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Scientific quality requirements document for the TROPOMI L01b data processor

Tropospheric Monitoring Instrument

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Document change record

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1.0.0	2012-06-19	-	Release
2.0.0	2012-11-26	-	Previous release
2.0.1	2013-03-27	-	Add text about requirement analysis and corresponding tables.
2.0.2	2013-04-02	-	Performance tables for the radiometric accuracy updated, tables for other performance parameters added.
2.0.3	2013-04-15	-	Review performance tables, add text explaining how the CKD values were chosen, add table for the SWIR, add summary tables for CKD/L01b errors..
2.0.4	2013-04-15	-	Add reflectance accuracy table.
2.0.5	2013-04-17	-	Small edits for consistency, slightly modified accuracies stemming for clarification of background and dark current errors.
2.0.6	2013-05-29	-	Small language edits, adjust tables, add a note to the scenarios to indicate that the dark current correction includes also offset and background.
2.1.0	2013-05-29	-	Prepared for review.
3.0.0	2013-06-26	-	Edited as per S5P-KNMI-L01B-1008-LI-RLF Issue B.4.

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1 Introduction

1.1 Identification

This document, identified as **S5P-KNMI-L01B-0008-RS**, **CI-6470-ScQRD**, contains the Scientific Quality Requirements Document (SCQRD) for the Level 0 to 1b Data Processor of the TROPOMI instrument. This requirements document is a constituent of the KNMI TROPOMI L01b technical baseline file (TBF).

1.2 Purpose and objective

This document describes the approach to be followed in the quantification of the error budget allocated to the processing of the TROPOMI data by the L01b processor.

This is done by first establishing a, at this stage simplified, processing model. Thereafter, a number of statistical techniques are applied to the model to show how the variance associated with the Calibration Key Data can be arrived at from the instrumental parameters (performance and read-out noise) and the calibration process. Finally, the mathematical expressions derived are applied to a number of concrete cases, and they are combined with an educated guess of the errors introduced by the processing, to derive the eventual radiometric accuracy.

It should be noted that this document aims at introducing an approach to the solution of the problem, and a first estimate of the results that can be expected. Detailed calculations, adapted to the concrete realization of the calibration plan and the processor will be developed further in subsequent documents.

Critical points that should be kept in mind when developing further the techniques presented here are mentioned.

1.3 Document overview

Based on the forward model and the processing steps described in [RD5], the variance of the signal is calculated at each step of the reverse model (§ 5). This is done in accordance with the statistical principles described in § 4. Based on the known instrumental parameters (summarized in § 6.2) and a few assumptions on the calibration of the instrument, a preliminary evaluation of the contribution that each processing step makes to the eventual accuracy of the results has been carried out. This is illustrated in § 6. A comparison with the TROPOMI top-level scientific requirements [AD1] allows us to identify the critical processing steps and calibration quantities.

2 Terms, definitions and abbreviated terms

Terms, definitions and abbreviated terms that are used in development program for the TROPOMI L01b data processor are described in [RD6]. Terms, definitions and abbreviated terms that are specific for this document can be found below.

2.1 Terms and definitions

Statistical uncertainty	The result of stochastic fluctuations arising from the fact that a measurement is based on a finite set of observations, and that each measurement has a finite precision. Examples are: the finite resolution of the instrument, Poisson fluctuations due to the finite sample size, and random variations of the system being examined [RD7].
Systematic uncertainty	The result of uncertainties (biases) associated with the measurement apparatus, assumptions made by the experimenter, or the models used in interpreting the data. Examples are: uncertainties that arise from the calibration of the measurement device or the parameters of the models used to make inferences [RD7]. There are three types of systematic uncertainties: • **Class 1**: Systematic uncertainty that is constrained by the result of a separate measurement. For instance, calibration measurements whose precision is limited by statistics. These uncertainties can be constrained by ancillary measurements, and mathematically can be treated as statistical uncertainties. • **Class 2**: Systematic uncertainties that arises from model assumptions (*e.g.* modeling errors) in the measurement or from poorly understood features in the data or analysis techniques that introduce a potential bias in the experimental outcome. • **Class 3**: Systematic uncertainties arising from lack of knowledge in the theoretical framework used to interpret the data.

In this document we deal with statistical uncertainties, and class-1 systematic uncertainties: this is done because at this stage of the development these are the only two types of uncertainties that can be estimated. Note also that, as common practice, we use the word “error” as a synonym for uncertainty.

2.2 Acronyms and Abbreviations

There are no new acronyms or abbreviations.

3 Applicable and reference documents

3.1 Applicable documents

[AD1] GMES Sentinel-5 Precursor system requirement document.
source: ESA; **ref:** S5p-RS-ESA-SY-0002; **issue:** 4 rev. 1 – Redlined Version - RLa; **date:** 2011-04-29 –Redlined version: 2012-07-04.

[AD2] Software development plan for TROPOMI L01b data processor.
source: KNMI; **ref:** S5P-KNMI-L01B-0002-PL; **issue:** 2.0.0; **date:** 2012-11-14.

[AD3] Software product assurance plan for TROPOMI L01b data processor.
source: KNMI; **ref:** S5P-KNMI-L01B-0003-PL; **issue:** 2.0.0; **date:** 2012-11-14.

[AD4] SRD requirements traceability analysis report.
source: KNMI; **ref:** S5P-KNMI-L01B-0027-RP; **issue:** 1.0.0; **date:** 2013-05-16.

3.2 Standard documents

There are no standard documents

3.3 Reference documents

[RD5] Algorithm theoretical basis document for TROPOMI L01b data processor.
source: KNMI; **ref:** S5P-KNMI-L01B-0009-SD; **issue:** 1.0.0; **date:** 2013-03-27.

[RD6] Terms, definitions and abbreviations for TROPOMI L01b data processor.
source: KNMI; **ref:** S5P-KNMI-L01B-0004-LI; **issue:** 2.0.0; **date:** 2012-06-27.

[RD7] Pekka K. Sinervo; Definition and Treatment of Systematic Uncertainties in High Energy Physics and Astrophysics. *In Statistical Problems in Particle Physics, Astrophysics, and Cosmology* (edited by Lyons L., Mount R. and Reitmeyer R.); (pp. 122–129) (SLAC, Menlo Park, California, 2003).

[RD8] Christine Osborne; Statistical Calibration: A Review. *International Statistical Review*; **59** (1991) (3), 309.

[RD9] Irma Lavagnini and Franco Magno; A Statistical Overview on Univariate Calibration, Inverse Regression, and Detection Limits: Application to Gas Chromatography/Mass Spectroscopy Technique. *Mass Spectrometry reviews*; **26** (2007), 1.

[RD10] Norman R. Draper and Harry Smith; *Applied Regression Analysis* (Wiley, 1998); 3^{rd} edition.

[RD11] Cheng Chi-Lun and Van Ness John W.; *Statistical Regression with Measurement Error: Kendall's Library of Statistics 6* (Wiley, 1999); 1^{st} edition.

[RD12] D. York, N. M. Evensen, M. L. Martínez *et al.*; Unified equations for the slope, intercept, and standard errors of the best straight line. *American Journal of Physics*; **72** (2004), 367; 10.1119/1.1632486.

[RD13] Instrument performance analysis report.
source: Dutch Space; **ref:** TROP-DS-0000-RP-0060; **issue:** 6.0; **date:** 2013-01-16.

3.4 Electronic references

There are no electronic references

4 Statistical Concepts

In this section we develop the statistical concepts that shall be applied to the computation of the variance of the signal through the L01b processing chain.

The problem we want to address is the following. We have an instrument comprising many electronic stages: detection, amplification, and digitalization. During operations the instrument is presented with an unknown signal (radiance, irradiance). At the end of the instrumental and electronic chain the input signal is converted to a digital number. Based on the on-ground and in-flight calibration, and by applying specific algorithms, the recorded digital number is converted back to an estimate of the input signal. The questions we seek to answer are:

- What is the variance of the estimated input signal?
- What components contribute most to the variance of the signal? We mean here instrument noise, calibration uncertainties, and algorithmic errors.

In the statistical literature this problem is identified with a few different names: inverse regression, univariate or multivariate calibration, statistical calibration, or discrimination. For a review see for instance [RD8].

In the L01b processor most algorithmic steps are, at least to the first order, linear. In the following section we describe a linear calibration model in detail. This allows us to explain the issues and the methods at play. Attention will also be given to the cases where the linear model does not apply, but detailed derivations for the cases where the linear model breaks down are postponed to a later updated of this document.

