

European Space Research and Technology Centre Keplerlaan 1 2201 AZ Noordwijk The Netherlands T +31 (0)71 565 6565 F +31 (0)71 565 6040 www.esa.int

DOCUMENT

Technical Note: Sentinel-3 OLCI-B spectral response functions from pre-flight characterisation

Prepared by Sentinel 3 CalVal Team Reference S3-TN-ESA-OL-660

Issue 1 Revision 0

Date of Issue 11/02/2016 Status For information

Document Type TN

Distribution



APPROVAL

Title	
Issue 1	Revision 1
Author CalVal Team	Date 11/02/2016
Approved by	Date

CHANGE LOG

Reason for change	Issue	Revision	Date
	1	1	08/01/2018

CHANGE RECORD

Issue 1	Revision					
Reason for change	Date	Pages	Paragraph(s)			
- First draft, based on OLCI A	27/11/2017	All	All			
 First version, new preflight data therefor update of all relevant plots, update of reference, small editing 		All	All			
-						



Table of contents:

1	INTRODUCTION	. 4
1.1	Scope	
1.2	Reference and Applicable Documents	5
1.3	Acronyms	5
2	BACKGROUND	
2.1	The OLCI instrument	
	OLCI spatial and spectral dimensions	
3	INPUT DATA	
4	SRF CALCULATION PROCEDURE	
	Instrumental line shape (ILS)	
	Spectral response function of the 21 OLCI spectral bands	
4.2.	1 CCD rows of a band	13
	2 Central wavelength of the CCD rows	
	3 Bandwidth of CCD pixels	
	4 Unweighted spectral response function	
	5 Spectral response function	
	In-band solar spectral irradiance	
	Band central wavelength	
	Representative spectral response function	
	PRE-LAUNCH UNCERTAINTY BUDGETS	
	Uncertainties associated to the central wavelength of each CCD row	
	1 Nominal uncertainty	
	2 Degraded uncertainty	
5.2	Uncertainties associated to the computation of the SRFs	20
_	Uncertainties associated to the in-band solar irradiance	
6 M E	OLCI-B SRF CALCULATED FROM PRE-LAUNCH CHARACTERISATIO	
	ASUREMENTS	
	File format descriptionFigures describing the SRFs of OLCI-B 21 spectral bands	
0.2 A Ni	NEX A: MATHEMATICAL MODEL DEFINING SPECTRAL PARAMETERS	25
	Linear Interpolation	
	Bilinear Interpolation	
	Trapezoidal Integration	
	NEX B: ESTIMATION OF A CAMERA MODULE SPECTRAL RESPON	
	CERTAINTY	
	OVERVIEW AND OVERALL BUDGET	
B.2	DETAILS ON INDIVIDUAL CONTRIBUTIONS	48 48
B.2.		
B.2.		40
B.2.		
B.2.		40
B.2.		49
B.2.		.49



1 INTRODUCTION

1.1 Scope

In the frame of pre-launch activities for Sentinel-3 OLCI-B instrument, a first version of the instrument Spectral Response Functions (SRF) based on on-ground characterisation measurements was derived. They are described in the present document.

Further calibration and validation activities are planned in the frame of the Sentinel-3B Commissioning Phase. These activities should allow verifying the in-flight performance of the instrument. It is in particular foreseen to review the pre-launch instrument spectral characterisation measurements from which the present SRFs are derived. If deemed necessary, an update of the SRFs might thus be provided at In-Orbit Commissioning Review (IOCR) [RD-01] after launch. Moreover, the spectral characteristics of OLCI-B will be monitored through the entire mission duration 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 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 provides uncertainty budgets associated to the previous calculations.
- Section 6 describes the actual dataset.



1.2 Reference and Applicable Documents

Reference documents

RD-01	Copernicus Sentinel-3B Calibration and Validation Implementation Plan	S3-PL-ESA-SY-807 V1-3
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	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-05	OLCI-B Commanding Sequences	S3-TN-ESA-OL-822
RD-06	S3B OLCI FM1-R camera: Analysis of spectrometric performance tests	S3-TR-TAF-OL-03549
RD-07	S3B OLCI FM2-R camera: Analysis of spectrometric performance tests	S3-TR-TAF-OL-03558
RD-08	S3B OLCI FM3-R camera: Analysis of spectrometric performance tests	S3-TR-TAF-OL-03567
RD-09	S3B OLCI FM4-R camera: Analysis of spectrometric performance tests	S3-TR-TAF-OL-03576
RD-10	S3B OLCI FM6-R camera: Analysis of spectrometric performance tests	S3-TR-TAF-OL-03585

Reference data sets

itelet ene	c data sets
RDS-01	OLCI-B Characterization and Calibration Data Base S3B_O_CCDB_V1.01
	S3B_OL_CCDB_CALI_AllFiles.20171219105206_1.nc4
	S3B_OL_CCDB_CHAR_AllFiles.20171219120937_1.nc4
	S3B_OL_CCDB_PROG_programmable.20170905104849_
	1.nc4

1.3 Acronyms

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



• TAS: Thales Alenia Space



2 BACKGROUND

2.1 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) has been successfully launched in February 2016, the second (S3B) is due to be launched in March 2018.

The OLCI instrument consists of 5 imaging-spectrometer-type cameras. The cameras integrated in OLCI-B are the Flight Models (FM) FM2-R, FM3-R, FM6-R, FM1-R and FM4-R. 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 right to left at spacecraft level and from West to East when their swath are projected at ground level on daytime descending node (see Figure 1).

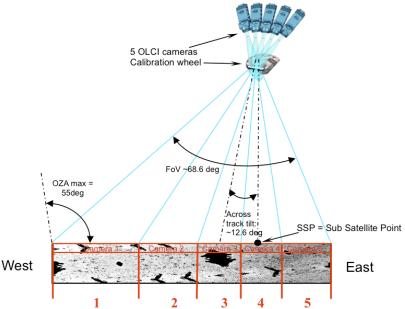


Figure 1: OLCI's 5 camera modules arranged in fan-shaped form creating a single swath on-ground.

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 2) 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.

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

¹ Copernicus programme site:



OLCI elementary spectral bands have a spectral resolution of about ~1.8 nm and a spectral sampling interval of ~1.25 nm. The 21 nominal programmable spectral bands are generated by a specific binning of consecutive CCD lines into variable width spectral bands. The binning into spectral bands is done in two steps: a first stage builds up so-called microbands by a specific readout electronic binning, the second stage builds the 21 spectral bands by numerical summing of the microbands.

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

2.2 OLCI spatial and spectral dimensions

Each individual CCD pixel (Figure 2) 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 instrument spatial pixel – the so-called detectors – and the detector indices are provided for each image grid spatial pixel, allowing to retrieve each of the 3 spectral quantities anywhere on the 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.



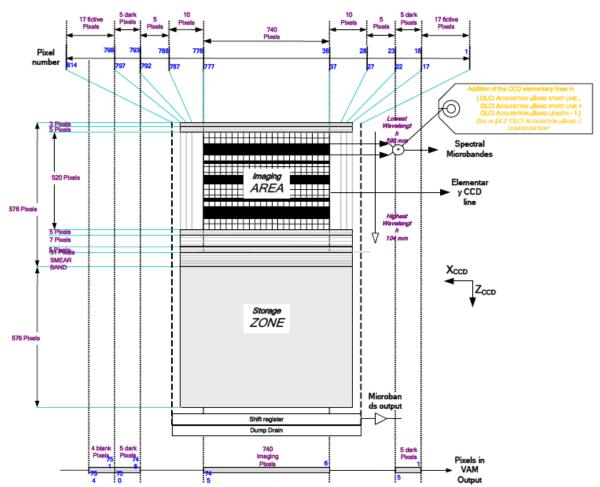


Figure 2: Dimension of the CCD and the allocation of imaged pixels.



3 INPUT DATA

Preflight spectral characterization measurement data were used to generate the provided OLCI spectral response function (SRFs) for all 5 modules and all 21 spectral bands. The actual data set used for the generation of the SRFs originates from [RDS-01] and is also stored in the pre-launch version of the Characterization and Calibration Data Base (CCDB).

Furthermore, the solar irradiance spectrum from Thuillier et al. [RD-04] 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 locations of the pre-flight characterisation on the CCD are indicated in the following by the subscript *tas*. 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 [RD-06,RD-07,RD-08,RD-09,RD10,RDS-1]:

- Central wavelength Λ_{tas} of CCD-pixel for: 5 modules x 41 rows x 9 columns (see Figure 4). Not all of the rows have been used, since some of the monochromatic measurements are less reliable due to spikes in the emission spectrum of the used Xenon lamp. The filtered and not used rows are: 44,49,64,176,188,266,270,335,488,508,573 (see RD-06,..., RD10)
- Instrumental line shape (ILS) convolution kernel at 5 modules x 41 rows x 9 columns x 61 sampling steps of 0.1nm
- 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-B spectral band setting was retrieved from:
 File S3B_OL_CCDB_PROG_programmable.20170905104849_1.nc4 of RDS-01
- Solar irradiance in units of W/m²/μm are obtained from: File S₃B_SY_CCDB_CHAR_Thuillier-Solar-Irradiance.20160831120423_1.nc4 of RDS-01



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 module, 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, inband irradiance) required by the data processing.

