International Conference on Space Optics—ICSO 2022

Dubrovnik, Croatia

3–7 October 2022

Edited by Kyriaki Minoglou, Nikos Karafolas, and Bruno Cugny,

Improving stray-light characterization beyond blooming, the experience of the FLORIS Optical Model Refurbished

International Conference on Space Optics — ICSO 2022, edited by Kyriaki Minoglou, Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 12777, 1277711 · © 2023 ESA and CNES · 0277-786X · doi: 10.1117/12.2689042

Improving stray-light characterization beyond blooming, the experience of the FLORIS Optical Model Refurbished

D. Nuzzi*[a], L. Pettinato[a], E. Fossati[a], R. Gabrieli[a], P. Coppo[a], M. Baroni[a], E. De Luca[a], L. Giunti[a], A. Cavanna[d], J. Romano[d], G. Postiglione[a], F. Galeotti[a], C. Pompei[a], M. Barilli[a], M. Barillot[b], M. Taccola[c]
[a]Leonardo S.p.A., Via delle Officine Galileo 1, Campi Bisenzio, Italy;
[b]Thales Alenia Space, Allée des Gabians 5, Cannes La Bocca Cedex, France;
[c]ESA Estec, Keplerlaan 1, Noordwijk, The Nederlands;
[d]Capgemini Engineering S.p.A., Via Guglielmo Marconi 30, Firenze, Italy

ABSTRACT

The FLuorescence EXplorer (FLEX) European Space Agency (ESA) mission with its payload, the FLuORescence Imaging Spectrometer (FLORIS), aims at performing quantitative measurements of the solar induced chlorophyll fluorescence from space, with the purpose of improving the monitoring of the health of Earth vegetation. The retrieval of a faint signal, such as the one from chlorophyll fluorescence, requires very low Stray-Light (SL) levels. The SL reduction in FLORIS implied constraints impacting the design, by means of using low roughness optical components, the integration, through a strict contamination control, but also the data processing with the need of a very accurate correction strategy making use of numerical models well correlated with experimental data, to be acquired during the On Ground Calibration (OGC) activities. In order to assess and validate the correction strategy, an accurate SL characterization has been anticipated during the FLORIS Optical Model Refurbished (OMR) campaign. Different methods, such as out-of-field and out-of-band measurements, have been investigated in order to avoid the detector blooming affecting measurements with high input signals. By combining the results from the different approaches, it has been possible to achieve up to 9-10 decades of explored dynamic range. The model, correlated with measurements, has finally proved to be capable to correct SL with a reduction factor >10, down to a level less than 40% of the required fluorescence error (10% of a fluorescence level of about 2 mW/m²/sr/nm).

Keywords: FLEX, FLORIS, Fluorescence, Stray-light, Blooming, Breadboard; Engineering-model.

1. INTRODUCTION

1.1 FLEX mission, FLORIS payload and Stray-Light

The FLuorescence EXplorer (FLEX) mission has been selected for the ESA Earth Explorer EE8 program [1]. FLEX will fly in tandem with Sentinel 3 mission, making use of data synergy with visible reflectance channels, from the OLCI [2], and surface temperature data, from the SLSTR ([3], [4], [5]) instruments. The mission objective is to perform quantitative measurements of the solar induced vegetation fluorescence aiming at monitoring the photosynthetic activity of plants. The measurement of the solar induced chlorophyll fluorescence directly addresses the photosynthetic efficiency of the terrestrial vegetation layer and complements traditional reflectance measurements used to infer parameters like Leaf Area Index (LAI) or chlorophyll absorption [6]. Under optimal conditions the fluorescence radiance emitted by plants represents only a small quantity (0.5%) of the overall absorbed light, but it increases up to 2% in absence of photosynthetic activity. As a consequence, fluorescence is a direct indicator of the status of health of vegetation. The fluorescence radiance (with a peak of the order of 2 $mW/m^2/sr/nm$) represents a small fraction of the Top Of Atmosphere (TOA) radiance (≈50-100 $mW/m^2/sr/nm$, as shown in Figure 1-1), and the aim of the FLEX mission is to measure the Sun Induced Fluorescence radiance (SIF) with a 10% of accuracy, i.e. with an error less than 0.2 $mW/m^2/sr/nm$. For this reason every Stray-Light (SL) signal that may affect spectral measurements shall be avoided or corrected down to a residual error less than 20% of the fluorescence error itself, i.e. ≤0.04 $mW/m^2/sr/nm$.

*davide.nuzzi@leonardo.com; phone +39 055 8950092; leonardo.com

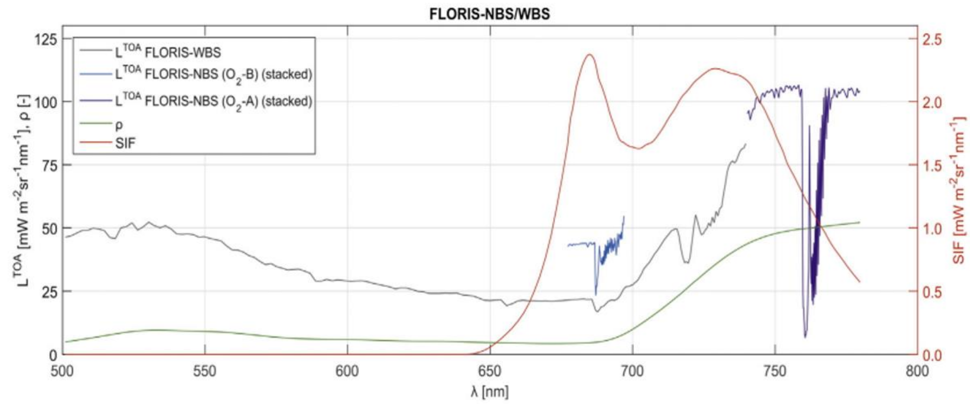

Figure 1-1 Typical spectra of TOA Radiance detected from FLEX (grey, blue and violet curves) compared with vegetation reflectance (green curve) and Sun Induced Fluorescence (SIF) radiance (red curve) [6].

The FLuORescence Imaging Spectrometer (FLORIS) is the FLEX payload [7]. It will be mounted on a medium/small size platform and will fly in a Sun synchronous orbit at a height of about 815 Km. The instrument architecture is based on a push-broom hyperspectral imager with a common telescope and two in field separated spectrometers [7]. Two different spectral channels (LR=500-758 nm, HR=677-697 and 740-780 nm) with high spectral sampling (respectively 2 nm and 0.1 nm) have been implemented by means of two spectrometers whose spatial co-registration has been enhanced by design through a common fore-optics with a ground spatial sampling of 300 m and a swath of 150 km. High efficient anti-reflection coatings, super-polished surfaces, tight particle contamination control during all phases of integration, optimised holographic gratings and a linear variable filter near the detector unit are the essential features implemented in order to keep under control the spatial and the spectral SL, having a direct impact on the fluorescence measurement accuracy within the O_2 absorption bands (O_2B=677-697 and O_2A=740-780 nm). The operative spectral region is selected by a band pass filter, placed just after the instrument aperture stop and in front of a polarization scrambler. The out-of-band SL is also mitigated by using two additional filters, one for each channel, coated on two folding mirrors placed near the double slit assembly, which constitutes the last element of the common fore-optics. Three identical backside illuminated frame transfer CCD detector units, cooled at −35°C, allow to cover the three spectral range (O_2B, O_2A and LR bands) with reduced smearing, low dark current and noise, and high well capacity (1.25 Me for a 42um *28 um pixel size).
The Stray-Light (SL) correction foresees the knowledge of the so called Spatial Point Source Transmittance (SPST), which roughly consists in the map of the ratio between the irradiance (W/m^2) measured at the focal plane and the input irradiance, i.e. the instrument response to a monochromatic, collimated beam for each wavelength and each Field Of View (FOV) point over a large domain of input energy values. The response of the instrument to a generic scene (extended and/or non-uniform) can be reconstructed through the superposition of all the SPSTs, each weighted with the scene radiance evaluated at that FOV and wavelength. Since a complete experimental characterization of the instrument SL is not feasible due to the enormous number of required measurements, the SL correction process will follow the scheme reported in Figure 1-2: SL is characterized through a certain number of SPST measurements impacting the residual errors, then these measurements are used to correlate a state-of-art mathematical model (implemented with the ASAP software) that allows to simulate all the SPSTs used in the correction algorithm which reconstructs the SL scene on the base of the acquired one.

