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ASPIICS Shadow Position Sensors Digital Twin and Illumination Testbed

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ABSTRACT

The PROBA-3 double-spacecraft formation flying mission of the European Space Agency (ESA) has been presented in recent papers with details about the mission profile, the operation objectives, and the implemented technologies. PROBA-3 will fly the externally occulted coronagraph ASPIICS (Association of Spacecraft for Polarimetric and Imaging Investigation of the Corona of the Sun), with the telescope on one satellite and the occulter on the other one, at 144m. The scientific objective is to realize an artificial total solar eclipse to observe the lower Sun corona. The high accuracy metrology control is the core of the mission and several sub-systems will be verified and validated to realize the coronagraphic formation. Between these, the Shadow Position Sensors (SPS), composed of eight photo-multipliers mounted around the ASPIICS entrance pupil monitoring the solar penumbra symmetry, will return the 3D positioning of the formation with the highest accuracy. The SPS on-ground calibration was completed in 2021 and one of the main aspects of the test has been the implementation of an illumination scheme to simulate the same conditions the SPS will experience in flight. This was realized using a suite of LED sources properly assembled in a testbed used to reproduce the expected observation configurations. This testbed is supported by a dedicated software able to simulate the different illumination conditions and to drive the control of the LEDs in order to feed each SPS sensor with the proper light flux. In this paper, we review the SPS metrology system, the calibration testbed setup, and we discuss the interface control software, the simulation tool, and the data acquisition procedure adopted to calibrate the LED sources.

Keywords: Formation flying; Coronagraph; Solar Physics; Calibration; Metrology; Space Mission.

1. INTRODUCTION

PROBA-3 - PRoject for OnBoard Autonomy - is the ESA mission where a spacecraft is used as an external occulter (Occulter Spacecraft - OSC) to create an artificial solar eclipse as observed by the ASPIICS coronagraph on board of a second spacecraft, the Coronagraph Spacecraft (CSC). The two satellites will orbit around the Earth on a highly elliptic orbit (HEO), with the perigee at 600 Km and the apogee at about 60000 Km. The orbital period is of 19.7 hours and the precise formation flight will be realized and maintained for about 6 hours over the apogee, where the gravity gradient is at minimum, in order to guarantee the observation of the solar corona with the required spatial resolution [1]. The relative and absolute alignment of the two spacecrafts is obtained by combining information from several metrology sub-systems. Between these, one of the most accurate ($3\sigma \leq 0.5$ mm on lateral positioning and ≤ 50mm on longitudinal positioning) is the Shadow Position Sensors (SPS) composed of eight silicon photo-multipliers (SiPM) mounted around the entrance pupil of the ASPIICS telescope [2]. The SPS will monitor the penumbra projected by the occulter spacecraft on the coronagraph pupil plane, whose intensity will change according to the relative and absolute position of the two satellites, as discussed in [3]. A dedicated algorithm [4] elaborates the radiometric measurements of the SPS (ADC digital output proportional to the SiPM photo-corrent) to monitor any misalignment of the spacecrafts and to inform the

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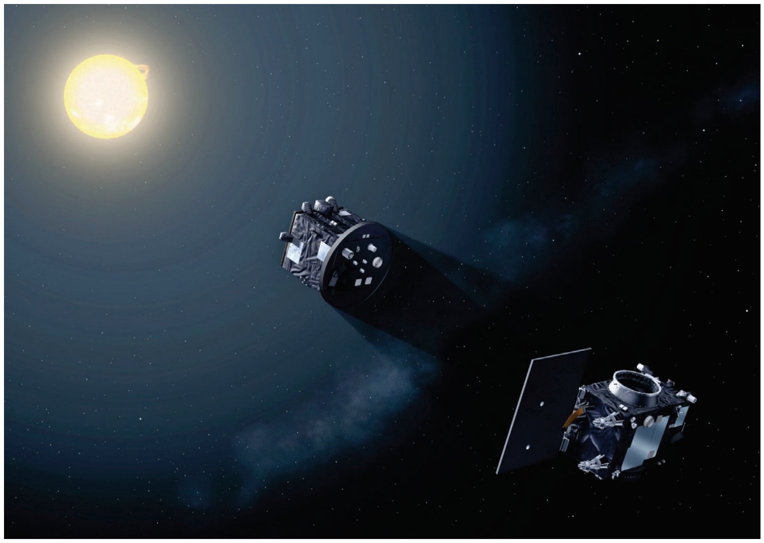


Figure 1. PROBA-3 formation flying rendering (Courtesy of ESA).

