

EARTH SPACE SOLUTIONS



Diffuser BRDF Analysis Modelling from On-Orbit Measurements

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Document number:

ESS_S3R_FR_001_rev3
Version: 2017-05-10

Distribution:

EUMETSAT
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2 EXECUTIVE SUMMARY

On Sentinel-3 OLCI, the solar diffuser is the radiometric standard for the instrument. The nonphysical degradation determined from the monitoring of solar measurements was an indication that the employed diffuser bidirectional reflectance (BRDF) model required an update. Special in-flight yaw manoeuvres were planned and successfully executed, that allowed OLCI to observe the sun under a variety of solar angles in a single day which were representative of the solar angles observed during the year. Employing the newly acquired solar measurements, and assuming no degradation took place during that single day, we will show comparisons with the diffuser Rahman reflectance model derived from the ground laboratory measurements. Differences of a $\sim 1\%$ are often found, most likely due to the model failing to describe the diffuser behaviour especially in the solar scattering plane. Next we'll show a new model approach, based upon second- and cross order dependency on solar azimuth and zenith angle for each pixel individually, and its derivation from the yaw manoeuvre measurements. The new model succeeds in describing the measurements down to the measurement noise of 0.1%. Remaining residuals, after some spatial smoothing in order to lower the measurement noise, are shown to be dominated by diffuser speckles that move around slowly in all measured dimensions. However, not enough solar azimuth angles were measured to characterise the varying speckles, which would have allowed further reduction of model residuals. The in-flight model is tied to the on ground model at a reference solar angle in order to determine the absolute calibration, allowing the new model to be employed during operational monitoring. Comparisons with other in-flight measurements under similar angles validate the new model down to the measurement noise. The new model applied with OLCI in-flight radiometric calibrations results in the expected physical degradation that is smooth in time irrespective of solar angles. Lessons learned and recommendations for future missions are:

1. During on-ground calibration repeat the reference geometry measurement in order to increase accuracy.
2. Cover more finely the range of solar geometries actually encountered in-flight during on ground calibration measurements.
3. Perform in-flight yaw maneuvers which allow very accurate in-flight calibration BRDF modelling at low risk and impact.
4. During in-flight calibration sample enough illumination angles with enough resolution to resolve the diffuser speckles
5. Perform system level diffuser characterization in addition to component level

3 INTRODUCTION

3.1 PURPOSE AND SCOPE

This document describes the results from EUMETSAT study **Diffuser BRDF Analysis Modelling from On-Orbit Measurements** performed by Earth Space Solutions with the goal to provide a recommendation towards the update of the existing BRDF model based only on pre-launch measurements (Kwiatkowska, 2016).

The on-orbit measurements giving rise to this study have been obtained following the recommendations from the Sentinel-3A Ocean and Land Colour Instrument (OLCI) In-Orbit Commissioning Review (IOCR) technical meeting (S3-MN-ESA-OL-752, 2016). The IOCR meeting recommended to execute a day sequence of Sentinel-3A yaw maneuvers in order to address the non-physical behavior of OLCI instrument degradation visible since the launch. The yaw maneuvers allowed to assess with real on-orbit measurements the “imperfect representation of the on-ground characterisation of the OLCI solar diffuser through a BRDF model”. EUMETSAT realized the sequence of the recommended maneuvers on 7 December 2016 (S3A_OPER_SOR_FCT114d_2016263T150000_0001, 2016).

The OLCI diffuser BRDF modeling from yaw maneuvers also fulfils the earlier recommendation, S3MAG-M4-A10, of Sentinel-3 Mission Advisory Group (EOP-SM/2773/CD-ik, 2014). Additionally, the activity answers to the OLCI calibration/validation task OLCI-L1B-CV-280 from the Sentinel-3 Calibration and Validation Plan (S3-PL-ESA-SY-0265, 2014).

This study has been realized in close collaboration with the Sentinel-3 Mission Performance Centre (S3-MPC). The critical steps of testing of newly derived OLCI diffuser BRDF models have been performed by S3-MPC with operational radiometric calibration data.

3.2 OLCI SOLAR DIFFUSER

Solar diffusers on Sentinel-3 OLCI are the primary radiometric standard for the instrument. OLCI calibration accuracy and thus the quality of its products strongly depends on how accurately the solar diffusers are characterized. OLCI has two diffusers for radiometric calibration, the nominal one and the reference one. The precise knowledge of diffuser bi-directional reflectance distribution function (BRDF) allows quantitative interpretation of OLCI radiometric response and temporal degradation via regular on-orbit calibration campaigns through the mission lifetime. The knowledge of BRDF is critical because the diffuser plates are not perfectly Lambertian and different in-flight calibration geometries result in different fractions of sunlight reflected to the instrument.

OLCI solar diffuser (SD) radiometric calibrations are performed near the orbital South Pole where the solar illumination geometry enables the sunlight to fall directly onto the SD plates. During each calibration sequence, the calibration wheel is rotated to move the diffuser plate into the instrument field-of-view (FoV) so that all five cameras view the sun and are calibrated at the same time. Sunlight incidence on SDs is oblique, around 65° of the solar zenith angle. As planned, the reference diffuser is deployed much less frequently than the nominal one and the characterization of the diffuser ageing is determined through on-ground analysis of data obtained from nominal and reference diffusers. OLCI's optical path is presented in Fig. 1 where the nominal and the reference SDs are described as “Radiometric cal. diffuser” and “Degradation monitoring”.

SD calibrations are used to derive OLCI absolute reference gains and instrument temporal degradation. The accuracy and temporal stability of the gains are critical to meeting OLCI mission requirements and the requirements of OLCI data products, which are much stricter for ocean color applications. The SD-related errors are the largest component of the total OLCI absolute radiometric uncertainty budget. These errors are associated with laboratory BRDF characterization, BRDF modelling, and diffuser alignment on the instrument. On orbit, any additional biases or artifacts in radiometric calibration are undesirable as they would add to the pre-launch instrument uncertainty budget or cause temporal trends unsuitable for many applications.

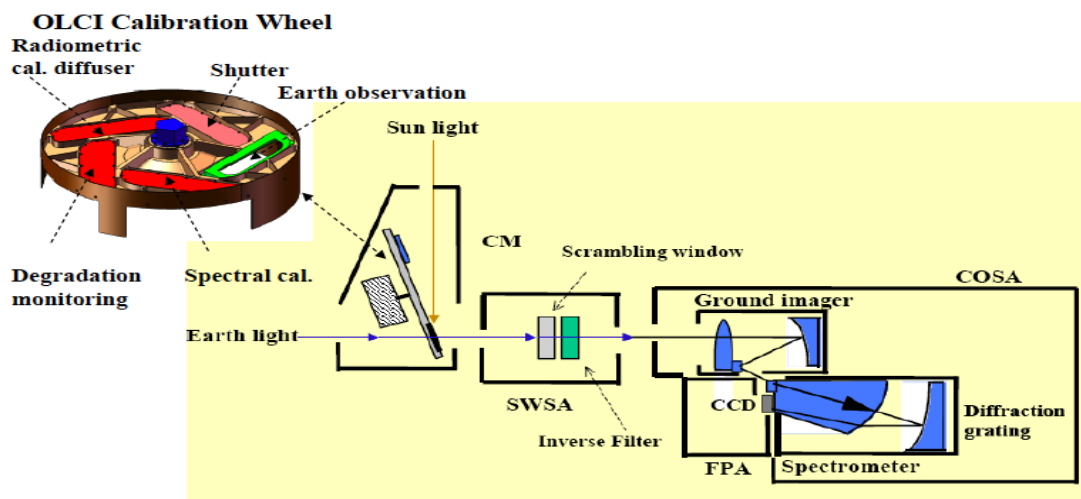


Fig. 1 OLCI Optical path

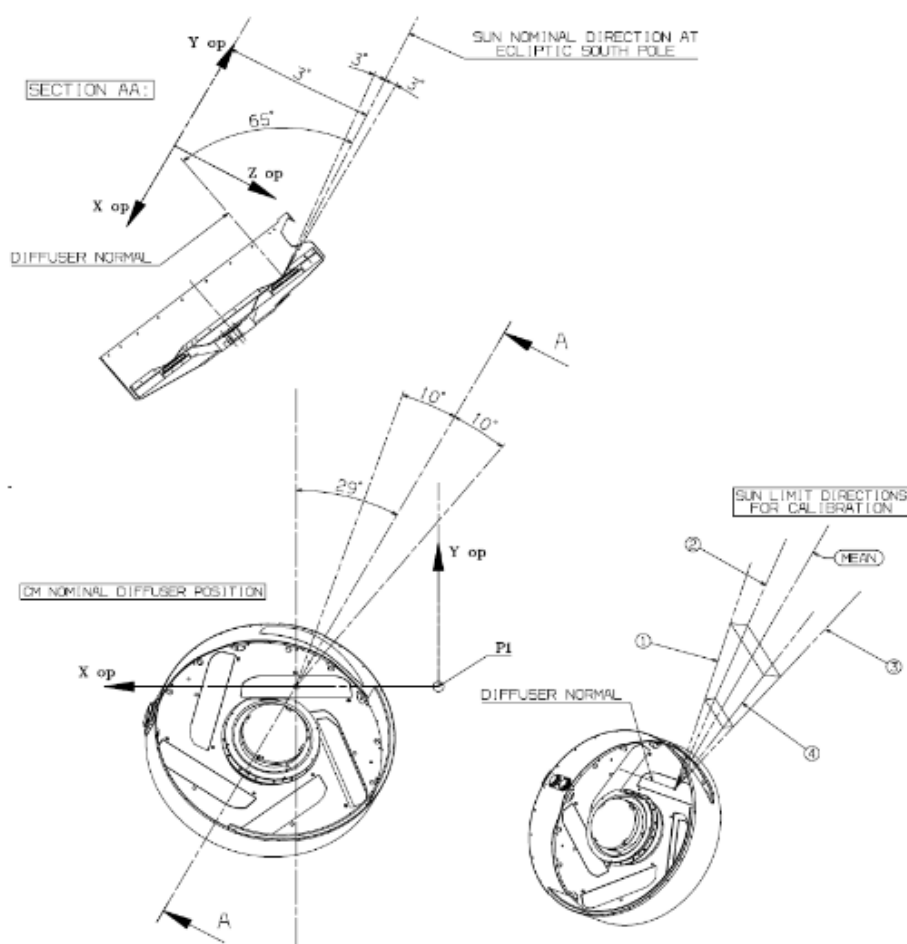


Fig. 2 OLCI mechanical drawings showing the diffuser geometry in the Instrument Reference Frame (IRF) with respect to Satellite Nominal Attitude Frame (SNRF). Drawings from Amselem, 2014

3.3 OLCI SOLAR DIFFUSER PRE-LAUNCH CHARACTERIZATIONS

BRDF measurements (relative and absolute) for OLCI SD flight modules were performed at Centre Spatial de Liège (CLS). Data for the following OLCI SD lab measurement analyses have been extracted from the Sentinel-3 Calibration and Characterization Database (SCCDB), launch version: S3A_OL_CCDB_CHAR_AllFiles.20160204112408_1.nc4.

OLCI SD pre-launch laboratory characterizations have applied a number of lessons learned from MERIS. The characterizations were performed at seven wavelengths spread across OLCI spectral range and at a set of seven solar incidence and nine observation angles on the diffuser. The wavelengths and geometries are given in Table 1. The geometries are given with respect to the diffuser normal.

Note: Only one solar geometry of OLCI's laboratory characterizations corresponds to the geometries actually encountered on-orbit. It is the geometry of -30.8730 solar azimuth and 65.00 solar zenith angle.

