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Radiation effects on image sensors

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Abstract: *Radiation is a major issue for satellite development, especially when using detectors, either for the mission itself, or for platform sensors. This paper will give CNES experience in the effects of radiations on detector and mission performances. Data from several satellites is presented (Earth observation, Astronomy, star trackers). We will make comparison between this data, to try to determine common behaviours. We will finish by describing the mitigation techniques against radiation effects.*

I. INTRODUCTION

Like other electronic devices, optoelectronic detectors are sensitive to radiation, and so are impacted by space environment.
Obviously detector degradation will have an impact on the application in which the detector is integrated.
Two main types of application concerns optical payload (for Earth observation, astronomy,…), and star trackers, used as attitude sensors for plate-form stabilization.
The management of this question requires a close collaboration between several teams, mainly Detector development, component reliability, end users of the detection chain (Image quality or AOCS teams)
Indeed, data have to be gathered during all the life time of the detector, from the very first steps of its development, until the end of life of the satellite in orbit.
CNES, as French Space Agency, has the chance to be involved in all these fields.
In Part II we will recall few topics on effect of radiation on the optoelectronic detectors
Parts III and IV will describe two types of impact "transient" and "permanent" of radiations on detectors, and their consequences for the satellite, using real in flight measurements on some CNES satellites
Part V will give the overall methodology followed by CNES to mitigate radiation effects on optoelectronic detectors

This study will be limited to CCD and CMOS image sensors (Silicon detectors), and some information about InGaAs. We will also limit the analyse to phenomena that are specific to detectors. That means that we will deal neither with SEU (Single Event Upset) nor with SEL (Single Event Latchup), that are possible in every digital components, and thus can affect CMOS detectors (but not CCD that are full analogue components)

II. RADIATION EFFECTS ON OPTOELECTRONIC DETECTORS

This part concerns either CCD or CMOS Silicon detectors

Radiation effects are usually classified in temporary and permanent ones

Permanent damages have a long term impact on performances. Energetic particles coming from space environment (protons and electrons) transfer part of their energy to the matter constituting the electronic devices through two mechanisms: one is the ionizing energy transfer, the other is the non-ionizing energy transfer. These two mechanisms are schematized in figures 1 and 2, respectively. [1], [2]

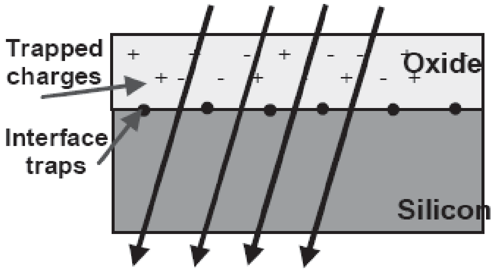

Fig. 1: Representation of energy transfer through the ionizing mechanism and its associated effects

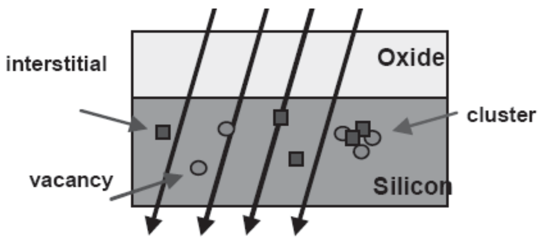

Fig. 2: Schematic representation of energy transfer through the non-ionizing mechanism.

One of the main effects of the ionizing energy transfer is the increase in the density of states at the Si/Si02 interface. These induced states behave as dark current generation centres from depleted areas [4]-[6]. Consequently, the main effect of the ionizing energy transfer is an increase in the surface dark current of detectors. From our experience, we can consider that for low ionizing dose levels (up to a few kRad (Si)) the mean dark current increase is proportional to the ionizing dose received.

The non-ionizing energy transfer leads to generation of displacement damage in the bulk. These defects act as generation centres inside the depleted region, and therefore raise the volume dark current [4]-[6]. Each displacement damage generation centre is localized and implies a sharp dark signal increase in the considered pixel. In contrary to ionizing effects, non ionizing ones impact a few part of the pixels, implying an increase in the Dark Signal Non Uniformity.