4.1 The Linear Univariate Calibration Problem

The univariate calibration problem can described as follows [RD9]. Consider a measuring device with a linear response linking the quantity of interest X to the device's response Y. In the linear univariate calibration model each measured Y_i is related to the corresponding X_i by

$$Y_i = \beta_0 + \beta_1 X_i + \varepsilon_i \tag{1}$$

where the ε_i are identically distributed with 0 mean and constant variance σ^2. Although not always necessary, in the following we assume that ε_i are normally distributed with 0 mean and unknown variance σ^2. Most stages in the instrumental chain can to the first order be described by a univariate regression model like the one described in Equation (1).

4.1.1 Establishing a Calibration Curve

Estimates B_0 and B_1 of the regression coefficients β_0 and β_1 are obtained from n calibration measurements $\{X_i, Y_i\}_{i=1\ldots n}$. By applying the least squares technique, the estimates of the regression coefficients and their variances can be calculated analytically by minimizing

$$Q = \sum_i \varepsilon_i^2 = \sum_i (Y_i - \beta_0 - \beta_1 X_i)^2 \tag{2}$$

with respect to β_i (that is $\partial Q / \partial \beta_i = 0 \forall i$, for instance [RD10]). We introduce [RD10]

$$
\begin{aligned}
\overline{X} &= \sum_i X_i/n && (3)\\
\overline{X^2} &= \sum_i X_i^2/n && (4)\\
\overline{Y} &= \sum_i Y_i/n && (5)\\
\overline{Y^2} &= \sum_i Y_i^2/n && (6)\\
\overline{XY} &= \sum_i X_iY_i/n && (7)\\
S_{XY} &= \sum_i (X_i-\overline{X})(Y_i-\overline{Y}) && (8)\\
&= n(\overline{XY}-\overline{X}\,\overline{Y}) && (9)\\
S_{XX} &= \sum_i (X_i-\overline{X})^2 && (10)\\
&= n(\overline{X^2}-\overline{X}^2) && (11)\\
S_{YY} &= \sum_i (Y_i-\overline{Y})^2 && (12)\\
&= n(\overline{Y^2}-\overline{Y}^2)\,. && (13)
\end{aligned}
$$

Then by solving the linear equations obtained from the partial derivatives above we obtain:

$$
\begin{aligned}
B_1 &= S_{XY}/S_{XX} && (14)\\
B_0 &= \overline{Y}-B_1\overline{X}\,. && (15)
\end{aligned}
$$

It is useful to also calculate the mean square about the regression

$$s^2=\sum_i (Y_i-B_0-B_1X_i)^2/(n-2)\,. \tag{16}$$

This is an estimate of the variance about the regression (or the unexplained variance), which in turn is an estimate of the true variance σ^2 (but only if the assumed model is correct). With this we can write the standard error[1] for the regression parameters:

$$
\begin{aligned}
s_{B_0} &= s\sqrt{\frac{1}{n}+\frac{\overline{X}^2}{S_{XX}}} && (17)\\
&= s\sqrt{\overline{X^2}/S_{XX}} && (18)\\
s_{B_1} &= s/\sqrt{S_{XX}}\,, && (19)
\end{aligned}
$$

where we made use of the fact that the variance of $\overline{Y}$ is s^2/n.

It is now possible to bound the calibration line, and to make an uncertainty prediction for a new measurement.

4.1.2 Inverse Regression

The analytical application of the calibration curve derived in the previous section is called inverse regression (or discrimination), that is the obtainment of the estimate X_0 from a measurement of Y_0, with a confidence interval for the true X_0. The confidence interval related to the variance of X_0 depends on two factors: the uncertainties on the regression coefficients B_0 and B_1, and the uncertainty of the experimental response reading. In the literature one finds expressions related to m experimental response readings, but in our case $m = 1$ in all cases, as a certain ground pixel is observed only once under some illumination condition.

---

[1] Strictly speaking the estimate of the standard error under the assumption that the regression model is correct.

Given then a measurement Y_0 it is

$$X_0 = \frac{Y_0 - B_0}{B_1} = \overline{X} + \frac{1}{B_1}(Y_0 - \overline{Y}) \,. \tag{20}$$

By applying the standard error propagation formalism [RD9][2], or using a graphical method [RD10], to Equation (20), we have

$$\begin{aligned} s^2_{X_0} &= s^2_{\overline{X}} + \frac{s^2_{Y_0}}{B_1^2} + \frac{s^2_{\overline{Y}}}{B_1^2} + \frac{1}{B_1^4}(Y_0 - \overline{Y})^2 s^2_{B_1} && (21) \\ &= 0 + \frac{s^2}{B_1^2} + \frac{s^2}{nB_1^2} + \frac{s^2}{B_1^2}\frac{(X_0 - \overline{X})^2}{S_{XX}} && (22) \\ &= \frac{s^2}{B_1^2}\left[1 + \frac{1}{n} + \frac{(X_0 - \overline{X})^2}{S_{XX}}\right] && (23) \end{aligned}$$

where we have again made use of the fact that $s^2_{\overline{Y}} = s^2/n$.

We see that the variance of the estimated X_0 comprises three terms:

1. **Instrumental error due to noise**: s^2/B_1^2: This is the variance about the regression scaled by B_1. This term is contributed by the noise of the device and cannot be reduced through calibration.
2. **Calibration error**: $s^2/(B_1^2 n)$: This is the contribution of the calibration to the variance. This term is contributed by the uncertainty in the parameters of the regression.
3. **Additional calibration error**: $(s^2/B_1^2)(X_0 - \overline{X})^2/S_{XX}$: This term is the additional uncertainty related to the fact that the uncertainly on the calibration line is not the same for all X. This quantity can be reduced by choosing a calibration strategy that makes S_{XX} as large as possible. Note that such a strategy would also make the error on the regression parameters (Equations (17) and (19)) as small as possible. This does not however means that one should calibrate only by measuring values at the extremes of the input range. Rather, more measurements should be performed closer to the extremes: in this manner the actual linearity of the calibration curve can be checked, and the calibration uncertainties can be reduced.

The instrumental error due to noise is a statistical uncertainty; the two components related to the calibration are class-1 systematic uncertainties according to the definition given in § 2.

4.1.3 Special Cases

4.1.3.1 The Case $\beta_1 = 1$ It holds:

$$\begin{aligned} B_0 &= \overline{Y} - \overline{X} && (24) \\ s^2 &= \frac{S_{YY}}{n-1} && (25) \\ s^2_{X_0} &= s^2\left(1 + \frac{1}{n}\right) && (26) \end{aligned}$$

4.1.3.2 The Case $\beta_0 = 0$ It holds:

$$\begin{aligned} B_1 &= \frac{S_{XY}}{S_{XX}} && (27) \\ s^2 &= \frac{S_{YY}}{n-1} && (28) \\ \sigma^2_{B_1} &= \frac{s^2}{S_{XX}} && (29) \\ s^2_{X_0} &= \frac{s^2}{B_1^2}\left[1 + \frac{1}{n} + \frac{(X_0 - \overline{X})^2}{S_{XX}}\right] \,. && (30) \end{aligned}$$

---

[2] If $Y = F(X_i)$, then $\sigma_Y^2 = \sum_i (\partial F/\partial X_i)^2 \sigma_i^2$, if the X_i are uncorrelated.

4.1.3.3 Charge Transfer Efficiency Model The forward model is in this case not linear. It can however be linearized as follows. For a charge packet in pixel (r,c) the signal evolves as

$$S_{\text{after}} = S_{\text{before}}\Omega^{r+N_r+c} \tag{31}$$

where Ω is the charge transfer efficiency, taken to be the same for both serial and parallel transfers, and N_r is the number of CCD rows. The latter is only slightly less than unity, so that we can write ($N \equiv r+N_r+c$: this is the total number of transfers in the frame region, the store region, and the serial register)

$$S_{\text{after}} = S_{\text{before}}(1-E)^N \approx S_{\text{before}}(1-NE) = S_{\text{before}} - NES_{\text{before}}\,, \tag{32}$$

where E is the charge transfer inefficiency.

This means that the model is linear, but bivariate (and of a special type: $Y = X - CXB_1$ where C is a known constant that varies depending on the pixel being looked at). We minimize

$$Q = \sum_i (Y_i - X_i - X_i N_i E)^2 \tag{33}$$

with respect to E and obtain:

$$E = \frac{\sum_i N_i X_i Y_i - \sum_i N_i X_i^2}{\sum_i N_i^2 X_i^2} \tag{34}$$

$$s_E^2 = s^2 \left(\frac{\sum_i N_i X_i}{\sum_i N_i^2 X_i^2} \right)^2 . \tag{35}$$

4.2 More Complex Calibration Models

We mention here a number of issues that must be investigated further as the instrumental response models evolve. All these issues have some relevance in the context of TROPOMI; below they are listed in approximate order of importance.

