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PROBA V Multispectral Imager: Status

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***Abstract* — PROBA V is an ESA mission devoted to the observation of the Earth's vegetation, providing data continuity with the Spot 4 and 5 vegetation payloads. Thanks to the heritage of the Proba series, the satellite's platform is smaller than a cubic metre, accommodating the main payload, i.e. the Vegetation Instrument (VI), and some technology demonstrators. The VI extremely wide viewing swath, together with a polar low Earth orbit, enables daily revisits during 2.5 years, with a possible extension to 5 years. The mission, whose satellite is developed by Belgian QuinetiQ Space, is actually in Phase D and the targeted launch is early 2013 with the VEGA launcher.**

The Vegetation Instrument is a high spatial resolution push-broom 4 spectral bands imager composed of three distinct Spectral Imagers (SI). Each SI has 34º Field Of View (FOV) across track, and the total FOV of the VI is 102º, covering an Earth swath of 2260 Km with ground sampling distance down to 96 m at Nadir for VNIR bands.

The spectral bands are centred around 460 nm for the blue, 655 nm for the red, 845nm for the NIR and 1600 nm for the SWIR. The imaging telescope is built from a Three-Mirrors Anastigmat (TMA) configuration, including two highly aspheric mirrors. The optics is manufactured from special grade aluminium by diamond turning. The material being identical to the whole structure, no defocus or stresses build up with temperature variations in flight.

This paper gives an overview of the VI performances, and focuses on the results of the optical tests and on-ground calibrations.

Keywords: Multispectral, Imager, TMA, performance.

I. INTRODUCTION

PROBA V is an Earth observation ESA mission developed in the frame of the Agency's General Support Technology Programme (GSTP) and managed by ESA's Technical and Quality Management Directorate.

Based on a PROBA small satellite platform, the three-axis stabilised satellite weights about 160 kg and has a volume of 800 x 800 x 1000 mm^3. The main payload is the Vegetation Instrument (VI). Its mission objective is to perform remote sensing of vegetation on the Earth surface in four spectral bands: Blue, Red, Near Infrared (NIR) and Short Wave Infrared (SWIR), guaranteeing the continuity in the acquisition of Vegetation data after decommissioning of SPOT-5 Vegetation instrument. Therefore, the same orbital parameters, the same spectral bands, a similar ground sample distance and spectral performance have been adopted.

Since PROBA V project is being developed in the frame of ESA's In-Orbit Demonstration programme, the platform has been designed to accommodate up to four "guest" payloads in addition to the VI: an X-Band transmitter based on a Gallium nitride RF amplifier, an Energetic Particle Telescope (EPT), a complementing radiation monitoring system, and an innovative air traffic surveillance system.

PROBA V will fly in a near-polar Sun-synchronous circular Earth orbit at about 820 km, covering on daily basis the regions between +75N to +35N and between -35S to -56S, while the complete Earth surface is revisited every two days. The VI operates in push-broom mode: with an overall Field of View (FoV) of 102°, the swath width is about 2285 km.

QinetiQ Space NV (Belgium) leads an industrial team responsible for the development of the flight satellite platform, the main payload and the Ground Segment. OIP Sensor Systems (Belgium) is in charge of the main instrument and, at the time of writing, it is performing an intense campaign of optical testing. A separate team, led by VITO (Flemish Institute for Technology Research, Belgium), is in charge of all activities related to the development of the User Segment. With a scheduled launch date in early 2013, the instrument is currently in its final assembly and test phase.

II. Vegetation Instrument

As the design of the Vegetation Instrument is highly influenced by the requirement to fit the small PROBA platform, the VI is significantly small and light, and it uses very limited amount of power compared to satellites such as SPOT and Sentinel: with dimensions of 200 x 812 x 350 mm^3, it weights around 35 kg and consumes about 43.2 W [1][2].

At the same time, for continuity reasons performance requirements similar to Vegetation instrument of SPOT 5 must be kept, imposing huge challenges and miniaturization actions for the development of the VI.

This 102° across-track FoV multispectral imager is formed by three separate Spectral Imagers (SIs). With a FoV of 34°, each SI covers part of the swath, observing the Earth with a Ground Sampling Distance (GSD) ranging from 96 m at nadir to 360 m at the edge of the swath in VNIR (Fig. 1 and Fig. 2)

The three SIs are identical in design and very similar in performance. Their optics is based on an all-reflective design, in TMA ("Three Mirror Anastigmat") telescope telecentric configuration (two mirrors are aspheric, one is spherical) with 110 mm focal length. Each TMA has two focal planes (see Fig. 3): one for the VNIR bands and one for the SWIR, respectively equipped with a linear 5200 pixels VNIR detector and 3 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 minimise thermal gradients (and resulting thermo-elastic deformations), all elements are completely built in aluminium: optical bench, star trackers and the TMA's structure and mirrors. The three TMAs and the star tracker optical heads are fixed on the aluminium bench, thus allowing a precise co-alignment (see Fig. 4). 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 the detectors, are thermally separated from the optical bench, to maintain it in a stable thermal environment.

