PROBA-V US Calibration Plan (US-13)

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.   INTRODUCTION

1.1   Scope

The present document is the User Segment Calibration Plan for the VEGETATION Instrument for the PROBA-V User Segment project (PV02), under contract between VITO (supplier, Mol, Belgium,) and ESA (customer) as part of the PROBA-Vegetation (PROBA-V) project.
In the project the Calibration Plan it is referred to as US-13.

1.2   Applicability

This document applies to the to the PROBA-V User Segment and all identified subsystems. This document has to be delivered at US-SRR, US-PDR and US-CDR. This document is subject to change between the above mentioned review cycles and will reach a "final" status at US-CDR.

2.   REFERENCES

All applicable and reference documents for the PROBA-V PV02 project, either initiated by ESA or the consortium, are listed in [N77D7-PV02-PM-18-US-ApplicableAndReferenceDocumentsList].

2.1   Project reference documents

Project reference documents are listed in Table 1:

[PVDOC-623]	Detailed Processing Model IQC
[PVDOC-611]	Technical Note on Sun Glint
[PVDOC-621]	Algorithm Theoretical Baseline Document IQC
[PVDOC-655]	Technical Note: Effect of straylight on Rayleigh calibration
[PVDOC-647]	Technical Note on Radiometric calibration algorithm prototype results
[PVDOC-645]	Technical Note on Ground Calibration
[PVDOC-161]	User Segment Geometric Calibration Plan
[PVDOC-401]	User Segment Ground to Ground ICD
[PVDOC-402]	User Segment Software ICD
[PVDOC-656]	Software Design Document IPC

Table 1: Project reference documents

2.2   Other reference documents

References to the scientific literature are listed in Table 2

LIT1	Govaerts and Clerici,2004	Y.M. Govaerts and M. Clerici . Evaluation of Radiative Transfer Simulation Accuracy over Bright Desert Calibration Sites. IEEE Trans on Geoscience and Remote Sensing, VOL-42, NO-1, January 2004
LIT2	Six et al.,2004	Delphine Six, Michel Filya,, Severine Alvain, Patrice Henry, Jean-Pierre Benoist. Surface characterisation of the Dome Concordia area (Antarctica) as apotential satellite calibration site, using Spot 4/Vegetation instrument Remote Sensing of Environment 89 (2004) 83–94
LIT3	Stone, 2008	Stone, 2008. Use of the Moon for in-flight calibration stability monitoring QA4EO-WGCV-IVO-CLP-001 (Ceos Cal/Val portal) (2008)
LIT4	Cox and Munk,1964	Cox and Munk . Slopes of the sea surface deduced form photographs of sun glitter Bull. Scripps Inst. Oceanogr., Univ. Calif. 6, 401-488.

LIT5	Hagolle et al., 2004	Hagolle, O.; Nicolas, J.-M.; Fougnie, B.; Cabot, F.; Henry, P.. Absolute calibration of VEGETATION derived from an interband method based on the Sun glint over ocean . IEEE Transactions on Geoscience and Remote Sensing, Volume 42, Issue 7, July 2004 Page(s): 1472 - 1481
LIT6	Hagolle et al,, 1999	O. Hagolle, Ph. Goloub, P.-Y. Deschamps, H. Cosnefroy, X. Briottet, T. Bailleul, J.-M. Nicolas, F. Parol, B. Lafrance and M. Herman . Results of POLDER In-Flight Calibration. IEEE Trans on Geoscience and Remote Sensing, VOL. 37, NO. 3, MAY 1999
LIT7	Itten et al., 2008	Itten, K.I.,. F. Dell'Endice, A. Hueni , M. Kneubühler,D. Schläpfer, D. Odermatt, F. Seidel, S. Huber, J. Schopfer, T. Kellenberger, Y. Bühler, P. D'Odorico, J. Nieke, E. Alberti, and Koen Meuleman, APEX – the Hyperspectral ESA Airborne Prism Experiment *Sensors 2008, 8,* 6235-6259
LIT8	Nieke J., 2001	Nieke J. Technical Note 1 Compilation of Scientific Varaibles. Specification of an airborne spectroradiometer to calibrate and validate spaceborne Earth Observation sensors APEX Study, APEX-TN1, 16 July 2001.
LIT9	Hovis et al, 1985	W.A. Hovis, J.S. Knoll, G.R. Smith;; Appl. Optics; Aircraft measurements for calibration of an orbiting spacecraft sensor Vol. 24; pp 407-410 (1985)
LIT10	Cosnefroy et al, 1996	H. Cosnefroy, M. Leroy and X. Briottet. Selection and Characterization of Saharan and Arabian Desert Sites for the Calibration of Optical Satellite Sensors.Remote Sens. Environ. 58 (1996), pp. 101–114.
LIT11	Fougnie et al., 2002.	Fougnie, B., P. Henry, A. Morel, D. Antoine, and F. Montagner . Identification and Characterization of Stable Homogeneous Oceanic Zones: Climatology and Impact on In-Flight Calibration of Space Sensors over Rayleigh Scattering Ocean Optics XVI, Santa Fe, NM, November 18-22, 2002
LIT12	Loeb,1997	Loeb, N. In-Flight calibration of NOAA AVHRR visible and near-IR bands over Greenland and Antarctica Int. j. remote sensing, 1997, vol. 18, no. 3, 477± 490
LIT13	Veenhuis,2006	Veenhuis B, Variability in Surface Reflectance of the Greenland Ice Sheet (1982-2005) using Satellite Remote Sensing Senior thesis. Ohio State University, 2006

Table 2: Scientific Literature References

3.   TERMS, DEFINITIONS AND ABBREVIATED TERMS

General terms, definitions and abbreviations used within the scope of this document are listed in [PVDOC-303] Directory of Acronyms and Abbreviations.

4. RADIOMETRIC CALIBRATION AND VALIDATION PLAN

The User Segment Calibration Plan assumes that the instruments have been verified and validated against their respective specifications before launch and that the satellite in-orbit verification and validation is completed prior to the start of the Cal/Val operations.

The User Segment Calibration Plan also depends on and assumes a complete and accurate pre-flight calibration and characterization.

The User Segment Calibration Plan describes the radiometric vicarious calibration activities for both the Commissioning phase and the Operational phase. The Cal/Val commissioning phase will start after the satellite in orbit verification and validation and is scheduled to be a three-months activity.

The objectives of the Cal/Val activities during the commissioning phase are:

- To verify instrument performance after launch

- To check for instabilities of the radiometric calibration with respect to temperature, or other driving parameters. Due to the very short period of only 3 months this objective may not be fully accomplished at the end of the commissioning phase (e.g. full temperature range (winter-summer) not encountered)

- To perform in-flight instrument radiometric calibration

- To validate that the calibration meets the absolute and relative accuracy requirements

- To deliver at the end of the commissioning phase this calibration in the form of the Instrument Calibration Parameter (ICP) file

- To update Cal/Val plan for the operational phase to start at the end of the commissioning phase for the whole duration of the mission

The objectives of the Cal/Val activities in the operational phase are :

- To continuously monitor the instrument calibration parameters and performance in order to be able to compensate for drifts caused by systematic changes such as ageing of the instruments

- To update the ICP file as needed to maintain the accuracy of the calibration and continuity of product quality

4.1   Radiometric sensor model

The Cal/Val activities are intended to provide the instrument calibration parameters (ICP) allowing the PF (Processing Facility) to produce reliable Level 1B (radiometrically corrected at pixel level) products starting from digital number (DN).

The conversion starting from digital number (DN) data to effective spectral radiance is based on a radiometric sensor model. Three stages are distinguished in the conversion:

As a first stage, the acquired DN result must be corrected for nonlinearity. This is done by the nonlinearity parameter: a parameter that maps the full digital range of the instrument (from 1 to the maximum bit, eg. 4095 for a 12-bit instrument) to the digital range that would have been present for a linear response of the instrument. Thus:

$$DN_i^k = \frac{DN_{i,acquired}^k}{NL(DN_{i,acquired}^k)}$$

The second stage is a correction for **dark current**, which is a signal source independent of the spectral radiance signal. The objective here is to deduce and then subtract the dark signal offset, and retrieve an intermediate DN result which is in direct relation to the spectral radiance signal:

$$DN_{cor1,im}^k = DN_i^k - dc_{im}^k$$

Equation 1: Dark current offset correction

In the third stage the effective spectral radiance result is retrieved by applying three scaling factors:
- the gain factor G for scaling over integration time and ADC(analog-to-digital conversion) gain
- the equalisation scaling factor g for response non-uniformity differences of different pixels
- the absolute radiometric calibration parameter A which is the scaling parameter that covers all remaining effects

The gain factor G covers the conversion from the digital value to a stored electron charge, and the scaling of the stored charge to the incident electric current I via integration time. Because the integration time can be varied, an index m is introduced as a difference in gain factor:

$$electrons_{im}^k = \frac{DN_{cor1,im}^k}{G_{ADC}}$$

$$I_i^k = \frac{electrons_{im}^k}{t_{int,m}}$$

$$G_m = t_{int,m} \cdot G_{ADC}$$

$$I_i^k = \frac{DN_{cor1,im}^k}{G_m}$$

The equalisation factor g corrects for variations in the pixel response and is pixel dependent. Therefore, a pixel index i is used to indicate the difference in scaling for different pixels.

The absolute radiometric calibration parameter covers the remaining scaling from a equalized electric current to an effective radiance signal. Combining these, the effective spectral radiance can be derived. Note the spectral band index k, indicating that all parameters can be different for

different bands:

$$L_{TOA,i}^{k} = \frac{DN_{cor1,im}^{k}}{G_{m}^{k} A^{k} g_{im}^{k}} \quad \text{with} \quad L^{k} = \frac{\int_{0}^{\infty} S_{k}(\lambda) L(\lambda) d\lambda}{\int_{0}^{\infty} S_{k}(\lambda) \lambda d\lambda}$$

Equation 2: Conversion to effective spectral radiance

The equations can be summarized into a single equation describing the full relation between acquired DN data and effective spectral radiance:

$$L_{TOA,i}^{k} = \frac{\dfrac{DN_{i,acquired}^{k}}{NL(DN_{i,acquired}^{k})} - dc_{im}^{k}}{G_{m}^{k} A^{k} g_{im}^{k}}$$

Equation 3: Sensor model relation

The ICP files will need to contain all parameters of the model. The model will be used in two stages:

- **pre-launch calibration**: at this stage, both the digital output and the input effective spectral radiance are known up to a given accuracy, and the calibration parameters determining the relation between both can be derived;
- **post-launch calibration**: at this stage, the effective radiance must be derived from the digital output and the calibration parameters currently used. The initial values of the calibration parameters is fixed by the pre-launch calibration measurements, these parameters are then updated and validated by the vicarious calibration activities

4.2   Pre-launch radiometric calibration and characterization

The User Segment Calibration Plan depends on and assumes a complete and accurate pre-flight calibration and characterization as explained in the next sections. For details on the pre-flight calibration and characterisation activities we refer to the related PV-01 documents.

4.2.1   Purpose and scope prelaunch calibration

From the perspective of the post-launch calibration, careful in-lab calibration and characterization under operating environmental conditions, such as temperature and vacuum, and the full range of possible viewing conditions are essential

(1) To ensure that related mission requirements are met over the sensor's range of operating conditions

(2) To minimize the risk of bringing to light undiscovered problems after launch and therefore to promote mission success

(3) To determine all the influencing parameters on the sensor response

(4) To elaborate the radiometric sensor model (including temperature sensitivities, linearity, stray light (spatial and cross talk) etc.) describing the conversion from at-sensor radiances to digital numbers

(5) To accurately initialize all the parameters of the radiometric model.

(6) To provide the pre-launch calibration data needed for the initial radiometric processing of post-launch data (eg. absolute calibration coefficients, equalization coefficients, dark current values,…)

(7) To provide calibration/characterization data sets which cannot be obtained in flight (e.g. spectral response curves)

(8) To maximize the success of the proposed vicarious calibration algorithms. For example, the validity of the camera to camera calibration method proposed by IQC critically depends on the validity of the equalization coefficients of the individual pixels obtained in the lab.

(9) To make up a realistic pre- and post- launch calibration error budget taking into account all influencing parameters (and their uncertainties) on the sensor responsivity. For example detailed spectral characterization and knowledge of the accuracy of this characterization and the stability of the spectral response curves (both spatially and temporally) are required in order to make an accurate calibration error budget

4.2.2   Pre-flight radiometric calibration and characterisation data

In [PVDOC-645] a detailed specification and clarification of the pre-flight calibration and characterisation requirements as given in the SRD [PVDOC-009]and MRD [PVDOC-003] can be found. It is out of the scope of the User Segment Calibration Plan document to describe in detail the on-ground calibration and characterisation.

In this document we will list shortly the pre-flight calibration and characterisation data needed in order to perform in-flight vicarious calibration and validation.

The pre-launch calibration/characterisation measurements should allow to accurately initialize

the parameters of the sensor radiometric model. The pre-flight calibration parameters listed in Table 3 will be used in the first months of the mission when vicarious calibration data are scarce or still need to be analyzed in detail. Their influence on the sensor in-flight calibration will diminish with time when more and more vicarious calibration data will become available.Table 3 also lists which of these parameters is passed to the Processing Facility for application on image data, and from what source.