Guidance and Navigation Control system about the correction required to maintain the formation. A rendering of the PROBA-3 mission flight concept is given in figure 1.
The high accuracy required to the SPS asked for a very accurate testing and calibration. In the following sections, we review the simulation tools and the hardware designed and developed to support the calibration activity.

2. SPS SYSTEM REVIEW

The Shadow Position Sensors (SPS) metrology system is built of two main parts: 1) an electronic board housing the 8 SiPMs, the proximity electronics, and the cabling and connectors to link with the external harness; 2) a mechanical flange housing the electronics and interfacing with the ASPIICS telescope.

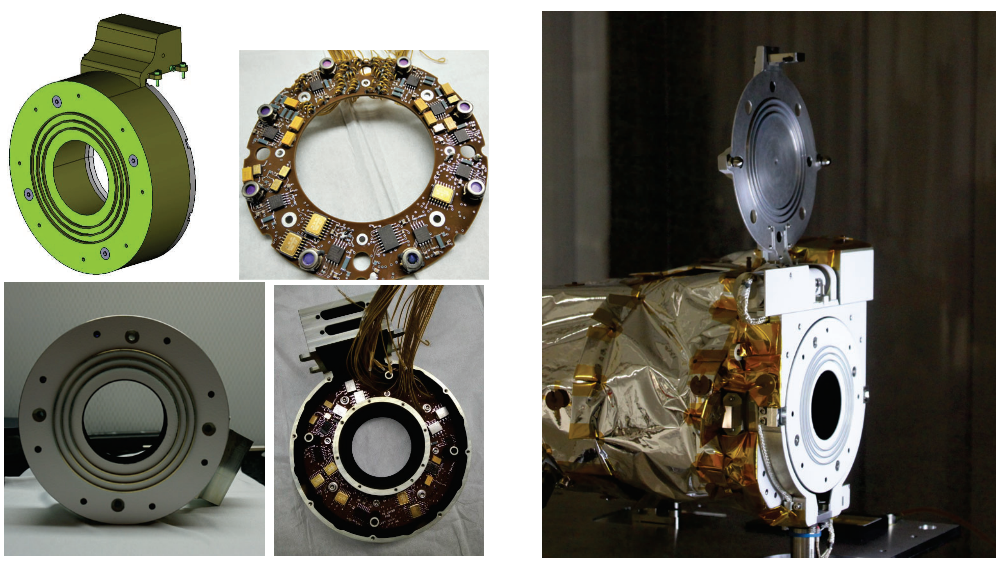


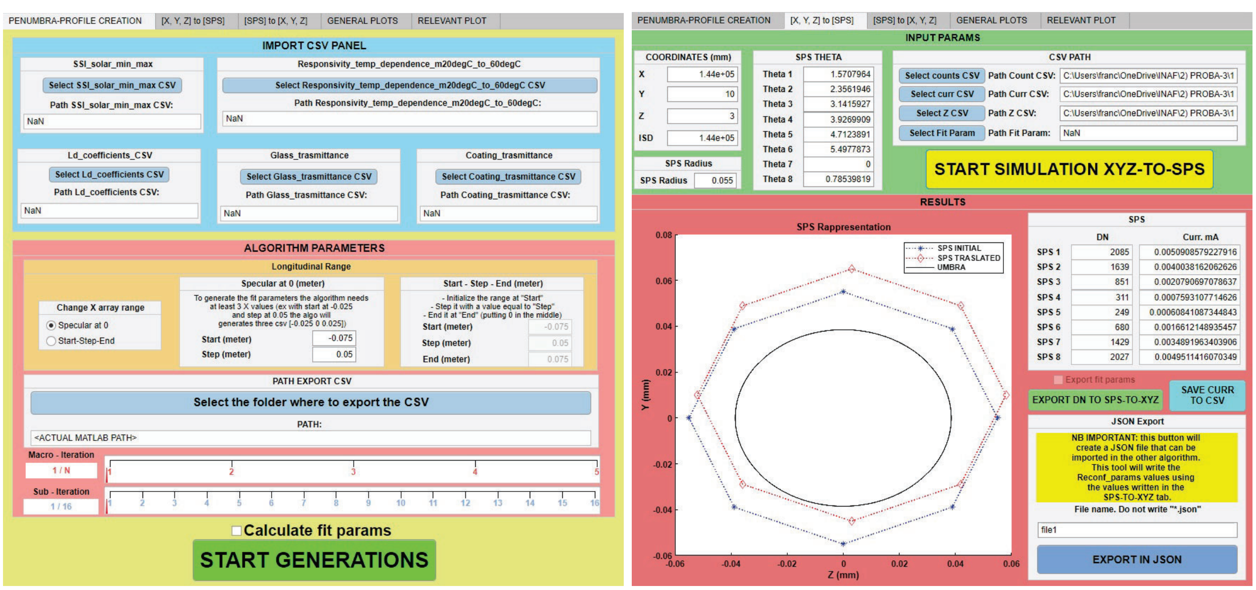
Figure 2. The SPS unit. Left clockwise) 3D CAD rendering of the SPS mechanical flange; the SPS electronics board with the 8 SiPM (front view); the board when inserted into the flange (back view), with the cabling of the output connectors; the assembled SPS. Right) the SPS mounted in front of the ASPIICS telescope during on-ground calibrations (surrounded by the Front Door Assembly).

The flange is designed with a periscope on its upper side where the connectors are mounted [2]. The SPS mechanical flange, the SPS board before and after the insertion into the flange, and the SPS assembled on the ASPIICS telescope (surrounded by the Front Door Assembly) are shown in figure 2.
Opening the telescope front door, as is the case in figure 2 right panel, the SPS is exposed to the penumbra generated by the occulter (figure 1) and a continuous monitoring (at 2Hz) of the solar radiation symmetry around the telescope entrance pupil is performed in closed loop with the on-board control software to provide the Guidance and Navigation Control with the proper correction to any relative (OSC/CSC) and absolute (PROBA-3/Sun) formation misalignment [5]. The SiPMs are grouped in two independent sets, named channel A and channel B, that can be used separately or simultaneously, depending on the operation the mission is carrying