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RADIATION INDUCED CHARGE TRANSFER INEFFICIENCIES IN THE SENTINEL 4 INSTRUMENT: MODELING, PERFORMANCE, AND CORRECTION

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INTRODUCTION

Sentinel 4 is an imaging UVN (UV-VIS-NIR) dispersive spectrometer, developed by Airbus DS under an ESA contract in the frame of the joint EU/ESA COPERNICUS program. The instrument is introduced in a dedicated presentation in this conference.

Sentinel 4 relies on two Charge-Coupled Devices (CCDs) to collect the photon flux. The photo-generated charges are then transferred across the length of the CCD, from pixel to pixel, towards an output node. Of great importance is the so called ‘charge transfer inefficiency’ (CTI) defined as the fraction of the charge packet lost at each transfer.

During the development phase, the CTI effect may be improved by a variety of strategies ranging from silicon wafer improvements to CCD clocking optimization. Through such efforts, scientific CCDs typically achieve CTI performances lower than 0.00001.

Once in space, the CCDs will be inevitably exposed to energetic particles, mostly MeV protons emitted by the sun, which will induce defects in the CCD silicon lattice by displacement damage. As a result, the radiation induced (RICTI) of the devices will slowly increase (deteriorate). Over the last decade, this type of CTI has been identified as an extremely critical radiometric error in astronomic missions such as Hubble, Gaia, and Euclid. Due to ever stringent radiometric requirements, newer Earth observation missions, such as Sentinel 4, are also expected to be critically affected.

Ultimately, the RICTI effect translates into a spectral (and spatial) distortion at L1b. The distortion is rather complex as it depends, on at least, the following parameters:

- The signal level in the pixel of interest
- The number of transfers that occurred prior to read out
- The signal level available in the surrounding pixels
- The amount of radiation exposure that the detector has seen
- The type of semiconductor material in which the photo-electric conversion is carried out.

This work aims at providing a brief overview of the tools developed in the context of the S4 project to quantify and correct the detrimental effects of RICTI. The paper is divided into four sections each devoted to elaborating on the following topics:

- Our understanding of the capture and release of electrons by radiation traps within an electronic cloud
- An overview of the algorithm developed to predict the impact RICTI on L1b products in S4
- A quantitative approximation of the radiometric errors induced by the RICTI expected for our instrument
- A description a potential correction algorithm to reduces the RICTI impact on radiometric performances to an acceptable level

GOVERNING EQUATION

Consider an electron cloud sitting within a detector pixel which has been damaged by radiation. The cloud contains a total of N_T traps. Some of these are occupied by electrons, $N_{o,i}$. The question arises: given such an initial state, how would the number of free and occupied traps evolve after a certain time has passed? This section provides a brief overview of our physical understanding of this problem.

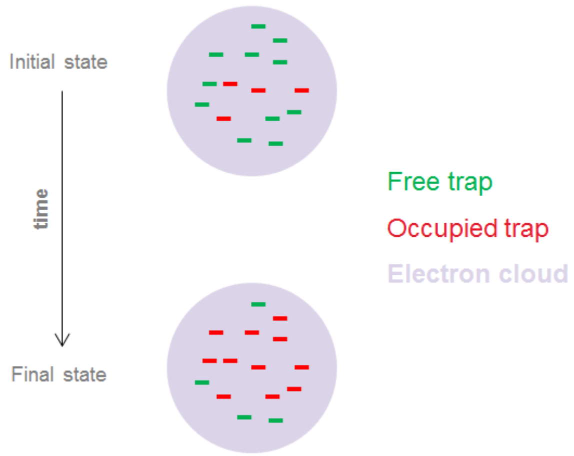

Fig. 1. Governing equation. The basic problem of trap occupation change within an electron cloud

This basic problem may be described by a rate equation, afterwards referred to as the *Governing Equation* , of the form:

$$N_o(t) = \frac{\tau_r}{\tau_r+\tau_c} N_T \; + \left(N_{o,i} - \frac{\tau_r}{\tau_r+\tau_c} N_T\right) \; e^{-\left(\frac{1}{\tau_r}+\frac{1}{\tau_c}\right)t}$$