A second permanent damage of the non-ionizing energy transfer is to generate Random Telegraph Signal (RTS) [7},[8] corresponding to a random fluctuation. of the dark signal along time, and showing bi or multilevel of the signal.

A third permanent damage is an increase of the Charge Transfer Inefficiency (CTI), which impact is to create a lag between two images (even inside a line for CCD devices).

Transient effects are related to ionizing effect of a particle crossing the detector. As per definition, this deposit does not permanently damage the detector: it just generates false information during the particle crossing.

III. TRANSIENT EFFECTS

This .section illustrates several examples of temporary effects, observed in orbit, and we discuss the consequences for the satellite

Spot 5 is a satellite developed under CNES responsibility, for Earth Observation with 2.5m ground resolution.

Figure 3 shows temporary false information on images.

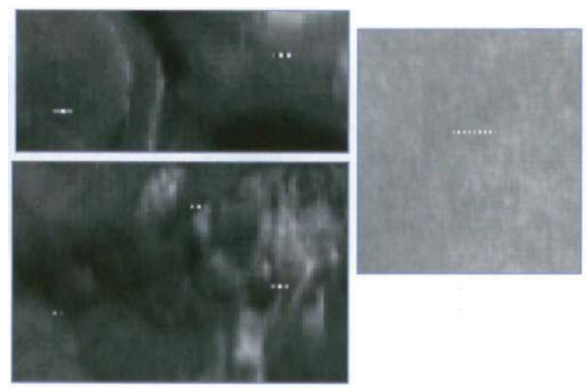

Fig 3:. Example of temporary effects on SPOT5 - CNES credits, SPOT IMAGE distribution

This kind of dotted figure is due to the fact that SPOT 5 CCD detectors uses 2 registers for the readout (one for odd pixels, the other for the even ones) : the dotted line is due to the fact that a proton has hit one of the register during a line readout, depositing charges only on odd pixels.

For Earth Observation, this phenomenon is not a major concern because, on one hand it occurs essentially in the SAA (South Atlantic Anomaly), which is not a region of major interest, and, on the other hand, it can be easily detected and corrected by on ground software.

Another story concerns the same kind of phenomenon, but for star trackers: this kind of sensor is used to determine the satellite attitude in space, by comparing the stars in their field of view, with a catalogue of known stars. The objects of interest of such sensors are stars that image is spread over a few pixels: every unattended white pixel can be analyzed by the on board software as a star, leading to misunderstandings of the algorithm: if too many "bright" pixels are present, the software can eventually shut down: in this case the satellite becomes unable to determine its attitude and move to a "survival" configuration, that causes an unavailability for the mission. Figure 4 shows an image of JASON 1 star tracker, when crossing the SAA

Fig 4: image of JASON 1 star tracker

To avoid the shutdown of the star tracker (and thus the unavailability of the satellite) software filters have to be implemented, in order to separate real stars (spread over a few pixels) from bright pixels that are in general only on one pixel.

IV. PERMANENT DAMAGES

As explained in Part II, the radiation effects have an impact on several detector parameters: the mean dark current increase, the dark current non-uniformity, RTS noise and CTI degradation .

Mean dark current increase

The mean dark current is the number of electrons generated per second when the detector is in darkness, and averaged over a large number of pixels.

The mean dark current increase is due to both the ionizing dose and the non-ionizing dose. For the considered missions and shielding configurations, ionizing dose is mainly generated by the protons interaction with the detector. Secondary emission of electrons by surrounding materials can also contribute to this effect.

In order to compare degradations observed on various detectors, we need to use a common scale. We decide to express the mean dark current increase as a function of the ionizing dose received, even if non-ionizing dose has an impact as well. Furthermore, we express the dark current as a function of the pixel active surface. To calculate the dark current in pA/cm2, the total surface of storage areas has been taken into account, including MOS storage capacity oxides as well as LOCOS oxides.