Aluminium manufacturing of the mirrors was operated by AMOS (Belgium) via Single Point Diamond turning (SPDT), achieving a roughness of maximum ~4 nm without further post-processing or coating. The amount of in-field stray-light and Modulation Transfer Function (MTF) degradation are therefore within requirements (see Section IV) [3].

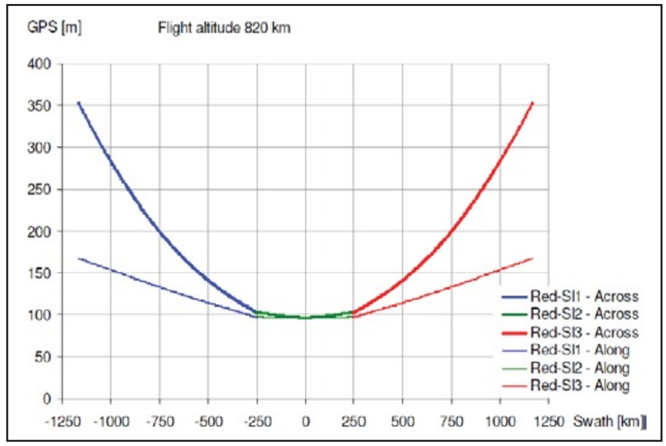

Fig. 1. Ground Pixel Size[1] as a function of across track distance in the ground of the VNIR channels.

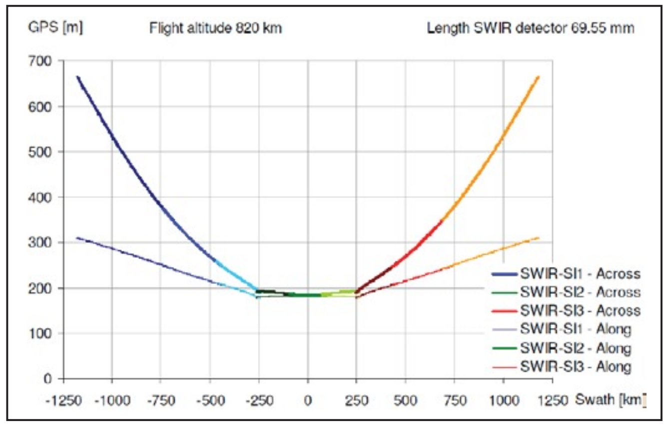

Fig. 2. Ground Pixel Size as a function of across track distance in the ground of the SWIR channels.

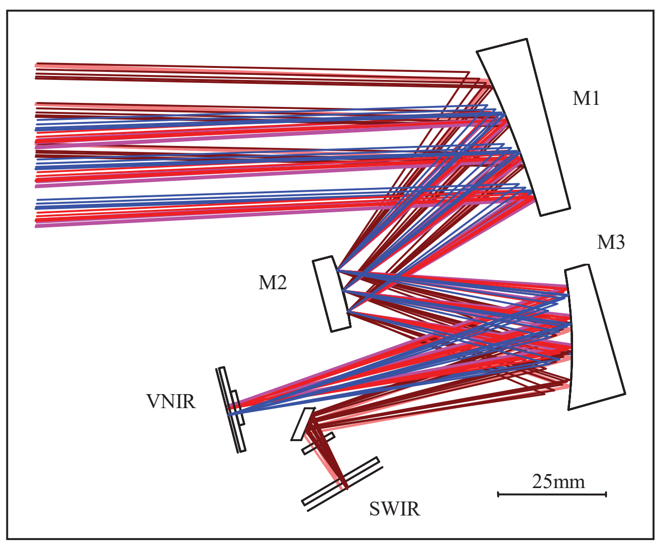

Fig. 3. Raytracing of the TMA. The two focal planes are visible.

[1] The Ground Pixel Size (GPS) is the footprint of a pixel on the ground. In the across track direction, the GPS is also the ground sampling distance. In the along-track direction the GSD is determined by the sampling time and not by the size of the footprint of the pixel.

