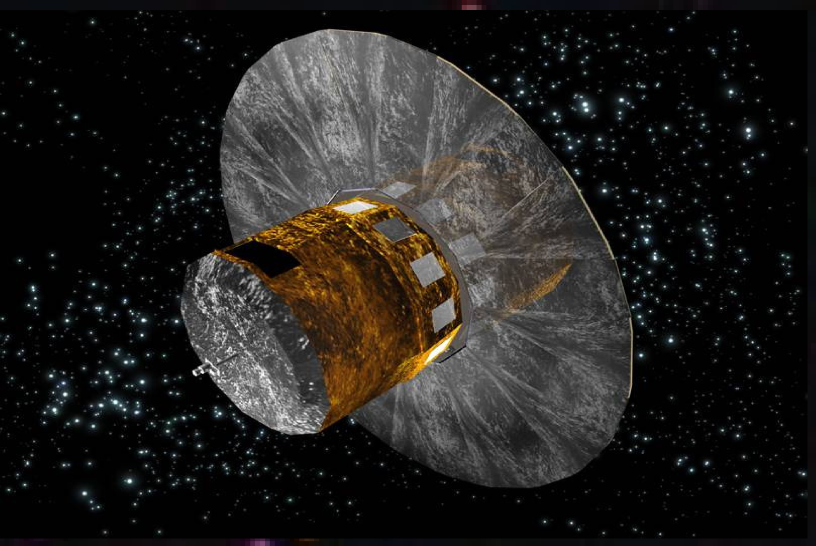


# Trapping the traps in Gaia CCDs


Frederic Raison & Juanma Martin-Fleitas

(Gaia SOC, ESA/ESAC Madrid. frederic.raison@sciops.esa.int, jfleitas@sciops.esa.int)


## Abstract


Gaia is an ESA cornerstone mission, designed to create a three-dimensional map of the Milky Way with unprecedented positional accuracies. To reach this level of accuracy, radiation damage impact on Gaia CCDs must be calibrated and corrected. Different models have been developed to reproduce the charge trapping effects which cause high charge transfer inefficiency. Here we use simulations to assess the feasibility of the determination of the trapping model parameters from calibration data.


## Mission Overview

Gaia [1] will measure the positions, distances, space motions and radial velocities for one thousand million stars in our Galaxy, producing its first stereoscopic and kinematic census, complete to 20-th magnitude. Gaia will provide detailed information to study the origin and history of our galaxy, its dynamical, chemical and star formation evolution and to study the physics of the stars and their evolution. Gaia is also expected to provide data to allow the detection of tens of thousands of Brown Dwarfs, White Dwarfs, resolved galaxies, extragalactic supernovae and distant quasars. Gaia data will allow the detection and orbital classification of extra-solar planetary systems and minor bodies in our Solar System. It will also provide a number of stringent new tests of general relativity and cosmology.

Gaia has two telescopes, which are separated by an extremely high-stable basic angle of 106.5°. The two fields of view (FOV) are combined into a single Focal Plane. The instantaneous image centroids give the relative separations of the thousands of stars simultaneously present in the combined fields. Gaia operates in a continuously scanning motion, with one full revolution every six hours. Hence the whole sky is systematically scanned such that a 5 years mission yields around 70 observations for each object.

## Focal Plane

The Focal Plane (FPA) of Gaia comprises all Gaia instruments: the Astrometric Field (AF), the Photometric Field (BP/RP) and the Spectrometric Field (RVS), as well as the Sky Mapper (SM), the Basic Angle Monitoring (BAM) and the Wavefront Sensor (WFS). It is a huge Focal Plane with 106 CCDs, 938 million pixels in total. Its size is approximately half a square-meter representing a total active area of 0.75 deg².

Due to the large amount of CCDs and the limited downlink bandwidth, the amount of data to be gathered has been reduced by defining windows around the selected objects. Gaia is a scanning satellite, hence stars transit through the FPA continuously in the along-scan direction, CCDs are operated in Time-Delayed Integration (TDI) mode synchronized with the star motion on the FPA.