Parameter	Description	Units	Sent to PF
A^k	The absolute calibration coefficient per spectral band and per spectral imager at reference IT and reference ADC gain	DN/W m^{-2} sr^{-1} µm^{-1}	by ICP file
dc_{im}^k	the dark current coefficient per spectral band and per pixel for the full range of ITs and at reference ADC gain	DN	by ICP file
g_{im}^k	The equalisation coefficients per pixel, per spectral band at reference IT and reference ADC gain.	No Unit	by ICP file
Bad pixel map	List of defect of degraded detectors		by ICP file
G_{ADC}^k	Reference gain per spectral band	DN/electron	by ICP file
t_{int,m_0}	Reference IT per spectral band	ms	by ICP file
$t_{int,m}$	Range of ITs used to determine dark current coefficients	ms	by L0 data

Table 3: Required pre-launch radiometric parameters with possible update in-flight

Table 4 lists those ground calibration and validation data which are essential for the in-flight radiometric calibration but which will not be updated after launch. Table 4 lists if and how these parameters are passed to the Processing Facility as well.

Parameter	Description	Units	Sent to PF
$S^k(\lambda)$	The spectral response per spectral band in function of wavelength[1]	No unit	not sent
NL	Non-linearity correction factors LUT	No Unit	by ICP
Dark vs Temp	Analytic relation dark current – temperature	An analytical function	delivered as LUT by ICP (see [PVDOC-402])
Par vs Temp	Any other variation of radiometric with temperature (eg. Spectral response curve vs temp)	An analytical function	N/A

[1] Variation over the FOV and with Temperature should be analyzed on ground. Under the assumption that the spectral misregistration requirement is met an average spectral response will be used in the sensor model.

Table 4: Required pre-launch radiometric parameters with no update in-flight

Finally, pre-launch camera performance analysis is needed to verify if performance requirements with respect to temporal stability, spectral misregistration, polarisation and stray light are met. Not meeting these performance requirements will decrease the accuracy that ca n be achieved with in-flight radiometric calibration, and will impact the usefulness of some of the calibration approaches.

As the on-ground calibration and characterisation is still ongoing and no final results are available, it is assumed in the User Segment Calibration Plan that the specifications are met. In section 4.4.1.3.1, an outlook is given on how failure in meeting the performance requirements may affect the achievable in–flight calibration uncertainty. This analysis should however be revised once the on-ground calibration, characterisation and verification is finalized and all information is made available to the IQC taking into account all non-compliances.

4.3   In-flight Cal/Val plan

4.3.1   Overview in-flight calibration tasks

Following table provides a list of Cal/Val tasks for both commissioning and operational phase.

Task	Description
C1	Dark current characterisation: determination of the instrument response in the absence of an illumination signal
C2	In–flight calibration[1] of absolute calibration coefficient through **Rayleigh** calibration method
C3	In–flight calibration[1] of absolute calibration coefficient through **Desert** absolute calibration method[2]
C4	In–flight calibration[1] of absolute calibration coefficient through **interband sun glint** calibration method
C5	In–flight calibration[1] of absolute calibration coefficient through **interband deep convective clouds** calibration method
C6	Radiometric calibration synthesis
C7	Stability monitoring through lunar observations
C8	Stability monitoring over stable deserts[2]
C9	Stability monitoring over Antarctica[3]
C10	Calibration Validation by APEX underflights[4]
C11	Calibration Validation by reflectance based methods[4]
C12	Cross-sensor validation against SPOT-VGT[2]
C13	Camera-to-camera offset monitoring
C14	High frequency multi-angular calibration
C15	Low frequency multi-angular calibration
C16	Detection of defective or degraded pixels
C17	Non-linearity check
C18	Image quality performance evaluation

Table 5: List of in-flight Cal/Val tasks

Task C6 brings together the results of tasks C2, C3, C4 and C5, tasks which are designed to determine the best radiometric absolute calibration coefficients. This task will be used to correct

if necessary the latest estimation of these coefficients. Temporal stability monitoring of the absolute calibration coefficients is done in tasks C7 to C9. For the other calibration parameters it is always assumed that the latest estimation is also considered the most reliable by default. A correction to the estimation of these estimations is therefore simply by issuing a new estimation.

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[1] The in-flight radiometric calibration relies on several different and independent methods because

- ⇨ The methods are not always suitable for all bands and combination of methods are needed to allow accurate calibration of all spectral bands
- ⇨ Independent validation of the results is required to determine and to account for systematic errors in one or more techniques. For instance uncertainties in the characterization of target BRDF or assumptions in aerosol characteristics can induce systematic errors (Govaerts and Clerici., 2004 [LIT1]).To reduce random error effects, calibration coefficients derived over a large number of images will be averaged.
- ⇨ For some calibration methods the number of useful calibration scenes may be rather limited
- ⇨ With one method the full dynamic range of the sensor can't be covered (both bright (e.g. deserts) and dark calibration areas (e.g. oceans) are therefore needed)
- ⇨ The uncertainty in the calibration results can be decreased by consistency check of the different methods

[2] Acquisitions for this task will start already during commissioning, however due to seasonal effects which are difficult to correct for reliable results based on this method will be only available after at least nine months of acquisitions

[3] Acquisitions are limited to the local summer months.

[4] The feasibility of this task during the commissioning phase depends on time of the commissioning and availability of aircraft and field team

4.3.2 Description of the different tasks

This section describes (1) the methodology used for the different tasks, (2) the required calibration acquisitions and (3) the expected output of the different task

For details on the algorithms behind the different methods and their implementation we refer to IQC-ATBD [PVDOC-621] and IQC-DPM [PVDOC-623].

For the determination of the calibration acquisition frequency and/or number of sites the following considerations were made :

- The frequency of acquiring calibration data for SPOT-VGT was examined. It was concluded that more calibration images for PROBA-V are needed in order to obtain enough data for each of the three cameras (e.g. a sun glint spot seen by the eastern looking camera cannot be used for the middle camera). This can be obtained by increasing the number of sites and/or acquisition frequency.
- Experience with SPOT-VGT also showed that a large amount of the acquired calibration data could not be used due to cloud coverage. This again indicates the need for either more frequent acquisitions and/or larger number of sites.
- Limiting a calibration method to only one site may result in a biased calibration result, and therefore more than one calibration area per method is preferred
- Orbit simulations are performed to calculate the sun glint probability for the different sun glint calibration sites over a period of one year
- Frequency for lunar calibration is determined according to the recommendations by Stone (2008) (LIT3).
- The frequency and number of manoeuvres should be minimized as it may impact normal operations (when performing manoeuvres)
- Useful acquisitions over Antarctica and Greenland are restricted to local summer
- It is known that calibration results obtained from 'stable' deserts (the standard 20 sites as foreseen) show some 'unexplained' seasonal variation: Long time series are needed to eliminate these seasonal effects from the calibration results.
- Finally on-board power/memory constraints are taken into account (limiting factor)

The selection of the calibration areas was based on literature, experience with SPOT-VGT or recommendations by calibration experts :

- Stable deserts : recommended by Cosnefroy et al. (1996) [LIT10] and used for SPOT-VGT
- Rayleigh calibration zones: recommended oceanic sites by Fougnie et al., 2002 [LIT11] and used for SPOT-VGT
- Sun glint : same as for Rayleigh calibration (to decrease uncertainty in marine contribution). Some extra sites are added to increase number of suitable images.
- Antarctica: The DomeC site has been recommended by Six et al (2003) (LIT2) and used for SPOT-VGT
- Greenland : based on Loeb (1997) [LIT12]and Veenhuis (2006) [LIT13]
- Clouds : Maledives and Hawai sites have been successfully used for SPOT VGT ; the tropical western Pacific has been added as recommended by Dave Doelling (personal communications)

4.3.2.1 Task C1 : Dark current characterisation

4.3.2.1.1 Description of the approach

Dark current 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. It is therefore important to monitor the dark current in orbit by taking images during the night time portion of the orbit over dark ocean sites.

As dark current is temperature dependent and because there is no active thermal control mechanism, the temperature will be continuously measured using thermistors.

The effect of temperature difference on dark current values between day/night side and over the orbit is taken into account via an on ground determined temperature-dark current function.

4.3.2.1.2 Calibration acquisitions

▪ **Calibration areas**

Images taken during night from ocean sites (situated in Northern hemisphere in winter (e.g. PacN2_W) and Southern hemisphere during summer (e.g. PacSE) will be used to determine the dark current values for the different detectors.

Name	Min. lat	Max lat	Min. lon	Max lon
PacN2_W	17	23.5	-180	-159
PacSE	-45	-20.7	-130	-110

Table 6: Dark current calibration zones

To check the temperature variation of the dark current along the orbit some extra oceanic sites will be added along the same orbit during commissioning.

▪ **Mode**

Images should be taken during night in uncompressed mode preferably in a prolonged image capture mode, where the integration time can be extended as far as 10s.Frequency for the VNIR. To do this the line sampling period(LSP) setting of 10s for the VNIR, 20s for the SWIR must be set.
If this approach fails, the fallback is to acquire at least 7,5s of lines at default LSP (corresponding to 500 lines for a default LSP of 15ms for the VNIR, 250 lines at LSP of 30ms for the SWIR).

  ▪ Commissioning phase: weekly at one site; several sites along the orbit: weekly first month, two-weekly during the next 2 months.

  ▪ Expected frequency during operational phase: weekly over 1 site, preferably at new moon

4.3.2.1.3 Output

  ▪ Input for ICP file : In-flight dark current values for each pixel and each spectral band

  ▪ Evolution/stability of dark current values during the commissioning period

  ▪ Differences between in-flight and on-ground dark current values

  ▪ Inputs for bad pixel maps

- Decision on frequency of dark current calibration acquisition after commissioning phase

4.3.2.2   Task C2: In –flight calibration of absolute calibration coefficient through Rayleigh calibration method

4.3.2.2.1   Description of the approach

The so-called Rayleigh scattering calibration method has been successfully applied to other sensors (POLDER, PARASOL, SPOT/VEGETATION, MERIS,…) and detailed descriptions exist in the literature. The at-sensor radiance at short wavelengths over dark deep oceans comes mainly from Rayleigh scattering (scattering by air molecules). Rayleigh or molecular scattering can accurately be calculated based on the surface pressure and viewing angles. The contribution of aerosol scattering can be derived from the NIR reference band where molecular scattering is negligible. The aerosol content estimated from the NIR band is then transferred to the BLUE and RED band to model the TOA radiance with a radiative transfer code. The simulated radiance values are then compared with the measured values to derive the absolute calibration coefficient. To reduce the perturbing part of the signal due to ocean reflectance and presence of foam strict pixel selection procedures are used. Pixels can only be chosen within oligotrophic areas with well known weak and stable chlorophyll content. To minimize foam radiance meteorological data are used to select zones with low wind speed. For the acquisitions the integration time should be increased in order to increase the signal over the dark oceans.

The Rayleigh calibration approach allows for absolute calibration of the BLUE, and RED bands taken the NIR band as reference band. The method cannot be applied to the SWIR band as the Rayleigh scattering is there too small. The results can be transferred to other bands (NIR, SWIR) based on inter-band calibration approaches as sun glint (for both NIR and SWIR) or clouds (NIR) as described in the next sections. The accuracy of the absolute calibration coefficient can be increased by iteration of the inter-band and the Rayleigh calibration methods until the results converge

4.3.2.2.2   Calibration acquisitions

▪   **Calibration areas**

Calibration over Rayleigh scattering requires special acquisitions over some selected oceanic sites (see Table 7).

Ocean	Name	Min. lat	Max lat	Min. lon	Max lon
South of Atlantic	AtlS	-20	-10	-32.5	-11
South of Indian	IndS	-30	-21	84.5	105
North of Atlantic	AtlN	17	27	-62.5	-39
North of Pacific	PacN	15	23.5	-180	-159
North-West of Pacific	PacN1_W	10	23	139.5	166
South-East of Pacific	PacSE	-45	-20.7	-130	-110

Table 7: Rayleigh calibration zones

▪   **Mode**

Images should be taken with high integration time settings

▪   **Frequency**

Commissioning/ Operational phase : Daily acquisitions over the defined oceanic sites. The number of acquisitions can be reduced for days where there are conflicts with other large calibration campaigns. Calibration will not be performed for the orbits for which land data is in the swath in order not to impact the normal operations (other IT).

4.3.2.2.3   Output

- Estimates of absolute calibration coefficients for blue and red band for the different sites

- Stability of retrieved absolute calibration coefficients for blue and red band

- Input to *Task C6 Radiometric Calibration Synthesis* in order to determine the absolute calibration coefficients for the ICP files

- Differences between in-flight and on-ground absolute calibration coefficients

- Diagnostic plots to detect potential problems with instrument performance and calibration:

    - Plots of estimated absolute calibration coefficients versus VZA/detector as input to *Task C15 low frequency multi-angular calibration*

    - Plots of estimated absolute calibration coefficients versus AOT to detect possible problems with the NIR absolute calibration

    - Plots of estimated absolute calibration coefficients versus reflectance to detect possible problems caused by non-linearity of the instrument and/or stray light.

    - Plots of estimated absolute calibration coefficients versus date of acquisition in order to detect drift in the absolute calibration coefficients for blue and red band for the different sites

    - Plots of absolute calibration coefficients against longitude and/or Rayleigh scattering to detect potential problems with instrument polarization sensitivity. The Rayleigh scattering is highly polarized and the degree of sky polarization depends on the view zenith angles and sun zenith angles (polarization is highest for large angles).