OLCI SD BRDF laboratory characterization parameters						
wavelengths	400.0	490.0	560.0	681.0	780.0	900.0 1020.0
Solar zenith	65.000	63.962	68.351	68.225	63.832	68.004 63.604
Solar azimuth	-30.873	-19.763	-20.105	-39.492	-39.767	-29.794 -29.760
Sensor zenith	34.030000	35.859000	32.354000	36.499000	38.182000	39.890000
	31.640000	30.102000	28.615000	24.190000	26.646000	21.861000
	26.096000	27.468000	28.907000	22.509000	21.539000	20.710000
	19.182000	22.174000	16.192000	19.628000	20.160000	20.864000
	19.182000	19.432000	19.873000	22.511000	25.124000	20.001000
	21.108000	20.355000	19.770000	24.193000	25.441000	26.775000
	31.644000	33.591000	29.853000	29.355000	27.896000	26.502000
	34.033000	35.672000	37.341000			
Sensor azimuth	239.09900	234.94600	243.64700	242.05200	243.83400	245.48700
	235.75100	233.26000	230.53200	219.46800	215.44900	224.31000
	224.92700	228.15800	231.09800	213.19300	208.52600	203.47400
	184.56300	183.96600	185.37100	193.50100	199.16900	204.51400
	175.42400	169.41900	163.61600	146.79700	150.45400	142.25700
	153.94100	159.17900	164.75600	140.52300	136.79900	133.41200
	124.24400	128.48100	119.53300	128.06700	130.92400	134.06400
	120.89600	118.88800	117.03500			

Table 1: OLCI solar diffuser BRDF characterization parameters from laboratory measurements. Geometry is given in the solar diffuser reference frame.

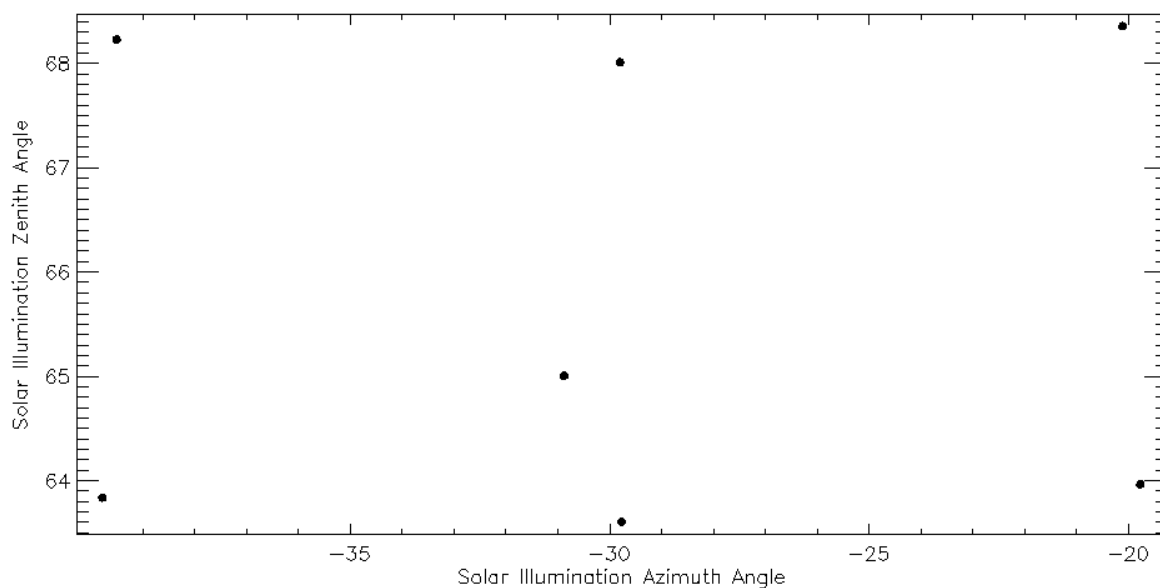


Fig. 3 On ground OLCI solar diffuser BRDF characterization solar geometries

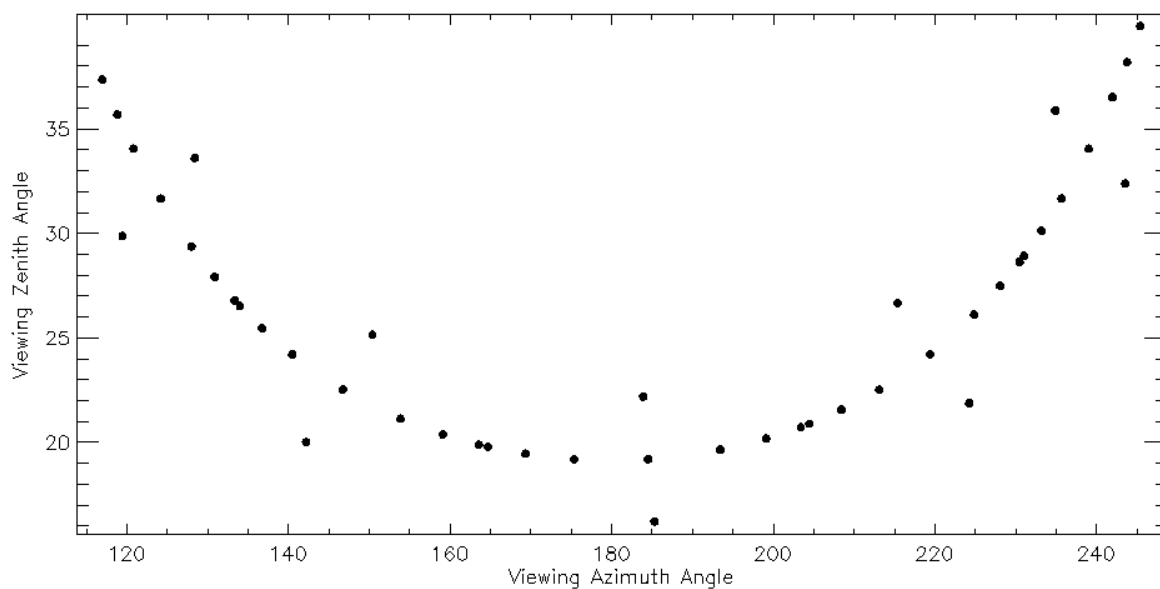


Fig. 4 On ground OLCI solar diffuser BRDF characterization viewing geometries

OLCI BRDF characterizations are traceable to the international standards at PTB/NPL and have the absolute uncertainty of 0.2 % to 0.34 %, as shown in Table 2.

	Absolute		Relative spatial	
	Perf	Req	Perf	Req
400 nm	0.338%	0.50%	0.301%	0.30%
490 nm	0.206%	0.50%	0.063%	0.30%
560 nm	0.226%	0.50%	0.134%	0.30%
681 nm	0.214%	0.50%	0.097%	0.30%
780 nm	0.252%	0.50%	0.171%	0.30%
900 nm	0.225%	0.50%	0.078%	0.30%
1020 nm	0.242%	0.50%	0.080%	0.30%

Table 2: OLCI SD lab BRDF characterization uncertainties defined as 1σ .

The diffuser characterization data from the laboratory was used to derive an analytical model of the SD BRDF as a function of observation geometry so that it can be applied with continuous geometries encountered on-orbit. Rahman, modified Rahman, Hapke and Verstraete models have been tested (Houbrechts and Plessier, 2010; OLCI L1 DPM, 2015). The best results were obtained with the Verstraete model, followed by the modified Rahman, with errors from ± 0.4 to $\pm 0.6\%$ peak-to-peak. The modified Rahman (Rahman2) model was selected for operational approximation of OLCI's SD BRDF, more details below.

Recommendation: Cover more finely the range of solar geometries actually encountered in-flight

3.4 RAHMAN MODIFIED MODEL

The On-ground Calibration BRDF Measurements were originally described by the reflectance model developed by Rahman (Rahman, 1993), slightly modified for the Hot-spot effect (S3-TN-CSL-OLCI-10018). This modified model is referred to as the Rahman2 model.

The reflectance ρ of a surface illuminated from direction θ_i, ϕ_i and observed from direction θ_r, ϕ_r for a wavelength λ is dependent on the following four free parameters: $\Theta, \rho_0, \rho_1, k$

$$\rho(\theta_i, \phi_i; \theta_r, \phi_r; \lambda) = \rho_0 \cdot M(\theta_i, \theta_r, k) \cdot F(g) \cdot [1 + R(G)]$$

$$M(\theta_i, \theta_r, k) = (\cos\theta_i \cdot \cos\theta_r)^{k-1} \cdot (\cos\theta_i + \cos\theta_r)^{k-1}$$

$$F(g) = \frac{1 - \Theta^2}{[1 + \Theta^2 + 2 \cdot \Theta \cdot \cos(g)]^{1.5}}$$

$$\cos g = \cos\theta_i \cdot \cos\theta_r + \sin\theta_i \cdot \sin\theta_r \cdot \cos(\phi_i - \phi_r)]^{0.5}$$

$$1 + R(G) = 1 + \frac{1 - \rho_1}{1 - G}$$

$$G = [\tan^2 \theta_i + \tan^2 \theta_r - 2 \cdot \tan\theta_i \cdot \tan\theta_r \cdot \cos(\phi_i - \phi_r)]^{0.5}$$

For the On-ground Calibration of the OLCI Diffuser Measurements each wavelength band is considered completely independent of all other bands with no correlation. Operationally the BRDF is calculated for each pixel at the measured wavelengths, which is then interpolated to the band of interest.

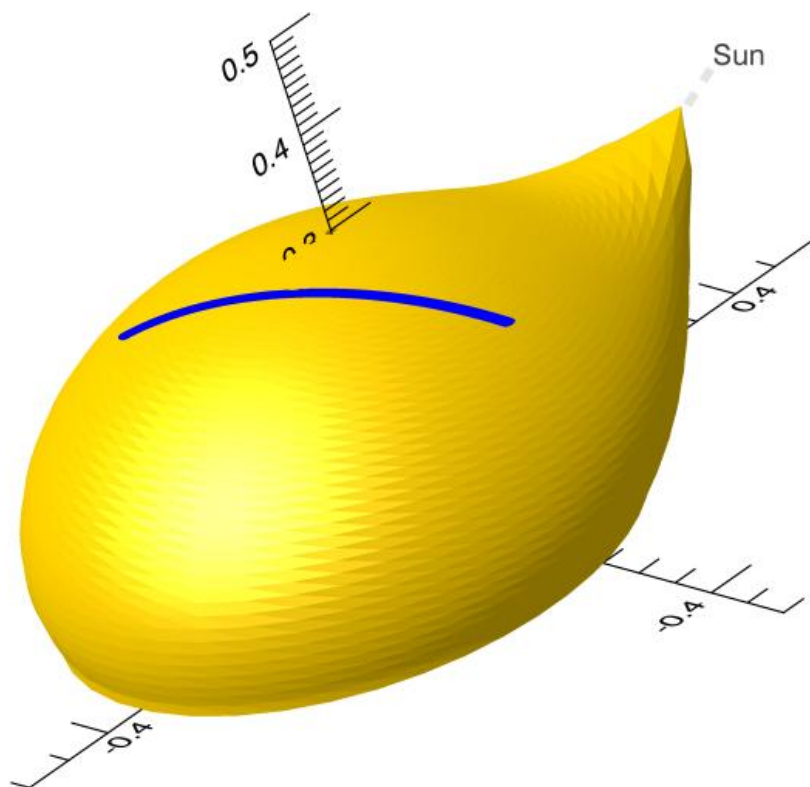


Fig. 5. Modelled on-ground BRDF response for a sza of 65 degrees and the camera viewing angles in blue. Note the smoothness of the model in this area.