out. Note that both the channels can be also used with the front door closed. The channel A is covered with neutral density filters (OD=2) to observe the full Sun for in-flight calibration purposes; the channel B is directly exposed thanks to dedicated holes, visible in the picture 2, to perform both metrology measurements and cross-correlation measurement with channel A under particular illumination conditions (e.g., Sun crescent). More details can be found in [2], [3], and [5].

3. SPS DIGITAL TWIN AND ILLUMINATION TESTBED

3.1 SPS Digital Twin

To support the testing and the calibration of the SPS system, a software tool has been developed to simulate the SPS observations in different formation configurations. This tool considers the synthetic maps of the 2D penumbra profile generated by fitting with a 3th order pseudo-paraboid the expected irradiance distribution on the telescope pupil plane, at different inter-satellite distances (ISD) around the nominal position [3]. From these illumination maps, and knowing the SPS acquisition characteristics, it returns the power flux expected on each SiPM (illumination simulator) and the corresponding readouts for any formation alignment specified by the user in the software GUI. The simulation tool is integrated in an end-to-end code that incorporates the metrology algorithm [4], as well. This permits to simulate the full measurement chain in order to verify the capability of the metrology loop to return the same input position with the associated error (measurement accuracy). In particular, it represents an effective way to test the performances and the robustness of the acquisition procedure and data processing by checking how the estimated error on the [x,y,z] position coordinates (formation alignment), calculated by the algorithm, changes while varying the penumbra fitting parameters [3].
All the modules of this code have been written in Matlab language. In figure 3, the main user interfaces to command the e2e simulation are shown. A clear and detailed description of the software architecture, of the functionalities, and of the outputs is given in [6].



