

BUILDING A CALIBRATION AND VALIDATION SYSTEM FOR THE PROBA-V SATELLITE MISSION

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KEY WORDS:

ABSTRACT:

The VEGETATION instruments on board of the SPOT-4 and SPOT-5 satellites have provided users daily low resolution (1 km ground sampling distance, GSD) remote sensing images on a global scale for vegetation monitoring for more than 10 years. To ensure the continuity of this service, the ESA PROBA-V (V for Vegetation) mission is under development, due to be launched in 2012. VITO will continue to process and archive the imagery and products as it now does for the VEGETATION instruments, and it will assume responsibility for calibration and validation of this mission.

The PROBA-V minisatellite will fly a very compact and lightweight wide swath instrument consisting of three Three-Mirror-Anastigmatic (TMA) cameras (to cover the 2250 km swath width), each equipped with blue, red, near-infrared line detectors and an array of staggered short-wave infrared (SWIR) detectors. All these detectors have different viewing angles within a camera, also causing different object viewing times; there is a minimal across-track overlap between the adjacent cameras and a significant difference in GSD and MTF between the detectors and cameras; the distributed cameras and the lightweight design result in a mandatory use of a thermo-elastic model and characterization data in the imaging and calibration chain. This setup complicates both the geometric and radiometric calibration procedures. The absence of an on-board calibration facility adds to the difficulty.

To prepare for this challenge, an end-to-end simulator is being built to characterize the effects of optical performance, alignment, thermal cycling, atmosphere, etc., ... But to simulate is not enough: new solutions to known problems need to be thoroughly evaluated. Cross-calibration with other (satellite and airborne) sensors, observing stable objects (deserts, polar regions, the moon, etc.) sun glint, etc. have all been reviewed. Next to that, VITO will start operating the airborne APEX imaging spectrometer in the near future, which will provide valuable under flight data.

1. INTRODUCTION

Land monitoring applications based on low resolution images typically include:

- Environmental stress: Environmental stress are certain conditions which limit a normal growth of vegetation. Pollution, draught, desert locust, plant diseases, overpopulation, and erosion are potential hazards which can disrupt a sustainable development.
- Land management : land-use and land-cover
- Agriculture (crop type, crop condition, ...)
- Global climate monitoring (biophysical parameters, fire and burned surfaces)
- Urban and transport development (transport infrastructure, land use, ...)
- Forestry (forest type, forest extent, forest health, ...)
- Desertification monitoring, flood monitoring
- Terrain (elevation, slope, ...)
- Soil management (soil type, soil moisture, soil erosion, ...)
- Water management and land ice monitoring (surface water quality, groundwater quantity, land ice coverage, ...)
- Civil Security (humanitarian aid and security, ...)

Apart from the applications themselves, time series analysis to monitor trends in vegetation change is gaining importance worldwide. To be able to detect trends in land cover change,

sufficiently long time series of remote sensing data are of utmost importance.

The VEGETATION instruments on board of the SPOT-4 and SPOT-5 satellites have provided users daily low resolution (1 km ground sampling distance, GSD) remote sensing images on a global scale for vegetation monitoring for more than 10 years. The overall objectives of the VEGETATION system are to provide accurate measurements of basic characteristics of vegetation canopies on an operational basis, either for scientific studies involving both regional and global scales experiments over long time periods (for example development of models of the biosphere dynamics interacting with climate models), or for systems designed to monitor important vegetation resources, like crops, pastures and forests. VEGETATION has an almost complete global coverage daily; however, most users prefer to use 10-day syntheses. Although both satellites are still operational, they are close to or beyond the end of their foreseen lifespan.

To ensure the continuity of this service, the ESA PROBA-V (V for Vegetation) mission is under development, due to be launched in 2012. The PROBA-V instrument is significantly smaller than VEGETATION, hence a new camera concept was required. The challenges related to calibration and validation of this system are discussed below.

2. PROBA-V

2.1 System description

The Project for On-Board Autonomy (PROBA) program of the European Space Agency is dedicated to satellite missions that demonstrate innovative technologies (ESA,2009). Within this program, PROBA-V is a remote sensing micro-satellite being developed for the purpose of global monitoring of vegetation. To be launched in 2012, it will deploy new technologies such as the very compact wide field of view telescope and new multispectral detectors (Mellab, 2009).

Within the ESA project, it is a joint effort of Verhaert Space (prime, responsible for the platform), OIP (instrument) and VITO (principal investigator, responsible for the user segment) From an altitude of 825 km, the satellite will make near-polar orbits to offer daily global coverage of all land masses for latitudes above 35° and two-daily coverage for lower latitudes.