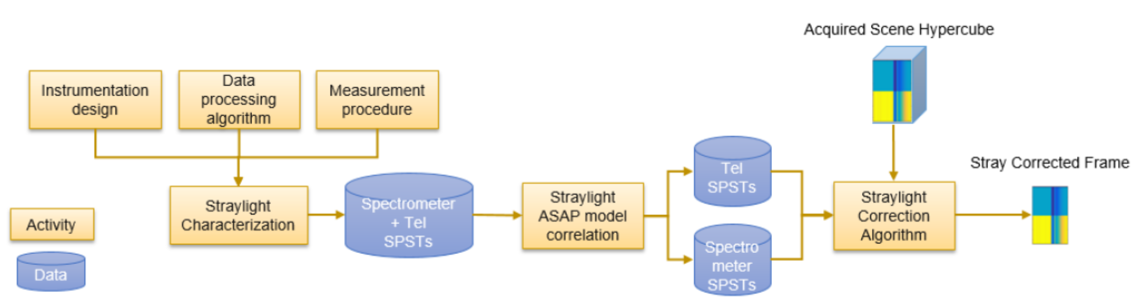

Figure 1-2 Scheme of the FLORIS SL correction process

The major challenge in the measurement of the SPSTs is represented by the need of covering a high dynamic range with a sufficient accuracy in order to obtain the desired level of accuracy in the SL correction. This is because also the regions where the signal level is very low with respect to the primary one (10^{-9}-10^{-10}) can give a non-negligible contribution to the extended scene reconstruction, which is obtained as the superposition of a large number of SPST maps. Such a high dynamic range (9-10 orders of magnitude) cannot be obtained by using a single detector acquisition but it is necessary to combine several acquisitions with different fluxes and integration times.

The SL characterization of the FLORIS flight model will be performed during the On Ground Calibration (OGC) campaign. The SPST measurement, the data processing, the model correlation and the SL correction algorithm have been tested during the FLORIS development phases. In fact, the design, the realization and the test of a breadboard device similar to the flight unit during the early phases of a space mission represent a fundamental task because it allows to anticipate technical problematics which may occur during the realisation of the flight unit, and to reduce risks related to critical components (such as detectors, optics, mechanics), alignment procedures and early verification of the instrument performance. This is essential for an innovative high spectral resolution spectrometer, like FLORIS, devoted to the measurement of the vegetation fluorescence, where optical performances as spectral resolution, image quality, polarization sensitivity, distortions and Stray-Light (SL) are of fundamental importance for the retrieval of the weak fluorescence signals emitted from vegetation within the total reflected and the atmospheric scattering contributions. To this scope a breadboard of the FLORIS instrument, including the optical bench, the telescope and the two HR and LR spectrometers, was built and tested in previous phases A-B1-B2 [8], [9]. An engineering model, called Optical Model Refurbished (OMR), for the High Resolution channel has been built in phases C-D, with the primary aim of improving the SL measurements and the SL-model correlation by an accurate validation of the end-to-end SL correction strategy, but also that of completing the performance measurements, allowing also tests in vacuum conditions.

A common effect that occurs when illuminating a CCD with a high level of energy, obtained through a large integration time or a high photon flux, is represented by the blooming, i.e. a rather uncontrolled spill over of charges from a given pixel to its surrounding ones due to an excess of charge beyond the saturation level. The charge emerging from a pixel due to the blooming will spoil the response of the neighbouring pixels and may also affect all the pixels along the read-out direction, where the blooming charge excess is smeared during the reading process. The blooming effect is particularly relevant for the SPST measurement, where high energy levels are required in order to reach the dynamic range needed for the correction accuracy. The net effect of blooming on the measured SPST is that of limiting the dynamics, thus preventing to achieve the desired accuracy for the SL correction. The attempt to overcome the blooming issue led to a two-fold investigation: (i) how blooming propagates and affects the SPST map reconstruction; (ii) how to improve the measurement approach in order to limit blooming and to increase the dynamic range. For this last point in particular several approaches have been pursued, among which the out-of-field and the out-of-band measurements gave the most significant results.

In the following sections the paper will describe the OMR and the setup for the SL measurements. The blooming issue and the subsequent investigations will be presented together with the results of the different type of measurements. The main results will be finally summarized by presenting the foreseen residual SL errors, evaluated from analysis and measurements, to be compared with requirements.

1.2 The FLORIS Optical Model Refurbished

The FLORIS Optical Model Refurbished (OMR) is an engineering model of the payload FLORIS developed in the C-D phase of the FLEX program. The FLORIS OMR hosts the High-Resolution (HR) channel of the FLORIS instrument which is constituted by the following subsystems: the High Resolution SPEctrometer (HRSPE), working in the two O_2 absorption spectral bands (O_2B=677-697 and O_2A=740-780 nm) with a spectral sampling of 0.093 nm; the OMR TELescope (TEL), with the PFM 5 lens design, covering the instrument field of view of ~11°; the Polarization SCrambler Assembly (PSCA), including the aperture stop, a band-pass filter and a dummy Polarization Scrambler (PSC), i.e. an optical flat with same thickness and AR coating of the PFM PSC; the HR Focal Plane System (HR-FPS), including the two CCDs, one for each of the two HR spectral bands, the proximity electronics and the two Video Acquisition Units (VAUs). The HR-FPS also carries a Linear-Variable Filter (LVF) aligned with the detector sensitive areas; The OMR Slit and HR Folding mirror (HRF) with the breadboard design, but similar features of the Flight Model (FM) [8]. No Calibration Unit and no low-resolution channel have been implemented on board of the OMR. The block scheme of the OMR internal structure is reported in Figure 1-3.

