAM, which is based on the TIMEPIX sensor developed by CERN for terrestrial applications. On PROBA-V, technology demonstrating flight hardware will be flown. The TIMEPIX detector is capable of detecting all charged particles (including MIPs and heavy ions) depositing more than ~5 keV in the pixel-sensitive volume, with an efficiency of 100%.
- A fibre-optical cable demonstrator, called HERMOD. The aim is to validate this new technology in orbit and there is also the further aim of deploying this instrument on a launcher and large satellites to replace traditional copper harness and provide improvements in terms of mass, speed, and reliability.

4. Predicted mission performance

The key aspect for the PROBA-V mission performance is the continuity of the SPOT 4 and 5 VEGETATION data product. The same orbital parameters, the same spectral bands, and a similar ground sampling distance and spectral performance have been adopted. In addition to continuation of the SPOT-VEGETATION product, performances have been increased to achieve enhanced ground sampling distance, from 1 km to 1/3 km.

4.1. Orbit parameters

PROBA-V will be flown at an altitude of 820 km on a near-polar sun-synchronous orbit. The local time of the descending node is chosen to be close to that of the SPOT 5 satellite (10:30 am), in order to benefit from optimum light conditions.

In contrast to SPOT, PROBA-V will not carry any propulsion module for orbit maintenance and correction. It will thus rely on orbit parameters at launch to maintain the local time of descending node between 10:30 and 11:30 am during its operational nominal mission lifetime.

4.2. Ground-sampling distance

In regard to the pixel size at detector level and the optics features, the ground-sampling distance (GSD) varies from 100 m and 180 m at nadir up to 350 m and 660 m at the extremity of the swath for the VNIR and SWIR channels, respectively (see Figure 8).

4.3. Geolocation

Geolocation performances depend on platform-pointing accuracy, the thermo-elastic behaviour of the instrument, and the platform and geometric calibration accuracy on the ground and in orbit. The expected performances of all these contributors have been mathematically modelized or measured where possible in order to produce the expected geolocation performances in orbit. These analyses show an absolute geolocation accuracy of 200 m for VNIR and 300 m for SWIR, as shown on Figure 9.

Since PROBA-V is a small platform with passive thermal control (except for survival heaters on the instrument and the battery), specific attention has been paid to the in-orbit geometric calibration during the design of the complete system. A thermal behaviour model of the instrument and spacecraft along orbits and its impact on pointing has been realized and implemented in the user segment processing facility. The model will need to be calibrated on a regular basis using a large set of Landsat ground control points for matching. The target is to calibrate on a monthly basis.

4.4. Instrument spectral responses

The spectral responses of all spectral imagers were measured using a double-pass monochromator with suitable slit widths. The spectral response and registration have been

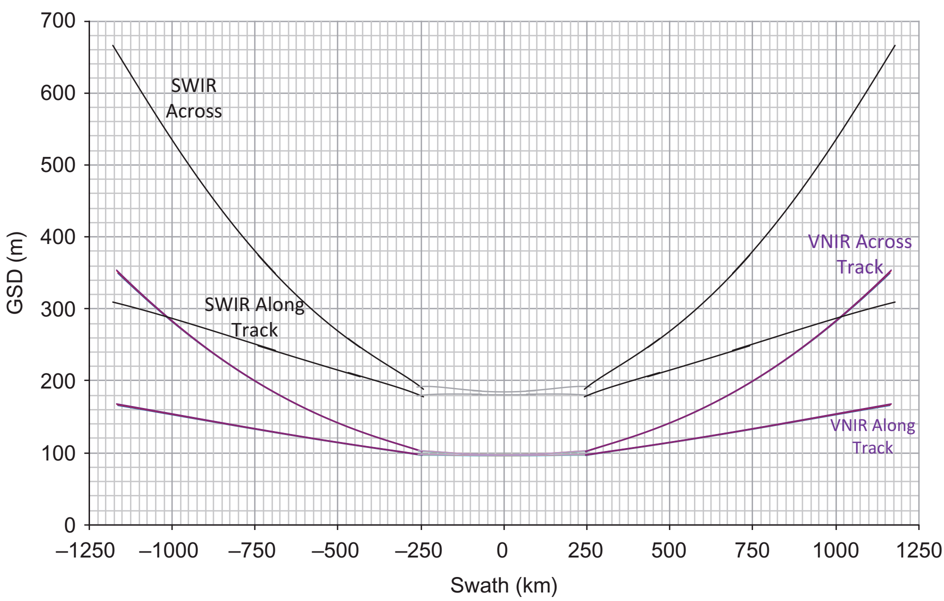

Figure 8. Ground pixel size as a function of across-track and along-track distance on the ground for the VNIR/SWIR channels.

