

UV light induced photodegradation of Silicon CCD and its impact on Sentinel-5 instrument calibration

T. Bartusch*, A. Sell, G. Hechenblaikner, T. Memminger, M. Haiml
Airbus Defence and Space GmbH, 82024 Taufkirchen, Germany

ABSTRACT

Unprotected silicon detectors can experience degradation when exposed to deep-UV (DUV) radiation. High-energy photons provide sufficient energy to break chemical bonds in coatings and the silicon detector surface, potentially resulting in a reduction of quantum efficiency (QE). Space-based environmental monitoring of trace gases relies on imaging spectrometers operating in the deep-UV. The UV-VIS channel of the Sentinel-5 instrument covers the 270 nm – 500 nm spectral range and is therefore continuously exposed to DUV radiation, making the assessment of its sensitivity and vulnerability to UV light essential. We performed a parameterized test series on a Sentinel-5 CCD sensor, exposing multiple spots on the sensor surface to light of different wavelengths and fluences using both continuous-wave (cw) and pulsed modes with LEDs and lasers. Induced damage and recovery times were quantified via changes in QE, and the degradation impact was probed across the deep-UV, UV, and VIS spectral ranges. The results reveal that photo-degradation is proportional to the accumulated photon count (fluence) and independent of intensity or pulse duration within the tested parameter space. A QE reduction of a few percent was observed exclusively in the deep-UV region (below 300 nm), and the induced damage only affects the QE within this specific spectral range. Furthermore, a fraction of the damage recovers within a few days at room temperature. Our analysis shows that the expected lifetime UV radiation dose for the UV-VIS CCD is lower than the threshold required to impact the Sentinel-5 spectral calibration or instrument sensitivity (SNR).

Keywords: CCD, UV, QE, degradation, light induced damage, Sentinel-5

1. INTRODUCTION

The Sentinel-5 instrument [1, 2] is an environmental monitoring imaging spectrometer on board of MetOp-SG Satellite A. The first one (PFM) was launched in August 2025 as part of the EU Copernicus program, whereas 2 more instruments (FM2 and FM3) are currently assembled, tested and calibrated. Sentinel-5's primary objective is to quantify trace gases of environmental importance globally on earth with daily revisit time. The spectrometer consists of 5 sensors, three silicon CCD arrays [3] for the UV, VIS and NIR spectral range and two HgCdTe (MCT) infrared sensors for the SWIR spectral range. Some important trace gases have their specific spectral fingerprint in the UV. Among those are for instance ozone (O_3) detected in the deep UV (270nm-300nm), sulphur dioxide (SO_2) (300nm-320nm), formaldehyde (HCHO) and nitrogen dioxide (NO_2) (320nm-370nm). On the other end of the Sentinel-5 instrument spectrum are carbon monoxide (CO) and methane (CH_4) resolve in the SWIR1 band (1590nm-1675nm) and SWIR3 band (2305nm-2385nm).

Silicon sensors are prone to degrade when exposed to ultraviolet radiation [4, 5]. UV light, especially with wavelengths below 300nm (photon energy above 4 eV) is able to excite valence electrons of chemical bonds in semiconductors and dielectrics which may even break them, generating tangling bonds, moving atoms to interstitial positions or generating color centers in oxides. Several improvements in passivation and protective treatments have been implemented to make silicon sensors more resilient against UV radiation [6-9].

Any instrument needs to be calibrated on ground before launched to orbit. Calibration of spectral characteristics of Sentinel-5 is based on a narrow linewidth tunable cw-laser. However, those laser systems are very complex and need significant maintenance. Therefore, options of tunable pulse laser systems with 1-10 kHz repetition rate with nanosecond pulse durations are considered as well. In contrast to cw laser beams, pulsed laser beams with the same average power exhibit orders of magnitude higher peak power. Pulsed laser irradiation might potentially worsen the damage behavior of solid-state sample, like CCDs. The test series presented in this paper was initiated to check and validate the use of tunable pulsed laser systems for Sentinel-5 calibration purposes. The test philosophy was to illuminate small spots of the CCD with various test parameters and check the change of QE afterwards. Important to note, the test method was not designed to measure absolute QE precisely but to detect changes as small as 0.01%, measured by the local degradation in the

illuminated spot compared (normalized) to the photo-responsivity in the unilluminated vicinity of the damage spot. Parameter space consisted of variable wavelengths for the illumination, variable wavelengths for probing changes of (spectrally resolved) QE, pulse energy, illumination duration, and comparison between pulsed and continuous (cw) illumination. The following section describes the test setup, followed by a comprise description of the test results.

2. TEST SETUP

All steps of the test were performed on an ISO5 clean workbench to reduce the presence of particles during handling. Before the campaign was started an initial characterization of the presence of dust particles on the surface was done. After ending the campaign, the same measurement was done.

The radiation test was performed in different parts. As baseline, the initial characterization was done with an integrating sphere to measure the response of the complete non-damaged detector. The setup was a measurement with three different fiber coupled LEDs (280nm, 340nm and 530nm) which are fed into the integrating sphere with an UV fiber and a 2" port for the illumination. The used LEDs are shown in Figure 2-3. The useage of three different wavelength covers a wide part of the spectrum. Other advantages are that the change of the wavelength is quick, the alignment itself is not modified during the change and the complete setup can stay in a dark compartment to reduce the stray light. Figure 2-1 shows the principle and Figure 2-2 shows the real setup apart from the shielding compartment. The readout of the Detector was done with the usual EGSE.