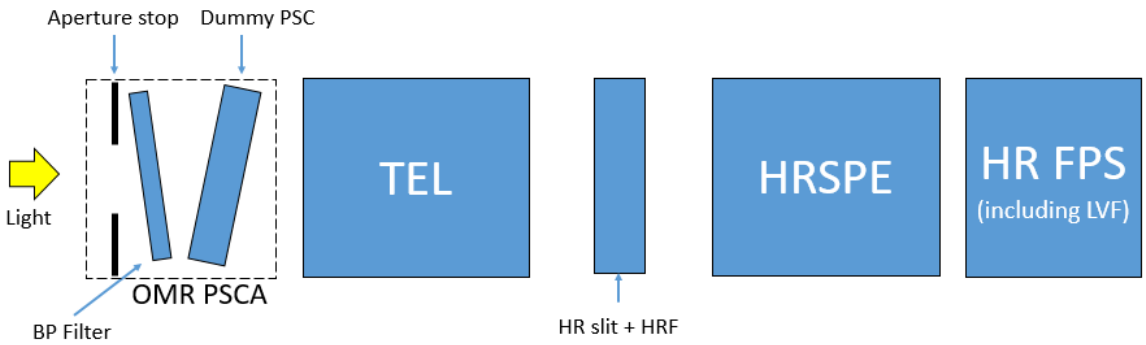

Figure 1-3 Scheme of the subsystems inside the FLORIS OMR

The main objectives of the OMR campaign have been: (i) anticipation of SL measurements for the correlation of the SL model to be used for the characterization of the instrument SL and for image correction; (ii) the validation of the AIT methodologies for the alignment of the instrument; (iii) a first assessment of the performances in vacuum conditions. According to point (i), the OMR has been designed in order to be representative of the FLORIS Flight Model (FM) in terms of the optical interfaces. This means that all the surfaces of the OMR optical elements are representative of the FM design at least for what primarily affects SL, e.g. the surface roughness and the coatings. In Table 1-1 the main features relevant for the SL are reported, comparing the OMR and the FM optical parameters.

Table 1-1 Comparison of the main subsystem specifications between FLORIS OMR and FM with specific focus on SL relevance

Subsystem	OMR	FM
HRSPE	- Optics roughness from 0.5 to 0.75nm rms - Holographic grating with 1450 grooves/mm	- Optics roughness from 0.5 to 0.75nm rms - Holographic grating with 1450 grooves/mm
TEL	- 5 Lens design, same of FM telescope - Lenses roughness from 0.5 to 2.5 nm rms	- 5 Lens design - Lenses roughness from 0.5 to 1 nm rms
PSCA	- BP filter - FM representative coating only for BP filter - No scrambler present, only optical flat with AR coating - Measured BTDF data on representative samples	- BP filter - Dual Babinet scrambler - Measured Bidirectional-Transmittance Distribution Function (BTDF) data on representative samples
HRFPS	- LVF as-built coating data - LVF BTDF measured data on representative sample	- LVF as-built coating data - LVF BTDF measured data on representative sample
SLITA	- Breadboard design: Slit and HRF on separated elements- - HRF roughness about 2 nm rms	- FM assembly design with HR and LR slits, HRF and LRF folding mirrors - HRF and LRF as-built coating data - BTDF measured data on fully representative HRF and LRF samples

In addition to the optical representativeness, particular care has been taken to keep as low as possible particle and molecular contaminations, which have been monitored throughout the whole integration process, taking place inside a ISO 5 clean room, thanks to dedicated PAC and MOC samples placed on the OMR bench. In order to accomplish also objectives (ii) and (iii), the mechanical layout, which was based on the optical bench used in the phase A-B1-B2 pre-development breadboard activities [8], has been modified in order to host the FM design of the sub-assemblies relevant for the optical performance, allowing the test of AIT procedures foreseen for the FM unit. The optical bench of the OMR model after integration is shown in Figure 1-4: the PFM design of the PSCA, TEL, HR-FPS and the Mirror of the HRSPE are visible.

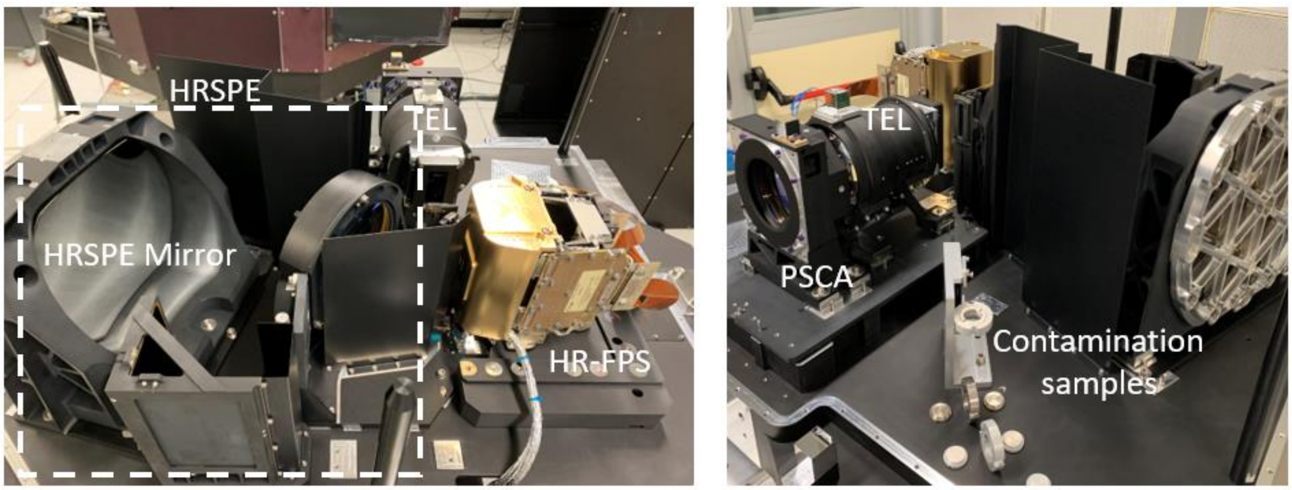

Figure 1-4 OMR model internal layout

2. STRAY-LIGHT MEASUREMENT

The instrument SL characterization is performed through the measurement of the so called Spatial Point Source Transmittance (SPST) maps. In principle a SPST map depicts how the SL of a point source spreads over the whole area of the instrument detector. Since a generic illumination pattern can be represented as the superposition of certain number of point sources with the corresponding wavelength, each weighted with its intensity, analogously it is possible to reconstruct the instrument SL up to the desired level of accuracy by measuring an adequate number of SPST maps, with the needed spatial and spectral sampling which is driven by the accuracy target level for the SL correction. As anticipated in the introduction, the measured SPST are used to determine the values of some parameter of the SL ASAP model, thus correlating the model prediction with the actual instrument behavior. At the end of this chain, the SPST maps provided by the model will form the database used to feed the SL correction algorithm.

The actual measurement of a SPST map sets some difficulties related to the fact that, in order to obtain a detectable signal over the whole detector or to achieve a determined dynamic range, it is needed to illuminate the setup with a very high energy flux or, if this is not possible due to hardware limitations (e.g. the maximum output of the available light source), integrating for a long time. In fact, the most of the energy will be concentrated in the spot and its surroundings while the remaining part is illuminated only by the SL whose intensity, excluding possible intense local effects as ghosts, also decays with the distance from the primary spot. In addition to this general feature, it shall be also considered that in the FLORIS project the design and the integration strategy have been optimized in order to reduce as much as possible the SL signal, thus making the SL characterization task even more difficult. The first consequence of the above fact is that, a SPST map cannot be achieved by a single acquisition of the instrument detector but rather needs to be reconstructed starting from several images. Each of the images used for the reconstruction of a SPST map is obtained by illuminating the focal plane with a different energy level, being obtained either by varying the energy flux of the source, keeping integration time constant, or by varying the integration time with constant energy flux. The acquisitions corresponding to lower energy levels will provide information in the regions of the map that are close to the primary signal, while the ones corresponding to higher energy levels are needed in order to measure the SPST tails, i.e. regions far from the primary, while saturating the spot surroundings. Once the images are acquired, they are first corrected for dark and smearing and then used to reconstruct the SPST map. The map reconstruction foresees first to identify a 'valid region', where the image shows a signal within the range given by the noise level and the linearity limit of the detector, then to rescale the images according to the corresponding energy level. Each of the rescaled images will finally contribute to the final SPST map with its "valid region". An example of SPST map acquired during the FLORIS breadboard campaign with a service detector is given in Figure 2-1 [8]. This map reports the intensity in logarithmic scale and shows a dynamic range of more than 8 decades.