It is currently considered that users do not need individual SRFs related to each of the 740 CCD columns for each spectral band and that 3 in-FOV positions (West, centre, East, making a total of 315 SRFs as presented in section 6) are sufficiently representative. However, all SRF are provided (see section 6).

4.1 Instrumental line shape (ILS)

First, the ILS kernel is used to approximate individual CCD element spectral bandwidths. It is assumed that all 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 estimated σ for all CCD-columns and rows is shown in Figure 3.



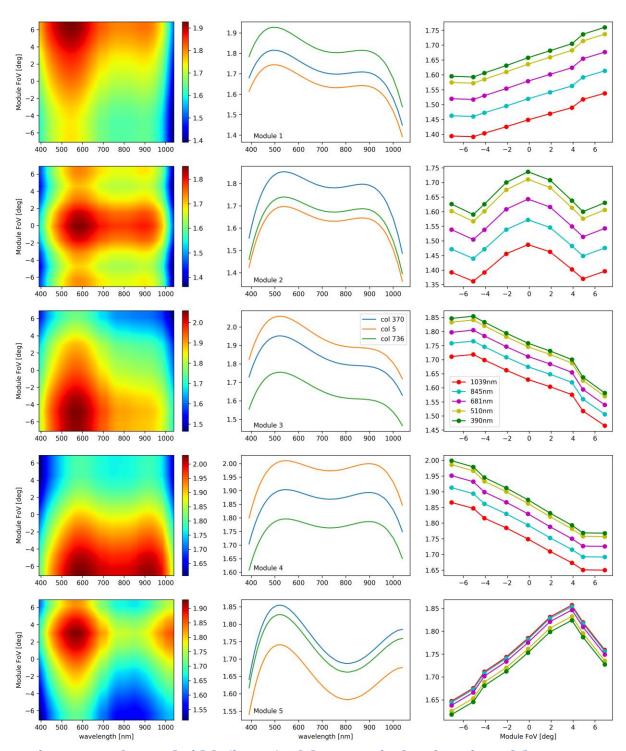


Figure 3: Left: Bandwidth (in nm) of the CCD pixel as function of the CCD row (wavelength) and CCD column (module FoV). Middle: Bandwidth as function of CCD row (wavelength). Right: Bandwidth as function of the module FoV (from East to West, directly related to the CCD column). The plots are provided for each individual module from top line to bottom line.



4.2 Spectral response function of the 21 OLCI spectral bands

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

4.2.1 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 after launch if deemed necessary by in-flight measurements to better homogenize channels positions between modules.

The current OLCI-B bands definitions are:

OLCI-B 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-B 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-B Spectral Band	Oa15	Oa16	Oa17	Oa18	Oa19	Oa20	Oa21
First/Last row	266	252	181	170	158	122	50
	267	263	196	177	165	137	81

Table 1: Pre-launch OLCI-B 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*.

4.2.2 Central wavelength of the CCD rows

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 2.2) does not accurately reflect the measured dispersion during the modules characterisation. This is illustrated in Figure 4. This is why a bi-linear interpolation (BLI, see Annex A.2) of the CCD-pixel central wavelength (Λ_{tas}) is used to estimate the central wavelength for all *bccr* and all CCD columns:

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



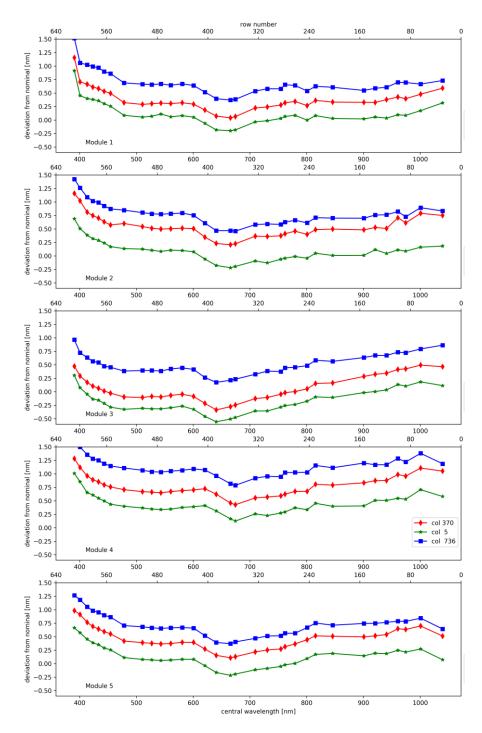


Figure 4: Deviation from the nominal dispersion law (i.e. the linear law describing the variations of the central wavelength with the CCD line) as function of central wavelength (bottom horizontal axis, based on nominal dispersion) and row number (top horizontal axis) for the five OLCI modules at three different CCD columns (indicated with red, green and blue) as provided by TAS. The same y-axis is kept for all modules.



4.2.3 Bandwidth of CCD pixels

The bi-linear interpolation (BLI) of the CCD pixel bandwidth (i.e, σ , see section 4.1) is used to estimate the bandwidth for all bccr and all CCD columns:

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

4.2.4 Unweighted spectral response function

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

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

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

which 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:

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

Using a Gaussian normalized to a maximum value of 1:

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

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.

4.2.5 Spectral response function

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

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

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

The relative weight is calculated from T_1, T_2, T_u and *CCDR* (see section 3).

$$w(col, \lambda^*) = T_1^*(\lambda^*) \cdot T_2^*(\lambda^*) \cdot T_{II}^*(col, \lambda^*) \cdot CCDR^*(\lambda^*)$$

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 5 the single contributions to the final relative weights are shown. Remarkable is the strong feature at around 400nm 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 [RDS-01].

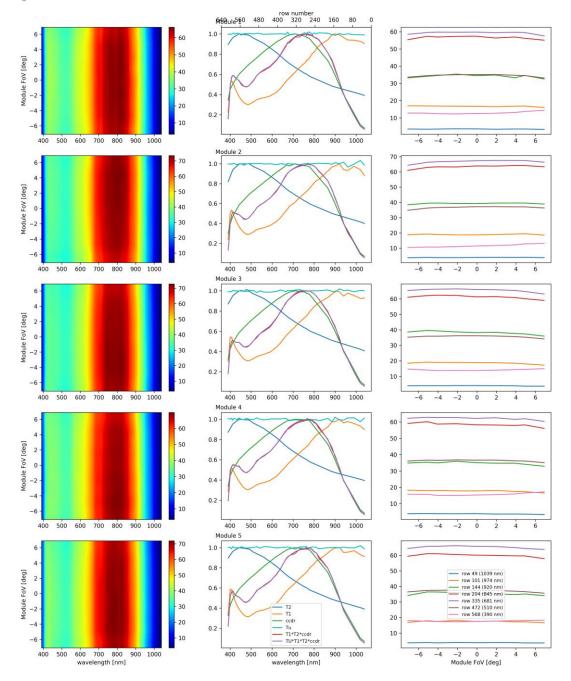


Figure 5: Left and Right: The weight (as described in the text) for the spectral response function for all modules, all wavelengths and field of views. Middle: The single contributions to the weight, each normalized to maximum value of 1. Right: The weight for the spectral response function as a function of CCD-column (FoV).



4.3 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 3), 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 4.2.4), at which sol and srf are linearly interpolated (indicated with the superscript s).

4.4 Band central wavelength

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

ength
$$cw$$
 is defined as the barycentre of the spectral response full $cw(band,col) = \frac{\int srf(band,col,\lambda) \cdot \lambda d\lambda}{\int srf(band,col,\lambda)d\lambda}$

The integrals are approximated using the trapezoidal rule. For skewed shapes, this quantity does not well correspond to the *middle* wavelength (the central 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).

4.5 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 2: The L2 nominal and the mean centre wavelengths of OLCI B.Table 2).

OLCI-B Spectral Band	Ob1	Ob2	Ob3	Ob4	Ob5	Ob6	Ob7
Nom L2 λ_c [nm]	400	412.5	442.5	490	510	560	620
Mean λ_c [nm]	400.6	411.9	443.0	490.4	510.4	560.4	620.3
OLCI-B Spectral Band	Ob8	Ob9	Ob10	Ob11	Ob12	Ob13	Ob14
Nom L2 λ_c [nm]	665	673.75	681.25	708.75	753.75	761.25	764.375
Mean λ_c [nm]	665.1	673.9	681.4	709.0	754.0	761.6	764.7
OLCI-B Spectral Band	Ob15	Ob16	Ob17	Ob18	Ob19	Ob20	Ob21
Nom L2 λ_c [nm]	767.5	778.75	865	885	900	940	1020
Mean λ_c [nm]	767.8	779.0	865.3	884.1	899.1	938.8	1015.7

Table 2: The L2 nominal and the mean centre wavelengths of OLCI B.

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 6).