The following parameters were found, Table 3:

Wave-length [nm]	ρ_0	k	Θ	ρ_1
400	0.2176	-0.0313	0.1135	-0.2714
490	0.2212	-0.0255	0.1151	-0.2630
560	0.2198	-0.0269	0.1140	-0.2584
681	0.2234	-0.0207	0.1149	-0.2488
781	0.2114	-0.0303	0.1178	-0.3205
900	0.2114	-0.0300	0.1195	-0.3364
1020	0.2175	-0.0254	0.1178	-0.2948

Table 3 Parameters of OLCI SD lab BRDF Rahman2 model

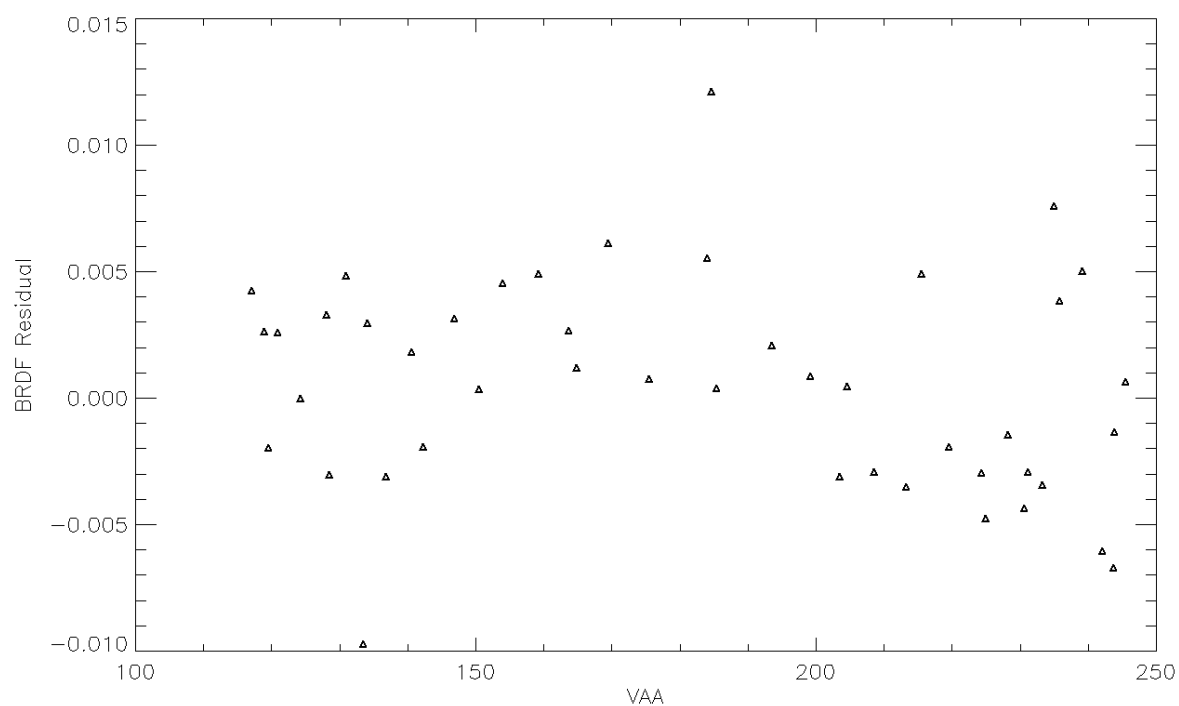


Fig. 6. Relative difference between Rahman2 model and On-ground Calibration BRDF Measurements as function of viewing azimuth angle (VAA), for 400nm.

A general overview of the magnitude of raw uncertainties of the Rahman model fit of the lab BRDF measurements is given in Fig. 6. Differences exceeding 1% are found. Other wavelengths show similar behavior.

3.5 IN-FLIGHT BEHAVIOUR

In flight application of the Rahman2 BRDF model to derive gain corrections showed unphysical gain evolution, as shown in Fig. 7. Only Camera 5 is shown here, but all camera's show similar unphysical increases and decreases, while a smoothly (exponential) increasing gain is expected based upon normal in-flight degradation due to UV exposure. This gain behavior was shown to be due to the BRDF model [Bourg, private communication]. The issue of the pre-launch Rahman2 model is particularly visible in Fig. 7 in the early mission calibrations as well as in the calibrations after the day 260 which are obtained for different solar azimuths achieved with test yaw maneuvers and the 1-day sequence of yaws.

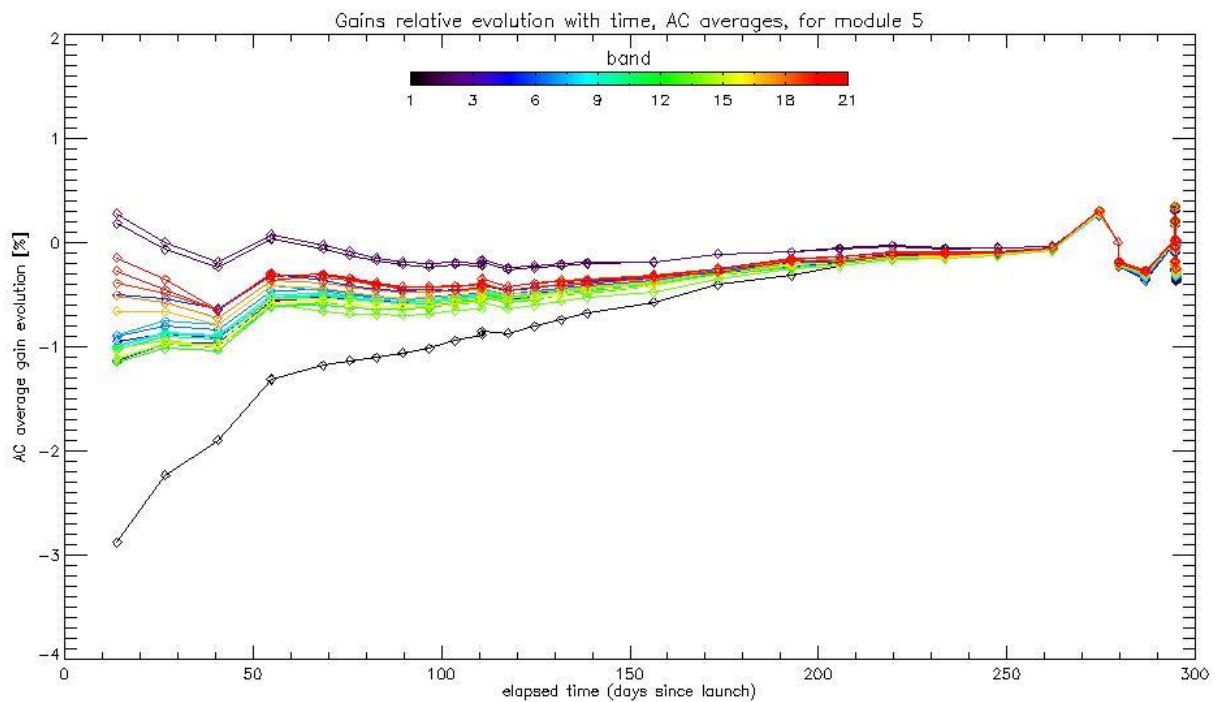


Fig. 7 In-flight derived gains evolution for module/camera 5 as function of time. Unphysical behaviour is clearly present. [Bourg, private communication]

4 YAW MANEUVERS

4.1 MOTIVATION

In order to tackle the BRDF model issues, special space craft maneuvers were planned to yaw the satellite. These yaw maneuvers allow observation of the sun under various geometries [EUM/RSP/MEM/14/781172 by Kwiatkowska, 2016.]. As the sun moves across the sky relative to OLCI during the year, the planned geometries were representative of the encountered solar geometries over a year.

The advantage of performing these manoeuvres during a single day is that instrument degradation should be minimal between them. In total, 7 yaw manoeuvres with standard radiometric calibrations S01 were performed on 7 Dec 2016 and are employed in this study. All wavelength bands were measured. There also were 3 earlier test yaw manoeuvres, on 17, 22, and 29 Nov 2016, however these test data were not used in this study.

4.2 YAW MANEUVER GEOMETRIES

In total 7 yaw manoeuvres with standard radiometric calibrations S01 were performed on 7 Dec 2016. During each manoeuvre a solar azimuth was fixed (or varied very little), while the sun moved across the diffuser field of view in zenith direction.

The measured geometries are shown in Table 4 and in Fig. 8, Fig. 9, and Fig. 10. For verification the first measured geometry was repeated at the end of the manoeuvres, Cal# 1 and 7 in Table 4. Additionally these two geometries were planned to be as close as possible to the on-ground reference geometry, i.e. the only solar geometry of OLCI's laboratory characterizations actually encountered on-orbit, as described in section 3.3. The seven yaw manoeuvres provided a scan across the sun in solar zenith direction.

Cal#	Type	target SAA in SC frame [deg]	target centre SEA in SC frame [deg]	yaw bias [deg]
1	S01	28.919	-2.179	0.117
2	S01	35.0		-5.957
3	S01	32.3		-3.249
4	S01	27.41		1.648
5	S01	23.8		5.265
6	S01	21.3		7.771
7	S01	28.919		0.158
8	S05	28.919		0.166

Table 4 Definition of OLCI radiometric calibrations realized on 7 Dec 2016 (S3A_OPER_SOR_FCT114d_2016263T150000_0001, 2016). S01 is the standard radiometric calibration, as used in this study. S05 is the diffuser ageing calibration obtained with the reference diffuser, S05 measurements were not used in this study. SAA is the solar azimuth angle, SEA is the solar elevation/zenith angle, yaw bias is the yaw angle executed by the S3A spacecraft, and the geometries are expressed in the spacecraft (SC) reference frame.

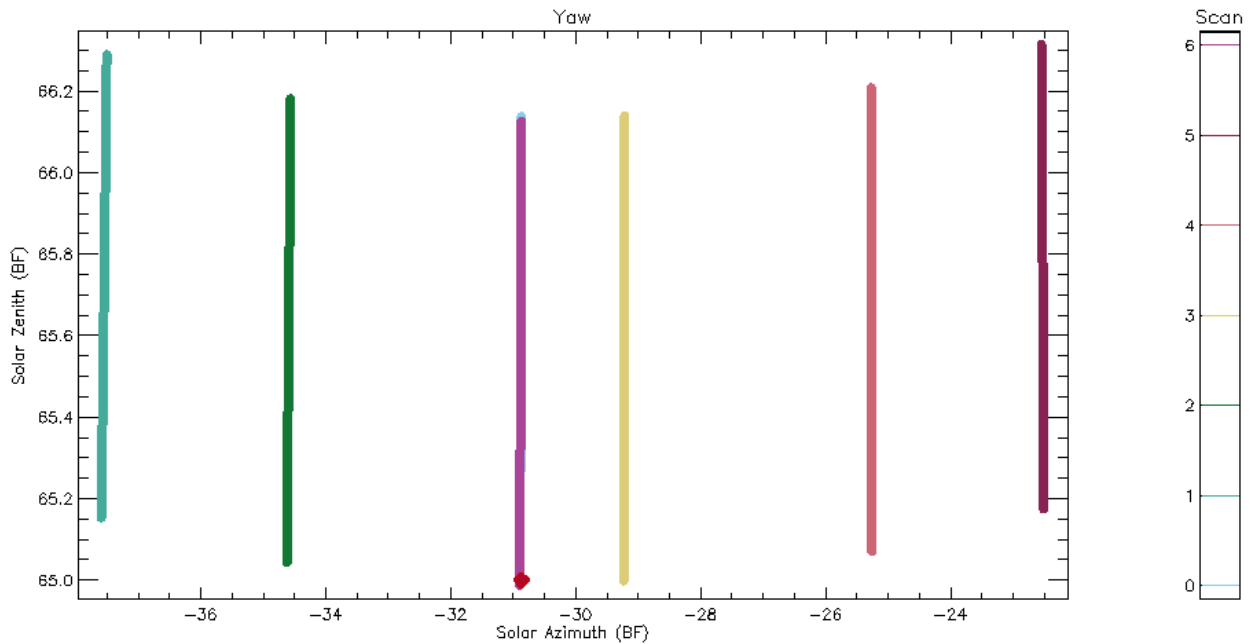


Fig. 8 Measured Solar angle during Yaw maneuvers. Red dot indicate reference on ground geometry. First and last scan overlap. BF indicates angles are in BRDF Diffuser frame.