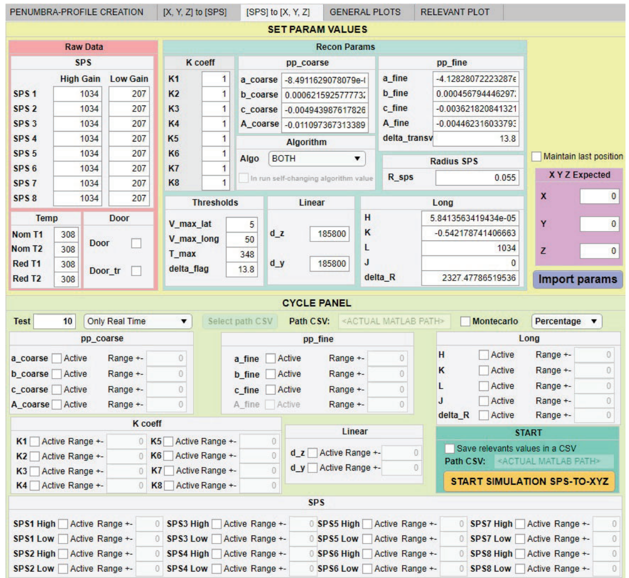


Figure 3. Main control interfaces of the SPS e2e simulator.

3.2 SPS Illumination TestBed

3.2.1 Light sources and mechanical interface

The outputs of the illumination simulator are used to drive the light intensity emitted by a suite of 12 Light Emitting Diodes (LED), grouped in 4 sets of 3 LEDs each. The 4 sets are named "Illumination LED System" (ILS) and the LEDs of each set, having different radiances, are used in combination to cover the huge dynamic range of the solar radiation, from dark umbra to full Sun. The light emitted by each source is injected in a waveguide and the three weaveguides from each ILS are joined in a single fiber that can interface with a supporting flange, named "counter-flange", being aligned in front of the SPS to properly illuminate the eight SiPMs, one channel at a time. A description of the LED system and of a preliminary testbed setup is presented in [7]. Recently, we reviewed the design of the mechanical counter-flange in order to use some collimators, where attaching the fiber output SMA connectors, to relax the alignment requirements. Each collimator can be directly screwed on the flange, as shown in figure 4, left panel.

Figure 4. The illumination testbed. Left) The counter-flange adapted to screw the output collimators. Center) The 12 LED units with the optical guides plugged in. Right) Final setup with 4 collimators mounted on the counter-flange and illuminating the SPS channel B, during the SPS calibration campaign.

The central panel of figure 4 shows the LED suite with the optical guides plugged in. The collimators with the optical fibres attached, screwed on the counter-flange and illuminating the SPS channel B across the holes on the telescope front door, are shown in figure 4, right panel.

3.2.2 Light source control software

The power emitted by each LED is set using a second software tool (LabView) that permits to regulate the input value to the digital-to-analog converter (DAC) in the LED controller, on the base of the corresponding illumination conditions required on the SPS. This process is divided in three main steps:

a. Load the table with the irradiance distribution expected on the plane around the coronagraph entrance pupil [in nW], at the selected ISD (default: nominal);

b. Load the calibration curve of each LED (see §4) to automatically set the DAC level;

c. Drive the emitting LED sources to recreate the same illumination conditions as expected in flight.

The software is made of different modules, each performing one of the steps listed above. In the following, we describe each module separately to make the information flow clear.
Making reference to the GUI presented in figure 5, in the boxes **(a)**, at first, the user can input the (xyz) coordinates of the center of the SPS reference frame (the center of the ASPIICS entrance pupil) with respect to the center of the penumbra. This permits to simulate any decentered position of the CSC along the three reference axes in the OCS/Sun absolute frame. Note that in the ASPIICS convention, the x-axis is along the line of sight, the y-axis is orthogonal to plane on which the telescope is mounted, and the z-axis forms a right-handed triad.