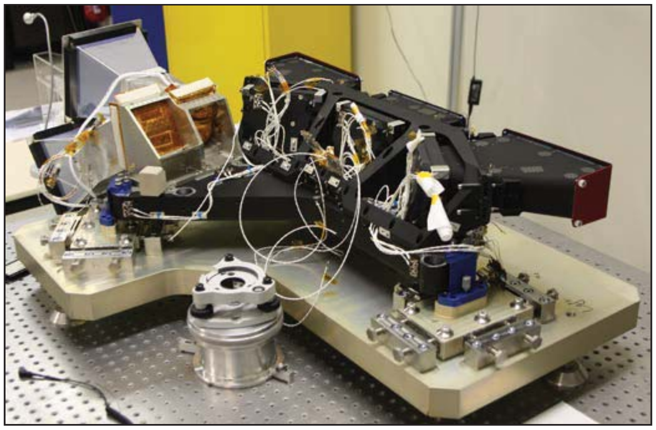

Fig. 4. Vegetation Instrument, during integration phase. On the left of the bench the startrackers are visible.

III. Spectral Imager Design

The design of the Spectral Imager is shown in Fig. 5. The principal optical parameters, the dimensions of the optics (excluding mounts) and the main features of the detectors are given in TABLE I. The TMA is designed for f/6, but is used at f/7.

The Focal Plane Assembly (FPA) consists of the spatially separated VNIR and SWIR detectors, protected by windows (see Fig. 3). The SWIR channel is reflected by a flat mirror, which serves for folding the SWIR beam in order to minimise the volume, and the VNIR channels pass next to this mirror. The FPA is mounted and aligned onto the TMA interconnecting structure, which is in titanium.

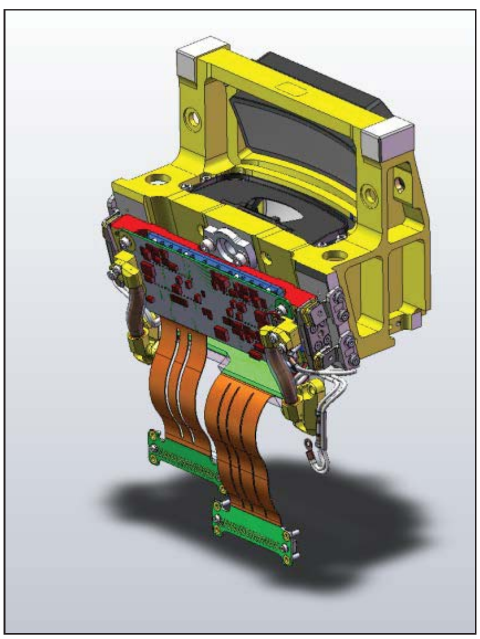

Fig. 5. Spectral Imager, with opto-mechanics (grey and yellow parts) and electronics components visible.

TABLE I. TMA and Detectors Data

Parameter	Value
Focal Length	110 mm
Maximum Aperture	18.5 mm
f/#	7
FOV	67.6 x 10.8 mm^2 34.6° x 5.5°
Length	90 mm
Width	110 mm
Height	140 mm
Detectors	3 x 5200 pixels, 13 µm (E2V)- Quadric-linear TH1547 3 x 1024 pixels, 25 µm (Xenics)-mechanical butting (130 to 160 pixels overlap)
Spectral bands	VNIR: 0.415-0.500 µm (Blue) 0.580-0.770 µm (Red) 0.730-0.960 µm (NIR) SWIR: 1.480-1.760 µm

The VNIR detector, an AT71547 quadrilinear type from E2V (France), consists of 4 photo-detector lines, each line containing 6000 photodiodes with 13 µm pitch and anti-blooming system. The green line is not used; the spectral separation of the other three lines is obtained via a spectral window mounted on the detector's transparent window. Anti-reflective coating is added on the window, whose front surface has also a black mask. The SWIR detector is custom designed by XenICs (Belgium), and adapted for the specific use on PROBA V. The device is split into three sections (see Fig. 6), each one formed by a Read-out Integrated Circuit (ROIC) chip and a Photodiode Array (PDA) chip with 1024 pixels on 25 µm pitch.

Three major blocks build the electronic of the VI: the VNIR and SWIR read-out electronics, the centralised Data Handling Unit, the Power Supply Unit. The electronic is designed to minimise Single Point Failures [2].

Each TMA is protected from stray-light by a proper baffle in Carbon Fibre Reinforced Plastic (CFRP) (see Fig. 7).