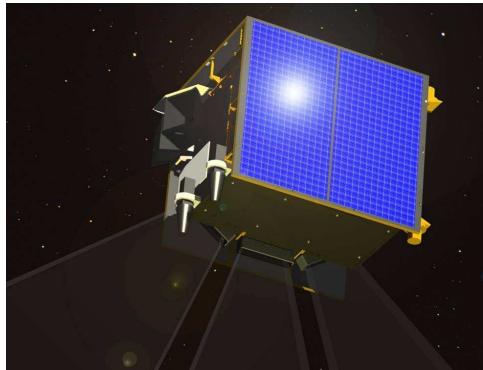


Figure 1: the PROBA-V spacecraft

To achieve this, the imaging instrument will cover a wide swath of 2250km. The corresponding field of view of 101° will be obtained using three identical camera systems pointing left, down and right. Each camera has an equal FOV, the side cameras cover a larger portion of the swath (875km. vs. 500km.). Each camera contains a set of push-broom (line) sensors to image 4 spectral bands. The BLUE, RED, and near infrared (NIR) sensors have 6000 pixel wide arrays in the across-track direction.

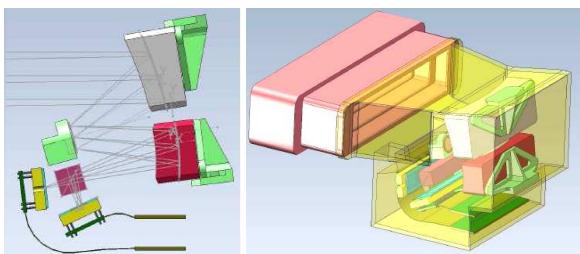


Figure 2: details of the Three-Mirror-Anastigmatic telescope

For the central camera, this results in imaging with a ground sampling distance (GSD) of 100m in the across-track direction. Imaging in the along track direction is matched to this. The side cameras view the earth under larger angles and therefore their across-track GSD varies from 100m to more than 300m at the far sides. The short wave infrared (SWIR) spectral band has an 3000 pixel wide array. Its pixels are twice as large and have a similar geometry: square (200m by 200m) in the centre varying to 200m by 600m at the edge of the side cameras.

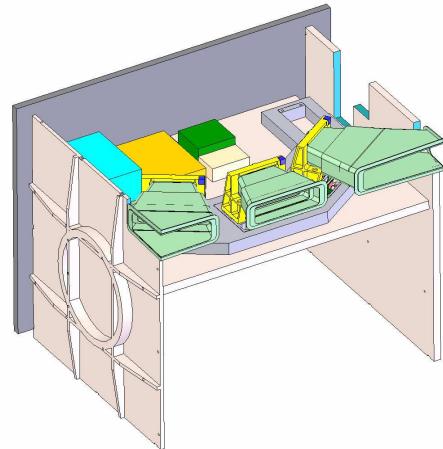


Figure 3: the three TMA telescopes on the optical bench in PROBA-V

2.2 Comparison with SPOT-VEGETATION

The main goal of the PROBA-V mission is to provide enhanced data continuity to the Vegetation instrument carried by the SPOT-4 and SPOT-5 missions. Therefore the image quality, including radiometric and geometric accuracy should be equal or better than that of SPOT-VEGETATION. However, the platform and the instruments are fundamentally different in many aspects (Dries, 2009).

	SPOT-4	SPOT-5	PROBA-V
volume	2x2x5.6 m ³	3.1x3.1x5.7 m ³	0.8x0.8x1 m ³
mass	2760 kg	3 000 kg	160 kg
power	2100 W	2100 W	153 W

Table 1: characteristics of the satellites

PROBA-V will have no on-board propulsion, therefore there is a risk that the initial orbit after launch might not exactly match the planned one. This could reflect in different overpass times, leading to less favorable imaging, different from VEGETATION imaging. As no orbit adjustments are possible during the lifespan, the orbit will increasingly deviate over time, increasing the overpass timing problem and reducing the useable lifespan.

The spectral bands will be chosen to match those of SPOT-VEGETATION very closely. Radiometric performance is determined by two aspects: the signal to noise ratio that can be achieved by the sensors, and the accuracy of the radiometric calibration. The latter will be addressed further on. In comparison with VEGETATION, PROBA-V lacks an on-board calibration facility, so it relies on vicarious calibration methods completely.

	VEGETATION	PROBA-V
volume	0.7x1.1x1.1 m ³	0.81x0.35x0.20 m ³
mass	152 kg	33.36 kg
GSD (nadir)	1 km	100-200 m
GSD (edge)		300-600 m
swath	2 250 km	2 250 km
geometric acc.	<0.3 pixel	<0.3 pixel

Table 2: characteristics of the instruments

Whereas VEGETATION covers the whole swath for each band with a single line sensor, PROBA-V does the same with 3

partial swaths (one for each telescope) for the VNIR channels, and with 9 partial swaths (3 mechanically butted sensors per telescope) for the SWIR channels.

PROBA-V images the earth with a much higher spatial resolution than VEGETATION (100-300m versus 1 km). This dramatically increases the data volume. In the derived product, a much higher resolution can be obtained. Therefore, products will be generated with at two different resolutions: at 1km resolution which ensures compatibility with VEGETATION, and at 300m which is the highest resolution that can be obtained over the whole field of view.

3. SIMULATION

3.1 Image Quality

PROBA-V is a fundamentally different instrument compared to the VEGETATION instrument. Also the platform is small and has limited power, mass and memory resources. On the other hand, the goal of PROBA-V is to guarantee the continuity of the VEGETATION products, which means that image quality has to be followed up very closely. This is as system-level task, taking into account all technical decisions at the platform, instrument and user segment level. Some examples are given in the next paragraphs.