1. **Errors in X** We have also assumed that during the calibration X is known without error (rather, that the error is small enough not to have any effect). If this is not the case the regression model is more complex, but at least for the linear case there exist solutions ([RD11] and [RD12]). All measurements affected by shot noise will have an error in X that must be dealt with.

2. **Weighted Regression** We have assumed that the measurement error is the same for all measurements. If this is not the case the calibration curve must be calculated via a weighted regression.

3. **Models** Other models may be required to accurately represent the data (here linearity refers to the model parameters):

   - Higher order linear models: $Y = \sum_j \beta_j X^j$.
   - First order multivariate linear models: $Y = \beta_0 + \sum_{i=1\ldots} \beta_i X_i$.
   - Models that allow for covariance terms. These should be considered even when just dealing with the linear regression case.
   - General non-linear models.

   Linear models of a higher order may be required to model some of the effects, for instance non-linearity effects. Some models may be linearized by the application of a transformation function (for instance $Y = \exp(\beta_0 + \beta_1 X)$), but then the standard theory can be applied only if one is sure that the transformed instrumental noise has the required statistical properties.

4. **Calibration Design** The literature abounds with discussions about what is the calibration strategy that gives the more tightly bound calibration line. This is called experimental design. In general one wants to make sure that the entire measurement range that will be used in operations is used in calibration (intuitively, this is what makes s_{XX}^2 smaller). If this is not possible, or a choice must be made, it will be useful to spend some time thinking about these aspects.

5 Processing Model

Here we describe a simplified processing model, aimed at establishing a number of equations that can be used to estimate the variance associated with the estimated input signal measured. In the processing model we proceed from the telemetered signal toward the entrance aperture of the detector. In this section all algorithms are expressed as far as possible as

$$S' = S f_C + o_C \tag{36}$$

where f_C is a suitable conversion factor and o_C is an offset. With respect to the quantities and operations occurring in the forward model we proceed as follows. If the forward model is

$$Y = B_0 + B_1 X \tag{37}$$

the reverse model is written as

$$X = b_0 + b_1 Y \tag{38}$$

where

$$\begin{aligned} b_0 &= -\frac{B_0}{B_1} && (39)\\ b_1 &= \frac{1}{B_1}. && (40) \end{aligned}$$

With reference to Equation (36) it is:

$$\begin{aligned} f_C &= b_1 && (41)\\ o_C &= b_0. && (42) \end{aligned}$$

At each step the variance contributed by the current correction sums quadratically with the pre-existing variance:

$$\sigma^2_{\mathrm{after}} = \sigma^2_{\mathrm{before}} b_1^2 + s^2 b_1^2 \left[1 + \frac{1}{n} + \frac{(X - \overline{X})^2}{S_{XX}}\right]. \tag{43}$$

At each step the following quantities are Calibration Key Data:

- b_0, b_1: the model parameters.
- s^2: the mean square about the calibration line.
- $n, \overline{X}, S_{XX}$: parameters describing some of the details of the calibration.

5.1 Implementation in the L01b Processor

There are two approaches possible to the actual calculation of the variance in the L01b processor. They both give the same result, but one preserves more information about the sources of the variance.

Consider the simple linear model described in § 4.1, and how it is applied in the processing model with Equations (20) and (23). In this case the three components of the variance are clearly identified and can be evaluated separately if needed. On the other hand, a purely numerical solution based on the first part of Equation (20) and the standard error propagation formalism, requires only B_0, B_1 and the corresponding error estimates.

5.2 Processing Details

Here we make explicit all the processing steps and how the signal and its variance evolve through the L01b processor. The processing steps are taken from [RD5]. For algorithmic steps that are not linear, or that have not been described as a special case (§ 4.1.3), we apply the standard error propagation formalism. In this case the separate effect of the instrumental and calibration components is not visible. The assumption is made that every step could be calibrated independently, and therefore act as an independent source of variance. This is not a realistic assumption: for instance, while it is at least in theory possible to determine the gain of each individual step, it is not possible to determine the read-out noise with the same granularity.

In the following S is the signal, and σ^2 its variance. At the start of the processing chain the signal is a digital number, and its variance is 0. Processing steps marked with a dagger (†) do not apply to the SWIR.

5.2.1 Co-addition Correction (†)

$$S \mapsto Sn_c \tag{44}$$
$$\sigma^2 \mapsto \sigma^2 n_c^2. \tag{45}$$

5.2.2 ADC Conversion

$$S \mapsto Sg_{ADC} \tag{46}$$
$$\sigma^2 \mapsto \sigma^2 g_{ADC}^2 + s_{ADC}^2 g_{ADC}^2 \left[1 + \frac{1}{n_{ADC}} + \frac{(S - \overline{X}_{ADC})^2}{S_{XX,ADC}}\right]. \tag{47}$$

5.2.3 ADC PGA Gain and Offset Correction (†)

$$S \mapsto Sg_{PGA} + o_{PGA} \tag{48}$$
$$\sigma^2 \mapsto \sigma^2 g_{PGA}^2 + s_{PGA}^2 g_{PGA}^2 \left[1 + \frac{1}{n_{PGA}} + \frac{(S - \overline{X}_{PGA})^2}{S_{XX,PGA}}\right]. \tag{49}$$

5.2.4 ADC Programmable Offset Correction (†)

$$S \mapsto S + o_{ADC} \tag{50}$$
$$\sigma^2 \mapsto \sigma^2 + s_{ADCO}^2 \left(1 + \frac{1}{n_{ADCO}}\right). \tag{51}$$

5.2.5 ADC CDS Gain and Offset Correction (†)

$$S \mapsto Sg_{CDS} + o_{CDS} \tag{52}$$
$$\sigma^2 \mapsto \sigma^2 g_{CDS}^2 + s_{CDS}^2 g_{CDS}^2 \left[1 + \frac{1}{n_{CDS}} + \frac{(S - \overline{X}_{CDS})^2}{S_{XX,CDS}}\right]. \tag{53}$$

5.2.6 Voltage to Charge Conversion

Note that this step comprises two gains. One is the CCD gain proper, that can be set to two different values, and one is the video gain, built in into the device.

$$S \mapsto Sg_{V2C} + o_{V2C} \tag{54}$$
$$\sigma^2 \mapsto \sigma^2 g_{V2C}^2 + s_{V2C}^2 g_{V2C}^2 \left[1 + \frac{1}{n_{V2C}} + \frac{(S - \overline{X}_{V2C})^2}{S_{XX,V2C}}\right]. \tag{55}$$

5.2.7 ROR Binning Correction (†)

$$\begin{aligned} S &\mapsto Sn_{ROR} && (56)\\ \sigma^2 &\mapsto \sigma^2 n_{ROR}^2\,. && (57)\end{aligned}$$

5.2.8 CTE Correction

In the reverse model we have (see § 4.1.3.3):

$$S_{in} = \frac{S_{out}}{\Omega^N} \approx S_{out}(1+NE) \tag{58}$$

$$\begin{aligned} S &\mapsto S(1+NE) && (59)\\ \sigma^2 &\mapsto \frac{\sigma^2}{(1-NE)^2} + \sigma_E^2 \frac{N^2S^2}{(1-NE)^4}\,. && (60)\end{aligned}$$

5.2.9 Background Correction

Let D be the dark current, then:

$$\begin{aligned} S &\mapsto S - DT_f && (61)\\ \sigma^2 &\mapsto \sigma^2 + s_D^2\left(1+\frac{1}{n_D}\right)T_f^2\,. && (62)\end{aligned}$$

5.2.10 Smear Correction (†)

Let[3] $C \equiv 1 + (N_r - 1)\tau_p/T_f$ (note: $c \equiv 1/C$, and we assume that all times have no error), then

$$\begin{aligned} S &\mapsto Sc && (63)\\ \sigma^2 &\mapsto \sigma^2 c^2\,. && (64)\end{aligned}$$

5.2.11 Exposure Time Correction

Let T_f be the frame time, and note that $t_f \equiv 1/T_f$, then

$$\begin{aligned} S &\mapsto St_f && (65)\\ \sigma^2 &\mapsto \sigma^2 t_f^2\,. && (66)\end{aligned}$$

5.2.12 PRNU Correction

$$\begin{aligned} S &\mapsto Su && (67)\\ \sigma^2 &\mapsto \sigma^2u^2 + s_{PRNU}^2 u\left[1+\frac{1}{n_{PRNU}}+\frac{(S-\overline{X}_{PRNU})^2}{S_{XX,PRNU}}\right]\,. && (68)\end{aligned}$$

---

[3] We assume a simplified model for image smear, where the signal in a pixel is modified according to $S = S + S(N_r - 1)\tau_p/T_f$, where τ_p is the parallel transfer time, and T_f is the frame time.