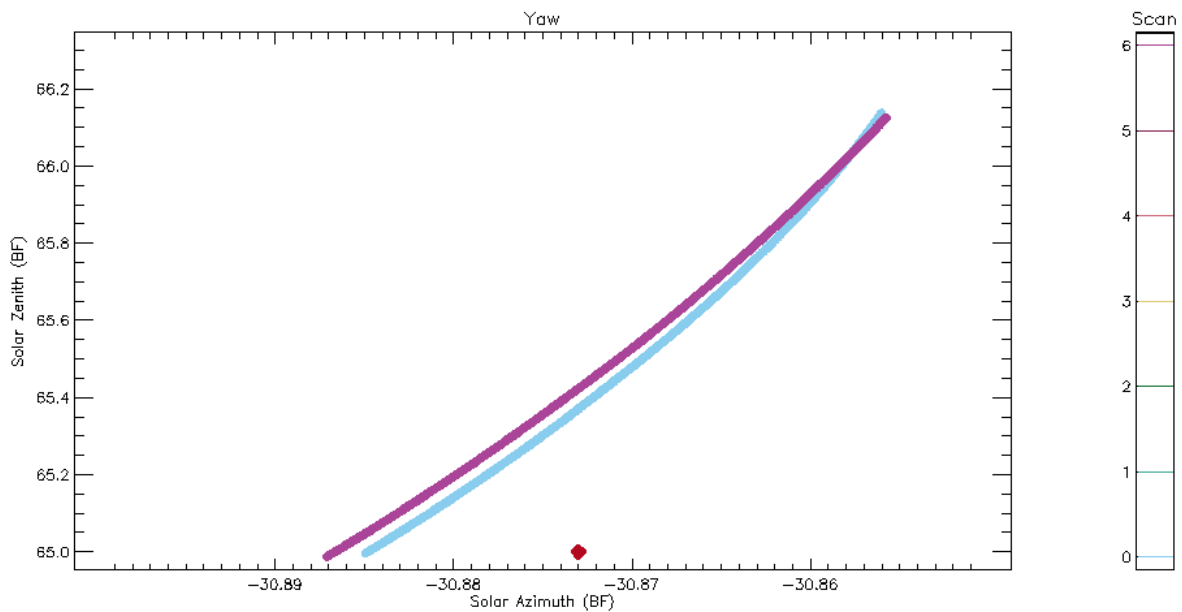


Fig. 9 Same as previous figure, but now zoomed in around on ground reference geometry. BF indicates angles are in BRDF Diffuser frame.

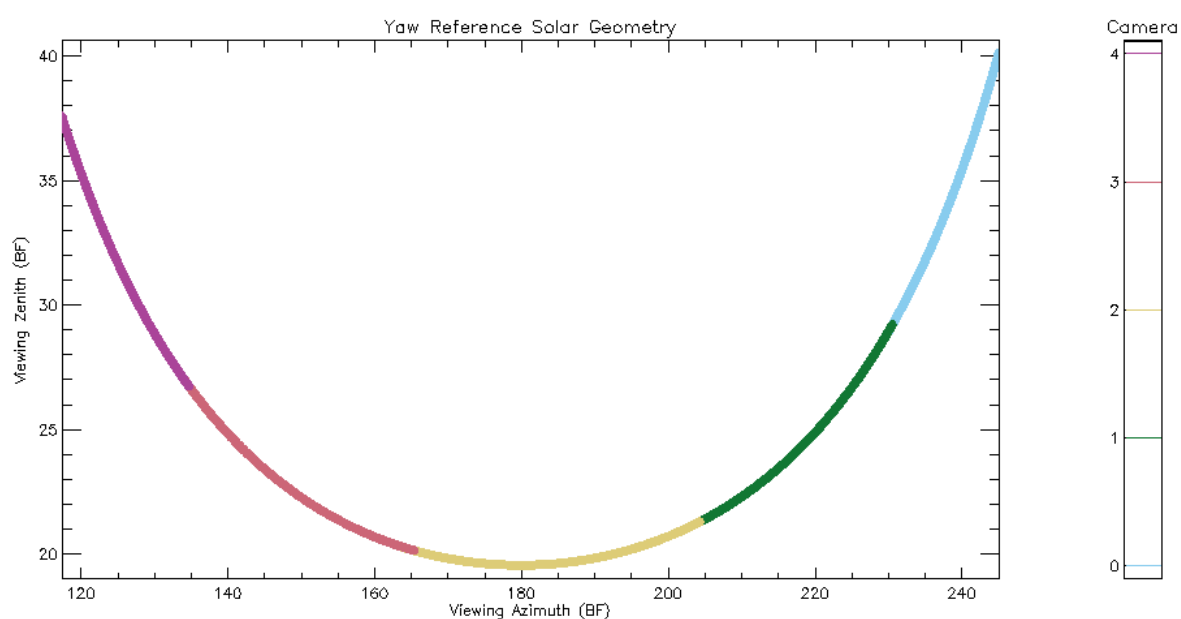


Fig. 10 Viewing angles for measurement closest to on ground reference geometry. BF indicates angles are in BRDF Diffuser frame.

4.3 YAW MANEUVER ANALYSIS

A complicating factor is that all pixels have their own gain and are not absolutely calibrated. Fig. 11 shows the measured signal corrected for all known instrumental effects except straylight. This signal is expressed in corrected counts. Each pixel clearly has its own gain. As such pixels cannot be absolute compared to each other, only relative. Because the relative comparison between pixels is needed, the choice was made to normalize all measurements to the yaw measurement closest to the on-ground reference geometry, as in Fig. 9. This was done to tie the yaw measurements to the pre-launch absolute BRDF value. This single solar geometry of OLCI's laboratory characterizations that is actually encountered on-orbit is referred from now on as yaw reference geometry.

To show the intrinsic noise present in the observations, Fig. 12 shows the measured signal (corrected counts) as function of zenith angle for all scans for a selected (central) pixel. Noise is similar for all pixels, and has a 1σ of about 0.1%.

Fig. 13 shows, as verification, for each pixel the ratio between the first and the seventh yaw maneuvers. These maneuvers have very similar geometries, and all observations were averaged over those solar zenith angles that were observed by both maneuvers. As expected some degradation is present with the lowest wavelengths affected the most. The last band shows some unexpected results for camera 1-4, clearly an instrumental effect, as diffuser degradation should not depend on camera. The largest degradation for the lowest wavelength/band is 0.03% over the seven calibrations.

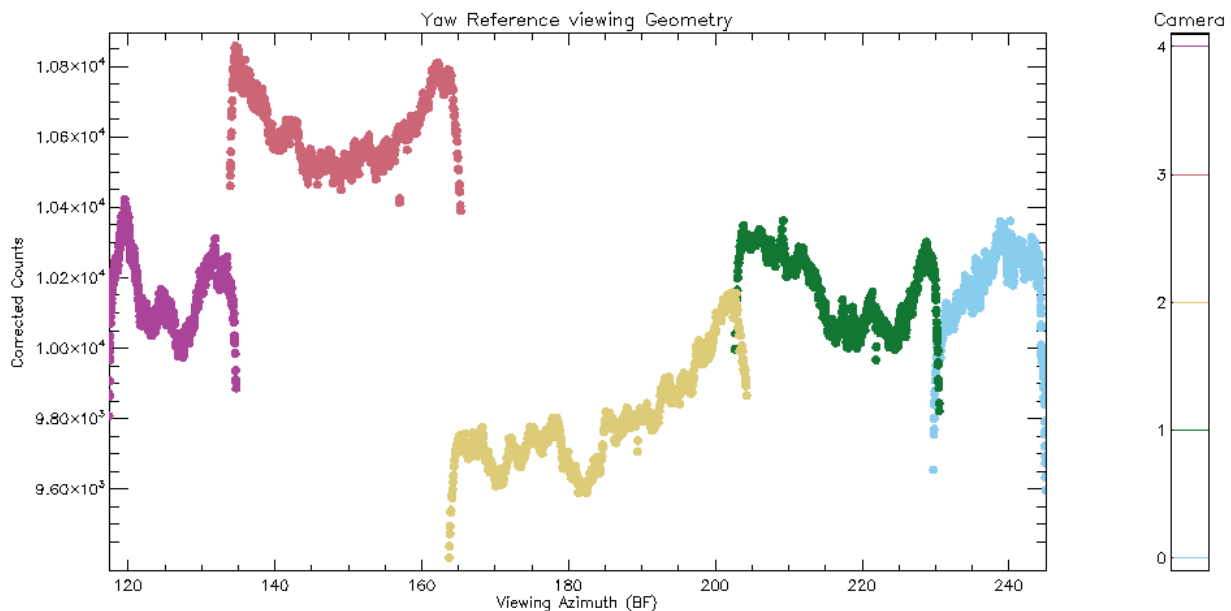


Fig. 11 Measured signal (Corrected counts) as function of viewing azimuth for all pixels for the measurement closest to on ground reference geometry. Each pixel clearly has its own gain. BF indicates angles are in BRDF Diffuser frame.

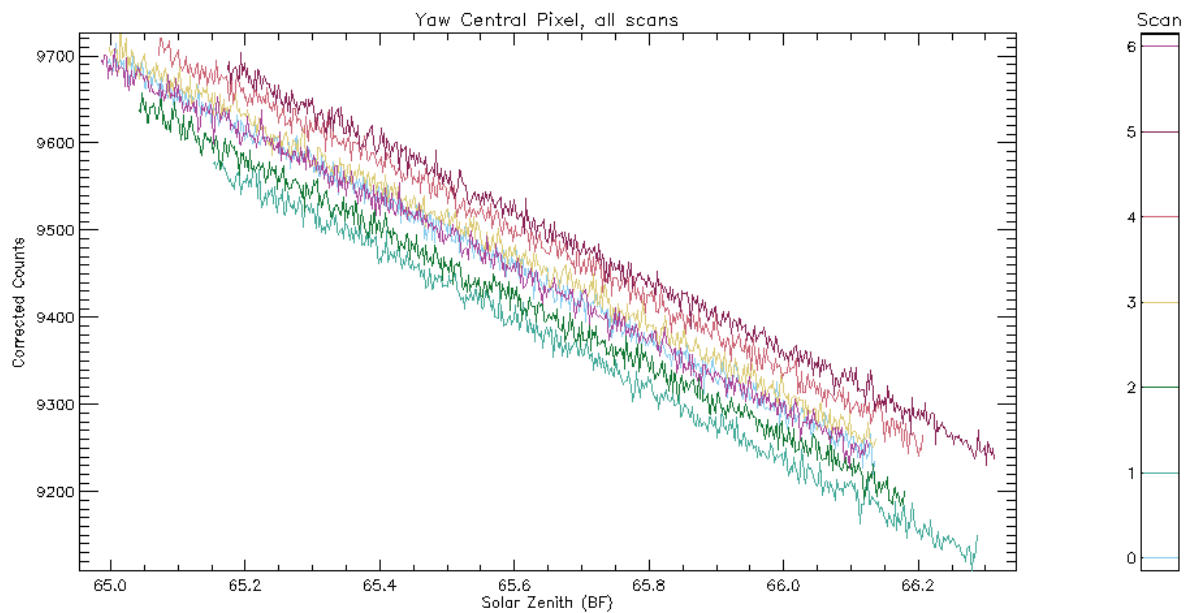


Fig. 12 For central pixel of central camera the measured signal (corrected counts) as function of solar zenith angle for all yaw maneuvers (scans)