Points of focus are the mission and system-level requirements such as SNR, MTF, radiometric and spectral requirements and the geolocation accuracies, and the more refined lower level requirements that can be derived from that. The MTF e.g. is influenced by the instrument, platform-instrument mechanical interface, platform motion and the onboard and user segment data processing (resampling).

Similarly, the SNR is affected by both noise in the instrument and the onboard data reduction processing. The image data volume captured by the PROBA-V platform during continuous operational imaging is much larger than the capacity for data transmission allows. Several measures are taken to reduce this problem. Images are only collected over land, and imaging of polar regions is omitted. Still, a very significant reduction is to be achieved by on-board data reduction. CCSDS lossy compression is used with compression ratios tuned per band to optimize image quality within the given data rate restrictions (Livens and Kleihorst, 2009).

To help making these technical decisions at system-level, ad-hoc studies are performed and a system performance simulator has been developed, which is discussed in more detail in the next section. The SPS will also be used to validate the in-flight radiometric and geometric calibration strategies defined for the PROBA-V mission

3.2 System Performance Simulator

The SPS (System Performance Simulator) is the main tool for evaluating the PROBA-V system and sub-system performance against specific mission, user and system requirements. In order to evaluate the system, the SPS will simulate data as if it were coming from the real PROBA-V instrument. Afterwards the simulated data can be analyzed using performance indicators; this allows a first validation of the system performance on the basis of simulations. The algorithmic core of the SPS is composed of a set of C, C++, Fortran, Java or Matlab stand-alone executables.

The SPS consists of 3 algorithmic cores: (1) The *scene generator*, (2) the *instrument pixel simulator, data reduction and formatting* (3) the *L1/L2a processing module*.

3.2.1 The Scene generator generates a Top of Canopy (TOC) scene located on earth with all ground scene elements (GSE) being equally sized. It also calculates the longitude/latitude and height co-ordinates for every GSE Test scenes as well as actual scenes can be used.

These scenes are either test patterns, or derived from high resolution hyperspectral data cubes. The latter ones are then copied and mirrored to fill a sufficiently large area.

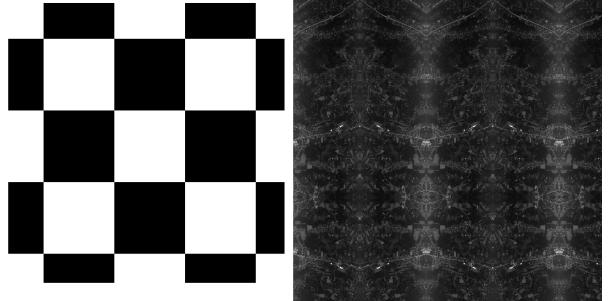


Figure 3: Test pattern and actual TOC scene simulation

3.2.2 The Instrument Pixel Simulator calculates and stores what every detector pixel is seeing of the simulated earth (which has been built in the scene generator). When the requested segment of scan-lines is processed and stored, the image is released to the next stage :

- The *data layout* block is used for handling the instrument input data. The *calculate meta data* block handles ancillary output data, to be used in the ground processing for keeping track of instrument behavior. The output data format is representative for the in-flight generated ancillary data that will be sent to the ground in a separate file.
- The earth model provides a model for the earth and the earth's atmosphere. The generated scene is linked to this model and a corresponding longitude / latitude / height grid is generated.
- The *local scene module* block calculates the local image of what the pixel of a certain band is seeing.
- The *geo-referencing* module calculates the longitude, latitude and height coordinates for a given detector pixel, starting from his viewing angle and respective transformation. This position can then be corrected for refraction of the atmosphere and for the terrain model.
- The *system SRF* block calculates the System Spectral Response, which has to be applied to the input scene. The system filter consists of the quantum efficiency of the sensor, the transmission of the spectral filters and the optics throughput.
- The *MTF* module describes the system's optical blur caused by instrument behavior (satellite motion blur, optical blur, sensor sampling). The system blur is then reworked as a

spatial blur line spread function (LSF), both for along-track and across-track, and this for every pixel position and the given optical defocus value. This value can be configured to check the influence of focus defects.

- The *simulate* block will calculate the radiometric output and convert it to Digital numbers.
 - First the spatial blur LSF is applied by a convolution with the (input) scene for every detector pixel.
 - From the blurred image, the Digital number signal and SNR are then calculated, using additional instrument parameters such as the dark current, read noise, stray light and signal noise. The result shows the digital image registered by the instrument.

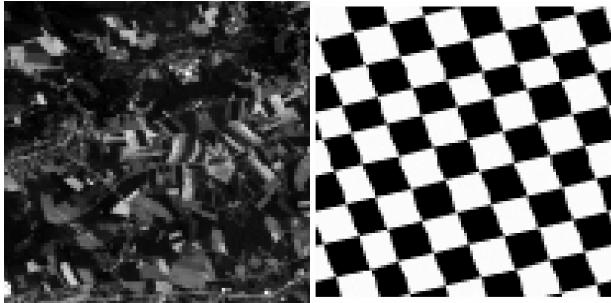


Figure 4: Test pattern and actual TOC simulation image

The Data Processing module describes all the data processing done on the DN image registered in the satellite system, until the further processing done on-ground. This consists of three operations which are applied to the image as a whole: (1) the on-board binning (taking together a number of bin pixels), (2) the on-board radiometric non-uniformity corrections and defect pixel/column/row replacement and (3) the on-board compression and on-ground decompression, with a compression factor cf.