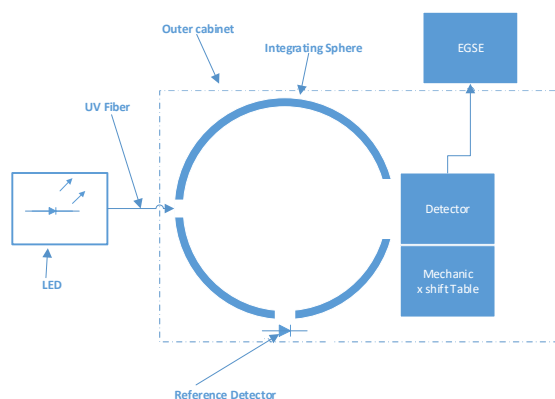


Figure 2-1, Principle of homogeneous illumination

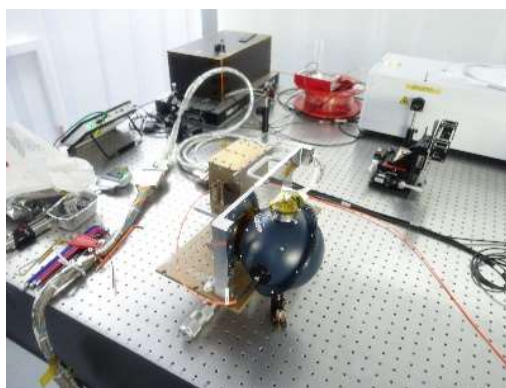


Figure 2-2, Detector with integrating sphere without shielding cabinet



Figure 2-3, Fiber coupled LEDs

For the reference measurement, a calibrated and thermal controlled photo diode was used (Hamamatsu S2592-03). The operation of the LEDs was performed via a commercial constant current source.

After taking the initial measurement, the first series of radiation damage was performed. The principle is shown in Figure 2-4. The laser was passed through a fixed attenuator, the pinhole and a stray light shield. The power of the Laser was brought into minimum condition to have half well for the alignment for avoidance of damage and the spot then was brought to specific locations of the detector. After finishing this step from the series, the spot was moved into the next position which was safely away from the old spot to avoid overlap. The reduction of stray light was also a big point on this setup. So, the complete setup was set into a compartment and on the position of the quadratic (0.5mm x0.5mm) pinhole was an additional shield for the remaining light from the Ekspla NT-242 nanosecond pulsed laser system with a repetition rate of 1 kHz. The real setup without parts from the shielding is found in Figure 2-5 and with complete shielding in Figure 2-6.

The movement of the Detector assembly to deliver the light to the desired position was done by a linear stage with multiple 3mm shims for height adjustment and the pinhole for the beam limitation was adjusted by a 3D translation device. This setup was necessary because the laser was used without a fiber to avoid degradation during the test campaign. So, the setup had to be matched to the free air laser output. The laser was equipped with a motor driven variable attenuation (Rochon-Prism) stage so the power could be adjusted in a big range. Nevertheless, the attenuation factor was not sufficient enough and additional fixed filters were brought into the beam (OD 1 to OD 3). The process of the damaging series was performed in the following way that half well at the wavelength was settled and a local characterization was done with half well (off/on/off/on/off) and then the calculated power was brought to the spot and the power was applied to the position. After finishing, a post-characterization was done in the same way as done in the pre-characterization. The power was measured with a Thorlabs Power meter which could be flipped into the spot after the pinhole and then was able to measure the power of the beam directly.

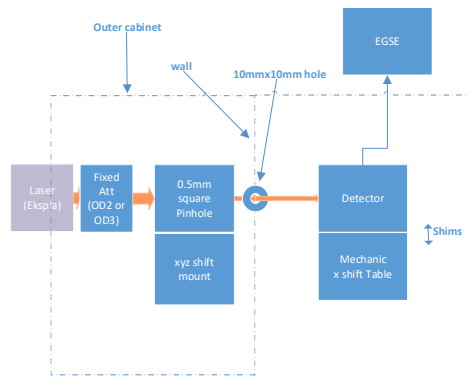


Figure 2-4, Principle of the laser introduced radiation damage



Figure 2-5, setup with view to the detector and removed parts from the shielding

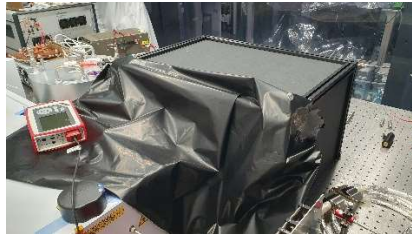


Figure 2-6, setup with complete shielding

After a line of spots was finished, shims were used to modify the height and proceed with a new line to strictly avoid overlap.

In addition, after a series of damage was finished, an intermediate measurement with the integrating sphere was done. This is shown in Figure 2-7

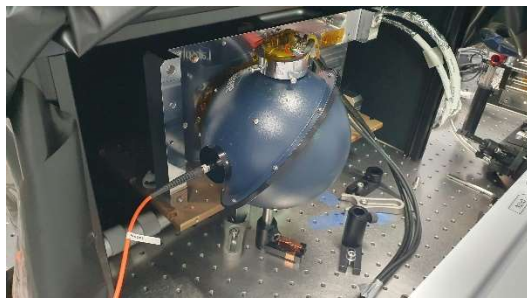


Figure 2-7, Picture of the integrating sphere with a view to the linear translation stage

The next test series was the use of damaging power from the CW LEDs. The principle of operation is shown in Figure 2-8.

The advantage of the setup was that the power provided from the LEDs could be fed in by the fiber so a free placement of the spot on the Detector was possible. This helped saving space to the laser depending measurements which are only addressable by the linear stage and the shims. The process was as following. The location of the spot was selected. The power set to half well (measured by the power meter and the EGSE readout), then the local pre-characterization, followed by the radiation itself and closed by a post-characterization. After finishing, an integrating sphere measurement was done again. The real setup is found in Figure 2-9 which also shows the switchable power sensor.