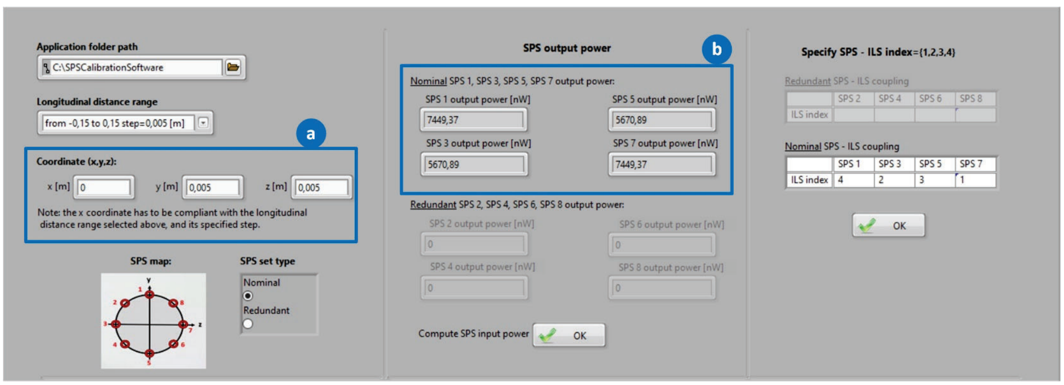


Figure 5. GUI of the module to estimate the input power on the SPS for an user-set formation alignment configuration.

By using the tables with the expected irradiance distribution, in the boxes **(b)**, the module returns the corresponding input power expected on each SPS for the selected position (case for the channel A). These values are automatically loaded by a second module where the best combination of DAC levels (DN) for the 3 LED of each ILS, is calculated in order to have the required output flux. Figure 6 shows the GUI of this second module.
In **(c)**, the SPS power values returned by the first module are shown with the tolerance (set by the user) applicable to calculation. Clicking on the OK button, the calculation starts and the best solution is given in **(d)** and it can now be used to drive the LEDs.
At this point, the user can open a third module, the GUI is presented in figure 7, where it is possible to select the ILS being used **(1)** and to establish the ILS controller USB connection with the user PC, by specifying the corresponding PC COM port assigned to the USB plug **(2)**. The connection is confirmed by clicking on **(6)**. For each setting, a pop-up with a confirmation message appears in order to have full control of the procedure.
Once the ILS controller - PC connection is established, three numeric controls **(4)** are enabled. The user can input the DAC level for the 3 LED of each ILS, obtained from the previous calculation. The ILS Arduino-like controller is a 12 bits unit so the values can range from 0 to 4095 DN. The three LED chassis are labeled based on the light intensity produced under the same input voltage. In descending order: LED1 (high power), LED2 (medium power), LED3 (low power).
At this point, a string, containing the input information, reported in the box **(8)**, is sent to the ILS controller (Send DAC levels) **(5)**. In this case too, a pop-up window appears confirming that the data has been successfully sent to the ILS controller or to inform about any communication error.