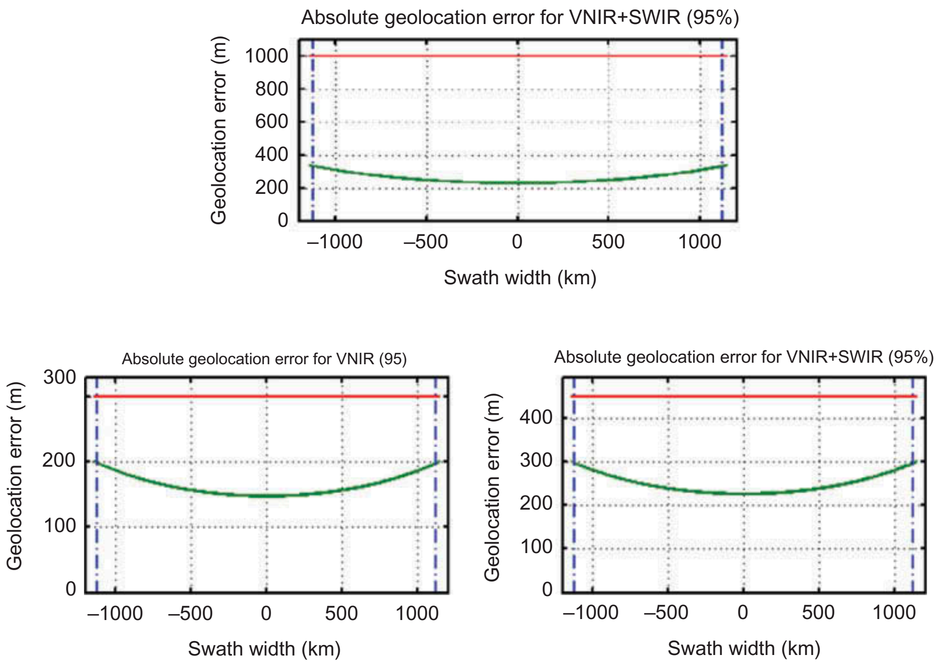

Figure 9. Predicted (green) vs. required (red) geolocation performances for the VNIR and SWIR bands for the 1 km and 1/3 km products.

analysed via measurement of the spectral transmission of the SI, with data correction for monochromator signature and then normalization. Figure 10 depicts the measured normalized spectral response for the VNIR and SWIR bands of one spectral imager for one particular field of view. In the VNIR bands, the differences between PROBA-V and VGT2 (SPOT 5) spectral responses are of the same order as for VGT1 (SPOT 4) and VGT2

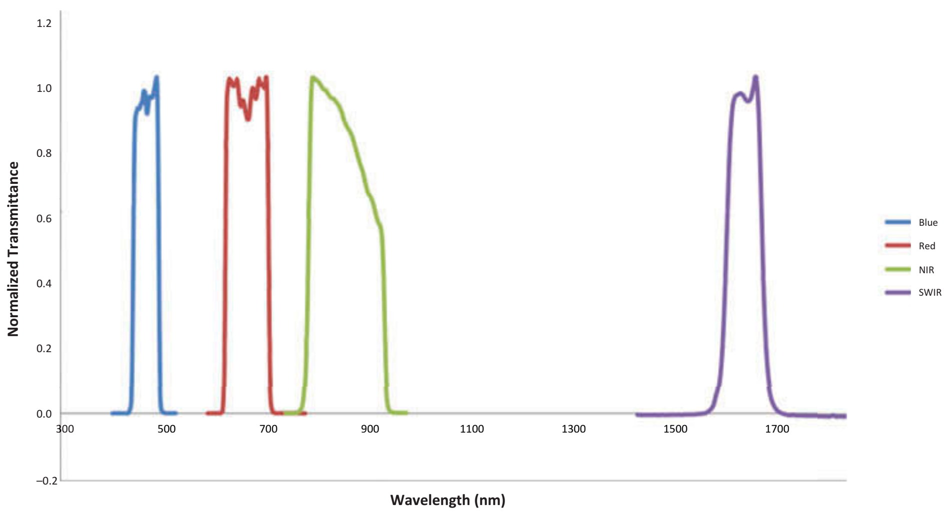

Figure 10. Measured spectral responses.