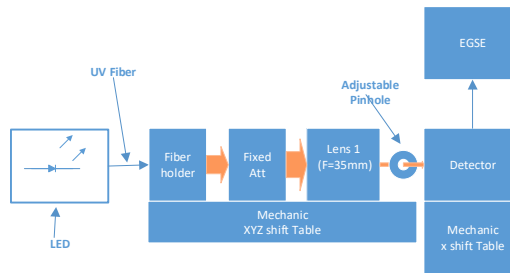


Figure 2-8, Principle of the LED CW damage test

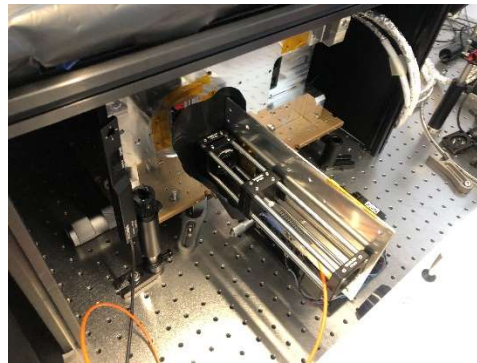


Figure 2-9, Setup with the optics on a 3D translation stage

The tests were done with different wavelength in all configurations to get a better look over the damage mechanism.

After finishing the damage test campaign. A full spectrum characterization was done with a MSH300 double monochromator and the integrating sphere and the principle is shown in Figure 2-10.

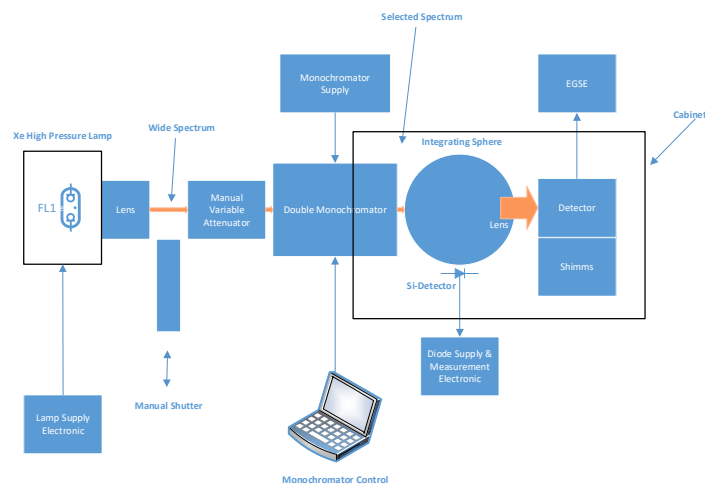


Figure 2-10, Block diagram of the setup with the double monochromator

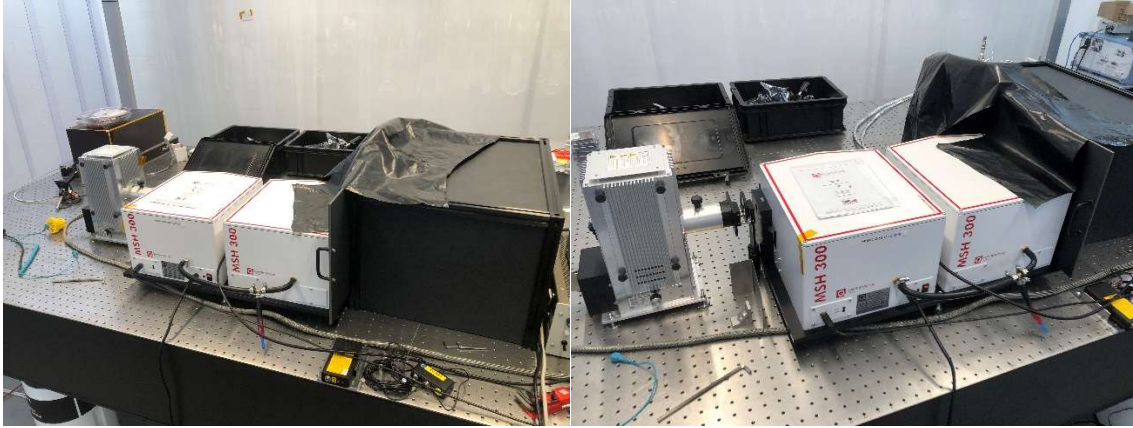


Figure 2-11, Pictures from the double monochromator and the light source with shutter and variable attenuator

The characterization was performed in the range of 280 nm to 520 nm in steps of 10 nm by feeding the light into the sphere and adjusting the level as good as possible to the previously used levels (slightly above half well) to stay in the linear range of the Detector. Especially on the lower wavelength close to 270 nm this was not possible because the provided spectrum of the lamp. The lamp was a Xenon High pressure lamp. It was also possible to feed the light direct into the integrating sphere to reduce losses and degradation during the test campaign. The practical setup is shown in Figure 2-11.

3. RESULTS

The damage test sequence was grouped as summarized in Table 3.1: The first two series have been focused on pulsed 270nm laser spots, one versus power (up to 3000x full well saturation), the second versus duration (up to 1000s). Further test series addressed increasing damage wavelengths from 300nm to 500nm. Pulsed irradiation has been compared to continuous wave (cw) illumination by LEDs at 280nm and 340nm. One long time test has been performed with 68h cw illumination with low power.

Table 3-1. Test sequence grouping.