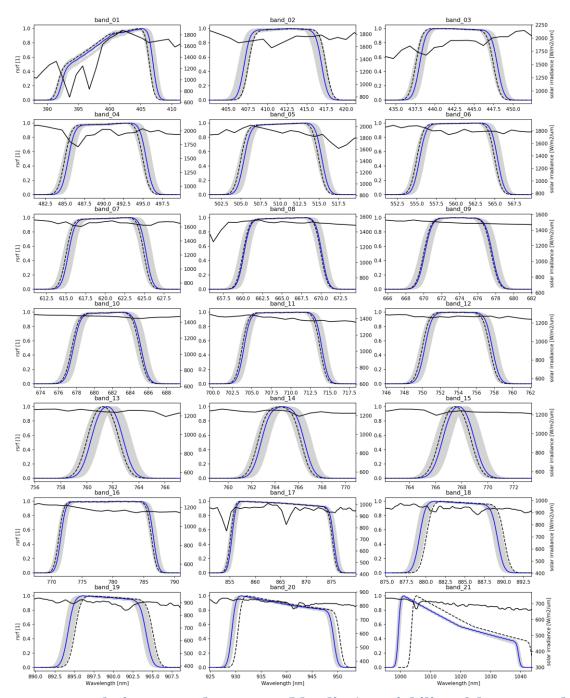


Figure 6: Mean relative spectral response (blue line), variability of the mean relative response over the field of view (shaded area) and mean relative spectral response shifted to nominal (black dashed line)





5 PRE-LAUNCH UNCERTAINTY BUDGETS

5.1 Uncertainties associated to the central wavelength of each CCD row

5.1.1 Nominal uncertainty

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:

$$\mathring{a}$$
 (fixed_bias) + $\sqrt{\mathring{a}$ (random)² = $(0.10 + 0.03) + \sqrt{(0.04^2)} = 0.17$ 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:

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

This budget applies to the module 5 (camera FM4-R).

5.1.2 Degraded uncertainty

For most of the cameras mounted aboard OLCI-B (FM2-R, FM3-R, FM6-R, FM1-R, which are the modules 1-4), an anomaly in the monochromator operation has prevented the nominal error budget presented in the paragraph above to be fulfilled. This anomaly translates as a bias on measured wavelength of 0.15 to 0.25nm, usually over the whole spectral range but sometimes on a restricted one.

A cross-check with earlier measurements of the same camera, and above all with further measurements performed at instrument level, have allowed to detect and reduce this error, if not to correct it. However, this additional measurement introduced an increase of the uncertainty.



In that case, the characterisation could be described as follows:

- The central wavelength of the pixels is characterised at camera level in a relative way (in other words, this is a characterisation of the dispersion law)
- The doped diffuser, that serves as wavelength reference for in-flight calibrations, is separately characterised in an absolute way
- The observation of the doped diffuser by the cameras (at instrument level) allows to compare the camera dispersion law to the characterised absolute wavelengths of the diffuser. The spectral bias that affects the camera can be retrieved through the best fit between both data sets.

The uncertainty budget settles as follows:

	budget in nm	Bias	Random
	Monochromator wavelength relative accuracy	0.03 nm	
Camera dispersion law	Monochromator Wavelength Repeatability		0.015 nm
characterisation	Accuracy of the computation of the pixel		
	response curve maximal value		0.04 nm
Diffuser absolute	Monochromator absolute wavelength accuracy	0.08 nm	
characterisation	Peak localisation / Photometric accuracy		0.10 nm
Determination of	Measurement resolution/SQR(Nb of		
camera spectral bias	Wavelength)		0.02 nm
	Total per type	0.11 nm	0.11 nm
	Total	0.22	nm

Table 3: Degraded uncertainty of the camera central pixel wavelength.

It happens the estimated uncertainty is of the same order of magnitude as the observed spectral shift. This budget applies to all modules but module 5 (FM-4R).

5.2 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 Table 4.

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)	1.81%	1.56%	1.13%	0.80%	0.66%	0.53%	0.44%	0.44%	0.48%	0.63%

Table 4: Spectral relative accuracy of the response measurement.

5.3 Uncertainties associated to the in-band solar irradiance

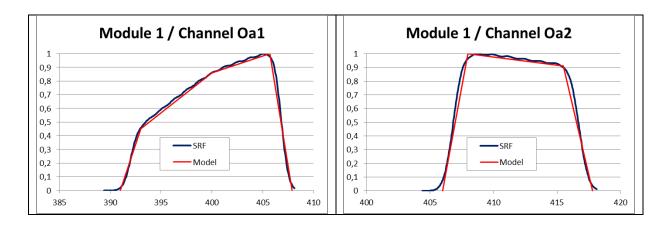
The OLCI in-band extra-terrestrial solar irradiances are computed by convolving the individual CCD column SRF for a given OLCI spectral band and module with the Thuillier et al. (RD-04) extra-terrestrial solar spectral irradiance spectrum at 1 AU.

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 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-04).

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 7). The in-band irradiance is then computed by numerical integration, using the spectral sampling of the Sun spectrum as per Thuillier data (RD-04), 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. 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 0.19nm, which is the budgeted wavelength uncertainty.
- Case 4: same as above, but wavelengths shifted towards shorter ones.





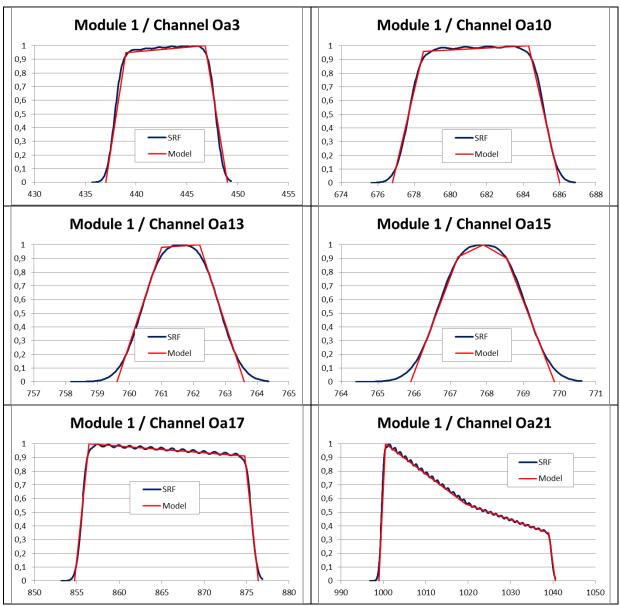


Figure 7: Example plots of simplified SRFs (red) used to estimate the uncertainty associated to the in-band solar irradiance compared to the original SRF (blue)

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



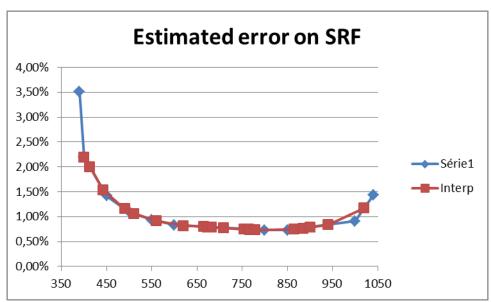


Figure 8: SRF error considered for cases 1 and 2

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	Oa ₇	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%
Accum	0.6%	0.2%	0.4%	0.12%	0.3%	0.16%	0.04%	0.06%	0.08%	0.06%	0.11%

	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%
Accum	0.01%	0.06%	0.24%	0.17%	0.11%	0.14%	0.06%	0.02%	0.05%	0.06%

Table 5: 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.



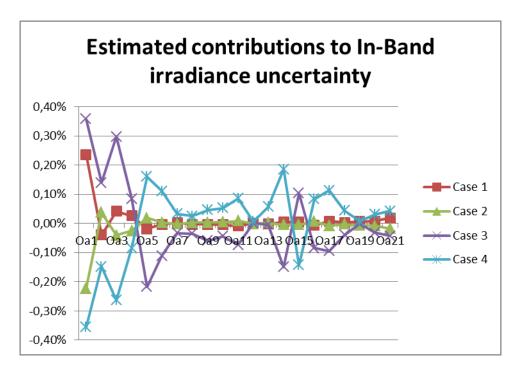


Figure 9: Estimated uncertainties associated to the in-band solar irradiance by propagating uncertainties associated to the OLCI spectral band center wavelength and the uncertainty associated to the OLCI spectral band SRFs

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 1. Conversely, the propagation of the uncertainty associated to the centre wavelength of the OLCI spectral bands is significant in nearly all channels.