Moreover the mean dark current is expressed for a temperature of 20°C, using well known rule for Silicon (on satellites, detector temperature is regulated at a constant value).

The mean dark current increase will be then expressed in pA / cm² / kRad(Si) @ 20°C.

Figure 5 shows mean dark current increase for different satellites:

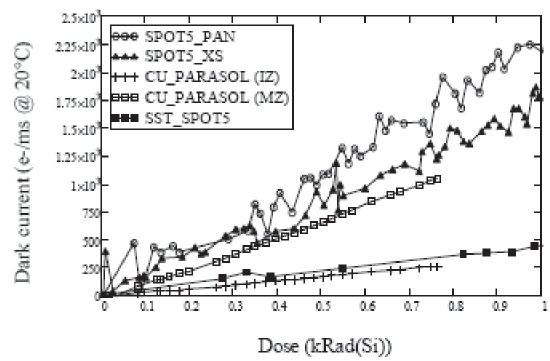

Fig 5: Cumulative mean dark current measured in orbit, vs ionizing dose

We clearly see that for all detectors (on different satellites) mean dark signal increases quite linearly with the Total Ionizing Dose. Nevertheless the slope is very different from one detector to the other, reflecting the fact that mean dark current increase depends on the detector technology, especially pixel design.

Worst slope, for SPOT 5 PAN detector (linear array of photodiodes) is 2,3 nA/cm2/kRad(Si) @ 20°C

Another example could be given for Corot satellite, with astronomical purposes (astero-sismology and search for exoplanets). The CCD is backthinned, in MPP mode, and at low temperature, giving a very low dark signal. Indeed, in an inverted mode the Si/SiO2 interface can be flooded with holes during integration. As a consequence, the surface dark current is suppressed and the bulk dark current will dominate the total dark signal.

The pixel pitch is 13.5µm and the integration time was set to 32 s (exoplanet channel). The ionizing dose deposited per year is about 700 Rad.

Corot CCD dark signal increase is given Figure 6, which exhibit real measurements, same points re-computed for -35°C, and predicted lines [13]

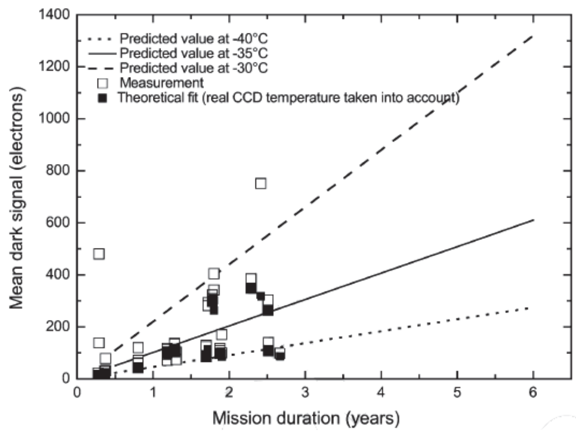

Fig 6:. Corot CCD Dark signal increase

Effects of mean dark signal increase

Dark signal increase has several consequences for the detector, and thus the mission, performances:

- Increase of the noise in darkness, that is (in electrons) the sqrt of the number of electrons
- Decrease of the useful dynamic range

The impact depends on the type of missions

For Earth Observation, mean dark signal is quite low and does not degrade the overall performances. Figure 6bis shows the SNR (Signal to noise ratio) over SPOT 5 life time: no degradation is present

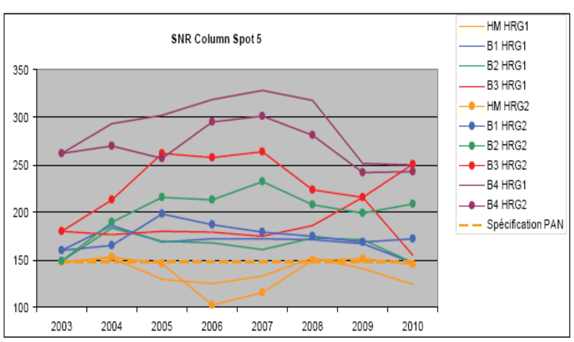

Fig 6 bis: Evolution of SPOT 5SNR over time

For astronomy mission, the main impact is the noise increase leading to a degradation of the capability of detecting low signal variations.