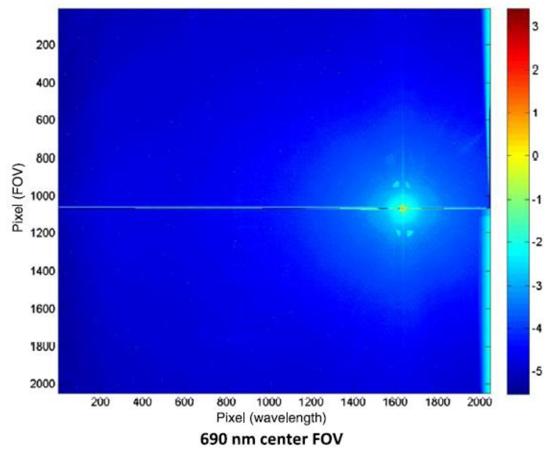

Figure 2-1 SPST map acquired during the FLORIS breadboard campaign [8]. The primary spot is at 690 nm wavelength and axial FOV, the intensity is in logarithmic scale. The four triangular feature are due to the not optimized grating used for the breadboard. The horizontal dark line is due to the blooming of the service detector while the bright vertical feature on the right part is due to the service camera read-out register.

In order to reach the accuracy levels required for the FLORIS project a dynamics extending over 10 orders of magnitude shall be explored. Such an extended range requires an illumination system with specific features and capable of providing high light fluxes.

2.1 The test setup

In order to obtain a SPST acquisition, the illumination system, namely the Optical Ground Support Equipment (OGSE), used for the measurement shall produce an illumination accommodating the following requirements:

i. Produce a collimated beam covering the entire instrument aperture (~80 mm)
ii. Beam shall be monochromatic compared to the instrument spectral resolution
iii. Have a sufficient intensity in order to reach the desired dynamic range
iv. Have the possibility to change the beam wavelength over the instrument spectrum and the beam orientation over the instrument FOV in order to measure different points in the focal plane
v. Have the possibility to vary the beam intensity in a controlled way over several decades
vi. Monitor the beam intensity
vii. It shall not introduce significant SL or it shall be characterized in order to correct acquisitions

The FLORIS OGSE have been developed in order to fulfill all the above specifications and, for this reason, it is an articulated instrument which is structured as follows: a super-continuum laser provides the light intensity with a broad spectrum covering the whole instrument need; a monochromator, capable of selecting the wavelength with bandwidth as narrow as 0.03 nm, is then coupled to the aforementioned laser; the output of the monochromator is focalized onto the core of a multimode optical fiber which is used to route the light to the collimator target; in the optical fiber path a photodiode is used to monitor the signal intensity during acquisition and a fiber attenuator allows for the remote control of signal attenuation up to 80 dB. Finally, a collimator collects the light coming out from a target producing a collimated

beam with a width up to ~150mm. The collimator is mounted over a hexapod, capable of modifying the beam angle w.r.t. the instrument entrance pupil and of covering the entire instrument FOV (>11 deg). The OGSE collimator is constituted by four spherical mirrors and its design is thought for assuring a good optical quality and reduced SL, making use of internal black screens and a black cover. During the OGSE commissioning tests the collimator SL has been measured and used for the correlation of the model with respect measurements.
SL measurements during the OMR campaign have been performed both in air and in vacuum and the two setups are shown in Figure 2-2.

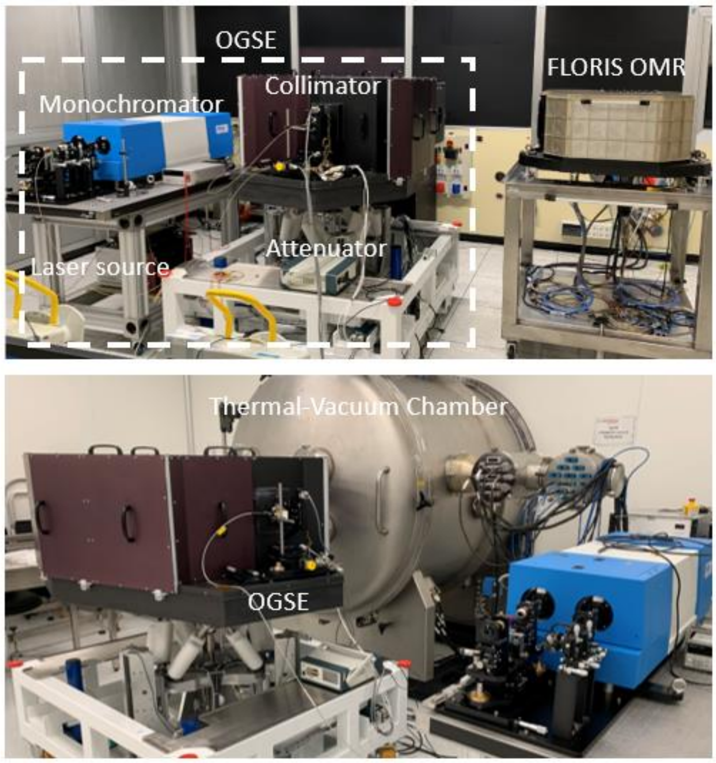

Figure 2-2FLORIS OMR SPST measurement setup for 'in-air' measurement (top panel) and for the vacuum measurement (bottom panel) where the OMR is inside the TVC

Both setups foresee to place the collimator in front the aperture stop of the OMR which has been placed, in turn on a dedicated trolley for test in air and on the baseplate of the Thermal Vacuum Chamber (TVC) for test in vacuum. The main difference in the setups, besides the environmental conditions during the tests, is the presence of the TVC window which introduces two extra optical surfaces between the OGSE collimator, which is outside the TVC, and the OMR.

2.2 Blooming Effect on the SPST measurement

Since the SL signal is faint, the SPST measurement requires a very intense illumination in order to achieve a good SNR in the tails of the map and to obtain a good correlation with the model. Although the high CCD saturation level (e.g. 2 Me), the needed intense illumination can cause the blooming effect, which consists in a charge overflow from one pixel to the neighboring ones, due to an excess of charge exceeding the saturation level. In fact, as the saturation of the illuminated pixels occurs, the storage capacity of the CCD well is exhausted, and the excess charge overflows in the adjacent pixels, producing a spurious signal of non-illuminated pixels. In addition, the emerging excess of charge may be smeared during the charge transfer process producing stripes of spurious signal along the read out direction, thus affecting pixels that lays very far from the primary spot. The result of the blooming is that the image is corrupted being the signal not correctly reproducing the actual physical situation. The SL information on the blooming affected region is thus completely lost. As a consequence, on the SPST map the achievable dynamic range is limited by the blooming expansion, i.e. if the blooming spreads onto a detector region before the SL signal is detected, then the SL in that region is not measurable and increasing the input flux or the integration time will not improve this situation.

