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DOCUMENT

Technical Note: Sentinel-3 OLCI-A spectral response functions



APPROVAL

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2 INTRODUCTION

2.1 Scope

In the frame of pre-launch and commissioning activities for Sentinel-3 OLCI-A instrument, spectral Response Functions (SRF) based on on-ground and inflight characterisation measurements were derived. They are described in the present document.

Further calibration and validation activities are planned. These activities will allow verifying the inflight performance of the instrument. It is in particular foreseen to monitor the spectral characteristics of OLCI-A through the entire mission duration [RD-01, RD-12] and this might again lead to updates of the instrument SRFs at a later stage in the mission lifetime.

This technical note is divided in the following sections:

- Section 2 provides some background information on OLCI from an instrumental point of view.
- Section 3 provides a description of the data used for the generation of the OLCI SRFs. These are data from the instrument on-ground and inflight characterisation.
- Section 4 documents the methodology followed to derive the SRFs for the 21 OLCI spectral bands from the characterisation data as well as the computation of the in-band extraterrestrial solar irradiance, the spectral bandwidth and the central wavelength for each band.
- Section 5 describes the methodology for the inflight spectral characterisation.
- Section 6 provides uncertainty budgets associated to the previous calculations.
- Section 7 describes the actual dataset.



2.2 Reference and Applicable Documents

Reference documents

RD-01	Sentinel-3 Calibration and Validation Implementation Plan	S3-PL-ESA-SY-0380 v4
RD-02	Donlon, C. et al., "The Global Monitoring for Environment and Security (GMES) Sentinel3 mission"	RSE, Vol. 120, p.37557, (2012)
RD-03	The Sentinel-3 Ocean and Land Colour Imager in Optical Payloads for Space Missions, ISBN 9781118945148	Wiley, Jan-2016
RD-04	Sentinel-3 Calibration and Validation Implementation Plan	S3-PL-ESA-SY-0380 v4
RD-05	Thuillier G., M. Hersé, D. Labs, T. Foujols, W. Peetermans, D. Gillotay, P. C. Simon, and H. Mandel, "The solar spectral irradiance from 200 to 2400 nm as measured by the SOLSPEC spectrometer from the ATLAS and EURECA missions"	Sol. Phys., 214: 1-22 (2003)
RD-06	OLCI FM5R camera: Analysis of spectrometric performance tests	S3-TN-TAF-OL-03194 v1
RD-07	OLCI FM7 camera: Analysis of spectrometric performance tests	S3-TN-TAF-OL-03094 v1
RD-08	OLCI FM8 camera: Analysis of spectrometric performance tests	S3-TN-TAF-OL-03150 v1
RD-09	OLCI FM9 camera: Analysis of spectrometric performance tests	S3-TN-TAF-OL-03167 v1
RD-10	OLCI FM10 camera: Analysis of spectrometric performance tests	S3-TN-TAF-OL-03184 v1
RD-11	Nominal and Special OLCI Commanding Sequences (use cases and operational aspects)	S3-TN-ESA-OL-0572 v2.1
RD-12	Sentinel-3 CAL/VAL Plan for the MPC Commissioning Phase – OPT	S3MPC.ACR.PLN.008, issue 1.4, 08/10/2015
RD-13	Chance, K., and Kurucz, R. L., 2010, An improved high resolution solar reference spectrum for earth's atmosphere measurements in the ultraviolet, visible, and near infrared.	J. Quant. Spect. Rad.Trans., 111, 1289– 1295.

Reference data sets

RDS-01	OLCI-A Characterization and Calibrati	on Data Base	S3A_O_CCDB_V7.02
	S3A_OL_CCDB_CHAR_AllFiles.201511200)3949_1.nc4.	_2015_20_11_OL



2.3 Acronyms

CCD: Couple-charged device FM: Flight Models FoV: Field of View GMES: Global Monitoring for Environment & Security ILS: Instrument Line Shape LUT: Look-up Table OLCI: Ocean and Land Colour Instrument S3: Sentinel-3 SRF: Spectral Response Function TAS: Thales Alenia Space



3 BACKGROUND

3.1 The OLCI instrument

The Ocean and Land Colour Instrument (OLCI) is a visible-near-infrared push-broom imaging spectrometer onboard the Sentinel-3 (S3) series of satellites [RD-o2] as a part of the Copernicus¹ programme (formerly referred to as Global Monitoring for Environment & Security, or GMES). Four OLCI instruments will ultimately be developed and tested in the frame of the Sentinel programme. The development activities are carried out by a consortium led by Thales Alenia Space (France) [RD-o2]. All four instruments are currently at various development stages and are already (or will be) integrated in the respective S3 satellites, named in alphabetic order as S3A, S3B, S3C and S3D. The first of the series (S3A) was launched in February 2016.

The OLCI instrument consists of 5 imaging-spectrometer-type cameras. The cameras integrated in OLCI-A are the Flight Models (FM) FM5R, FM9, FM7, FM10 and FM8. Since those cameras are not integrated in a sequential order, and for clarity, the cameras are re-named as module 1, 2, 3, 4, 5 moving sequentially from East to West at spacecraft level and in reversed order when their swath are projected at ground level (see Figure 1).



Figure 1: OLCI's 5 camera modules arranged in fan-shaped form creating a single swath on-ground.

Each one of the 5 OLCI cameras is equipped with its own CCD. The CCDs are composed of image areas of 740 x 520 detectors (see Figure 3) amounting to 3700 ground pixels (740 pixels x 5 camera) over a 1270 km swath and for a spectral range from 390 to 1040 nm.

¹ Copernicus programme site:

[[]http://ec.europa.eu/growth/sectors/space/copernicus/index_en.htm]



OLCI elementary spectral bands have a spectral resolution of about \sim 1.7 nm and a spectral sampling interval of \sim 1.25 nm. The 21 nominal programmable spectral bands are generated by binning the signal of consecutive CCD lines into variable width spectral bands.

The following scheme gives the correspondence between camera pixels and instrument field angle.



Figure 2: Correspondence between camera pixel and instrument field angle.

3.2 OLCI spatial and spectral dimensions

Each individual CCD pixel (figure 3) can be referred to by the following dimensions:

1. CCD-column:

There are 740 columns on each module CDD, imaging a total across track field of view of approximately 14 degrees. The column numbering used in this document is such that index increases when pixel's projection on ground varies from East to West for daytime orbits.

Important note to users: The CCD column index described above is defined with respect to the OLCI instrument: it follows the order of the read-out electronics, implying that its spatial ordering is in reversed order with respect to that of the modules (module index increases from West to East at descending node while pixel index increase from East to West). OLCI Level 1 and Level 2 products have adopted another convention, that preserves spatial continuity, for both the image grid (the L1/L2 product pixels) and the instrument grid: in the Instrument Data annotation file (instrument_data.nc), common to L1 & L2, central wavelengths, bandwidths and in-band irradiances are provided for each image grid spatial pixel – the so-called detectors – and the detector indices are provided for each image grid. The ordering of the "detectors" – that are actually equivalent to what we call here CCD columns – is however generalised over the 5 modules, increasing West to East and starting at 0. The column index col of module m in the above equation is related to detector_index d of a Level 1b product as follows: $d = m \cdot 740 - col$

2. CCD-row:

The spectral dimension of the CCD varies from the NIR (1040nm) to UV (390nm) wavelengths. The nominal (idealized) dispersion law, giving the CCD-row number and central wavelength of CCD-pixel is relative to the CCD reference line (line 335 at 681.875 nm):

 $\lambda_n(row) = 681.875 - 1.25 * (row - 335)$

Which is equivalent to:

$$\lambda(row) = 1100.625 - 1.25 * row$$

Note that all wavelengths in this document are given with respect to vacuum conditions.