6 OLCI-B SRF CALCULATED FROM PRE-LAUNCH CHARACTERISATION MEASUREMENTS

6.1 File format description

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

- **S3B OL SRF o 20180102.nc4** providing:
 - o *center_wavelength*, the central wavelength of relative spectral response (in nm) for : 21 bands x 5 modules x 740 CCD columns
 - o *bandwidth_fwhm*, the bandwidth full_width_half_maximum (in nm) for: 21 bands x 5 modules x 740 CCD columns
 - o *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
 - o *relative_spectral_response*, the SRFs for: 21 bands x 5 modules x 740 CCD columns x 200 sampling wavelengths



- o 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
- S3B OL SRF o 20180102 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
- S3B OL SRF o 20180102 mean.nc4
 - o 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')

6.2 Figures describing the SRFs of OLCI-B 21 spectral bands

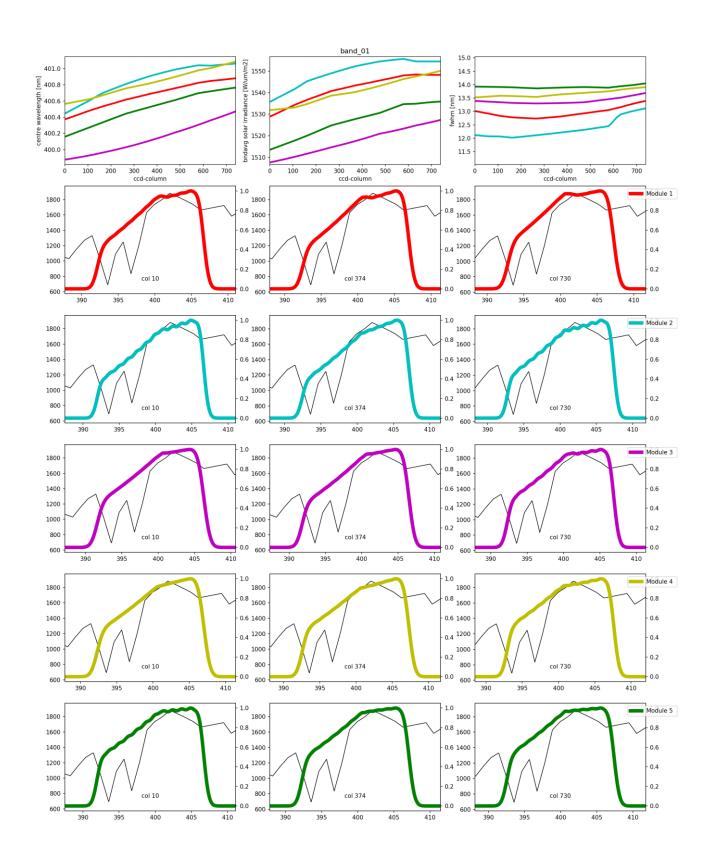
The previously described dataset is visualised in this section.

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).

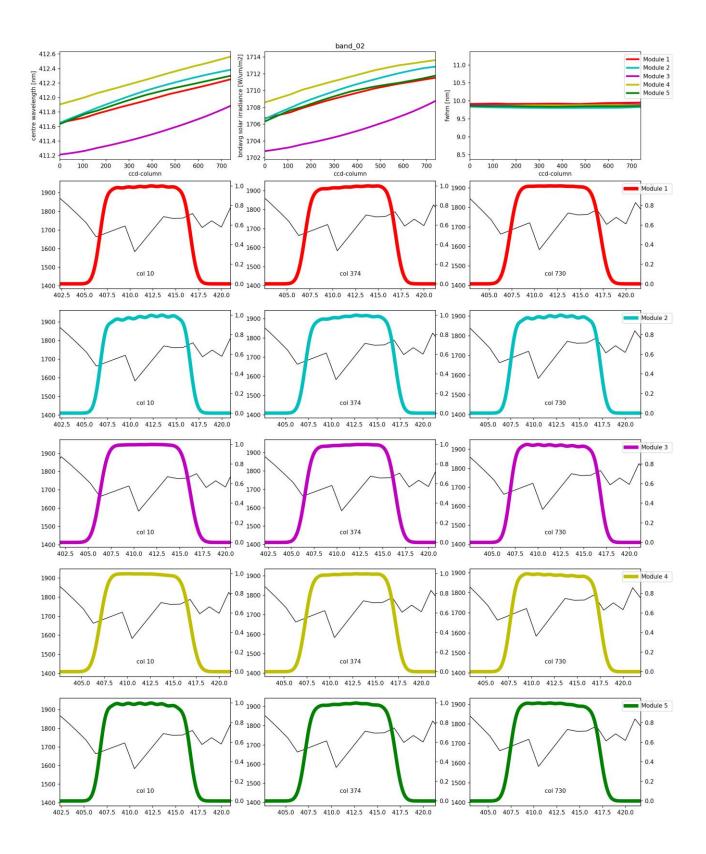
Then only at CCD column 10, 374 and 730, the shape of the SRF is plotted for each of the module. In addition, in the centre row, the Thuillier et al. (RD-04) spectrum is plotted versus the wavelength to illustrate the potential influence of spectral calibration uncertainties on the in-band irradiance value.



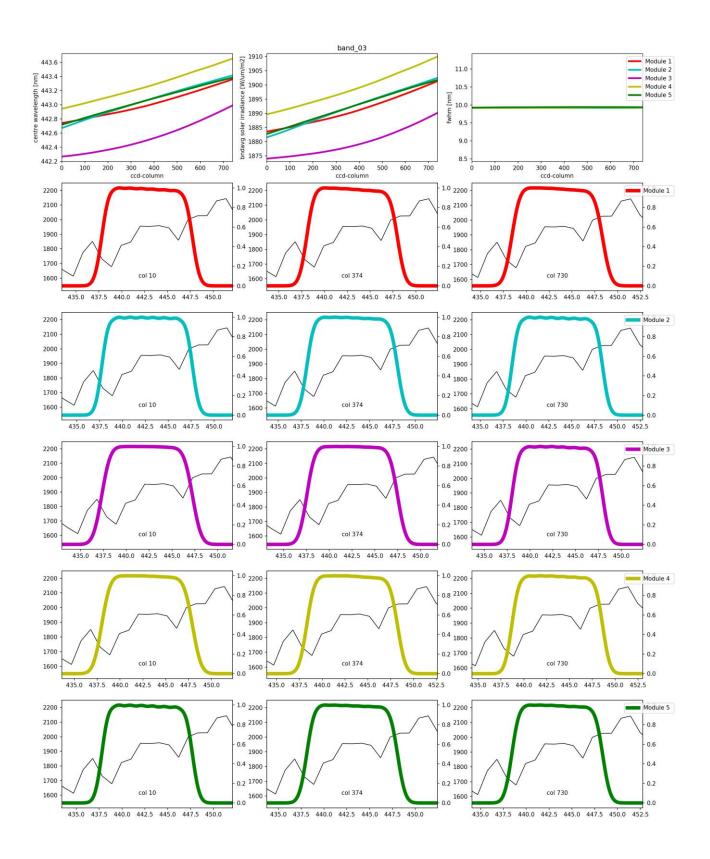


Page 27/50 **Sentinel-3 OLCI-B preflight spectral response** Date 11/02/2016 Issue 1 Rev 1