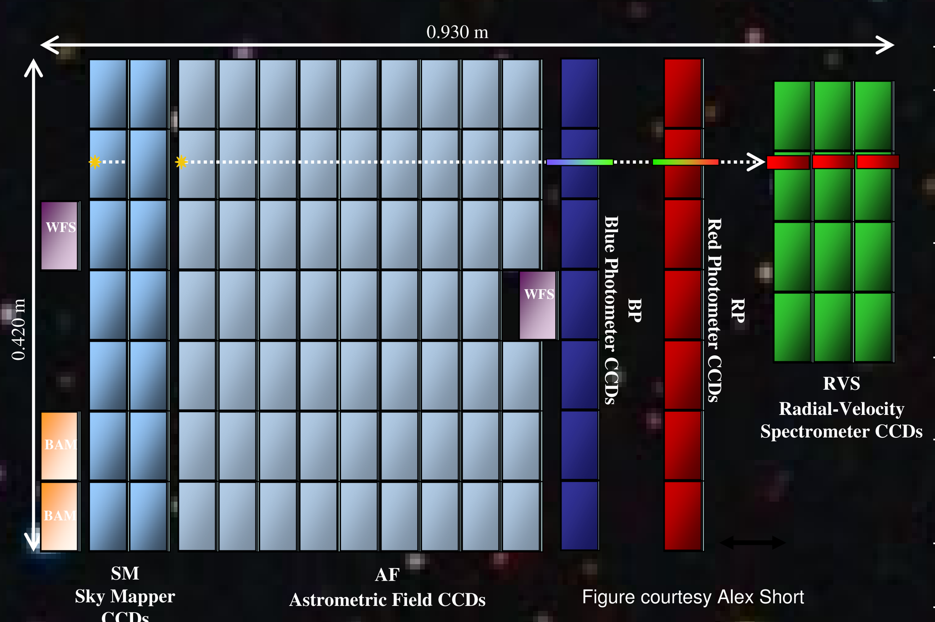
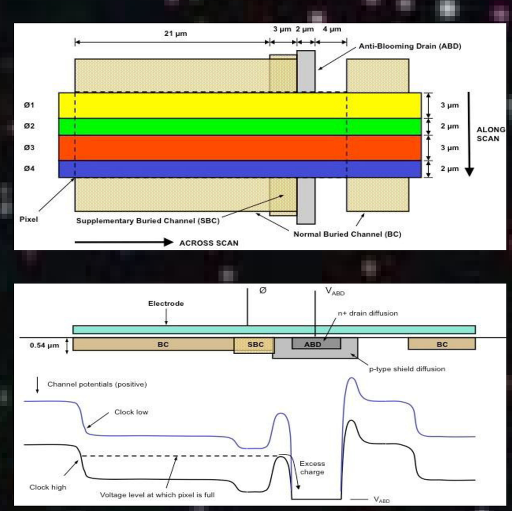



Figure courtesy Alex Short

| Instrument | Function | Characteristics |
|---|---|---|
| SM | Objects pre-Selection | One SM per FOV |
| AF1 | Confirmation / rejection<br>Priority, windowing and sampling management<br>AOCS speed | Direct imaging<br>Nominal AF CCD |
| AF2-9 | Astrometric observation | 7 μarcsec at 10mag<br>10 – 25μarcsec at 15mag<br>100-300μarcsec at 20mag |
| BP<br>RP | low-resolution spectro-photometers | range: 330 – 680 nm (BP)<br>range: 640 - 1050nm (RP) |
| RVS | slitless spectrograph resolve the Ca triplet | range: 847 - 874 nm<br>resolution (λ/Δλ): ~ 11000 |
| BAM | Basic Angle Monitoring | Laser Interferometer |
| WFS | Telescope Alignment | Shack-Hartmann<br>Wave-Front Sensor |

### Gaia CCDs

Gaia CCDs have 4500 lines x 1966 columns, with pixels of 10 μm size in the along-scan x 30 μm in the across-scan direction. Each CCD includes antiblooming drains, a parallel summing well for binning of successive lines and 12 special gate electrodes to shorten the effective exposure time in TDI mode. A Charge Injection structure comprising a diode and a gate electrode is included in each CCD. This allows to inject an adjustable amount of charges on a whole CCD line so as to fill traps. A supplementary buried channel (SBC) of 3-4 μm width is included in each CCD, effectively reducing the effective width of the buried channel in which small signals are stored and transferred, therefore reducing the number of traps with which these small signals can interact with.




## Trap parameters determination from trails

Radiation impact calibration requires a model of the trapping effect. Current models developed by ESA and the Gaia Data Processing and Analysis Consortium (DPAC) are based on the Shockley-Read-Hall theory (SRH). In the SRH model, the parameters to be determined are, for each species, their release/trapping time constant and the trap density. At this time, there is a large uncertainty on the knowledge of the trap parameters .