#	mode	WL	Sat.	Duration
1	pulsed	270	1x – 3000x	100 s
2	pulsed	270	100x & 1000x	1 s – 1000 s
7	pulsed	300	100x – 3000x	100 s
6	pulsed	340	100x – 3000x	100 s
8	pulsed	400	100x – 3000x	100 s
9	pulsed	450	100x – 3000x	100 s
5	pulsed	500	10x – 3000x	100 s
3	cw	280	1x – 3000x	100 s
4	cw	280	1x	68 h
10-12	cw	340	100x – 3000x	100 s

Each illumination parameter configuration was applied to a separate spot on the CCD with known coordinates. This allows to probe all spots at the same time with flat field illumination from the integrating sphere at 280nm, 340nm and 530nm, and to evaluate recovery times from repeated probe measurements. The position of the spots have been recorded with attenuated power levels and the position of each group on the CCD is shown in Figure 3-1.

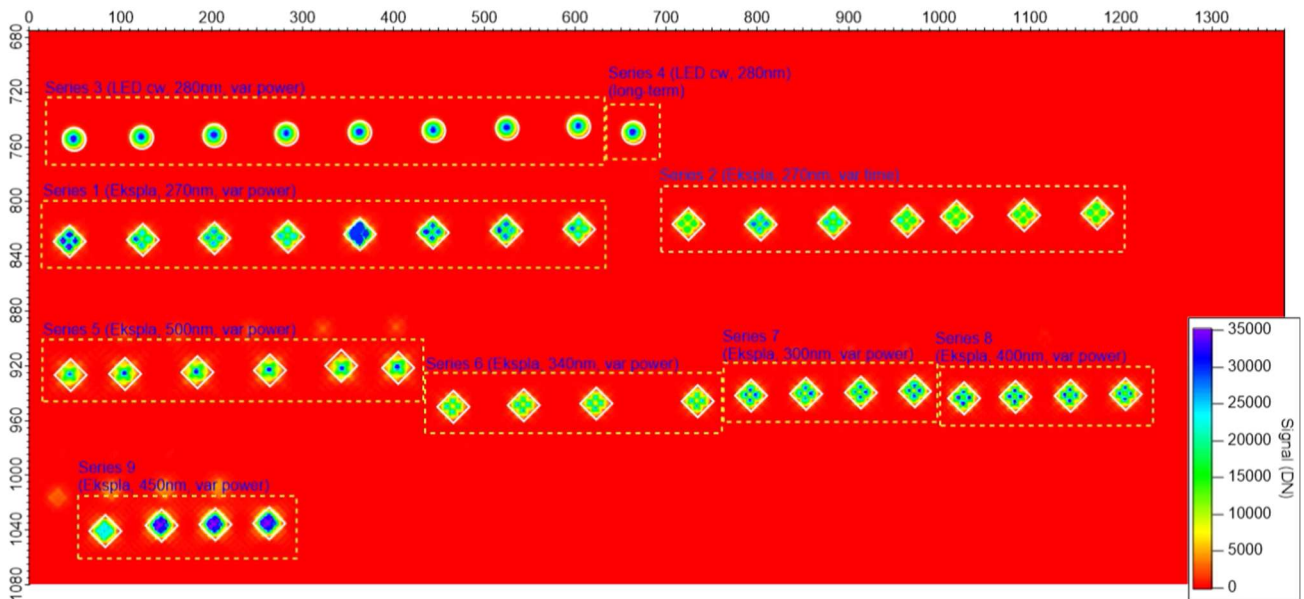


Figure 3-1, Location and size of the laser / LED spots on the CCD. Coordinates are pixel number.

The spots from the pulsed laser source are generated by a $500\mu\text{m} \times 500\mu\text{m}$ shadow mask, rotated by 45° relative to the CCD edge. The diffraction pattern on the sensor is shown in Figure 3-2. The distance of the pinhole to the sensor was chosen to generate a pattern with 4 peaks which makes alignment of the pinhole to the center of the laser beam more convenient and to check on spatial effects of light induced degradation. The distance pinhole to sensor was kept constant which resulted in different diffraction pattern for different wavelengths, see Figure 3-3. Continuous wave illumination was generated by single mode fiber coupled LEDs. Due to lower available power of LEDs compared to the laser, the fiber output was directly projected to the CCD surface without a square pinhole. The spot was Gaussian shaped in this case.

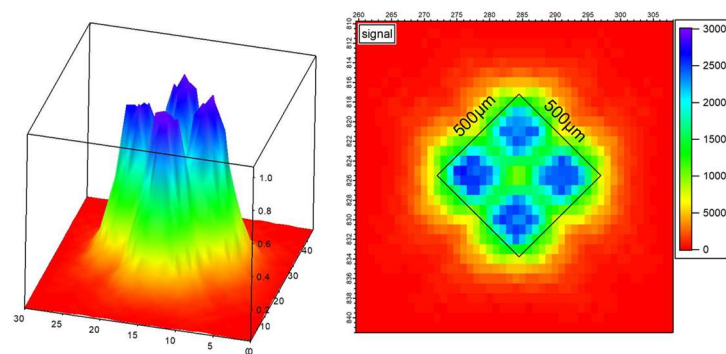


Figure 3-2, Diffraction pattern of pinhole at the CCD sensor surface for 270nm.