- Quicklooks of input images and retrieved absolute calibration coefficients to detect possible problems caused by stray light (detection of patterns in retrieved calibration coefficient in function of distance to clouds, cloud coverage etc.)

4.3.2.3　Task C3: In –flight calibration of absolute calibration coefficient through Desert absolute calibration method

4.3.2.3.1　Description of the approach

Deserts are well suited as calibration test sites because they are usually relatively stable over time and are seldom covered by clouds. Also they are spatially homogeneous (good for multi-angular calibration). Following Govaerts and Clerici (2004) a set of 18 suitable test sites have been selected in North Africa and Saudi Arabia from the 20 deserts identified by Cosnefroy et al., 1996. The absolute calibration over these deserts relies on the comparison between cloud-free TOA reflectance as measured by the PROBA-V sensors and the modelled TOA reflectances values for these targets. The modelled TOA reflectance values are determined by three types of factors:

- o surface properties
- o atmospheric conditions
- o observation conditions including solar zenith angle, view zenith angle and relative azimuth angle.

The test sites are all covered by the normal operational imaging of PROBA-V. This has the advantage that they are imaged almost daily. No special settings are be used for their observation.

4.3.2.3.2　Calibration acquisitions
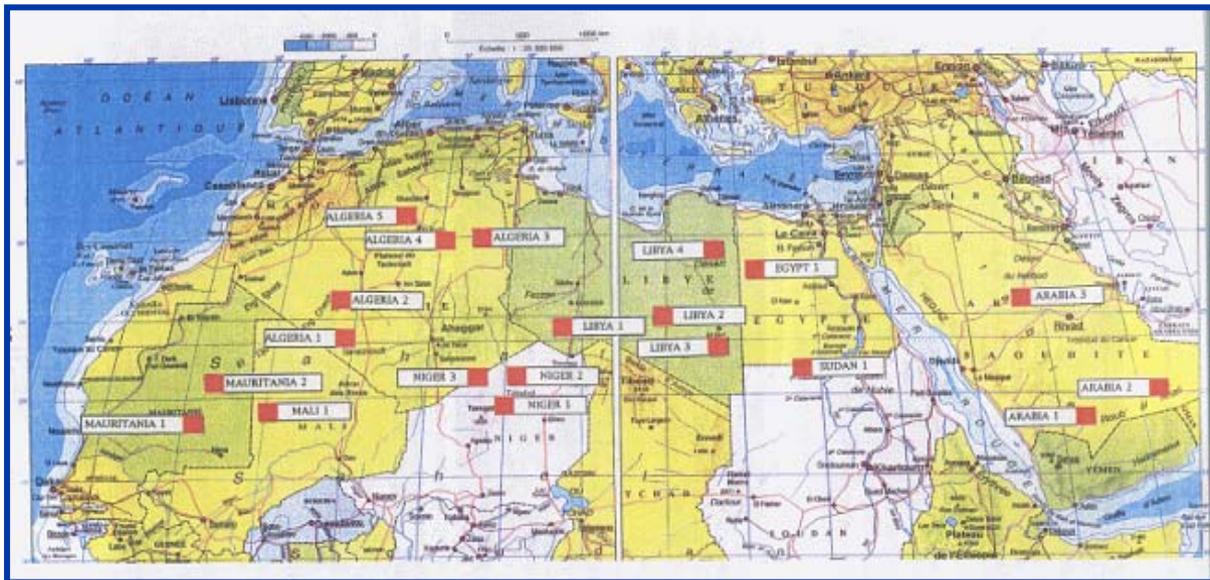
- ▪ **Calibration areas**

Figure 1: Location of desert sites used for radiometric calibration

- ▪ **Mode**

Normal operational settings

- ▪ **Frequency**

Continuously as observations are part of the normal operations of PROBA-V

4.3.2.3.3   Output

- Estimates of absolute calibration coefficients for blue, red, NIR and SWIR bands for the different desert sites

- Stability of retrieved absolute calibration coefficients

- Input to *Task C6 Radiometric Calibration Synthesis* in order to determine the absolute calibration coefficients for the ICP files.

- Differences between in-flight and on-ground absolute calibration coefficients

4.3.2.4   Task C4: In –flight calibration of absolute calibration coefficient through interband sun glint calibration method

4.3.2.4.1   Description of the approach

This method uses the specular reflection of the sun on the ocean surface. This sun glint reflection is high and spectrally flat (after removing atmospheric effects) if observed with the different bands under the same geometry. This method is operationally used for SPOT-VGT to transfer the absolute calibration of one reference band (RED) to other spectral bands (NIR and SWIR).

However for PROBA-V the observing geometry varies in function of the bands. Largest differences are observed in the viewing azimuth angles for the SWIR bands compared to the VNIR bands. This is illustrated in Figure 2 with a mean difference in viewing azimuth of 14.9°.
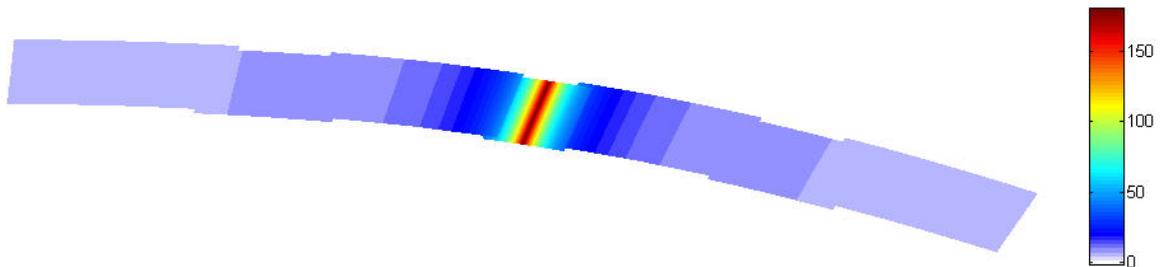
Figure 2: Viewing Azimuth Angles

The figure gives the absolute difference (deg) between two projected images (azimuth viewing angles) of the SWIR and the RED band in the plate carrée projection(lat/lon). It covers 30 km along track and the entire swath.

As VZA and VAA angles are not the same for the different spectral bands, the probability of observing sun glint and the sun glint reflectance will also not be the same for the different spectral bands. The effect of this difference is being analysed and results are given in technical note on sun glint ([PVDOC-611]).

This extra uncertainty increases the absolute calibration error in the SWIR from 4.7 (VGT, no angle differences) to 6-7 %, which is higher than the mission absolute calibration requirement of 5%. Furthermore with the sun glint calibration approach we will not be able to calibrate the western looking camera directly (no sun glint observations possible for this camera). The SWIR band of the western looking camera can be calibrated relatively to the middle camera using the overlapping pixels (see section Camera-to-camera offset monitoring).

4.3.2.4.2   Calibration acquisitions

▪ **Calibration areas**

Same calibration areas as for Rayleigh calibration with some extra zones if sun glint opportunities over Rayleigh zones are scarce (Table 8) . The IPC will determine the probability of observing sun glint for these sites taking into account the viewing and sun angles. This will allow to change the acquisition setting for these areas.

Name	Min. lat	Max lat	Min. lon	Max lon
AtlS	-20	-10	-32.5	-11
IndS	-30	-21	84.5	105
AtlN	17	27	-62.5	-39
PacN	15	23.5	-180	-159
PacN1_W	10	23	139.5	166
PacSE	-45	-20.7	-130	-110
PacN3	25	31	-180.00	-159
PacifEqu1	-10	5	160.00	180
PacifEqu2	-10	5	-140.00	-110
PacifEqu3	0	10	-140.00	-110

Table 8: Sun glint calibration zones

- **Mode**

Images should be taken with short integration time settings

- **Platform**

No manoeuvre

- **Frequency**

Commissioning/ Operational phase : Daily acquisition (in case of opportunities) over the oceanic sites with high sun glint probability. Calibration will not be performed (or kept to minimal during commissioning phase) for the orbits for which land data is in the swath in order not to impact the normal operations (other IT).

4.3.2.4.3   Output

- Estimates of absolute calibration coefficients for blue, red, NIR and SWIR bands

- Stability of retrieved absolute calibration coefficients

- Input to *Task C6 Radiometric Calibration Synthesis* in order to determine the absolute calibration coefficients for the ICP files.

- Differences between in-flight and on-ground absolute calibration coefficients

4.3.2.5   Task C5: In –flight calibration of absolute calibration coefficient through inter-band deep convective clouds calibration method

4.3.2.5.1   Description of the approach

This approach makes use of large, bright, thick, high altitude, convective clouds over oceanic sites. Their reflective properties are spectrally flat in visible and near-infrared and the only contributions to the observed signal are from the cloud reflectance, molecular scattering and ozone absorption which can be modelled with RTF. Using the RED band as reference (assumed to be well calibrated by the Rayleigh approach) to retrieve cloud optical thickness, the BLUE and NIR band can be calibrated. The method is not suited for the SWIR band as clouds are no longer spectrally uniform in this spectral region.

4.3.2.5.2   Calibration acquisitions

- **Calibration areas**

Calibration over clouds requires special acquisitions over some selected oceanic sites (Table 9).

Name	Min. lat	Max lat	Min. lon	Max lon
Hawai	7	25	-175	-150
Maledives	-15	0	65	80
Pac_tropW	-20	10	110	140

Table 9: Deep convective clouds calibration zones

- **Mode**

Images should be taken with short integration time settings

- **Frequency**

Commissioning/ Operational phase: Daily acquisitions over the defined oceanic 'cloud' sites. The number of acquisitions can be reduced for days where there are conflicts with other large calibration campaigns (e.g. Antarctica acquisitions or dark current acquisition during new moon). Calibration will not be performed for the orbits for which land data is in the swath in order not to impact the normal operations (other IT).

4.3.2.5.3   Output

- Estimates of absolute calibration coefficients for blue and NIR band
- Input to *Task C6 Radiometric Calibration Synthesis* in order to determine the absolute calibration coefficients for the ICP files
- Differences between in-flight and on-ground absolute calibration coefficients
- Diagnostic plots to detect potential problems with instrument performance and calibration:
  - Plots of estimated absolute calibration coefficients versus VZA/detector as input to *Task C15 low frequency multi-angular calibration*
  - Plots of estimated absolute calibration coefficients versus date of acquisition in order to detect drift in the absolute calibration coefficients for blue and NIR band
  - Plots of estimated absolute calibration coefficient against reflectance in order to

detect non-linearity problems

4.3.2.6   Task C6: Radiometric calibration synthesis

4.3.2.6.1   Description of the approach

A statistical methodology will be followed for handling results obtained from the different in-flight calibration methods (task C2,C3, C4 and C5) and combining them in a hierarchical scheme into overall best estimates for the radiometric absolute calibration coefficients.

The method is based on precise handling of accuracies in accordance with the ISO GUM (expression of uncertainty in measurements) and QA4EO guidelines.

The approach is schematically illustrated with Figure 3 .
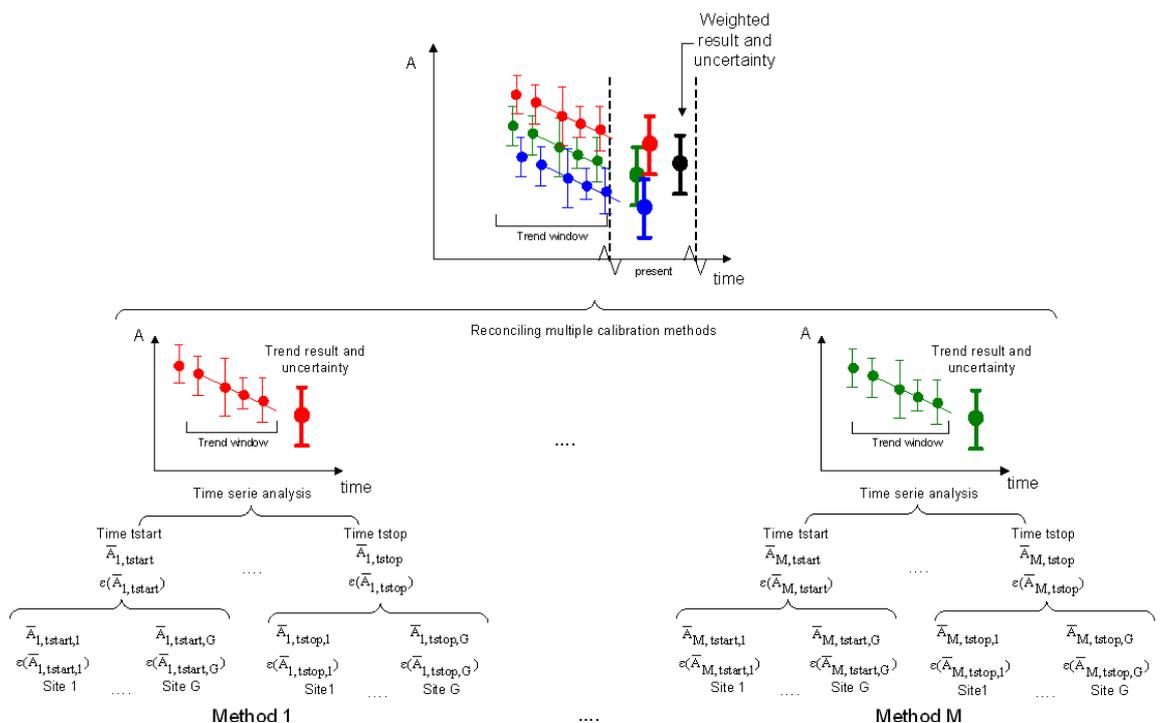
Figure 3: Radiometric calibration synthesis: calculation of best estimate of A^k

First error assessment is performed and errors are classified into systematic and random errors. To achieve maximal robustness against outliers, estimations are done using Median and Median Absolute Deviation (MAD) estimators throughout. Outliers are detected and removed from the estimations. After calibration over individual sites, spatial averaging over multiple sites is performed by weighting results according to their respective accuracies.