5.2.13 Straylight Correction

In the forward model we take

$$S_{\text{after}} = S_{\text{before}} + S_{\text{sl}}\,. \tag{69}$$

Suppose now that only a certain fraction β of the straylight can be corrected for:

$$S_{\text{before}} = S_{\text{after}} - \beta S_{\text{sl}}\,. \tag{70}$$

Then in the processing mode we can write:

$$\begin{aligned} S &\mapsto S - \beta S_{\text{sl}} & (71)\\ \sigma^2 &\mapsto \sigma^2 + \beta^2 \sigma_{\text{sl}}^2\,. & (72)\end{aligned}$$

Additionally, assume that the straylight is a fraction α of the incident light $S_{\text{sl}} = \alpha S_{\text{before}}$ so that $\sigma_{\text{sl}}^2 = \alpha^2 \sigma_{\text{before}}^2$. Then substituting and rewriting we have

$$\begin{aligned} S &\mapsto \frac{S}{1+\alpha\beta} & (73)\\ \sigma^2 &\mapsto \frac{\sigma^2}{1-\beta^2\alpha^2}\,. & (74)\end{aligned}$$

5.2.14 Slit Irregularity Correction

We assume that the slit irregularity is known from mechanical measurements, and for each pixel it is known with a certain error. In the forward model the signal evolves as

$$S_{\text{after}} = S_{\text{before}} F_{\text{s}} \tag{75}$$

where F_{s} is a suitably normalized slit transmission factor. In the processing model we have then:

$$\begin{aligned} S &\mapsto S f_s & (76)\\ \sigma^2 &\mapsto \sigma^2 f_s^2 + S^2 \sigma_s^2\,. & (77)\end{aligned}$$

5.2.15 Radiance Sensitivity Correction

In a fashion similar to what done at the previous step, we have

$$\begin{aligned} S &\mapsto Sr & (78)\\ \sigma^2 &\mapsto \sigma^2 r^2 + S^2 \sigma_r^2\,. & (79)\end{aligned}$$

6 Results

6.1 Spreadsheet Implementation

The equations shown in § 5.2 have been coded in a spreadsheet, and this has been used to ascertain the overall accuracy that can be reached in the L01b processor. A number of assumptions must be made in order to be able to evaluate the calibration uncertainties. In particular we need to assume a value for n, the number of calibration measurements used, and come up with a guess for the calibration values $\overline{X}$ and S_{XX}. The number n will simply be assumed to be the same for all calibration steps. As far as the two other terms are concerned, we proceed as follows.

Let $[a,b]$ be the allowed range for X, and assume that the n calibration measurements are uniformly distributed in the range. Then $\overline{X} = (b+a)/2$, and $X_i = a + i(b-a)/(n-1)$, $i = 0\ldots(n-1)$. Then we use S_{XX} from Equation (3) where we can make use of:

$$
\begin{aligned}
\overline{X^2} &= \frac{\sum_i X_i^2}{n} && (80)\\
&= \frac{1}{n}\sum_i \left[a^2 + \frac{2ia(b-a)}{n-1} + \frac{i^2(b-a)^2}{(n-1)^2}\right] && (81)\\
&= a^2 + \frac{2(b-a)}{n(n-1)}\sum_i i + \frac{(b-a)^2}{n(n-1)^2}\sum_i i^2 && (82)\\
&= a^2 + \frac{(n+1)(b-a)}{(n-1)} + \frac{(n+1)(2n+1)(b-a)^2}{6(n-1)^2}. && (83)
\end{aligned}
$$

In order to simplify this expression we shall assume $n \approx n \pm 1$, and we have

$$\overline{X^2} \approx a^2 + (b-a) + \frac{(b-a)^2}{3} \qquad (84)$$

which finally leads to

$$S_{XX} \approx \frac{n}{12}(a-b)^2. \qquad (85)$$

In order to simplify the spreadsheet implementation we make however use of an alternative approximation that does not depend on the detailed knowledge of the allowed input range. We proceed to evaluate the average of the additional calibration error over a number of measurements (we use $E[...]$ to denote the averaging process):

$$
\begin{aligned}
E[(s^2/B_1^2)(X_0-\overline{X})^2/S_{XX}] &= \frac{(s^2/B_1^2)}{S_{XX}}E[(X_0-\overline{X})^2] && (86)\\
&= \frac{(s^2/B_1^2)}{nE[(X_0-\overline{X})^2]}E[(X_0-\overline{X})^2] && (87)\\
&= (s^2/B_1^2)\frac{1}{n} && (88)
\end{aligned}
$$

>From this we shall take the additional calibration error to contribute **on average** another $1/n$ factor to the total variance. Note that this should not be taken to mean that this contribution can be rendered arbitrarily small: it is just a simplification to ease the calculations in the spreadsheet.

6.2 Wavelength Bands and Instrumental Parameters

For each wavelength band given in [AD1] we have identified two cases, one for a low signal and one for a high signal condition. In each case we have taken the lowest signal per pixel detected: the results presented represent therefore the worst possible case in each band and scene condition. In Table 1 we summarize the signal levels used, and in Table 2 the instrument parameters used to calculate them. The instrument parameters we extracted from [RD13].

6.3 Error Budget Tables

For each performance parameter we summarize the relevant requirements and the applicable algorithmic steps. The analysis of which requirements are applicable is based on [AD4].

6.3.1 Radiometric Accuracy

The error budget tables for the radiometric accuracy are enclosed in the Appendix.

Reference signals

band	signal low (DN)	signal high (DN)
1	820	820
2	16	16
3	820	1640
4	820	8200
5	410	1310
6	400	1310
7	500	500
8	500	500

Table 1: The reference signals per frame, as Digital Number.

6.3.1.1 Absolute Radiometric Accuracy The following requirements have to do with the radiometric accuracy:

- OB-UVN-0320, OB-UVN-0330, OB-UVN-0440
- OB-SWI-0320, OB-SWI-0330, OB-SWI-0440

The SRD [AD1] defines the absolute radiometric accuracy. Based on the definition, errors that cancel out when averaging samples in time do not need to be taken into account in the estimation of the accuracy. These are:

- CTE errors (only for UVN)
- Exposure smear errors (only for UVN)
- Offset error (only for UVN and in case of dynamic offset correction)
- Memory effects (SWIR only)
- Pixel-to-pixel non linearity (SWIR only).

Any (residual) errors caused by polarization will be ignored as well, as these are expected to cancel out by averaging too.

Additionally, for reflectance measurements the following also cancel out and can therefore be ignored:

- Pixel response non uniformity (UVN only)
- Slit irregularity.

Finally, stray light is explicitly excluded from the requirements mentioned above. For reflectance, only the error on irradiance sensitivity is taken into account and not the error on radiance sensitivity. This is valid, as the radiance sensitivity is derived from the instrument BSDF and the absolute radiometric calibration. The algorithms involved are summarized in Table 3, and the accuracy on the reflectance are summarized in Table 13: the requirement in bands 7 and 8 seems difficult to achieve, unless the accuracy of the CKD for voltage to charge conversion is pushed to better than 0.2%. Section 6.3.3 provides an analysis of additive errors for UVN. The residuals that count for the absolute radiometric accuracy are shown in Table 4. The remainder of the error budget can be decomposed between the other contributing effects.

6.3.1.2 Relative Radiometric Accuracy The following requirements have to do with the radiometric accuracy:

- OB-UVN-0340.a, OB-UVN-0340.b, OB-UVN-0460
- OB-SWI-0340.a, OB-SWI-0340.b, OB-SWI-0460

Instrument parameters

	1 (UV)	2 (UV)	3 (UVIS)	4 (UVIS)	5 (NIR)	6 (NIR)	7 (SWIR)	8 (SWIR)
slit width / along track slit size (mm)	0.56	0.56	0.28	0.28	0.28	0.28	308	308
spectral sampling (nm/pix)	65	65	0.19-0.18	0.19-0.18	0.11-0.10	0.11-0.10	0.084-0.097	0.084-0.097
wavelength range (nm)	270-300	300-320	310-405	405-495	675-725	725-775	2305-2345	2345-2385
optical throughput BOL	415	207	476	341	387	379	290	290
optical throughput EOL	374	186	428	307	348	341		
diffuser BRDF (1/sr)	0.13	0.13	0.13	0.13	0.14	0.14	0.16	0.16
QE @196K	513	624	715	725	863	863	0.8	0.8
dark current BOL (e/pix/s)	160 @233K	160 @233K	160 @233K	160 @233K	160 @233K	160 @233K	2.5k @140K	2.5k @140K
pixel full well [ke]	700	700	700	700	700	700	535	535
register full well [ke]	3000	3000	3000	3000	3000	3000	N/A	N/A
PRNU (global)	0.6%	0.6%	0.5%	0.4%	0.6%	0.6%	4.7%	4.7%
PRNU (local)	0.2%	0.2%	0.3%	0.3%	0.2%	0.2%		
Charge to voltage conversion (m V/e)	0.7 (L) / 1.4 (H)	0.7 (L) / 1.4 (H)	0.7 (L) / 1.4 (H)	0.7 (L) / 1.4 (H)	0.7 (L) / 1.4 (H)	0.7 (L) / 1.4 (H)		
AVC gain	5	1.5	1.5	1.35	1.5	1.5		
Read-out noise (e rms) at high gain	40	40	40	40	40	40	111	111
AVC noise at 1x gain (m V)	95	95	95	95	95	95		
ADC noise at 1x gain (m V)	173	173	173	173	173	173		
Binning factor (centre)	16	4	4	4	4	2	N/A	N/A
Exposure time radiance (ms)	216	216	36	36	54	54		
CCD gain radiance (m V/e)	1.4	1.4	0.7	0.7	0.7	1.4		
ADC gain radiance	6.67	0.91	0.96	0.81	0.77	0.85		
Exposure time irradiance (ms)	54	54	40	40	108	108		
CCD gain irradiance (m V/e)	1.4	1.4	1.4	1.4	0.7	1.4		
ADC gain irradiance	1.4	8.18	1.11	0.93	0.84	0.92		

