Proton-induced degradation of Charge Transfer Efficiency on FLEX CCD detectors: measurement and impact on instrument performance

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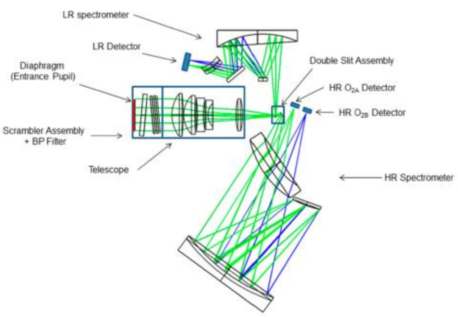
INTRODUCTION

The exposure of Coupled-Charge Devices (CCD) to high-energy particles in space leads to a degradation of their performances. One of the observed mechanisms is the creation of defects in the CCD silicon lattice by displacement damage, inducing a reduction of the Charge Transfer Efficiency (CTE), i.e. the ability of the device to efficiently transfer the photo-induced charge to the read-out output node. Hence a reduction of the imaging quality of the detector. We present here a comparison of the modelled and measured optical quality of the FLEX CCD exposed to a high energy proton flux. The optical quality was directly measured on an irradiated flight representative device. A physical model of the detector, including an accurate modelling of the charge trapping dynamic, is used to generate synthetic scenes affected by CTE degradation from which the optical quality is assessed and compared to the measurement. Eventually the correlation of the model and the measurement will allow to accurately assess the performances of a detector exposed to space radiation environment.

THE FLEX INSTRUMENT

The Fluorescence Imaging Spectrometer (FLORIS) instrument, embarked on ESA's FLEX mission, is designed to monitor the photosynthetic activity of the terrestrial vegetation layer by measuring the chlorophyll sun-induced fluorescence signal[1]. FLORIS is composed of two separate spectrometers, the Low Resolution, covering a spectral band from 500nm to 758nm with a spectral resolution lower than 2nm, and the High Resolution, covering two spectral ranges from 677nm to 697nm and from 740nm to 780nm both with a spectral resolution lower than 0.3nm or 0.5nm, depending on the spectral bands, sharing a common imaging telescope.[2] Three identical CCDs are used for these three spectral bands. These detectors are based on the CCD325 from Te2V.



FLORIS optical layout

MEASUREMENT TEST DATA ON IRRADIATED CCD

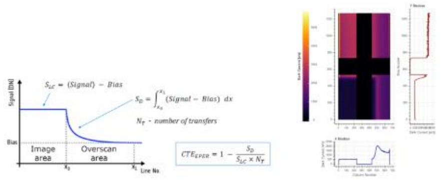
A proton irradiation campaign has been performed on a dedicated model of the FLEX CCD. By adequately masking the sensor surface, four different doses were deposed on the four quadrants of the CCD.

Quadrant	40-MeV proton dose [p^+/cm^2]
BAE	0.0
BAF	4.9×10^9
CDG	9.7×10^9
CDH	1.9×10^{10}

Experimental proton doses on CCD

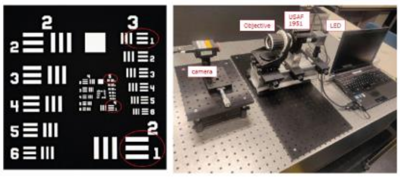
The expected proton dose to be received by the CCD along its operational lifetime in orbit is 6×10^9 p^+/cm^2. The quadrant CDG is therefore considered as representative with safe margin.

The first type of optical measurement performed on the CCD consists in illuminating the sensor in flat field by means of an integrating sphere, and modify the CCD clocking to transfer additional pixels in order to read-out the charge delayed by CTE reduction. The CTE can be inferred from the integration of the charge measured in the over-scanned region, i.e. the deferred signal. This method is referred to as the Extended Pixel Edge Response. The results of this measurement are later on used as inputs to the CTE modelling framework (CDM) described below



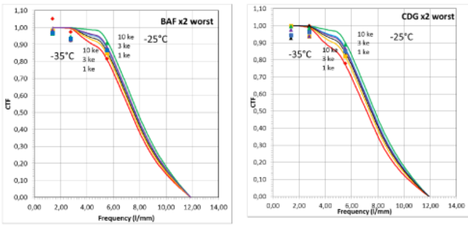
Extended Pixel Edge Response method for CTE measurement

A direct assessment of the image quality is performed through the measurement of the Contrast Transfer Function (CTF), on the test bench shown on CTF is a typical figure of merit of the image quality of optical systems that is measured as the contrast of a periodic square pattern on the detector plane. Targets contains patterns of different spatial periods, allowing to sample the CTF curve and plot it against spatial frequency.