In principle, these parameters can be determined for a specific irradiation level from in flight data or ground tests. In both cases, the parameters could be inferred from the analysis of charge release data profile after injection called trail analysis .

### SRH theory

Capture Probability

$$Pc = 1 - \exp(-t/\tau_c)$$

$$\tau_c = 1/\sigma v n$$

$\tau_c$ : $e^-$ capture time constant
σ : trap cross-section
v : $e^-$ thermal velocity
n : $e^-$ density in vicinity of trap

Release Probability

$$Pr = 1 - \exp(-t/\tau_r) )$$

$$\tau_r = \exp(E/kT)/\chi\sigma v N$$

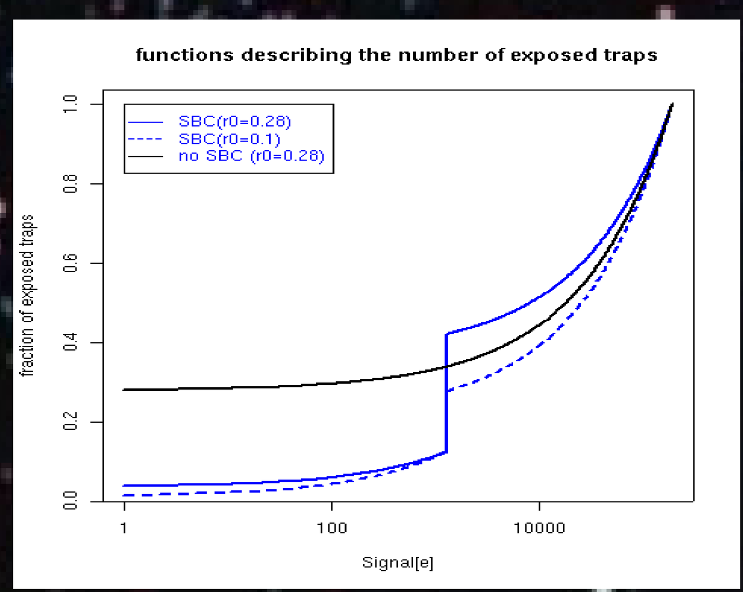
$\tau_r$ : $e^-$ release time constant
E : trap energy level
k : Boltzmann constant
T : CCD temperature
χ : entropy factor
N : effective density of states in conduction band

| Trap species | $T_r$ [s] |
|---|---|
| E center: phosphorus atom-vacancy (P-V) | 30 to 600 |
| W+: vacancy-vacancy | 33 to 200 |
| Unknown: up to 12 species | $2x10^{-2}$ to $8x10^{-2}$ |
| W-: multiple bounded vacancies | $10^{-5}$ to $8x10^{-4}$ |
| A center: oxygen atom-vacancy (O-V) | $10^{-6}$ to $10^{-7}$ |

*This table illustrates the uncertainty on the knowledge of trap species release time constants.*

### Charge cloud description

Some microscopic (at pixel level) and macroscopic (at pixel column level) CCD simulations have been conducted to reproduce the trapping/release process. Apart from a trapping/release model, all these simulations assume a charge cloud description model. Here we present simulations based on the Philbrick [3] implementation of the SRH theory .



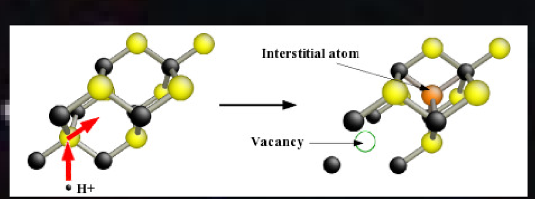

- The number of traps seen depends on the number of charges in each well.
- The number of traps seen by a quasi empty charge packet is set with a parameter r0 (here 0,28 and 0,1).
- Parameter r0 and CCD design (Supplementary Buried Channel or not), will both impact significantly response at low signal.
- Finally, the amount of trapped/release charges from/into a charge packet is going to depend on both the trapping/release probabilities and the amount of traps seen.

## Radiation Damage: Traps & CTI

Gaia will be exposed to radiation mainly due to Solar activity, firstly Gaia will be launched during a Solar maximum in 2011 and secondly, when orbiting in L2, due to solar flares throughout the mission time, when solar particles flux is expected to reach thousands per cm² per second. There are two types of radiation damage [2]: Ionizing damage which leads to charge accumulation in the oxide layer of the MOS structure of each pixel, and therefore effectively to a shift in the potential with the same voltage applied to the gate. Ionizing radiation tests are being planned to be conducted on Gaia CCDs to determine how sensitive they are and its possible effects in Charge Transfer Inefficiency (CTI).