Temporal averaging has to accumulate results obtained over time, but also allow for real-world longer term variation and evolution. We employ a weighted linear regression model that yields a best estimate for the current radiometric calibration coefficient and its accuracy, based on results over a time window.

Estimates obtained with different methods are combined taking into account their respective accuracies. Possible bias between methods is dealt with explicitly by making reasonable bias assumptions. Finally, an update strategy is proposed in which the operational radiometric calibration coefficients are updated whenever a significant change is detected according to a statistical criterion.

The proposed scheme offers a statistically-based unified and systematic methodology compliant with ISO GUM and QA4EO for managing diverse vicarious calibration results and extracting operational calibration coefficients. The system is intended to aid human experts in establishing and maintaining high quality radiometric calibration.

4.3.2.6.2   Calibration acquisitions

N/A

4.3.2.6.3   Output

- Input for ICP file : absolute calibration coefficients for the different spectral bands
- Plots of the official (=ICP) absolute calibration coefficients versus date to monitor drift of the PROBA-V instrument
- Estimated accuracy of the absolute calibration coefficient for the different bands
- Estimates of consistency of absolute calibration estimates obtained with the methods under task C2,C3, C4 and C5 over time

4.3.2.7   Task C7: Stability monitoring through lunar observations

4.3.2.7.1   Description of the approach

The moon is an ideal target to check the temporal stability of PROBA-V (for all spectral bands) as the photometric properties of the moon are virtually invariant and the sun's illumination is well characterized. Stability monitoring has been achieved with sub-percent per year precision. The main advantage of lunar multi-temporal calibration over desert sites is that calibration results can be obtained immediately (no seasonal effects). A platform manoeuvre during night is required to point the sensor at the moon. Due to varying brightness with geometry of illumination and viewing ([LIT3] Stone, 2008), highest precision can be obtained by viewing the moon monthly at a same phase angle, preferably near 7 degrees when radiance levels will be similar to clear land. Also, it is recommended that during commissioning phase as many Moon observations as feasible are made, to establish a baseline for on-orbit stability

4.3.2.7.2   Calibration acquisitions

- **Calibration areas**

Moon

- **Mode**

Nominal settings (TBC)

- **Platform**

Lunar calibration requires a special platform manoeuvre during night to point the field-of-view towards the moon. A constant scan rate is needed when imaging the moon to allow for an overscanning of the moon in along-track direction

- **Frequency**

  - Commissioning: monthly observations at a phase angle of 7°, preferably for all cameras and at least for the central camera. To observe the moon with the 3 cameras, the manoeuvre has to be repeated for 3 different orbits. It is recommended that during commissioning phase as many Moon observations as feasible are made, to establish a baseline for on-orbit stability

  - Operational phase: monthly at a phase angle of 7°, preferably more than one observation should be made (several orbits and preferably also for the other cameras)

4.3.2.7.3   Output

- Plots of the inter temporal calibration coefficient $A_{k(t,t0)}$ for the different spectral bands(blue, red, NIR, SWIR) , which tracks the instrument degradation at time t by reference to an initial time t0(=time of first lunar observation with $A_{k(t,t0)} = \dfrac{A_{k(t)}}{A_{k(t0)}}$

4.3.2.8   Task C8: Stability monitoring over stable deserts

4.3.2.8.1   Description of the approach

The same deserts as used for the absolute calibration can also be used for multi-temporal calibration. **Several months of data are required** in order to be able to take into account seasonal variation. All new acquired data are then compared to comparable data of the same desert site in this reference database. Comparable means they have either **approximately corresponding** geometries. The angles defining the geometry are the sun zenith angle (SZA), the view zenith angle (VZA) and the relative azimuth angle (RAA).

A angle pair is considered approximately matching if :

$$(SZA_{ref} - SZA_{new})^2 + (VZA_{ref} - VZA_{new})^2 + (RAA_{ref} - RAA_{new})^2 / 4 < tol^2$$

where a sensible value for the tolerance is: $tol = 10$

The comparison is performed on BOA reflectance, meaning that all data are atmospherically corrected data with SMAC considering ozone, water vapour, pressure (from ECMWF) and AOT.

4.3.2.8.2   Calibration acquisitions

See section 4.3.2.3.2

4.3.2.8.3   Output

- Plots of the estimated inter temporal calibration coefficient $A_{k(t,t0)}$ for the different spectral band (blue, red, NIR, SWIR) after at least 9 months of acquisition (no immediate results)

4.3.2.9   Task C9: Stability monitoring over Antarctica

4.3.2.9.1   Description of the approach

The advantage of Antarctica is the possibility of acquiring several images a day during austral summer, which opens the possibility of near simultaneous overpasses with other satellites. Furthermore the inter-annual variation of the calibration site DomeC (75S, 123E) is found to be very small ([LIT2] Six et al, 2003), allowing the comparison of PROBA-V data with archived VGT imagery. As BRDF effects for snow and ice cannot be neglected it is essential to include a BRDF model to allow for proper calibration if observations are not made under similar geometric conditions. Acquisitions over Antarctica require a change of integration time to prevent saturation. In any case, for sensor calibration, acquisition during the month December are preferred because they show a remarkable stability with a standard deviation always less than 0.02. Another advantage of December is to provide the smallest solar zenith angles, thus minimizing topographic and atmospheric effects.

The Dome-C site can also be used to monitor the stability of the PROBA-V sensor. As suitable acquisitions are limited to the austral summer, only inter-annual drift analysis can be performed. If it is expected that the PROBA-V sensor performance degrades much faster, the Antarctica multi-temporal calibration method should be combined with other methods as the moon and deserts to detect changes over shorter time periods.

4.3.2.9.2   Data acquisition

- **Calibration areas**

The Dome C area is about 716 x 716 km² large. The area is divided into 36 grid boxes of 120 x 120 km². Dome C station is located in grid box 15. The calibration is done on 4 of these grid boxes where spatial studies have indicated that the area within grid box is sufficient homogenous.
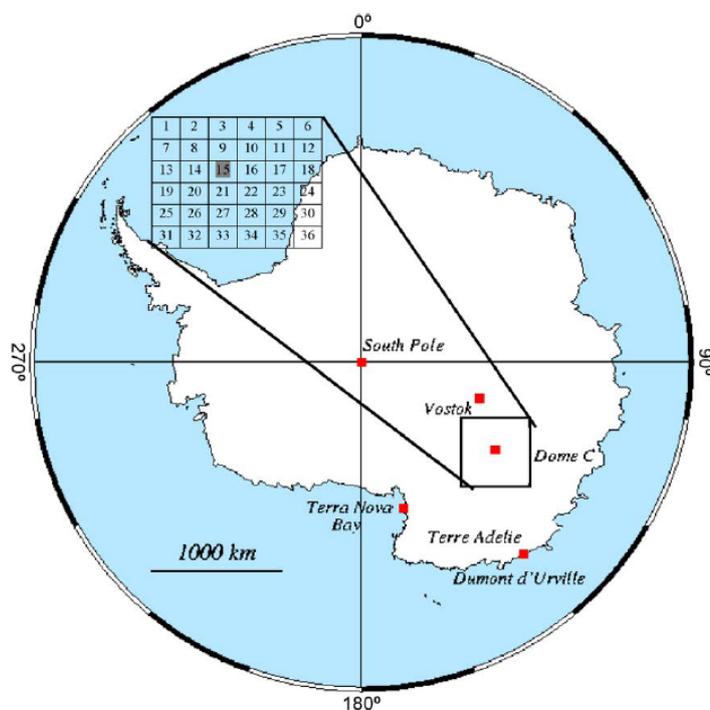
Figure 4: Location of Dome C calibration site (75°s, 123°E)

- **Mode**

Images should be taken with low integration time settings for the VNIR and high integration time settings for the SWIR. For the SWIR this probably means an increased LSP. Due to the coupling of LSP (line sampling period), the LSP for the VNIR will also be increased although the lower IT. This will cause an under-sampling of the area. Another option is to split the acquisitions for VNIR and SWIR for which we can then better optimize IT/LSP. This has as drawback that the number of calibration acquisitions will be doubled. Both options will be evaluated during commissioning

- **Platform**

No manoeuvres required

- **Frequency**

Commissioning/Operational phase: data should be acquired 3 to 4 times a day during December and January

4.3.2.9.3　Output

- Plots of inter-annual calibration drift of the different spectral bands

4.3.2.10 Task C10: Calibration validation : Apex underflights

4.3.2.10.1   Description of the approach

The well-calibrated hyperspectral airborne sensor APEX (Itten, 2008 [LIT7]) can serve as an excellent instrument to carry out an in-flight radiometric calibration of PROBA-V. The main advantages of using APEX are (Nieke, 2001 [LIT8])

> 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),
> 4) no calibration panel is required,
> 5) APEX allows fast sampling over a large calibration reference site and thus can be used for calibration of low, medium as well as high resolution space borne sensors.

This in-flight calibration experiment can be performed over clear sky conditions above at least one of the prime large and homogenous earth calibration reference sites (e.g. Tuz Gölü, Turkey, one of the eight CEOS endorsed core instrumented IVOS Sites provisionally called LANDNET sites). If there there is suspicion that the PROBA-V detectors might behave non-linear, more calibration sites should be selected covering the full dynamic range (water, sand, ice,…).
In the direct method the radiance values measured by APEX (wavelength range from 380 nm to 2500 nm) are converted to TOA radiances using a radiative transfer model to take residual scattering and absorption between aircraft and satellite into account. The TOA radiances from APEX are then spectrally resampled to the spectral response curves of PROBA-V and compared to the PROBA-V TOA measurements to check or compute the absolute calibration coefficients. In the indirect method APEX radiance is converted to surface reflectance using a radiative transfer model (MODTRAN) taking into account the viewing and observation geometry and atmospheric properties. The direct method without using ground-truth instruments may not reach the same accuracy as the indirect method (Hovis, 1985 [LIT9]). Therefore we propose to follow the indirect comparison method.

In order to have the same illumination conditions, APEX acquisitions should be timed to coincide with the PROBA-V overpass. That means at Tuz Gölü at TBD (dependent on PROBA-V launch) LST (Local Solar Time). Furthermore, to have the same viewing conditions for PROBA-V and APEX, the nadir center lines should coincide as well.

Under normal operational geometry only a limited number of pixels in the center PROBA-V sensor can be calibrated using APEX. In order to fully exploit the possibilities of this calibration method and to be able to calibrate also the left and right sensor, the PROBA-V sensor will be tilted (roll manoeuvre) +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 manoeuvre) -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 (+/- 14°) results in a swath width of 3491 m and 3.5 m pixels. A swath width of 3491 m corresponds to approximately 34 100 m PROBA-V pixels.
Averaging of pixels (34x34 PROBA-V pixels for the BLUE, RED and NIR and 11x11 PROBA-V pixels for the SWIR) is required to reduce uncertainties due to inhomogeneities of the calibration reference site and misregistration between APEX and PROBA-V.

Due to high operational costs, calibration on the basis of aircraft underflights cannot be

considered as a fully operational method for the exploitation phase but will be performed as validation once a year.

4.3.2.10.2   Data acquisition

▪ **Calibration areas**

Tuz Gölü, Turkey, one of the eight CEOS endorsed core instrumented IVOS Sites provisionally called LANDNET sites.

▪ **Mode**

Normal operational settings (or decreased IT in case of risk of saturation)

▪ **Platform**

Optionally, roll manoeuvre to allow for nadir looking geometry for the overlapping part of 2 cameras; once roll at -17.5°, once at 17.5°

▪ **Frequency**

- ▪ Commissioning :   once at 17.5° and once at 17.5° under the condition that July/August falls in the commissioning phase and that there is funding available for flight and field operations

- ▪ Operational phase : yearly in July/August under the condition that funding is available for flight and field operations

4.3.2.10.3   Output

- ▪ Independent validation of the absolute calibration coefficient for all bands for at least one of the cameras (if no manoeuvre)
- ▪ Absolute calibration of the camera overlap area and inter-camera calibration for all bands in case of manoeuvre

4.3.2.11 Task C11 Calibration validation by reflectance based method

4.3.2.11.1   Description of the approach

In the reflectance-based method, ground-based reflectance measurements are used as input. At the time of the PROBA-V overpass, the spectral reflectance of the calibration reference site (eg. instrumented CEOS LANDNET sites) is measured under optimal (cloud-free) weather conditions by a field crew using a well-calibrated field spectroradiometer. Furthermore, the atmospheric and meteorological conditions during the overpass have to be accurately characterized using sun photometer measurements (Langley method is used to determine AOT, Ångstrom coefficient and water vapor) and meteo station data. Using a radiative transfer model, the averaged surface reflectance spectra are converted to TOA radiances and convolved to PROBA-V spectral response functions to allow comparison to radiances measured by PROBA-V. The accuracy of the reflectance-based method is generally lower than for radiance based method due to uncertainties in the aerosol modelling. This method is cause problems for sensors with coarse ground resolution (300 m-1200 m) because of the time required to sample the calibration reference site. Because of the high costs of mobilization of field teams to perform reference reflectance measurements and the lower accuracies of the method, the reflectance-based method will only be applied to validate the operational calibration methods at an ad hoc basis through collaboration with other teams or by joining international calibration/validation exercises.