(SPOT 5). NDVI (normalized difference vegetation index) differences of up to 2% compared with VGT2 can be expected, which will need to be cross-calibrated. However the bands are placed well within the spectral range for vegetation measurements, so when comparing PROBA-V images, the reflectances are consistent. The impact of slight spectral misregistration has been analysed for radiometry for VNIR, where errors of the order of up to the noise equivalent delta radiance (NEdR) can be expected.

For SWIR, a shift to the shorter spectrum wavelength is observed compared with VGT2, resulting in higher contrast for NDWI (normalized difference water index). The PROBA-V SWIR spectral response curve is situated far enough from the strong water vapour absorption region.

4.5. Radiometric – MTF – SNR

The instrument MTF (modular transfer function) was measured with an opto-mechanical set-up (including collimator and slits) and is well within the requirement of 0.3 at Nyquist frequency for most of the FOV and typically 0.8 at the centre of the swath. As an illustration, the across-track MTF measured on the ground is shown in Figure 11 at the expected in-orbit temperature (263 K) in the blue band at different positions in the field of view.

Requirements for minimum, maximum, and reference radiance and radiometric resolution and signal to noise ratio (SNR), for each spectral band, are reported in Table 3. In addition, requirements of 5% absolute radiometric accuracy, polarization sensitivity less than 3%, and 1% worst non-linearity all complement the key radiometric performance requirements.

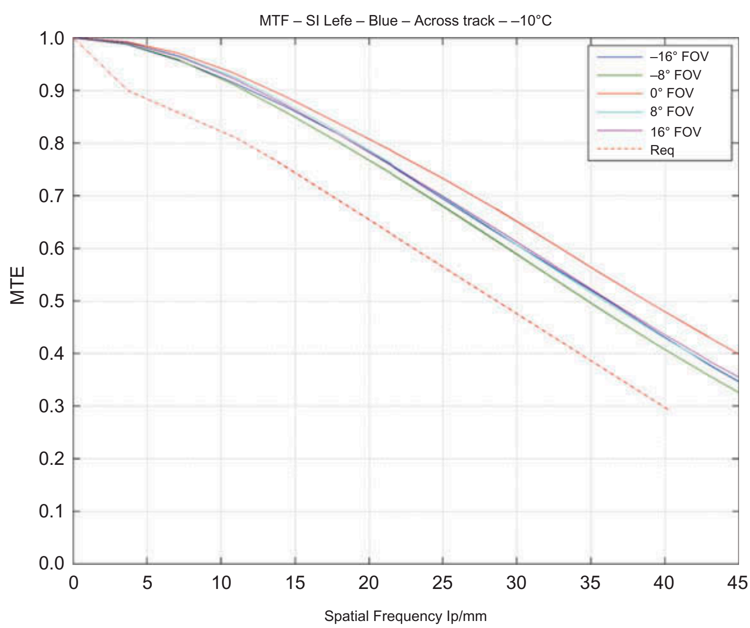

Figure 11. Measured MTF blue band MTF.
Note: Req, requirement.

Table 3. Radiometric performance requirements.

Spectral band	ToA spectral radiance (ToA, (W m^{-2} sr^{-1} μm^{-1})) Min	Reference	Max	NEdR (W m^{-2} sr^{-1} μm^{-1})	SNR @ reference ToA radiance
Blue	39	111	567	0.59	188
Red	10	110	446	0.33	333
NIR	4	106	296	0.27	393
SWIR	0.6	20	58	0.06	333

The verifications of all those requirements were performed through an intensive calibration campaign on the ground.

Polarization sensitivity was analysed and was shown to be slightly higher than 3% in the blue at the edge of the field of view. The non-linearity performances were proven to be within ±0.5% of 10–90% of the dynamic range and, at low or high radiances, non-linearity is fully characterized and can thus be corrected on the ground.