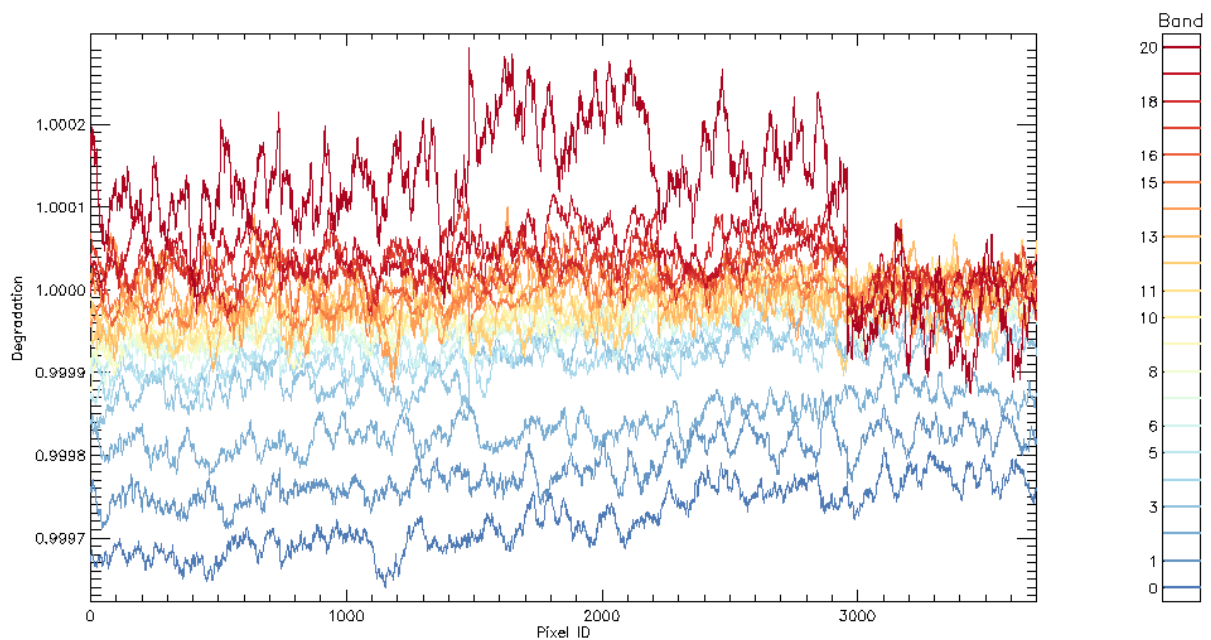


Fig. 13 Degradation as ratio between first and last yaw maneuvers averaged over overlapping solar zenith range.

4.4 CORRECTIONS

All measurements were obtained from the corrected counts X_c in the provided radiometric calibration break-point files. Each was then corrected for straylight, solar geometry and solar distance as follows:

$$X' = X_c / \cos\theta_i \cdot (1 + S) \cdot E$$

The solar zenith angle θ_i and Expected solar Irradiance E (which is corrected for solar distance and band-size) were also obtained from break-point files. The straylight-correction S was specially provided for this study by S3-MPC.

Corrected counts were provided at the measured microbands and were averaged per OLCI band per table provided by S3-MPC.

The measurements with a strong drop in straylight correction, always near edge of FOV in the zenith direction, were not employed in this study, as instrumental effects near the edge of the field of view are not always known to the highest accuracy. This reduced the number of solar zenith angles from 536 to 336 measurements per scan. Tests have shown this to have little impact beyond improved residuals.

4.5 INFLIGHT & ON-GROUND RAHMAN2 MODEL

Already strong suspicions exist that the Rahman2 model does not describe the BRDF response adequately. The on-ground Rahman2 model was compared with the (corrected) relative measurements of the yaw maneuvers. Fig. 14, shows the relative difference between model and measurement, as a function of pixel number (which is coupled to observation angle) and solar measurement (which is coupled to illumination angle). The solar measurements on the y-axis show the measurements from the 7 yaw maneuvers (each taken at a different azimuth angle) and with solar zenith angles steadily increasing within each yaw maneuver. Representing the data in this manner allows easy observation of any systematic effects. The data is clipped at 0.5%. Clear systematic effects can be seen both as a function of observation angles and solar azimuth angles. Other bands show similar effects.

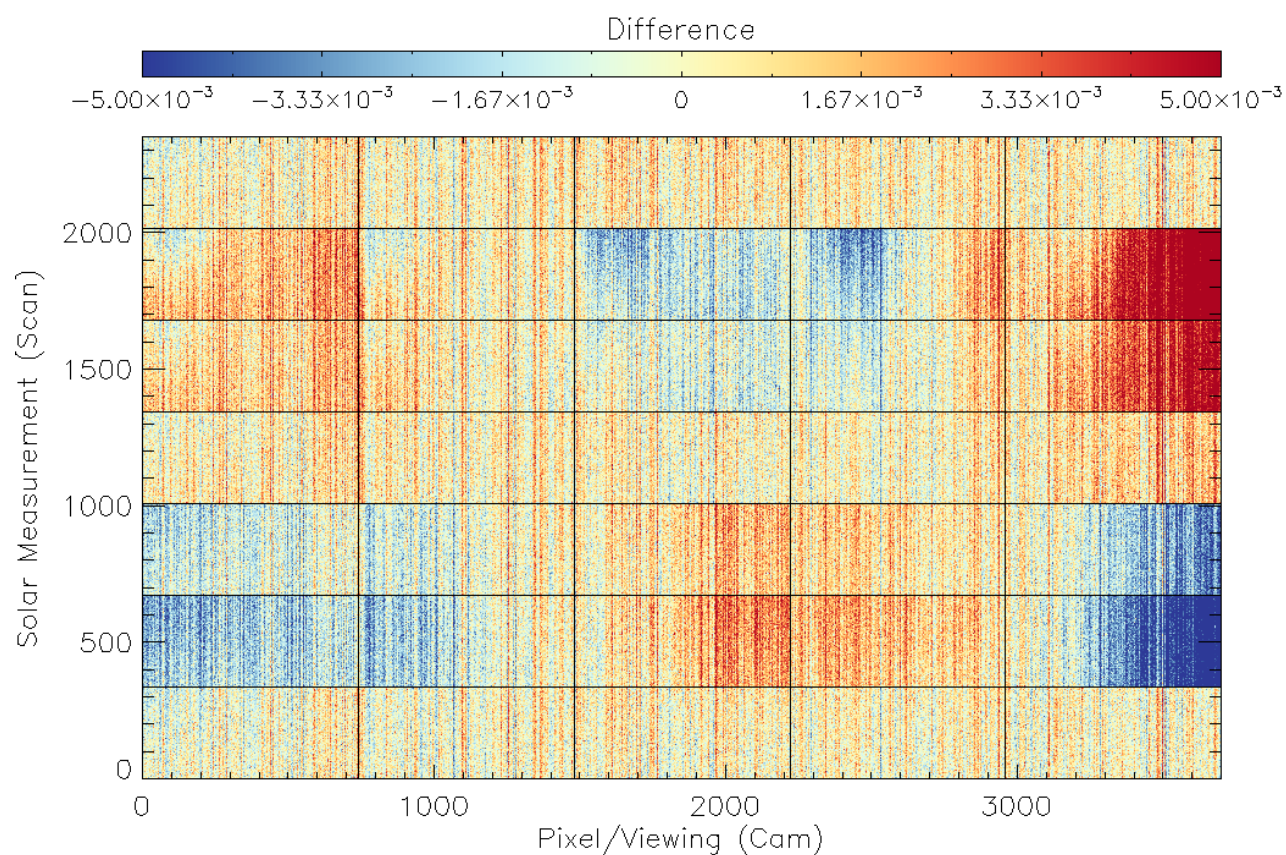


Fig. 14 Difference between In-flight Yaw Maneuver Measurements and On-ground Calibration BRDF Measurements model results for first band, values have been clipped at $\pm 0.5\%$. Solid curves show camera boundaries and yaw maneuvers

5 NEW MODELS

Different models were studied in order to describe the measurements. Each model was fitted using a least-square fitting method (Markwardt, 2009) in order to determine the free parameters with all measurements having equal weight.

In order to estimate the uncertainty or error for each model parameter the model parameters were determined with all measurements having the same weight. Residual for each measurement was derived by subtracting the fitted model. The standard deviation was determined for these residuals, which approximates the measurement uncertainty.

Each measurement was then given a weight reverse proportional to its squared residual, except for clear single outlier measurements (not shown here) where the difference between model and measurement was more than 4 times the residual standard deviation. These outliers were given zero weight.

The model was then fitted again with the estimated weights resulting in more physically estimated uncertainties on the model parameters.

5.1 RAHMAN2

The first new model attempted to describe the yaw maneuver observations was of course the Rahman2 model. Rahman2 was used to understand whether the model was still correct but the parameters changed in-flight. Fitting the Rahman2 model to the relative corrected observations resulted in unphysical parameters and only the slightest improvement over Fig. 14, still with clear systematic effects.

5.2 RAHMAN2 PER PIXEL

Describing the BRDF for all pixels with a single model assumes that all pixels observe the exact same diffuser surface and all instrument effects are corrected for. This is an optimistic assumption as (unexpected) instrumental effects are likely present. However, due to the construction geometry of Sentinel-3A OLCI Instrument different pixels are observing different parts of the diffuser surface. Any imperfections on the diffuser surface will thus differ from pixel to pixel (more on this later), hence the Rahman2 model can, instead of being applied to all observation angles and illumination angles, be applied to a single pixel with a pre-determined observation angle. In such case, the dependence on observation angle is removed and only the illumination angles of measurements are input to determine the four free Rahman parameters.

The results are shown in Fig. 15 which has the exact same layout as Fig. 14. Most of the residuals are noise but some structure can be seen, most prominently in camera 4, which seems to slightly shift between yaw maneuvers. Careful investigation shows these areas to be at 180° degrees difference between solar and viewing azimuth angle. This confirms that the Rahman2 fails to describe the measurements properly for backscattering geometry.