The Formatting module reorganizes the obtained data to a standard L1a data layout which is the standard data structure accepted by the processing facility of PROBA-V.

3.2.3 The L1/L2a processing module transforms the received L1a (raw) data to L2a (projected) data. This module is a copy of the processing facility of PROBA-V which core is described in section 4.4.

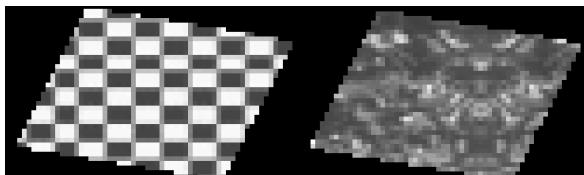


Figure 5: projected test pattern and actual TOC simulation image

3.2.4 The ICP file generator produces an Instrument Calibration Parameters file in ASCII format. It is modeled after the ICP files to be sent by the Image Quality Center to the processing chain for geometric and radiometric calibration of the satellite data.

4. CALIBRATION

4.1 Calibration plan

Radiometric and geometric instrument performance measurements will be done both on ground and in-flight. The on-ground calibration of the PROBA-V instrument will be performed at CSL (Liège, Belgium) prior to integration on the platform at Verhaert Space. A complete calibration report describing the radiometric and geometric performance characteristics before launch will be compiled. Radiometric and spectral performance characteristics that will be verified on ground are: signal-to-noise, dark currents, linearity, stray light, pixel non-uniformity, polarization sensitivity, spectral response and spectral misregistration. Geometric performance characteristics include MTF, bore sight, spatial misregistration.

The assessment of the PROBA-V performance, the analysis of the image quality and the calibration after launch will be performed by the PROBA-V Image Quality Center (IQC) located at VITO. Outgassing phenomena during launch, aging of the optical parts and cosmic ray damage are likely to cause variations in the characteristics of PROBA-V instrument. This makes it necessary to perform in-orbit stability monitoring and calibration.

The Image Quality Center will ensure the highest possible image quality, both radiometrically and geometrically. Given the constraints on power consumption and the small size and weight of the platform, only vicarious calibration techniques will be used to monitor sensor performance over time; no on-board calibration facility is available. A complete calibration plan to assess the radiometric and geometric performances in-flight is being outlined. The objective of the calibration plan is to achieve a complete PROBA-V calibration at end of the commissioning phase with :

- A full in-flight radiometric characterization and calibration including :
 - Dark current determination
 - Calibration of the absolute calibration coefficients of the three cameras.
 - Equalization among detectors or multi-angular calibration: to correct for sensitivity variation over PROBA-V wide field-of-view.
 - Characterization of response non-linearity
 - Radiometric image quality performance analysis : Noise, MTF, SNR
- A full in-flight geometric characterization and calibration including :
 - Geometric sensor model calibration: Post-launch check and calibration of all parameters of the geometric sensor model for each sensor including
 - Continuous absolute geometric accuracy check
 - Image geometric quality performance indicators such as absolute location accuracy, multi-temporal co-registration accuracy, multi-spectral co-registration accuracy

The approaches and methods for these in-flight radiometric and geometric characterization and calibration are discussed in the next sections.

4.2 Radiometric calibration

The Image Quality Centre (IQC) will monitor the stability of the different parameters of the Sensor Radiometric Model. Degradation of these parameters after launch is expected due to aging of the optical parts. Therefore the IQC will, if needed, supply the processing facility (PF) with new calibration parameters for the processing of the raw images.

The Sensor Radiometric Model defines the relation between the raw digital output which is registered by the sensor and sent down for data processing, and the derived effective spectral radiance assumed to be present at the sensor. An approximately linear relationship between digital output and effective radiance can be assumed, defined as :

$$DN_j^k = A^k \cdot g_{jm}^k \cdot G_m^k \cdot L_j^k + dc_{jm}^k \quad (1)$$

where the superscript k and subscript j identify respectively the spectral band and the pixel. DN is the raw digital output, A the absolute calibration coefficient, L the effective radiance, G the gain and m the gain number and dc the dark signal. g is pixel relative sensitivity or equalization coefficient.

The initial values of the calibration parameters are fixed by the pre-launch calibration measurements. After launch these parameters are monitored, validated and, if needed, updated by the vicarious calibration activities.

Dark current (dc_{jm}^k) is caused by thermally generated electrons that build up in the pixels. The magnitude of the dark current is expected to increase with time due to space radiation. Moreover, noticeable variations of dark current are expected over the course of the year as a result of temperature effects. It is therefore important to monitor the dark current in orbit. Images taken during the nighttime portion of the orbit over dark ocean sites will be used to determine the dark current values for all pixels.