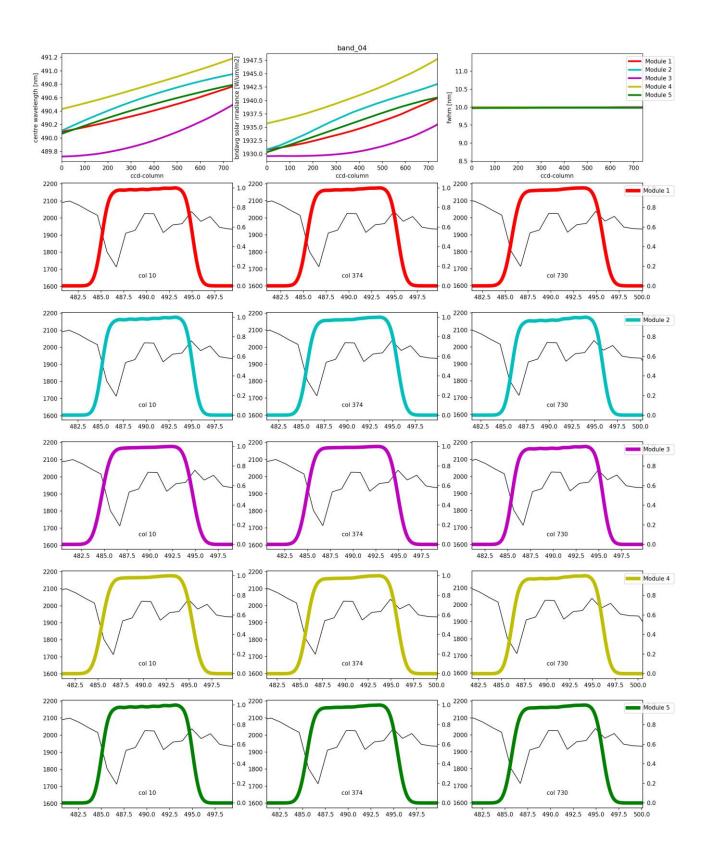




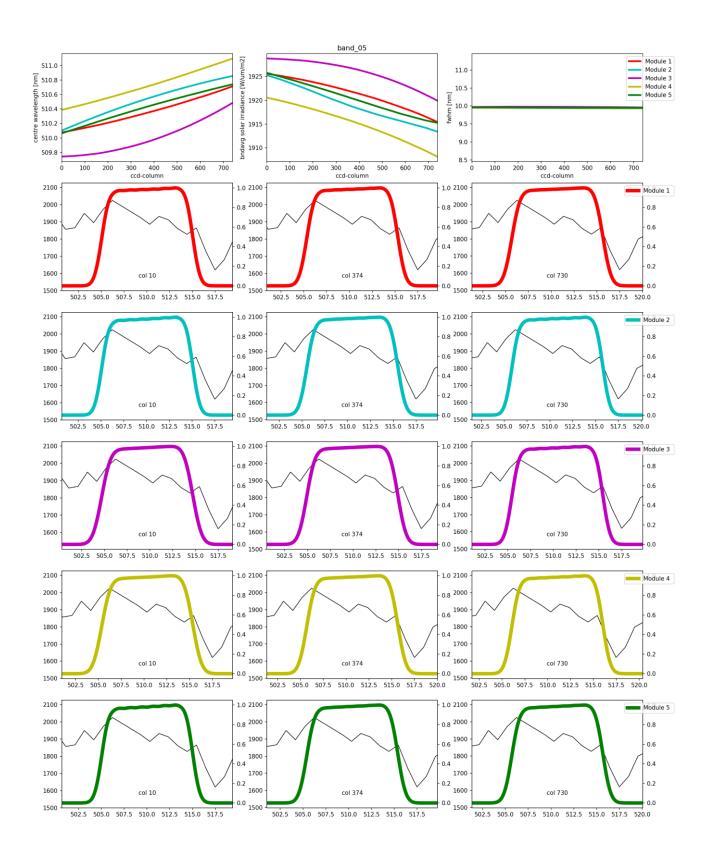




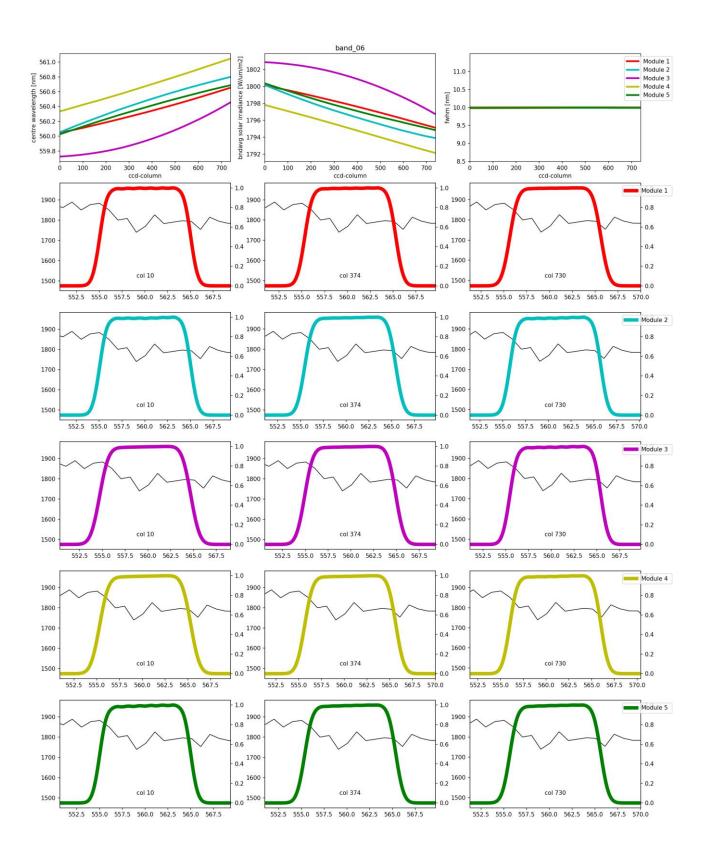




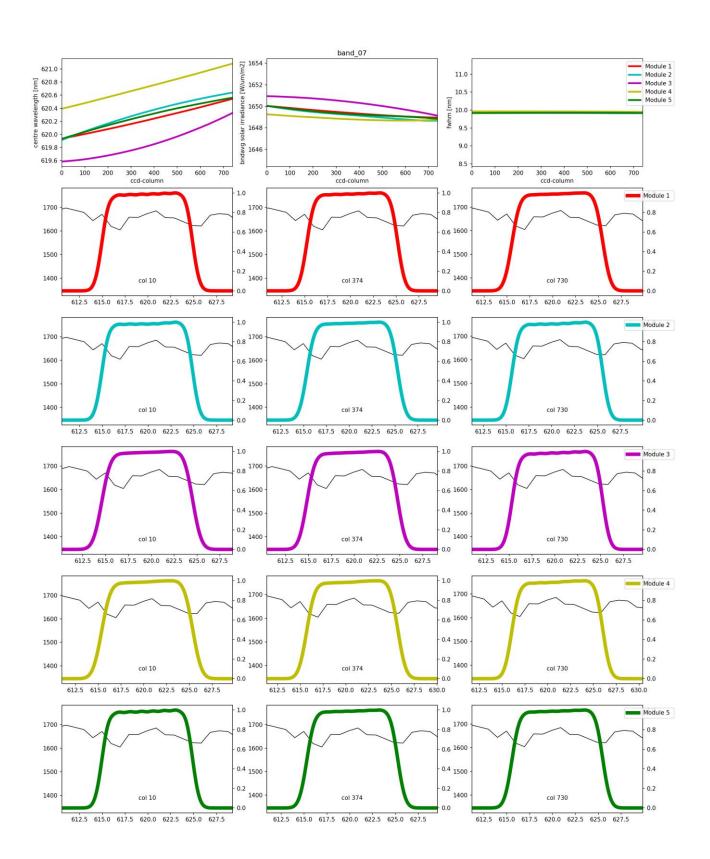




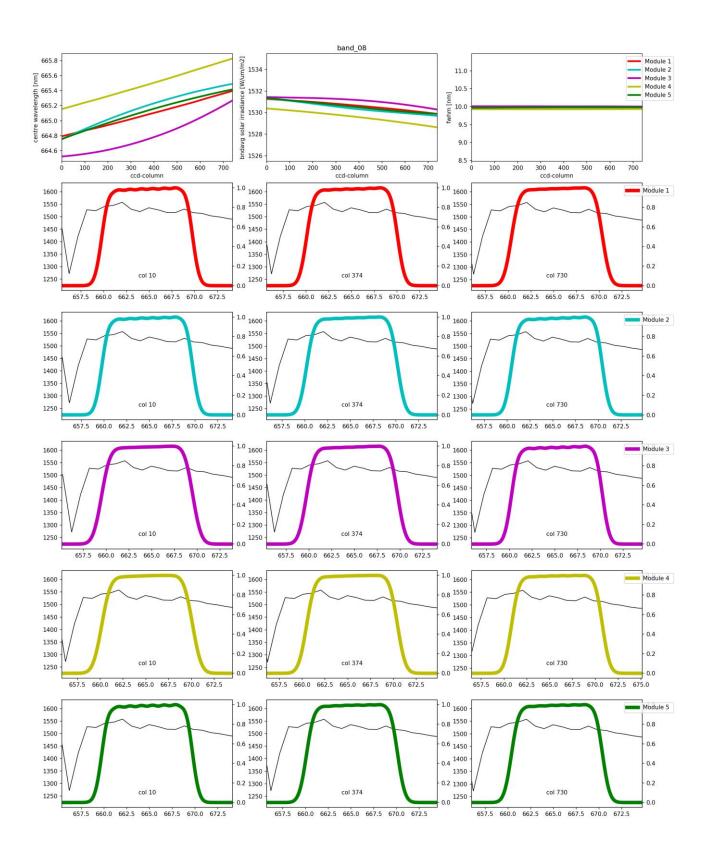






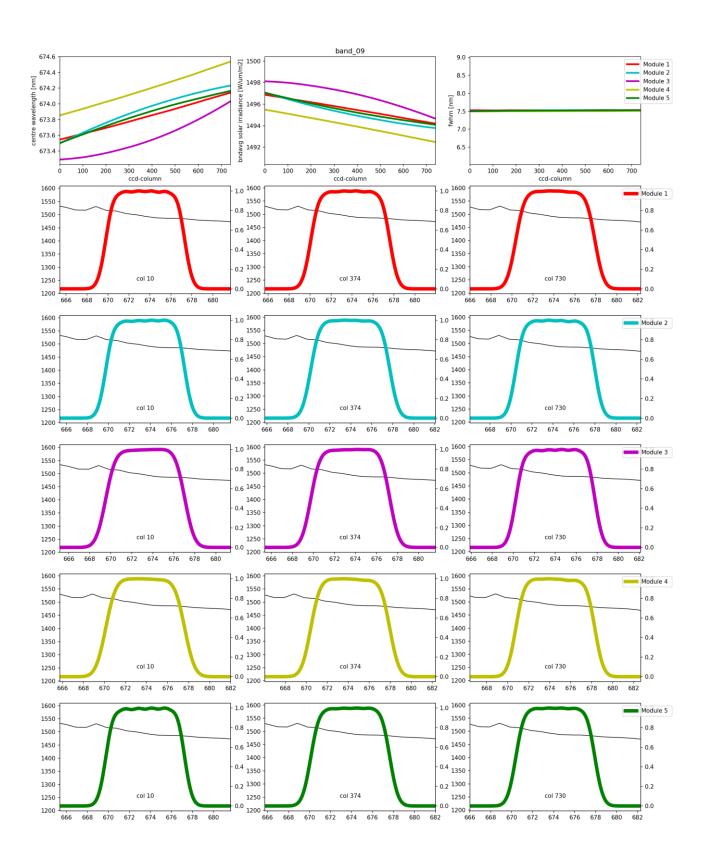






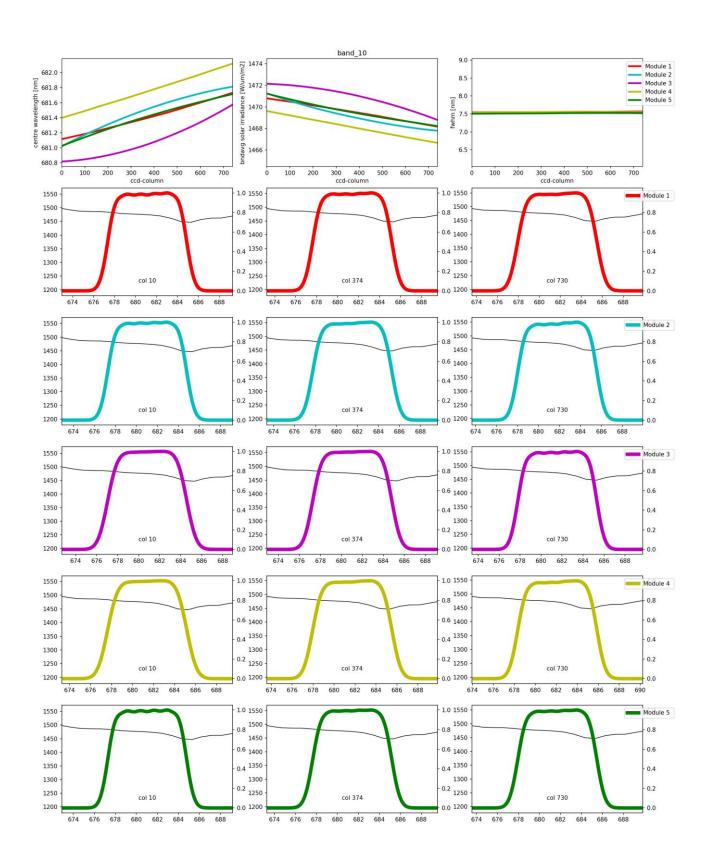