The capture of charges by a trap is considered to be stochastic processes best described by an exponential decay time constants given by:

$$\tau_c = \frac{1}{\sigma_{trap} v_{thermal} n_e}$$

The release of charges from a trap is thought of in similar terms as charge capture:

$$\tau_r = \frac{1}{\psi \cdot \chi \cdot v_{th} \cdot N_c \cdot \exp(-\frac{E_t}{k \cdot T})}$$

The electron density within the cloud is directly linked to the capture time. It is formulated as:

$$n_e = \frac{S}{V_c} = \frac{S^{1-\beta} \cdot FWC^{\beta}}{V_{FWC}}$$

Where the volume of the charge is related to the number of electrons present as

$$V_c = V_{FWC} \left(\frac{S}{FWC}\right)^{\beta}$$

The parameter β may take values between 0 and 1. For the case $\beta = 0$, the volume of the cloud would remain constant independently of the signal level. For the case $\beta = 1$, the volume of the cloud scales linearly with signal level.

CTI MODEL

Applying the basic problem outlined in the previous section to solving the RICTI effect to an entire spectral or spatial line in the S4 detector is not straightforward. Consider for a second what happens as charges are transferred across a CCD and assume that the observer is pegged to a particular pixel on the detector. The important points are illustrated in Fig. 2.

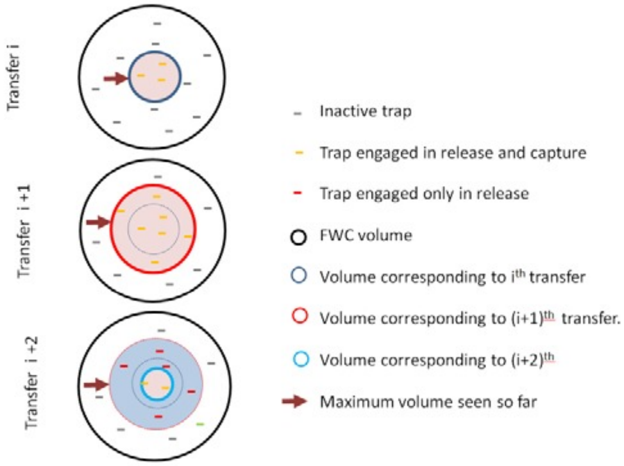

Fig. 2. Evolution of cloud size and trap occupation as the detector transfer takes place

In particular, the following steps are noted:

- Transfer i: New charge packet is transferred to the pixel of interest. This is the orange volume in figure. Within it traps will be engaged in capture and release. Traps outside are inactive. The basic equation can be applied to the orange volume

- Transfer i+1: Charge packet is moved out and a larger charge packet is transferred into the pixel. Traps within new orange volume are also engaged in capture and release. Note that since the electron cloud is larger, more traps are engaged as volume is larger

- Transfer i+2: Charge packet is moved out and a smaller charge packet is transferred into the pixel. Traps within the orange volume (volume A) are engaged in capture and release. However, traps outside of orange volume but within the *'maximum volume seen so far'* (volume B) are only engaged in release. This is the blue volume

To account for this, the basic equation needs to be solved independently in volume A and volume B, and the net change of occupied traps in the pixel corresponds to the summation of the net change of occupied traps in each of the two volumes. A generic scheme of the Sentinel 4 CTI model is presented in Fig. 3.

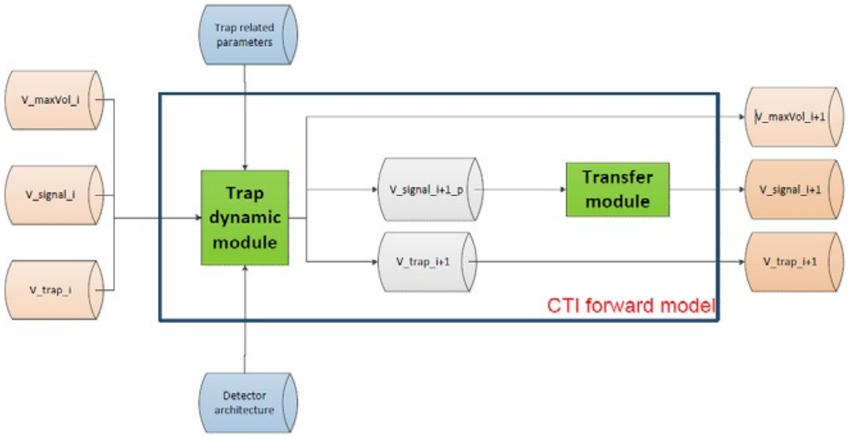

Fig. 3. Overall scheme of the S4 RICTI forward model

The overall principle is as follows:

- **Three vectors** are taken in representing the state of the pixels at a particular point in the read out sequence. The length of the vectors corresponds to the total number of pixels within a spectral row (including imaging and memory zone pixels). The three vectors correspond to the number of electrons in the conduction band for each pixel (V_signal_i), the trapped number of electrons per pixel (V_trap_i), and the maximum cloud volume that each pixel has seen so far in the transfer process (V_maxVol_i)

- The **Trap dynamic module** ingests these vectors together with the trap and detector related parameters. Then the basic equation is applied to separately, and twice (once Volume A, and then again Volume B) to each pixel to compute the change of trapped electrons which occurred within the transfer period. From here, three new vectors are produced representing: Number of electrons in the conduction band for each pixel after one transfer period ($V\_signal\_i + 1\_p$), the trapped number of electrons per pixel after one transfer period ($V\_trap\_i + 1$) and the maximum cloud volume that each pixel has seen so far in the transfer process after one transfer period ($V\_maxVol\_i + 1$)

- The **Transfer module** transfers the free electrons from one pixel to the next thus producing the vector $V\_signal\_i + 1$

- The process is repeated until all electrons have been read out.

PERFORMANCES

In this chapter we utilized the RICTI forward model to compute how RICTI would distort real S4 spectra. A few important comments follow:

- The S4 instrument features a different detection chain for the UVVIS and the NIR. For simplicity, we focus only on the NIR path in this work since it is the most sensitive to RICTI effects.

- The RICTI effect will tend to distort spectral as well as spatial lines. This discussion pertains only to effects that act only on the spectral domain

- Several qualification campaigns have been carried out on radiated S4 detectors by ESA[1,2] and by ADS independently. The results of these breadboards have been analyzed to derive the relevant trap parameters which are required for this simulation. A detailed explanation of this work is outside of the scope of this paper. For reference, only the relevant trap parameters derived from the experimental data are summarized in Table 1.

- Since the RICTI effect is also highly sensitive on the detector architecture, for completion relevant parameters related to the NIR detector are provided in Table 2.

- The Absolute Radiometric Accuracy (ARA) is an instrument level performance requirement that is relevant in the context of the RICTI effect. It is defined as the unknown systematic measurement error of the value associated to a Level-1b spatial sample. The ESA requirement is for a ARA better than 2% (goal) including all possible effects

Table 1 –Trap parameters within then NIR detector

Trap Parameter	Units	Symbol	Trap 1	Trap 2
Number of traps per pixel at FWC	e	N_t	3.19	2.43
Trap capture cross section (m2)	m^2	σ_{trap}	1e-22	2.52e-23
Electron thermal velocity at 215 K (m/s)	m/s	v_{th}	1.92e5	1.92e5
Trap release constant at 215 K (microsec)	μs	τ_r	371	1480
Cloud volume dependency on signal	-	β	0.7	0.7

Table 2 – Detector parameters for the NIR path

Detector Parameter	Units	Value
Spectral pixels in image zone	-	713
Spectral pixels in memory zone	-	737
Trasfer period for Image to Memory	μs	2.50
Transfer period for Memory to Read out	μs	453.20

- Finally, the relative spectral radiometric accuracy (RSRA) is another performance requirement also relevant in the current context. It is defined as the relative variation of the systematic error of the spectral channels acquired in a given spectral window. The ESA requirement is for a RSRA better than 0.5 % (for a spectral window of 7.5nm).

Keeping the above points in mind, a typical applicable scene in the nir, is pushed through two simulations. In the first case, the detector does not have any radiation damage (nominal case). In the second case ,the detector has the RICTI damages that are expected to be incurred by the end of life of our instrument. The resulting L1b spectra are shown in the Fig. 4.