For the in-flight calibration of the absolute calibration coefficient (A^k) several independent approaches will be used. This allows for independent validation of the results and allows to deal with systematic errors inherent to one or more techniques. A distinction is made between absolute and relative calibration methods. The operational absolute calibration for BLUE and RED PROBA-V bands will be performed using the so-called Rayleigh calibration approach (Fougne et al., 2007). The results of the Rayleigh calibration method can be transferred to other bands (NIR, SWIR) based on ‘relative’ inter-band calibration approaches. They use bright and almost spectrally flat targets (Hagolle et al., 2004) such as sun glint spots over oceans or deep convective clouds (not suitable for SWIR) (Lafrance, et al., 2002). Due to their spatial homogeneity, stability and low cloud coverage the 20 stable deserts selected in North Africa and Saudi Arabia by Cosnefroy et al., 1996 are also ideal targets for absolute calibration and stability monitoring. The use of lunar observations for multi-temporal calibration is under investigation. Finally, a reflectance based method using simultaneously in-situ measured ground spectra of homogenous reference sites, will be also used at an ad hoc basis to validate the obtained values of A^k . To reduce both random and systematic error effects, calibration coefficients derived over a large number of images and obtained

with different methods will be statistically averaged to obtain A^k .

In the absolute and relative calibration methods techniques the three cameras are treated separately, which may introduce biases between the cameras. In the overlap zone, targets are simultaneously seen by 2 independent cameras. This overlap zone will be used for checking and correction for possible bias between cameras.

The equalization coefficient g_{jm}^k can be split up in a low and a high frequency term. The in-flight determination of the low frequency is performed using the 20 stable deserts with known bi-directional effects. High frequency variation can be assessed using images over Antarctica or Greenland.

The measurement of the linearity of the relation between effective spectral radiance and digital output is crucial, as systematic deviations from this linearity may occur in-flight. Possible causes of this are: saturation of the sensor because of surface full well (interface traps capturing electrons) and/or saturation of the electronics because of voltage cut off. In-flight linearity tests will be done by changing the integration time while imaging homogenous bright targets.

4.3 Geometric calibration & sensor model

The goal of geometric calibration of an optical sensor system is to model the line-of-sight for each pixel element of the imaging system. This is usually performed pre-launch in laboratory conditions where precise measurements enable to characterize the various aspects of the system (Poli, 2005). Due to possible launch effects and differences in operational conditions, a post-launch self-calibration is performed on a regular basis (at least once a year) to ensure geometric system stability.

The calibration comprises a thorough knowledge on various aspects influencing image geometry:

- Geometrical processing
 - Sensor model
 - Orbit & attitude
- Geometric calibration of all subsystems and their inter-relationships
 - Detectors
 - Cameras
 - Instrument
 - Absolute platform attitude
- Long term performance monitoring
 - Absolute localization
 - Multi-spectral and multi-temporal registration monitoring

4.3.1 Prior to launch

Initial analytical sensor model

For each pixel of the imaging system, the relative geometry has to be understood accurately before flight to build the initial rigorous sensor model (Poli, 2004):

- Size and location of each array element or pixel (s_x, s_y)

- Location and orientation of the different arrays or CCDs ((dx_i, dy_i, θ_i))
- Optical characteristics of the sensor system
 - Focal length (f)
 - Principal point ((x_0, y_0))
 - Radial distortions ((K_1, K_2, K_3))
 - Decentring lens distortions ((P_1, P_2))
- Sensor-platform geometry
 - Lever arm ((dX_0, dY_0, dZ_0))
 - Bore sight ($(d\omega, d\phi, d\kappa)$)

The sensor is modeled by means of the colinearity equations:

$$X = X_0 + (Z - Z_0) \frac{r_{11}(x' - x'_0) + r_{12}(y' - y'_0) - r_{13}f}{r_{31}(x' - x'_0) + r_{32}(y' - y'_0) - r_{33}f} \quad (2)$$

and

$$Y = Y_0 + (Z - Z_0) \frac{r_{21}(x' - x'_0) + r_{22}(y' - y'_0) - r_{23}f}{r_{31}(x' - x'_0) + r_{32}(y' - y'_0) - r_{33}f} \quad (3)$$

With

$$x' = x + dx = x + dx_i + dx_r + dx_d \quad (4)$$

$$y' = y + dy = y + dy_i + dy_r + dy_d \quad (5)$$

which models the actual sensor calibration or deviation from a theoretical pinhole camera system, taking interior orientation deviations (d_i), radial symmetric distortions (d_r) and radial-asymmetric or tangential distortions into account (d_d).