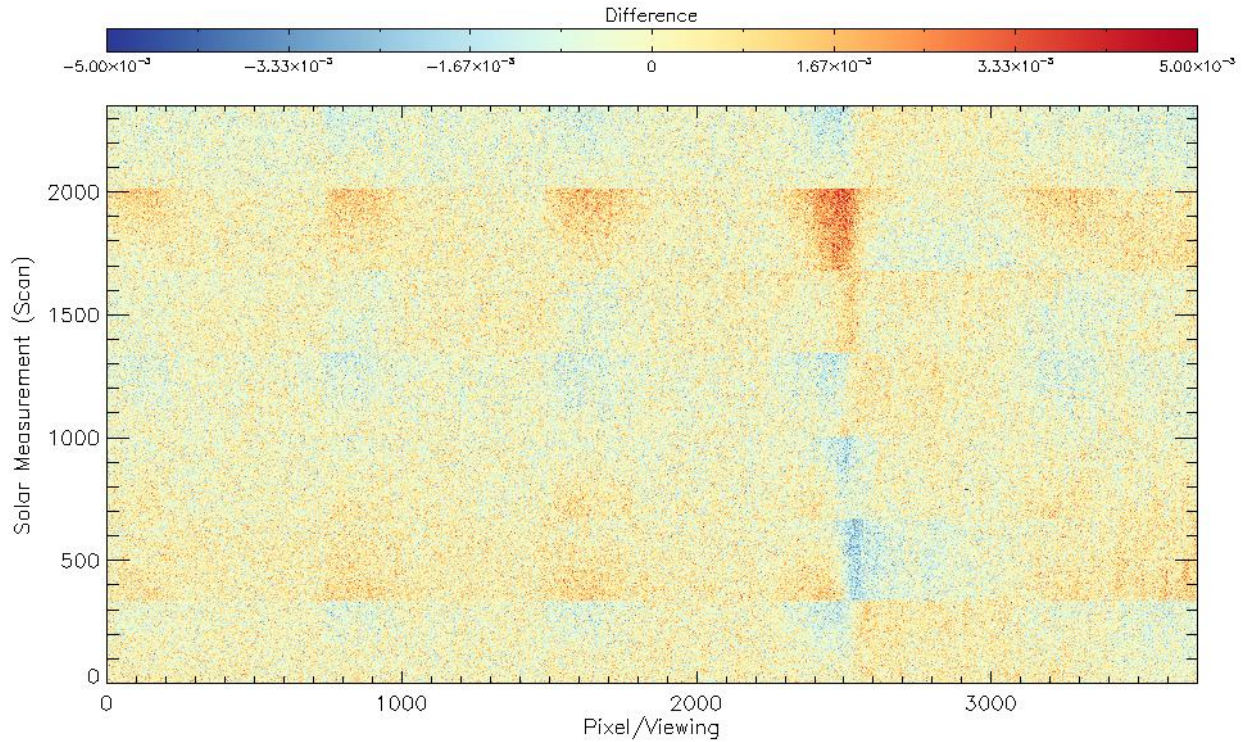


Fig. 15 Difference between In-flight Yaw Maneuver measurements and Rahman2 model (per pixel) results for first band, values have been clipped at $\pm 0.5\%$. Solid curves show camera boundaries and yaw maneuvers

5.3 POLYNOMIAL PER PIXEL

The very small observation range ($1.2^\circ \times 16^\circ$) of the total sky means that for OLCI SD most cosine or other trigonometry functions can be approximated with a linear or quadratic polynomial functions. The Rahman model is potentially overly complicated and hence too limiting to describe realistic reflection properties. A less limiting model is one where all changes as a function of difference illumination angle are described as orthogonal quadratic functions with a linear cross-term depending on:

$$\Delta\theta_i = (\theta_i - \theta_i^{base})/\theta_i^{scaling}$$

$$\Delta\varphi_i = (\varphi_i - \varphi_i^{base})/\varphi_i^{scaling}$$

$$R = P_0 \cdot (1 + P_1 \cdot \Delta\theta_i + P_2 \cdot \Delta\varphi_i + P_3 \cdot \Delta\theta_i \cdot \Delta\varphi_i + P_4 \cdot \Delta\theta_i^2 + P_5 \cdot \Delta\varphi_i^2)$$

Where R is the BRDF reflectance and P_0 - P_5 are free parameters to be determined by least-square fitting to the measurements for each pixel. All angles are difference angles with respect with the chosen base illumination angles, scaled between 0 and 1, so that each parameter value indicates its own relative weight to the total modelled signal for these measurements with $\theta_i^{base} = 65.12$, $\varphi_i^{base} = -30.12$, $\theta_i^{scaling} = 0.69$, and $\varphi_i^{scaling} = 7.7$. The only reason for this rescaling is to make sure the fit values carry the same weight.

Note that this model is also applied per pixel and thus no observation angle dependence is present. No correlation is assumed between bands, and thus the model is applied separately for each band. Also no relative correction is needed

as each pixel can be described individually with its own gain. See Section 0 for more details how the in-flight model can be absolutely calibrated to the on-ground measurements.

Fig. 16 shows the resulting residuals for first band. The differences are much smaller and no systematic structures are immediately visible.

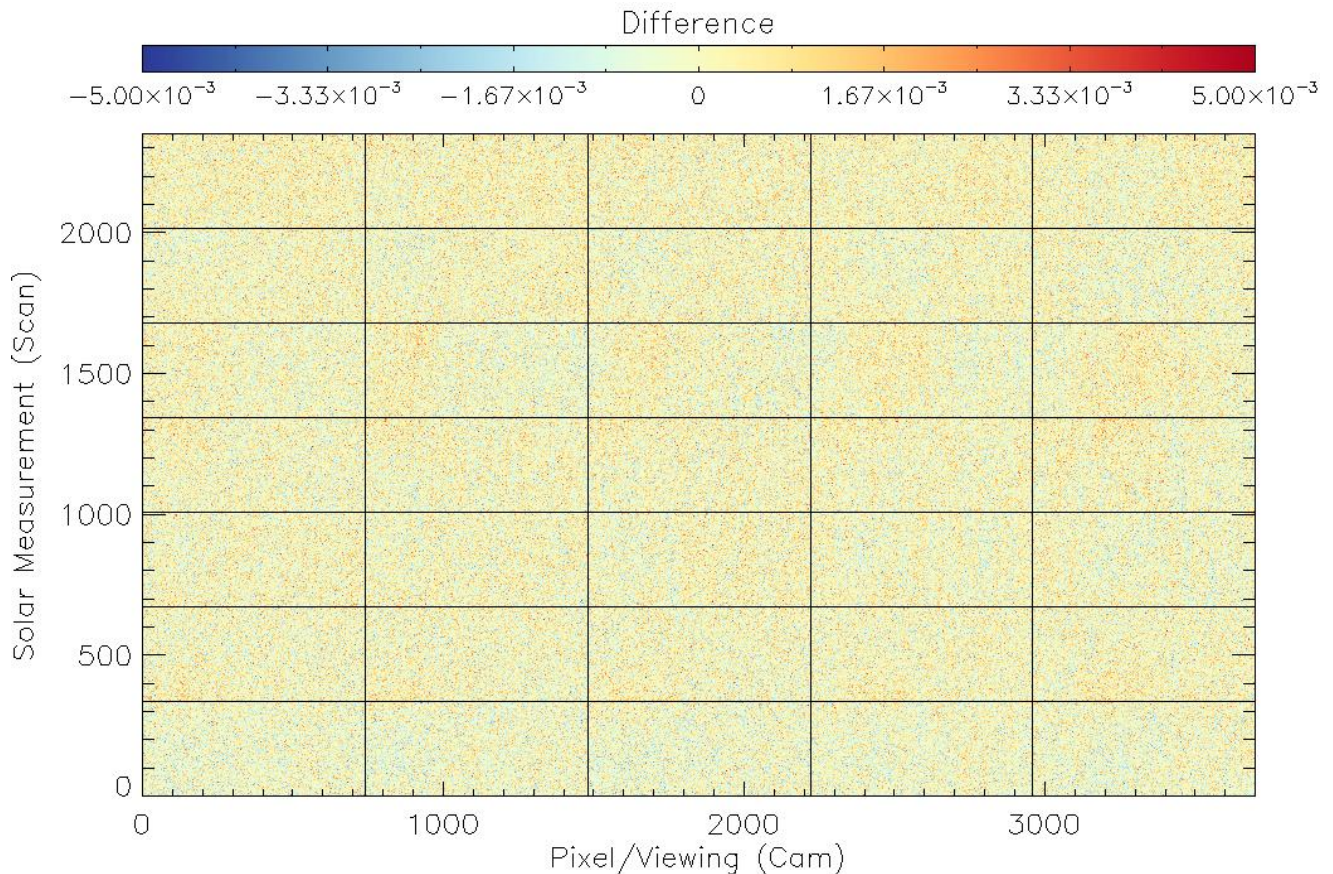


Fig. 16 Difference between In-flight Yaw Maneuver Measurements and Polynomial model results per pixel, values have been clipped at $\pm 0.5\%$. Solid curves show camera and yaw maneuver boundaries.

The residuals are significantly reduced and no systematic structures can be observed at this scale. Zooming in on an arbitrary camera and smoothing the residuals in both solar angles directions however shows a clear changing pattern as the result of diffuser speckles (Snel & Krijger, 2017) that slowly vary over wavelength, illumination and observation angles. The model does not describe these quick changing speckles and hence can be seen in the residuals. Do note that the speckles are an order of magnitude smaller than the measurement noise. Fig. 17 shows these speckles for band 14 which seems to suffer most from speckles. There is no discernable correlation in speckle pattern between different bands (not shown here).

There are similar speckles for first and seventh yaw measurements which were taken at very similar (but slightly shifted) solar angles, which shows these residuals are not random but reproducible speckles. As these speckles change slowly it is possible to characterize and model them as well. Regrettably the number of yaw maneuvers does not allow this detailed characterization of the observed speckles.

Recommendation: Measure more azimuth angles during yaw maneuvers to characterize speckles

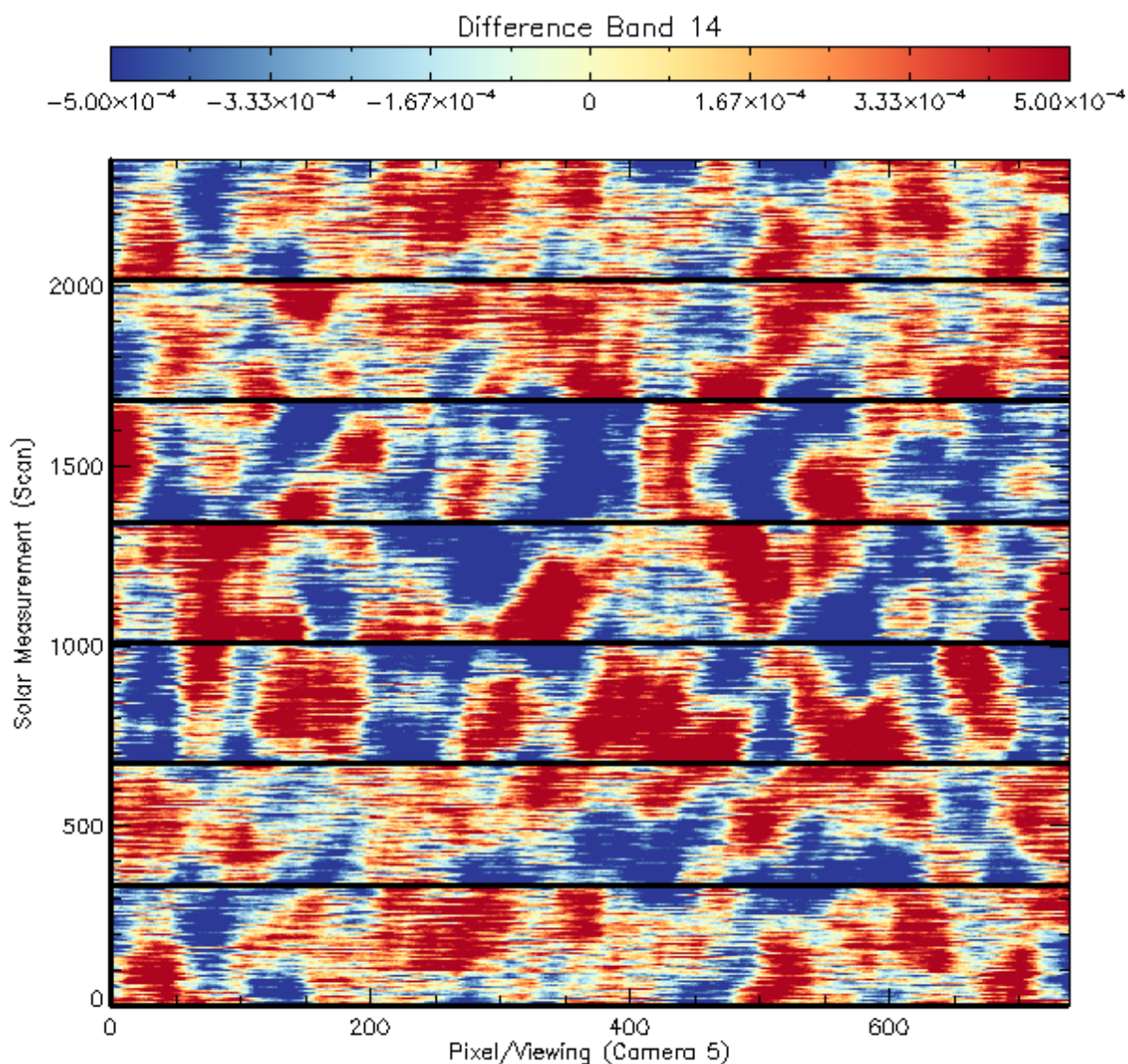


Fig. 17 Residuals for camera 5 for band 14 show clear speckles. These speckles change slowly as function both illumination, observation angle and wavelength.