On a first impression, the two spectra coincide. Nevertheless, when the difference between these is plotted, it becomes clear that significant deviations are found as shown in Fig. 5. This is especially true for the regions close to the deep absorption lines.

The ARA and the RSRA were then computed using the distorted CTI spectra and the results are shown in Fig. 6. It is clear that the impact of the RICTI effect on these two performance requirements is extremely critical. In the case of the ARA, the RICTI effect consumes almost 50% of the budget. In the case of the RSRA, the situation is more critical as the RICTI effect by itself consumes the entire budget available

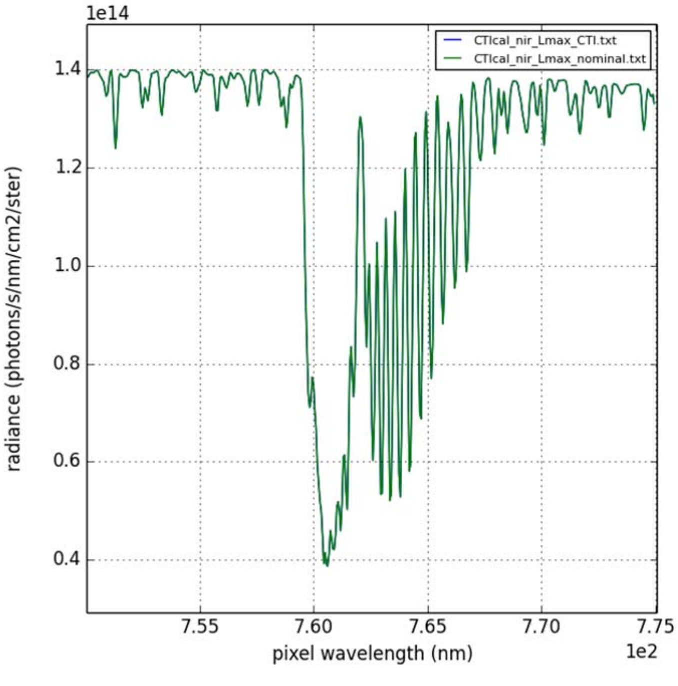

Fig. 4. L1b spectra produced in the simulation. The 'nominal' corresponds to the L1b product associated with a detector lacking RICTI. The 'cti' spectrum corresponds to the L1b product associated with the S4's end of life

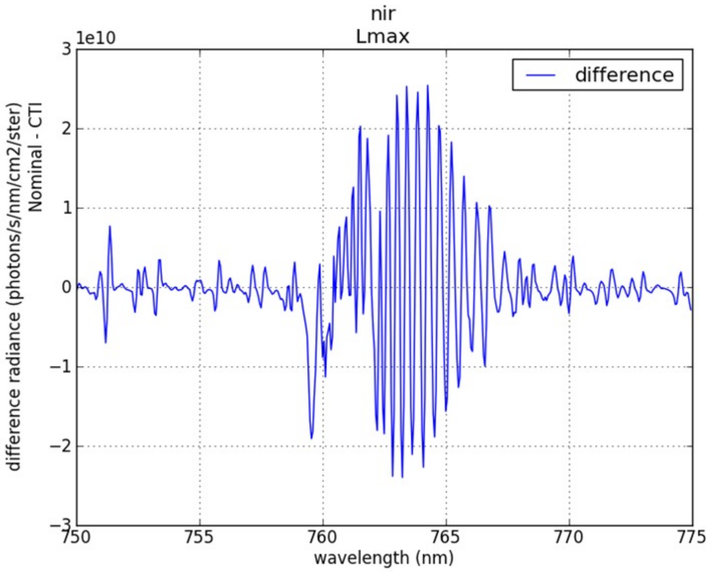

Fig. 5. Difference between the 'nominal' and the 'cti' spectrum revealing spectral distortion caused by the RICTI effect

CORRECTION

It was shown that the radiometric errors induced by the radiation-CTI effect can simply not be accommodated within the performance budgets. In particular the case of RSRA becomes severe. Strategies are thus necessary to reduce achieve overall compliances to these two performance requirements. A simple alternative would be to allow for the detectors to deteriorate through the lifetime of the instrument, but to introduce a specific RICTI correction algorithm into the L1b processor. For this approach to be feasible, the demand on computational resources must be kept low, the speed of the correction must be fast, and the physical parameters required must be either known a priori or must be accessible through the calibration/verification routines in orbit.