The distortions can be modeled via the following analytical models:

$$dx_i = dx_0 + \frac{x'}{f} df \quad (6)$$

$$dy_i = dy_0 + \frac{y'}{f} df \quad (7)$$

$$dx_r = x'(r^2 K_1 + r^4 K_2 + r^6 K_3) \quad (8)$$

$$dy_r = y'(r^2 K_1 + r^4 K_2 + r^6 K_3) \quad (9)$$

$$dx_d = (r^2 + 2x'^2)P_1 + 2x'y'P_2 \quad (10)$$

$$dy_d = 2x'y'P_1 + (r^2 + 2y'^2)P_2 \quad (11)$$

However, since PROBA-V doesn't use traditional optics but a TMA design, it is expected that traditional distortions models will not allow a complete modeling of the optics characteristics. For this, an extra approach is foreseen whereby distortions (from theoretical pinhole model) for each sensor are projected for each pixel onto the focal plane. This approach is used successfully by Leica for the calibration of their ADS40 line scanner (Templemann, 2003), in a production environment. Based on reference data, an algorithm is developed that transform the one dimensional pixel location in the CCD array (pixel/column number) into focal plane coordinates (often in micrometer units):

$$x' = F(column) = p_0 + p_1 column + p_2 column^2 + p_3 column^3 + \dots \quad (12)$$

$$y' = G(column) = q_0 + q_1 column + q_2 column^2 + q_3 column^3 + \dots \quad (13)$$

The exact algorithm has to be decided on based on reference data, either in orbit collected, or received from optics modeling and laboratory calibration measurements. The distortions have to be projected onto the focal plane.

For PROBA-V, this is done based on modeling results of the instrument builder optics, providing us with viewing angles for

each pixel. This viewing angles are projected onto the focal plane to map the distortions in a generic way:

$$[x, y] = D[\tan(across), \tan(along)] \quad (14)$$

with D the distance between the focal point and the fictive plane on which a set of viewing angles is projected. When assuming a focal length of 110 mm, $D \sim 0.11$ meter.

A perfectly straight CCD in a perfect pinhole camera would result in a straight line with all pixels equally spaced. First results from the instrument builder data provide these focal plane distortion maps:

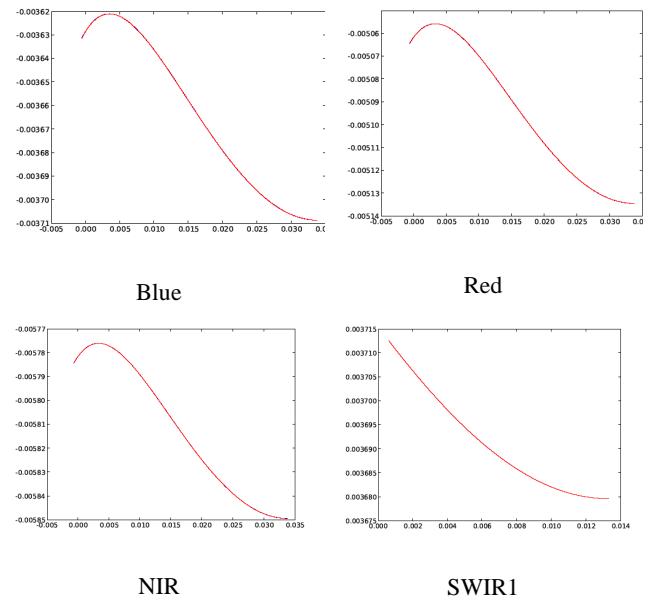


Fig. 6: Sensor line models for different detectors. X-axis = relative position of pixel to sensor center across track; in Y-axis = relative position of pixels in along track direction.

The above results clearly indicates non-pinhole behavior of the TMA design.

The next step is to model the distortion maps by means of a minimal set of parameters. The combination of Equations (2) through (14) then define the full geometric sensor calibration model and allow to define the viewing angles of each sensor element based on a limited set of parameters.

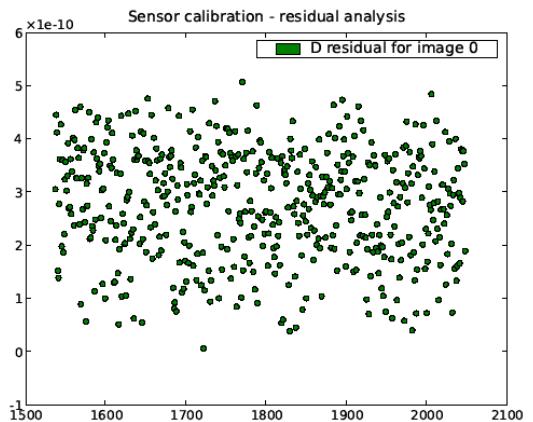


Fig. 7: Residual projected error at 800 km when using a sensor line model to describe the detector geometry

The abovementioned approach has been implemented in a development environment. As a test, the original instrument builder viewing angles are projected onto a fictive plane at 800km from the sensor. Then, the approach (colinearity equations in combination with distortion map) is used to project pixels onto the same fictive plane. Below, the distances between the projected points are illustrated (units ~ meters; note the scale factor: 1e-10). The X-axis represents the pixel location or column number.

Extended analytical sensor model for thermal deformations

Since it is expected that PROBA-V will be sensitive to thermal deformations, the sensor model will be adapted to take this extra parameter into account.