During the OMR SL measurement campaign the blooming and the associated negative effects have been observed as shown in Figure 2-3. Blooming relevance has been enhanced also due to the absence of an anti-blooming feature on the FLORIS CCD. This choice was initially done in order to meet the primary CCD design drivers, i.e. to obtain a high quantum efficiency in order to maximize the SNR, and a short row transfer time in order to reduce the smearing effect. In fact, implementing an anti-blooming feature would have reduced the pixel sensitive area with possible impacts on the image read-out. The left panel of Figure 2-3, shows an example of blooming obtained on one of the CCDs of the OMR focal plane (FM representative) with nominal parameters: It appears that charge spilled beyond the illuminated pixels, causing blooming extends mainly in the horizontal direction, corresponding to the spectrum. This results in a saturated spectral stripe which is then smeared along the read-out direction which is along the column (ACT FOV) direction in FLORIS CCD. Concerning the read-out process, the CCD is divided into two parts since there are two reading registers, one at the top and one at the bottom of the CCD. The read out is then performed starting from the detector center toward the two extremities. Depending on which of the two halves of the detector the primary spot is located, the charge belonging to the bloomed stripe will be smeared along the spatial direction toward the top or the bottom of the detector. In this way the corrupted part of the image is not limited to the pixels saturated by the blooming, but also affects all the bands of any blooming affected pixel (even the non-saturated ones), from the position of the primary up to the top/bottom of the detector. Since this effect cannot be corrected by the usual background and smearing corrections, it becomes a blooming long range effect which spoils not only the pixel directly affected by blooming but also pixel which are far apart from them. The right panel of Figure 2-3 shows a SPST map measured on the HR2 detector (the one corresponding to the O_2A spectral band) and it highlights how the long range blooming effect corrupts the SPST. In this acquisition the illuminated spot lies in the top half of the detector. Blooming has spread in the horizontal direction, but the illumination intensity is such that it has not reached yet the pixels of the bottom half. Then the part of the SPST in the bottom half of detector is reliable, and the SL is correctly measured. On the opposite, the SPST map lying in the top half is corrupted by the long range effect of blooming.

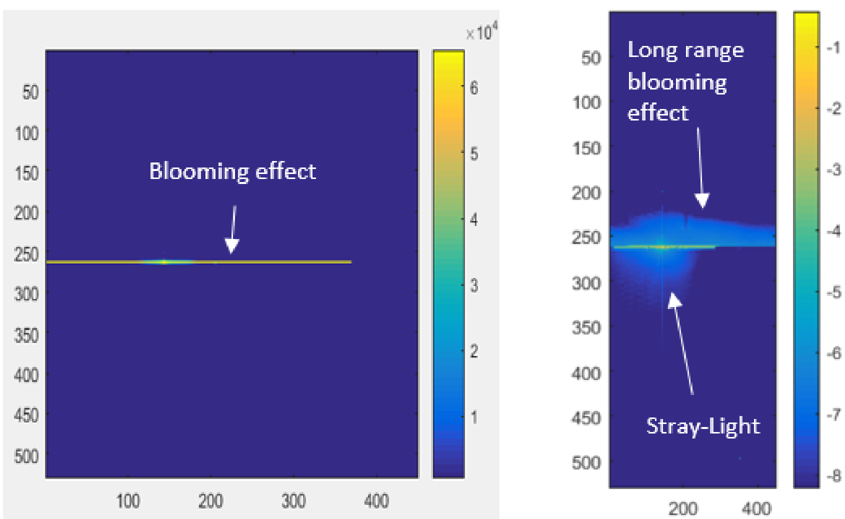

Figure 2-3 – Left: density plot (linear scale) of an high flux acquisition on HR2 detector, the blooming produces a stripe in the spectral direction. Right: Example of in field, in band SPST map (logarithmic scale) with nominal voltage configuration. Long range blooming effect overcomes SL signal in the illuminated top half.

The blooming and its long range effect on the SPST prevented to reach the desired dynamics range for the SL characterization and it needed an investigation devoted to overcome the issue following two main paths: understanding/characterizing blooming behavior, and finding new methods of measuring the SL also improving the extraction of information from the available data. As for the blooming understanding, attempts have been made in order to characterize the long range blooming effect, separating it from the actual SL signal and then using the obtained characterization for correcting further acquisitions. Unluckily, these attempts were unsuccessful due to the fact that the

accuracy required to distinguish the faint SL signal behind blooming is too high for the measurement setup and the obtained results appear not to be sufficient to correct blooming in a generic measurement.
During the investigation for better understanding the blooming features of the CCD, it was discovered that one of the accessible parameters, the so called Image Clock High Level, is able to influence the blooming behavior. In particular, by modifying this setting from the default value, the blooming changed its preferential spreading direction from the horizontal (spectral), to the vertical (spatial) direction, i.e. the ACross-Track (ACT) FOV corresponding to the read-out direction, as shown in Figure 2-4. This has been a significant improvement of the situation since, if blooming spreads in the read-out direction, the number of corrupted columns is much lower and a larger part of the SPST map is not corrupted by blooming.

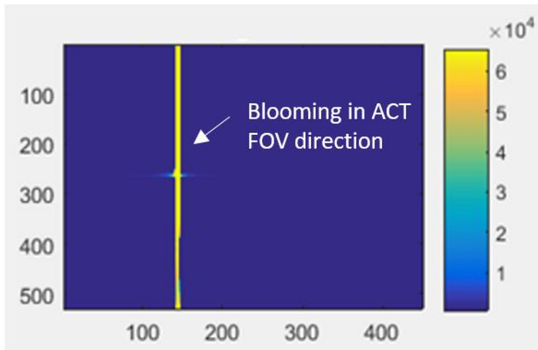

Figure 2-4 – High flux measurement with modified clock high voltage. The blooming preferential direction turns from horizontal (spectrum) to vertical (FOV ACT).

However, despite the optimized voltage setting, blooming artefacts are still present at very high signals, still posing a limit to the accessible dynamics of the map. The best tradeoff between signal intensity and artefacts allows to reach 8-9 orders of magnitude as shown in Figure 2-5.

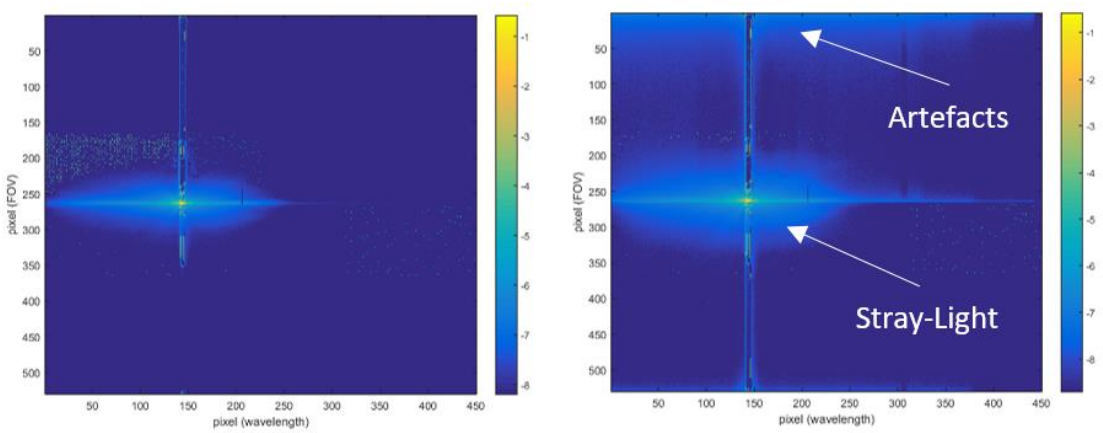

Figure 2-5 Example of in field, in band SPST map measured with optimized voltage setting. The SPST map reconstruction is more reliable, but some artefacts appear at very high signals. Left: SPST map reconstructed using acquisitions up to 0,5 sec integration time. Right: SPST map reconstructed using acquisitions up to 1,6 sec integration time. The figure shows how increasing the signal to gain a better dynamic range of 8-9 orders of magnitude introduces electronic artefacts related to blooming and saturation.