Page 34/50 **Sentinel-3 OLCI-B preflight spectral response** Date 11/02/2016 Issue 1 Rev 1





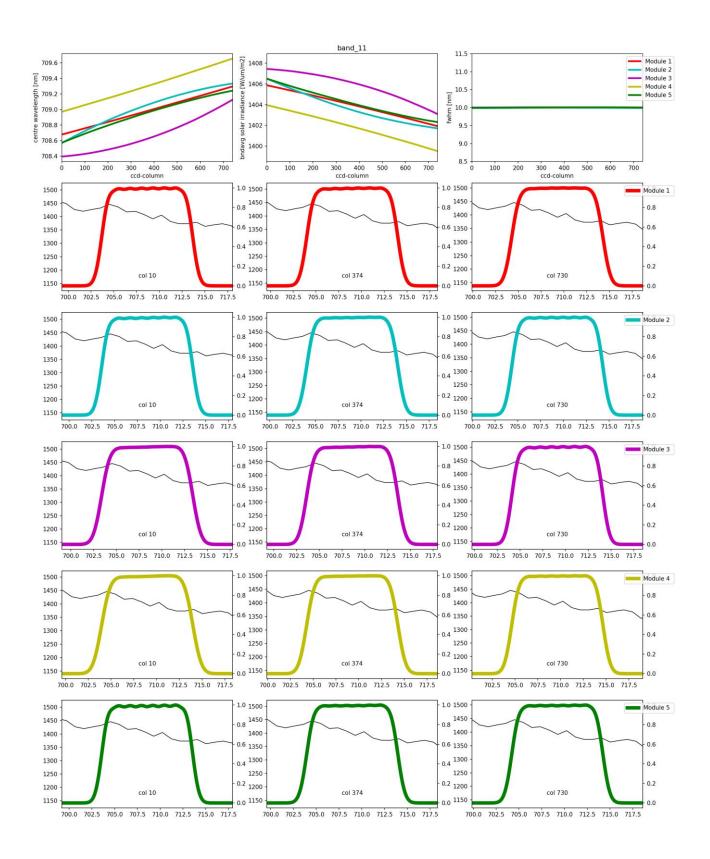
Page 35/50 **Sentinel-3 OLCI-B preflight** spectral response Date 11/02/2016 Issue 1 Rev 1



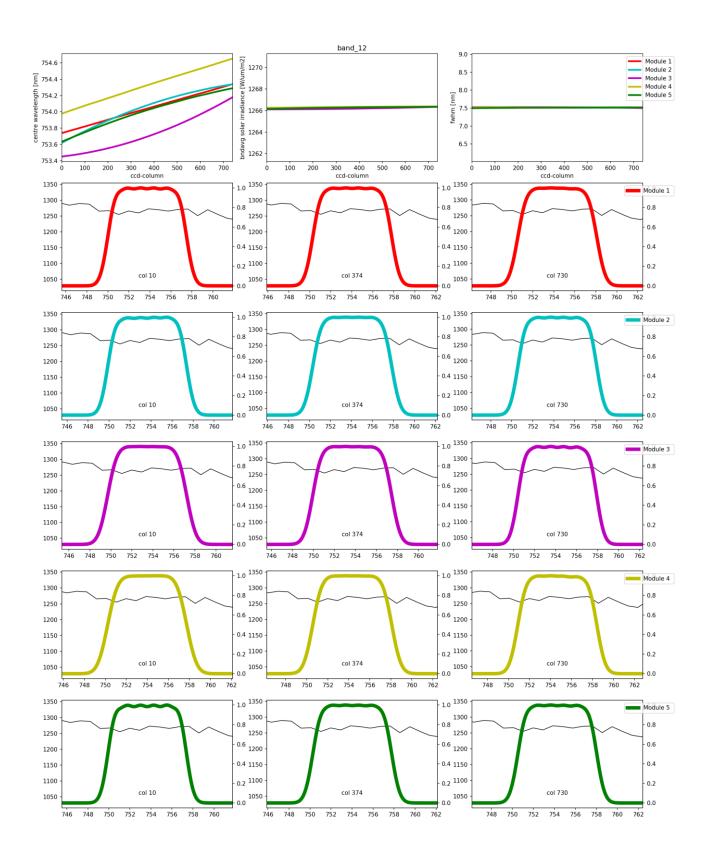


Page 36/50 **Sentinel-3 OLCI-B preflight spectral response** Date 11/02/2016 Issue 1 Rev 1