Thermal effects can be modeled at the level of the distortion map model, which provides most flexibility. A preliminary analysis of the instrument builder data reveals the effect of temperature induced deformations, and illustrates the need for calibration:

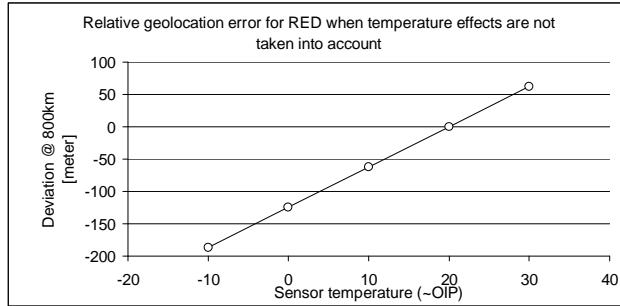


Fig. 8: Projected error at 800 km when temperature induced detector deformations are not taken into account

Then the deformations are modeled by an empirically developed 4th order polynomial with 7 unknowns, of the form:

$$x' = F(\text{col}) = \sum_{k=-2}^4 p_k \text{col}^k \quad (15)$$

The initial model parameters can be estimated by fitting this polynomial function trough the projected instrument builder data using least square optimization. Preliminary analysis indicate that a third order polynomial function (p_4 is not significant) allows to model the distortions correctly and these parameters are linearly correlated to temperature. This is illustrated below, for the sensor sensitive to red:

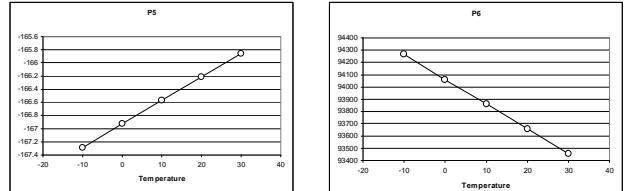
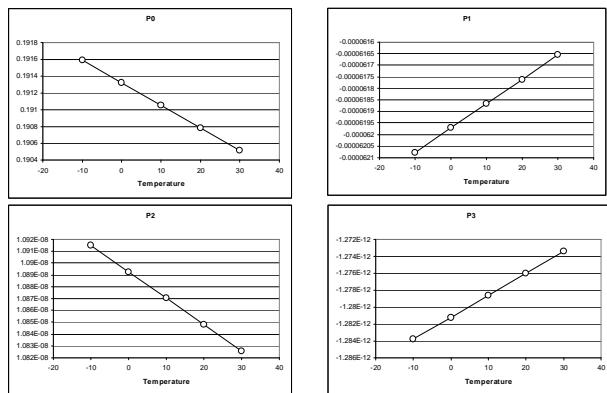


Fig. 10: Temperature dependency of sensor line model parameters

The maximum geolocation error of these initial 4th order analytical temperature specific models was 2 m.

Further statistical analysis are being undertaken to define the final sensor model.

4.3.2 In-orbit

An overview of the self-calibration workflow is given by the following figure:

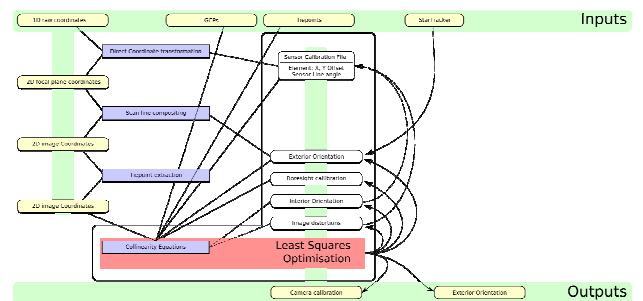


Fig. 11: In orbit geometric calibration procedure

Raw pixel 1D coordinates (column number) are converted to focal plane coordinates based on a lookup table, representing the sensor line model. Scanlines are then composed to create an initial image that can be used to identify ground control points. Exterior orientation is gathered from two on-board star trackers and GPS systems. Traditional least square optimization is used to optimize sensor model parameters based on a global set of control points.

4.4 Georeferencing

Modeling the geometry of a PROBA-V Earth observation images consists in defining a relation linking any point (p,l) of the image (Level 1A raw data) to geodetic coordinates (lat,lon) expressed in a reference system attached to the Earth and hence, indirectly, to any point (x,y) in a user-selected projection. To achieve this goal two approaches are used (Riazanoff, 2004) (Figure 12):

- The direct georeferencing for generating Level 1B product,
- The indirect georeferencing for generating Level 2 product.

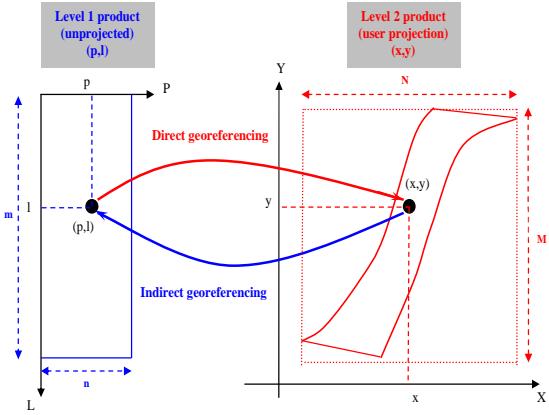


Fig.12: Direct and indirect georeferencing models

The direct georeferencing is based on the estimation of the ground coordinates of the points measured in the images through a forward intersection of its line of sight with an earth model. This is performed using the satellite position/velocity measurements and attitudes respectively provided by the on-board GPS and star tracker. The direct model consists of the following steps

- line dating: calculation of a line's acquisition time t
- platform data interpolation: calculation of the satellite position $P(t)$, the satellite velocity $V(t)$ and the satellite attitude $q(t)$.
- viewing direction calculation: calculation of a pixel's viewing direction in the inertial coordinate system.
- earth location calculation: calculation of the (lat,lon) coordinates of the intersection of the pixel's line of sight with the earth model.