The noise increase will lead to a certain degradation of the capability of detecting faint signals. This is illustrated by the ratio between real noise and photon noise. Figure 7 gives the drift of this ratio over time

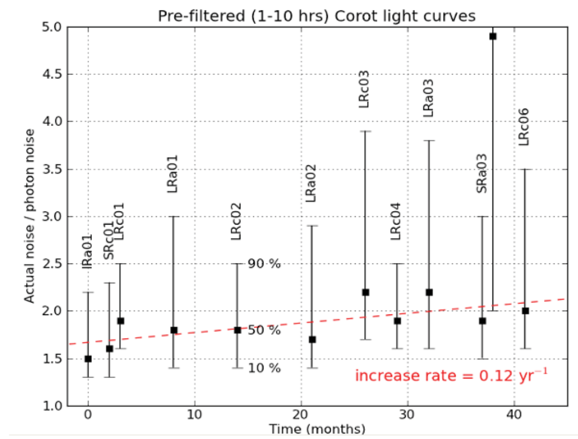

Fig 7: Evolution of Corot detection ratio
(Credit P. Bordé)

This figure exhibits a slight drift of this ratio but very low (0.12 per year), with very few impact on overall mission performance.

Same impact is present for star trackers, reducing the number of useful stars

Dark signal non uniformity (DSNU)

The DSNU is the non uniformity of the dark signal over the detector: it can be expressed in % (related to he mean dark signal) or in physical units. It can be given as peak-to-peak or RMS value, but in certain cases, we give the number of "bright" (or "hot") pixels (with a dark signal higher than a certain limit)

DSNU increase is meanly due to displacement damage in the silicon created by energetic particles. These defects act as generation centres lying within the depleted region, and therefore raise dark signal in the volume [4-6]. Each displacement damage generation centre is localized and implies a sharp dark signal increase in the considered pixel. As a consequence of the statistical nature of displacement damage, the main effect of the non-ionizing energy transfer is an increase in DSNU, and especially the apparition of a tail in the dark current distribution..

Examples For Earth Observation satellites [12]

Figure 8 gives an histogram of the dark signal over all pixels of the detector of PARASOL Satellite after 800 days in orbit (PARASOL is a CNES micro-satellite that observes aerosol distribution in the atmosphere) the corresponding Displacement damage: equivalent fluency (30MeV protons) is 3.10^9 proton/cm²: We clearly see the tail in the distribution

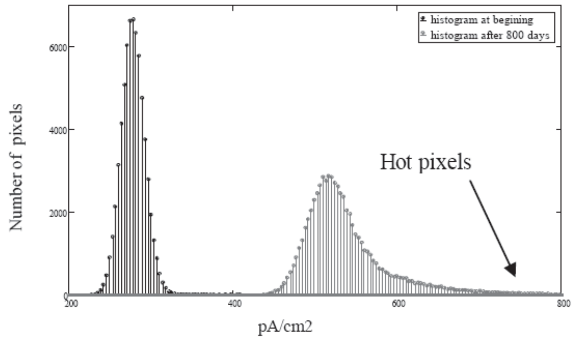

Fig 8: Dark current histograms of one of the detectors just after launch and after 800 days in orbit

One interesting parameters is the amplitude of dark current jumps. We call "jump" a sudden (but permanent) increase in a pixel dark signal after proton interaction. Figure 9 shows the dark current of 1 pixel over time