Figure 3: Dimension of the CCD and the allocation of imaged pixels.



4 INPUT DATA

4.1 Preflight Data

The preflight data set used for the generation of the SRFs originates from [RDS-01] and is part of the OLCI-A Characterization and Calibration Data Base (CCDB).

Furthermore, the solar irradiance spectrum from Thuillier et al. [RD-05] was used for the calculation of the 21 OLCI in-band extra-terrestrial solar irradiance (given at an Earth Sun distance of 1 astronomical unit (AU)).

The preflight characterization was only performed for restricted number of location in the module field of view and spectral wavelengths. These locations on the CCD are indicated in the following by the subscript $_{tas}$. Consequently, a spatial and spectral interpolation of the instrument characterization data is required to extend these data to the entire CCD rows and columns.

The characterization data:

- Central wavelength Λ_{tas} of CCD-pixel for: 5 modules x 41 rows x 9 columns. Not all of the rows have been used, since some of the monochromatic measurements are less reliable (RD-06/7/8/9/10) due to spikes in the emission spectrum of the used Xenon lamp. The filtered (not used) rows are: 64, 176, 180, 270
- Instrumental line shape (ILS) convolution kernel at 5 modules x 41 rows x 9 columns x 61 sampling steps
- Transmission of the imaging sub-assembly, T₁, at: 5 modules x 42 wavelengths
- Transmission of the spectrometer, T₂, at: 5 modules x 18 wavelengths
- Uniformity of the transmission across the module FOV, T_U , at 5 modules x 42 wavelengths x 9 columns
- CCD Detector Spectral Responsivity of the detector, the CCDR, at 5 modules x 23 wavelengths

Additional data:

- OLCI-A spectral band setting was retrieved from: File S3A_OL_CCDB_PROG_programmable.20151113211730_1.nc4 of RDS-01
- Solar irradiance in units of W/m²/ μ m are obtained from: File S3A_SY_CCDB_CHAR_Thuillier-Solar-Irradiance.20110407133714_1.nc4 of RDS-01

4.1.1 Instrumental line shape (ILS)

First, the ILS kernel is used to approximate individual CCD element spectral bandwidths. It is assumed that they have a Gaussian shape, normalized to a maximum value of 100. A Gaussian can be described by 3 parameters: a (=100), μ and σ .

$$ils(\lambda) = a \exp\left(\frac{-(\lambda-\mu)^2}{2 \sigma^2}\right)$$



The bandwidth σ is estimated using the full width at half maximum *fwhm*:

$$\sigma = \frac{fwhm}{\sqrt{ln256}}$$

The estimation of σ is performed for all given CCD-columns and rows. Results are shown in Figure 4. A bi-linear interpolation (*BL1*, see Annex A.2) of the pixel bandwidth is later used to estimate the central wavelength for all needed CCD rows and all CCD columns:

$$\sigma_{c,r}(col, row) = BLI(\sigma(col_{tas}, row_{tas}), col, row)$$

4.1.2 Central wavelength of the CCD elements

The nominal dispersion law (i.e, the linear law describing the ideal variation of the central wavelength with the CCD lines, see definition in section 3.2) does not accurately reflect the measured dispersion during the modules characterisation as shown in Figure 5. Hence a bi-linear interpolation (BLI, see Annex A.2) of the CCD-pixel central wavelength (Λ_{tas}) is later used to estimate the central wavelength for all needed CCD rows and all CCD columns:

$$\lambda_{c,r}(col, row) = BLI(\Lambda_{tas}(col_{tas}, row_{tas}), col, row)$$

4.1.3 Relative weight of the CCD elements

In order to calculate the spectral response functions, the wavelength dependence of the instrument response must be considered. The wavelength dependence arises from the spectral dependence of the optical components and the spectral dependence of the CCD response, which all have been quantified on ground. However only the relative weight w of the CCD elements which are binned into one band need to be known. The relative weight is calculated from T_1, T_2, T_u and CCDR (see 4.1):

$$w(col,\lambda) = T_1^*(\lambda) \cdot T_2^*(\lambda) \cdot T_U^*(col,\lambda) \cdot CCDR^*(\lambda)$$

 λ is the considered wavelength. The superscript * indicates that T_1, T_2 and *CCDR* have to be linear interpolated to λ , and T_U has to be bi-linear interpolated to *col* and λ .

In Figure 6 the single contributions to the final relative weights are shown. Remarkable is the strong feature at around 400 nm of T_1 . This originates from the so called *inverse filter* that is used to flatten the module spectral sensitivity and to counter-balance the CCD spectral responsivity [RD-05].

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Figure 4: Left: Bandwidth (in nm) of the CCD pixel as function of the CCD row (wavelength) and CCD column (module FoV). Middle: Bandwidth as function of CCD row (wavelength). Right: Bandwidth as function of the module FoV (directly related to the CCD column). The previous plots are provided for each individual module from top line to bottom line.

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Figure 5: Deviation from the nominal dispersion law (i.e. the linear law describing the variations of the central wavelength with the CCD line) as function of central wavelength (bottom horizontal axis) and row number (top horizontal axis) for the five OLCI modules at three different CCD columns (indicated with red, green and blue) as provided by TAS.





Figure 6: Left and Right: The weight (as described in the text) for the spectral response function for all modules, all wavelengths and field of views. Middle: The single contributions to the weight, each normalized to maximum value of 1. Right: The weight for the spectral response function as a function of CCD-column (FoV).



4.2 Inflight data

4.2.1 Spectral campaigns

During dedicated campaigns, OLCI can be configured to transmit detector counts in 46 specific μ bands consisting of a single CCD-row each, instead of the 21 nominal binned bands. For the purpose of the inflight spectral characterisation three different settings have been defined, where the bands are grouped around *spectral features* of a) the solar irradiance (Fraunhofer lines), or b) the atmospheric transmission (the pronounced oxygen absorption band at 760nm) and c) the spectral features of the erbium doped diffuser ('pink diffuser'). In any case the goal was to compare the measured spectral shape with simulated spectral shapes assuming different deviations of the centre wavelengths of the μ bands from their nominal position. The spectral campaigns were:

- So3: 44 µbands grouped around 3 Erbium features lines on erbium doped diffuser
- So2: as So3 but on diffuser 1
- So7: 45 µbands grouped around 8 solar Fraunhofer lines on diffuser 1
- So9: 45 µbands grouped around 4 solar Fraunhofer lines and the oxygen A absorption on earth view
- So8: as So9 but on diffuser 1

The So2 measurement was used twofold, either as the calibration reference for the So3 spectral calibration or like the So7, exploiting solar features. The band settings are shown in Figure 7 and listed (as spectral row numbers) below together with the center wavelength of the associated spectral feature:

- So₃/o₃:
 - o 405nm: [546,547,548,549,550,551,552,553,554,555,556,557,558,559,560]
 - o 520nm: [456,457,458,459,460,461,462,463,464,465,466,467,468,469]
 - o 800nm: [234,235,236,237,238,239,240,241,242,243,244,245,246,247,248]
- So7:
 - o 395nm: [560,561,562,563,564,565,566,567,568,569]
 - 409nm: [551,552,553,554,555]
 - 430nm: [534,535,536,537,538]
 - 486nm: [490,491,492,493,494]
 - o 589nm: [407,408,409,410,411]
 - o 656nm: [354,355,356,357,358]
 - 854nm: [195,196,197,198,199]
 - o 866nm: [186,187,188,189,190]
- So8/o9:
 - o 485nm: [489,490,491,492,493,494]
 - o 656nm: [354,355,356,357,358]
 - 770nm: [258,259,260,261,262,263,264,265,266,267,268,269,270,271, 272,273,274,275]
 - 854nm: [195,196,197,198,199]
 - o 1006nm: [72,73,74,75,76,77,78,79,80,81,82]





Figure 7: Position of the used bands for the spectral campaigns. (Upper So7, second and lowest: So2/So3, third: So8/So9.) Further is shown: the solar irradiance at the top of atmosphere (upper and second), the solar irradiance at bottom of atmosphere (third) and the spectral reflectivity of the pink diffuser at high resolution and in arbitrary units.

During the commissioning phase 22 spectral campaigns were performed (So2 and So3 are done in conjunction):

S07: 2016/03/01, 2016/04/22, 2016/05/31 S08: 2016/03/01, 2016/04/15 S02/S03: 2016/03/01, 2016/04/18, 2016/05/31 S09: 2016/03/01, 2016/04/14, 2016/04/15, 2016/04/18, 2016/04/28, 2016/04/29, 2016/05/04, 2016/04/18, 2016/06/09, 2016/06/13, 2016/06/20, ...

The corresponding orbit identifiers are given in the appendix C.

4.2.2 Spectral feature look-up table for Fraunhofer lines

In preparation for the spectral campaigns, for each spectral feature, a look-up table lut has been created. Each look-up table is five dimensional:

- 1. module number (always 5)
- 2. band number of spectral feature
- 3. $\delta \lambda$: deviation of row d central wavelength from nominal
- 4. δd : deviation of row dispersion from nominal (1.25nm)
- 5. δbw : deviation of row bandwidth from nominal (1.8nm *fwhm*)

Each entry of the look-up table is the convolution of the row relative spectral response *ils* with the high resolution reference data *hrd* (SAO2010 solar irradiance for the Fraunhofer lines [RD-13], and spectrally highly resolved radiative transfer simulations for the oxygen absorption band):

$$lut(module, band, \delta\lambda, \delta d, \delta bw) = weight(module, \lambda_{center}) \cdot \int ils(\lambda_{center}, bw)(\lambda') \cdot hrd(\lambda')d\lambda'$$
$$ils(\lambda_{center}, bw)(\lambda) = a \exp\left(\frac{-(\lambda - \lambda_{center})^{2}}{2\sigma^{2}}\right)$$
$$\lambda_{center} = \lambda_{center}(band, \delta\lambda, \delta d); \qquad \sigma = \frac{bw}{\sqrt{ln256}}$$

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The weight is calculated from T_1 , T_2 , T_u and *CCDR* (see section 4.1):

weight
$$(\lambda) = T_1 (\lambda) \cdot T_2 (\lambda) \cdot T_U^* (\lambda) \cdot CCDR (\lambda)$$

4.2.3 Central wavelength and bandwidth of the CCD elements from Fraunhofer features

The central wavelength and bandwidth of a CCD element belonging to a spectral feature have been estimated by optimizing/minimizing the Euclidian distance between the measurement and the look-up table entries:

$$\sum_{k=1}^{band} \left[Norm(lut(module, band, \delta\lambda, \delta d, \delta bw)) - Norm(measurement(band)) \right]^2$$

The measurements have been corrected for the dark signal. *Norm* was applied to the measurement and to the look-up table entry alike, to break the dependency on absolute calibration and unconsidered slowly varying residual instrumental effects. *Norm* simply divides a sequence *seq* of numbers by their linear fit (actually, this is similar to the differential optical absorption spectroscopy, where slowly varying contributions are removed by a polynomial fit).

$$Norm(seq) = seq/linear(seq)$$

The minimization is applied for all ccd-columns (field of view) for all spectral features and for all modules. Eventually the field of view dependency is smoothed by a second order polynomial. The root mean squared distance between the polynomial fit and the individual retrievals is regarded as the precision (not the accuracy) of the inflight characterization of the individual bands. Figure 8 and Figure 9 show two examples for the So7 spectral campaign measurement of the Fraunhofer lines at 430nm and 853nm. It is evident, that the 430nm Fraunhofer line produces less noisy results than the 853nm line. The reason is the larger line strength of the 430nm feature.



Figure 8: Example for the result (green line) of the inflight spectral μ-band characterisation using the Fraunhofer line at 430nm for module 3. The abscissa is the ccd-column (field of view dimension). The ordinate is the band central wavelength in nm (left) and band fwhm in nm (right). The red line is the pre-flight characterisation; the yellow line is the nominal value. The shaded area specifies the precision.



Figure 9: As Figure 8, but for the Fraunhofer line at 852nm.

The mean uncertainties related to the spectral features are:

feature	395	405	409	430	486	520	589	656	770	800	854	866	1006
$\lambda[nm]$	0.03	0.13	0.15	0.05	0.12	0.07	0.18	0.10	0.02	0.4	0.13	0.20	0.45
bw[nm]	0.03	0.3	0.3	0.2	0.1	0.2	0.35	0.25	0.02	0.7	0.3	0.4	nan

Table 1: Precision of the wavelength and bandwidth estimation for each spectral feature (the low intensity of the 1006 nm feature did not allow an estimation of the bandwidth).

4.2.4 Central wavelength from pink diffuser features

The absolute central wavelength of specific rows of the CCD array is determined from on-orbit observations of a dedicated diffuser showing marked spectral absorption lines thanks to rare earth doping. The wavelength calibration is achieved by matching the OLCI measurements, normalised to those of a non-doped diffuser, to the reference spectrum of relative spectral hemispherical reflectance of the spectral calibration diffuser, characterised on ground.

The OLCI spectral calibration measurements are composed of acquisitions with a dedicated band setting, that appropriately sample several spectral features of the spectral diffuser, from two successive orbits – in order to minimise the diffuser BRDF variations – the first one using the nominal "white" diffuser and the second one using the spectral diffuser.

Acquisitions are done at the highest OLCI spectral resolution, i.e. with each micro-band being composed of only one CCD row; the 45 useful micro-bands of OLCI allow for the simultaneous measurement of three absorption lines.

Once corrected for the main instrumental effects (non-linearity, dark offset and smear), the ratio of corrected counts from the spectral diffuser over the white ones is the best estimate of the spectral diffuser's relative spectral reflectance that can be measured on-orbit, and it can be matched to its reference, characterised on-ground, in order to derive absolute central wavelength at the corresponding CCD rows.





Figure 10: spectral diffuser relative reflectance spectrum (solid line) with (nominal) OLCI micro-channels (symbols).