3. GOING BEYOND BLOOMING

The second path followed during the blooming investigation concerns the SL measurement approach and how the available information is used for the correlation of the ASAP model. Blooming poses a limit to the measurement dynamic range

creating artefacts that prevent the desired SL detection. This limit is not acceptable for FLORIS project, since the analysis show that the SPST maps shall cover a range up to 10 orders of magnitude with respect to the primary signal in order to minimize the correction contribution to the L1b SL budget.
For this reason, different trials have been performed in order to define a measurement strategy that will finally allow to retrieve the needed information during the OGC campaign. A first attempt to overcome the blooming artifacts for retrieving the SL signal have been made by trying to exploit the center of the detector as a physical barrier for blooming as noted in commenting Figure 2-3, where the primary spot was on the upper half of the CCD but close to the center. The result of this positioning is that the upper part of the SPST map is corrupted while the lower half is not, reporting correct SL data. Repeating the same measurement slightly changing the illumination position in such a way that the spot lays in the bottom half, one obtains the inverted situation with good data in the upper part and corrupted data in the lower. Combining the good data from both images a complete map can be reconstructed. In a similar way, these data allow to construct also a blooming map by subtracting measured SL from the corresponding ‘corrupted’ data. This same set of maps has been used for the attempt of blooming characterization described in the former section. Although this technique provided quite good results in retrieving SL information, it does not represent a significant improvement, being only applicable to those measurements close to optical axis while it is not useful for all the other FOVs.
A better way to get rid of the blooming is to avoid the CCD direct illumination. This is achievable performing the SPST measurement using an Out Of Band (OOB) wavelength, i.e. such that the primary spot falls outside the sensitive area of the CCD in a dark masked area. Having the illuminated spot out of the sensitive area of the CCD, the OOB measurements allow to detect the SL signal without producing blooming. OOB measurements provide a dynamic range of 9-10 orders of magnitude, with this limitation given by the OGSE maximum light intensity, thus, besides the order achieved during the OMR campaign, future improvements are possible by increasing the OGSE output. Similar considerations apply to the Out Of Field (OOF) measurements, where the primary spot is produced slightly shifted in ALong Track (ALT) direction with respect to the instrument slit in such a way that it is blocked. Although similar in principle, the OOB and OOF measurements provide different information. The OOB measurements are similar to a nominal SPST, but they are missing the SL of the fore-optics, i.e. the PSCA and the TEL, which would be located in correspondence of the primary spot falling outside the CCD sensitive area. The OOF measurements, on the contrary, give exactly this missing information about the SL contribution of the optical elements before the slit. In fact, being the primary signal blocked by the slit, the only light that cross the HRSPE and reach the detector is the SL produced by the fore-optics. An example of the OOB and OOF measured maps are shown in Figure 3-1.

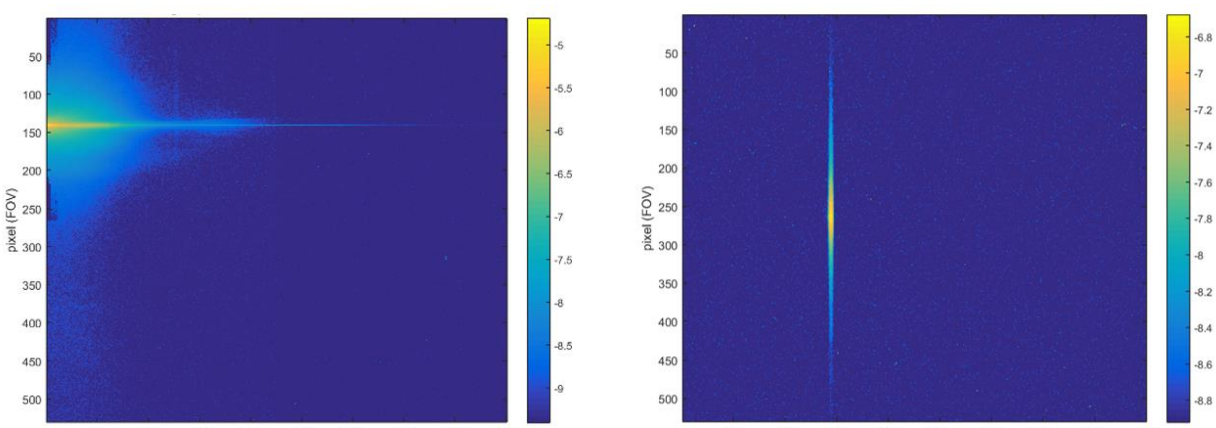

Figure 3-1 Left: Example of OOB measured SPST map, 9-10 orders of magnitude have been reached. Right: Example of OOF SPST map. The illuminated spot is blocked by the slit chip and the SL generated by fore-optics is visible through the slit aperture.

Considering the complementary information coming from the OOB and OOF measurements and the improved SPST obtained with the optimal clock voltage providing good data up to 8-9 decades, a set of measurement is available making it worth to do some considerations on the purpose of SL measurements and the results they allow to achieve.
As the SL correction relies on a SPST database created with ASAP (see Figure 1-2), the measurement process can be considered successful as long as the information gained is sufficient to correlate the ASAP model of FLORIS in a reliable way up to the desired level. Concerning the tuning of the fore-optics parameters, the OOF SPST maps can be used and, being not limited by blooming, they lead to a good correlation up to 9-10 orders of magnitude, i.e. very close to value

foreseen by the analysis. Conversely, for the tuning of the HRSPE parameters, the in-field measurements, both the in band and the OOB, are needed. Thanks to the fact that the optical design of the HRSPE is such that the beam footprint on the illuminated optical elements does not vary significantly between the in band and the OOB condition, the combined use of the available measurements allows a reliable correlation of the ASAP model HRSPE parameters up to the same 9-10 orders of magnitude. Nevertheless, this consideration does not apply to the LVF filter positioned in front of the detector, that is not illuminated in the OOB case. This implies that the parameters related to LVF shall be tuned using the in band measurements only, which provides a reliable correlation up to 8-9 decades.

Summarizing, the in-band, in-field SPST are limited by the blooming to an 8-9 decade dynamics while OOB and OOF measurements already show an extra order of magnitude and can be further improved by increasing the OGSE beam intensity. The combined use of all these data allows to obtain an ASAP model able to generate SPST maps reliable up to 9-10 orders of magnitude with the only exception of the LVF contribution, that is reliable only up to 8-9 orders of magnitude. The error analysis that will be detailed in the next section shows that the correction performance obtained using such a database already allows to properly minimize the error contribution to L1b SL associated to SL correction.