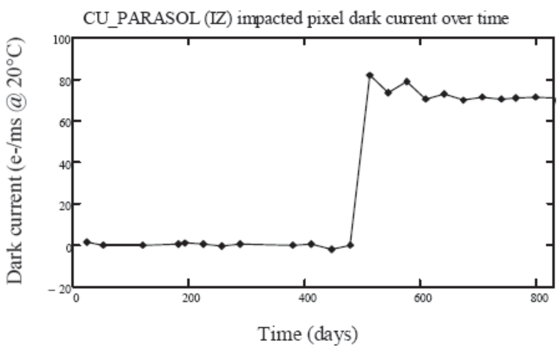

Fig 9: PARASOL pixel jump observed in orbit

In order to compare the different detectors behaviours, jump amplitudes are expressed in electrons generated per millisecond at a temperature of 20°C

Figure 10 shows the histogram of the jump values for several detectors Spot 5 payload, Parasol payload, Parasol star tracker (in orbit duration: 3 years for Parasol, 5 years for Spot)

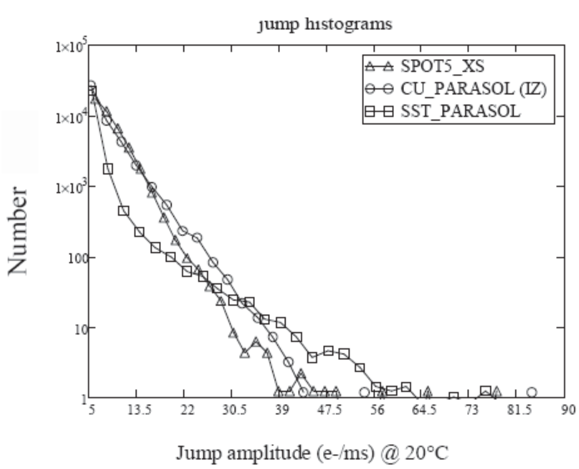

Fig 10: histogram of jump values

It clearly appears that the values are quite similar, leading to the question: why this similarity?

First element to explain that is that a jump can present an annealing [11], so it can be either transient (with rapid and strong annealing),or semi-permanent (with slow or delayed annealing), or permanent (without any annealing).

Figure 11 shows both jump values and DSNU for Parasol satellite. It is obvious that after event 2, DSNU decreases quickly to its former value, showing that the jump does not exist anymore: it is clearly as sign of cure of the pixel

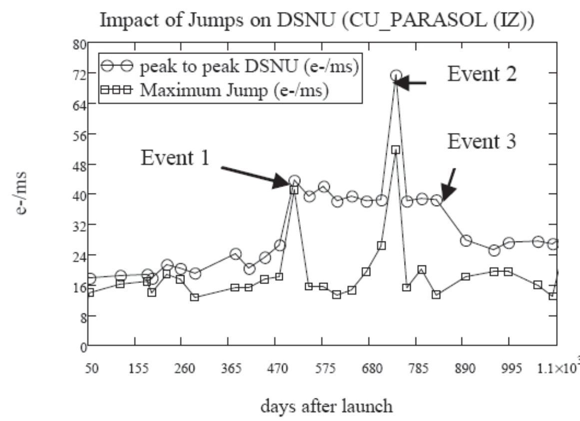

Fig 11: DSNU and jump vs time

Another way to analyse this phenomenon is given by Corot data. Figure 12 shows the number of "bright" pixels vs time:

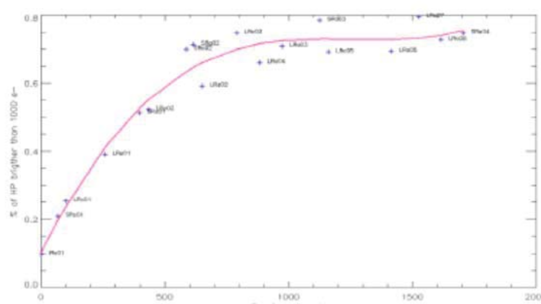

Fig 12: number of bright pixels vs time for Corot

it clearly shows a saturation of the number of bright pixels : this is a sign that a kind of equilibrium exists between the degradation rate, and the cure rate, explaining why the long term distribution of bright pixels is the same for different satellites (cf fig 9).