The matching process is applied on a pixel-by-pixel basis, for each of the \sim 500 acquisitions. The time variability of a calibration sequence (standard deviation) can be used as a proxy for the precision. No attempt is made to estimate the bandwidth.

Feature	410	524	800
Standard deviation [nm]	0.06	0.02	0.05

Table 2 : Precision of the wavelength estimation for each observed spectral feature of
the Erbium doped diffuser.





Figure 11: Example for the result (green line) of the inflight spectral μ-band characterisation using the 3 observed spectral lines of the Erbium-doped diffuser. The abscissa is the CCD-column (field of view dimension). The ordinate is the band central wavelength in nm. The red line is the pre-flight characterisation; the grey area illustrates the measurement repeatability (±2σ).

4.2.5 Consistency of Fraunhofer and pink diffuser measurements

As mentioned before, the S02/S03 band settings could be used twofold, either with solar Fraunhofer spectral features using the measurements on diffuser 1, or with Erbium spectral features using the measurements on the pink diffuser. Both methods should produce consistent results. This has been tested and it is exemplary shown for the 2016/03/01 campaign in Figure 12. Both methods agree very well within their uncertainty, the mean distance is smaller than 0.03nm for 409nm and 520nm features and smaller than 0.18nm for the 800nm feature, where however, the Fraunhofer method can hardly work, since the solar features are weak. It should be mentioned, that the Erbium method shows a tiny curvature over the field of view for module 4 and 3 (not shown), which has neither been observed during the pre-flight characterisation, nor on the other modules.





Figure 12: Result of the Fraunhofer calibration (green line) and the Erbium calibration (blue line) for the 409nm (left), 520nm (middle) and 800nm (right) spectral features. The shaded area is the uncertainty of the Fraunhofer calibration. The upper line is for module 1 the lower line for module 4.

4.3 Combination of preflight and inflight data

We consider the preflight as well as the inflight spectral characterization as correct. Hence, differences between both must stem from their inherent uncertainty and/or from some kind of distortion during instrument integration, rocket launch or in orbit. The distortions are small (see e.g. Figure 8) and thus we can quantify the small effects of the distortion as a kind of Taylor series around the center of the CCD:

$$stb = o + \frac{370 - col}{740} * tc + \frac{335 - row}{670} * tr + \left(\frac{335 - row}{670}\right)^2 * qr$$

stb stands for shift, tilt and bend. The according coefficients offset (shift) *o*, column tilt *tc*, row tilt *rc* and bend *qr* are in units of *nm*.

The coefficients are calculated for the central wavelengths as well as for the bandwidth by minimizing the weighted root mean square difference between the bilinear interpolated preflight

$$BLI(\Lambda_{tas}(col_{tas}, row_{tas}), col, row_{central})$$

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and the modified inflight

$$\Lambda_{\text{inflight}}(col, row_{central}) + stb(col, row_{central}).$$

 $row_{central}$ is the particular central row of the spectral feature. The weights are the inverse squared uncertainties of the µband center wavelengths/ bandwidth of the respective spectral features.

$$\sum_{i=1}^{col features} \frac{1}{\sigma_{\lambda}(row_{central})^{2}} \Big(BLI(\Lambda_{tas}(col_{tas}, row_{tas}), col, row_{central}) - \Lambda_{inflight}(col, row_{central}) - stb_{\lambda}(col, row_{central}) \Big)^{2} \Rightarrow \min$$

The formula for the bandwidth optimization is accordingly. Basis was always the latest in flight characterizations. The following table gives an example for the current correction terms for the center wavelength (used dates: 20160531T114200_S07, 20160531T082002_S02, 20160620T091818S09)

	0	tc	tr	qr
Mod1	0.09	-0.08	0.14	-0.41
Mod2	0.05	-0.11	0.01	-2.22
Mod3	-0.04	-0.03	0.18	-0.48
Mod4	0.	-0.04	0.22	0.43
Mod5	0.12	0.01	-0.06	-0.86

The central wavelength and bandwidth of each CCD element are eventually calculated:

 $\lambda_{c,r}(col, row) = BLI(\Lambda_{tas}(col_{tas}, row_{tas}), col, row) - stb_{\lambda}(col, row)$

 $bw_{c,r}(col, row) = BLI(bw(col_{tas}, row_{tas}), col, row) - stb_{bw}(col, row)$



5 SRF CALCULATION PROCEDURE

This section describes the procedure to calculate the SRFs at any location in the FOV, for any of the 5 OLCI camera modules, and any of the 21 spectral bands. Taking all 740 pixels of each module into account for the 21 bands, there are actually 77700 SRFs which need to be generated with the described methodology to derive the full set of spectral parameters (central wavelength, FWHM, in-band irradiance) required by the data processing.

It is currently considered that if users do not need individual SRFs related to each of the 740 CCD columns for each spectral band, either 3 in-FOV positions (West, centre, East, making a total of 315 SRFs as presented in section 7) or a single mean SRF per band (making a total of 21) are sufficiently representative. However, this might be reconsidered at the end of the commission phase after the in-flight verification of the spectral calibration will be performed.

5.1 Spectral response function of the **21** OLCI spectral bands

In the following subsections the spectral responses are provided for the 21 OLCI spectral bands.

5.1.1 CCD rows of a band

The 21 OLCI spectral bands are constructed by binning individual consecutive rows. The binned rows are the same for all viewing directions (CCD-columns) and currently the same for all modules. However, instrument programing allows them to differ from module to module and this possibility may be used later if deemed necessary by in-flight measurements to better homogenize channels positions between modules. The current OLCI-A bands definitions are:

							-
OLCI-A Spectral Band	Oa1	Oa2	Oa3	Oa4	Oa5	Oa6	Oa7
First/Last row	556	548	523	485	469	429	381
	567	555	530	492	476	436	388
OLCI-A Spectral Band	Oa8	Oa9	Oa10	Oa11	Oa12	Oa13	Oa14
First/Last row	345	339	333	310	275	271	268
	352	344	338	317	280	272	270
OLCI-A Spectral Band	Oa15	Oa16	Oa17	Oa18	Oa19	Oa20	Oa21
First/Last row	266	252	181	170	158	122	50
	267	263	106	177	165	127	81

²⁶⁷²⁶³¹⁹⁶¹⁷⁷¹⁶⁵¹³⁷⁸¹Table 3: Pre-launch OLCI-A allocation of CCD row for the nominal band setting used
during nominal Earth Observation.

In the following the *band-contributing-ccd-rows* are abbreviated *bccr*.

5.1.2 Unweighted spectral response function

The unweighted spectral response function is calculated from the individual Gaussian contributions. 500 uniformly distributed wavelength sampling points λ^* in the closed interval $[\lambda_{min}, \lambda_{max}]$ are used:

$$\lambda_{min} = \lambda_{c,r}(col, row_{last}) - 5$$
$$\lambda_{max} = \lambda_{c,r}(col, row_{first}) + 5,$$



The interval starts 5 *nm* before the shortest and stops 5 *nm* after the longest centre wavelength of all *bccr*. For each one of the OLCI 21 spectral bands the unweighted spectral response function is calculated by:

$$srf^{*}(band, col, \lambda^{*}) = \sum_{all \ rows}^{in \ bccr(band)} G\left(\lambda^{*}; \lambda_{c,r}(col, row), \sigma_{c,r}(col, row)\right)$$

Using the µband center wavelength $\lambda_{c,r}$ and $\sigma_{c,r}$, and a Gaussian normalized to a maximum value of 1:

$$G(\lambda^*; \quad \lambda_{c,r}, \sigma_{c,r}) = \exp(\frac{-(\lambda^* - \lambda_{c,r})^2}{2\sigma_{c,r}^2})$$

This normalization's effect is that spectrally wider rows receive more energy. However, the variability of a single row bandwidth within a band is very low and this effect is negligible.