4.3.2.11.2   Data acquisition

▪ **Calibration areas**

Tuz Gölü, Turkey, one of the eight CEOS endorsed core instrumented IVOS Sites provisionally called LANDNET sites. Other CEOS sites may be used if data is made available

▪ **Mode**

Normal operational settings

▪ **Platform**

No platform manoeuvre. If due to logistic, operational or meteorological reasons the 17.5° roll manoeuvre could not be performed during APEX underflights (task C10), absolute calibration of the camera overlap area and inter-camera calibration can still be achieved by performing the roll manoeuvre over these calibration reference sites during these in-situ measurement campaign.

▪ **Frequency**

Once per year during July/August for Tuz Golü site. Ad hoc for other CEOS reference sites.

4.3.2.11.3   Output

▪ Independent validation of the absolute calibration coefficient for all bands for at least one of the cameras (if no manoeuvre)
▪ Absolute calibration of the camera overlap area and inter-camera calibration for all bands in case of manoeuvre
▪ Independent validation of the absolute calibration coefficient by other expert teams in case of joint international Cal/Val exercise
▪ Cross-calibration of the absolute calibration coefficient against other satellite sensors in case of joint international Cal/Val exercise

4.3.2.12 Task C12 Cross-sensor validation against SPOT-VGT

4.3.2.12.1   Description of the approach

In order to secure proper data continuity and consistency with VGT, cross sensor calibration is essential. The necessity of almost simultaneous observations (which will be not possible after the lifetime of SPOT-VGT) can be overcome by the use of stable sites. To avoid BRDF related differences only scenes acquired under the same viewing and illumination geometry are compared. This requires only a correction for differences in atmospheric conditions and spectral response (differences between VGT vs PROBA-V are minimal). On the other hand, a large reference database of VGT data is needed to find reference data taken under the same geometry. This database is under construction.

4.3.2.12.2   Data acquisition

See section 4.3.2.3.2

4.3.2.12.3   Output

- Quantification of difference in radiometric calibration of PROBA-V against SPOT-VGT for the four spectral bands
- Validation of the SPOT-VGT – PROBA-V cross-sensor calibration accuracy requirement

4.3.2.13 Task C13 Camera-to-camera offset monitoring

4.3.2.13.1 Description of the approach

To minimize inter-camera deviations a camera to camera calibration method is used based on the overlap area between two adjacent cameras in order to monitor possible offsets between cameras. This method allows also to transfer calibration coefficients from the centre camera to the outer cameras.

PROBA-V has 3 cameras in order to fit the swath requirement. The field of view (FOV) of each camera is 34.6 degrees. Since the outer cameras are pointed off-nadir for about 34.0 degrees, there is a zone of overlap. In the overlap zone, targets are simultaneous seen by 2 independent cameras. For these tie-points, (a) atmospheric conditions are the same, (b) solar zenith and azimuth are the same and (c) view zenith and view azimuth is the same. Given the identical viewing and illumination geometry, abstraction can be made with respect to target BRDF effects, atmospheric BRDF effects and atmospheric composition.

The camera to camera calibration method can deliver a continuous check with respect to the temporal evolution of the radiometric calibration coefficients.

4.3.2.13.2 Data acquisition

- **Calibration areas**

Overlap zones between two cameras

- **Mode**

Normal operational settings

- **Platform**

no platform manoeuvre

- **Frequency**

Acquired continuously during normal operations

4.3.2.13.3 Output

- Plots of differences in TOA radiances/reflectances for the overlap zones of the different cameras (camera 1 versus camera 2 , camera 2 versus camera 1)
- Validation of the relative camera-to-camera radiometric calibration accuracy requirement
- In case of lack of calibration observations for one of the cameras the continuous overlap regression results can be used to transfer absolute radiometric calibration results from one camera to an other

4.3.2.14 Task C14 High frequency multi-angular calibration

4.3.2.14.1   Description of the approach

Equalization or multi-angular calibration is required to correct for sensitivity variations at different points of PROBA-V wide field-of-view. The multi-angular calibration coefficient can be split into: (1) a low frequency term which refers to the variation of the optic transmission which slightly decreases with viewing angle; (2) a high frequency term which refers to variation of the sensitivity of the different pixels.

- **Antarctica (or Greenland)**

The high frequency term can be assessed during flight by a statistical approach using data from snowy areas in Greenland/Antarctica. A large number (> 600) uncompressed lines for each detector is needed. To achieve this, uncompressed images from Antarctica (Dome-C site) are taken for several orbits a day during local summer.
The method assumes that the high-frequency variations of the average of all the measurements characterize the sensitivity variations, while the low frequency is affected by the target and other effects.

- **Miscellaneous sites**

Another option to investigate high frequency variations over the FOV is using a very large number (at least 45000 lines for each detector) of uncompressed images of miscellaneous sites. Again, a frequency filtering technique can be used to isolate the high frequency term corresponding to the high frequency variation of the sensitivity differences between detectors. This method replaces the 'Antarctica/Greenland' equalization method during commissioning if this does not include the local summer of Antarctica (December-January) or Greenland (June-August) and for the equalization of the SWIR band.

4.3.2.14.2   Data acquisition

- **Antarctica (or Greenland)**

    - **Calibration areas**

Name	Min. lat	Max lat	Min. lon	Max lon
Greenl	70	77.5	-45	-35
Antarc	-77.34	-72.86	114.7	132.1

Table 10: Antarctica and Greenland calibration zones

    - **Mode**

Images should be taken without compression with low integration time settings for the VNIR and high integration time settings for the SWIR. For the SWIR this probably means an increased LSP. Due to the coupling of LSP (line sampling period), the LSP for the VNIR will also be increased although the lower IT. This will cause an under-sampling of the area. Another option is to split the acquisitions for VNIR and SWIR for which we can then better optimize IT/LSP. This has as drawback that the number of calibration acquisitions will be doubled. Both options will be evaluated during commissioning

- **Platform**

No platform manoeuvre

- **Frequency**

Commissioning/Operational phase : daily for at least 2 orbits during one week in Dec/Jan for Antarctica and June/July for Greenland

- **Miscellaneous sites**

  - **Calibration areas**

All cloud free sites

  - **Mode**

Images should be taken without compression (or lossless)

  - **Platform**

no platform manoeuvre

  - **Frequency**

Commissioning : Monthly at least 45000 lines for each pixel (can be done over different orbits) (only if no acquisition could be done over Antarctica or Greenland)
Operational phase : Every 6 months (April/October) at least 45000 lines for each pixel

4.3.2.14.3   Output

- Estimate of high frequency equalisation parameters
- Input to ICP file : equalisation parameters

4.3.2.15 Task C15 Low frequency multi-angular calibration

4.3.2.15.1   Description of the approach

Analysis of the estimated absolute calibration coefficients with the different methods (deep convective clouds, deserts, Rayleigh, sun glint) in function of VZA to study the low frequency multi-angular behaviour of the instrument.

4.3.2.15.2   Data acquisition

- Will make use of data and the results from Task 2, 3,4 and 5

4.3.2.15.3   Output

- In-flight validation of low frequency multi-angular calibration parameters
- Update of ICP file in case of large bias between pre-flight and in flight multi-angular

4.3.2.16 Task C16 Detection of defective or degraded pixels

4.3.2.16.1 Description of the approach

Bad pixels can either be dead pixels (exhibit no charge) or they can permanently deviate to such an extent that the above described calibration by equalization is no longer possible for these pixels. On the basis of statistical approaches, these bad pixels can be located and replaced through interpolation with neighbouring pixels.

4.3.2.16.2 Data acquisition

No data acquisition dedicated to this activity is foreseen. Instead, data acquired for desert calibration and dark current calibration will be used.

4.3.2.16.3 Output

- Input for bad pixel map (BPM ; see Annex 1)

4.3.2.17 Task C17 Non-linearity check

4.3.2.17.1   Description of the approach

Experimental in-flight linearity tests of the radiometric sensitivity will be performed by acquisition of images from large homogenous targets with different integration times (IT) in order to check if the linearity may have changed after launch. IT changes from 1,2 to 12 ms (VNIR) and 0,4 to 25,2 (SWIR) will be possible[1]. To have statistically relevant data the linearity checks will be performed on several large homogenous calibration segment (oligotrophic oceans (cfr Rayleigh calibration), deserts, Antarctica,..) which will cover a sufficient amount of pixels per IT (at least in the cross-track direction). 5 IT settings will be set over one zone, changing between ITs every second. These settings will be defined in the LCF file, which must be uploaded via IPC before the calibration starts (see Annex 1). Since the IT is defined for all bands of the VNIR detector together, it is possible that three different linearity check calibrations must be done, one for each band of the VNIR detector. Some time margin must be foreseen between checks to allow for the upload of new LCF files for the different bands. Using the creation date and version number of the LCF files, it can be tracked which LCF file and therefore which settings were used during a given linearity check calibration.

The ITs will be chosen to cover the dynamic range of the sensor for the band or bands that are calibrated over the zone. The required IT settings will be determined in function of the target signal level, but kept the same over different zones if possible.

4.3.2.17.2   Data acquisition

▪ **Calibration areas**

Large (at least 40 x 40 km)[2], homogenous areas with different albedo levels (deserts and selection from http://calval.cr.usgs.gov/sites_catalog_radiometry_maps.php)

▪ **Mode**

Fast integration time changes between min and max IT (to be defined in function of the target).

▪ **Platform**

no platform manoeuvre

▪ **Frequency**

Commissioning : Monthly for each band for +/- 5 targets
Operational phase : 6-monthly for each band and +/- 5 targets

4.3.2.17.3   Output

▪ Inflight validation of linearity of the instrument

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[1] This is currently under review in PV01. Ideally, the full dynamic range is covered with integration times within the default line sampling period of the detectors, ie. 12ms (15ms with 3ms buffer time) for the VNIR and 25ms (30ms with 5ms buffer time) for the SWIR.

[2] This time is coupled to the constraint of switching 5 integration times at a max frequency of 1Hz because of the OBSW commanding rate. Since the exact start of zone entry can't be known, the full time needed is that for 6 integration time switches, ie. 6s. At a ground scan velocity of 6,588km/s of the satellite, this corresponds to 40km.

4.3.2.18 Task C18 Image quality performance evaluation

4.3.2.18.1   Description of the approach

As there are no on-board light sources available on PROBA-V, an assessment of the instrument's image quality in flight will have to be done using ground targets. To determine instrumental noise effects on the measured signals, ground targets should be spectrally uniform over the measured range. As established elsewhere in this document, ground targets such as desert zones or snow zones are considered. To determine image contrast, done here by measuring instrument system MTF, ground targets should have regions of high contrast

4.3.2.18.2   Data acquisition

Dedicated data acquisition for noise effects will not be foreseen. Instead, data acquired from desert and Antarctica campaigns will be used.
Agricultural sites will be manually planned and selected for the MTF assessment.

4.3.2.18.3   Output

- Evolution of noise, MTF and SNR for the different spectral bands

4.3.3 Planning calibration acquisition commissioning phase

Unexpected findings during the commissioning phase may result in a modification of the calibration plan (e.g. calibration frequencies)
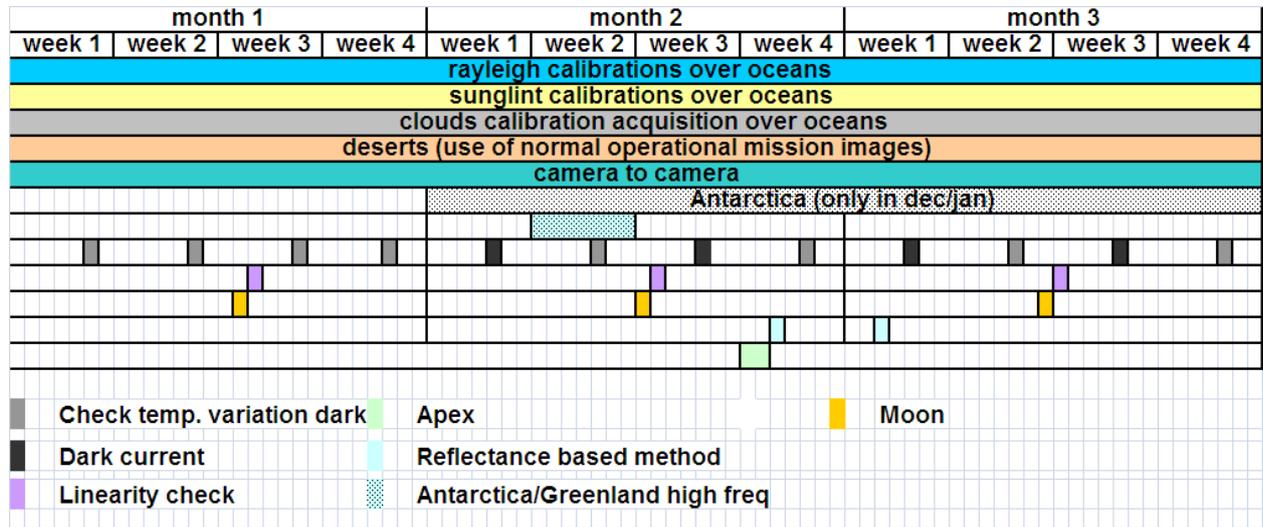
Figure 5 : Commissioning plan for radiometric calibration

Daily Acquisitions
- Rayleigh Oceans acquisition over defined oceanic sites
- Clouds acquisition over defined oceanic sites
- Sun glint acquisition over a number of oceanic sites (depending on sun glint probability)
- Deserts by use of normal operational mission images
- Camera to camera bias adjustment by use of normal operational mission images

If the months December/January are included in the commissioning phase :
- Antarctica acquisition in uncompressed mode for at least 2 orbits during one week in December/ January
- Antarctica: acquisition in binned/compressed mode (at least) 3 to 4 times a day during December/January

If the months June/July are part of the commissioning phase:
- Greenland acquisition in uncompressed mode for at least 2 orbits during one week in June./July

Weekly Acquisitions
- Dark current (oceans night) acquisition of at least 500 lines during night for each of the integration times over 1 site. At new moon these data should be acquired during the same night. To check the temperature variation of the dark current values images will be acquired during night for a number of oceanic sites along the orbit during the first month.