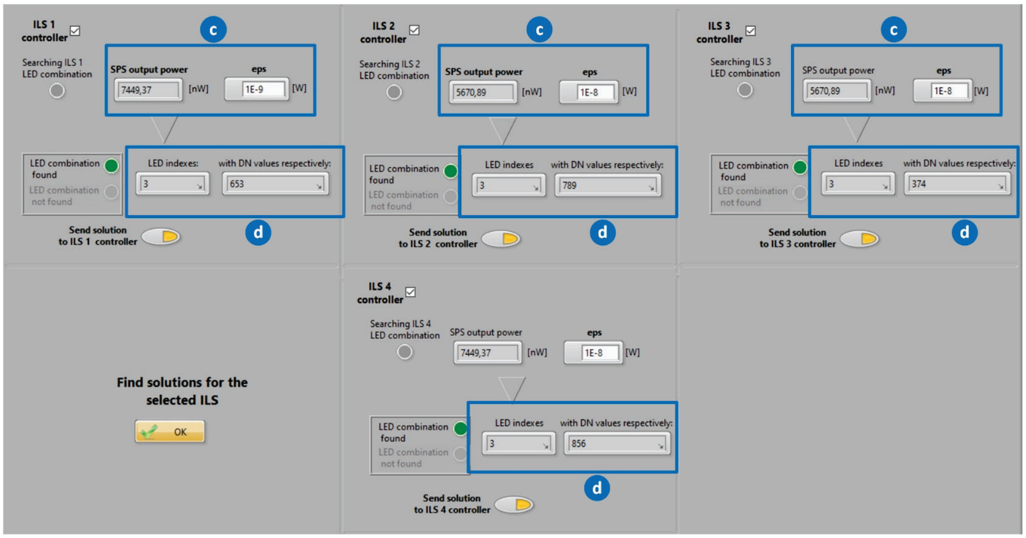


Figure 6. GUI of the module that calculates the best combination of the LED DAC levels to obtain the expected output power.

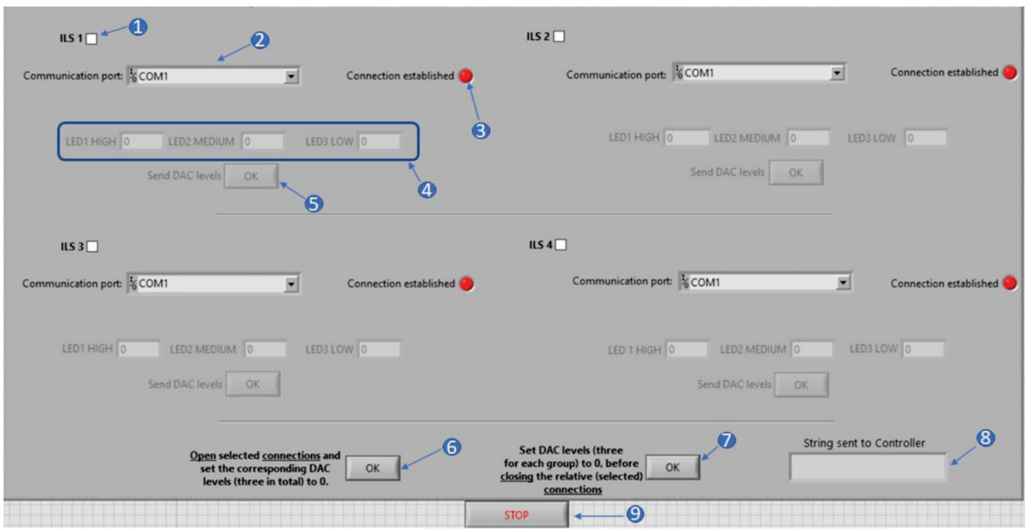


Figure 7. GUI to command the ILS LEDs.

When the illumination configuration setup is completed, the procedure can be finalized **(7)**. The LEDs automatically arrange the output power to properly feed the SPS with the expected light flux.
The user interfaces described above are, indeed, different windows of the same running algorithm. Some inputs can be given once, at the beginning of the test, so that the procedure can be simplified and automatized: having positioned the 4 ILSs in front of the SPS, and set a formation alignment configuration, the algorithm can be launched to command to emission of the LEDs.

4. LED CALIBRATION PROCEDURE

The correct tuning of each LED is based on a proper calibration of the source in order to reconstruct the right correspondence between the DAC settings and the emitted light power. This has been one of the most demanding activity done to realize the illumination testbed and it required several tests to check and confirm the calibration curve of each source. The calibration consisted in measuring the emitted power of all the 12 LEDs by varying the DAC setting range from 100 to 4000 DN at a fixed step (e.g, 50 DN) and obtaining the best fitting profile of the measurements distribution.