5.3.1 OFFSET MODEL

Investigations were made into different approaches for the model with either a multiplicative or additive offset. As expected no difference were found, and the choice was made to go with the multiplicative model as this would allow easier gain corrections in the future, as than only the first parameter, P_0 , needs to be adapted instead of rescaling the whole model.

$$R = P_0 \cdot (1 + P_1 \cdot \Delta\theta_i + P_2 \cdot \Delta\varphi_i + P_3 \cdot \Delta\theta_i \cdot \Delta\varphi_i + P_4 \cdot \Delta\theta_i^2 + P_5 \cdot \Delta\varphi_i^2)$$

$$R = P_0 + P_1 \cdot \Delta\theta_i + P_2 \cdot \Delta\varphi_i + P_3 \cdot \Delta\theta_i \cdot \Delta\varphi_i + P_4 \cdot \Delta\theta_i^2 + P_5 \cdot \Delta\varphi_i^2$$

5.3.2 WAVELENGTH AVERAGED MODEL

Other approaches were attempted after consultation with external experts (R. Snel and X. Xiong), of which one consisted of fitting all bands at the same time (effectively smoothing in wavelength dimension). This approach significantly reduces the number of fitting parameters yet increases the measured residuals. The intention was to reduce the impact of the measured speckles by smoothing them out as they changed between wavelengths. The averaged model should approximate non-measured azimuth angles better, even though measured azimuth angles were worse approximated because the speckles were not described. Validation by S3-MPC [Bourg, 2017, publication in progress] showed however no improvement, with some undesired structures present, and the decision was made not to employ this model.

5.3.3 PIXEL AVERAGED MODEL

The alternative approach was chosen after validation to average in the pixel dimension. During consultation with external experts (R. Snel and X. Xiong) it was decided that the impact of small-scale speckles could be optimally reduced by averaging over 41 neighboring pixels. Note that speckles are however present on all scales. The approach was for each pixel of interest to average 20 pixel measurements (normalized to the pixel of interest) to both sides of the pixel of interest for a total of 41 average pixel measurements. At the edges of the camera only as many pixels were averaged as were available between the pixel of interest and the edge. The resulting model parameters behave smoother in the pixel to pixel domain as expected. The residuals (not shown) are almost identical to those shown in Fig. 16.

Validation by S3-MPC [Bourg, 2017, publication in progress] showed decreased pixel to pixel variation compared to other models and the decision was made to employ this model for OLCI gain evolution.

In Fig. 18 the derived fitting parameters for each band are shown. Note that the chosen scaling of the input parameters allowed direct comparison of the fit-parameters with each other, where higher values indicate a large contribution to the signal. The model is thus dominated by linear solar azimuth dependence (ϕ_i middle plot Fig. 18), which can be seen to vary smoothly from pixel to pixel. Other dependencies are much smaller in their contribution (as can be seen by their smaller fitting parameters) of the final model signal, especially when taking the fitting uncertainty into account. These free parameters could possibly be removed from the model, however this would increase the residual (test not shown here) and introduce more cross-correlation between remaining free parameters, and the choice was made to retain them.

The average error per band and per camera is shown in Fig. 19. The lower wavelength bands have lower residuals than the mid-wavelength and higher wavelengths, as the measurements suffer from more speckle structure depending on the spectral width of the band.

Fig. 20 shows the ratio between gains derived from the model (referred to as Model#4 by Bourg) and gains derived from in-flight reference model, which are expected to be identical (except for measurement noise). More details will be available in the validation report by Bourg, 2017 (in preparation). Differences are indeed at the level of the measurement noise.

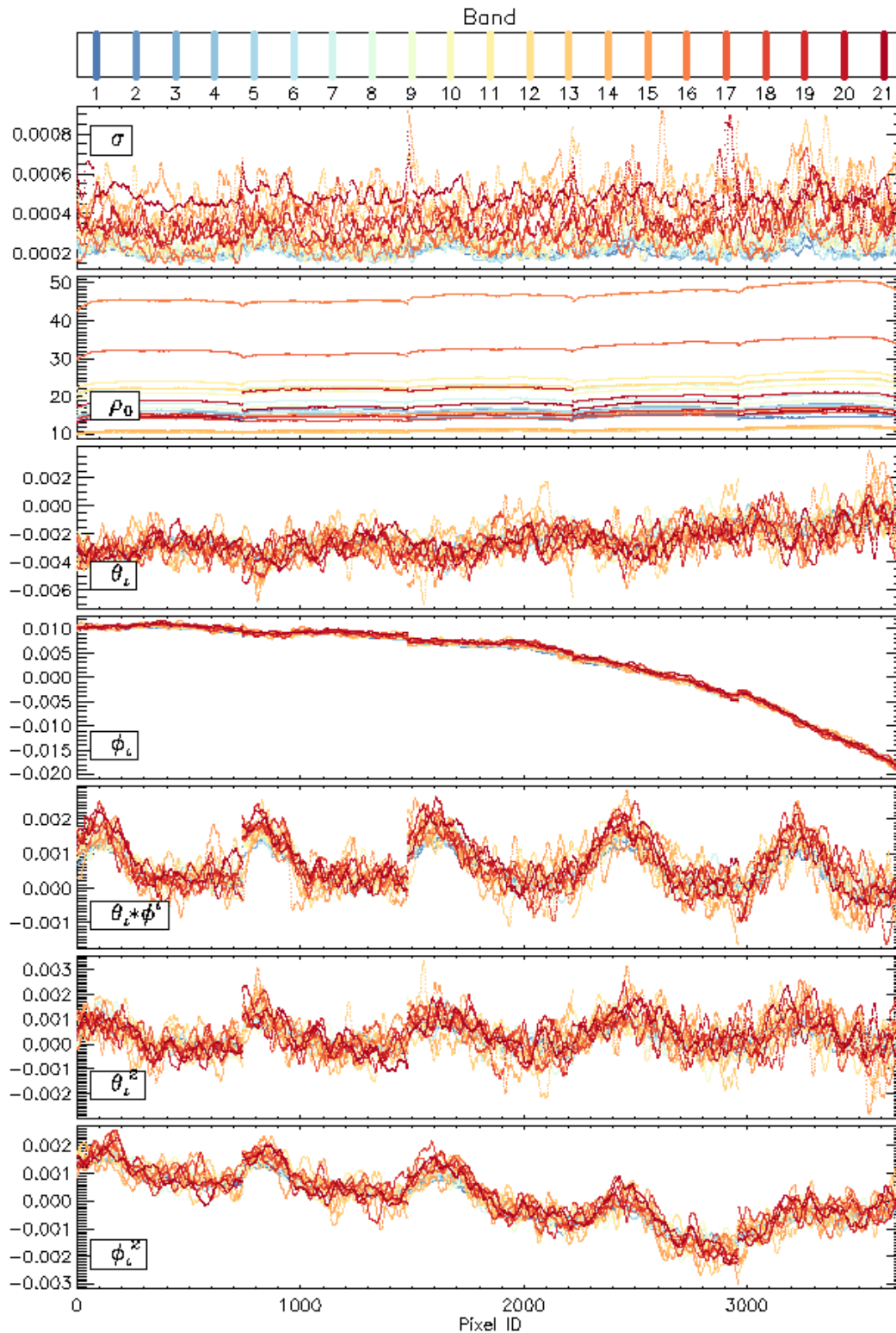


Fig. 18 Fitting error and fitting parameters as function of pixel ID, with different colors for the different bands as indicated on top.

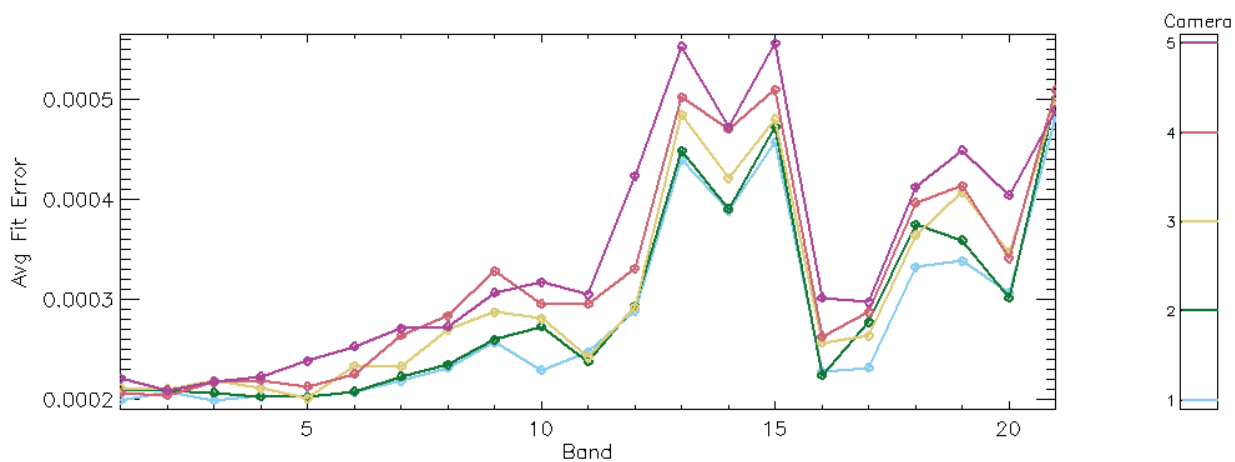


Fig. 19 Average Error per band and per camera

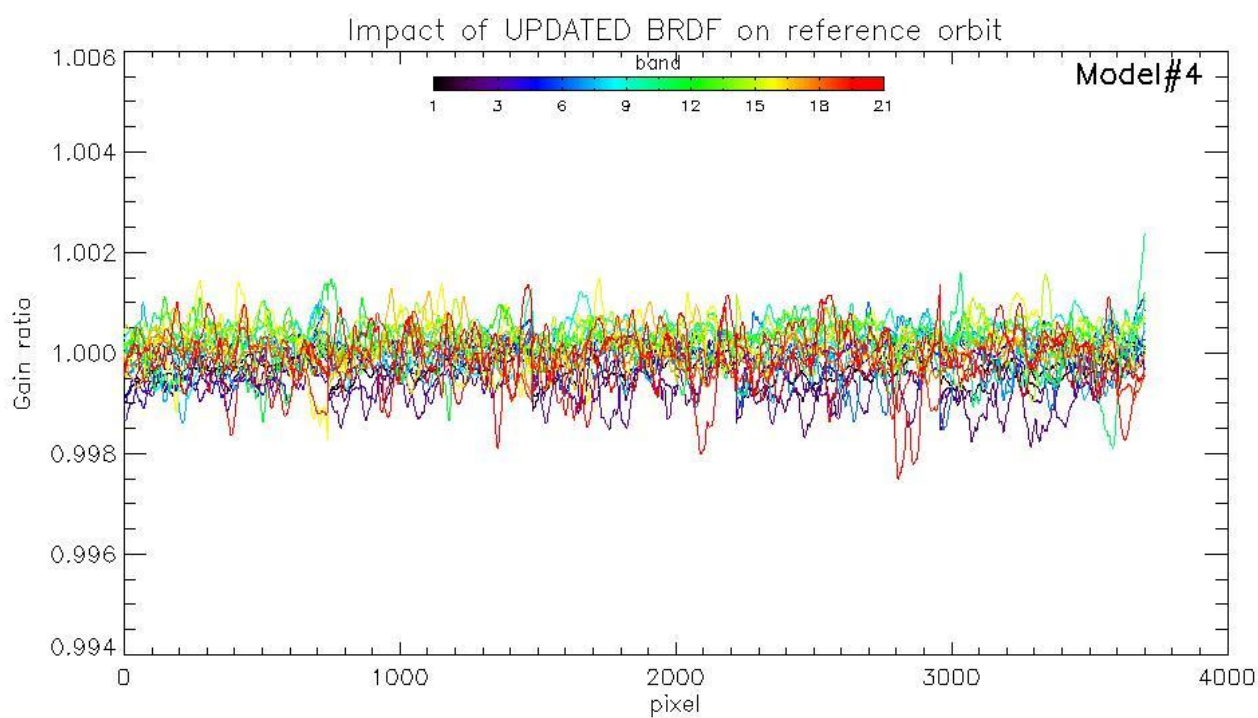


Fig. 20 Validation [Bourg, private communication] between new BRDF model and in-flight reference orbit. Model#4 refers to the employed pixel-averaged model.