The indirect georeferencing is used in reprojecting the image (generating Level 2) because it enables constructing the destination image point by point, retrieving for each point (x,y) of this destination image the coordinates (p,l) of the parent point in the input image. In PROBA-V the problem of determining which position in the input space, i.e. the (p,l) space, corresponds to the (x,y) coordinates in the destination image is performed using a polynomial predictions of which the coefficients are estimated based on a subsampling of the results of the direct georeferencing using least square optimization.

5. VALIDATION

5.1 Cross validation with other satellite sensors

In order to secure proper data continuity and consistency between VGT and PROBA-V cross sensor calibration is essential. The necessity of almost simultaneous observations can be overcome by the use of stable sites as deserts or Antarctica. This cross-sensor calibration is also considered as independent validation of routine calibration.

5.2 Underflights

ESA's well-calibrated hyperspectral airborne sensor APEX (Itten, 2008) sensitive in the wavelength range from 380-2500 nm can serve as an excellent instrument to carry out an independent validation of the in-flight radiometric calibration of PROBA-V under optimal weather conditions (cloud-free and low aerosol load). The main advantages of using APEX are (Nieke, 2001):

1. the measured radiance of APEX and PROBA-V can be compared directly when both view the same ground pixel at the same time
 2. the uncertainties of the atmosphere can be minimized by flying well above the boundary layer of the atmosphere and
 3. in contrast to PROBA-V, APEX can be re-calibrated on the ground in the Calibration Home Base (based at DLR, Oberpfaffenhofen)
 4. no calibration panel is required
 5. APEX allows fast sampling over a large calibration site and thus can be used for calibration of low, medium as well as high resolution space borne sensors
- One of the eight instrumented CEOS LANDNET sites will be selected as calibration site.

In order to have the same illumination conditions, APEX acquisitions should be timed to coincide with the PROBA-V overpass. Furthermore, to have the same viewing conditions for PROBA-V and APEX, the nadir center lines should coincide as well. In this configuration only the center PROBA-V sensor can be calibrated. To be able to calibrate also the left and right sensor, the PROBA-V sensor will be tilted (roll maneuver) +17,5°, which will allow nadir viewing of the left and center sensor (overlapping pixels) and subsequently in a next PROBA-V overpass tilted (roll maneuver) -17,5° which will allow nadir viewing of the center and right sensor (overlapping pixels). At 7 km altitude above ground level (AGL), the APEX FOV ($\pm 14^\circ$) results in a swath width of 3491 m and 3.5 m pixels. A swath width of 3491 m corresponds to approximately 35 100 m PROBA-V pixels and 11 300 m pixels.

The approach followed for validating the PROBA-V radiometric calibration using APEX underflights is the indirect comparison method (Teillet, 2001) which starts from APEX radiance which is converted to surface reflectance using a radiative transfer model (MODTRAN) as implemented in the VITO Central Data Processing Center (CDPC), (Biesemans, 2007) once the viewing and observation geometry and atmospheric properties are determined. The atmospheric properties (aerosol optical thickness at 550 nm-AOT550- and water vapor content) are obtained from sun photometer measurements taken at the calibration site during the APEX underflight and PROBA-V overpass using the Langley method.

After atmospheric correction of APEX radiance to surface reflectance a BRDF correction is performed to become reflectance for nadir APEX view angle and average solar zenith angle. Subsequently the surface reflectance is averaged for all pixels within a scan line. After that a BRDF correction is applied to convert the surface reflectance to an averaged PROBA-V viewing geometry. The BRDF corrected surface reflectance is converted with a radiative transfer model to TOA radiance by adding atmosphere using the same AOT550 estimate and water vapor content as used for the APEX atmospheric correction and using the same solar irradiance. Finally a convolution with the PROBA-V spectral response functions allows a comparison with PROBA-V measured TOA radiance

The change in calibration coefficients for the PROBA-V BLUE, RED, NIR SWIR bands is calculated based on a comparison of the measured PROBA-V radiance averaged over all PROBA-V pixels within the APEX FOV and the averaged BRDF corrected APEX-based TOA radiance.

6. CONCLUSIONS

PROBA-V is a minisatellite mission that aims to continue the observation time series started by SPOT-4 VEGETATION and continued by SPOT-5 VEGETATION. Although the whole PROBA-V satellite will be comparable in volume and mass to the original VEGETATION instrument, its instrument will provide better spatial resolution at a similar swath.

The constraints imposed by the minisatellite platform have an impact on the way calibration and validation of the observations is performed. The lack of an on-board calibration facility necessitates the use of a series of radiometric calibration methods, aimed at characterizing a single spectral band and then transferring that to the other spectral bands. On the geometric side, the construction of the instrument (three cameras with an array of detectors) is a complicating factor. Moreover, the traditional pinhole camera model is not adequate.

The System Performance Simulator is the main tool for evaluating the radiometric and geometric correction methods.

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