Note that even if the full range for the LED control is 0-4095, the lowermost and uppermost levels, where the LEDs are approaching flux nulling and saturation, have been discarded to have a more uniform distribution.
The power measurement was done using a calibrated photodiode, connected to a calibrated Keithley picoammeter, positioned and aligned at a fixed distance in front of the collimator with the fiber from each ILS plugged on, as shown in figure 8.

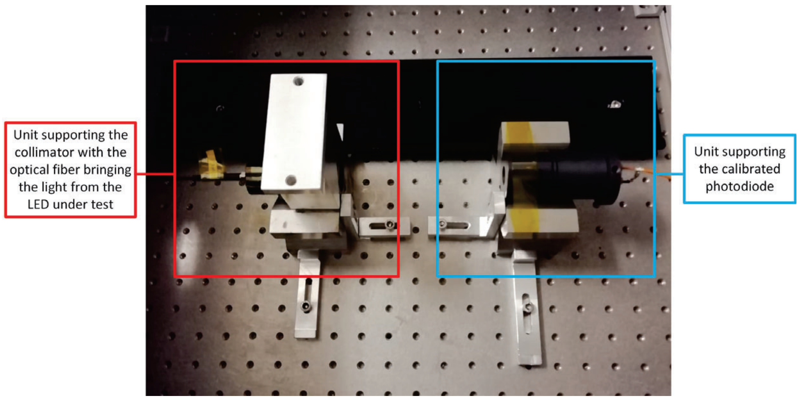


Figure 8. Setup for the calibration of the LEDs.

The units supporting the collimator and the calibrated photodiode were positioned into a black box that remained closed during all the test to prevent against any light pollution. The black box was opened only to change the collimator corresponding to a new source (one collimator for one ILS ⇒ 3 LEDs). Once closed the box, the calibrated photodiode started to continuously monitor the power emitted by each LED, one at a time, while changing the input DAC level. The procedure was repeated for all the sources, taking into account that for each LED a stabilization time was necessary between two subsequent settings, especially when the LED behaviour was investigated with large variation of the input DN.
In this case too, a dedicated software module has been developed to automatically and dynamically control the DAC level of the 3 LEDs of each ILS. With reference to the GUI shown in figure 9, the user can select the ILS being used and the PC COM port assigned to the USB LED plug (**1**, **2**). A section is dedicated to the preliminary stabilization of the LED at the beginning of the test (**3**, **4**, **5**) where the user can input the desired stabilization time and the acquisition time to monitor the stabilization.

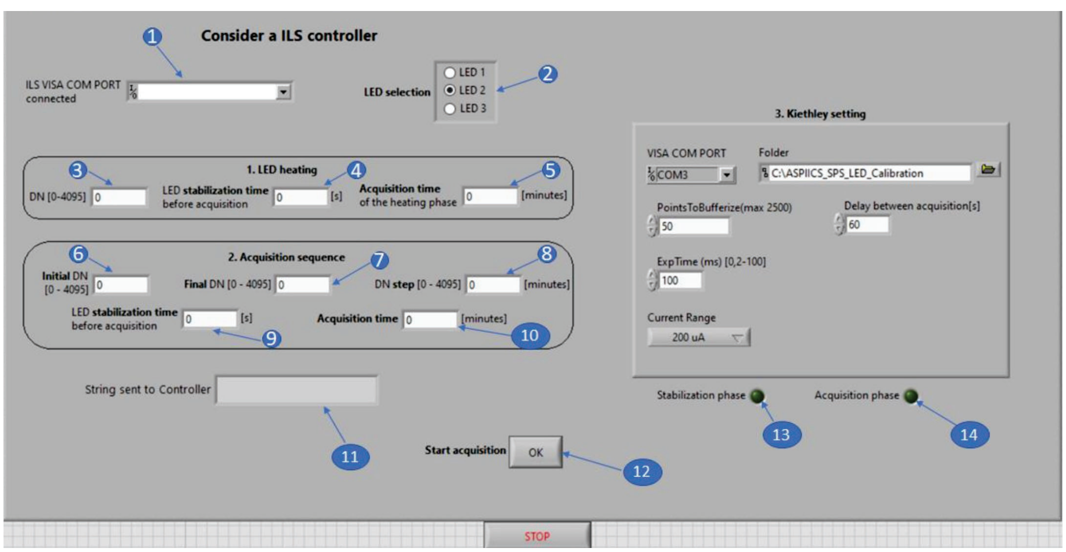


Figure 9. GUI to perform dynamic setting of the the ILS LEDs.