This theory has nevertheless to be confirmed by further in orbit satellites.

Impact of DSNU evolution on mission performances

for Earth Observation satellites, DSNU leads to increase the noise of the most impacted pixels: searching to limit this effect will lead either to reduce focal plan temperature, or temperature drift, during one image sequence) or to increase the rate of darkness calibration : the first one will induce constraints on satellite design (area of dissipative surfaces) or on operational constraints (rate of darkness calibration).

For Astronomy satellites, DSNU increase will reduce the number of pixels (and thus the area) really useful: if too much pixels are impacted, so the useful area may become too small.

RTS noise

RTS noise is due to bi or multi stable state of darkness current of a pixel (after displacement damage).

RTS noise is clearly present in orbit Figure 13 shows a real signal acquired on Parasol satellite detector.

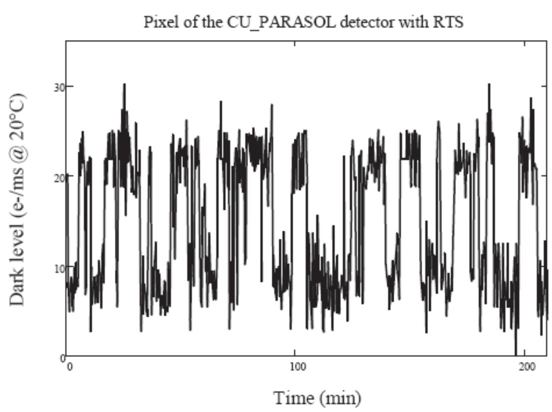

Fig 13: RTS signal on Parasol detector

Obviously, all missions are impacted by such phenomenon, which is random, and so quite impossible to calibrate.

For pushbroom Earth Observation satellites, this leads to "dotted" lines in images (cf fig 14).

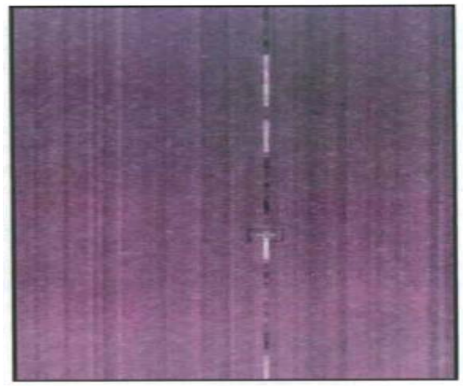

Fig 14: RTS effects on images
(Credit CNES - Distribution Spot image)

This kind of phenomenon is clearly to be reduced.

Charge transfer inefficiency

Displacement damage could lead to an increase in charge transfer inefficiency (CTI).

This kind of phenomenon is clearly visible on images from Corot satellites (fig 15 and 16):

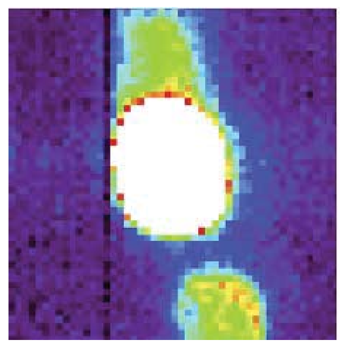

Fig 15: Image showing Vertical transfer inefficiency

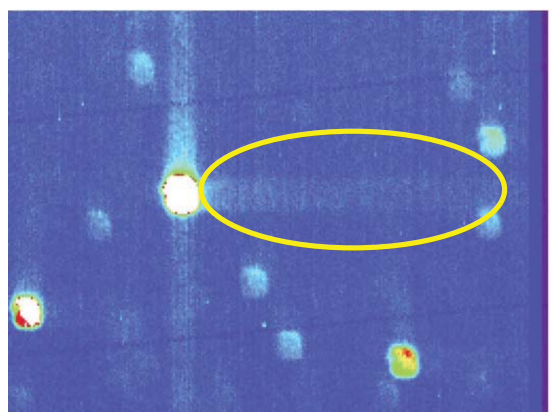

Fig 16: Image showing CCD register inefficiency

Impact of CTI degradation on performance mission

For Corot satellites, which purpose is to follow the radiance of faint stars, images are de-focused: so even CTI is present, it has no consequence on mission performance, because it is possible to gather all pixels by ground software processing.