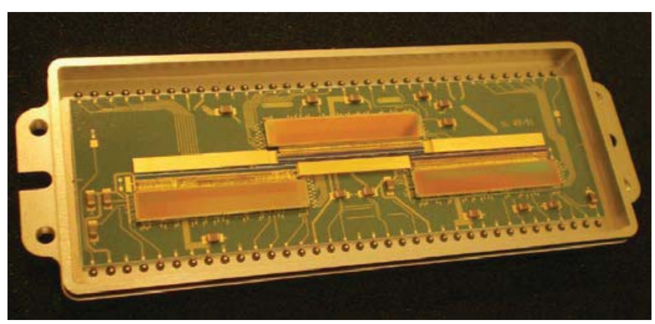

Fig. 6. Distribution of SWIR detector lines.

Fig. 7. Protector buffer in Carbon Fibre Reinforced Plastic.

IV. Simulations: Straylight

A reference analytical forward model for in-field straylight in the TMA was built, by simulating the Point Spread Function(s) of the instrument. The model includes the scattering from the mirrors due to surface roughness and due to surface particulate contamination but also several design specific scattering effects. Using the model and injecting synthetic or real scenes, the impact of straylight could be assessed. By using some samples as some cloudy scenes from MERIS, the relative contribution of straylight and the ratio of straylight to the Noise Equivalence delta Radiance (NEdR) at nominal radiance (L2) can be assessed. The impact of straylight reaches several times the NEdR at nominal radiance in the direct vicinity of a bright target. However, over vegetation, the straylight contribution is generally below the NEdR.

V. Updates on Instrument Performances

At the time of writing this paper, the instrument flight model has been assembled to its final configuration and it is undergoing an intense Spectral, Geometrical and Radiometric testing session at SI level at OIP facilities. Radiometric and Geometrical calibration optical tests at VI level are planned for early September at CSL. The optical test campaign will be concluded with a straylight test session [4]. After launch, foreseen by early 2013, in-orbit radiometric and geometric calibrations will take place, before full operation of the instrument.

Four Spectral Imagers have been built, one of them to be kept as spare. However, all the four SIs are thoroughly tested. Their preliminary key performances are given in this section.

A. *Geometrical Tests*

Scope of the geometrical tests is to verify the compliance to the requirements for each Spectral Imager. The latest measurements regarded MTF, Instantaneous FoV (IFoV), FoV, Line of Sight (LOS).

1) *MTF:* The requirements for MTF (taking into account only the static contributions for optics and detector) are summarized in TABLE II and TABLE III (the goal requirements are in Italic):

TABLE II. VNIR MTF

FoV	Frequency		Blue	Red	NIR
Centre	3.7 lp/mm *11.0 lp/mm*	Along Track	0.89 *0.79*	0.91 *0.81*	0.92 *0.79*
	3.7 lp/mm *11.0 lp/mm*	Across Track	0.90 *0.81*	0.92 *0.78*	0.91 *0.72*
Edge	6.5 lp/mm *19.2 lp/mm*	Along Track	0.87 *0.66*	0.89 *0.66*	0.89 *0.65*
	13.5 lp/mm *40.4 lp/mm*	Across Track	0.77 *0.29*	0.75 *0.26*	0.70 *0.18*

TABLE III. SWIR MTF

FoV	Frequency		SWIR
Centre	3.7 lp/mm *5.5 lp/mm*	Along Track	0.87 *0.81*
	3.7 lp/mm *5.5 lp/mm*	Across Track	0.86 *0.79*
Edge	6.2 lp/mm 9.3 lp/mm	Along Track	0.76 *0.61*
	13.3 lp/mm *20.0 lp/mm*	Across Track	0.48 *0.26*

With a proper opto-mechanical setup (including collimator and slits), OIP measured the MTF for all the SIs. With a width of 0.1 pixel, the slit was positioned at the collimator's focal plane, centered on the optical axis and therefore imaged on the detector of each SI. A scan of the slit over 5 pixels was performed, in along- and across- track directions. From each scan the intensity profile was taken, thus retrieving the PSF profile. The MTF was finally calculated from the PSF via Fourier transform in both directions [5]. For each SI, five field points (i.e. at 0°, ±8°, ±16°) have been measured per spectral band in VNIR, and nine field points in SWIR, distributed along the three sections of the detector (i.e. at 0°, ±4°, ±6°, ±12°, ±16°).

The instrument MTF is well within the requirement at Nyquist for all the spectral lines and measured field points.

2) *IFoV and FoV:* According to the requirements, the IFoV shall not be larger than 24.37 / 46.88 arc seconds for any position within the FoV and for all VNIR / SWIR bands, respectively, while the FoV for the along-track direction shall be equal or smaller than 5.5°.

Calculation of IFoV (and hence FoV) is done from the measurements done for the MTF. The IFoV requirements are met for all the spectral bands, all for field points and SIs. The IFoV is maximum at around the central angle of the FoV, and is decreased of about 1-2 arc sec at the edges.