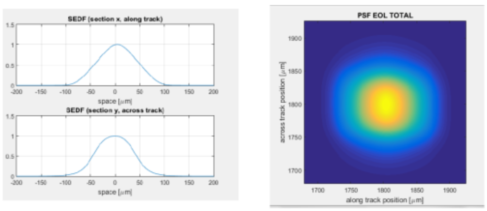
CTF measurement setup

Four different patterns are chosen in order to sample the CTF curve up to the Nyquist frequency (i.e. 11.9 lp/mm for 42µm pixels). The patterns are projected at the two edges of each detector image quadrant (close to the center of the detector, and close to the store area) in order to cover the highest and lowest, respectively, number of transfers through the image section. These positions correspond to worst and best cases, respectively, regarding the impact of the CTE on the image quality. Additionally the pattern are slightly tilted in order to reach a sub-pixel sampling of the pattern profiles. Finally the CTF is measured at three signal levels (1 ke-, 3 ke- and 10 ke-) and two detector temperatures (238K, 248K).



CTF measurement results, and comparison with MTF model

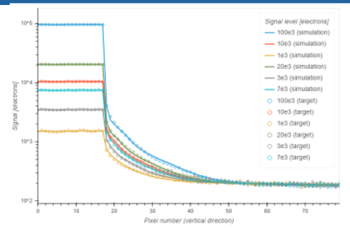
One of the key performance to monitor in order to assess the severity of the CTE effect is the spatial resolution, through the full width at half maximum (FWHM) of the point spread function. The figure below shows the point spread function at the end of the operational life, including the effect of CTE measured in the CDG quadrant as described above. This figure illustrates that the FWHM of the PSF remains within the range required for FLEX (100 µm in the focal plane equivalent to roughly 360 meters on ground, i.e. 1.2 times the spatial sampling distance (SSD)) .



Optical point spread function, including CTE effect after exposition to a proton dose of 9.7×10^9 p^+/cm^2

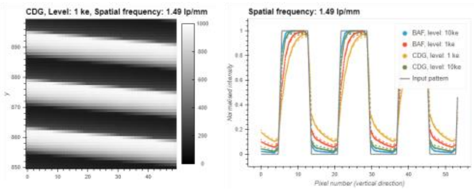
CTE MODELLING AND SIMULATIONS

Using the calibration mode of the python-based simulation framework Pyxel[3], we calibrate the fast analytical Charge Distortion Model (CDM)[4], against laboratory test data of the irradiated detector. CDM is used to efficiently simulate the effect of charge trapping and de-trapping during serial/parallel transfer. We calibrate the model for 4 different trap species.

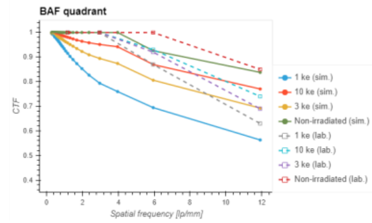


The target test data from laboratory measurements (circles) and the simulated charge profiles (lines) after calibration, showing the distinct charge trails and giving a visual impression of how well CDM can fit the FLEX test data over a wide range of signal level.

The fitted parameters are used to generate synthetic CTF curves by applying the CDM model to images of periodic square patterns, tilted for sub-pixel resolution, and observing the change of contrast as a function of both spatial frequency and signal level. for two irradiation levels (CDG and BAF). Finally, we compare the generated curves with the laboratory measurement data. The significant deviation with the measurements, could suggest that the found parameters have not reached the global minimum. More research is needed in order to validate the improve the simulations and match them with the measurements.



Effect of calibrated CDM model on periodic patterns. Contrast at different spatial frequencies is computed from cross sections shown on the right.



Comparison of measured (dashed line) and simulated (solid line) CTF for different signal level of input patterns

CONCLUSIONS

We have presented the results of measurements and modeling of the effect on the FLEX CCD of Charge Transfer Inefficiency induced by proton damage in the crystalline lattice of the detector. A flight representative device has been irradiated for this purpose and optical measurements were then performed. The measurement results presented above have been used first to have a direct evaluation of the degradation of FLORIS optical performance degradation through the measurement of the Contrast Transfer Function of the CCD and second, to generate calibration input data to feed into the detector model (CDM). This calibration data is used to derive the trap species parameters, by fitting it thanks to an evolutionary algorithm. After the calibration step, the model is then used on synthetic scenes similar to the measurement scenes, and compute the CTF from these synthetic scenes. The outputs of the model are compared to the test results and show discrepancies which are so far unexplained. The next phase of this work will be dedicated to understand and solve this mismatch, aiming at eventually obtain an accurate modelling framework for assessing the optical quality of a detector affected by Charge Transfer Inefficiency

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