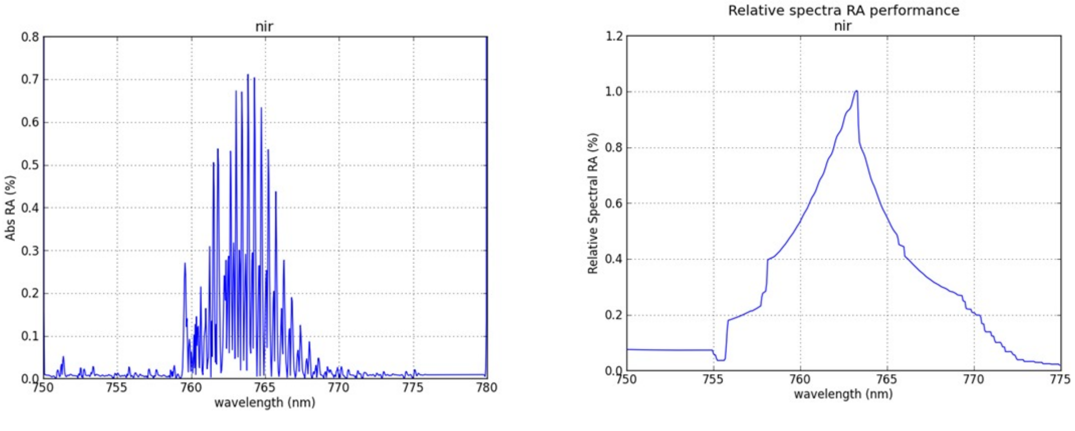

Fig. 6. Applicable performances. On the right: the ARA. On the left: the RSRA. In both cases the effect of the RICTI effect is critical

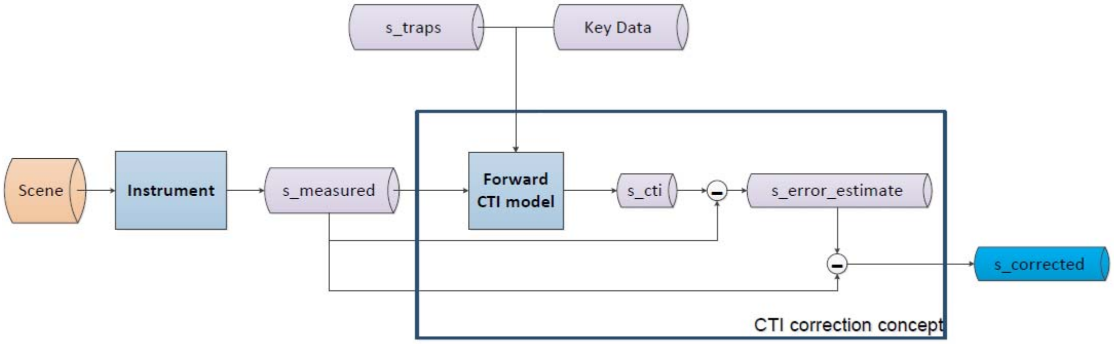

Fig. 7. Schematic showing the proposed RICTI correction concept

A RICTI correction concept which meets all these constrains is sketched out in Fig. 7. It is a forward correction concept, very similar to the straylight correction concepts found in state of the art scientific instrumentation.

The algorithm works as follows:

- A scene from the earth enters the instrument and a vector $s_{measured}$ is produced. This corresponds to one spectral line in the detector. If the detectors have been exposed to radiation damage, the vector $s_{measured}$ would contain a distorted spectra which needs to be corrected
- A second vector, s_{traps}, tracks the number of occupied traps, for a specific trap species, for the spectral row under consideration. This vector has a complex dependency in the charge volumes that have previously visited a given pixel. In addition, the vector would also have a dependence on the amount of radiation damage accumulated. Specifically this means that at BOL, the vector is simply zero. As mission time goes by, the total number of available traps grows and this vector starts to be non-zero. The growth of traps in orbit is a parameter that would be monitored in orbit
- Key Data is must also be made available for the operation of this correction concept. Parameters that are required include transfer times, detector layout, etc. In addition trap related parameters would form part of this data set including trap species capture times, trap species release times, and cloud volume dependences. These trap parameters would indeed be characterized on ground through measurements
- These vectors are pushed into the CTI forward model which is equivalent to that described in the *CTI model* section. This effectively implies is that a distortion will be calculated on a spectrum that is potentially already distorted.
- The outcome is a new vector: s_{cti}. This is a spectra that has been distorted with the aid of the forward model
- To estimate the cti error, $s_{errorEstimate}$, associated with $s_{measured}$, the following operation is carried out:

$$s_{measured} = s_{measured} - s_{cti}$$

- The corrected spectrum would then be:

$$s_{corrected} = s_{measured} - s_{errorEstimate}$$

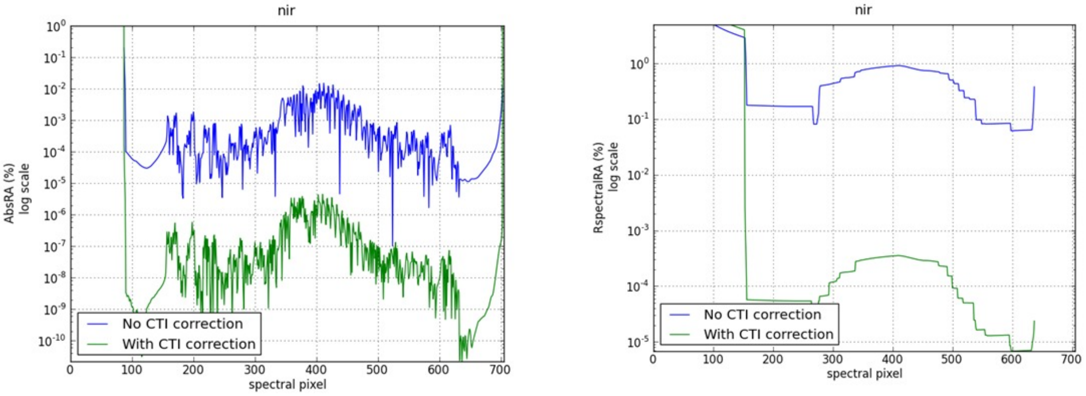

Fig. 8. Correction efficiency comparing the performances obtained with an uncorrected spectrum against a corrected spectrum. On the right: ARA. On the left: the RSRA

The improvement in ARA and RSRA was tested by carrying out a dedicated simulation. The scenes ingested were slightly different from the scenes used in the previous chapter. Nevertheless, the trap and detector characteristics were equivalent. The improvement in ARA and RSRA when the proposed correction concept is implemented is shown in Fig. 8.

These results show that the proposed concept has the capability of reducing the error on AbsRA and on RsRA induced by the RICTI effect by approximately 3 decades. Such large correction efficiencies imply that the CTI effect would be a minimal contributor to the radiometric error budgets

PARAMETER LIST

For clarity, we summarize all the parameters that are used in the document in this section.

Parameter	**Description**	**Units**
V_{FWC}	Volume of electron cloud at FWC	m^3
V_c	Volume of electron cloud	m^3
$S(t)$	Number of electrons within a pixel (time)	e
S_{FWC}	Number of electrons at FWC	e
β	Volume dependence of cloud	-
N_T	Total number of traps within a pixel	e
$N_o(t)$	Number of occupied traps within a pixel (time)	e
$N_{o,i}$	Initial number of occupied traps within a pixel	e
τ_r	Release time constant	$1/s$
τ_c	Capture time constant	$1/s$
n_e	Electron density	e/m^3
v_{th}	Electron thermal velocity	m/s
σ_{trap}	Trap cross-section	m^2
ψ	Field enhancement factor	-
χ	Entropy factor	-
N_c	Effective density of states (bottom conduction band)	-
k	Boltzmann constant	J/K
T	Temperature	K

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[2] T. Prod’homme et al., “Radiation-induced charge transfer inefficiency in Charge-Coupled Devices: Sentinel-4 CCD pre-development as a case study”, *SPIE*, 2014