In order to obtain further improvement for the in-field measurement, other attempts have been tried among which it is worth citing the SPST with the source synchronized with the acquisition, and the trial with the extended source. The first one has been obtained introducing a shutter in the OGSE which has been synchronized with image acquisition. This avoided CCD illumination during the readout. The measurement results showed no improvement of the blooming effect, but allowed to understand that the image readout is not sufficient to completely clean the CCD from spurious charge due to saturation and blooming. The test with the extended source consists in illuminating the instrument with a target producing an image with an area of several pixels. This allows to distribute the same amount of energy on more pixels thus reducing the saturation over each pixel and making the blooming appear only for larger integrated fluxes. The extended source is not a rigorous SPST measurement, but it is representative of an SPST in the region outside the primary and in case of uniform SL tails (i.e. in the absence of ghosts). The extended source setup required a significant change in the OGSE configuration and allowed only partial results which are still under evaluation. Other measurements with extended source are planned before the end of 2022 and will give a final response on the actual suitability of this solution.

4. SL PERFORMANCES AND CORRECTION RESULTS

The FLORIS SL L1b level (after SL correction) requirement foresees to achieve a residual SL signal of 0.04 $mW/m^2/sr/nm$ in the reference vegetation scene and for all the of the O_2B and O_2A spectral bands at a distance larger than 40 SSD from a sharp transition between a uniform and infinite bright zone (defined from Top Of Clouds, TOC, radiances) and a similar dark zone (defined from the reference radiances).

In order to discuss about the SL correction, it is useful to divide the SL into two parts: the correctable part, including all the SL signals which can be measured and are included in the ASAP model, and the non-correctable part, which include all the not directly measurable SL terms. In particular, the non-correctable SL includes the ACross-Track (ACT) out-of-field SL, i.e. the SL contribution coming from the part of the actual scene exceeding the instrument FOV in the ACT direction, which will be not accessible using the real acquisition data, and the scattering SL deriving from the extra contamination introduced after the OGC, i.e. during the AIT/AIV activities at spacecraft level. This latter term cannot be included in the model because it is due to activities which necessarily will take place after the completion of the OGC SL characterization, which will set the correlated parameters of the ASAP model providing the SPST database used by the correction algorithm.

According to the SL correction strategy (see also Figure 1-2), the SL signal is obtained by convolving the instrument SPST maps with the acquired scenes, where the SPST maps are those generated by the ASAP optical model correlated with the measurements performed during the OGC campaign. The correctable terms can be evaluated by using the measured in-field (within instrument FOV), in-band (within O_2A and O_2B bands), ALT Out-Of-Field and Out-Of-Band between 697 and 740 nm signals, lower than 677 nm and higher than 780 nm signals. For the evaluation of the ALT Out-Of-Field SL the signals to be used are those acquired before and after the acquisition to be corrected, while for the Out-Of-Band SL the signals can be extrapolated from the in band ones or measured by using the LR spectrometer data (500-758 nm range). Once the estimated SL scene is obtained, the correction is performed by subtracting it from the measured scene.

Before evaluating the results at level L1b (i.e. after SL correction), it is needed to simulate the SL scene deriving from the synthetic requirement pattern at the L0 level. The left panel of Figure 4-1 shows the requirement scene where the transition between the bright and the dark zone has been located at the center of the ACT FOV, while the right panel shows the SL pattern obtained simulating the instrument behavior. Please note that the L0 level SL in Figure 4-1 also contains the non-correctable SL terms since the exact knowledge of the scene allowed also the evaluation of the OOF ACT SL contribution,

while the extra contamination SL has been estimated thanks to the ASAP model and the results of a contamination measurement performed with a mock-up of the calibration unit and the telescope.
The SL at L0 level at 40 SSD from the transition is reported in Figure 4-2, showing a SL signal up to 0.95 mW/m^2/sr/nm against the requirement value of 0.7 mW/m^2/sr/nm. This non-compliance for the L0 level SL is mainly due to extra SL attributed to the grating and probably due to spurious effect in the holographic production process (see Figure 4-2).

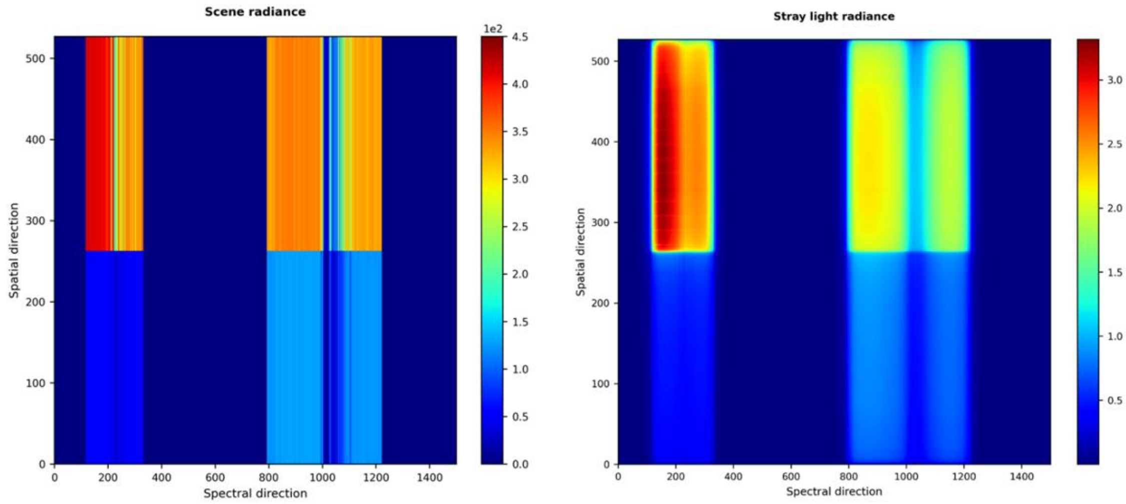

Figure 4-1 Reference scene radiance (mW/m^2/sr/nm) (left) and corresponding L0 (without correction) SL radiance (right). The upper part of the figures represents the TOC cloud radiances while the lower part represents the reference vegetation radiances.

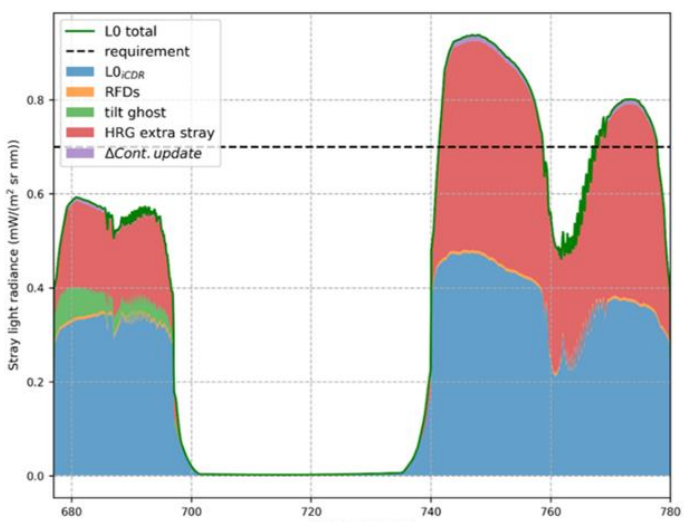

Figure 4-2 L0 level SL at 40 SSD from the transition zone (different colors reports the magnitude of the different SL contributions).

Starting from the scene of Figure 4-1 the SL correction algorithm can be applied and the final corrected SL at L1b level achieved as shown in Figure 4-3, where the total residual L1b level SL are reported together with the correctable and non-correctable contributions to be compared with the requirement value.