5.1.3 Spectral response function

The spectral response function $srf(band, col, \lambda^*)$ is calculated from srf^* by applying the relative weight $w(col, \lambda^*)$ (see section 4) and a final normalization to its maximum value:

 $srf^{w}(band, col, \lambda^{*}) = srf^{*}(band, col, \lambda^{*}) \cdot w(col, \lambda^{*})$ $srf(band, col, \lambda^{*}) = srf^{w}(band, col, \lambda^{*})/\max(srf^{w}(band, col, \lambda^{*}))$

5.2 In-band solar spectral irradiance

The in-band solar spectral irradiance *ir* is defined as:

$$ir(band, col) = \frac{\int srf^{s}(band, col, \lambda) \cdot sol^{s}(\lambda)d\lambda}{\int srf^{s}(band, col, \lambda)d\lambda}$$

where $sol(\lambda)$ is the solar spectral irradiance (REF-01, see section 4), if the Sun Earth distance is exactly 1 AU. The upper integrals are approximated using the trapezoidal rule (see appendix A), therefore srf and sol need common wavelength sampling points. We choose 5000 equidistant points in the interval $[\lambda_{min}, \lambda_{max}]$ (Section 5.1.2), at which sol and srf are linearly interpolated (indicated with the superscript ^s).

5.3 Band central wavelength

The central wavelength *cw* is defined as the barycentre of the spectral response function:

$$cw(band, col) = \frac{\int srf(band, col, \lambda) \cdot \lambda \, d\lambda}{\int srf(band, col, \lambda) d\lambda}$$

The integrals are approximated using the trapezoidal rule. For skewed shapes, this quantity does not well correspond to the *middle* wavelength (the wavelength of the middle CCD row). Hence, in particular the central wavelengths of band 1 and band 21 differ notably from their nominal positions (400 nm and 1020 nm).



5.4 Representative spectral response function

While some L2 algorithms take the particular band characteristics per pixel (e.g. retrievals using the O2 absorption at 760 nm), other L2 algorithms correct L1b radiances for the across track variations of the centre wavelength of the SRF, via the so-called *smile correction*. The output products of the according L2 processing having a spectral dimension (e.g., the water leaving reflectance or land surface reflectance) are thus provided at the so-called L2 nominal wavelengths (Table 4). The *smile correction* however does not account for the across track variations of the shape of the spectral response at each OLCI module CCD column. Instead single representative spectral response functions are used. They are calculated from a simple arithmetic average of all SFR of a particular band, afterwards shifted to the nominal centre. (Figure 13)

OLCI-A Spectral Band	Oa1	Oa2	Oa3	Oa4	Oa5	Oa6	Oa7
Nom L2 wavelength	400	412.5	442.5	490	510	560	620
[nm]							
OLCI-A Spectral Band	Oa8	Oa9	Oa10	Oa11	Oa12	Oa13	Oa14
Nom L2 wavelength	665	673.75	681.25	708.75	753.75	761.25	764.375
[nm]							
OLCI-A Spectral Band	Oa15	Oa16	Oa17	Oa18	Oa19	Oa20	Oa21
Nom L2 wavelength	767.5	778.75	865	885	900	940	1020
[nm]							

Table 4: The L2 nominal wavelengths.





Figure 13: Mean relative spectral response (blue line), variability of the mean relative response over the field of view (shaded area) and mean relative spectral response shifted to nominal (black dashed line).



6 UNCERTAINTY BUDGETS

6.1 Temporal Stability

To investigate the spectral stability of OLCI, the most frequent spectral campaign So9 has been utilized. For each So9 spectral feature and each module, the mean central wavelength (over the field of view) has been calculated. Shown in Figure 14 is this central wavelength for the four spectral features of So9, relative to the calibration on 2016-03-14. It turns out, that all modules show a clear but different temporal evolution. It is a shift towards longer wavelengths. The shift is the same for all spectral rows within a module. The observed evolution speed is between: 0.0 nm/yr (module 5), 0.4 nm/yr (module 4). Neither for the bandwidth nor for the field of view dependency an evolution could be observed (not shown).

The spectral shift has an impact on the inband solar irradiance. To quantify the impact, the inband solar irradiance has been calculated based on all So9 campaigns, respectively. The change within the considered 90 days is below 0.1% for all bands, except band 1 and band 3, where the spectral gradient of the solar irradiance is largest (Figure 15). Here the change goes up to 0.28 % (band 1 camera 1) within 90 days.

However, this error does not contribute to the uncertainty budget if top of atmosphere reflectance is considered. Since the radiometric calibration is performed every two weeks using a reflectance standard, the maximum change of the solar constant in this period due to spectral shifts of the instruments will be less than $0.016\% \approx 0.1\% \cdot \frac{14d}{90d}$ for most bands and less than $0.05\% \approx 0.28\% \cdot \frac{14d}{90d}$ for the most sensitive band 1.



Figure 14: Temporal evolution of the module mean central wavelength of the μ-bands belonging to the used spectral features at 485nm, 665nm, 770nm (oxygen absorption) and 854nm (from upper to lower row), for modules 1 to 5 (from left to right). The abscissas are the day-of-year number of 2017.



Camera 1	Camera 2	Camera 3	Camera 4	Camera 5
band 01				
	معر			
0.289/	0.16%	0.169	0.249	0.10%
0.20%	0.16%	0.10%	0.24%	0.10%
band 02				
0.05%	0.03%	0.03%	0.04%	0.03%
0.05%	0.03%	0.03%	0.04%	0.02%
band 03			000	
0.16%	0.09%	0.09%	0.13%	0.05%
band 04				
0.08%	0.04%	0.05%	0.07%	0.03%
band 05				
	0.05%	0.05%	0.08%	0.0317
-0.09%	-0.03%	-0.05%	-0.08%	-0.03%
band 06		•		
-0.05%	-0.03%	-0.03%	-0.04%	-0.02%
band 07				
-0.01%	-0.01%	-0.01%	-0.01%	-0.00%
band 08				
-0.02%	-0.01%	-0.01%	-0.01%	-0.01%
pang 09				
-0.03%	-0.02%	-0.02%	-0.03%	-0.01%
band 10				
-0.03%	-0.02%	-0.02%	-0.03%	-0.01%
band 11				
-0.05%	-0.03%	-0.03%	-0.04%	-0.02%
band 12	• • • • • • • • • • • • • • • • • • • •	• • • • • • • • • • • • • • • • • • • •	• <u>•</u> •••••	• <u>•</u> ••••••••••••••••••••••••••••••••••
0.00%	0.00%	0.00%	0.00%	0.00%
band 13				
-0.01%	-0.01%	-0.01%	-0.01%	-0.00%
band 14				
0.07%	0.04%	0.04%	0.06%	
[10.07/0	-0.04/0	-0.0470	0.00 /0	-0.03 %
band 15			0 0 000	· · · · · · · · · · · · · · · · · · ·
0.03%	0.02%	0.02%	0.03%	0.01%
band 16				
-0.04%	-0.02%	-0.02%	-0.03%	-0.01%
band 17				
		• • • • • •		
0.01%	0.00%	0.00%	0.00%	0.00%
pand 18	• • • • • • • • • • • • • • • • • • •	• • • • • • • •		· · · · · · · · · · · · · · · · · · ·
-0.02%	-0.01%	-0.01%	-0.02%	-0.01%
band 19				
-0.00%	-0.00%	-0.00%	-0.00%	-0.00%
band 20				
-0.02%	-0.01%	-0.01%	-0.02%	-0.01%
bahd 21		· · · · · ·		
-0.03%	-0.01%	-0.01%	-0.02%	-0.01%
bahd 21 -0.03% 60 80 100 120 140 160 12 [doy]	-0.01%	-0.01%	-0.02%	-0.01%