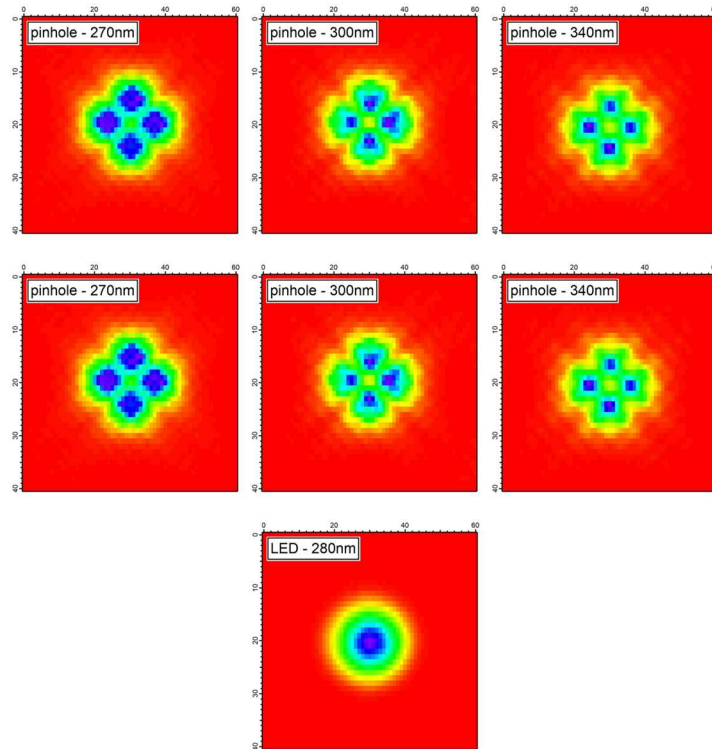


Figure 3-3, Diffraction pattern of pinhole for various laser wavelengths and the direct focused LED spot in comparison.

The first two test sequences applied 270nm pulsed laser illumination, one with variable power and 100s fixed duration, the other with variable duration and fixed power levels. The test sequence for variable power is shown in Figure 3-4: The pristine area of the detector is flat field illuminated with an integrating sphere sourced with 3 chopped LEDs at 280nm, 340nm, and 530nm. Subsequently, the sensor is spot illuminated with the pulse Ekspla laser tuned to 270nm. The spot size on the detector is about 10 to 20 pixels FWHM. Before applying the damage power for 100s, an image of the laser spot with 50% full well signal is recorded to pin-point position and shape of the spot. Each power level is applied to a new spot, 2-3 mm displaced from the previous one. After the first 4 doses (1x, 3x, 10x, 30x) a intermediate LED flat field reference is taken, before continuing with the next 4 doses (100x, 300x, 1000x, 3000x), followed by a final LED flat field reference.

The change in QE is extracted from the normalized ratio of the final LED reference to the initial LED reference.

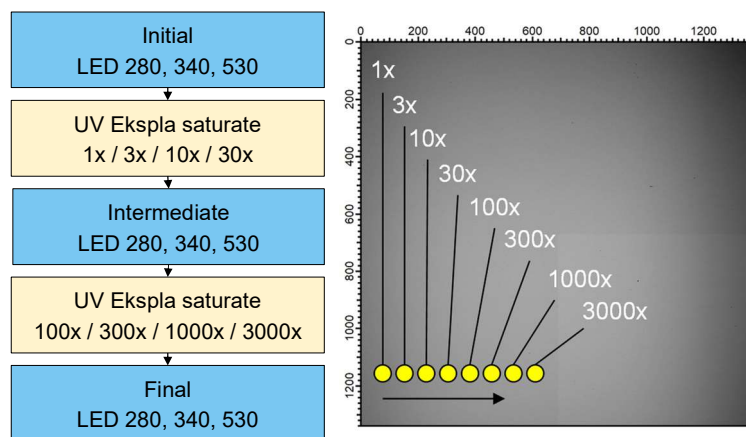


Figure 3-4, Test sequence for variable power.

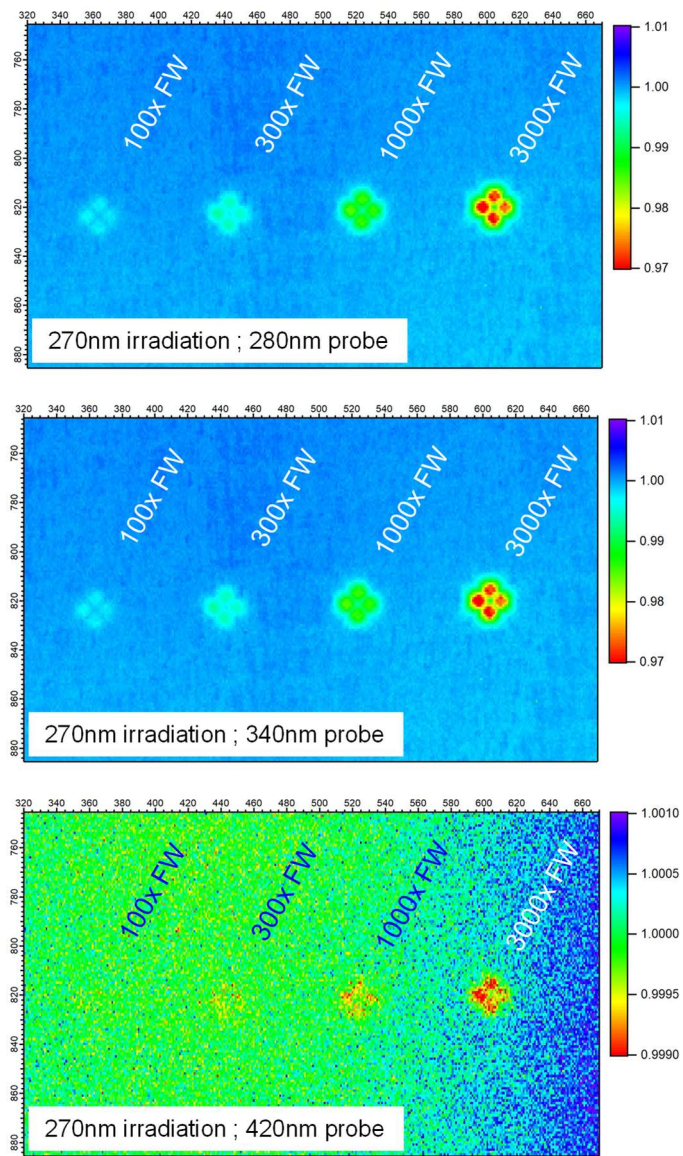


Figure 3-5, spot damage illumination at pulsed 270nm, flat field probe at cw 280nm, 340nm, and 530nm.