Table 2: Summary of the UVN instrumental parameters. All offsets have been taken to be 0. This means that they are taken to be known and that can be subtracted off. Any unexpected changes (fluctuations and uncorrected trends) will have to be evaluated as part of the analysis of systematic errors.

Algorithm summary

	OB-UVN-0320	OB-SWI-0320	OB-UVN-0330.a	OB-UVN-0330.b	OB-UVN-0330.c	OB-UVN-0330.d	OB-SWI-0330	OB-UVN-0440	OB-SWI-0440
Radiance	x	x							
Irradiance								x	x
Reflectance			x	x	x	x	x		
Requirement	2,00%	2,00%	1,90%	1,60%	1,60%	1,60%	1,50%	2,00%	2,00%
Band	1-6	7-8	1	2	3-4	5-6	7-8	1-6	7-8
Co-addition correction (UVN/SWIR)	0	0	0	0	0	0	0	0	0
Offset correction (UVN)									
Gain correction (UVN)	+		+	+	+	+		+	
Voltage to charge correction (UVN)	+		+	+	+	+		+	
ROR binning correction (UVN)	0		0	0	0	0		0	
CTE correction (UVN)									
PRNU correction (UVN)	+							+	
Smear correction (UVN)									
Offset correction (SWIR)		+					+		+
Pixel to Pixel Gain correction (SWIR)									
Voltage to charge correction (SWIR)		+					+		+
Memory effect correction (SWIR)									
Dark current correction (UVN/SWIR)	+	+	+	+	+	+	+	+	+
Background correction (UVN/SWIR)	+	+	+	+	+	+	+	+	+
Exposure time correction (UVN/SWIR)	0	0	0	0	0	0	0	0	0
Straylight correction (UVN/SWIR)									
Slit irregulariy correction (UVN/SWIR)	+	+						+	+
Radiance sensitivity correction (UVN/SWIR)	+	+							
Irradiance sensitivity correction (UVN/SWIR)			+	+	+	+	+	+	+
Irradiance gonio correction (UVN/SWIR)			+	+	+	+	+	+	+

Table 3: Effects contributing to the error budgets for absolute radiometric accuracy. Algorithms marked with a + are considered; those marked with a 0 are considered but because of their nature do not contribute any error.

Band	Dark Current	Background	Dark Current and Background Residual
1 (UV)	11.5%	33.3%	0.1%
2 (UV)	1.2%	3.3%	0.0%
3 (UVIS)	0.0%	0.1%	0.0%
4 (UVIS)	0.0%	0.1%	0.0%
5 (NIR)	0.0%	0.1%	0.0%
6 (NIR)	0.0%	0.1%	0.0%

Table 4: Additve errors contributing to the error budgets for absolute radiometric accuracy.

The SRD [AD1] defines both the relative spatial radiometric accuracy and the relative spectral radiometric accuracy. The relative radiometric accuracy requirements are primarily solved by the method of characterization: the radiometric accuracy is measured relative to the nadir position. As a result, the relative radiometric accuracy error budget is defined by these measurements and as such the error budgets for requirements OB-UVN-0340.a, OB-SWI-0340.a, OB-UVN-0340.b, OB-SWI-0340.b can be contributed fully to these measurements. For requirements OB-UVN-0460, OB-SWI-0460, also the error budget on irradiance gonio needs to be taken into account.

6.3.2 Stray Light

The following requirements have to do with stray light:

- OB-UVN-0310
- OB-SWI-0310

For these stray light requirements, only a decomposition into L01b and CKD needs to be made; a further decomposition is not necessary or possible. The error budgets are for this purpose split equally between the two components.

6.3.3 Additive Errors

6.3.3.1 UVN Exposure Smear The following requirement has to do with exposure smear:

- OB-UVN-0246

Exposure smear is determined by the exposure time, the row transfer time and the integral of the detector signal along a detector column. Table 5 shows the expected exposure times (from [RD13]) and the corresponding exposure smear as a fraction of the integral signal along a detector column.

Band	Exposure Time (ms)	Total Smear	Maximum contrast	Worst-case smear
1 (UV)	216	0.3%	1.1	0.3%
2 (UV)	216	0.3%	3.4	1.0%
3 (UVIS)	36	1.8%	7.8	14.0%
4 (UVIS)	36	1.8%	14.0	25.2%
5 (NIR)	54	1.2%	33.0	39.6%
6 (NIR)	54	1.2%	35.0	42.0%

Table 5: Smear estimates

The exposure smear contribution is the highest in high contrast scenes. The worst case situation occurs is case of a small viewing angle with a low signal where the remainder of the scene has a high signal. For this worst-case scenario, the total smear contribution for the low signal is provided in Table 5 as well. The worst case is band 6, where the total smear contribution can be as large as 42%. In order to correct this, the smear correction model in the L01b must have an accuracy better than 1% / 42% = 2.4% (threshold), 0.1% / 42% = 0.24% (goal). For scenes that are homogenous in the flight / along-track direction, a straightforward model is only limited by signal to noise and this accuracy can be achieved without any special measures.

Band	Maximum contrast	Worst-case smear error
1 (UV)	1	0.0%
2 (UV)	3	0.1%
3 (UVIS)	8	0.2%
4 (UVIS)	14	0.4%
5 (NIR)	33	1.0%
6 (NIR)	35	1.0%

Table 6: Maximum smear errors after correction

The ATBD [RD5] specifies an equation that allows to calculate the maximum error in case the exposure smear correction algorithm in the L01b does not take into account variations in the flight direction. This equation is dependent on the co-addition time (taken as 1080 ms), the number of (illuminated) detector rows (864) and the observed contrast. The worst case errors (after correction) are given in Table 6. From this table it can be concluded that with a straightforward exposure smear correction algorithm, the residual error is compliant, with band 6 being right at the requirement threshold of 1.0%. Note that this is a worst case error, so real life performance of the algorithm will be much better and for scenes that are homogenous in the flight direction the exposure smear correction will be limited by signal-to-noise only.

6.3.3.2 UVN Total Additive Errors The following requirement has to do with the total additive errors:

- OB-UVN-0335

The following algorithms can introduce additive errors:

- (detector and electronics) offset correction
  - UVN detector offset is in the order of 12 ke/pix/s (NIR CCD DRB)
  - No specific offset is introduced in the electronics and there are measures in the electronics to avoid any algorithms; these include decoupling in the signal chain and correlated double sampling. We assume a maximum unforeseen electronics offset of 0.1% ADC Full Scale, which corresponds to about 16 DN.
  - When these offsets are very stable, they can be calibrated using dedicated measurements. In that case, it is very easy to obtain millions of offset data points and the offset correction in the L01b will be extremely accurate. In case however these offsets drift, it will be necessary to perform a dynamic offset correction. Such a correction can be done using the data from the CCD read-out register (ROR). As this will have fewer data points (we assume 250 columns per band in the ROR can be used to determine the dynamic offset, as we need to derive a system offset for both even and odd signal chains), having a dynamic offset correction is considered the worst-case situation, and therefore this is the baseline for the error budget analysis. Using four overscan columns for dynamic offset may improve this situation.
- Dark current correction
  - UVN detector dark current is in the order of 160 e/s/pixel ([RD07])
  - The detector is thermally stabilized, so a thermal dependency is not considered necessary for correcting the dark current.
- Background correction
  - Background correction corrects for any unforeseen pixel dependent offsets. There are no specific requirements for background signal levels. We assume a maximum unforeseen background signal of 100 e per pixel. This is in the same order of magnitude of dark current signal and of noise levels in the analogue video chain and as such this seems a fair assumption.