For the 1 km product, the SNR requirements are largely met for the whole swath. For the 1/3 km product, the SNR performance is dominated by compression noise. Consequently, for scenes with a high entropy content, compression will degrade the performance to below the requirements. Without compression impact, SNR is met for the whole swath.

Integration timetables have been derived to compensate for lighting variation across different latitudes and seasons. These tables lead to a use of dynamic range, which is in line with the known history from SPOT-VGT2, and allow for a reasonable optimization of dynamic range to reduce the impact of compression. With the current list of possible instrument settings, all configurations necessary for nominal and calibration acquisitions can be performed with radiometric performances in line with the requirements.

During the nominal operation, the Vegetation in-orbit calibration will rely on vicarious calibration performed on a regular basis. A number of calibration methods were selected in order to meet the mission performances:

- dark current measurement over deep oceans;
- Rayleigh calibration;
- sun glint over oceans;
- convective cloud measurement over specific areas of the Earth;
- desert observations;
- under-flight cross-calibration with airborne calibration campaigns;
- cross-calibration with SPOT-VEGETATION.

In addition to the above methods, calibration based on lunar observation will allow improvement in radiometric calibration. Imaging of the moon will require agile manoeuvring of the satellite based on pre-programmed attitude manoeuvres.

4.6. Straylight

A reference analytical forward model for in-field straylight in the TMA was built, by simulating the point spread function(s) (PSF) of the instrument (Versluys et al. 2012). The model includes the scattering from the mirrors due to both surface roughness and surface particulate contamination, but also several design-specific scattering effects. The model was verified by testing, where the along-track PSF was measured accurately (down to 1×10^{-8}) by successively illuminating one detector line in the centre field of view as reference by a concentrated (approximately 3-pixel-wide) powerful light source attenuated by increasing drastically the light intensity of the source but moving it along track away from the detector line (Stockman et al. 2012).

Using the verified model and injecting synthetic or real scenes, the impact of straylight could be assessed. By using some natural cloudy scenes from the Medium Resolution Imaging Spectrometer (MERIS) as samples, the relative contribution of straylight and the ratio of straylight to the NEdR at nominal radiance were assessed. The impact of straylight was several-fold that of NEdR at nominal radiance in the direct vicinity of a bright target (e.g. clouds). However, over vegetation, the straylight contribution is expected to be below NEdR. After injecting synthetic scenes such as an adjacent bright and dark scene, the impact of the bright to the dark side was shown to be less than 2% at 20 detector pixels away from the border.

5. Development

The classical ESA development approach was adapted to the gap-filler objectives and the constraints of a PROBA mission. The project life cycle was split into the classical ESA space project phases but shortened to a total development time of 3 years.

The PROBA model philosophy is based on a structural and thermal model and the proto-flight model of the spacecraft and the Vegetation instrument. The proto-flight model approach at spacecraft and instrument levels was further supported by partial electrical models of most of the bus units to build an avionics test bench (flat sat) and a complete electrical model of the instrument. Moreover, the key instrument technologies were initiated upfront, validating the miniaturized TMA concept before the start of the mission development.

In the area of software validation, spacecraft testing, and operations preparation, the project optimized the available resources. This has been translated into the usage of a common environment for spacecraft testing and operations and the production of a software validation facility in the early phase of the project. This latter tool simulates the entire spacecraft and allows execution of the on-board software executable code in this facility as if it was running in real hardware, while enhanced testing and debugging capabilities are available. This facility is also connected to the common spacecraft testing and spacecraft operations environment to provide a spacecraft simulator for the operation teams.

6. Summary

The development of the PROBA-V flight segment was a challenge since it had to fulfil the ESA objectives of in-orbit technology demonstration, Earth environment monitoring, and preparatory Earth observation, while ensuring the continuation of the SPOT-VEGETATION image data towards the Vegetation user community. The miniaturization of the Vegetation instrument from 150 kg down to 30 kg was only possible thanks to a number of new technologies developed in recent years, allowing a very compact instrument design with excellent performance.

The satellite was successfully launched on board the ESA launcher VEGA on 7 May 2013.

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