Two-weekly Acquisitions
- To check the temperature variation of the dark current values images will be acquired during night for a number of oceanic sites along the orbit after the first month.

Monthly Acquisitions
- Linearity Check for each band for 5 targets
- At least 45000 lines for each pixel of miscellaneous sites
- Moon observations at a phase angle of 7°. As many observations as feasible, to establish a baseline for on-orbit stability

Once
- At least two Apex Underflights, once at -17.5° and once at 17.5°

Ad-hoc
- Reflectance based method by use of normal operational mission images

4.3.4 Planning calibration acquisition operational phase

A preliminary vicarious calibration plan for the operational phase is given in Figure 6.
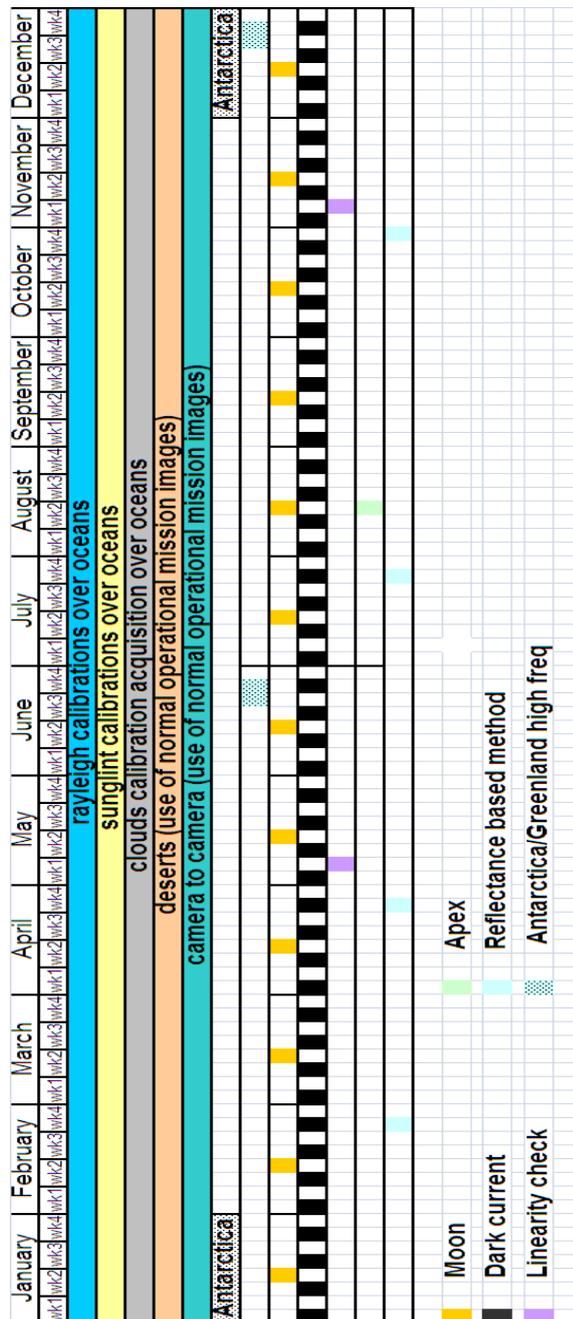
Figure 6: Calibration plan for operational phase

<u>Daily Calibration Acquisitions</u>

- Rayleigh Oceans acquisition over defined oceanic sites
- Clouds acquisition over defined oceanic sites
- Sun glint acquisition over a number of oceanic sites

- Deserts by use of normal operational mission images
- Camera to camera bias adjustment by use of normal operational mission images

December/January
- Antarctica: acquisition in compressed mode (at least) 3 to 4 times a day; during one week daily for 2 orbits acquisition in uncompressed mode

June/July
- Greenland : during one week daily acquisitions in uncompressed mode

Weekly Calibration Acquisitions
- Dark current (oceans night) acquisition of at least 500 lines during night for each of the integration times over 1 site. At new moon these data should be acquired during the same night

Monthly Calibration Acquisitions
- Moon observations at a phase angle of 7°, preferable for all cameras

6-Monthly Calibration Acquisitions
- Linearity Check for each band for 5 targets
- At least 45000 lines for each pixel of miscellaneous sites (April/October)

Yearly Calibration Acquisitions
- Apex Underflights

Ad hoc
- Reflectance based method by use of normal operational mission images

4.3.5 Summary

Table 11 gives an overview of the different radiometric calibration methods. It contains all information with respect to the required instrument settings, requested platform manoeuvres and the time interval/frequency during both commissioning and operational phase.

CALIBRATION METHOD	DAY/NIGHT	POINTING ACCURACY	ACQUISITION SETTINGS	BANDS	MANEUVERS	REMARKS	INTERVAL (TBC)
Dark Current (oceans night)	Night	relaxation of pointing accuracy allowed RELEVANCE: power and memory budget	- No compression (or lossless) - Long integration time and line sampling RELEVANCE: change CR setting, line sampling setting and integration time setting in calibration mode over non-imaging region => increase of data over the ROI => no risk of losing nominal data	BLUE, RED, NIR, SWIR	no platform maneuver	best moment new moon	Operational phase : At least 7,5 seconds of lines (corresponding to 500 lines for a frame time of 15ms) should be obtained weekly during night over 1 site. At new moon these data should be acquired if possible during same night. Commissioning: Similar to operational phase + To check the temperature variation of the dark current values images will be acquired during night for a number of oceanic sites along the orbit. This should be done weekly during the first month, two-weekly during the next months.
camera to camera bias adjustment	Day	no relaxation allowed	Normal operational settings	BLUE, RED, NIR, SWIR	no platform maneuver	no special programming	continuous (no special programming)
Linearity Check Sensor	Day	no relaxation allowed	• IT adjustment (in steps) • No compression RELEVANCE: Calibration mode to implement IT looping of 5 different ITs, over a non-masked region => Unavoidable loss of nominal data until looping is finished and switch back to calibration mode	BLUE, RED, NIR, SWIR (separately) RELEVANCE: Buffer of 5s to image all bands simultaneously can be relaxed as will be handled in the IPC (each band is imaged separately, SWIR strips are imaged together).	no platform maneuver		Commissioning: Monthly for each band for 5 targets Operational phase : 6-Monthly for each band and 5 targets RELEVANCE: Low frequency of acquisition => Loss of nominal data limited to about 8 times/year (2 times for each band) during operational phase
Rayleigh Oceans	Day	sub-degree accuracy needed	IT adjustment RELEVANCE: Calibration mode to implement IT and/or gain change over a masked region => IPC will try to ensure no coverage is crossed during calibration or mode switch (5s + band buffer before and after in baseline) to avoid loss of nominal data. This check can be overided during calibration commissioning.	BLUE, RED, NIR RELEVANCE: Buffer of 5s to image all bands can be relaxed as will be handled in the IPC (only VNIR bands are imaged).	no platform maneuver		Commissioning/Operational phase : Daily acquisitions overdefined oceanic sites.

CALIBRATION METHOD	DAY/NIGHT	POINTING ACCURACY	ACQUISITION SETTINGS	BANDS	MANEUVERS	REMARKS	INTERVAL (TBC)
APEX Underflight (roll maneuver Proba-V)	Day	no relaxation allowed	Normal operational settings	BLUE, RED, NIR, SWIR	nadir looking geometry for 3 cameras => roll maneuver of 17.5° (can be performed without blindness of startrackers)=> 2 cameras nadir at same time. **RELEVANCE:** Calibration mode to implement maneuver over a non-masked region => Unavoidable loss of nominal data. 170 seconds (160 because of maneuver before and after are lost 5 to mode switching, 5 to image all bands).	If due to logistic, operational or meteorological reasons the 17.5° roll manoeuvre could not be performed during APEX underflights, absolute calibration of the camera overlap area and inter-camera calibration can still be achieved by performing the roll manoeuvre over these calibration reference sites during these in-situ measurement campaign.	**Commissioning:** at least twice, once -17.5° and once 17.5° ; **Operational phase :** Yearly **RELEVANCE:** Low frequency of acquisition => Loss of land data limited to about 1 time/year during operational phase
Reflectance based method	Day		Normal operational settings	BLUE, RED, NIR, SWIR	no platform maneuer	no special programming	ad hoc
Clouds (Oceans)	Day	relaxation of pointing accuracy allowed **RELEVANCE:** calibration mode buffer for geometric accuracy of ROI (1s in baseline) can be relaxed	IT adjustment **RELEVANCE:** Calibration mode to implement IT and/or gain change over a masked region => IPC will try to ensure no coverage is crossed during calibration or mode switch to avoid loss of nominal data. This check can be overrided during calibration commissioning.	BLUE, RED, NIR **RELEVANCE:** Buffer of 5s to image all bands can be relaxed as will be handled in the IPC (only VNIR bands are imaged).	no platform maneuer		**Commissioning / Operational phase :** Daily acquisitions over at least 1, preferably all, of defined oceanic sites.
Sun glint (Oceans)	Day	relaxation of pointing accuracy allowed **RELEVANCE:** calibration mode buffer for geometric accuracy of ROI (1s in baseline) can be relaxed	IT adjustment **RELEVANCE:** Calibration mode to implement IT and/or gain change over a masked region => IPC will try to ensure no coverage is crossed during calibration or mode switch to avoid loss of nominal data. This check can be overrided during calibration commissioning.	BLUE, RED, NIR, SWIR	No platform maneuer		**Commissioning/operational phase :** - Daily acquisition over defined oceanic sites
Antarctica/Greenland	Day	relaxation of pointing accuracy allowed **RELEVANCE:** calibration mode buffer for geometric accuracy of ROI (1s in baseline) can be relaxed	• IT and/or gain adjustment • No compression **RELEVANCE:** Calibration mode to implement IT and/or gain change over a masked region => IPC will try to ensure no coverage is crossed during calibration or mode switch to avoid loss of nominal data. This check can be overrided during calibration commissioning.	BLUE, RED, NIR, SWIR	No platform maneuer	Aim: pixel to pixel correction (equalization, using high frequency filtering)	**Commissioning/Operational phase :** daily for at least 2 orbits during one week (TBC) in December/January for Antarctica and June/July for Greenland **RELEVANCE:** Calibration mode over Antarctica a possible risk for sunbathing and thus power budget.

CALIBRATION METHOD	DAY/NIGHT	POINTING ACCURACY	ACQUISITION SETTINGS	BANDS	MANEUVERS	REMARKS	INTERVAL (TBC)
Antarctica	Day	relaxation of pointing accuracy allowed **RELEVANCE:** calibration mode buffer for geometric accuracy of ROI (1s in baseline) can be relaxed	• IT and/or gain adjustment **RELEVANCE:** Calibration mode to implement IT and/or gain change over a masked region => IPC will try to ensure no coverage is crossed during calibration or mode switch to avoid loss of nominal data. This check can be overrided during calibration commissioning.	BLUE, RED, NIR, SWIR	No platform maneuer	Aim: cross-satellite and multi-temporal calibration	**Commissioning/ Operational phase:** data should be acquired at least 3 to 4 times a day during December and January **RELEVANCE:** Calibration mode over Antarctica a possible risk for sunbathing and thus power budget.
Miscellaneous Sites	Day	relaxation of pointing accuracy allowed **RELEVANCE:** calibration mode buffer for geometric accuracy of ROI (1s in baseline) can be relaxed	• No compression (or lossless) **RELEVANCE:** change CR setting in calibration mode over non-masked region => increase of data over the ROI, unavoidable loss of nominal data.	BLUE, RED, NIR, SWIR	no platform maneuer		**Commissioning :** Monthly at least 45000 lines for each pixel (can be over different orbits) **Operational phase:** Every 6 months (April/October) at least 45000 lines for each pixel (TBC) **RELEVANCE:** Low frequency of acquisition => Loss of nominal data limited to about 2 times/year during operational phase.
Deserts	Day	relaxation of pointing accuracy allowed	Normal operational settings	BLUE, RED, NIR, SWIR	no platform maneuer	no special programming	continuous (no special programming)
Moon (TBC)	Night **RELEVANCE:** power and memory budget	relaxation of pointing accuracy allowed **RELEVANCE:** calibration mode buffer for geometric accuracy of ROI (1s in baseline) can be relaxed	Normal operational settings	BLUE, RED, NIR, SWIR	Moon maneuver with constant scan rate (0.2°/s, TBC) **RELEVANCE:** Calibration mode to implement maneuver over a non-imaging region (TBC)	Lunar calibration requires a special platform manoeuvre during night to point the 3 different cameras at the moon.	**Commissioning:** monthly observations at a phase angle of 7°. It is recommended that during commissioning phase as many Moon observations as feasible are made, to establish a baseline for on-orbit stability **Operational phase :** monthly at a phase angle of 7°, preferably more than one observation

Note : Following acquisition settings should be independently changeable for calibration :
Integration time*, Gain, Compression (on or lossless)   (* in steps)

Note : Calibration with IT different from operational IT, which are possible to do over masked regions, will not be performed for the orbits for which nominal data is in the swath in order not to impact the normal operations .