Figure 15: Temporal evolution of the in-band solar irradiance in units of % relative to the calibration on 2016-03-14. It is shown for all modules (from left to right) and all bands (upper to lower). The number within each plot is the maximum deviation during the 90 days.



6.2 Pre-launch uncertainty budgets

In the following sections an attempt to define the uncertainties associated to the OLCI spectral bands centre wavelength, SRFs and in-band extra-terrestrial solar irradiance is detailed based on pre-launch characterization measurement uncertainties.

These uncertainty budgets will be complemented after the commissioning phase by those associated to the in-flight calibration of the instrument [RD-01, RD-11] which will be done by a) making in-flight measurements of a spectral calibration diffuser, b) reprogramming the OLCI instrument to make precise measurements of solar Fraunhofer lines and atmospheric O2-A absorption lines.

6.2.1 Uncertainties associated to the central wavelength of each CCD row

The uncertainty associated to the measurement of the central wavelength of the CCD pixel (preflight measurements carried out by TAS AIT) can be split into 3 contributors:

- Calibration accuracy of the monochromator (fixed, unknown bias of maximum amplitude 0.1nm)
- Relative accuracy of the monochromator (between the calibration wavelengths and any other one, again unknown fixed bias of amplitude 0.03nm)
- Accuracy of the pixel spectral localisation measurement (essentially random and about 0.04nm).

These uncertainties were combined (following TAS AIT suggestion) as:

$$\sum (fixed_bias) + \sqrt{\sum (random)^2} = (0.10 + 0.03) + \sqrt{(0.04^2)} = 0.17 \text{ nm (3-sigma value)}$$

The previous uncertainty figure is derived from a theoretical uncertainty budget. However, the comparison of the camera characterization data with on-ground instrument spectral calibration using the spectral diffuser calibrated independently (not by TAS AIT) using different means gave results in agreement by about 0.05nm.

Uncertainty of the transmission function leads to an additional uncertainty on the barycentre of about 0.05 nm (assumed root mean square value of a random error).

Using the above uncertainty summation rule, the overall central wavelength uncertainty becomes:

$$(0.10+0.03) + \sqrt{(0.04^2+0.05^2)} = 0.19nm$$
 (3-sigma value)

6.2.2 Uncertainties associated to the computation of the SRFs

The spectral relative uncertainty on the SRF is primarily driven by the uncertainties associated to the measurements of the module transmission functions, estimated in appendix B between 0.7% and 3.5% depending on the wavelength. A synthesis is provided in in Table 5.



Another contribution would be the spectral relative accuracy on the ILS measurement, however this one should be very small since:

- the relevant measurements are those performed close to the maximum, hence with higher signal,
- the measurements are fitted by a model, which reduces the effect of noise and of spectral random errors.

For more details the reader is referred to annex B.

Wavelength (nm)	390	400	450	500	550	600	800	850	1000	1040
Total (1-σ error)	3.51%	2.20%	1.42%	1.10%	0.93%	0.83%	0.73%	0.73%	0.91%	1.43%
Table = Created valative accuracy of the regrange magnement										

Table 5: Spectral relative accuracy of the response measurement.

6.2.3 Uncertainties associated to the in-band solar irradiance

The OLCI in-band extra-terrestrial solar irradiances are computed by convolving the individual CCD column SRF for a given OLCI spectral band and module with the Thuillier et al. (RD-05) extra-terrestrial solar spectral irradiance spectrum at 1 AU.

In the following section, an estimate of the uncertainty associated to the OLCI in-band extraterrestrial solar irradiance due solely to uncertainties associated to the OLCI spectral characterization.

In addition to these estimates, the reader should also be aware that there are intrinsic uncertainties associated to the extra-terrestrial solar irradiance reported by Thuillier et al. (RD-05).

A purely analytical derivation of the uncertainty budget of the in-band solar irradiance is difficult to establish. Instead, the uncertainties were assessed by numerical simulations and restricted to the case of module 1. To this end, the SRF of each OLCI spectral band is first approximated by a simple template, using 4 or 5 fixed wavelengths and linear interpolation in-between (Figure 16). The in-band irradiance is then computed by numerical integration, using the spectral sampling of the Sun spectrum as per Thuillier data (RD-05), and by linear interpolation of the SRF between these 4 or 5 fixed wavelengths.

The in-band solar irradiance is then computed, after some uncertainties are propagated to the SRF definition points.

- Case 1: the SRF values at these 4 or 5 fixed wavelengths that are neither 0 nor 1 are decreased by twice the uncertainty at these wavelengths (see Table 5). This approach assumes that the maximum absolute response has been increased by the response uncertainty while other wavelengths are affected by the same uncertainty but in the opposite direction (i.e. decreased).
- Case 2: same as above, but with the opposite sign on the uncertainty of the absolute response.
- Case 3: the wavelength at the 4 or 5 fixed wavelengths is shifted towards larger ones by 0.18nm, which is the budgeted wavelength uncertainty.
- Case 4: same as above, but wavelengths shifted towards shorter ones.





Figure 16: Example plots of simplified SRFs (red) used to estimate the uncertainty associated to the in-band solar irradiance compared to the original SRF (blue).





The error on the response is plotted below for completeness. It is interpolated from the values already provided in appendix B.

The comparison of all these 4 perturbed cases with the nominal one provides an estimation of the potential error. The estimated uncertainties are tabulated and plotted below.

	Oa1	Oa2	Oa3	Oa4	Oa5	Oa6	Oa7	Oa8	Oa9	Oa10	Oa11
Nom	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Case 1	0.24%	-0.04%	0.04%	0.03%	-0.02%	0.00%	0.00%	0.00%	0.00%	0.00%	-0.01%
Case 2	-0.22%	0.04%	-0.04%	-0.03%	0.02%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%
Case 3	0.36%	0.14%	0.30%	0.08%	-0.22%	-0.11%	-0.03%	-0.04%	-0.06%	-0.04%	-0.07%
Case 4	-0.36%	-0.15%	-0.26%	-0.08%	0.16%	0.11%	0.03%	0.03%	0.05%	0.05%	0.09%

	Oa12	Oa13	Oa14	Oa15	Oa16	Oa17	Oa18	Oa19	Oa20	Oa21
Nom	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Case 1	0.00%	0.00%	0.01%	0.00%	-0.01%	0.01%	0.00%	0.01%	0.01%	0.02%
Case 2	0.00%	0.00%	-0.01%	0.00%	0.01%	-0.01%	0.00%	-0.01%	-0.01%	-0.02%
Case 3	0.00%	0.00%	-0.15%	0.10%	-0.08%	-0.09%	-0.04%	0.00%	-0.03%	-0.04%
Case 4	0.01%	0.06%	0.19%	-0.14%	0.08%	0.11%	0.04%	0.01%	0.03%	0.04%

Table 6: Estimated uncertainties associated to the in-band solar irradiance by propagating uncertainties associated to the OLCI spectral band center wavelength and the uncertainty associated to the OLCI spectral band SRFs.