### Radiation induced traps

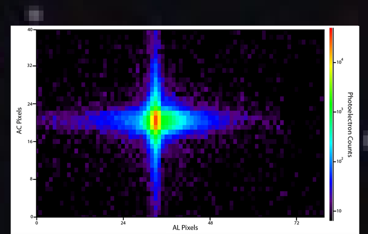
Non-Ionizing damage which is mainly displacement damage of silicon atoms in the lattice caused by particle impact (mainly protons). These defects (vacancies, V) can wander through the lattice to locations where they can form stable complexes, for example with Phosphor (P) impurities in the CCD's buried channel (where charge transport takes place). These stable complexes introduce localized energy levels within the forbidden bandgap of the semiconductor which can capture a single electron from the conduction band, retain it and then, due mainly to thermal energy, release it again to the conduction band. This is called a "trap". Depending on the type of complex (P-V, V-V, etc.), different "trap species" are created. Depending on the release time traps are grouped in "fast" and "slow". Traps lead to deferred charge during charge transfer, hence the CTI increases with non-ionizing radiation damage.




*Non-ionizing or displacement damage: incident radiation interacts directly with the atomic nucleus with enough energy to displace the atoms from their positions in the crystal lattice.*

### Centroiding and radiation damage

Traps affects the point spread function (PSF) in several ways. Electrons are trapped from the front of the PSF and released behind the PSF, producing a centroid shift and charge loss if charge is released outside the observation window. This dramatically affects Gaia performances. Fast traps will be responsible for centroid shifts which severely affects the astrometry measurements, producing errors in the position estimation. Slow traps will affect both, astrometry, since its measurements will have bigger RMS centroiding errors (PSF distorted and S/N is reduced), and the photometry, by inducing errors in the estimation of magnitudes and colors. Most important, is that both effects are variable, they change with trap occupancies, they are different in different areas of the CCD, and they change during mission. The effect to be measured is in the order of milli-arcseconds!



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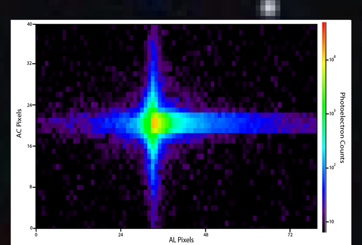

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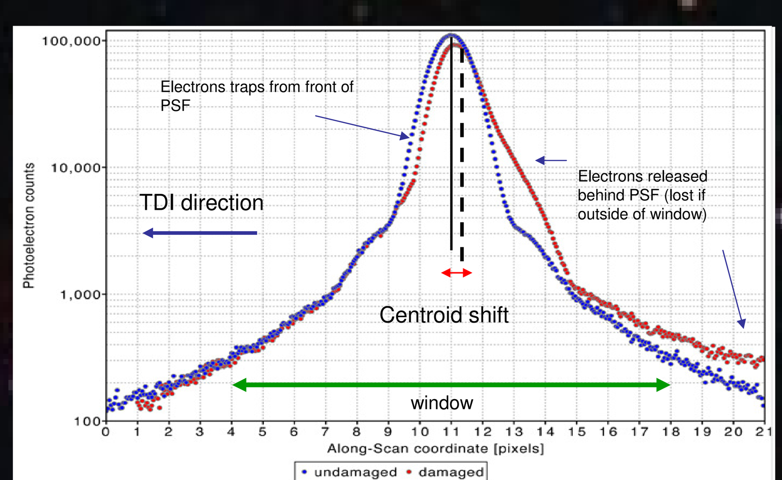
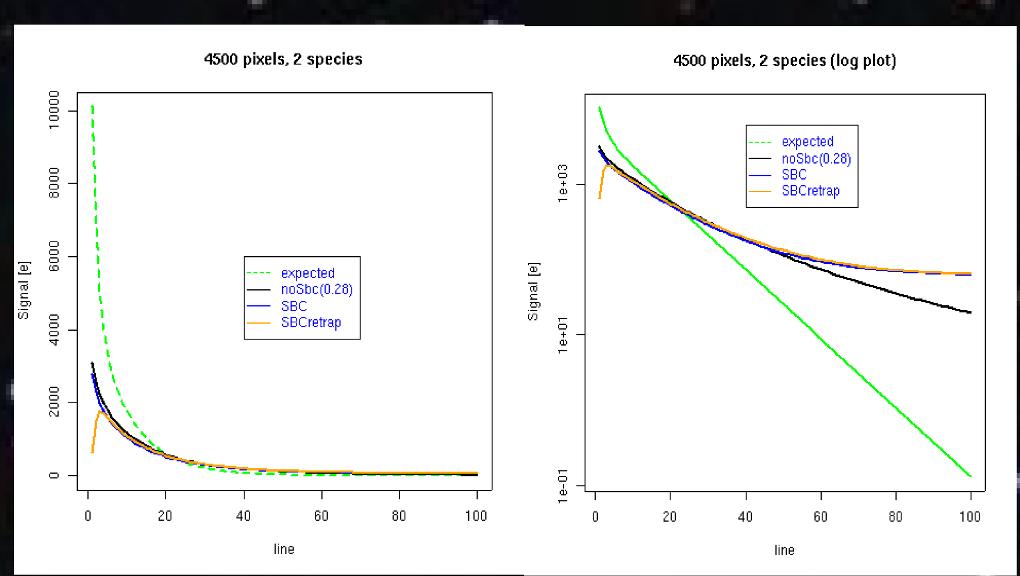