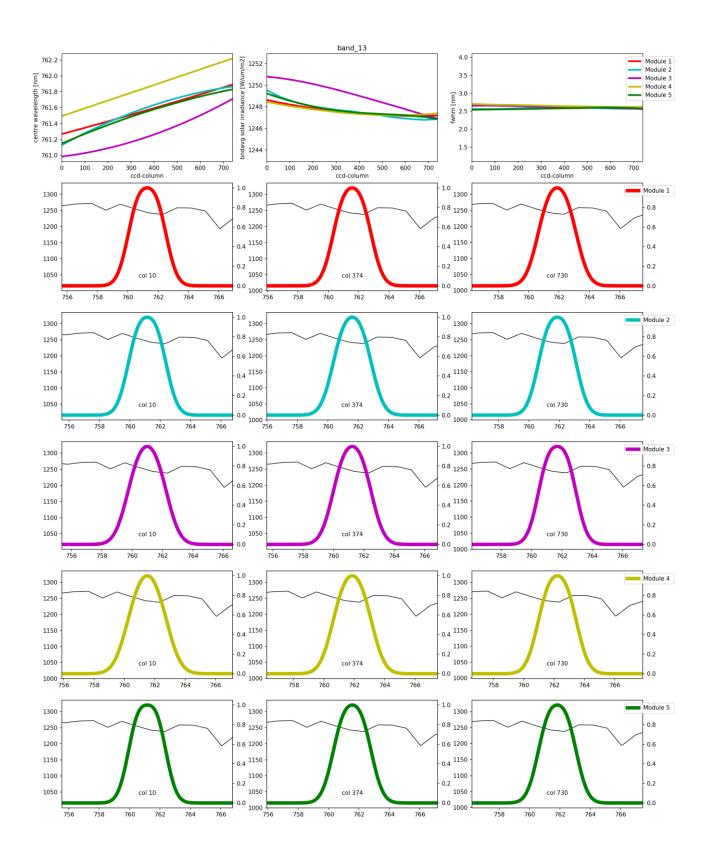




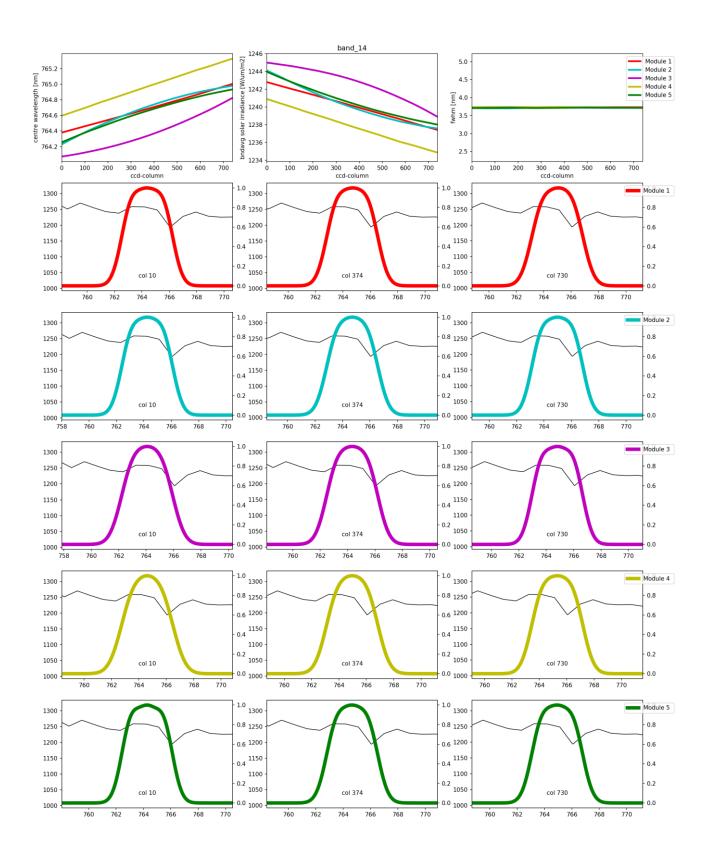




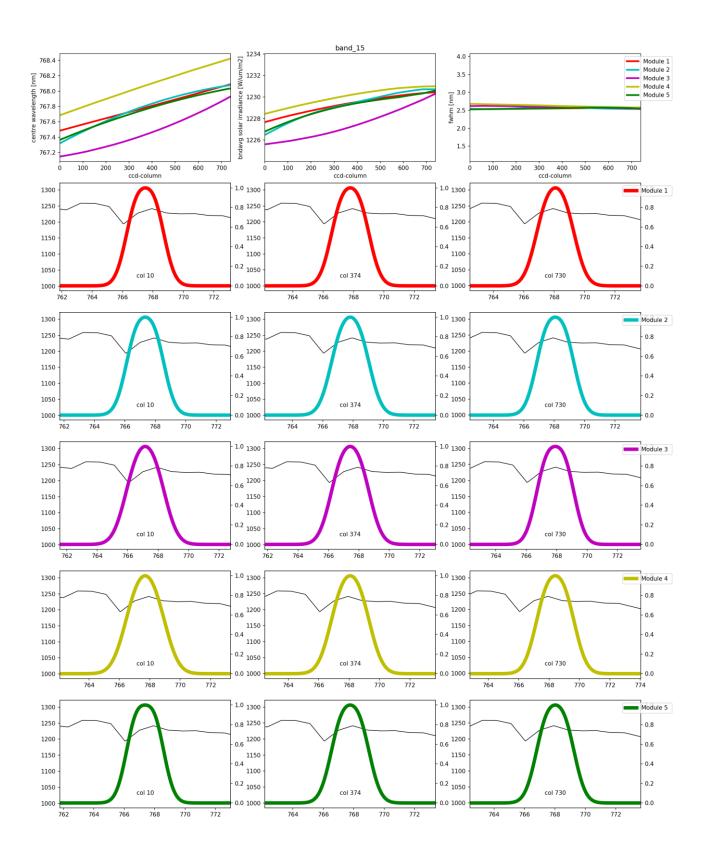






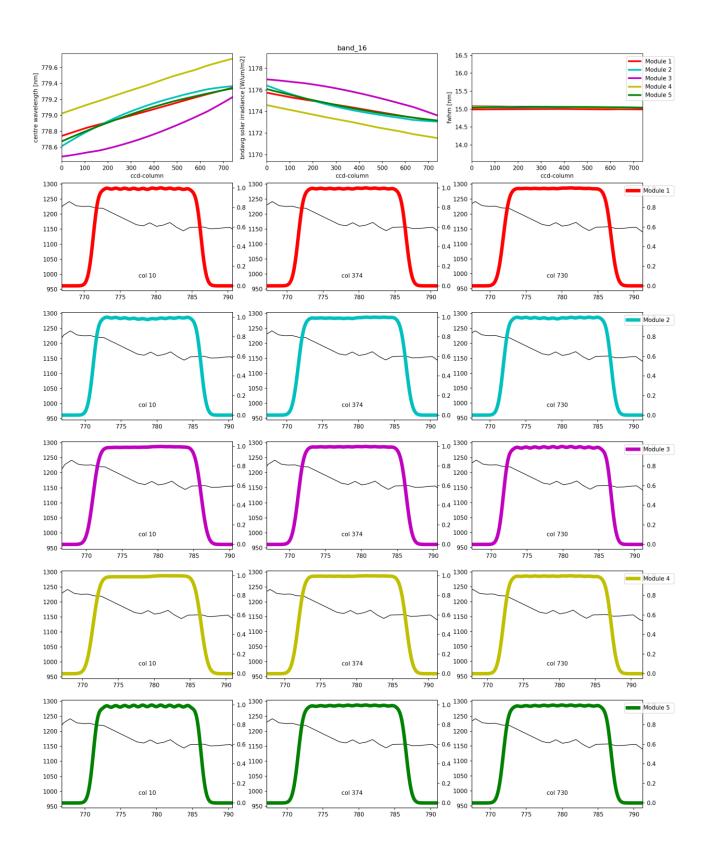






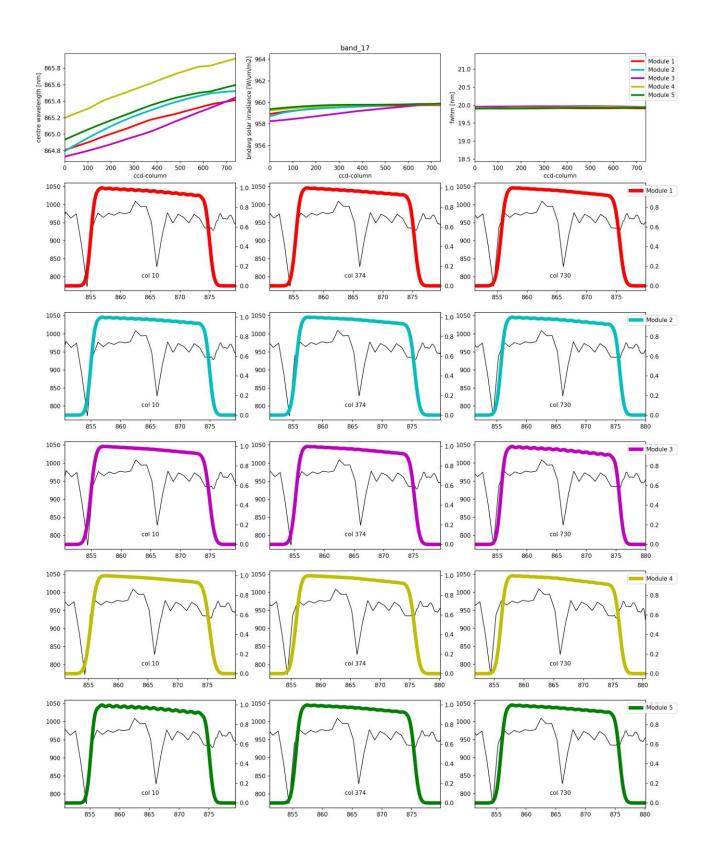
Page 41/50 **Sentinel-3 OLCI-B preflight spectral response** Date 11/02/2016 Issue 1 Rev 1





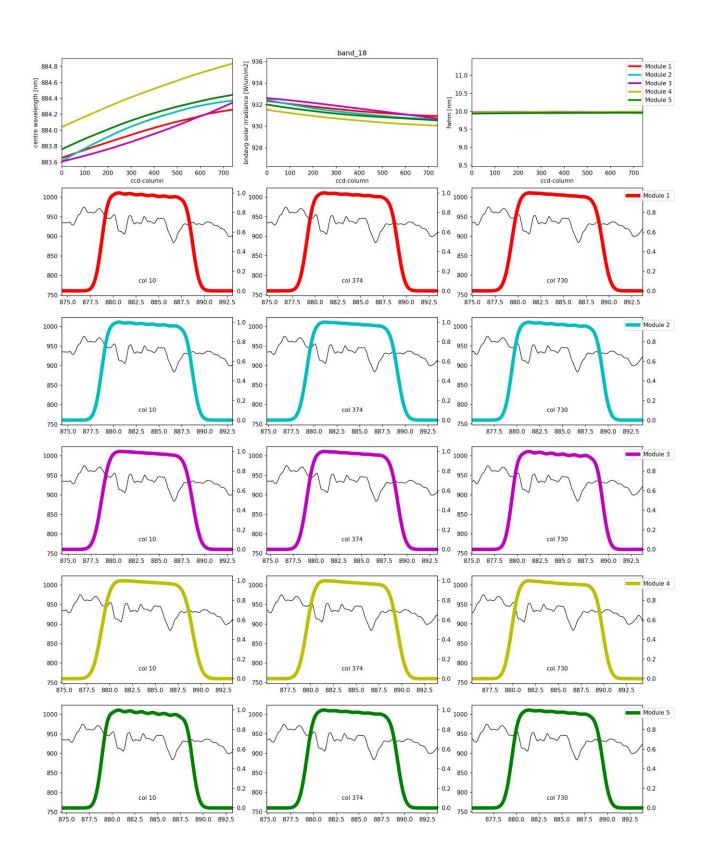
Page 42/50 **Sentinel-3 OLCI-B preflight spectral response** Date 11/02/2016 Issue 1 Rev 1