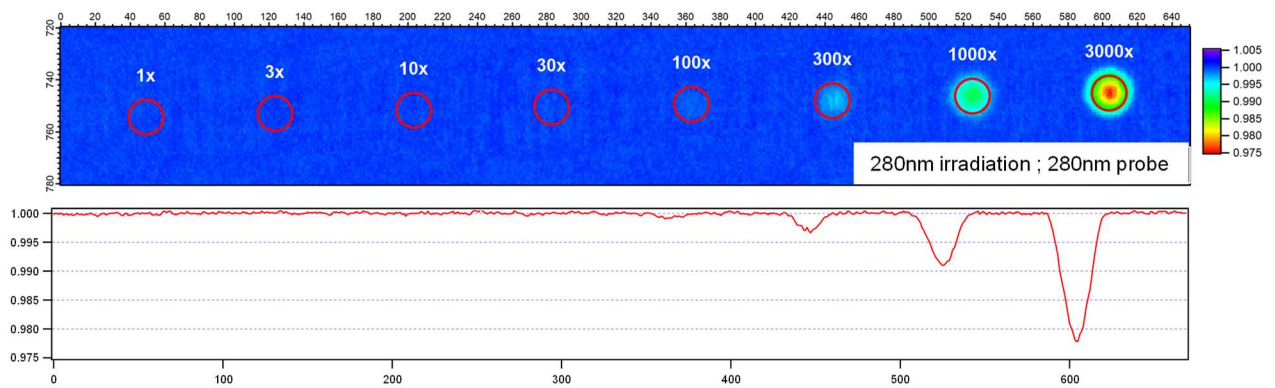


Figure 3-6, spot damage illumination at cw 280nm, flat field probe at cw 280nm.

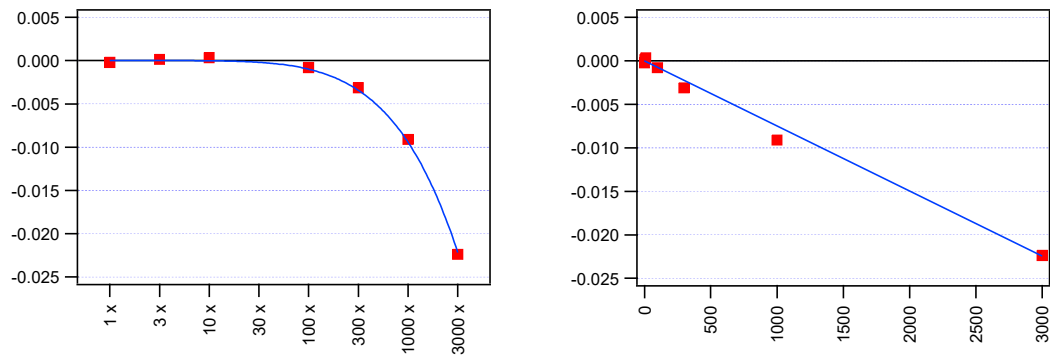


Figure 3-7, QE photo degradation versus power level.

From the first test series several observations can be summarized: Severe over saturation (100x or more) is required to generate within 100s measurable impact on the QE. Therefore, many sub-sequent test series started at higher power levels like 100x FW, see Table 3-1.

Furthermore, UV photo-induced damage changes QE in the UV (below 300nm) only and has negligible impact on the visible QE. There is no difference between nanosecond pulsed and cw illumination, which was unexpected. The induced degradation is linear with the applied fluence, i.e. the product of duration times power. The last observation has been substantiated by a test at just saturation for 68h.

In the following increasing illumination wavelengths have been tested, confirming that the sensitivity of the CCD to UV is mainly limited to deep UV (below 300nm) and visible light even at severe over illumination is no threat for the CCD.