Figure 18: Estimated uncertainties associated to the in-band solar irradiance by propagating uncertainties associated to the OLCI spectral band center wavelength and the uncertainty associated to the OLCI spectral band SRFs.

It can be seen that the propagation of the spectral response uncertainty (cases 1 & 2) results into almost negligible contributions to the in-band solar irradiance, except for channel Oa1. Conversely, the propagation of the uncertainty associated to the centre wavelength of the OLCI

spectral bands is significant in nearly all channels. The cumulated uncertainties may reach 0.6% for channel Oa1. It however remains below 0.2% for all channels but Oa1, Oa3 and Oa5. •



7 OLCI-A SRF PROVISION

7.1 File format description

The spectral characterisation information is provided in three files with three different levels of details. The current files are:

S3A_OL_SRF_20160621.nc4

(https://sentinels.copernicus.eu/documents/247904/2700530/S3A_OL_SRF_20160713.nc4) providing:

- *center_wavelength*, the central wavelength of relative spectral response (in nm) for
 : 21 bands x 5 modules x 740 CCD columns
- *bandwidth_fwhm*, the bandwidth full_width_half_maximum (in nm) for: 21 bands x 5 modules x 740 CCD columns
- *solar_irradiance*, the band averaged solar spectral irradiance (in mW/m2/nm at sun earth distance of 1 AU) for: 21 bands x 5 modules x 740 CCD columns
- *relative_spectral_response*, the SRFs for: 21 bands x 5 modules x 740 CCD columns x 200 sampling wavelengths
- *relative_spectral_response_wavelength*, the wavelengths at which the SRFs are sampled (in nm) for: 21 bands x 5 modules x 740 CCD columns x 200 sampling wavelengths
- S3A_OL_SRF_20160621_subset.nc4

(https://sentinels.copernicus.eu/documents/247904/2700530/S3A_OL_SRF_20160713_subset.nc4)

- The same as the **full** file, but reduced to the spectral response functions at only three CCD columns (located at Eastern, center, Western part) for each module and each one of the 21 spectral bands
- S3A_OL_SRF_20160621_mean_rsr.nc4

(https://sentinels.copernicus.eu/documents/247904/2700530/S3A_OL_SRF_20160713_mean_rsr.nc4)

• The same as the **full** file, but reduced to a single representative (mean) spectral response function, in-band solar irradiance, bandwidth and centre wavelength per band. This dataset is only relevant for L2 products that are based on L1b radiances which have been corrected for the viewing zenith dependence of their spectral characteristics ('smile correction')

7.2 Figures describing the SRFs of OLCI-A 21 spectral bands

The previously described dataset is visualised in this section.

The plots for the 315 SRFs associated to 3 CCD columns across the FOV (west, centre, east) for each of the 5 OLCI modules and for each of the 21 spectral bands are provided.

For each OLCI nominal spectral band the following is shown: the variation of the centre wavelength (nm), of the in-band irradiance and of the FWHM [nm] over the FOV of each module (top row left to right).

Then only at CCD column 10, 374 and 730, the shape of the SRF is plotted for each of the module.

In addition, in the centre row, the Thuillier et al. (RD-05) spectrum is plotted versus the wavelength to illustrate the potential influence of spectral calibration uncertainties on the in-band irradiance value.

















































































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ANNEX A: NUMERICAL METHODS

A.1 Linear Interpolation

Given a function $f: R \to R$ at two data points x0 and x1, linear interpolation is performed to find an approximation of *f* for any x, lying between given sampling points:

$$f(x) \approx f(x_0) + \frac{f(x_1) - f(x_0)}{x_1 - x_0} (x - x_0)$$

A.2 Bilinear Interpolation

Given a function $f: \mathbb{R}^2 \to \mathbb{R}$ at four data points (x_0, y_0) , (x_0, y_1) , (x_1, y_0) and (x_1, y_1) , bilinear interpolation can be performed to find an approximation of f for any (x, y), lying between given sampling points. First x and y are scaled to (\tilde{x}, \tilde{y})

$$\widetilde{x} = \frac{x - x_0}{x_1 - x_0} \qquad \widetilde{y} = \frac{y - y_0}{y_1 - y_0}$$

so that the four sampling points $(x_0, y_0) \dots (x_3, y_3)$ are transformed to (0,0), (0,1), (1,0), (1,1). Then the approximation is found by:

$$f(x,y) \approx f(x_0,y_0)(1-\tilde{x})(1-\tilde{y}) + f(x_1,y_0)(\tilde{x})(1-\tilde{y}) + f(x_0,y_1)(1-\tilde{x})(\tilde{y})f(x_1,y_1)\tilde{x}\tilde{y}$$

A.3 Trapezoidal Integration

Given a function $f: R \to R$ at N+1 uniformly distributed sampling points ($x_1, ..., x_{N+1}$), the definite integral of f(x) over the interval $x_1 ... x_{N+1}$ can be approximated by:

$$\int_{x_{1}}^{x_{1}} f(x)dx \approx h \cdot \frac{1}{2} \cdot \sum_{i=1}^{N} (f(x_{i}) + f(x_{i+1}))$$

Using the sampling distance $h^{x_1} = \frac{x_{N+1} - x_1}{N}$

A.4 Linear Fit

Given a data set $\{x_i, y_i\}^n$ of *n* pairs, a linear regression assumes a linear relationship between the dependent variable y, the regressor x and the stochastic component ϵ :

$$y_i = a \cdot x_i + b + \epsilon_i$$

The best estimates (under several assumptions) of the *parameter* a,b are: $\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})$

$$a = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{x})}{\sum_{i=1}^{n} (x_i - \bar{x})^2}$$
$$b = \bar{y} - a\bar{x}$$

A.5 Polynomial Fit

Given a data set $\{x_i, y_i\}^n$ of *n* pairs, a polynomial regression assumes a polynomial relationship between the dependent variable y, the regressor x and the stochastic component ϵ :

$$y_i = a_m \cdot x^m + \dots + a_2 \cdot x^2 + a_1 \cdot x_i + a_0 + \epsilon_i$$

The best estimate (under several assumptions) of the *parameter* vector \vec{a} is:

$$\vec{a} = (X^T X)^{-1} X^T \vec{y}$$

using the response vector $\vec{y} = \{y_1, \dots, y_n\}$ and the design matrix $X = \begin{bmatrix} 1 & \cdots & x_1^m \\ \vdots & \ddots & \vdots \\ 1 & \cdots & x_n^m \end{bmatrix}$



ANNEX B: ESTIMATION OF A CAMERA MODULE SPECTRAL RESPONSE UNCERTAINTY

B.1 Overview and overall budget

The radiometric response is evaluated through 3 steps:

- Measurement of the camera response at a given set of wavelengths, using the GSE Scrambling Window Unit (SWU)
- Adjustment of SWU transmission data to reproduce the measured response, for the same set of wavelengths (correlation coefficient)
- Computation of the camera response by replacing the SWU GSE transmission by the flight one.