For Star Trackers, the question is more tricky, because process is in flight and in real time : Even if star images are de-focused, if CTI becomes too large, the level of signal measured on a star image will decrease leading to a more difficult detection, and even a false detection if the star apparent magnitude changes.

This phenomenon is particularly awkward for satellites at medium altitude, where proton environment is hard: that is the case for JASON satellite (1355 km)

For Earth Observation satellites, CTI degradation could lead to a smoothing of sharp black to white edge, which is characterized by the MTF (Modulation Transfer Frequency) degradation.

Up to known we have not noticed any significant degradation for in orbit MTF: Figure 17 shows SPOT 5 MTF evolution during 9 years in orbit:

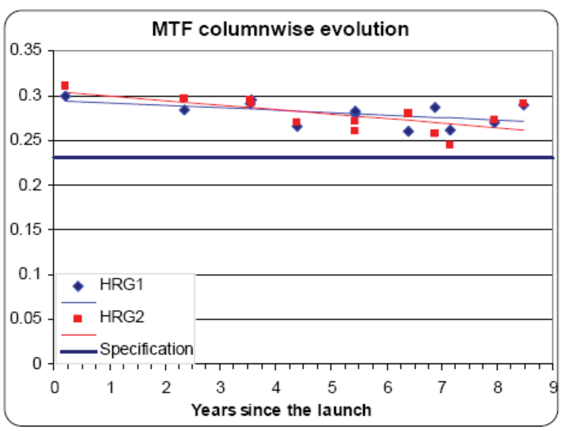

Fig 17: SPOT 5 MTF evolution

V. Radiation effect mitigation

.As radiations are part of space environment, we have to mitigate their effects for present and especially for future satellites. This mitigation spreads of the whole life of the satellite, from its very early development up to the end of life.

It requires a strong cooperation between several teams:

- Quality insurance teams, to determine irradiative environment, and the ground test plan for the detectors
- Satellite mechanical development teams, to determine the shielding of the satellite that will protect the detector against radiations
- Satellite thermal development teams, to determine the temperature regulation of the detector
- Mission teams, that compute the impact of detector performance degradation on mission performances
- On ground processing teams, that receive and process data for in flight satellite analysis
- Detector development teams, that coordinate this process

The main steps of the mitigation are the following:

During the satellite development cycle:

- Determination of space environment, knowing the expected life duration, and orbital parameters
- Determination of effective irradiative environment at detector level, knowing satellite shielding
- Determination of on ground irradiation test plan for the detector
- Measurement of performance degradation after detector on ground irradiation
- Determination of End of life detector performance
- Determination of impacts on mission performances
- Interaction with satellite design to modify shielding or temperature regulation

After launch

- Follow up of satellite data
- Determination of detector performance drifts
- Comparison with predicted data,

We can then learn from this comparison, to improve the development of the next generation of satellites:

- more realistic test plan
- more realistic performance degradation
- improvement in whole satellite design (and mission duration)

VI. Conclusion

Radiation is a major concern in satellite development, especially when using detectors, either for the mission itself, or for ancillary sensors.

Up to know, we have manage the effects on mission performances, by proper design.

But up to know we have mainly use CCD detectors in space, and yet the CMOS detectors are coming for the future satellites.

Some questions are asked, to determine the proper ground test conditions, and the behaviour in space for CMOS detectors. The diversity of CMOS technologies makes the answer tricky, and will require a lot of work in the following month and years.

Acknowledgment

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