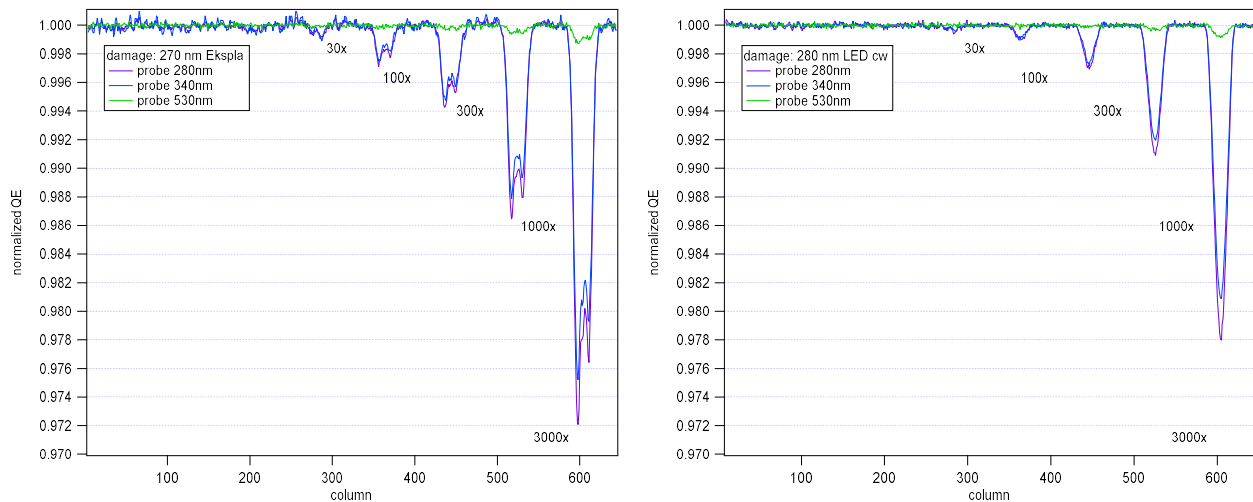


Figure 3-8, QE photo degradation for 270nm pulsed (left) and 280nm cw (right) illumination.

Comparison between short term (Figure 3-8) and long term (Figure 3-9) illumination: A QE decrease of 2.2% was observed for 3000x FW and 100s, resulting in -0.0264% per FW*hour. A QE decrease of 1.8% was observed for 1x FW and 68h, resulting in -0.0265% per FW*hour. Therefore, we expect that even very low light levels of deep UV applied over years will induce a QE degradation proportional to the total integrated fluence. Note however, that a small fraction of the degradation seems to recover over several week, but not all.

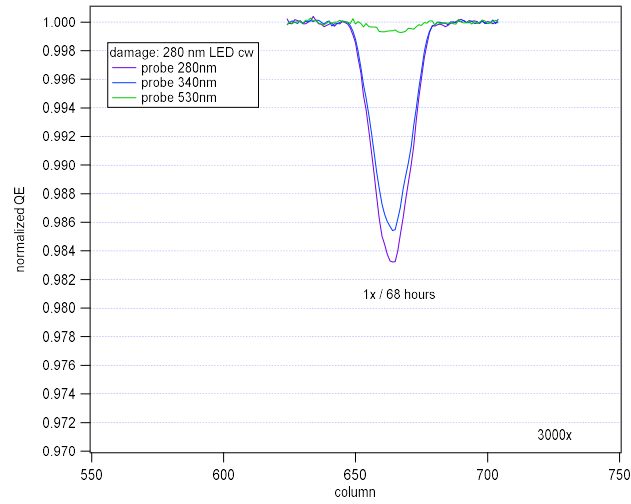


Figure 3-9, QE photo degradation for 280nm cw long term illumination.