The spectral relative accuracy of the response measurement is described by the following table, where all given contributions correspond to the standard deviation (1-sigma error).

Wavelength nm	390	400	450	500	550	600	800	850	1000	1040
Spectroradiometer spectral relative error (1)	1.4%	1.4%	1.0%	0.7%	0.6%	0.5%	0.4%	0.4%	0.4%	0.5%
Spectroradiometer operation in front of the GSE source (2)	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Repeatability of the source (3)	0.7%	0.6%	0.5%	0.34%	0.2%	0.1%	-0.1%	-0.1%	-0.2%	-0.3%
Repeatability of the spectroradiometer (4)	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Influence of camera noise (1000 acquisitions) (5)	3.1%	1.5%	0.7%	0.6%	0.45%	0.4%	0.3%	0.3%	0.6%	1.2%
Relative accuracy of SWU (between models) (6)	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%
Total (1-sigma error)	3.51%	2.20%	1.42%	1.10%	0.93%	0.83%	0.73%	0.73%	0.91%	1.43%

Table 7: Spectral relative accuracy of the response measurement as total value and its contributors.

The final spectral relative uncertainty on the response between 2 wavelengths can be taken as the root square sum of the respective errors for these 2 wavelengths.

For example, for any pair of wavelengths in the range 1000-1040nm, the accuracy settles to 1.7%, and to 4% for any pair in the range 390-410nm.



B.2 Details on individual contributions

B.2.1 Spectroradiometer spectral relative error (1)

The radiance of the uniform light source that is used during camera tests is measured by a transfer etalon, which is a spectroradiometer calibrated beforehand.

This calibration suffers from its own inaccuracy, mainly originating from the knowledge of the reference standard and from the noise and repeatability of the spectroradiometer.

From the calibration certificate (No. CAL-130-15-030 dated 12/06/2015, by Instrument System GmbH), we know the absolute uncertainty ranges between 1.9 and 3.3% (2-sigma error), depending on wavelength. No detail is available, however a relative uncertainty has been estimated and reported in line (1) in the Table 7 above.

B.2.2 Spectroradiometer operation in front of the GSE source (2)

This contribution essentially covers the mispositioning of the spectroradiometer in front of the source (centering and orientation). While this may have an effect on absolute measurements, this is considered as essentially independent of the wavelength. In a conservative approach, a small value has been included in line 2 of the above budget.

B.2.3 Repeatability of the source (3)

The source radiance is first characterized using the etalon spectroradiometer, then it is used by to characterize the camera response, usually in a separate session. The repeatability of the source is actually driven by that of its power supply. A small deviation of the current flowing through the lamp will be compensated by means of a diaphragm located between the lamp and the sphere, according to the indication of a monitoring photodiode. While the effect of the latter is independent of the wavelength, the former has a slight impact on the power of the lamp, hence its temperature, hence its spectrum. This is reflected in the line 3 of Table 7.

B.2.4 Repeatability of the spectroradiometer (4)

No detailed measurement result is available, however this contribution has been experimentally quantified to better than 0.1% (3-sigma error) in the AIT absolute budget. In a conservative approach, this term is set to 0.1% (1-sigma) in the Table 7.

B.2.5 Influence of camera noise (1000 acquisitions) (5)

The camera response is characterized through a sequence of 1000 successive acquisitions, each affected by the noise which is essentially the photonic one (square root of the number of electrons at CCD level). Averaging the 1000 frames allows to significantly reduce the uncertainty. The figures in line 5 of Table 7 above have been assessed according to the signal effectively measured during the characterization of one of the cameras. This contribution is clearly the driver of the overall accuracy.

B.2.6 Relative accuracy of SWU (between models) (6)

The accuracy on the total transmission of the SWU is estimated as 1% by the provider, irrespective of wavelength. This results from the cumulated uncertainty on each coating transmission measurement or substrate transmission estimation.



The accuracy on the comparison of GSE and flight SWU transmission is expected better, since only the inverse filter coating is different (assuming identical behaviours of the 2 inverse filters when placed under vacuum). The estimated resulting uncertainty is 0.5%.

The accuracy on the ratio of transmissions after interpolation between provided wavelengths can be estimated the same: 0.5% (contribution 6 in the overall budget).



ANNEX C: USED ORBITS FOR INFLIGH CHARACTERISATION

		-
S3A_OL_0_CR0_	20160301T110937_20160301T111130_20160302T091754_0113_001_222	LN1_D_NR
S3A_OL_0_CR0_	20160301T193434_20160301T193627_20160302T100131_0113_001_227	LN1_D_NR
S3A OL 0 CR0	20160301T211534 20160301T211727 20160302T100141 0113 001 228	LN1 D NR
S3A OL 0 CR0	20160414T095448 20160414T095936 20160414T114125 0287 003 079	MAR O NR 001
S3A OL 0 CR0	20160414T221123 20160414T221610 20160414T232148 0287 003 086	MAR O NR 001
S3A OL 0 CR0	20160414T233452 20160414T233940 20160415T010322 0287 003 087	MAR 0 NR 001
S3A OL 0 CR0	20160415T113804_20160415T113957_20160415T125329_0113_003_094	MAR O NR 001
S3A OL 0 CR0	20160418T120012_20160418T120205_20160418T131626_0113_003_137	MAR 0 NR 001
S3A OL 0 CR0	20160418T220737 20160418T221224 20160418T231805 0287 003 143	MAR O NR 001
SJA OL O CRO	20160418T233106_20160418T233553_20160419T005854_0287_003_144	MAR 0 NR 001
S3A OL 0 CR0	20160428T085114_20160428T085601_20160428T104202_0287_003_278	MAR 0 NR 001
S3A OL 0 CR0	20160428T224847_20160428T225335_20160429T000518_0287_003_286	MAR 0 NR 001
S3A OL 0 CR0	20160429T001217 20160429T001704 20160429T014634 0287 003 287	MAR 0 NR 001
S3A OL 0 CR0	20160504T093608 20160504T094055 20160504T112622 0287 003 364	MAR O NR 001
SJA OL O CRO	20160504T215242_20160504T215730_20160504T231004_0287_003_371	MAR 0 NR 001
SJA OL O CRO	20160504T231611_20160504T232059_20160505T004839_0287_003_372	MAR 0 NR 001
SJA OL O CRO	20160531T082002_20160531T082155_20160531T094216_0113_004_363	MAR 0 NR 001
S3A OL 0 CR0	20160531T114200_20160531T114353_20160531T130100_0113_004_365	MAR 0 NR 001
S3A OL 0 CR0	20160609T090409 20160609T090856 20160609T110633 0287 005 107	MAR O NR 001
S3A OL 0 CR0	20160613T090005 20160613T090452 20160613T104419 0287 005 164	MAR 0 NR 001
S3A OL 0 CR0	20160620T091818 20160620T092305 20160620T110245 0287 005 264	MAR O NR 001