6 UNCERTAINTIES

6.1 ABSOLUTE CALIBRATION

The On-ground Calibration BRDF Measurements are measurements of the diffuser only at component level. The In-flight Yaw Maneuver Measurements are measurements that include all other instrumental effects including radiometric sensitivity. The Yaw were corrected for all instrument effects (including straylight), except radiometric sensitivity. The in-flight measurements are not absolutely calibrated and hence the model can only be determined relatively.

The following approach was taken to create an absolute calibrated diffuser response:

$$BRDF(\theta_i, \varphi_i; \theta_r, \varphi_r) = \frac{BRDF_{\theta_i^{ref}, \varphi_i^{ref}; \theta_r, \varphi_r}^{On-ground}}{BRDF_{\theta_i^{ref}, \varphi_i^{ref}; \theta_r, \varphi_r}^{In-flight}} \cdot BRDF_{\theta_i, \varphi_i; \theta_r, \varphi_r}^{In-flight}$$

where the in-flight derived BRDF model is normalized to the ratio between the on-ground model and the in-flight model at the chosen illumination reference angles: $\theta_i^{ref} = 65.000$, $\varphi_i^{ref} = -30.873$. For the on ground measurement not all viewing directions were measured, hence the on-ground model must be employed at the reference angles.

With this approach it is possible to normalize to different reference angles, if so desired, or when degradation affects the diffuser (Krijger et al, 2014).

This means that the absolute uncertainty of the new BRDF model consists of the on-ground calibration measurements absolute uncertainty, as described in Table 2, interpolated to each band central wavelength. Operationally each band BRDF is derived by interpolating between BRDFs calculated for ground measured wavelengths. Results are shown in Table 5 Uncertainties (expressed as 1σ) for the relative performances of the model

. However these are lower limit as comparison between on-ground model and measurement already show 1% variation.

Recommendation: Increase on-ground characterization accuracy by repeating reference angles measurements.

6.2 RELATIVE CALIBRATION

The new model derived from inflight measurements described the measurements very well. The average variation (expressed as 1σ) per pixel is given in Table 5, and shows the new model is for relative calibration (0.021%-0.05%) an order of magnitude within requirements (0.3%). This is however a lower limit on the uncertainty, as speckles for unmeasured azimuth angles will increase the uncertainty slightly.

6.3 UNCERTAINTY OVERVIEW

The derived uncertainties are summarized in Table 5 Uncertainties (expressed as 1σ) for the relative performances of the model

, however these are estimated to be lower limit uncertainties, as absolute calibration shows 1% residuals with the model, while relative uncertainty cannot predict unmeasured speckles.

Band	Absolute [%]		Relative [%]	
	Perf	Req	Perf	Req
1.	0.338	0.5	0.021	0.3
2.	0.320	0.5	0.021	0.3
3.	0.276	0.5	0.021	0.3
4.	0.206	0.5	0.021	0.3
5.	0.212	0.5	0.021	0.3
6.	0.226	0.5	0.023	0.3
7.	0.220	0.5	0.024	0.3
8.	0.216	0.5	0.026	0.3
9.	0.215	0.5	0.029	0.3
10.	0.214	0.5	0.028	0.3
11.	0.225	0.5	0.027	0.3
12.	0.242	0.5	0.033	0.3
13.	0.245	0.5	0.049	0.3
14.	0.246	0.5	0.043	0.3
15.	0.247	0.5	0.050	0.3
16.	0.252	0.5	0.025	0.3
17.	0.233	0.5	0.027	0.3
18.	0.228	0.5	0.038	0.3
19.	0.225	0.5	0.039	0.3
20.	0.231	0.5	0.034	0.3
21.	0.242	0.5	0.050	0.3

Table 5 Uncertainties (expressed as 1σ) for the relative performances of the model

7 LESSONS LEARNED

We summarize here the recommendations and lessons learned during this study, as described in the previous sections.

Recommendation 1: During on-ground calibration repeat the reference geometry measurement in order to increase accuracy.

In this study the uncertainty of the BRDF model is dominated by the uncertainty of the on-ground reference measurement. Multiple measurements will reduce the random noise by the square root of the number of repeated measurements. As the residuals are on the order of 1% with a requirement of 0.5%, at least 4 or more repeated measurements should be taken as a recommendation.

Recommendation 2: Cover more finely the range of solar geometries actually encountered in-flight during on ground calibration measurements.

The current measured lab geometries are far outside the actually in-flight encountered geometries. The fitted Rahman 2 model attempts to reduce residuals also for these extreme angles that are never encountered, including the intrinsic noise present at these extreme angles. Covering the range of solar geometries more finely and more closely towards actual solar geometries will allow on ground determined models to better describe the important geometry range. The number of measurements is dependent on available resources, but a minimum of 5x5 grid or even 7x7 grid in solar angles is recommended as this allows second order dependencies to be identified.

Recommendation 3: Perform in-flight yaw manoeuvres allows very accurate in-flight calibration BRDF modelling at low risk and impact.

The measurements in this study derived from yaw manoeuvres, based upon the original suggestion in Kwiatkowska, 2016, "Sentinel-3 OLCI Yaw Manoeuvres" EUM/RSP/MEM/14/781172, have allowed for derivation of a very accurately relative BRDF model at least an order of magnitude more accurate than the pre-launch model. Strong recommendation would be to also implement yaw manoeuvres for future missions as early as possible after instrument is stable post-launch, and verify and improve the on-ground BRDF model. The recommendation is also to improve the accuracy of the execution of yaw manoeuvres to reach the reference azimuth geometry at a bias better than 0.02 degrees.

Recommendation 4: During in-flight calibration sample enough illumination angles with enough resolution to resolve the diffuser speckles

In this study the speckles changed fully between sampled illumination angles which did not allow their characterization. Sufficient number of yaw manoeuvres should be performed to derive a proper BRDF model, which turns out is possible with 6 (and a 7th verification) manoeuvres. Speckles repeat consistently for identical solar geometries, but vary quickly between solar azimuth angles. In order to describe and model these speckles more azimuth angles should be measured. As no correlation could be determined between speckles at different azimuth angles, no estimate can be given how many angles are needed for this characterization. An assumption can be that the variation in solar azimuth angle is similar to that in solar zenith angle. In solar zenith angle we see order 0.5° variation. Experience from other missions indicate in the order of 0.1° - 0.2° steps, which would result in 80-160 yaw manoeuvres which is unrealistic. A careful balance between yaw manoeuvre risk and required relative accuracy improvement must be considered, resulting in recommendation in order of 28 or more yaw manoeuvres when speckles need to be characterized.

Recommendation 5: Performing system level diffuser characterization in addition to component level

Laboratory measurements of the many different combinations of viewing and illumination angles take significant effort and resources. Therefore only a few selected combinations of geometries are measured, forcing the need for interpolations over a large number of geometries. The system level geometries might differ slightly from the

component level geometries after installation of the components (as in the case of OLCI), which increases the component measurement uncertainties.

Measuring at system level enables all viewing angles to be measured simultaneously (thus decreasing the measurement time), and at the exact in-flight viewing geometries. Also any instrument characteristics that are unknown at component level will show up at system level and be directly sampled, such as speckles, scratches on diffuser surface, reflections, *and the absolute BRDF values*. The larger costs of system level calibration can be minimized by optimizing the number of measured geometries between system and component level, but both should include re-measuring of the reference geometry.

Hence measuring the diffuser BRDF at system level in addition to component level will greatly improve the final accuracy.

8 ACKNOWLEDGMENT

The authors would like to acknowledge Marloes Schaap her aid in manuscript preparation.

The authors acknowledge all the invaluable input and discussions with Ralph Snel, Xiaoxiong (Jack) Xiong, Ludovic Bourg and Ewa Kwiatkowska. OLCI Diffuser description section adapted from Kwiatkowska, 2016.

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10 APPENDICES

10.1 MODEL NETCDF-DESCRIPTION

Files:

pmodel_s3r_model_poly4_170314.h5

s3r_model_poly4.pro

The netcdf file pmodel_s3r_model_poly4_170314.h5 has been delivered which contains the parameters required for the model as employed in s3r_model_poly4.pro.

Under the header 'Model_parameters' the model parameters as floats with dimensions 740x5x21x6, namely pixel (740), camera (5), band (21) and the 6 P_0 - P_5 as follows:

$$\Delta\theta_i = (\theta_i - \theta_i^{base})/\theta_i^{scaling}$$

$$\Delta\varphi_i = (\varphi_i - \varphi_i^{base})/\varphi_i^{scaling}$$

$$R = P_0 \cdot (1 + P_1 \cdot \Delta\theta_i + P_2 \cdot \Delta\varphi_i + P_3 \cdot \Delta\theta_i \cdot \Delta\varphi_i + P_4 \cdot \Delta\theta_i^2 + P_5 \cdot \Delta\varphi_i^2)$$

With P_0 - P_5 free parameters determined by least-square fitting to the measurements for each pixel. All angles are difference angles with respect with the chosen base illumination angles, scaled between 0 and 1 so that each parameter value indicates its own relative weight to the total modelled signal for these measurements with $\theta_i^{base} = 65.12$, $\varphi_i^{base} = -30.12$, $\theta_i^{scaling} = 0.69$, and $\varphi_i^{scaling} = 7.7$.

10.2 DATASET NETCDF-DESCRIPTION

The following file contains all yaw maneuver measurements

s3r_yaw_data.h5

geo_sza : Solar zenith angle

geo_saa: Solar azimuth angle

geo_vza: Viewing zenith angle

geo_vaa: Viewing azimuth angle

band**_irad: Expected Irradiance

band**_s: Straylight correction factor

band**_xc: Corrected Counts

band**_xb: Straylight and geometry Corrected BRDF counts

where $xb = xc / (\cos(sza * \pi/180) * (1+S) * IRAD)$

10.3 YAW MANEUVERS

Document describing the yaw maneuver planning:

EUM/RSP/MEM/14/781172 by Kwiatkowska, 2016

Sentinel-3 OLCI Yaw Manoeuvres.doc