  - For the background correction, we assume a simple subtraction with calibration data based on background measurements that are acquired using identical settings as the measurement that needs to be corrected for background signal. It is assumed that 50 measurements can be averaged for deriving the background calibration data.

- Exposure smear correction
  - See analysis of exposure smear in Section 6.3.3.1.
- Stray light correction
  - Stray light is explicitly excluded from this requirement.

In Table 7 an overview is provided of all additive terms (offsets) before correction in the L01b for the worst case situation, i.e. low radiance reference scene. Next, we will analyze to what extent we can correct for the above errors in the L01b. For the detector in electronics offsets, this is shown in Table 8. For adding noise terms, the root-sum-square method is used, as prescribed by the SRD [AD1]. The noise at the AFE input includes the read-out noise and the AVC noise as specified in Section 6.2. The AVC noise is expected to be present at the end of the AVC and therefore does not include the AVC gain factor. Similarly, the noise at the ADC input includes the previous noise terms with the ADC noise added, where again, the ADC gain (including the AFE PGA gain) are not included in the noise term. From this the total detector and electronics offset is calculated, together with the corresponding noise term. This results in the detector and electronics offset for a single pixel in the ROR. This SNR is then improved by averaging the pixels in the ROR. The offset error is then taken is 1/SNR. Similarly, the dark current and background signals are analyzed, and the results are shown in Table 9.

For the dark current and background correction, it is required to correct the background and dark current measurement for offset. As a result, the offset error as derived in Table 8 needs to be taken into account. Also, co-addition and averaging is taken into account. In Table 9 the offset error is added after averaging, but as the offset correction is a dynamic correction per measurement, the actual errors is most likely smaller, as the residuals of the offset correction are expected to improve by averaging. Using the analysis from the offset correction, dark current and background correction and smear correction, it is now possible to assess the total additive error after correction. This is provided in Table 10. The values shown are percentages of the worst case signal for the low level radiance reference scene. Table 10 shows the compliancy of the additive errors with SRD requirement OB-UVN-0335. The offset residual for band 6 (NIR) is just at the requirement of 1.0%. The error for band 6 is dominated by the exposure smear residual, which is a very worst case situation, as described in Section 6.3.3.1, that is never expected to occur.

6.3.4 Multiplicative Errors

The following requirement has to do with the multiplicative errors:

- OB-SWI-0240

For this linearity requirements, only a decomposition into L01b and CKD needs to be made; a further decomposition is not necessary / possible. The error budgets are for this purpose split into halve, i.e. 50% of the budget for the L01b and 50% for the CKD.

Band	**Low Pixel Filling**	**Binning Factor**	**Low Register Pixel Filling (ke)**	**Exposure Time (ms)**	**Dark current (ke)**	**Background signal (ke)**	**Low ADC Filling (DN)**	**Dark Current**	**Background Signal**	**Detector Offset**	**Electronics Offset**	**Exposure Smear**	**Total Offset**
1 (UV)	0	16	4.8	216	0.55296	1.6	819.2	1.15E-01	33.3%	250.0%	2.0%	0.3%	297.1%
2 (UV)	0	4	12.0	216	0.13824	0.4	16.384	1.15E-02	3.3%	100.0%	97.7%	1.0%	203.2%
3 (UVIS)	0	4	300.0	36	0.02304	0.4	409.6	7.68E-05	0.1%	4.0%	3.9%	14.0%	22.1%
4 (UVIS)	0	4	600.0	36	0.02304	0.4	819.2	3.84E-05	0.1%	2.0%	2.0%	25.2%	29.2%
5 (NIR)	0	4	300.0	54	0.03456	0.4	409.6	1.15E-04	0.1%	4.0%	3.9%	39.6%	47.7%
6 (NIR)	0	2	138.0	54	0.01728	0.2	376.832	1.25E-04	0.1%	8.7%	4.2%	42.0%	55.1%

Table 7: Offset (additive errors) before correction in L01b.

Band	Detector Offset (uV)	Read-out Noise (uV)	Offset at AFE input (uV)	Noise at AFE input (uV)	Noise at ADC input (uV)	Total Offset (DN)	Total Noise (DN)	Offset SNR (pixel)	Offset SNR (ROR avg)	Offset error (ROR avg)
1 (UV)	16800	40	84000	221	1487	4617	12	378	5978	0.02%
2 (UV)	16800	40	25200	112	201	204	2	124	1958	0.05%
3 (UVIS)	8400	86	12600	160	231	115	2	61	959	0.10%
4 (UVIS)	8400	86	11340	150	211	91	2	53	833	0.12%
5 (NIR)	8400	86	12600	160	212	96	2	55	867	0.12%
6 (NIR)	16800	40	25200	112	198	192	2	118	1870	0.05%

Table 8: Detector and electronics offset correction analysis.

Band	Dark current (ke)	Background signal (ke)	DC+bkgnd (ke)	DC+bkgnd (uV)	shot noise (uV)	Read-out Noise (uV)	Total Noise (uV)	Signal at AFE input (uV)	Noise at AFE input (uV)
1 (UV)	0.6	1.6	2.2	3014.1	65.0	40.0	76.3	15070.7	393.1
2 (UV)	0.1	0.4	0.5	753.5	32.5	40.0	51.5	1130.3	122.5
3 (UVIS)	0.0	0.4	0.4	296.1	14.4	86.0	87.2	444.2	161.7
4 (UVIS)	0.0	0.4	0.4	296.1	14.4	86.0	87.2	399.8	151.3
5 (NIR)	0.0	0.4	0.4	304.2	14.6	86.0	87.2	456.3	161.7
6 (NIR)	0.0	0.2	0.2	304.2	20.6	40.0	45.0	456.3	116.5

Band	Noise at ADC input (uV)	Total DC+bkgnd (DN)	Total Noise (DN)	DC+bkgnd SNR	DC+bkgnd Co-add SNR	DC+bkgnd Avg SNR	Offset error (ROR avg) (DN)	DC+bkgnd Error (DN)	DC+bkgnd Error
1 (UV)	2627.6	841.5	21.6	39.0	87.2	1378.8	0.8	1.4	0.2%
2 (UV)	205.8	24.4	1.7	14.5	32.3	511.4	0.1	0.2	0.6%
3 (UVIS)	232.4	19.5	1.9	10.2	56.0	884.9	0.1	0.1	0.7%
4 (UVIS)	212.0	18.7	1.7	10.7	58.7	928.2	0.1	0.1	0.7%
5 (NIR)	213.1	18.9	1.8	10.8	48.2	762.9	0.1	0.1	0.7%
6 (NIR)	199.4	19.2	1.6	11.7	52.4	828.6	0.1	0.1	0.7%

Table 9: Dark current and background correction analysis.

Band	Dark Current	Background	Detector Offset	Electronics Offset	Exposure Smear	Dark Current and Background Residual	Detector and Electronics Offset Residual	Exposure Smear Residual	Total Offset	Residual Offset
1 (UV)	11.5%	33.3%	250.0%	2.0%	0.3%	0.1%	0.0%	0.0%	297.1%	0.1%
2 (UV)	1.2%	3.3%	100.0%	97.7%	1.0%	0.0%	0.1%	0.1%	203.2%	0.2%
3 (UVIS)	0.0%	0.1%	4.0%	3.9%	14.0%	0.0%	0.0%	0.2%	22.1%	0.2%
4 (UVIS)	0.0%	0.1%	2.0%	2.0%	25.2%	0.0%	0.0%	0.4%	29.2%	0.4%
5 (NIR)	0.0%	0.1%	4.0%	3.9%	39.6%	0.0%	0.0%	1.0%	47.7%	1.0%
6 (NIR)	0.0%	0.1%	8.7%	4.2%	42.0%	0.0%	0.0%	1.0%	55.1%	1.0%

Table 10: Additive error analysis including L01b correction.

A Radiometry Error Budget Tables

In the following sections and tables we show what is the accuracy on the CKD parameters necessary to achieve the required radiometric accuracy (Table 3). The tables can be read for both the absolute radiance and irradiance requirements. The only difference between the two cases is the last step: in the case of the absolute irradiance the last step combines the irradiance sensitivity and gonio correction. The error can be distributed quadratically between the two components. The tables show five columns:

1. The accuracy required on the CKD parameter;
2. The cumulative (all steps up to the current) accuracy caused just by the CKD accuracy;
3. The accuracy of the L01b processor step;
4. The cumulative accuracy of the L01b processor;
5. The total caused by the CKD and the processor.