Assumptions:
Calibration mode implies that 5 seconds of imaging are lost before and after passing ROIs because of adjustments on-board (mode switching)
Calibration mode implies that max 5 more seconds of imaging in nominal mode are lost before and after passing ROIs because of the gap between bands (value can be reduced in IPC).
Calibration mode implies that max 1 more second of imaging in nominal mode are lost before and after passing ROIs because of a margin to account for ROI geolocation error.

Table 11 : summary table radiometric calibration

4.4 Radiometric quality budget

4.4.1.1 Requirements

With respect to the radiometric image quality the following accuracy requirements have been specified ([PVDOC-618 IQC Software Requirements Specifications Document)]:

- *Multi-temporal calibration accuracy* (IQC_SRS_PERF_001): The IQC shall perform 3% radiometric accuracy after 6 months for multi-temporal calibration over high reflectance, spatially uniform scenes - under the condition that the instrument performance requirements are met with respect to the spectral mis-registration requirement, the stability of the instrument (VI-PER-240), polarization (VI-PER-270), linearity (VI-PER-260) and straylight (VI-PER-280, VI-PER-290, VI-PER-300, VI-PER-310)

- *Inter-band calibration accuracy* (IQC_SRS_PERF_002): The IQC shall perform 3% radiometric accuracy after 6 months for an interband calibration over high reflectance, spatially uniform scenes - under the condition that the instrument performance requirements are met with respect to the spectral mis-registration requirement, the stability of the instrument (VI-PER-240), polarization (VI-PER-270), linearity (VI-PER-260) and stray light (VI-PER-280, VI-PER-290, VI-PER-300, VI-PER-310).

- *Absolute radiometric calibration* (IQC_SRS_PERF_003): The in-flight radiometric calibration approach shall be able to provide after 6 months in orbit an absolute radiometric calibration accuracy within 5% over high reflectance, spatially uniform scenes.

4.4.1.2   Approaches

The multi-temporal calibration coefficient, which tracks the instrument degradation at time t by reference to an initial time t0, is defined as:

$$A_{t,t0}^{k} = A_{t}^{k} \Big/ A_{t0}^{k}$$

The multi-temporal calibration accuracy is the accuracy of the estimate for $A_{t,t0}^{k}$. Multi-temporal calibration accuracy will be assessed by using images over stable desert sites, the moon and Antarctica.

Calibration over stable deserts has the advantage that the daily acquisitions throughout the year are possible without impact on the routine mission. However both CNES and Govaerts and Clerici 2004 reported a seasonal trend in desert calibration data. To correct for these seasonal effects more than 1 year of data is required, meaning that with the deserts approach multi-temporal calibration accuracy can only be accurately assessed after one year of data acquisition.

The main advantage of lunar multi-temporal calibration is that calibration results can obtained immediately while for the desert calibration data over at least one year are needed to correct for seasonal variations. However the moon calibration requires a platform manoeuvre during the night to point the sensor to the moon. The feasibility of the moon calibration depends on the results of the ongoing analysis by VES and OIP with respect to the stability of the detectors and thermo-elastic stability of the payload both during and after the moon manoeuvre.

The Dome C area in Antarctica is also suited for multi-temporal calibration as it is extremely homogenous and flat with only very small inter-annual variations. Unfortunately acquisitions are limited to the summer months (November till February). Therefore Antarctica is mainly suitable to assess long term stability trends.

The inter-band calibration is defined by reference to band k_0 as:

$$A^{k,k0} = {A^k}\Big/{A^{k0}}$$

The interband calibration accuracy is the accuracy of the estimate for $A^{k,k0}$. Interband calibration accuracy will be assessed by using images over sun glint spots and deep convective clouds.

Deep convective clouds allow to assess the interband calibration accuracy of BLUE and NIR band with respect to the RED band. It can however not be used for the SWIR band.

The sun glint calibration approach is, on the other hand, also suitable for the SWIR band. However, due to the chosen local time (around 10h30) of the descending node in the sun-synchronous orbit of PROBA-V, sun glint can't be observed by the western looking camera. Furthermore the difference in viewing angles between the spectral bands increases the uncertainty in the sun glint calibration method (for detailed analysis see[PVDOC-611],Technical Note on Sun Glint)

The absolute radiometric calibration accuracy is the accuracy of the estimate for A^k. The operational methods in use are calibration over Rayleigh, stable deserts, sun glint and clouds:

⇨ Rayleigh: estimate A^k for BLUE, RED, needs A^{NIR} as input
⇨ Sun Glint: estimate A^k for BLUE, NIR and SWIR, needs A^{RED} as input
⇨ Clouds   estimate A^k for BLUE and NIR, needs A^{RED} as input
⇨ Deserts: estimate A^k for all bands: BLUE, RED, NIR and SWIR

Furthermore ground-based measurements and APEX underflights will be performed at an ad hoc basis to validate the radiometric calibration coefficients by independent means.

The methods selected per spectral band and per calibration type are listed in Table 12.

Absolute Calibration	BLUE	RED	NIR	SWIR
Operational				
Rayleigh	x	x	Ref.	-
Sun glint (through inter-band)	x	Ref.	x	x
Clouds (through inter-band)	x	Ref.	x	-
Deserts	x	x	x	x
APEX(*)	x	x	x	x
Reflectance based method (*)	x	x	x	x
Interband Calibration	BLUE	RED	NIR	SWIR
Sun Glint	x	Ref.	x	x
Clouds	x	Ref.	x	-
Multi-temporal Calibration	BLUE	RED	NIR	SWIR
Deserts	x	x	x	x
Antarctica	x	x	x	x
Moon	x	x	x	x

(*): ad hoc approaches

Table 12: Overview of calibration approaches/types

The algorithms for all these vicarious calibration methods are described in detail in [PVDOC-621], IQC Algorithm Theoretical Baseline Document.

4.4.1.3   Error budgets

A distinction is made between pre and post launch 'image quality budgets'.

4.4.1.3.1 Error budget estimates before launch

In Table 13 the expected achievable radiometric calibration accuracy (based on the pre launch knowledge) for the different methods is listed.

	BLUE	RED	NIR	SWIR
Absolute calibration				
Rayleigh	< 4%	< 5 %	ref	N/A
Sun glint	< 3%	ref	< 4%	6-7 %
Clouds	<< 4%	ref	< 4 %	N/A
Deserts	5-6 %	5-6 %	5-6 %	5-6 %
Inter-band calibration				
Sun glint	< 2 %	ref	< 2 %	5-6 %
Clouds	<< 2%	ref	< 2%	N/A
Multi-temporal calibration				
Deserts (> 1 year data required)	1-2 %	1-2 %	1- 2 %	
Antarctica (for long term stability checks only)	2%	2%	2%	2%
Moon	1%	1%	1%	1%

Table 13: Achievable radiometric accuracies.

This table is compiled on the basis of following analyses :

4.4.1.3.1.1 Sensitivity analysis

For the different radiometric calibration methods described and prototyped, the theoretical error budget is first determined following this approach: the prototypes are run taking into account the uncertainty of the different input parameters (e.g. aerosol model). The output of the prototypes is analysed statistically to determine the error budget associated with this uncertain input parameter.

This approach has been followed for the already available prototypes (Rayleigh, Deep convective clouds (DCC), sun glint). Details of the approach and results can be found in [PVDOC-611]. In table Table 14, Table 15 and Table 16. Error analysis results are given for respectively Rayleigh, Sun Glint and DCC. Due to the large separation on the image plane between the VNIR array and the central SWIR array the expected uncertainty for sun glint calibration approach for PROBA-V SWIR bands is higher than for other missions. This has been analyzed in depth in the technical note on sun glint ([PVDOC-611]). .

Error Sources	2-sigma error (%)	
	BLUE	RED
Pressure	0.693	0.425
Wind speed	2.501	3.335
NIR calibration	0.720	2.065
Aerosol model	1.331	2.580
Ozone	0.036	0.333
Water vapour	0.157	0.181
Chlorophyll	1.261	0.388
Total absolute	**3.262**	**4.745**

Table 14: Summary of Rayleigh absolute calibration error budget.

Error Sources	2-sigma error (%)		
	BLUE	NIR	SWIR
calibration error 3% in RED band	1.7	3.2	3.3
Water reflectance	2	0.1	0.1
uncertainty sea water refraction index	0.3	0.6	2
ozone (5%)	0.3	0.5	0.3
water vapor (20 %)	0.1	0.8	0.1
Aerosols	1.5	1	2
5% relative uncertainty Cox-Munk	0	0	5
Total	**3.1**	**3.5**	**6.6**

Table 15: Summary of sun glint absolute calibration error budget.

Error sources	2-sigma error (%)	
	BLUE	NIR
Cloud effective radius (10 µm)	0.761	1.363
Microphysical model	0.499	1.210
Cloud top height	0.172	0.024
Cloud geometrical depth	0.046	0.005
Ozone (20%)	0.399	0.460
Atmospheric profile	0.006	0.003
Red calibration error (3%)	*2.945*	*3.061*
Total interband	**1.009**	**1.880**
Total absolute	*3.113*	*3.592*

Table 16: Summary of DCC absolute/interband calibration error budget.

4.4.1.3.1.2   Literature reported accuracies

Literature has been reviewed for accuracy estimates obtained for other missions using the same or similar vicarious calibration approaches. An overview table of reported accuracies is given in Table 17.

TYPE	METHOD	BLUE	RED	NIR	SWIR	Referentie
ABSOLUTE						
	Rayleigh calibration	3-4%	-	ref	-	Hagolle et al (1999) (Polder)(LIT6)
		3.50%	3.50%	ref	-	Vermote and kaufmann (1995) (AVHRR)(LIT13)
		3.00%	2.00%	ref	-	Henry P (2008)(LIT14)
		-	4%	9.10%	30%	Govaerts,2001 (SEVIRI)(LIT15)
	Sun glint	4%	ref	3.50%	-	Hagolle et al (1999)(Polder) (LIT6)
		5%	ref	5%	-	Hagolle and Cabot (MERIS)(LIT16)
		3.50%	ref	3.90%	4.70%	Hagolle et al,2004(VGT) (LIT5)
	Clouds	-	5.70%	4.40%	-	Govaerts, 2001 (SEVIRI)(LIT15)
	Deserts	-	5.80%	6.20%	6.20%	Govaerts, 2001 (SEVIRI)(LIT15)
	Reflectance based method	3.36%	3.36%	3.36%	3.36%	Kneubuhler et al,2003(LIT17)
		2-4%				Lyapustin et al,2007 (MISR)(LIT18)
		3%+1%	3%+1%	4%+1%	-	Bruegge et al ,2007 (LIT19)
		3.3-4.9%	3.3-4.9%	3.3-4.9%	3.3-4.9%	Dinguirard and Slater(1999) (LIT20)
	Underflights	1.8-2.8%	1.8-2.8%	1.8-2.8%	1.8-2.8%	Nieke,J (2001, APEX report)(LIT8)
INTERBAND						
	Sunglint	1-2%	ref	1-2%	2%	Henry P (2008)(LIT14)
		3.30%	ref	3.30%	-	Vermote and kaufmann (1995)(LIT13)
	Sunglint (iterated with rayleigh)	1%	ref	1%	-	Delwart et al (MERIS)(LIT21)
	Clouds	-	ref	2%	-	Vermote and Kaufmann(1995)(LIT13)
	Clouds	1-2%	ref	1-2%	-	Henry P (2008)(LIT14)
	Clouds	3%	-	-	-	Lafrance et al (2002) (polder) (LIT22)
MULTI-TEMPORAL						
	Deserts	1-2%	1-2%	1-2%	-	Henry P (2008)(LIT14)
	Deserts	3.40%	-	1.83%	-	estimates for polder
	Antarctica	1%				Henry P (2008)(LIT14)
	Moon	1-3%				Stone, Kieffer(2007)(LIT23)
MULTI-ANGULAR						
low freq	Deserts	2.30%	-	0.80%	-	Hagolle et al (1999) (Polder)(LIT6)
High freq	Antarctica	0.10%	0.10%	0.10%	0.15-0.2%	Fougnie et al (2000) (VGT)
CROSS-SENSOR						
	Deserts	2-3%	2-3%	2-3%	-	Henry P (2008)(LIT14)
	Antarctica	1-2%	1-2%	1-2%	1-2%	Henry P (2008)(LIT14)

-: no information available or method not applicable or spectral band not available

Table 17. Achievable accuracies according to literature

4.4.1.3.1.3   Prototype validation results on SPOT VGT1/VGT2

The Rayleigh, Sun glint and Deep Convective Clouds (DCC) algorithmic prototypes have been applied to a series of SPOT-VGT1/VGT2 images (see [PVDOC-647]). An uncertainty analysis has been performed on the obtained results. These are listed in the following tables.