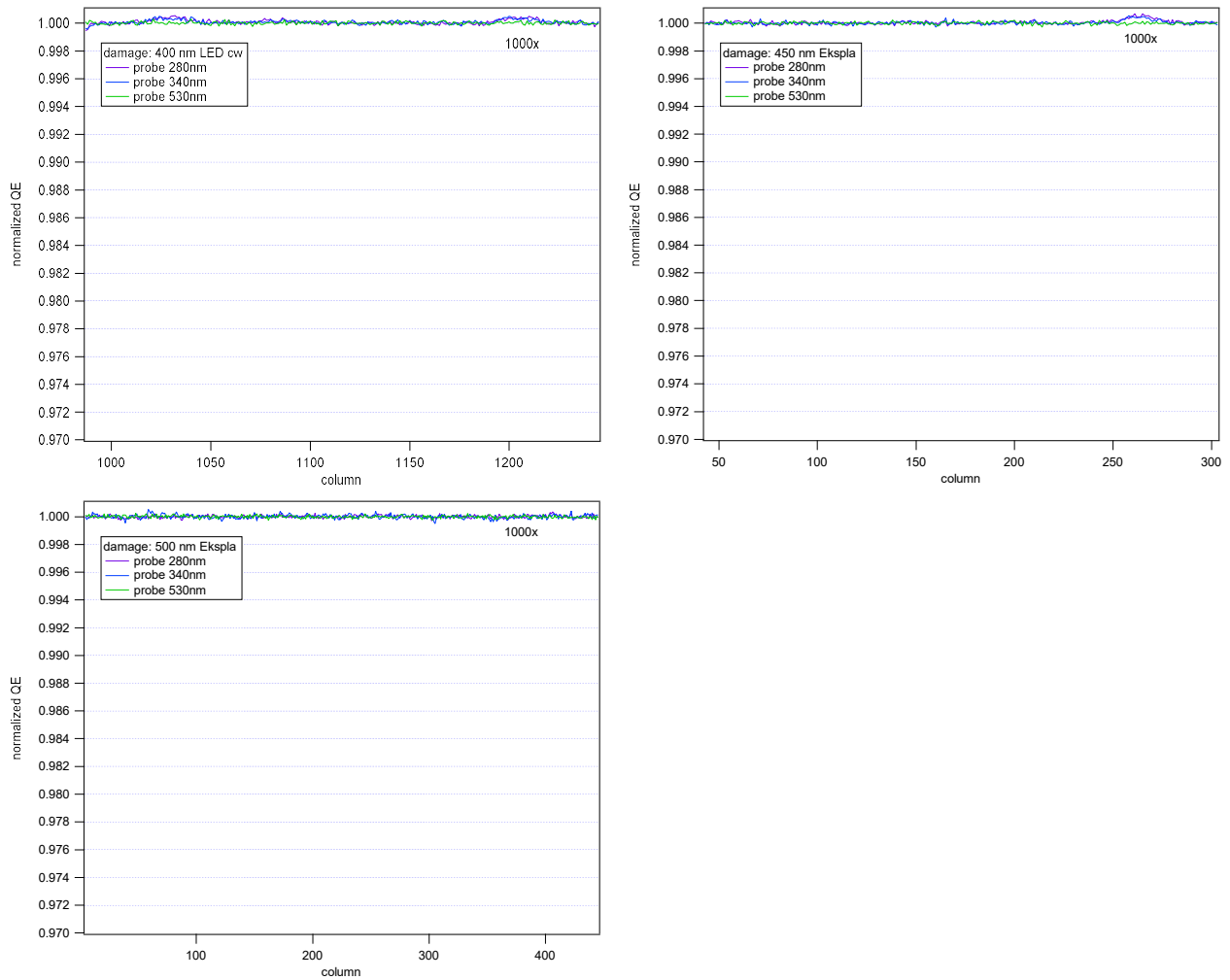


Figure 3-10, QE photo degradation for nanosecond pulsed illumination in the visible spectral range.

Barely detectable photo-degradation by visible light (below 0.01%) has been observed.

4. CONCLUSION

Degradation of the CCD photosensitivity has been observed. This effect is significant for short wavelengths, mainly below 350nm. A QE degradation by 2% has been observed upon illumination with 270 nm with a dose of 500 nJ per pixel ($7e+11$ ph/pixel). Whereas only a few 0.01% QE change has been observed for the same fluence when illuminated at 400 nm.

When damage is induced, at whatever wavelength, the change of QE is dominant in deep UV (280nm), still high in near UV (340nm) and barely detectable in VIS (400nm, 450nm, 500nm, 530nm). This is a strong indication, that the observed photo-degradation in the UV is related to the high energy of UV photons able to break chemical bonds.

The effect is linear with the total dose (fluence), independent on pulse duration (5 ns and above, incl. cw), average intensity (3000x full well per second) power, and illumination duration (up to 1000 sec).

About 1/3 of the degradation recovers within 1-2 week at room temperature, main part is persistent over several weeks.

Three direct conclusions can be drawn from the results:

Pulsed laser systems can be used for Sentinel-5 on-ground calibration without risk of detector degradation, even for severe over-illumination during straylight kernel generation. Calibration exposure time, especially with high saturation shall be thoroughly planned and limited to necessary amount. Automatic shut-down the laser in case of unintentional “freeze” of the test setup shall be foreseen as protective measure. Due to the very low signal levels in deep-UV the total mission lifetime fluence exposed to the CCD is small enough to avoid impact on calibration and sensitivity of the UV channels.

ACKNOWLEDGEMENTS

The Sentinel-5/UVNS project is funded by European Commission under an ESA contract, as part of the Space Component of the Copernicus Programme.

REFERENCES

- [1] J. Irizar, M. Melf, P. Bartsch, J. Koehler, S. Weiss, R. Greinacher, M. Erdmann, V. Kirschner, A. Perez Albinana, D. Martin, “Sentinel-5/UVNS”, Proc. SPIE 11180, International Conference on Space Optics — ICSO 2018, 1118004 (2019); <https://doi.org/10.1117/12.2535923>
- [2] Jess Köhler, Rik Jansen, Juan Irizar, et al. “Sentinel 5 instrument and UV1 spectrometer subsystem optical design and development”, Proc. SPIE 11852, International Conference on Space Optics — ICSO 2020, 118522M (2021); <https://doi.org/10.1117/12.2599430>
- [3] J. R. Janesick, “Scientific Charge-Coupled Devices”, SPIE Press, Bellingham (2001), ISBN: 9780819480392, <https://doi.org/10.1117/3.374903>.
- [4] F. Li, A. Nathan, and O. Nixon, “Deep-ultraviolet-induced damage of charge coupled device image sensors”, J. Vac. Sci. Technol. A 22, 996 (2004); <https://doi.org/10.1116/1.1689301>
- [5] N. O, J. Huras, S. Kullar, and S. Sahinovic, “248-nm UV Damage Mechanism in MPP CCD's”, Proc. IEEE Workshop on CCDs and Advanced Image Sensors, Paper R06 (2003)
- [6] J. R. Janesick, T. Elliott, D. Janesick, and J. McCarthy, “The ultraviolet flash technology: A method for promoting quantum efficiency stability in back-illuminated charge-coupled devices”, Proc. SPIE 0782, 114 (1987). <https://doi.org/10.1117/12.940656>
- [7] M. E. Hoenk, P. J. Grunthaner, F. J. Grunthaner, R. W. Terhune, M. Fattahi, and H. Tseng, “Growth of a delta-doped silicon layer by molecular beam epitaxy on a charge-coupled device for reflection-limited ultraviolet quantum efficiency”, Appl. Phys. Lett. 61, 1084 (1992); <https://doi.org/10.1063/1.107675>
- [8] M. E. Hoenk, A. D. Jewell, G. Kyne, J. Hennessy, T. Jones, C. Shapiro, N. Bush, S. Nikzad, D. Morris, K. Lawrie, and J. Skottfelt, “Surface Passivation by Quantum Exclusion: On the Quantum Efficiency and Stability of Delta-Doped CCDs and CMOS Image Sensors in Space”, Sensors 23, 9857 (2023); <https://doi.org/10.3390/s23249857>.
- [9] S. Nikzad, M. E. Hoenk, F. Greer, B. Jacquot, S. Monacos, T. J. Jones, and J. Blackburn, “Delta-doped electron-multiplied CCD with absolute quantum efficiency over 50% in the near to far ultraviolet range for single photon counting applications”, Appl. Opt. 51, 365 (2012); <https://doi.org/10.1364/AO.51.000365>