It is obvious but worth noticing that other choices of CKD and L01b errors are possible that lead to the same eventual accuracy. The values chosen here are educated guesses. Finally, note that the CKD and L01b errors are the same for all bands, and have been chosen so that the required accuracy is reached in the worst band (UV1). This means that in the remaining bands the requirements are almost always easily achieved. Another choice could have been made, namely make the CKD errors vary per band, and calibrate each band so that its accuracy is closer to what prescribed by the SRD. This has not been done to present a consistent picture of the calibration, but it should be kept in mind that there will be some latitude to reduce the number of measurements for some CKD parameters when performing the on-ground calibration. The results are summarized in Tables 11 and 12.

CKD and L01b accuracy

Algorithm	UVN CKD accuracy	SWIR CKD accuracy	L01b accuracy
Gain	0.6%		0.3%
Voltage to charge	0.6%	0.3%	0.3%
PRNU	0.6%		
Dark current	2%	0.2%	
Slit irregularity	0.6%	0.6%	0.3%
Radiance	0.6%	0.6%	0.6%
Irradiance + Gonio	0.6%	0.6%	0.3%

Table 11: Summary of required CKD and L01b accuracies.

Radiometric accuracy

Band	ABSRAD/IRR
UV(1)	1.9%
UV(2)	1.6%
VIS(3)	1.5%
VIS(4)	1.5%
NIR(5)	1.5%
NIR(6)	1.5%
SWIR(7)	2.0%
SWIR(8)	2.0%

Table 12: Summary of the absolute radiometric accuracy.

Reflectance accuracy

Band	Reflectance accuracy
1	1.5%
2	1.2%
3	1.0%
4	1.0%
5	1.0%
6	1.0%
7	1.8%
8	1.8%

Table 13: Reflectance accuracies.

A.1 Error Budget Table for Band 1

This is the table summarizing the error budget for Band 1. The dark current correction includes also the offset and background components.

Scenario UV(1) low ,accuracy 1.88%	**CKD accuracy**	**CKD cumulative accuracy**	**L01b accuracy**	**L01b cumulative accuracy**	**total**
Measured		0.00%	0.00%	0.00%	0.00%
Co-addition correction		0.00%	0.00%	0.00%	0.00%
Gain correction	0.600%	0.60%	0.30%	0.30%	0.67%
Voltage to charge correction	0.600%	0.85%	0.30%	0.42%	0.95%
ROR binning correction		0.85%	0.00%	0.42%	0.95%
PRNU correction	0.600%	1.04%	0.00%	0.42%	1.12%
Dark current correction	2.000%	1.57%	0.00%	0.42%	1.62%
Exposure time correction		1.57%	0.00%	0.42%	1.62%
Slit irregularity correction	0.600%	1.68%	0.30%	0.52%	1.76%
Radiance or Irradiance+Gonio sensitivity correction	0.600%	1.78%	0.30%	0.60%	1.88%

Scenario UV(1) high ,accuracy 1.88%	**CKD accuracy**	**CKD cumulative accuracy**	**L01b accuracy**	**L01b cumulative accuracy**	**total**
Measured		0.00%	0.00%	0.00%	0.00%
Co-addition correction		0.00%	0.00%	0.00%	0.00%
Gain correction	0.600%	0.60%	0.30%	0.30%	0.67%
Voltage to charge correction	0.600%	0.85%	0.30%	0.42%	0.95%
ROR binning correction		0.85%	0.00%	0.42%	0.95%
PRNU correction	0.600%	1.04%	0.00%	0.42%	1.12%
Dark current correction	2.000%	1.57%	0.00%	0.42%	1.62%
Exposure time correction		1.57%	0.00%	0.42%	1.62%
Slit irregularity correction	0.600%	1.68%	0.30%	0.52%	1.76%
Radiance or Irradiance+Gonio sensitivity correction	0.600%	1.78%	0.30%	0.60%	1.88%

A.2 Error Budget Table for Band 2

This is the table summarizing the error budget for Band 2. The dark current correction includes also the offset and background components.

Scenario UV(2) low ,accuracy 1.61%	**CKD accuracy**	**CKD cumulative accuracy**	**L01b accuracy**	**L01b cumulative accuracy**	**total**
Measured		0.00%	0.00%	0.00%	0.00%
Co-addition correction		0.00%	0.00%	0.00%	0.00%
Gain correction	0.600%	0.60%	0.30%	0.30%	0.67%
Voltage to charge correction	0.600%	0.85%	0.30%	0.42%	0.95%
ROR binning correction		0.85%	0.00%	0.42%	0.95%
PRNU correction	0.600%	1.04%	0.00%	0.42%	1.12%
Dark current correction	2.000%	1.24%	0.00%	0.42%	1.31%
Exposure time correction		1.24%	0.00%	0.42%	1.31%
Slit irregularity correction	0.600%	1.37%	0.30%	0.52%	1.47%
Radiance or Irradiance+Gonio sensitivity correctio	0.600%	1.50%	0.30%	0.60%	1.61%

Scenario UV(2) high ,accuracy 1.61%	**CKD accuracy**	**CKD cumulative accuracy**	**L01b accuracy**	**L01b cumulative accuracy**	**total**
Measured		0.00%	0.00%	0.00%	0.00%
Co-addition correction		0.00%	0.00%	0.00%	0.00%
Gain correction	0.600%	0.60%	0.30%	0.30%	0.67%
Voltage to charge correction	0.600%	0.85%	0.30%	0.42%	0.95%
ROR binning correction		0.85%	0.00%	0.42%	0.95%
PRNU correction	0.600%	1.04%	0.00%	0.42%	1.12%
Dark current correction	2.000%	1.24%	0.00%	0.42%	1.31%
Exposure time correction		1.24%	0.00%	0.42%	1.31%
Slit irregularity correction	0.600%	1.37%	0.30%	0.52%	1.47%
Radiance or Irradiance+Gonio sensitivity correctio	0.600%	1.50%	0.30%	0.60%	1.61%

A.3 Error Budget Table for Band 3

This is the table summarizing the error budget for Band 3. The dark current correction includes also the offset and background components.

Scenario UVIS(3) low ,accuracy 1.47%	**CKD accuracy**	**CKD cumulative accuracy**	**L01b accuracy**	**L01b cumulative accuracy**	**total**
Measured		0.00%	0.00%	0.00%	0.00%
Co-addition correction		0.00%	0.00%	0.00%	0.00%
Gain correction	0.600%	0.60%	0.30%	0.30%	0.67%
Voltage to charge correction	0.600%	0.85%	0.30%	0.42%	0.95%
ROR binning correction		0.85%	0.00%	0.42%	0.95%
PRNU correction	0.600%	1.04%	0.00%	0.42%	1.12%
Dark current correction	2.000%	1.04%	0.00%	0.42%	1.12%
Exposure time correction		1.04%	0.00%	0.42%	1.12%
Slit irregularity correction	0.600%	1.20%	0.30%	0.52%	1.31%
Radiance or Irradiance+Gonio sensitivity correction	0.600%	1.34%	0.30%	0.60%	1.47%

Scenario UVIS(3) high ,accuracy 1.47%	**CKD accuracy**	**CKD cumulative accuracy**	**L01b accuracy**	**L01b cumulative accuracy**	**total**
Measured		0.00%	0.00%	0.00%	0.00%
Co-addition correction		0.00%	0.00%	0.00%	0.00%
Gain correction	0.600%	0.60%	0.30%	0.30%	0.67%
Voltage to charge correction	0.600%	0.85%	0.30%	0.42%	0.95%
ROR binning correction		0.85%	0.00%	0.42%	0.95%
PRNU correction	0.600%	1.04%	0.00%	0.42%	1.12%
Dark current correction	2.000%	1.04%	0.00%	0.42%	1.12%
Exposure time correction		1.04%	0.00%	0.42%	1.12%
Slit irregularity correction	0.600%	1.20%	0.30%	0.52%	1.31%
Radiance or Irradiance+Gonio sensitivity correction	0.600%	1.34%	0.30%	0.60%	1.47%

A.4 Error Budget Table for Band 4

This is the table summarizing the error budget for Band 4. The dark current correction includes also the offset and background components.