	VGT1			VGT2	
	BLUE	**RED**		**BLUE**	**RED**
$\varepsilon(\Lambda A)$ **(%)** (interband)	**2.515**	**0.277**		**2.144**	**0.0492**
$\varepsilon'(\Lambda A)$ **(%)** (absolute)	**2.597**	**1.963**		**2.240**	**1.944**

Table 18. Accuracy estimates (2-sigma) of the Rayleigh calibration results

	VGT 1				VGT 2		
	BLUE	**NIR**	**SWIR**		**BLUE**	**NIR**	**SWIR**
$\varepsilon(\Lambda A)$ **(%)** interband	2.299	1.548	1.754		1.440	2.361	5.300
$\varepsilon'(\Lambda A)$ **(%)** absolute	2.859	3.645	3.737		2.228	4.058	6.268

Table 19. Accuracy estimates (2-sigma) of the Sun Glint calibration results

	VGT2	
	BLUE	**NIR**
$\varepsilon(\Lambda A)$ **(%)** interband	0.290	0.459
$\varepsilon'(\Lambda A)$ **(%)** absolute	3.322	3.908

Table 20. Accuracy estimates (2-sigma) of the deep convective clouds calibration results

4.4.1.3.2 Error budget estimates after launch

The statistical approach used to determine the absolute calibration coefficient A^k to be used by the processing facility is illustrated in Figure 3 and details are given in [PVDOC-621], IQC Algorithm Theoretical Baseline Document.

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 weighted averaged. The accuracy of the 'final' estimate of A^k is determined 'statistically' taking into account the individual uncertainty, image noise, in-between method bias,.... This is described in detail in [PVDOC-621], IQC Algorithm Theoretical Baseline Document.

4.4.1.3.3 Instrumental effects

Error estimates in previous graphs are given under the assumption that the instrument performance is within the requirements for polarization sensitivity, spectral mis-registration , stray light etc. Not achieving these requirements can lead to a decreased radiometric calibration accuracy.

In [PVDOC-655]the effect of stray light on calibration accuracy is analyzed .Table 21 is taken from this TN and gives the extra uncertainty to be added to the Rayleigh error budget in function of the stray light contribution.

Case Approach 2	Add TOA reflectance	Error (2sigma,%) in Rayleigh cal result BLUE	Error (2sigma, %) in Rayleigh cal result RED
Case 1bis	+ 0.001 (0.1% Clouds)	0.989134	2.000329
Case 2bis	+ 0.002 (0.2 % Clouds)	1.999969	3.832266
Case 3bis	+ 0.003 (0.3% Clouds)	2.781382	5.009739
Case 4bis	+ 0.004 (0.4 % Clouds)	3.366538	6.267664
Case 5bis	+ 0.005 (0.5 % Clouds)	3.875302	7.177472

Table 21. Effect of stray light on Rayleigh calibration uncertainty: extra error introduced by stray light

The effect of instrument polarization sensitivity on TOA radiance uncertainty in general have been analyzed. With respect to inflight calibration methods, instrument Polarization sensitivity will mainly influence the Rayleigh and Sun glint Calibration. For sun glint it is the polarization difference between bands which will cause uncertainties in the calibration results. For Rayleigh calibration the absolute value of the polarization sensitivity is more important than the difference between band. The blue band is most sensitive to the polarization due to the fact that the Rayleigh scattering, which is highly polarized, is high in blue band.

Effect of instrument polarization on Rayleigh and Sun glint calibration is analyzed using the most recent available polarization data for PROBA-V (Table 22). Assuming a 70% polarization radiance signal, the maximum error in Rayleigh and Sun glint calibration caused by instrument polarization sensitivity is given in respectively Table 23 and Table 24.

		blue	red	nir	swir
DoP	0 mm	3.69%	0.24%	0.44%	0.35%
DoP	12 mm	2.88%	0.38%	0.47%	0.37%
DoP	26 mm	0.47%	0.91%	0.48%	0.43%
DoP	edge	2.79%	1.31%	0.37%	0.60%

Table 22. PROBA-V Polarisation sensitivity

	blue	red
0 mm	2.58%	0.17%
12 mm	2.02%	0.27%
26 mm	0.33%	0.64%
edge	1.95%	0.92%

Table 23. Effect of instrument polarisation on Rayleigh calibration uncertainty: extra error introduced by instrument polarisation sensitivity

	blue	NIR	SWIR
0 mm	2.75%	0.48%	0.41%
12 mm	2.28%	0.60%	0.53%
26 mm	0.97%	0.97%	0.94%
edge	2.87%	1.18%	1.34%

Table 24. Effect of instrument polarisation on Sun glint calibration uncertainty: extra error introduced by instrument polarisation sensitivity

The effect of spectral mis-registration on TOA radiance spectra has been analyzed in a study for the PI. Figure 7 gives the effect of a 5 nm shift of the SWIR band to shorter and longer wavelengths.
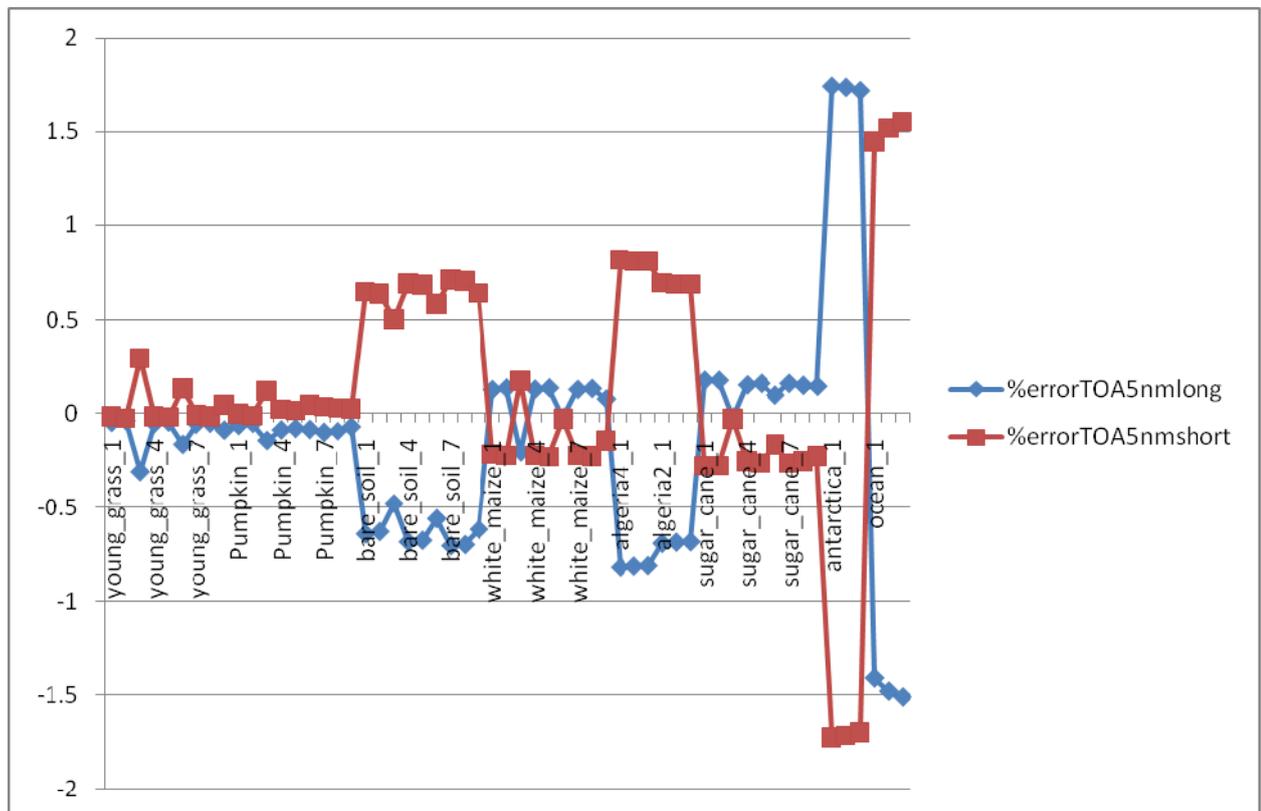
Figure 7. Effect of 5 nm spectral mis-registration of SWIR band on measured TOA radiances

5.   GEOMETRIC CALIBRATION AND VALIDATION PLAN

The geometric calibration and validation plan is described in [PVDOC-161].

6.   CALIBRATION INTERACTION DURING COMISSIONING

The first geometric ICP file based on vicarious calibration will be available after roughly one month of geometric calibration acquisitions. Due to the very short period of the commissioning phase , which will last only 3 months, the vicarious radiometric calibration acquisition, processing and analysis has to start before the availability of the in-flight geometric ICP file. Processing of these first vicarious radiometric calibration acquisitions will be performed with the pre-flight geometric ICP file. As the operational vicarious calibration radiometric calibration approached are based on large homogenous targets and not on combination of very localized pixels and field data, it is thought that this will have a minor effect on the radiometric vicarious calibration results. Nevertheless, when the first in-flight geometric ICP file will be available, a reprocessing will be performed on a selected set of the vicarious radiometric image data to analyze the effect of the new geometric ICP file on the radiometric results. If the effect is non-negligible, all previously required radiometric scenes will be reprocessed.

ANNEX 1: DEFINING CALIBRATION SETTINGS FILES

Introduction

The Image Quality Center is responsible for the definition of certain instrument settings established for or by radiometric calibration activities. These instrument settings are uploaded via the Instrument Programming Center to the satellite by way of three dedicated files:

- Integration Time Matrix (ITM) file
- Bad Pixel Map (BPM) file
- Linearity Check File (LCF) file

The upload of these files is done as a nominal request to the MCC [PVDOC-656]. Since it is not always the case that these requests are accepted, it's important to track the versioning of these files. For this reason, the creation date of the files is stored as part of the file name, and a version number both in the file name and in the file format is used to keep track of the file for later reference.

The file format of the three files is described in the US Ground to Ground ICD[PVDOC-401]. To create these files in compliance with the format, formatting tools have been developed. These will be discussed below.

Integration time matrix (ITM) Tool

As described in the ICD, the purpose of the ITM file is to have a list of solar zenith angles for every one of 256 integration time settings possible for the VNIR detector and for the SWIR detector. This list is used to determine, based on the currently determined solar zenith angle for the satellite, which integration time setting must become the active one in nominal operations.

The ITM tool therefore requires 2 lists of 256 values, one for each detector. If the list is not of the required length, the program will fail with the error "ITM list for **Detector** incomplete", where **Detector** can be either VNIR or SWIR.

The ITM tool also requires a version number. If the required information is provided, an ITM file will be created according to the format and with the filename: "ITM_**dd_mm_yyyy**_v**C**.txt". Here:

- **dd_mm_yyyy** determines the creation date : 02_03_2012 means March 2, 2012.
- **C**: determines the version number, which is a number between 0 and 255.

An initial set of values for the ITM file will be determined based on input by PV01 and the PI. An update of the ITM file, if necessary, can be done if requested by the PI.

Bad Pixel Map (BPM) Tool

Bad Pixel Map data is used in the on-board software to replace bad pixel data prior to compression. This can have a beneficial effect on the compression result. A bad pixel map must be given per detector, since bad pixels can be different for each physical array. Each map contains a 0 or 1 value for each of the pixels of the given array. The complete instrument is covered by 18 maps, all of which are described in a BPM file.

The BPM tool therefore requires 18 lists of values, with each list having an amount of values equal to the number of pixels for the physical array (in the BPM format it is required to specify the number of pixels for each physical array). A set of 18 different tags is defined to identify each different array. If a list for one of the arrays is not of the required length, the program will

fail with the error "BPM list for **Tag** incomplete", where **Tag** is one of the 18 tags for the array.

With respect to versioning and file naming, the BPM tool uses the same approach as the ITM tool.

An initial set of values for the BPM file will be determined based on input by PV01. An update of the BPM file will be issued when new bad pixels are detected as a result of calibration (see section 4.3.2.16).

Linearity Check File (LCF) Tool

The LCF file defines the integration time settings to be used during the Linearity Check calibration. A sequence of 5 integration time settings is required per detector. Switching between integration times of the sequence is done every second, and every 5 seconds the sequence is repeated until the end of the calibration. In addition, the gain settings of the different bands can be adjusted for the duration of the entire calibration, if required.

The LCF tool requires 2 lists of 5 integration time code values, one list for the VNIR detector and one for the SWIR detector. In addition, 2 list of gain setting values are required, a list of 3 values for the VNIR detector and a list of 1 value for the SWIR detector. If an integration time list is not of the required length, the program will fail with the error "LCF IT list for **Detector** incomplete", where **Detector** can be either VNIR or SWIR. If a gain list is not of the required length, the program will fail with the error "LCF gain list for **Detector** incomplete" in the same manner.

Also, if an integration time code is not in the range [0-255], the program will fail with the error "Bad IT code, code must be within [0-255]."

With respect to versioning and file naming, the LCF tool uses the same approach as the ITM tool.

An initial set of values for the LCF file will be determined based on input by PV01 and the PI. An update of the LCF file will be issued if needed for calibrations (see 4.3.2.17).