The across-track FoV is as expected, being around 34.7° for the various VNIR spectral channels and about 34.5° for the SWIR ones. The along-track FoV results slightly less than 5° for all the SIs.

3) LoS: Line of sight was accurately measured via prior alignment of all the setup with the SIs.

B. Spectral Tests

Spectral tests conducted at SI level regarded the Spectral Response and Misregistration, to be in line with the requirements. The Spectral Misregistration, intended as the maximum shift of the central wavelength (CWL) of the spectral band over the FoV in one spectral imager and also as the maximum shift of the CWL between the different spectral imagers, shall be always less than 1 nm.

For the spectral measurements, a double-pass monochromator with suitable slit widths has been used for scanning the spectrum, while the SI has been mounted on a support table and rotated to reach the same field points as for the MTF measurement. The spectral response and registration have been analysed via measurement of the spectral transmission of the SI, with data correction for monochromator signature and then normalization. Figure 8 depicts the typical measured spectra for VNIR and SWIR bands of the SIs.

The measurement of the spectral response is overall in line with the requirements for Blue for all the considered fields and all the SIs, while it is out of specs in some other wavebands, although foreseen by simulations.

Spectral misregistration is below 1 nm in Blue and Red for all the SIs; it is slightly higher than the requirements, but according to the expected values from the simulations, in NIR and SWIR for some fields and SIs.

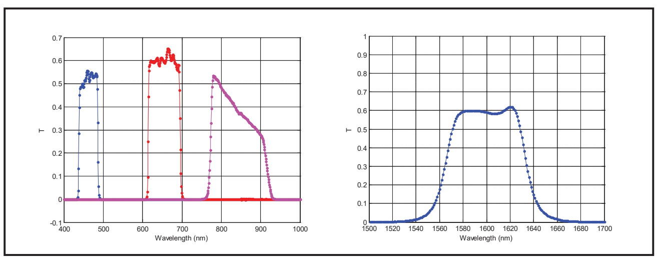

Fig. 8. VNIR (left) and SWIR (right) spectral measurements.

C. Radiometric Performances

At the time of writing, the Radiometric performances have not been tested yet. They will involve the verification of the requirements about the Linearity, Maximum Radiance, Radiometric Resolution, Signal-to-Noise Ratio (SNR), and the effects of Polarization and Stray Light.

Requirements for minimum, maximum and reference radiance and radiometric resolution (in terms of NEdR) and SNR, for each spectral band, are reported in TABLE IV.

TABLE IV. Radiometric Performances

Spectral Band	Spectral Radiance (ToA, W/m2.sr.µm)				NEdR (W/m2.sr.µm)	SNR @ L2 (reference)
	L1	L2	L3	L4		
Blue	39	111	236	567	0.59	188
Red	10	110	231	446	0.33	333
NIR	4	106	212	296	0.27	393
SWIR	0.6	20	38	58	0.06	333

VI. In Orbit Calibrations

Before delivering of data to the User Segment, some in-orbit calibration will take place, in particular geometric and radiometric. The former is needed, in a monthly basis, since no active thermal control of the instrument is possible due to power budget limitations. The latter will rely on vicarious calibration, performed on a regular basis, following various methods such as:

4) Dark current measurement over deep oceans.
5) Deserts observation.
6) Cross calibration with SPOT/Vegetation.
7) Moon observation: the imaging of the Moon will require an agile manoeuvre of the satellite based on pre-programmed attitude maneuvers.

VII. Conclusions

The development of the PROBA V Vegetation Instrument was a challenge since it had to fulfill the ESA objectives of in-orbit technology demonstration, the Earth environment monitoring and preparatory Earth Observation, while ensuring the continuation of the Spot-Vegetation image data towards the Vegetation User community. Technological improvement led to reduce the overall weight from 130 kg of SPOT 5 Vegetation instrument to the actual 30 kg, together with a power reduction from 150 W to 25 W. This improvement became feasible thanks to a number of new technologies developed in the last years, namely Single Point Diamond Turning fabrication of the aspheric mirrors and efficient VNIR and SWIR detectors, allowing a very compact instrument design with great performance.

The instrument is now undergoing a complete set of tests before assembly onto the spacecraft early this autumn. During summer the VI has entered the optical calibration campaign, and at the time of the Conference a throughout description of the optical performances will be available.

Acknowledgment

The authors wish to acknowledge the efforts of all the people involved, now and in the past, to the development of PROBA V mission, within ESA as well as from all the companies that actively participated to this challenging technological mission.

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