Scenario UVIS(4) low ,accuracy 1.47%	**CKD accuracy**	**CKD cumulative accuracy**	**L01b accuracy**	**L01b cumulative accuracy**	**total**
Measured		0.00%	0.00%	0.00%	0.00%
Co-addition correction		0.00%	0.00%	0.00%	0.00%
Gain correction	0.600%	0.60%	0.30%	0.30%	0.67%
Voltage to charge correction	0.600%	0.85%	0.30%	0.42%	0.95%
ROR binning correction		0.85%	0.00%	0.42%	0.95%
PRNU correction	0.600%	1.04%	0.00%	0.42%	1.12%
Dark current correction	2.000%	1.04%	0.00%	0.42%	1.12%
Exposure time correction		1.04%	0.00%	0.42%	1.12%
Slit irregularity correction	0.600%	1.20%	0.30%	0.52%	1.31%
Radiance or Irradiance+Gonio sensitivity correctior	0.600%	1.34%	0.30%	0.60%	1.47%

Scenario UVIS(4) high ,accuracy 1.47%	**CKD accuracy**	**CKD cumulative accuracy**	**L01b accuracy**	**L01b cumulative accuracy**	**total**
Measured		0.00%	0.00%	0.00%	0.00%
Co-addition correction		0.00%	0.00%	0.00%	0.00%
Gain correction	0.600%	0.60%	0.30%	0.30%	0.67%
Voltage to charge correction	0.600%	0.85%	0.30%	0.42%	0.95%
ROR binning correction		0.85%	0.00%	0.42%	0.95%
PRNU correction	0.600%	1.04%	0.00%	0.42%	1.12%
Dark current correction	2.000%	1.04%	0.00%	0.42%	1.12%
Exposure time correction		1.04%	0.00%	0.42%	1.12%
Slit irregularity correction	0.600%	1.20%	0.30%	0.52%	1.31%
Radiance or Irradiance+Gonio sensitivity correctior	0.600%	1.34%	0.30%	0.60%	1.47%

A.5 Error Budget Table for Band 5

This is the table summarizing the error budget for Band 5. The dark current correction includes also the offset and background components.

Scenario NIR(5) low ,accuracy 1.47%	**CKD accuracy**	**CKD cumulative accuracy**	**L01b accuracy**	**L01b cumulative accuracy**	**total**
Measured		0.00%	0.00%	0.00%	0.00%
Co-addition correction		0.00%	0.00%	0.00%	0.00%
Gain correction	0.600%	0.60%	0.30%	0.30%	0.67%
Voltage to charge correction	0.600%	0.85%	0.30%	0.42%	0.95%
ROR binning correction		0.85%	0.00%	0.42%	0.95%
PRNU correction	0.600%	1.04%	0.00%	0.42%	1.12%
Dark current correction	2.000%	1.04%	0.00%	0.42%	1.12%
Exposure time correction		1.04%	0.00%	0.42%	1.12%
Slit irregularity correction	0.600%	1.20%	0.30%	0.52%	1.31%
Radiance or Irradiance+Gonio sensitivity correction	0.600%	1.34%	0.30%	0.60%	1.47%

Scenario NIR(5) high ,accuracy 1.47%	**CKD accuracy**	**CKD cumulative accuracy**	**L01b accuracy**	**L01b cumulative accuracy**	**total**
Measured		0.00%	0.00%	0.00%	0.00%
Co-addition correction		0.00%	0.00%	0.00%	0.00%
Gain correction	0.600%	0.60%	0.30%	0.30%	0.67%
Voltage to charge correction	0.600%	0.85%	0.30%	0.42%	0.95%
ROR binning correction		0.85%	0.00%	0.42%	0.95%
PRNU correction	0.600%	1.04%	0.00%	0.42%	1.12%
Dark current correction	2.000%	1.04%	0.00%	0.42%	1.12%
Exposure time correction		1.04%	0.00%	0.42%	1.12%
Slit irregularity correction	0.600%	1.20%	0.30%	0.52%	1.31%
Radiance or Irradiance+Gonio sensitivity correction	0.600%	1.34%	0.30%	0.60%	1.47%

A.6 Error Budget Table for Band 6

This is the table summarizing the error budget for Band 6. The dark current correction includes also the offset and background components.

Scenario NIR(6) low ,accuracy 1.47%	CKD accuracy	CKD cumulative accuracy	L01b accuracy	L01b cumulative accuracy	total
Measured		0.00%	0.00%	0.00%	0.00%
Co-addition correction		0.00%	0.00%	0.00%	0.00%
Gain correction	0.600%	0.60%	0.30%	0.30%	0.67%
Voltage to charge correction	0.600%	0.85%	0.30%	0.42%	0.95%
ROR binning correction		0.85%	0.00%	0.42%	0.95%
PRNU correction	0.600%	1.04%	0.00%	0.42%	1.12%
Dark current correction	2.000%	1.04%	0.00%	0.42%	1.12%
Exposure time correction		1.04%	0.00%	0.42%	1.12%
Slit irregularity correction	0.600%	1.20%	0.30%	0.52%	1.31%
Radiance or Irradiance+Gonio sensitivity correction	0.600%	1.34%	0.30%	0.60%	1.47%

Scenario NIR(6) high ,accuracy 1.47%	CKD accuracy	CKD cumulative accuracy	L01b accuracy	L01b cumulative accuracy	total
Measured		0.00%	0.00%	0.00%	0.00%
Co-addition correction		0.00%	0.00%	0.00%	0.00%
Gain correction	0.600%	0.60%	0.30%	0.30%	0.67%
Voltage to charge correction	0.600%	0.85%	0.30%	0.42%	0.95%
ROR binning correction		0.85%	0.00%	0.42%	0.95%
PRNU correction	0.600%	1.04%	0.00%	0.42%	1.12%
Dark current correction	2.000%	1.04%	0.00%	0.42%	1.12%
Exposure time correction		1.04%	0.00%	0.42%	1.12%
Slit irregularity correction	0.600%	1.20%	0.30%	0.52%	1.31%
Radiance or Irradiance+Gonio sensitivity correction	0.600%	1.34%	0.30%	0.60%	1.47%

A.7 Error Budget Table for Band 7

This is the table summarizing the error budget for Band 7.

Scenario SWIR(7) low ,accuracy 2.04%	**CKD accuracy**	**CKD cumulative accuracy**	**L01b accuracy**	**L01b cumulative accuracy**	**total**
Measured		0.00%	0.00%	0.00%	0.00%
Co-addition correction		0.00%	0.00%	0.00%	0.00%
Offset correction	0.010%	0.24%	0.30%	0.30%	0.39%
Voltage to charge correction	0.300%	0.39%	0.30%	0.42%	0.57%
Dark current correction	0.200%	1.75%	0.00%	0.42%	1.80%
Exposure time correction		1.75%	0.00%	0.42%	1.80%
Slit irregularity correction	0.600%	1.85%	0.30%	0.52%	1.93%
Radiance or Irradiance+Gonio sensitivity correction	0.600%	1.95%	0.30%	0.60%	2.04%

Scenario SWIR(7) high ,accuracy 2.04%	**CKD accuracy**	**CKD cumulative accuracy**	**L01b accuracy**	**L01b cumulative accuracy**	**total**
Measured		0.00%	0.00%	0.00%	0.00%
Co-addition correction		0.00%	0.00%	0.00%	0.00%
Offset correction	0.010%	0.24%	0.30%	0.30%	0.39%
Voltage to charge correction	0.300%	0.39%	0.30%	0.42%	0.57%
Dark current correction	0.200%	1.75%	0.00%	0.42%	1.80%
Exposure time correction		1.75%	0.00%	0.42%	1.80%
Slit irregularity correction	0.600%	1.85%	0.30%	0.52%	1.93%
Radiance or Irradiance+Gonio sensitivity correction	0.600%	1.95%	0.30%	0.60%	2.04%

A.8 Error Budget Table for Band 8

This is the table summarizing the error budget for Band 8.

Scenario SWIR(8) low ,accuracy 2.04%	**CKD accuracy**	**CKD cumulative accuracy**	**L01b accuracy**	**L01b cumulative accuracy**	**total**
Measured		0.00%	0.00%	0.00%	0.00%
Co-addition correction		0.00%	0.00%	0.00%	0.00%
Offset correction	0.010%	0.24%	0.30%	0.30%	0.39%
Voltage to charge correction	0.300%	0.39%	0.30%	0.42%	0.57%
Dark current correction	0.200%	1.75%	0.00%	0.42%	1.80%
Exposure time correction		1.75%	0.00%	0.42%	1.80%
Slit irregularity correction	0.600%	1.85%	0.30%	0.52%	1.93%
Radiance or Irradiance+Gonio sensitivity correction	0.600%	1.95%	0.30%	0.60%	2.04%

Scenario SWIR(8) high ,accuracy 2.04%	**CKD accuracy**	**CKD cumulative accuracy**	**L01b accuracy**	**L01b cumulative accuracy**	**total**
Measured		0.00%	0.00%	0.00%	0.00%
Co-addition correction		0.00%	0.00%	0.00%	0.00%
Offset correction	0.010%	0.24%	0.30%	0.30%	0.39%
Voltage to charge correction	0.300%	0.39%	0.30%	0.42%	0.57%
Dark current correction	0.200%	1.75%	0.00%	0.42%	1.80%
Exposure time correction		1.75%	0.00%	0.42%	1.80%
Slit irregularity correction	0.600%	1.85%	0.30%	0.52%	1.93%
Radiance or Irradiance+Gonio sensitivity correction	0.600%	1.95%	0.30%	0.60%	2.04%