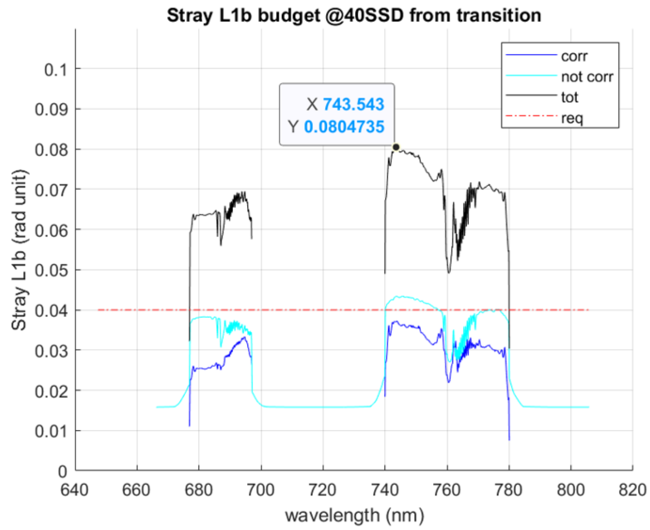

Figure 4-3 L1b (after correction) SL level at 40 SSD from the transition between a bright and a black scene.

The max residual stray is 0.08 mW/m^2/sr/nm, which is about a factor 2 larger than the requirement of 0.04 mW/m^2/sr/nm, with a reduction with respect to the L0 SL level of a factor larger than 10. Looking at the relative importance of the correctable and non-correctable terms it is evident that they are of the same order of magnitude and that the non-correctable term alone already exceeds the requirement. Considering also that the non-correctable term has the same value both at level L0 and L1b, the correction factor of the correctable part is more than twice the overall value with a correctable SL reduction between 20 and 25. Finally a further analysis of residual SL contribution shows that the worst contributor of the correctable term is the error in the SPST measurement while for the non-correctable part the worst contributor is due to the extra contamination introduced after the OGC campaign.

5. CONCLUSIONS

The FLORIS project requirement for the SL level necessitates to correct the SL from the acquired data. The SL correction strategy to be implemented requires, in turn, a direct measurement of the SL behavior of the instrument (i.e. the measured SPST maps) which will be used to correlate the ASAP model, which will finally provide the input SPST maps to the SL correction algorithm. Directly measuring the SPST map of a system, designed in order to reduce as much as possible the already faint SL signal, is a challenging task due to the high dynamics to be achieved in order to get to the required accuracy. In order to anticipate the issues related to this characterization, which have to be performed during the FLORIS OGC campaign, an engineering model, the OMR, have been developed to reproduce the HR-channel with similar characteristic to the FM model. In order to test the OMR a specific OGSE have been designed and validated. Besides the challenge posed by the SL measurement itself, the blooming effect and the absence of an anti-blooming feature on the FLORIS CCD set a severe constraint on the achievement of the desired accuracy for the SL correction needed by the project correction strategy. The blooming issue has been thus investigated finding the most suitable detector settings and introducing new different measurements allowing an improvement on the accessible dynamics. The Out-of-Band and Out-Of-Field measurements together with best results for the nominal in-band and in-field SPST maps allowed for satisfactory correlation of the ASAP model used to generate the SPST database for the correction algorithm. The correction level achieved for the correctable SL term is a factor >20 with respect to the L0 level, bringing the correctable SL below the requirement value of 0.04 mW/m^2/sr/nm on the worst case scenario of the requirement scene. The SL level coming from the not correctable term, principally coming from the estimated extra-contamination after the OGC campaign, is of the same order or a little higher than requirement. As a consequence, the current max total L1b residual SL error (0.08 mW/m^2/sr/nm) is higher than requirement of about a factor two. Further investigations for refining the SL measurements are ongoing together with the evaluation of possible improvements for the L0 and L1b SL, mainly based on more precise evaluations on the worst contributors to the overall non-compliances to SL requirements, i.e. the contribution attributed to the HR grating spurious effects and the extra-contamination after the OGC campaign.

ACKNOWLEDGEMENTS

The FLORIS OMR activities have been performed in the framework of the FLEX European Space Agency (ESA) program. It is also remarked that the view expressed herein can in no way be taken to reflect the official opinion of the European Space Agency.

REFERENCES

[1] Drusch, M.; Moreno, J.; Del Bello, U.; Franco, R.; Goulas, Y.; Huth, A.; Kraft, S.; Middleton, E.M.; Miglietta, F.; Mohammed, G.; et al. The Fluorescence Explorer Mission Concept—ESA's Earth Explorer 8. IEEE Trans. Geosci. Remote Sens. 2017, 55, 1273-1284, doi:10.1109/TGRS.2016.2621820.

[2] Nieke, J.; Borde, F.; Mavrocordatos, C.; Berruti, B.; Delclaud, Y.; Riti, J.B.; Garnier, T. The Ocean and Land Colour Imager (OLCI) for the Sentinel 3 GMES Mission: Status and first test results. Proc. SPIE 2012, 8528, 85280C.

[3] Coppo, P.; Ricciarelli, B.; Brandani, F.; Delderfield, J.; Ferlet, M.; Mutlow, C.; Munro, G.; Nightingale, T.; Smith, D.; Bianchi, S.; et al. SLSTR: A high dual scan temperature radiometer for sea and land surface monitoring from space. J. Mod. Opt. 2010, 57, 1815–1830, doi:10.1080/09500340.2010.503010.

[4] Coppo, P.; Mastrandrea, C.; Stagi, M.; Calamai, L.; Nieke, J. Sea and Land Surface Temperature Radiometer Detection Assembly Design and Performance. J. Appl. Remote Sens. 2014, 8, 084979, doi:10.1117/1.JRS.8.084979.

[5] Coppo, P.; Brandani, P.; Faraci, M.; Sarti, F.; Dami, M.; Chiarantini, L.; Ponticelli, B.; Giunti, L.; Fossati, E.; Cosi. M.; Leonardo spaceborne infrared payloads for Earth observation: SLSTRs for Copernicus Sentinel 3 and PRISMA hyperspectral camera for PRISMA satellite, Applied Optics, Vol. 59, N. 23, 2020. doi.org/10.1364/AO.389485.

[6] Cogliati S., W. Verhoef, S: Craft, N. Sabater, L. Alonso, J. Vicent, J. Moreno, M. Drusch, R. Colombo, "Retrieval of sun-induced fluorescence using advanced spectral fitting methods", Remote Sensing of Environment, 169 (2015), 344-357, https://doi.org/10.1016/j.rse.2015.08.022

[7] Coppo P., A. Taiti, L. Pettinato, M. Francois, M. Taccola and M. Drusch, Fluorescence Imaging Spectrometer (FLORIS) for ESA FLEX Mission, Special Issue "Remote Sensing of Vegetation Fluorescence and Photosynthetic Efficiency" (ISSN 2072-4292), Remote Sens. 2017, 9, 649; MDPI editor, doi:10.3390/rs9070649.

[8] Coppo P., L. Pettinato, D. Nuzzi, E. Fossati, A. Taiti, R. Gabrieli, A. Campa, M. Taccola, J.L. Bezy, M. Francois, L. Erdmanm, P. Triebel, D. Lehr," Instrument predevelopment activities for FLEX mission," Opt. Eng. 58(7), 075102 (2019), doi: 10.1117/1.OE.58.7.075102.

[9] Altbauer A., P. Sandri, D.A. Laang, L. Pettinato, R. Gabrieli, P. Coppo, M. Taccola, D. Nuzzi, "Flex Low Resolution Spectrometer Breadboard Activities", Proceedings of ICSO 2020 Conference on Space Optics, 30 March-2 April 2021.