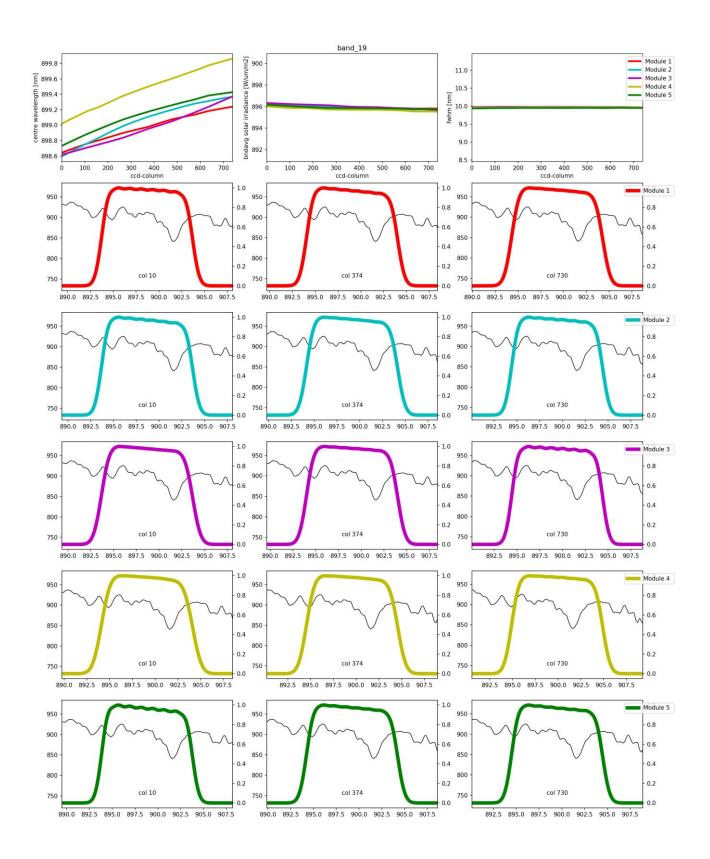
Page 43/50 **Sentinel-3 OLCI-B preflight spectral response** Date 11/02/2016 Issue 1 Rev 1





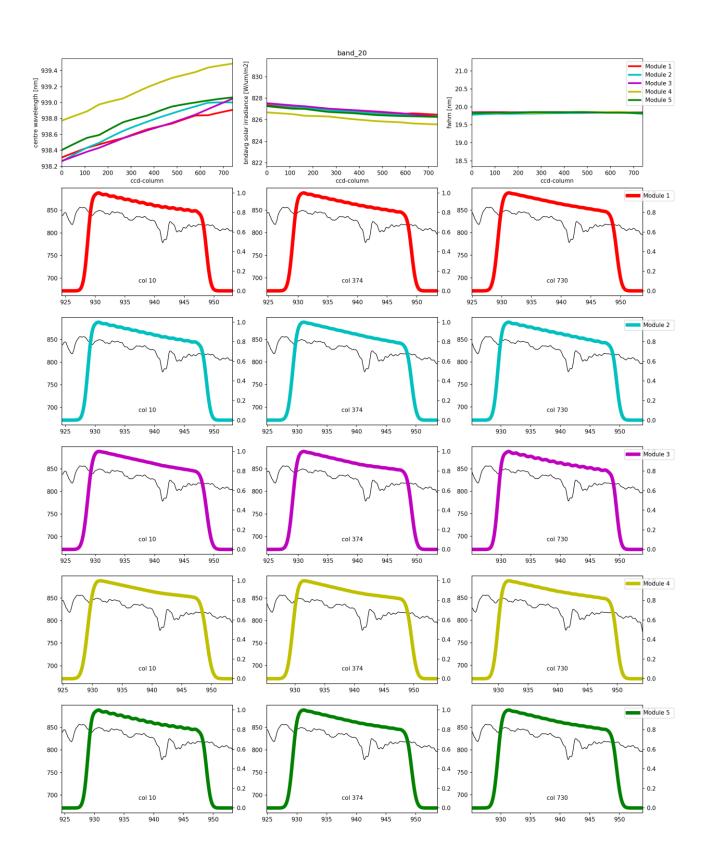
Page 44/50 **Sentinel-3 OLCI-B preflight spectral response** Date 11/02/2016 Issue 1 Rev 1





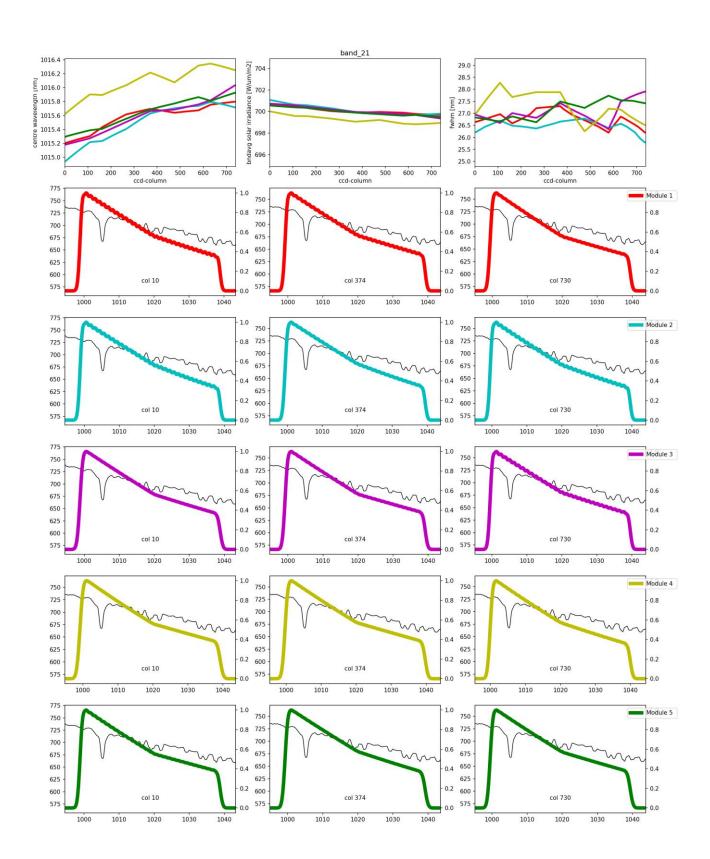
Page 45/50 **Sentinel-3 OLCI-B preflight spectral response** Date 11/02/2016 Issue 1 Rev 1





Page 46/50 **Sentinel-3 OLCI-B preflight spectral response** Date 11/02/2016 Issue 1 Rev 1





Page 47/50 **Sentinel-3 OLCI-B preflight spectral response** Date 11/02/2016 Issue 1 Rev 1



ANNEX A: MATHEMATICAL MODEL DEFINING SPECTRAL PARAMETERS

A.1 Linear Interpolation

Given a function $f: R \to R$ at two data points xo 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})

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

so that the four sampling points (x_0, y_0) ... (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:

$$\int_{x_1}^{x_{N+1}} f(x)dx \approx h \cdot \frac{1}{2} \cdot \sum_{i=1}^{N} (f(x_i) + f(x_{i+1}))$$

using the sampling distance

$$h = \frac{x_{N+1} - x_1}{N}$$



ANNEX B: ESTIMATION OF A CAMERA MODULE SPECTRAL RESPONSE UNCERTAINTY

B.1 OVERVIEW AND OVERALL BUDGET

The radiometric response is evaluated through 2 steps:

- Measurement of the camera response at a given set of wavelengths, at instrument level and using the flight Scrambling Window Unit (SWU)
- Adjustment of SWU transmission data to reproduce the measured response, for the same set of wavelengths (correlation coefficient).

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	1.4%	1.4%	1.0%	0.7%	0.6%	0.5%	0.4%	0.4%	0.4%	0.5%
relative error (1)										
Spectroradiometer operation in	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
front of the GSE source (2)										
Repeatability of the source (3)	0.7%	0.6%	0.5%	0.34	0.2%	0.1%	-0.1%	-0.1%	-	-0.3%
				%					0.2%	
Repeatability of the	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
spectroradiometer (4)										
Influence of camera noise (1000 acquisitions) (5)	0.9%	0.3%	0.1%	0.1%	0.1%	0.0%	0.0%	0.0%	0.1%	0.2%
Total (1-sigma error)	1.81 %	1.56 %	1.13 %	0.80 %	0.66 %	0.53 %	0.44 %	0.44 %	0.48 %	0.63 %

Table 6: 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 RSS of the respective errors for these 2 wavelengths.

For example, for any pair of wavelengths in the range 1000-1040nm, the accuracy settles to 0.8%, and to 2.4% 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 inacurracy, mainly originating from the knowledge of the reference standard and from the noise and repeatability of the spectroradiometer.

From the calibration certificate (No. CAL-130-16-090 dated 15/12/2016, 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 6 above. This contribution is clearly the driver of the overall accuracy.

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 characterised using the etalon spectroradiometer, then it is used by to characterise 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 the above Table 6.

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 above Table 6.

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

The camera response is characterised 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 the Table 6 have been assessed according to the signal effectively measured during the characterisation of one of the cameras.

B.2.6 Relative accuracy of SWU (between models)

The responsivity being measured using the flight SWU, no contribution is to be considered here.