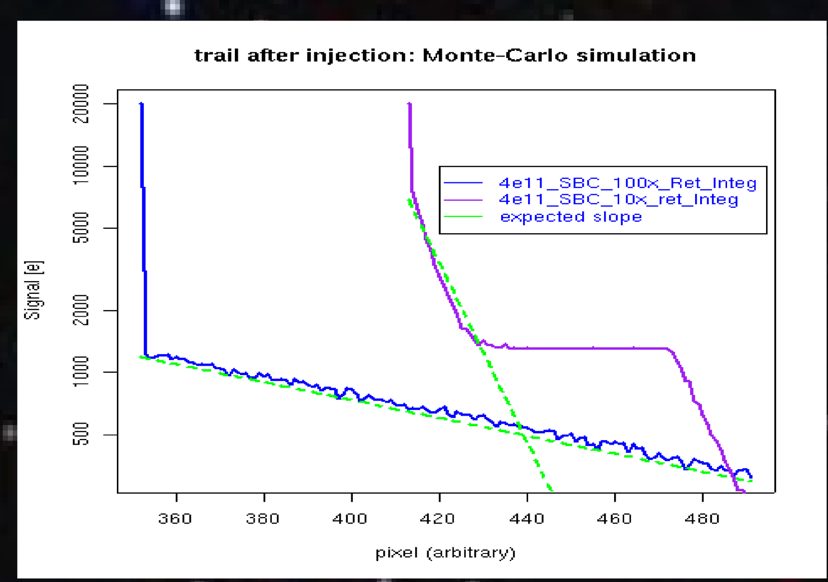

*Radiation damage of the Gaia CCDs is impacting centroiding and flux determination.*

## Simulation results

We focused here on the determination of the trap release time constant. Note that this can be measured by a number of pixels in the context of the TDI mode. We used two kinds of simulation environments to assess the impact of the trapping and CCD model parameters on the trails profile. The R project to understand the different effects (left plots) and an experimental Java code to perform more realistic Monte-Carlo simulations (right plot). In both cases, we compare the simulated trail with an expected one for a given set of trap parameters .




On these 2 plots, simplistic simulations reproduce the impact of the SBC and re-trapping effect with 2 trap species. In this configuration, the strongest deviation from the expected slope is obtained when having a SBC with potential re-trapping of the charges (after release).




With this Monte-Carlo simulation using only 1 specie, we compare the impact of the charge release time constant. In the case of a 100 pixels constant (blue), the slope does not deviate significantly from the expected response. However, the 10 pixels constant curve show more subtle effects. Note that the expected response curve offset is arbitrary.

## Conclusion

Radiation induced traps produce centroiding shifts and charge loss affecting severely Gaia mission performances. The understanding of the physical nature of this phenomenon is crucial to design strategies for the mitigation of its effects.

We have tried to model the charge trapping effect using the SRH theory. From the preliminary simulations we have made, it appears that the trap parameters determination from trail analysis alone must be done with great care. The trail's profile is the result of both the trapping model and from the charge cloud model. On top of that, it is impacted by a re-trapping effect. Other direct experimental measurement methods should be used, like pocket pumping, DLTS or First Pixel Response method, at least to provide a basis for comparison.

## References


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*Image credits: Alex Short (ESA), Anthony Brown & Thibaut Prod'homme (Sterrewacht Leiden), George Seabroke (The Open University, Milton Keynes) , ESA.*