The dynamic acquisition sequence is then selected by giving in input the DN values corresponding to the starting

and to the final DAC levels, the step (**6**, **7**, **8**), the stabilization time for each level (**9**) and the acquisition duration (**10**). The string with the input parameters is confirmed in (**11**) and the acquisition is finally enabled (**12**).
A section is included to set the acquisition parameters of the Keithley picoammeter and the folder where saving the output file with the photodiode readouts (the right part of the GUI in figure 9). The output data are currents (A) that are converted in input power (W) knowing the responsivity of the photodiode.
Once completed the calibration tests, the resulting output power distribution of each LED has been fitted with a 2d order polynomial and the fitting profiles have been uploaded in the simulation tool used to illuminate the SPS. A representative calibration profile for the 3 LEDs of the ILS4 is shown in figure 10.

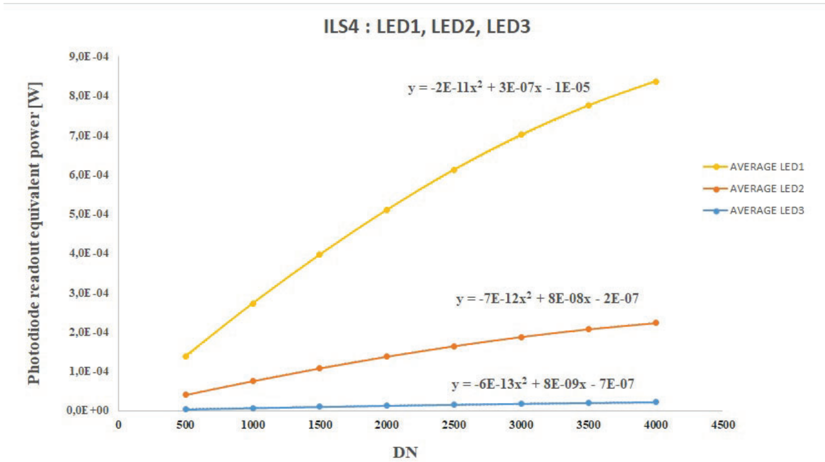


Figure 10. Typical calibration curve of the LED sources.

As a final remark, it must be noted that even if the used LED sources are monochromatic at 632nm, with a FWHM=5nm, this does not represent a critical limitation to reproduce the operation conditions of the SPS because each SiPM has been assembled with a bandpadss filter [500-660]nm glued to the front window of the SiPM cap [2], as shown in figure 11. This was required to limit the variation of the SPS responsivity with respect to environment temperature: the selected waveband was demonstrated to be that where the solution accuracy of the metrology algorithm (measurement error) shows the lower variation with the temperature.

Figure 11. SPS bandpass filter (center) glued on the front window of the SiPM cap (right).

5. CONCLUSIONS

The ASPIICS coronagraphic telescope being flown on the PROBA-3 ESA formation flying mission is now being finally assembled on the platform with all the sub-systems tested and calibrated. Between these, the SPS - Shadow Position Sensors, one of the most accurate metrology sub-systems aimed at realizing and maintaining the correct alignment of the formation, has successfully completed the calibration test campaign in 2021. In this paper, we quickly review the SPS metrology system and we discuss the SPS simulator (Digital Twin), including the metrology algorithm, and the Illumination Testbed designed and developed at INAF, the Italian National Institute of Astrophysics, to reproduce in laboratory the same expected conditions the SPS will experience in flight. In particular, we show how the use of the Illumination Testbed in combination with the SPS Digital Twin is a powerful tool that effectively supported the SPS calibration.

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